

Increased Water Availability and Flood Risk Due to Reduced Evaporation at Lime Down

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Summary

1. Solar installations are designed to capture solar energy in the form of electricity, and remove it from site for use elsewhere. Solar energy also drives evaporation of water from land surfaces. In solar sites, there will therefore be less energy available to evaporate water, and evaporation will be reduced. This will result in an increase in soil moisture in solar sites, and the effective production of water, which can be a benefit in dry areas, and increase flood risk in wet areas. In dry areas, the additional water is the basis for *agrivoltaism*, the co-location of agriculture and solar energy production for mutual benefit. Studies on agrivoltaic sites have confirmed the increase in soil moisture which occurs due to solar installations. This report suggests a method of calculating the excess water due to reduction of evaporation, applies it to the Lime Down Solar Farm and considers whether it will increase flood risk.
2. At Lime Down, the additional water generated from evaporation restriction, calculated using fairly conservative assumptions, amounts to about 233,000 cubic metres per annum. This will increase soil wetness and increase the flow of rivers and streams both on- and off site. Off-site the proportional increase in flows will be small, but needs to be considered in the context of the cumulative effects of other solar developments which feed into the same rivers. In the small watercourses on site, the proportional effects will be larger. Both need to be considered in flood risk assessments. The increased soil moisture will increase flood risk by increasing the area of saturated ground close to the panels, and extend the time during which the ground is saturated. In the Autumn the catchments will become more flood-sensitive at an earlier date in time for the Autumn storm season, and the flood-sensitive period will be prolonged in Spring. The additional water needs to be considered in the flood risk assessments and mitigation strategies, and provides another reason for not consenting the Lime Down Solar Farm in such a flood-sensitive area.

Author

3. I am an Emeritus Professor of Geography and Environmental Science at the University of Reading. I have been involved in hydrological research since 1977, first as an environmental scientist in the electrical generation industry working on the effects of acid rain on freshwaters, and after I returned to academic life in 1999, working on modelling and monitoring freshwaters, and hydrology and climate change. I am a co-author of the standard paper on climate change and the water environment in England and Wales, and co-led the modelling work packages of two large EU-funded projects, EUROLIMPACS and REFRESH, which investigated the predicted effects of climate change on waters across Europe. My publications on hydrological topics have been referenced more than 1000 times. I live adjacent to the Lime Down area. The evidence I have produced is based upon my professional expertise, and is my true and professional opinion.

Introduction

4. The replacement of agricultural crops or natural vegetation with solar panels can have a number of profound hydrological effects, which have not been widely studied in the UK. Most solar farms around the world are located in sunny environments where the climate is much drier than the UK, often arid or semi-arid. Though research and experience in dry areas is still relevant, the relative importance of the various hydrological mechanisms are likely to change in wetter areas. In this report I will briefly review the evidence that solar farms can make the ground wetter, and describe some mechanisms which may account for this. I will attempt to quantify the effects for the Lime Down Solar Farm, and assess the potential implications for flooding on- and off-site.

Effects of Solar Farms on Soil Wetness

5. There is ample evidence that solar panel installations on soil and vegetation surfaces cause an increase in wetness. Increased soil moisture and water availability is the main benefit supporting the practice of *agrivoltaism* – co-location of solar panels and agriculture for mutual benefit (e.g. [1]). Agrivoltaic systems are becoming widespread around the world, but not in the UK, where the additional water is less likely to be a benefit, and the other main advantage – shading of crops from intense sunlight – is not applicable. In a meta-analysis of 42 studies round the world, Chen et al. [2] noted an average 300% increase in soil moisture in fields with solar panels, though with wide variability. Reviews of agrivoltaic systems (e.g. [1] quote large numbers of papers in which soil moisture increases in the agrivoltaic scheme. Some studies of pure solar farms show the same thing. In the UK, Armstrong et al. [3] made a year's micrometeorological study of a solar farm near Swindon. The data in this paper are hard to evaluate because they are presented as smoothed by a statistical model, but essentially soil moisture was higher than in the open field, both under the panels and in the gaps between the panels, for the first 9 months of the year, and the same everywhere for the remaining 3 months. The results of such studies will of course depend on the weather in the year in question. Adeh et al., [4] working in an area of Oregon, USA, with a Mediterranean climate, followed the time course of soil moisture in a solar farm from saturated conditions in early spring to dry summer conditions. Soil moisture under the panels remained high whereas areas partially shaded by panels were a little drier and control areas away from the influence of the solar farm dried quickly. Redistribution of water complicates these studies: for instance, Wu et al. [5] in a study in China found that moisture content increased by 60% under the middle

of the panels but by 114% under the bottom edge. In a dry site in Colorado, USA, Choi et al. [6] found a statistically significant increase in soil moisture under panels, most pronounced under the lower edge. Bajehbaj et al. [7] working in Pennsylvania, USA, found higher soil moisture under driplines, but lower under panels compared to outside. Yavari et al 2022 [8] review these and other studies in which soil moisture under panels increases. As well as the academic literature, photographs of solar panels in the UK standing in pools of water are commonplace (see e.g. the expert report from Stop Lime Down's Soil and Agriculture consultant). Though moderated by site conditions, it seems clear that solar farms in general increase soil moisture.

Mechanism of Moisture Generation: Reduced Evaporation

6. The major reason behind the increase in soil wetness in solar farms is likely to be reduced evaporation. Evaporation from land surfaces is driven by solar energy. The whole purpose of a solar farm is to capture this energy and move it offsite in the form of electricity, for use elsewhere. There will therefore be less solar energy available on site for evaporating water. To illustrate the potential magnitude of this effect, if the Applicant's estimate of the energy output from the scheme of 438,000 MWh yr⁻¹ from ES Ch 7 [APP-059] paragraph 7.10.73 is accepted, then the site will lose the ability to evaporate 642,984 cubic metres of water per year (see Annex 1 for calculation). For comparison, rainfall on the 878 ha of solar PV areas (ES, Ch3 [APP-055] Paragraph 3.2.8) will supply 7,436,000 cubic metres annually (Annex 1). This calculation shows that the export of energy is likely to be significant in reducing evaporation and cannot be neglected.

7. Evaporation in catchment areas is sometimes referred to as evapotranspiration to recognise that much of it takes place through uptake of water by plant roots and evaporation from leaves (transpiration). Evapotranspiration is driven by solar energy, but can be restricted by water availability. Evapotranspiration with an adequate supply of water is known as Potential Evapotranspiration (PET), and can be calculated relatively easily (see Paragraph 10 below). Evapotranspiration when water supply is restricted is known as Actual Evapotranspiration (AET). A few papers report direct measurements of AET under solar panels compared to the outside. Marrou et al. [9,10] measured both PET and AET reductions under panels in an irrigated agrivoltaics scheme in Montpellier, France (43°N). For a lettuce crop, AET was reduced by 29% under full panel cover, 25% with half the panel density. As expected, PET was reduced

a little more, by 38% and 31% respectively. For a cucumber crop, the reduction was somewhat less, 19% and 14% for AET, 27% and 19% for PET. A study in Greece [11] calculated a reduction in PET under solar panels of about 466 mm, though the baseline was not stated. Annual rainfall in this area is about 630 mm, so the reduction in AET would be much less than 466 mm due to lack of water availability. The increase in water percolation due to panel construction was calculated to be between 38 and 82 mm yr⁻¹ – a benefit in this dry area.

8. Latent heat fluxes approximate to AET and have been measured in a number of studies. Jiang et al. [12] measured a 47% decrease in latent heat flux under panels in an arid area of China. Chang et al. [13] modelled a widespread decrease in latent heat fluxes over northern China due to solar panel installation. They state that the decrease in evaporation and thus increased water availability will bring benefits to this largely dry region. It can be seen that what data there are support the theoretical prediction that solar panels will reduce evaporation, but there are few data from wet areas. Reductions in evaporation would be expected to be greater in wet areas, as water is available most of the time, and more incoming solar radiation would be expected to be dissipated as latent heat than in dry areas, rather than warming surfaces.
9. Reduced evaporation provides an explanation for the observed increase in soil moisture in solar farms, but quantifying the amount of additional water due to reduced evaporation is a difficult problem. Ideally it would be based on micrometeorology of a solar installation, quantifying energy transformations and fluxes and their effect on evaporation. The data to evaluate this under UK conditions do not exist. However, it is possible to scope the magnitude of the problem by making a few assumptions. The method suggested is as follows:
 - a) Calculate average evaporation in the area. This gives evaporation in the absence of solar panels.
 - b) Reduce evaporation on the panel area by the efficiency of the panel expressed as a percentage. This allows for energy export as electricity by the panel. It assumes that evaporation is directly proportional to the energy input, and that the panel does not modify the energy flux in any other way.
 - c) Calculate the additional water produced in the catchment by the reduced evaporation.
 - d) Note that this calculation uses the actual panel area, not the area of ground occupied by panels. The number of panels at Lime Down is stated to be 598,260 in ES

(Chapter 7 [APP-059], paragraph 7.10.11, each of an area of 3.12 m², generating a total panel area of 1,866,571 m²).

10. The standard method for estimating evapotranspiration is the Penman-Monteith Model, developed by two British physicists, which exists in numerous variants. For instance, the UN Food and Agriculture Organisation adopted one of these as a standard method for scoping evapotranspiration in 1998 [14]. Essentially it calculates evapotranspiration from an adequately-watered, actively growing grass sward, and has proved to give reasonable results in a variety of environments throughout the world. The Penman-Monteith Model assumes an adequate supply of water at all times, and hence calculates PET. If water availability is limited, the amount of water evaporating will be reduced. This is the Actual Evapotranspiration (AET). AET is much more difficult to estimate than PET, and varies considerably between years and seasonally. In the UK, the average ratio AET to PET ranges from 1.0 in the wettest areas of the country in the mountains of the west (i.e. evaporation is rarely limited by water availability) to 0.78 in the driest areas of SE England [15]. These are high values by world standards. The high values mean that solar panels will have a larger effect on evaporation than in drier places, and also that the calculation is less uncertain. In the Lime Down area the AET/PET ratio is about 0.87 [15], Fig. 1.

11. Annual evaporation rates have been calculated using Penman-Monteith, up to the year 2015, for 671 British catchments by the CAMELS-GB Project [16]. This provides an independent estimate of evaporation calculated by experts in the field. The catchments include the Bristol Avon at Fosse Way upstream of Malmesbury, which is representative of Lime Down. I used the average PET calculated by CAMELS-GB for the Lime Down area for the years 2000 to 2015 as input to the calculation. AET was then calculated by multiplying by 0.87.

12. The calculation for Lime Down is:

Potential Evaporation	535.9 mm
Actual Evaporation	466.2 mm
Panel efficiency	23%
Evaporation reduction	107.2 mm
Panel Area, Lime Down	1,866,571 m ²
Additional Water generated	200,159 m ³ .

13. The presence of the solar farm is thus calculated to generate an extra 200,000 cubic metres of water annually at Lime Down. This is likely to be an underestimate for two main reasons. 1) as well as losing energy to electrical power, solar panels absorb short-wave solar radiation and re-radiate it as long-wave radiation. To the extent that they are more efficient at this than the grass sward they replace, this will also result in a loss of energy for evaporation; and 2) evaporation also depends on energy advected in by the wind. This is allowed for in the Penman-Monteith calculation. Many studies show reduced windspeed in solar arrays. For instance, Armstrong et al. [3], working in a solar park near Swindon, UK, showed an 86% reduction in windspeed under the panels and a 63% reduction in the gaps between the panels. Adeh et al., [4] working in Oregon, USA, demonstrated a 37% reduction in windspeed in the gaps between the panels at 0.5 m above ground level, and a 24% reduction at 1.2m, both reductions being statistically significant. Reduced windspeed would be expected to reduce evaporation. Opposed to these two mechanisms, heat transfer from the panels by various routes may warm and dry the air over the underlying vegetation, and this will tend to increase evaporation compared to the situation without panels. It is not possible to calculate an upper bound for loss of evaporation potential without more investigation of these effects. If the panels completely eliminated evaporation, the additional water at Lime Down would be 870,000 m³. This is very unlikely, but 500,000 m³ might be a credible precautionary value.
14. Another contributor to evaporation is interception loss, which is evaporation of stored water before it reaches the ground. Interception loss is an important additional contributor to evaporation in countries like the UK with long periods of low to moderate rainfall. Vegetation surfaces store water from precipitation, making it more available for evaporation from advected energy. Solar panels will be much less effective in storing precipitation than vegetation as they are smooth, whereas vegetation is rough on a fine scale, leaves being typically covered in hairs and other small protuberances. The slope of solar panels also induces immediate runoff, leaving much less time for evaporation of the intercepted water to take place. Interception loss from solar panels is likely therefore to be much smaller than for vegetation, though it will not be zero. Replacing vegetation with solar panels is likely therefore to lead to a reduction in interception. There appear to be no quantitative measurements of interception loss by solar panels in the literature, and therefore no basis apart from the theoretical considerations above for estimating how large the reduction in interception loss might be. A reduction of 50-80% would seem to be a reasonable value for the UK. The CAMELS

database provides an estimate of interception loss for a grass sward. For the Lime Down area in 2000 to 2015 this is 35 mm. Assuming conservatively that solar panels reduce interception loss by 50%, i.e. 17.5 mm, this leads to the generation of an additional 32,665 m³ of water in the Lime Down catchment. The total additional water generated by reduction of evaporation by solar panels is thus 200,159+32,665 = 232,824 m³.

15. There are a few papers which have measured actual evapotranspiration under solar panels compared to the outside which show that the above calculations are credible. Marrou et al. [9,10] measured both PET and AET reductions under panels in an irrigated agrivoltaics scheme in Montpellier, France (43°N). For a lettuce crop, AET was reduced by 29% under full panel cover, 25% with half the panel density. As expected, PET was reduced a little more, by 38% and 31% respectively. For a cucumber crop, the reduction was somewhat less, 19% and 14% for AET, 27% and 19% for PET. A study in Greece [11] calculated a reduction in PET under solar panels of about 466 mm, though the baseline was not stated. Annual rainfall in this area is about 630 mm, so the reduction in AET would be much less than 466 mm due to lack of water availability. The increase in water percolation due to panel construction was calculated to be between 38 and 82 mm yr⁻¹ – a benefit in this dry area. Latent heat fluxes approximate to AET and have been measured in a number of studies. Jiang et al. [12] measured a 47% decrease in latent heat flux under panels in an arid area of China. Chang et al. [13] modelled a widespread decrease in latent heat fluxes over northern China due to solar panel installation. They state that the decrease in evaporation and thus increased water availability will bring benefits to this largely dry region. The limited data from the scientific literature thus support the theoretical prediction that solar panels will reduce evaporation, but there are few data from wet areas. However, reductions in evaporation would be expected to be greater in wet areas, as water is available most of the time.

Implications

16. Once constructed, the Lime Down Solar Farm will effectively generate an additional 233,000 cubic metres of water annually in the Bristol Avon catchment. This needs to be taken into account in any Flood Risk Assessment. Though this is a large volume of water, the proportional increase in flow over the year on the main River Avon will not be large – about 0.22% at Great Somerford (see Annex 1 for calculations). However, there are numerous other solar schemes in the catchment, built, under construction and planned, and the cumulative effect of these

on this flood-prone river needs to be considered before Lime Down can be consented. It should be noted that the evaporation reduction mechanism only applies when panels are constructed over a water-storing surface such as soil or vegetation. Panels mounted over rapidly-draining surfaces such as rooftops, car parks etc will not make a significant difference to evaporation.

17. On smaller sub-catchments, the increased supply of water becomes more significant. On the Gauze Brook, which drains Area D of the scheme, the additional water adds 0.62% to the annual runoff. On the Norton Brook, which drains Area C and part of Area B, the increase is at least 2.6%. Both these streams have houses at risk on their banks. The small stream reaching the Avon on the west side of Norton would probably be similar to the Norton Brook. For the Sherston Avon in Malmesbury, draining Areas A, B and C, the increase is 0.44%. Though these figures may appear small, it must be questioned whether any increase is acceptable given the current prevalence of flooding.
18. Considering just the annual output of water is not adequate for assessing flooding, which occurs in extreme conditions. In its response to this point in Stop Lime Down's Relevant Representation, [[PDA-009](#)], SLD079, the Applicant states "Flood risk is determined by rainfall intensity, infiltration capacity and surface runoff generation during storm events, which occur over short timescales where evaporation rates are not the controlling factor, and any reduction in evaporation between rainfall events does not materially affect the capacity of vegetated soils to infiltrate and attenuate rainfall during subsequent storms." The last phrase is highly contentious. I am not suggesting that reduced evaporation has a direct role during storm events. However, reduced evaporation will increase the area of saturated ground close to the panels, and also mean that saturation occurs earlier in the hydrological cycle. This will be particularly significant in the Autumn, as the catchments will become more flood-sensitive at an earlier date in time for the Autumn storm season. "Surface runoff generation during storm events" is strongly influenced by the amount of saturated ground. This is the "saturation excess" runoff generation mechanism in which water cannot penetrate the soil because it is already saturated with water, as opposed to the "infiltration excess" mechanism in which water cannot penetrate because the soil intrinsically has a low infiltration rate, like many of the soils at Lime Down. Saturation excess is the basis of modern understanding of runoff generation, as described in all hydrology textbooks (e.g. Ward and Robinson, 2000) [17] Ch 7.

Conclusion

19. The export of electrical energy from the solar farm, and the smaller interception loss from the panels, leads to reduced evaporation and an increase in the water content of the catchment containing the solar farm. This additional water will ultimately leave the solar farm, either in surface runoff or groundwater or both. It will therefore increase the amount of water off site, in the rivers draining the panel sites. The onus should be on the Applicant to demonstrate that this does not constitute an increased flood risk, contrary to the requirements of the Overarching Policy on Renewable Energy, EN-1. The same processes will occur in other solar farms in the same catchment, giving rise to a cumulative effect on the drainage waters which may in total increase the flood risk significantly, even if the individual contributions do not. This also needs to be assessed. The additional water will increase the area of saturated ground around the panels and tend to make it appear earlier in the Autumn and persist longer in Spring. The catchment will therefore be at risk of flooding for longer.
20. Covering a relatively high proportion of the area of small headwater catchments in a high flood risk district with outsize solar panels is unwise. The Applicant has failed to demonstrate that this will not cause an unacceptable flood risk both on- and off site. This is particularly true given the low permeability and sensitivity to compaction of the catchment soils as demonstrated in other reports. The Applicant's plans to mitigate the risks are mostly too vague to be credible. In my view, the additional water generated by the mechanisms discussed in this report will lead to an unacceptable flood risk and should contribute to the application being rejected.

References

1. Chopdar, R.K., et al., *Comprehensive review on agrivoltaics with technical, environmental and societal insights*. Renewable and Sustainable Energy Reviews, 2024. **197**: p. 114416.
2. Chen, H., et al., *Ecological and environmental effects of global photovoltaic power plants: A meta-analysis*. Journal of Environmental Management, 2025. **373**: p. 123785.
3. Armstrong, A., N.J. Ostle, and J. Whitaker, *Solar park microclimate and vegetation management effects on grassland carbon cycling*. Environmental Research Letters, 2016. **11**(7): p. 074016.
4. Adeh, H.E., J.S. Selker, and C.W. Higgins, *Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency*. PloS one, 2018. **13**(11): p. e0203256.

5. Wu, C., et al., *Ecohydrological effects of photovoltaic solar farms on soil microclimates and moisture regimes in arid Northwest China: A modeling study*. Science of The Total Environment, 2022. **802**: p. 149946.
6. Choi, C.S., et al., *Effects of revegetation on soil physical and chemical properties in solar photovoltaic infrastructure*. Frontiers in Environmental Science, 2020. **8**: p. 140.
7. Bajehbaj, R.Y. et al., *Quantifying soil moisture and evapotranspiration heterogeneity within a solar farm: Implications for stormwater management* Journal of Hydrology 2024 **638** 131474
8. Yavari, R., et al., *Minimizing environmental impacts of solar farms: a review of current science on landscape hydrology and guidance on stormwater management*. Environmental Research: Infrastructure and Sustainability, 2022. **2**(3): p. 032002.
9. Marrou, H., et al., *Microclimate under agrivoltaic systems: Is crop growth rate affected in the partial shade of solar panels?* Agricultural and Forest Meteorology, 2013. **177**: p. 117-132.
10. Marrou, H., L. Dufour, and J. Wery, *How does a shelter of solar panels influence water flows in a soil–crop system?* European Journal of Agronomy, 2013. **50**: p. 38-51
11. Pisinaras, V., et al., *Conceptualizing and assessing the effects of installation and operation of photovoltaic power plants on major hydrologic budget constituents*. Science of The Total Environment, 2014. **493**: p. 239-250.
12. Jiang, J., et al., *Observed impacts of utility-scale photovoltaic plant on local air temperature and energy partitioning in the barren areas*. Renewable Energy, 2021. **174**: p. 157-169.
13. Chang, R., et al., *Projected PV plants in China's Gobi Deserts would result in lower evaporation and wind*. Solar Energy, 2023. **256**: p. 140-150.
14. Allen, R.G., et al., *Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56*. Fao, Rome, 1998. **300**(9): p. D05109.
15. Kay, A.L., et al., *A hydrological perspective on evaporation: historical trends and future projections in Britain*. Journal of Water and Climate Change, 2013. **4**(3): p. 193-208.
16. Coxon, G., et al., *CAMELS-GB: hydrometeorological time series and landscape attributes for 671 catchments in Great Britain*. Earth Syst. Sci. Data, 2020. **12**(4): p. 2459-2483.
17. Ward, R.C. and M. Robinson, *Principles of Hydrology*. 2000, London: McGraw-Hill.

Annex 1 – Calculations

1. Potential loss of Evaporation Capacity

Disclaimer: this calculation has been assisted by artificial intelligence (Claude.ai) and the output checked for “hallucinations”.

Question – to find the volume of water evaporated by 1 MWh of energy. Assumed to evaporate in place at environmental temperatures (20°C).

1 MWh = 3,600,000,000 J (3.6 GJ)

- Energy available: 3,600,000,000 J
- Latent heat of water at 20°C: 2,453,000 J/kg
- Mass evaporated: $3,600,000,000 \div 2,453,000 \approx 1,468 \text{ kg} = 1.468 \text{ m}^3$
- Applicant’s estimate of annual energy production 438,000 MWh yr⁻¹ from ES Ch 7 [APP-059] paragraph 7.10.73.
- Therefore potential loss of evaporation capacity is $1.468 \times 438,000 = 642,984 \text{ m}^3$

2. Changes in River Flow

All hydrological data from Centre for Ecology and Hydrology National River Flow Archive <https://nrfa.ceh.ac.uk/>.

On the Avon at Great Somerford, the annual water output is about 107,138,000 m³. Increased water output is 232,824m³, which is a 0.22% increase

On the Gauze Brook, the annual water output is about 9,151,700 m³. The Gauze Brook drains Area D of the Scheme which includes 24.3% of the panel area, implying an increased water output of 56,576 m³, which is a 0.62% increase.

For the Norton Brook, which is ungauged, the water flow can be assumed to be the same as the Gauze Brook scaled by their relative catchment areas. This will be an exaggeration of flow in the Norton Brook, because flow in the Gauze Brook is supplemented in the summer by a stream support borehole. Norton Brook catchment area is. 9.94 km² and the Gauze Brook 28.2 km². Annual output of the Norton Brook is thus $9,151,700 \times 9.94/28.2 = 3,225,813 \text{ m}^3$. The Norton Brook drains Area C of

the Scheme which includes 36.2% of the panel area, implying an increased water output of 84,282 m³, which is a 2.6% increase.

On the Sherston Avon at Malmesbury, the annual water output is about 31,557,600 m³. The Avon above Malmesbury drains Areas A, B and C of the Scheme which includes 59.9% of the panel area, implying an increased water output of 139,461 m³, which is a 0.44% increase.

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Comprehensive review on agrivoltaics with technical, environmental and societal insights

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ABSTRACT

The need for large-scale PV power generation is essential for reducing climate change, but land competition is a barrier. Agrivoltaic systems, which combine crop production and photovoltaic power generation, offer a potential solution by increasing the productivity and land use efficiency. Agrivoltaic systems can help in promoting sustainable agriculture and lowering greenhouse gas emissions. This review investigates the viability of agrivoltaic systems in a variety of locations, exploring into the technologies used, including panel height, interspace, configuration, and technical innovations. Agronomic practices related to crop selection and crop yield are also reported. Environmental impacts of agrivoltaic systems related to land and water use are discussed. The advantages of the agrivoltaic systems, such as increased land use efficiency, higher crop yields, and lower water use, are thoroughly examined. While the benefits of the agrivoltaic systems are discussed, the review also highlights the challenges associated, such as need for careful planning and the possibility of trade-offs between energy production and crop yields. The study offers technical, environmental and societal insights into agrivoltaic systems as a sustainable and financially viable solution for promoting sustainable agriculture and energy. The work emphasizes the significance of ongoing research and development, and provides recommendations in line with the Sustainable Development Goals.

1. Introduction

The demand for food and energy rises in tandem with the increase in global population [1]. This energy need cannot be met by fossil fuels due to their depletion and the effects of climate change. To reduce climate change, a transition from fossil fuels to renewable energy sources is both required and unavoidable. Solar energy has the ability to meet a substantial portion of the world's non-renewable energy needs and is currently the fastest-growing power generation technology. The expansion of solar farms simultaneously necessitates larger land areas. This expansion raises the possibility of land allocation conflicts between food production, preservation of biodiversity and electricity generation [2]. The amount of land required for multi-MW solar farm installations has been called into question due to rising concerns about global agricultural demand [3]. Further, water-energy-ecosystem nexus [4] and water saving in arid areas [5] are also of important concern. It is of utmost importance to find sustainable energy sources and production

methods that will not cause harm to the environment or hinder the production of food. Agrivoltaic system (AVS), also referred to as agro-photovoltaics [6], involve the installation of solar panels above agricultural crops, enabling the simultaneous production of electricity and crops on the same land [7]. This system was first proposed by Goetzberger and Zastrow in 1982 to increase agricultural output on the same land as solar energy plants [8]. AVS holds potential for improved land use and water saving. It is important to perform deep analysis and diversify overall energy systems with technological changes from environmental and climate change perspectives [9].

Fig. 1 explains the classification of AVS on the basis of the mounting of the PV panels. The two main types of AVS are fixed type AVS and dynamic type AVS. Fixed type AVS are stationary and take up more space on the land. This type of AVS covers ground mounted, stilt-mounted panels, PV greenhouses, and rooftop AVS [10,11]. Ground mounted AVS is further classified into tilted and vertical installations of PV panels. On the other hand, dynamic type AVS includes a variety of configurations that permit solar panels to move in order to follow the

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Abbreviations		HD	Half Density
AVS	Agrivoltaic System	UMass	University of Massachusetts
PV	Photo-voltaic	Si	Silicon
ICAR	Indian Agriculture Research Institute	CdTe	Cadmium telluride
CAZRI	Central Arid Zone Research Institute	CIGS	Copper Indium Gallium Selenide
CUTM	Centurion University of Technology and Management	GaAs	Gallium Arsenide
SDGs	Sustainable Development Goals	STPV	Semi-transparent Photo-voltaic
MW	Mega Watt	CPV	Concentrator Photovoltaic
MWh	Mega Watt Hours	CT	Control Tracking
kWp	Kilo Watt Peak	CAS	Concentrated-lighting Agrivoltaic System
LUE	Land Use Efficiency	EAS	Even-lighting Agrivoltaic System
LER	Land Equivalent Ratio	OPV	Organic Photovoltaics
WUE	Water Use Efficiency	BCR	Benefit-cost Ratio
FD	Full Density	GHG	Green House Gases

sun’s position; single or dual-axis solar trackers are the examples [11].

The type of AVS chosen will depend on the particular project requirements, the availability of land area, the climate, and the desired outputs. There has been an increased interest in agrivoltaic systems in recent years leading to development of commercial and research facilities at several locations worldwide. Fig. 2 depicts the location and details of some of the commercial and research facilities, while Table 1 shows a global comparison of the commercial and research facilities around the world.

From the data shown in Tables 1, it can be seen that a wide range of crops can be grown in AVS, including vegetables, fruits, and grains. This highlights the versatility and potential of the solar-powered farming. Some facilities use stilt-mounted PV modules or bifacial or semi-transparent double-glass modules. It is noted that while commercial facilities aim to maximize crop yields and generate revenue, research facilities often focus on exploring the potential benefits and limitations of AVS. Fig. 2 depicts a visual overview of commercial and research AVS

facilities, each of which is identified by a serial number from Table 1. It combines details of facilities with geographic locations, which are exhibited on a global horizontal irradiation map.

This review expands on the previous works in the field of agrivoltaics by thoroughly evaluating the performance and impact of the AVS technology. While the previous reviews focused on the specific aspects of agrivoltaics, such as panel types or land use efficiency, this review takes a comprehensive look at the subject. A thorough literature review of various research and commercial facilities across the globe is conducted in this work. Previous works on various aspects of AVS have been carefully reviewed and important points are reported here, compared and analyzed such as designs, configurations, factors affecting performance, crop selection and types, crop yield and energy outputs. Furthermore, the benefits, challenges and the resulting impacts on land and water use efficiency are also discussed and analyzed. On the basis of the review, several recommendations and future scope of work have been suggested. It provides a framework for investigating the impact of

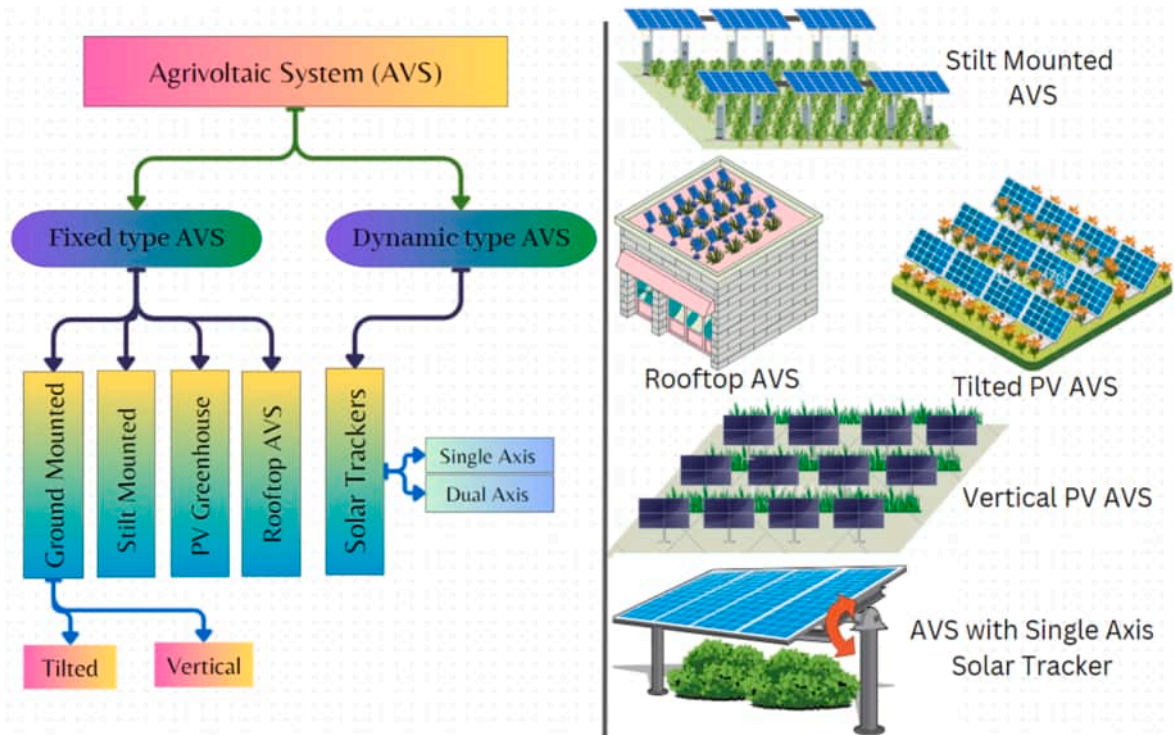


Fig. 1. Classification of AVS on the basis of mounting of PV panels.

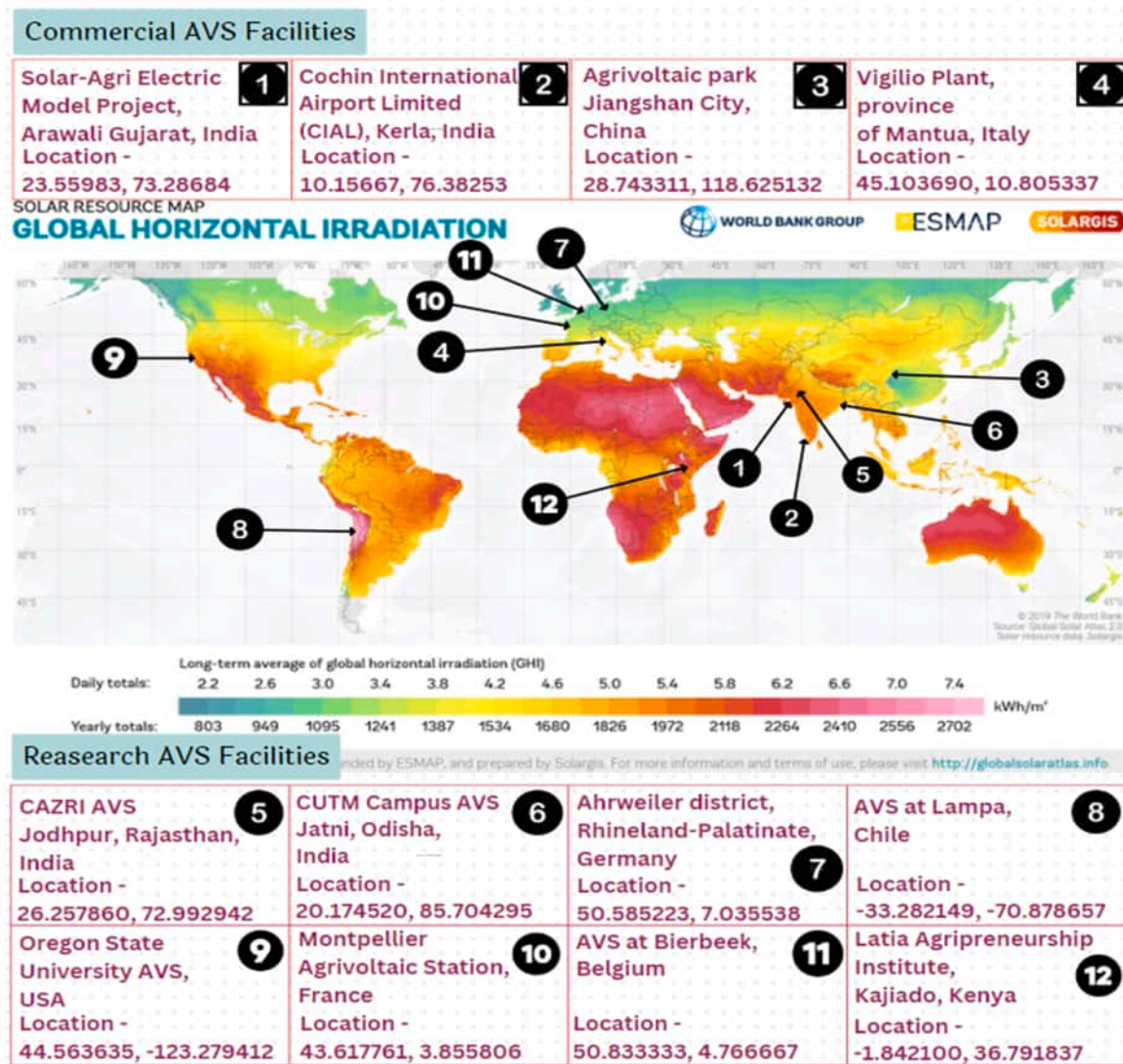


Fig. 2. Location of some commercial and research AVS facilities.

agrivoltaic systems on sustainable agriculture and energy harvesting. This review provides a valuable resource for researchers, policymakers, and practitioners by consolidating and synthesizing existing knowledge. This study will be useful in better designing and enhancing performance of AVS. Fig. 3 illustrates the organization of the review work into different sections and sub-sections.

2. Agrivoltaic systems: potential

Agrivoltaics offer considerable potential as a resource-efficient, co-productive renewable energy system, particularly in regions with dense populations or limited land area [10]. Dinesh et al. suggested that AVS approach can boost farm income by more than 30%, provided suitable crops are selected to minimize yield losses from shading effects [10]. However, its highest potential is anticipated in semi-arid and arid regions, where various synergistic side effects arising from lower radiation density incident on crops can be expected [24–26]. In these regions, crop cultivation often suffers from the adverse effects of high solar radiation and concomitant water losses. Water use efficiency has been shown to increase underneath the panels in agrivoltaic systems [3,24,27], and these findings are becoming even more relevant, as water demand for irrigation is expected to increase in prospective future climatic

conditions [28]. Table 2 shows the potential of AVS in different regions of the world.

Studies done in Montpellier, France [21] and Nagpur, India [30], which are shown in Table 2, show that adding PV panels to lettuce and grape farming can make the ground much more productive and valuable. Meanwhile, study in Japan [29] and the United States [31] shows that PV panels can be carefully placed to improve crop yields and water efficiency. Also, in dry parts of India, PV systems not only help make power, but they also help collect rainwater [16]. Finally, rooftop PV systems in Singapore improve urban usability and lower ambient temperatures [34], demonstrating the numerous benefits of agrivoltaics.

Several studies have been published in the last decade that emphasize the possibility of saving land resources while enhancing sustainable agriculture [8]. Dupraz et al. concluded that AVS can boost land use efficiency by 70% [35]. Another study by Barron-Gafford et al. looked at how AVS can improve crop yields in a number of ways, including by reducing plant moisture loss and solar (PV) panel thermal stress [36]. Fig. 4 demonstrates the significant potential of AVS, which is gaining attention due to its contribution towards the advancement of sustainable food and energy security. Solar panel shading in AVS improves crop quality and yield by reducing water loss and regulating temperatures [37]. AVS can boost renewable energy production, reducing fossil fuel

Table 2
Potential of AVS in different parts of the world.

Year	Type of PV Plant	Location	Crops	PV Capacity	Results	Ref.
2017	Solar Tracker	Montpellier, France	Lettuce	–	Dynamic PV panels could produce high lettuce biomass/land area unit under full-sun. On sunny days, solar tracking mode increased energy production/unit land area (+74%) compared to stationary (half density). Land Equivalent Ratio (LER) was always >1.	[21]
2019	Fixed, Stilt-mounted	Japan	Sweet Corn	4.5 kW	The low-density setup produced 4.9% more corn stover biomass and yielded 5.6% more corn/m ² than the control.	[29]
2019	Fixed, Tilted	Nagpur, Maharashtra, India	Grape	168.64 kW	Economic value could increase by > 15 times in comparison to conventional farming while yielding the same production. If adopted on a national scale, will meet the energy needs of over 15 million people.	[30]
2021	Fixed, Tilted	CAZRI, Jodhpur, India	Seasonal Vegetation	105 kW	System is most effective in arid zones. Connected to grid, annually generates 7,500,000 rupees/acre of electricity, additional benefit of rainwater harvesting.	[16]
2021	Fixed, Tilted	Oregon State University, Corvallis, OR, USA	Tomato	482 kW	Total crop yield was highest in the control full irrigated areas and decreased as shading increased. Water productivity was highest in areas which were both shaded and experiencing deficit irrigation. These results demonstrate the potential for water productivity improvements.	[31]
2021	Fixed	University of Tokyo, Japan	Rice	–	Fixed panels at 3 m above ground, shading rate - 27 to 39%, maintains at least 80% of rice yield. At 28% rice paddies in Japan, such systems could generate 284 million MWh per year	[32]
2022	Dummy PV panels	Korea	Soyabean, Rice, Onion, Garlic, Rye	–	Rice, soybean, adzuki bean, corn, rye, garlic, and onion were examined under the AVS to boost seed, vegetable, and forage production. AVS had no significant effect on rye and maize forage yield over two years, suggesting that AVS-grown forage crops were appropriate for cattle.	[33]
2022	Rooftop, Fixed	Singapore	Romaine lettuce	–	AVS offer potential to maximize the usability of rooftop spaces. In both sunny and cloudy day simulations, crops below a PV lowered ambient temperatures more than the canopy alone. On sunny and cloudy days, average ambient temperatures of PV panels were projected to drop 0.23 °C and 0.18 °C, respectively.	[34]

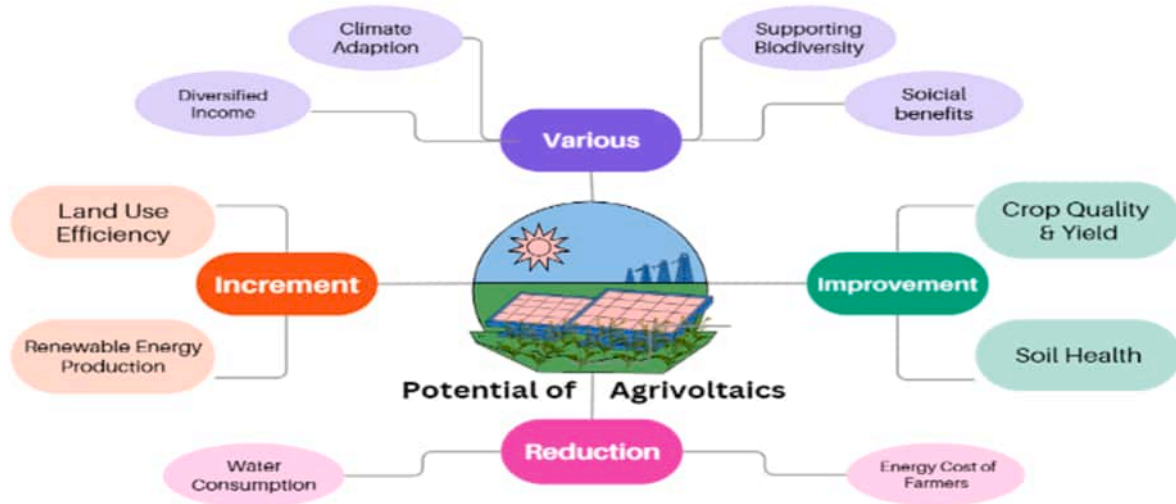


Fig. 4. Potential contributions of an AVS in different ways.

Table 3
Solution to mitigate the shading effect caused by opaque PV modules in AVS [11].

S. No.	Modifications in AVS	Details	Used in
1	Using shade tolerant crops	Lettuce, Clover Grass, Pome, Berry, Alfalfa, Broccoli, Cassava, Chard, Hog peanut, Kale, Kohlrabi, Mustard greens, Parsley, Spinach, Sweet potato	[21,33, 43–47]
2	Using modified pattern of PV module	Straight line, Checkboard and different densities of PV panels	[16,17, 21]
3	Using solar trackers	One axis, Two axis	[21,48, 49]
4	PV panel technology modification	Semitransparent, Bifacial and concentrating PV module	[44, 50–53]

possible solutions to mitigate the shading effect caused by opaque PV panels.

Table 3 shows that different modifications have been tried to improve the performance of AVS. These include the selection of shade-tolerant crops, the testing of various PV module patterns and densities, the implementation of solar tracking systems, and the use of advanced PV panel technologies. The goal of these modifications is to make agriculture and energy generation in AVS work better together. Technology considerations and configurations related to various solar PV aspects of AVS experiments in various parts of the world are presented in sub-sections.

3.1. Height and interspacing of solar PV modules in AVS

In AVS, the height and interspacing of PV modules are crucial for

optimizing the performance and interaction with the underlying agricultural produce. The specific configurations of height and interspacing can vary based on a number of variables, including crop requirements, solar panel design, available sunlight, and regional climate [11,54]. Some studies suggest that a panel height of around 3–4 m can provide an optimal balance between crop yield and solar energy generation in certain crops, such as vegetables and berries [46,55], while taller crops may need higher panels [29]. Trommsdorff et al. recommended in a case study of Maharashtra, India, that panel height should be between 3 and 4 m for sufficient light and efficient energy production [52]. Fig. 5 depicts the height of the PV panels in AVS at various locations around the world.

According to a review by Abidin et al. the optimal distance between plants in AVS plots for biomass production is either 1.21 or 1.52 m [20]. Ground-mounted and stilt-mounted solar panels in AVS have their own advantages and disadvantages which are briefly shown in Table 4. Plant development and accessibility are both influenced by the height of solar PV panels, with elevated structures increasing the scope of agricultural activities but also increasing maintenance costs by 38% [43,59].

Table 5 shows the impacts of height and interspacing of PV panels on agricultural production.

Data in Table 5 shows that a 4 m panel height reduces durum wheat yields by 8–11% in Montpellier, France. Similar yield effects are observed in Jodhpur, India, with the exception of medicinal plants, due to distinct interspacing. In Kansas, lettuce yields are reduced at 3.2 m spacing, but there is no effect at 6.4 m spacing. In Tucson, yield responses vary among chili and tomato varieties, with some experiencing significant increases. Agrivoltaic effects on crops are dependent on panel height, spacing, and shading, highlighting the need for site-specific considerations to simultaneously optimize agricultural production and solar energy generation.

3.2. Different designs of PV array

According to Weselek et al. to achieve maximum simultaneous energy and food production, it is recommended to cover only about one-third of the area with the solar panels in an AVS [8]. At the Montpellier Experimental Agrivoltaic Station, researchers have been studying the optimal use of photovoltaic structures in AVS since 2010 [60]. Over nearly a decade, they designed, built, and tested both full-density (FD) and half-density (HD) AVS. The FD structure maximizes solar power generation, but only half the sunrays reach the crops. Under the HD structure, up to 70% of the sun's rays can reach the crops, optimizing both electricity and agricultural output. Panels were installed at 4.0 m above ground level, inclined at 25° [60] (Fig. 6).

ICAR-CAZRI in Jodhpur, India installed an AVS with 105 kWp capacity, covering 4624 m² area with a fixed-tilt ground-mounted system using polycrystalline silicon PV modules with a 26° southerly tilt and E-W orientation [16,17] (Fig. 6). The AVS design was tested in five settings and three blocks (Table-6), and a full-density, one-row PV array (AVS-1) was found to provide the highest monetary returns per unit land area

Table 4

Comparison of stilt and ground-mounted solar panels in AVS.

Structure	Advantages	Disadvantages
Ground-mounted Solar Panels	Easier installation, maintenance and cleaning	Limited use of land for crops due to shading from the solar panels
	Lower installation costs	Risk of damage from farming equipment
Stilt-mounted Solar Panels	Can be integrated with farming operations	Higher risk of pest and disease in shaded areas
		Limited scope for water management
	Greater land-use efficiency for crops	Higher installation and maintenance costs
	Reduced risk of pest and disease in shaded areas	More complex installation and design
	Better scope for water management	May require additional support structures in windy areas
	Reduced risk of damage from farming equipment	

[17].

UMass Crop Research Farm conducted a trial where an AVS structure without concrete base was built 2.3 m above the ground, allowing 70% of solar energy to reach crops below. A 1.2–1.5 m spacing between AVS plots was found to be optimal for biomass output [65,66] (Fig. 7). In another AVS research project at CUTM Odisha, India, Giri et al. used a ground-mounted double-row SPV system. Since PV panel density is 50%, the lower row has continuous panels and the upper row has panels with uniform gaps [18] (Fig. 7). This ensures crops receive enough sunlight.

Yano et al. recommended a checkerboard pattern for AVS to achieve uniform radiation distribution due to alternating shadows cast by the structure. The optimal panel row spacing, height, density configuration, and tilting angle can be adjusted to suit the geographic location [67]. Willocks et al. also conducted research on a checkerboard layout of PV panels for growing potatoes in Belgium. Although the PV panels may help plants grow, they did not prevent frost sufficiently [68]. An AVS must be carefully designed to achieve a balance between crop yield and energy production. The system should be designed to make optimal use of available land, minimize crop shading, and maximize solar energy capture by the PV array. Design investigated range from 50% to 100% PV panel density.

3.3. Types of solar PV panels used in AVS

Pioneering progress in solar energy utilization across nations has been noticed in recent years, and PV technology has gained a significant market share in the contemporary electricity industry. Commercial PV cells are often made of silicon (Si), cadmium telluride (CdTe), copper indium gallium selenide (CIGS), or gallium arsenide (GaAs) [69,70]. Table 7 displays the percentage of the worldwide PV module market held by the most popular types.

Bifacial photovoltaic panels produce 20% more electricity than monofacial at a lower cost of electricity [71]. A vertical bifacial PV

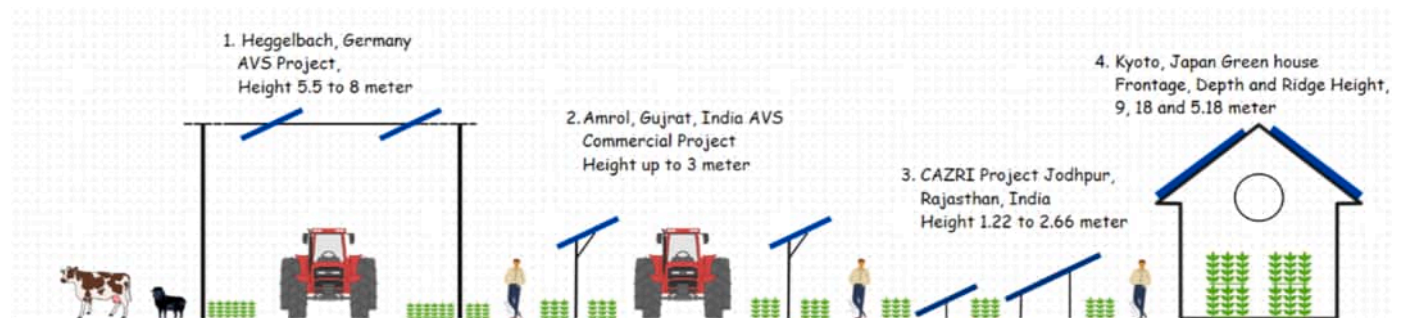


Fig. 5. Height of PV panels in different types of AVS at different location, height specification figure prepared using data sources, 1- [56], 2- [57], 3- [3], 4- [58].

Table 5
Impacts of PV panels specification on agriculture production.

Location	Crops	Specification	Impact on Crop	Ref.
Montpellier, France	Durum wheat	Height: 4 m	Reduction in yield 8–11%	[60]
Jodhpur, India	Vigna radiata, cuminum, cicer arietinum, aloevera, cassia angustifolia, convolvulus pluricaulis, capasicum annum	1.22 m, 1.94 m and 2.66 m, 3 m 6 m and 9 m interspaces	Yields were significantly affected for all crops excepting medicinal plants like aloe vera, cassia angustifolia, convolvulus pluricaulis	[17, 57]
Kansas, USA	Lettuce	Height: 4 m, 6.4 m for half density and 3.2 m for full density interspacing	Yield reduced for 3.2 m spacing, no impact for 6.4 m spacing	[10]
Tucson, USA	Chili and tomato	Height: 3.3 m, interspacing: 1 m	For Capsicum annum var. glabriusculum yield is three times higher, for Capsicum annum var. annum, no impact on yield, for Solanum lycopersicum var. cerasiforme yield is two times higher.	[36]
Chiba Prefecture, Japan	Maize	Height: 2.7 m	Yield variations based on row spacing	[29]
Ongjin-Gun, Republic of Korea	Grape	Height: 2 m	No significant impact on germination and grape growth	[61]
Southwest Germany	Red beet, winter wheat, potato, and red clover	Height: 5 m, Spacing: 6.3 m	Variable impact on crop height and yield	[26]
South Korea	Rice, potato, sesame, and soybean	Height: 4–4.5 m	No significant impact on growth, yield reductions for some crops	[62]
Monticelli d'Ongina, Italy	Soybean	Height: 4–4.5 m	Crop height variations and yield reductions under shading	[63]
South Korea	Sesame, mung bean, kidney bean, corn and soybean	Height: 5.42 m, Shading rates: 21.3–32%	Variable yield reductions depending on crop and shading rate	[64]

system could replace or modify existing AVS infrastructure with benefits such as requiring less land, being less disruptive to farming, and potentially saving installation costs [44,72]. Semi-transparent PV modules (STPV) have been found to be a better option for AVS in terms of cost, durability, and energy production, with organic photovoltaics or dye-sensitized solar cells being used to create wavelength-selective transparency in STPV modules [42]. Cho et al. found that a transparent module generated the highest amount of energy, although its performance depended on location and orientation. Long-term monitoring is needed to accurately measure module performance. Cho et al. found that a transparent module generated the highest amount of energy [61], although its performance depended on location and orientation. Long-term monitoring is needed to accurately measure module performance. Table 8 describes the types of panels used in AVS at different locations globally.

The results of Table 8 show that monofacial ground-mounted panels

and bifacial panels can increase power production and crop yields in various climates.

3.4. Solar trackers

Solar tracking is a technique for obtaining more energy from the sun by positioning and moving a photovoltaic (PV) solar collector perpendicular to the sun during the day [74]. A solar tracker is a device that moves solar panels so that they receive optimal sun radiation at all times of day [75].

Montpellier Experimental Agrivoltaic Research Station uses solar tracking system which involves two tracker types that are customized for plant growth with panel numbers, height, and a sun-tracking algorithm. The panels are continually readjusted to maintain a set angular range of -50° to $+50^\circ$ with respect to the horizontal plane. This mode generated more electricity with LER values > 1.5 . In control tracking (CT) mode, PV panels are initially parallel to the sunrays (90° from ST mode), catching sunlight efficiently in the morning and late afternoon. PVPs follow the sun for peak intensity from 11 a.m. to 3 p.m. The study shows agrivoltaic systems can maximize energy and crop yields [21]. Amaducci et al. simulated the Northern Italian Agrovoltaco system with solar trackers on hanging structures and panels on secondary axes. Long-term simulations showed that Agrovoltaco-grown corn yielded slightly less in non-drought conditions but more during drought stress than field-grown maize. Agrovoltaco increased rainfed maize yields and saved water [7]. Additional space and infrastructure for solar trackers can be a challenge when planning for and implementing AVS with tracking systems. For small-scale farmers, the added expense and complexity of a solar tracker system may reduce its economic viability.

3.5. Technology innovations

Several innovative technologies within the field of AVS are being studied world over. Concentrated-lighting Agrivoltaic System (CAS), an AVS technology that uses PV panels and concentrated light distribution to generate electricity and crops, was tested in Anhui Province, China. PV panels on a reflective support structure concentrate part of the solar spectrum, for optimum growth on crops below [76,77]. This improves land use, reduces direct sunlight on panels, and gives crops the light they need [77]. CAS dichroic polymer film splits sunlight into two parts for optimal plant growth and solar power generation and keeps soil cool and moist to reduce water consumption. It shades crops in summer [76,78, 79].

Another experiment in Anhui Province, China, showed that the even-lighting agrivoltaic system (EAS) uses translucent photovoltaic (PV) material to cover crops and generate electricity while providing uniform lighting [37], improving crop growth and yield. Grooved glass plates between PV panels split light into different wavelengths and direct it to PV cells at the optimal angle for energy conversion, improving energy generation efficiency [76,80]. EAS reduces water consumption, shades crops, and maximizes land use efficiency and sustainable agriculture [76,80,81].

According to Trommsdorff et al. [82], organic photovoltaics (OPV) has tailored absorption properties and wavelength-selective transparency, making it a promising solar cell option. ASCA, a Franco-German company, makes and sells OPV modules that have high transparency in the solar spectrum between 400 and 700 nm for photosynthesis [82]. Uchanski et al. found that thin-film semi-transparent PV panels in AVS may benefit from their uniform transparency and lower use of semiconductor absorber film [83]. AVS can use semi-transparent PV panels to increase plant light intensity without raising soil or air temperatures. These panels can be used in building-integrated and roof-mounted photovoltaics with indoor climate-controlled crop operations [61]. Farmers can use various types of sensors in AVS smart farming. Illuminance sensor, solar irradiance sensor, temperature and humidity sensors can closely monitor plant

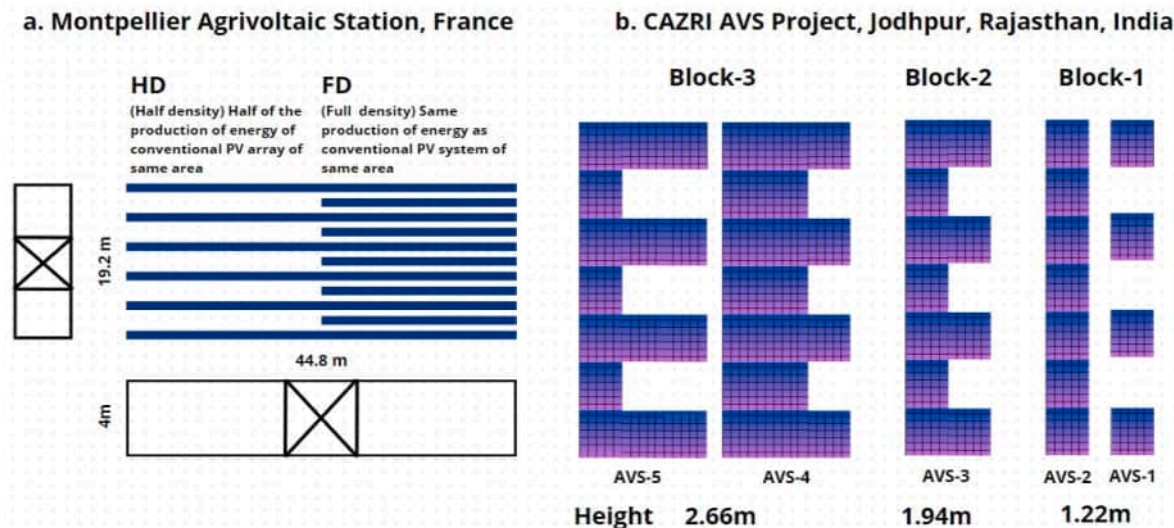


Fig. 6. AVS designs at Montpellier, France (a) and CAZRI, Jodhpur, India (b) Data source- [17,60].

Table 6
AVS design at ICAR-CAZRI, Jodhpur, Rajasthan, (India) [17].

System	Number of rows	PV density	Blocks
AVS-1	1	100%	Block - 1
AVS-2	1	50%	
AVS-3	2	Top row - 60% Bottom row - 100%	Block - 2
AVS-4	3	Top row - 60% Middle row - 100% Bottom row - 100%	Block - 3
AVS-5	3	Top row - 60% Middle row - 60% Bottom row - 100%	

growth in real-time conditions [84]. The digitization of agriculture and the incorporation of smart agricultural technologies into agrivoltaic systems optimize resource management, including irrigation, resulting in increased productivity and minimized environmental impact [85].

4. Agronomic practices and production

Agronomic practices for AVS are similar to typical agronomic practices in general [20], including crop, soil, and solar panel management to ensure resource efficiency and productivity. Fig. 8 shows the step-by-step progress of practices.

In AVS, agronomic practices include careful site selection and evaluation, followed by panel installation. Crop selection is an important step, discussed in Section 3.1. Soil preparation involves weeding, adding

Table 7
The most popular photovoltaic modules in the world market [69].

Material of PV panels	Global Market share
Gallium Arsenide (GaAs)	1%
Copper Indium Gallium Selenide (CIGS)	4%
Amorphous Silicon	5%
Cadmium Telluride (CdTe)	6%
Mono-crystalline silicon	30%
Poly-crystalline silicon	54%

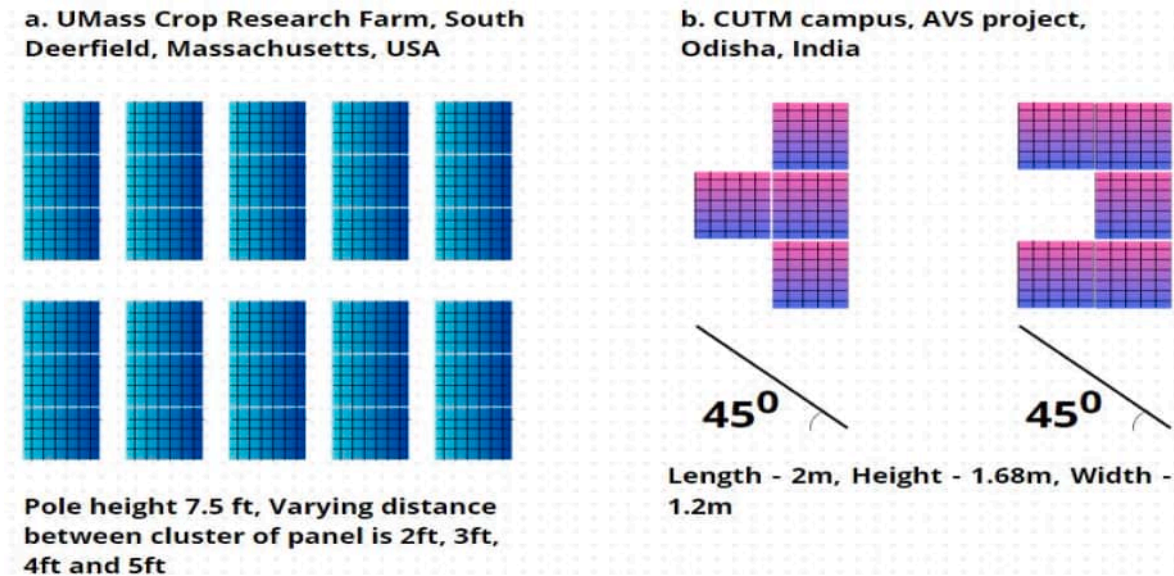


Fig. 7. AVS designs at UMass Research Farm, USA (a) and CUTM Campus Odisha, India (b) Data source- [18,65].

Table 8
Various solar panel technologies around the world used in AVS.

AVS technology	Location	Crops	Results	Ref.
Monofacial ground-mounted, tilted panels arranged in different densities	Jodhpur, India	Brinjal, Aloe vera, Spinach, Snap melon, Cluster bean	Full density one row PV array produced maximum electricity and crop, ensuring maximum monetary returns per unit land area. Best design for arid regions.	[17]
Bifacial PV panels (Simulation Study)	Maharashtra, India	Soybean, Cotton, Tomato, Banana	The electric yield of bifacial modules was 6.4% higher than that of monofacial modules when the same system configuration was simulated.	[52]
Ground mounted, Polycrystalline, E-W oriented, tilt angle 18°, 1.1 m height, total capacity 1435 kWp	USA	Semi-arid pasture	The heterogeneity of shade and sunlight distribution in the pasture, as a consequence of the photovoltaic (PV) panels, led to diverse microclimate, which in turn affected plant growth and soil moisture content differently across the region.	[8, 20, 73]
Fixed bifacial PV panels, S-N facing, E-W wings, and E-W vertical (Multi scale modeling approach)	USA	–	Specific yield increased by 39% for S-N facing, 18% for E-W wing, and 13% for E-W vertical bifacial systems compared to a ground-mounted mono-facial PV array.	[51]
Regular and controlled solar tracking with monofacial PV panels	Montpellier France	Lettuce	Dynamic PV panels may maximize lettuce biomass yield per land area unit at full sun. Controlled tracking enhanced crop growth and radiation but lowered electric production.	[21]
The E/W and N/S facing vertical installed bifacial PV modules (Modeling approach)	Pakistan	–	E/W vertical bifacial PV farms optimize crop light distribution. E/W vertical PV farms could reduce the water budget and be mounted in agrivoltaic systems in regions with scarce water.	[50]

Table 8 (continued)

AVS technology	Location	Crops	Results	Ref.
Vertical bifacial photovoltaic AVS (Optimization model)	Sweden	Oats and potatoes	Crop yield dropped by half when distance between rows was cut from 20 to 5 m. The optimal row distance for potato is 9.7 m, and for oat, it is 9.2 m, LER is 1.2	[44]
The tracking and backtracking for horizontal tracker solar PV panels,	Spain	Olive tree	Crops would not shade solar panels due to spacing between collectors. LER can rise from 28.9% to 47.2%.	[49]
Tinted semitransparent PV panels AVS	Italy	Spinach, Basil	Biomass-electricity co-generation is expected to yield a 2.5% financial gross gain for basil and 35% for spinach. Basil biomass yields remain unchanged, whereas spinach biomass yields decrease statistically. Both plants have more protein.	[45]
Highly transparent concentrator photovoltaic (CPV) modules	Japan	Unknown	Greater power generation and sunlight transmission than traditional PV, higher installation cost and necessitating solar tracking.	[53]

organic matter, and testing for nutrients [86]. Crops need careful irrigation and solar panels need regular cleaning [20]. Pest and disease management using cultural, biological, and chemical methods is essential [86]. Careful harvesting protects solar panels from accidental damage. Regular maintenance maintains solar panels clean by removing dust, debris, and dirt, thereby extending their lifespan. Crop rotation protects soil, prevents pests and diseases, and maximizes space and resources [20]. Finally, monitoring crop growth, soil moisture, and solar panel efficiency helps identify improvements and optimize system performance.

4.1. Crop selection

AVS crops must meet the system’s design, light, water, and economic requirements. Waghmare et al. [87] concluded in their review article that transpiration cooling from planted crops in agrivoltaic systems can improve solar PV module performance and lifespan by lowering their temperature. Plant leaves cool by evaporating latent heat. Plants types such as succulent plants (*Brahmi/Centella asiatica*, *Aloe vera*) can enhance the cooling and efficiency of PV panels [87]. Leafy greens like lettuce and spinach thrive in partial shade [88–90] while drought-tolerant beans and peppers need less water [3,16,17]. Inter-cropping with nitrogen-fixing crops maximizes space and reduces competition [90]. Economically viable crops, including medicinal herbs and specialty fruits, should also be considered [91]. Table 9 defines criteria for selecting crops in AVS.

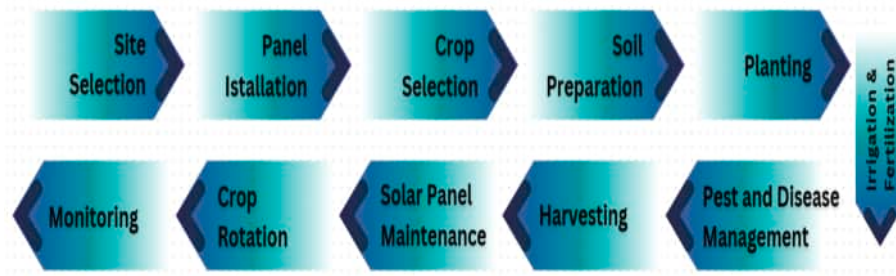


Fig. 8. Steps of agronomic practices in AVS

Light is the primary driver of photosynthesis in plants, but shade-tolerant plants adapt to low light conditions by increasing their chlorophyll content, antioxidant levels, and light utilization. These adaptations allow photosynthesis to be effective even with limited sunlight [92]. According to Santra et al. *aloe vera*, chickpeas, cluster beans, cumin, isabgol, mung beans, moth beans, sankhpuspi, and sonamukhi are AVS-friendly crops [3]. These crops are typically low in height and require minimal water, which makes them highly compatible with AVS [3,16,17,93].

4.2. Crop production in AVS around the world

Agriculture production of AVS in different location around the world is shown in Table 10.

The studies reviewed in Table 10 indicate that the effects of these systems on crop yield depend on several factors, including the type of crop, solar panel configuration, shading, and location. While some studies have reported slightly lower crop yields under AVS [7,33,46,94] others have found that they can increase crop productivity and diversify farmers' income streams [29,36,52].

Fig. 9 depicts a comparison of crop production without PV and in an AVS at different experimental setups. Bok choy and lettuce production were lower in the AVS compared to traditional farming. Corn production increased slightly under low density of panels in AVS. Both systems produced almost the same amount of kiwi fruit and winter cabbage. Therefore, factors such as crop selection, the amount of sunlight available, and the design of the system can all affect how efficient an agrivoltaic setup is for the crop production.

Table 9
Crop selection criteria.

Factors	Relevance
Shade tolerance	It is critical to choose shade-tolerant crops as solar panels shade the crops. Leafy greens, herbs, and some vegetables are best.
Water requirements	Ground-mounted agrivoltaic systems' solar panel foundations can suffer from excessive soil moisture. Succulents and other crops with low water requirements can be chosen to avoid stability problems [87].
Growth height	Consider crop height to avoid interfering with solar panel operation or blocking sunlight from other crops in ground-mounted AVS. Shorter crops like lettuce work best with this system.
Harvest timing	Solar panels may need cleaning or maintenance during the growing season, so harvest timing is important. Agrivoltaic systems may not be suitable for long-season or high-maintenance crops.
Microclimate	Crops that are adapted to the local microclimate and can tolerate solar panel-induced air temperature changes may be better for the system [20,87].
Economic value	To ensure the system's financial viability, the higher economic value crops should be considered.
Local market demand	Consider local crop demand. Selecting local market-demanded crops ensures a ready market for the harvest.

5. AVS: land and water use efficiency

The main reason for increased interest in agrivoltaic systems may be attributed to the possibility of positive environmental impacts with improved land and water use efficiency. AVS are considered to reduce evaporation and produce more food and energy per unit of land.

5.1. Land use efficiency (LUE)

Land use efficiency refers to the amount of food and/or energy that can be produced per unit of land area, and it is an important metric for evaluating the productivity and efficiency of AVS [103]. AVS increases LUE by producing both food and energy on the same piece of land, reducing the land area required to meet food and energy demands, and this is particularly important in areas with limited land availability [17, 56]. This integrated approach is essential for feeding a population expected to reach 10 billion by 2100 [104].

The land equivalent ratio (LER) is another metric used to evaluate the productivity of agricultural systems, defined as the ratio of the yield of the intercrop system to the yield of the same area of land when each crop is grown separately [105]. In the case of AVS, the crops and solar panels can be considered as intercropping system, where the solar panels are the intercrop [106]. The LER can be used to compare the productivity of an AVS to growing crops and generating electricity separately, as Dupraz et al. proposed [60]. In AVS, LER can be calculated by equation (1).

$$LER = \frac{\text{crop yield in AVS}}{\text{crop yield without PV}} + \frac{\text{PV electricity yield in AVS}}{\text{PV electricity yield without crop}} \quad (1)$$

If LER is greater than 1, the AVS is more efficient than a pattern of separate crops and PV arrays on the same area of land [31,36,56]. Fig. 10 shows a practical illustration of LUE. A comparative study was used to design an AVS plant in southern Italy, considering PV panel distance and module technology. The study compared three configurations, CONF#A (tracking), CONF#B (tracking) and fixed module technologies. In both configuration horizontal axis solar trackers with a maximum rotation angle of $\pm 55^\circ$ were used. Pitch distance (refers to the spacing between rows of PV modules) for CONF#A was 6 m and for CONF#B was 7.5 m. The modules are double-sided bifacial N-type panels, and their height extends from 2.0 to 4.0 m for both configurations. In fixed modules researcher used specifications of CONF#B without tracking mechanism [107]. Table 11 and Fig. 10 shows the results with average crop yield modification due to shadowing.

Table 12 displays the LER values of experimental and simulated AVS at various locations around the world.

Higher LER values in Tables 11 and 12 show the potential benefit of AVS. LER is influenced by several factors, including the type of crops grown, the solar panel configuration, and the local climate. Crop yield and energy yield are equally weighted in the LER calculation, which can misinterpret agricultural contributions [113]. LER is used to evaluate AVS efficiency, but it may not reflect the system's agricultural efficiency. LER can be high despite low crop yields [113].

Table 10
Agriculture production of AVS at different location around the world.

Location	Crop	Specification	Results	Ref.
Po Valley, Northern Italy	Maize	Polycrystalline panel, height 4.5 m above ground	Yield under AVS is slightly lower.	[7]
Monticelli d'Ongina, Italy	Soybean	Four shade depth level, 27%, 16%, 18%, 9%	Yield was on average reduced by 8%	[94]
Malaysia	Java Tea	Monocrystalline PV modules	Profitable returns, high humidity levels caused by water evaporation, PV shading can attract pests and increase the risk of crop damage	[95, 96]
Heggelbach, Germany	Potato, winter wheat	Dual bi-facial PV	Dual-use system limits shading from PV panels to 50% of any given land area. Potato production has a favorable price-performance ratio of 0.85, while winter wheat has an unfavorable ratio of 4.62.	[43]
South Korea	Rice, soybean, corn, rye, garlic, and onion	Panels were 1.5 m apart and 3.3 m high. Shade intolerant crop species	Forage quality from rye was similar between AVS and open field, rice yield was significantly lower with reductions of 18.7% in 2018 and 8.9% in 2019	[33]
South Korea	Broccoli	Bifacial solar panels, installed 3–4 m above ground	Crop production slightly decreased and broccoli metabolites were altered.	[46]
Jeonju, South Korea	Italian ryegrass, barley, maize	Stilt mounted solar PV	Reduced forage yield in significant percentage. Summer crops suffer more from shade than winter crops. The yield reduction is 18% or less.	[97]
Chiba Prefecture, Japan	Corn	Stilt mounted at 2.7 m from the ground, in high-density and low-density configuration	Corn stover biomass was 4.9% greater in the low-density configuration than the control, and corn yield per square meter was 5.6% higher in the low-density configuration	[29]
AZ, USA	Chiltepin pepper, jalapeno, tomato	Straight line configuration of PV modules in an open field system	Increased chiltepin pepper production 33%, tomato production is doubled but jalapeno production	[36]

Table 10 (continued)

Location	Crop	Specification	Results	Ref.
Montpellier, France	Lettuce	Farming under 25% and 50% PV cover ratio	reduced by 11% from conventional farming. Average yield factor 99% and 79% of the control cropping	[47]
Maharashtra, India	Grapes	Grape-Based AVS	Economic value increased 15 times compared to conventional farming. No change in grape production	[52]
Odisha, India	Turmeric, Ginger, Potato, Vegetable	Ground mounted polycrystalline PV	The benefit-cost ratio (BCR) of Turmeric- 1.86, Ginger-1.25, Potato-1.32, Vegetable- 1.61	[98, 99]

5.2. Water use efficiency

Water use efficiency is an important factor in AVS because it affects both crop yield and panel efficiency. It is a measure of how efficiently water is used in crop production, and is typically expressed as the amount of biomass or yield produced per unit of water used [114,115]. To assess the water use efficiency (WUE) in an AVS, the unit of biomass produced per unit of water consumed (measured as kg/m³) is calculated WUE_{PV} and compared with the biomass produced per unit of water consumed in a control zone (without PV) [11]. This comparison enables the determination of the impact of the PV system on WUE, as in equation 2

$$WUE = \frac{WUE_{PV} - WUE_{control}}{WUE_{control}} \quad (2)$$

According to literature survey, agrivoltaic systems have been shown to increase water use efficiency (WUE) and crop yields due to reduced water loss through evaporation [27]. Shade provided by solar panels reduces soil surface temperature, further reducing water loss and improving WUE. Rainwater harvesting can be particularly beneficial in water-limited regions [10]. Improved LER at CAZRI AVS by up to 1.62 indicates increased efficiency of crop production, potentially due to the improved water availability resulting from the system's shade and rainwater harvesting [16,17]. Rainwater harvesting system with an agrivoltaic systems has been designed at CAZRI [116]. Nordberg et al. concluded that AVS can help regulate temperature and humidity levels, protecting crops from heat stress during the hottest parts of the day [117]. Drip irrigation can be easily integrated into AVS and reduce water loss by delivering water only to the crops that require it [6,101]. The study at Oregon State University in Corvallis, US, found that the amount of late-season biomass in places with PV panels was up by a significant 90% [27]. In addition, these regions were 328% more water-efficient than control regions without PV panels [27]. The water used in cleaning solar panels can be utilized for irrigation purposes, thus leading to reuse of cleaning water and reduction in water requirement for irrigation purpose [4].

6. AVS: benefits

6.1. Economic

- Increased crop and electricity production: Agrivoltaic systems are designed to combine agriculture and solar power production on the same land [118]. Research has shown that AVS can increase crop

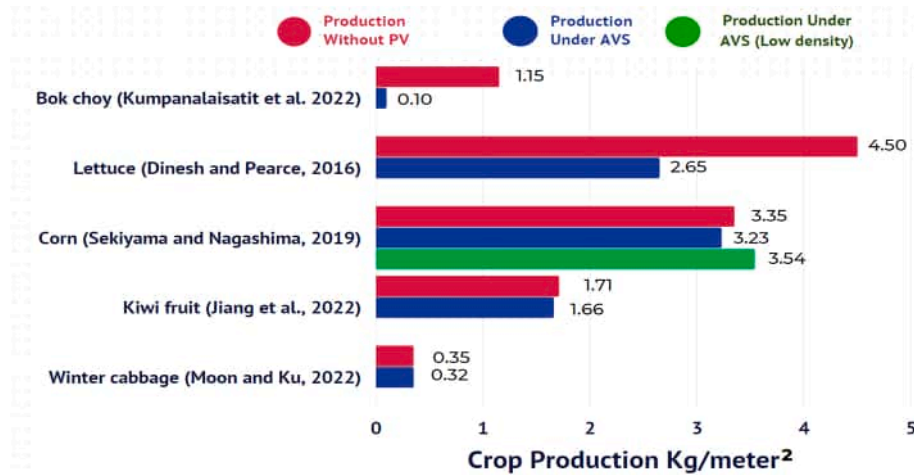


Fig. 9. Crop production comparison, source [10,29,100–102].

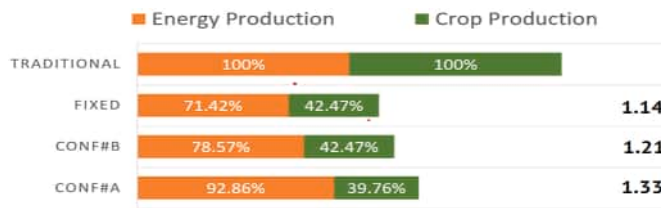


Fig. 10. Land use efficiency in AVS, source of data [107].

Table 11

AVS production and LER at a southern Italy plant with olive production and shadowing-modified average agricultural yield [107].

Configuration	Energy Production GWh/year/ Ha	Crop Production Ton/ Ha	LER
Traditional	1.4 100%	1700 100%	-
Fixed PV	1 71.42%	722 42.47%	1.14
CONF#B	1.1 78.57%	722 42.47%	1.21
CONF#A	1.3 92.86%	676 39.76%	1.33

productivity by shielding crops from extreme heat and providing a more stable environment for growth, leading to higher yields [16–18,29,36,38,43,52,95,96]. AVS can also help reduce the temperature of solar panels through transpiration cooling from planted crops, which can improve energy production efficiency [18,34,100]. Table 13 depicts the data on efficiency improvement at three different locations.

- Net economic benefit: Although farmers in AVS must accept lower crop yields, energy generation on the same land can benefit them and generate an overall financial gain, as shown in Table 14.
- Investment Opportunities: Proctor et al. suggested that AVS investment could transform energy and agriculture [120]. The initial costs of such systems may be outweighed by the benefits of sustainable energy, food production, and rural economic development. The article also suggested that the public and private sectors could collaborate to finance and implement these systems, and that government incentives and policies could boost investment [120].

Table 12

LER of AVS at different location around the world (demonstrating LER values greater than 1).

Location	Crop	LER	Specifications	Reference
Odisha, India	Turmeric	1.73	Portable, adjustable AVS structure	[18]
Anhui, China	Lettuce	1.64	Even-lighting AVS (EAS)	[37]
North Italy	Maize	1.0 to 3.0	Simulation study on Agrovoltaico system consisting solar tracker	[7]
Heggelbach, Germany	Winter wheat	1.71	Higher LER might be from bifacial PV module	[56]
	Celeriac and potato	1.76		
Montpellier, France	Durum wheat	1.7	Full density AVS	[108]
		1.3	Half density AVS	
Niger, Africa	Various	1.33 and 1.13	-	[109]
Chechen Republic, Russia	Beetroots and lettuce	1.7 and 1.4	Simulation study	[110]
Oregon, USA	Lamb growth and pasture production	1.81 for pasture, 2.04 for spring lamb production	Combined sheep grazing and solar energy	[111]
Chiang Mai, Thailand	Bok choy	1.80	Yield is 20% less than general cultivation	[112]

Table 13

Energy production efficiency improvement at different locations.

Location	Specification	Crop	Electricity production improvement	References
Singapore	Rooftop, Fixed	Romaine lettuce	3.05% - sunny day	[34]
Arizona, USA	Fixed PV	Chiltepin pepper, jalapeno, tomato	3.2% - cloudy day	[36]
Thailand	Fixed PV	Bok choy	1%	
			0.09%	[100]

Table 14

Overall financial gain in AVS.

Crop	Crop production in kg/m ²		Yield loss	Energy generation	Net economic benefit in comparison of single crop or electricity production	References
	Control	AVS				
Basil	0.16	0.135	15%	27.8 kWh/m ²	25%	[45]
Spinach	2.2	1.6	26%	17.6 kWh/m ²	35%	
Winter wheat	–	–	18.7%	83% of conventional PV system covering same area	56%	[119]

6.2. Environmental

- Reduced land use: Unlike solar panels, AVS can produce electricity and food on the same land. This reduces land use and protects habitats and biodiversity [91,118].
- Water conservation: The shading provided by solar panels in AVS can help reduce water loss due to evaporation, improving water use efficiency and lowering water consumption, especially in water-stressed areas [3,10,17,27].
- Reduced GHG emissions: AVS contributes to climate change mitigation by generating renewable energy and reducing GHG emissions associated with fossil fuel energy generation. This promotes a sustainable future and supports environmental preservation [6, 121–123].
- Improved microclimate: AVS enhances crop conditions by creating a favorable microclimate, resulting in increased yields and productivity [11,34,48]. Agrivoltaic systems integrated into the restoration of native habitat improve soil quality by enhancing water retention and carbon sequestration potential [41]. Native vegetation with deeper roots stabilizes the soil, thereby decreasing soil erosion and runoff [41].

6.3. Social

- Employment opportunities: The installation and maintenance of AVS can create employment opportunities for local communities, particularly in rural areas where job options may be limited [12,23,122, 124].
- Food security: AVS can help increase food production and improve food security in areas where arable land is limited or traditional farming practices are no longer viable [109,122,124,125].
- Community development: AVS can bring together different stakeholders, such as farmers, energy providers, and local communities, to work towards common goals, fostering social cohesion and community development, and developing valuable new skills [73,126].
- Contribution towards SDGs: Maity et al. explained that AVS can support the UN's Sustainable Development Goals (SDGs). These systems can provide food and energy security to impoverished populations, efficiently use water, reduce climate change, and increase biodiversity [127]. AVS can help achieve SDG 7 by providing affordable, reliable, sustainable, and modern energy for all. It can also reduce energy costs and boost rural economies [41,44]. Agrivoltaic systems also shade crops, reduce evaporation, and improve soil health, contributing to SDG 2 (zero hunger) and SDG 12 (sustainable consumption and production) [127].

7. Challenges

7.1. Financial challenges

- High installation costs: Installing AVS is costly due to the cost of solar panels, supporting structures, and maintenance, which may discourage farmers [128,129].

- Uncertainty of returns: Economic benefits of AVS depend on electricity prices, crop prices, and crop yields [48,130]. Farmers can't accurately assess the economic viability due to this uncertainty.
- Delayed harvesting season: Shading effect can reduce the amount of sunlight reaching crops, resulting in lower agricultural yields and longer harvest times. Farmers may miss out on selling their produce at peak prices, which may have a negative impact on income and increasing food demand [131].

7.2. Design and planning related challenges

- Integration with crop production: Establishing an AVS that works effectively with crop production is difficult. The design must consider crop type, spacing, height, PV panel orientation, and spacing [23,73].
- Coverage rate of PV panels: Huang et al. discuss the difficulties of determining photovoltaic panel coverage for agriculture [132]. Different regions have different crops and environments, and solar panel material affects transparency. Complexities make optimizing coverage rates for maximum electricity generation and crop growth difficult [132]. Managing effectively the sunlight balance between crops and solar modules is a challenge for which innovative methods need to be adopted [133].
- System sizing and layout: Determining the appropriate size and layout of an AVS requires careful consideration of several factors, including the available land area, the type and capacity of the PV panels, and the irrigation requirements [11].
- System maintenance and repair: AVS needs regular maintenance and repair to perform well. Cleaning panels, checking, and replacing system tools are included in it. Maintaining and repairing solar PV panels requires proper planning [134,135].

7.3. Agriculture practice related challenges

- Crop selection: Selecting the right crops that can withstand shading and match requirements, is important and challenging [28,72,96, 136].
- Irrigation management: Although panels can decrease water loss by evaporation and lower water demands [10], it is crucial to guarantee that crops receive sufficient water to sustain their productivity [28].
- Damage due to machinery and livestock: The positioning of PV panels can impact harvesting by obstructing access to crops. Agricultural equipment and livestock can harm solar panels [6,29].

7.4. Environmental, social and governance challenges

- AVS is a comparatively new technology so there are currently no established policies and regulations governing its implementation. Subsidies may not be available to support these systems [8,23,56, 137,138].
- There may be a lack of incentives for farmers to install AVS, or the incentives may not be sufficient to cover the costs of installation and maintenance [23,139].
- Communities that rely heavily on agriculture may welcome agrivoltaics as a new revenue source, whereas communities that rely on

non-agricultural industries may not see the benefits as clearly [140]. Agrivoltaics' benefits and risks affect social acceptance; education and working to inform communities can dispel myths and boost social acceptance.

- Agrivoltaic systems face land degradation and solar panel disposal issues [40,141]. To address end-of-life disposal issues, requires consideration of the entire life cycle of the system from design to disposal, with easily recyclable designs, and carefully implemented recycling programs [40].

8. Discussion and recommendation

This study investigated the case of agrivoltaic technology as a promising solution for increasing land productivity. Fig. 1 classifies AVS by PV panel mounting type as either fixed or dynamic. Fixed AVS (e.g., ground, stilt, rooftop, PV greenhouse) is land-intensive and stationary; ground installations are further classified as tilted or vertical. Single- or dual-axis solar trackers are utilized by dynamic AVS to monitor the sun. The selection is determined by project requirements, land availability, climate, and outputs. Table 1 demonstrates the variety of crops that thrive in AVS, demonstrating the adaptability of solar-powered agriculture for growing vegetables, fruits, and grains. Some facilities utilize PV modules with stilt-mounted, bifacial, or semi-transparent double-glass. Research facilities examine AVS's prospective benefits and limitations, whereas commercial sites prioritize yield and revenue. Fig. 2 provides a visual summary of global commercial and research AVS locations, integrating photos and geographic locations on a map of solar irradiation.

Table 2 displays successful AVS implementations around the globe, demonstrating increased combined outputs in the form of agricultural yield and energy production. AVS has significant potential, notably in densely populated or land-constrained regions as shown in Table 2. It has the greatest potential in semi-arid and arid regions, where it mitigates the negative effects of high solar radiation and conserves water, and can increase agricultural income. Researcher in Montpellier, France, and Nagpur, India, has found that PV panels do not negatively impact the yield of lettuce and grape cultivation. Research conducted in Japan and the United States demonstrates that optimal placement of PV panels increases crop yields and water efficiency. PV systems in India contributed to rainwater harvesting, whereas rooftop PV systems in Singapore improved urban usability and lowered ambient temperatures. AVS increases agricultural yields by decreasing plant moisture loss and regulating temperatures, thereby increasing land use efficiency by up to 70%. Fig. 4 demonstrates the significant potential of AVS to advance sustainable food and energy security, mitigate climate change, and improve agricultural sustainability.

Table 3 lists shade-tolerant crops, customized PV module designs, solar trackers, and enhanced PV panel technologies as solutions to mitigate AVS shading. These strategies boost agriculture-energy synergy. AVS performance optimization depends on panel height and spacing, which varies by crop type, solar panel design, sunlight availability, and climate as depicted in Fig. 5. Studies reveal that 3–4 m of panel height balances crop output and solar energy generation for particular crops. Higher crops may need taller panels installation. The relative advantages and disadvantages of ground-mounted and stilt-mounted solar panels in AVS are discussed in Table 4. It indicates that though ground mounted systems are easier to install and lower in cost than the stilt mounted systems, these are less efficient in the terms of land and water use efficiency. Table 5 shows how PV panel parameters affect agricultural production around the world. The data show that panel height and spacing greatly affect crop yields, underlining the need for customized AVS techniques to improve agricultural and energy generating outcomes.

To optimize energy and food production, numerous PV array configurations for agrivoltaic systems have been investigated and reported in Table 6 and Figs. 6 and 7. Researchers have examined full-density

(FD) and half-density (HD) structures, with FD maximizing solar power but obstructing crops, and HD allowing more sunlight to reach crops, thereby balancing electricity and agriculture. Typically, panels are affixed at a particular height and angle. Various AVS installations have been evaluated in terms of row configurations and PV panel densities, with each design seeking to strike a balance between crop yield and energy production. Checkerboard patterns have been suggested for uniform radiation distribution, but the precise design parameters vary widely depending on location and crop type. PV panel densities can range from 50% to 100%, and achieving the ideal equilibrium between crop yield and energy production is essential in AVS.

Agrivoltaic systems use various varieties of solar PV panels to maximize energy and crop production as summarized in Tables 7 and 8. Silicon (Si), cadmium telluride (CdTe), copper indium gallium selenide (CIGS), gallium arsenide (GaAs), amorphous silicon, monocrystalline silicon, and polycrystalline silicon are typical components of commercial PV cells. The market is dominated by monocrystalline and polycrystalline silicon panels, with 30% and 54% market shares, respectively. Bifacial PV panels, which capture sunlight from both sides, can generate 20% more electricity than monofacial panels. Also utilized are semi-transparent PV modules (STPV) with technologies such as organic photovoltaics, which offer cost, durability, and energy production advantages. Solar trackers can optimize the energy production of AVS. They are available in a variety of configurations, including constant angle tracking and control monitoring. While they increase energy production, solar tracking can add to the complication and expense of an AVS.

Innovative AVS technologies are making their way into this field such as Concentrated-lighting agrivoltaic systems (CAS), even-lighting agrivoltaic systems (EAS), organic photovoltaics (OPV) with tailored transparency, and thin-film semi-transparent panels. Smart farming technologies, including a variety of sensors, play a vital role in monitoring and optimizing crop development in real-time conditions, thereby contributing to increased productivity and decreased environmental impact. To maximize the synergy between agriculture and solar energy while mitigating potential drawbacks, the choice of technology in AVS should be based on local conditions and objectives.

The steps involved in agronomic practices for an AVS are shown in Fig. 8. Similar to the conventional agricultural practices, agrivoltaic systems require site selection, panel installation, crop selection, soil preparation, irrigation, pest management, harvesting, maintenance, and monitoring. Crop selection criteria are summarized in Table 9 with the factors involved and their relevance such as shade tolerance, water needs, growth height, harvest timing, microclimate adaptation, economic value, and local market demand. AVS crop production varies by location and system configuration. Studies conducted around the globe have yielded varied results as reported in Table 10. For instance, under AVS, maize production in Italy was marginally lower, whereas the price-performance ratio for potato production in Germany was favorable. In comparison to open fields, South Korea observed lower rice yields but similar forage quality in AVS. Japan has reported an increase in the biomass and yield of maize stover under specific conditions. In the United States, production of chiltepin peppers increased, tomato production doubled, but production of jalapenos decreased. The production of lettuce in France was affected by the PV cover ratio. Crop type, panel configuration, shading, and location determine the effect of AVS on crop yield. While some studies have found decreased yields, others have discovered increased productivity and economic benefits. Fig. 9 depicts crop production comparisons between conventional agriculture and AVS across multiple experimental setups, demonstrating that outcomes varied based on crop type, sunlight availability, and system design.

Table 11 and Fig. 10 showed the impact of different configurations of AVS systems employing bifacial solar PV panels on the LER. The LER may be increased with slight changes in configuration such as the pitch in this particular case leading to increased energy output though slight decrease in crop yield. LER values greater than 1 for AVS around

different locations of the world are reported in Table 12. It can be clearly seen that with different crops, configurations and locations the LER values are greater than 1.0 and may be as high as 3.0, as in a particular case. Though the crop yield usually decreases with an AVS, the added benefit is in form of simultaneous power production from an AVS. Table 13 reported the increase in electricity production due to cooling of solar PV panels at three different locations of the world, which lies in the range 0.09–3.2%. The overall financial gain from an AVS system with combined crop yield and power generation is reported in Table 14, which clearly demonstrates net economic benefits in the range 25–56%. According to Sultan et al. large-scale solar parks could be converted to AVS [142].

This review gives confidence about feasibility of AVS with different crops and PV technologies in different locations around the world. AVS has the potential to decrease water consumption and soil erosion, thereby improving the environmental sustainability. AVS supports energy and agricultural production, but to become widespread, it must overcome several obstacles. On the basis of the present study, the benefits, challenges, and recommendations for AVS have been summarized in Fig. 11. Agrivoltaic systems provide numerous advantages, such as increased crop and electricity production, economic gains, environmental advantages such as reduced land use, water conservation, and lower greenhouse gas emissions, as well as enhanced microclimates and soil health. Additionally, AVS contributes to social factors such as job creation, nutritional security, community development, and alignment with Sustainable Development Goals (SDGs). Agrivoltaic systems can directly or indirectly make positive impacts linked to SDG 1 (No poverty), 2 (Zero hunger), 7 (affordable and clean energy), 8 (Decent work and economic growth) and 13 (Climate action). AVS faces a number of obstacles, including high installation costs, uncertain returns, delayed harvesting seasons, complex design and planning requirements, crop selection difficulties, irrigation management issues, potential

damage from machinery and livestock, regulatory gaps, and differing community responses. In addition, AVS may encounter issues with land degradation and solar panel disposal. Installation of AVS in pollution affected sites [143] may be a challenge, which is still unstudied. To realize the maximum potential of AVS, stakeholders from various sectors must work together to address these challenges.

Several major recommendations and requirements for future work emanate from this comprehensive review of the agrivoltaic technology.

- Clear regulatory policies and incentives to support the AVS installers and users.
- Awareness efforts aimed at farmers and investors should emphasize the economic, environmental, and social benefits of AVS adoption.
- Customizing AVS designs for local conditions, implementing water-saving techniques, and engaging local communities are all critical first steps.
- Exploring smart farming technologies and taking into account the complete life cycle of AVS installations is important.
- Prioritize technological innovation, customization, sustainability, collaboration, and public awareness.
- Incorporate efficient optimized energy storage with improved solar panels and distribution system for maximum benefit to farming communities.
- In depth studies are required to test the viability of conversion of large-scale solar parks to agrivoltaic systems to optimize the land use.
- Studies from environmental monitoring perspectives are required to analyze effectiveness of AVS in pollution-affected sites.
- More research and development needs to be directed specifically in AVS field for development of improved indicators which better compare the land and water use efficiency for different locations and crops.

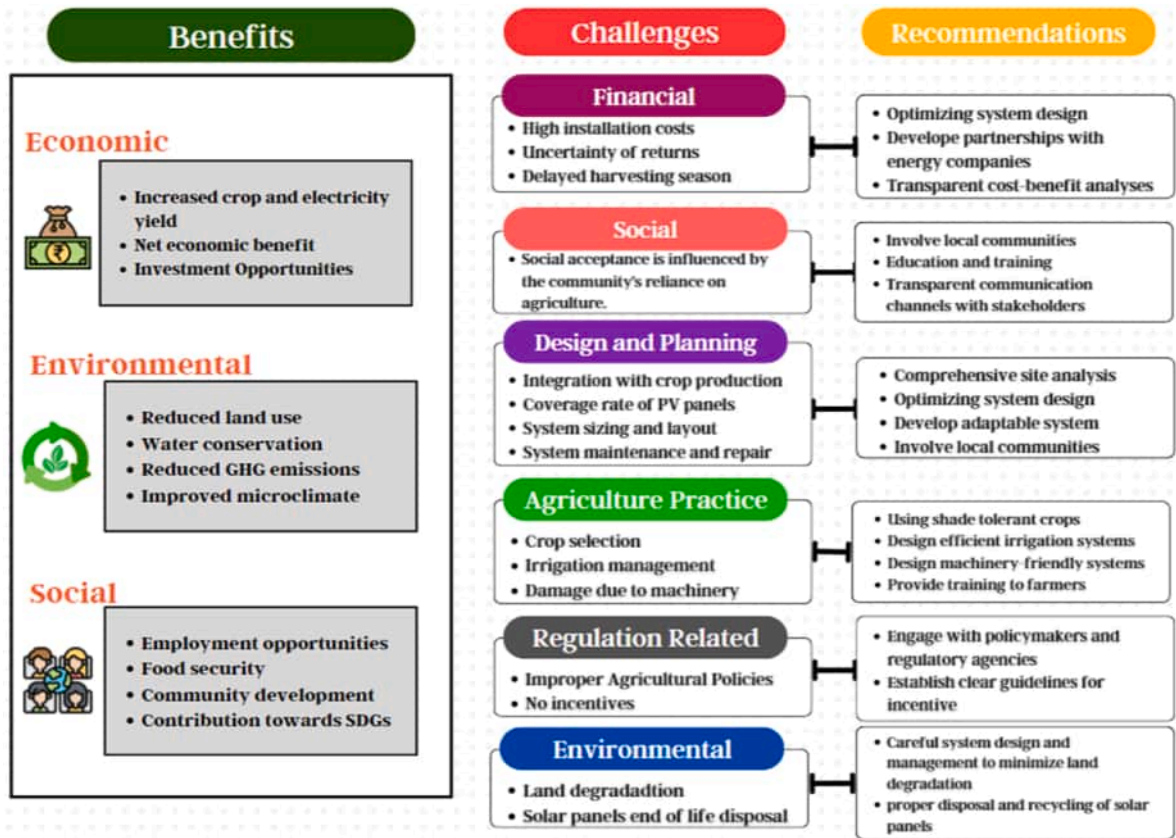


Fig. 11. AVS benefits, challenges and recommendations.

These steps can maximize potential of AVS to meet food and energy demands while supporting sustainability goals.

9. Conclusions

This review aimed at the investigation of the agrivoltaic technology from the technical, environmental and societal aspects. Through this comprehensive review it is clear that AVS can make agriculture and energy production more sustainable and equitable. Agrivoltaic systems have proven successful in a variety of climates and crops. Solar panels on agricultural land improve land-use efficiency, crop yields, and energy generation. In this work different technical aspects such as height, interspacing, configurations, solar PV technologies and innovations have been elaborated, with impact on power generation and crop yield. According to the findings, agrivoltaic systems can achieve LER levels ranging from 1.0 to 3.0, maximizing the utilization of valuable arable land. Furthermore, improvements in electricity production ranging from 0.09 to 3.05% have the potential to contribute to the renewable energy generation. While crop production reduces as a result of shading, the overall economic benefits of AVS can be significant, with potential gains of up to 56% in comparison to single crop or electricity production. These findings show that agrivoltaics have a promising future in addressing food and energy security challenges while optimizing land use. Review of the technical features of AVS reveal viability and importance of advances in location and crop specific agrivoltaic research. While AVS has benefits, it also faces considerable challenges. The findings demonstrate that energy and agriculture stakeholders, policymakers, and the community must collaborate to overcome system design, maintenance, cost, land availability, regulatory challenges, and social acceptability. Adopting AVS can contribute to global issues and SDGs by increasing food production, halting climate change, and supplying clean energy. Future AVS research requires technological advances, customization, development of specific indicators for better comparison of agrivoltaic systems around the world for optimized land and water use.

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CRediT authorship contribution statement

R.K. Chopdar: Conceptualization, Writing – original draft, Visualization. **N. Sengar:** Conceptualization, Writing – review & editing, Visualization, Supervision. **Nimay Chandra Giri:** Conceptualization, Writing – review & editing. **D. Halliday:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

- [1] Gerland P, Raftery AE, Ševčíková H, Li N, Gu D, Spoorenberg T, et al. World population stabilization unlikely this century. *Science* 2014;346:234–7. https://doi.org/10.1126/SCIENCE.1257469/SUPPL_FILE/GERLAND.SM.REVISION.1.PDF. 1979.
- [2] Dos Santos C. Agrivoltaic system: a possible synergy between agriculture and solar energy. 2019.
- [3] Santra P, Pande P, Kumar S, Mishra D, Singh R. Agri-voltaics or Solar farming: the concept of integrating solar PV based electricity generation and crop production in a single land use system, vol. 7; 2017.
- [4] Kuriqi A, Pinheiro AN, Sordo-Ward A, Garrote L. Water-energy-ecosystem nexus: balancing competing interests at a run-of-river hydropower plant coupling a hydrologic–ecohydraulic approach. *Energy Convers Manag* 2020;223. <https://doi.org/10.1016/J.ENCONMAN.2020.113267>.
- [5] Alhejji A, Kuriqi A, Jurasz J, Abo-Elyousr FK. Energy harvesting and water saving in arid regions via solar pv accommodation in irrigation canals. *Energies* 2021;14. <https://doi.org/10.3390/EN14092620>.
- [6] Mamun MA Al, Dargusch P, Wadley D, Zulkarnain NA, Aziz AA. A review of research on agrivoltaic systems. *Renew Sustain Energy Rev* 2022;161:112351. <https://doi.org/10.1016/J.RSER.2022.112351>.
- [7] Amaducci S, Yin X, Colauzzi M. Agrivoltaic systems to optimise land use for electric energy production. *Appl Energy* 2018;220:545–61. <https://doi.org/10.1016/j.apenergy.2018.03.081>.
- [8] Weselek A, Ehmman A, Zikeli S, Lewandowski I, Schindele S, Högy P. Agrophotovoltaic systems: applications, challenges, and opportunities. A review. *Agron Sustain Dev* 2019;39:1–20. <https://doi.org/10.1007/S13593-019-0581-3/TABLES/2>.
- [9] Malka L, Bidaj F, Kuriqi A, Jaku A, Roçi R, Gebremedhin A. Energy system analysis with a focus on future energy demand projections: the case of Norway. *Energy* 2023;272. <https://doi.org/10.1016/J.ENERGY.2023.127107>.
- [10] Dinesh H, Pearce JM. The potential of agrivoltaic systems. *Renew Sustain Energy Rev* 2016;54:299–308. <https://doi.org/10.1016/j.rser.2015.10.024>.
- [11] Toledo C, Scognamiglio A. Agrivoltaic systems design and assessment: a critical review, and a descriptive model towards a sustainable landscape vision (Three-Dimensional agrivoltaic patterns). *Sustainability* 2021;13:6871. <https://doi.org/10.3390/SU13126871>.
- [12] Patel B, Gami B, Baria V, Patel A, Patel P. Co-generation of solar electricity and agriculture produce by photovoltaic and photosynthesis-dual model by Abellon, India. *J Solar Energy Eng Trans ASME* 2019;141. <https://doi.org/10.1115/1.4041899/369328>.
- [13] Rahman A, Sharma A, Postel F, Goel S, Kumar K, Laan T. Agrivoltaics in India Challenges and opportunities for scale-up IISD REPORT. Winnipeg: International Institute for Sustainable Development; 2023. Manitoba Canada.
- [14] Xiao Y, Zhang H, Pan S, Wang Q, He J, Jia X. An agrivoltaic park enhancing ecological, economic and social benefits on degraded land in Jiangshan, China. *AIP Conf Proc* 2022;2635:020002. <https://doi.org/10.1063/5.0106454>.
- [15] Svanera L, Ghidessi G, Knoche R. Agrovoltaco®: 10 years design and operation experience. *AIP Conf Proc* 2021;2361:090002. <https://doi.org/10.1063/5.0055869>.
- [16] Santra P, Singh RK, Jain D, Yadav OP. Agri-voltaic system to enhance land productivity and income. *Indian Farming* 2018;68:108–11.
- [17] Poonia S, Jat NK, Santra P, Singh AK, Jain D, Meena HM. Techno-economic evaluation of different agri-voltaic designs for the hot arid ecosystem India. *Renew Energy* 2022;184:149–63. <https://doi.org/10.1016/J.RENENE.2021.11.074>.
- [18] Giri NC, Mohanty RC. Agrivoltaic system: experimental analysis for enhancing land productivity and revenue of farmers. *Energy Sustain Dev* 2022;70:54–61. <https://doi.org/10.1016/j.esd.2022.07.003>.
- [19] Trommsdorff M, Gruber S, Keinath T, Hopf M, Hermann C, Schönberger F, et al. Agrivoltaics: opportunities for agriculture and the energy transition - a guideline for Germany. 2022. Freiburg, Germany.
- [20] Abidin MAZ, Mahyuddin MN, Zainuri MAAM. Solar photovoltaic architecture and agronomic management in agrivoltaic system: a review. *Sustainability* 2021;13:7846. <https://doi.org/10.3390/SU13147846>. 7846 2021;13.
- [21] Valle B, Simonneau T, Sourd F, Pechier P, Hamard P, Frisson T, et al. Increasing the total productivity of a land by combining mobile photovoltaic panels and food crops. *Appl Energy* 2017;206:1495–507. <https://doi.org/10.1016/J.APENERGY.2017.09.113>.
- [22] Agrivoltaics for pear orchards – pv magazine International n.d. <https://www.pv-magazine.com/2020/10/02/agrivoltaics-for-pear-orchards/>. [Accessed 28 July 2023].
- [23] Randle-Boggis RJ, Lara E, Onyango J, Temu EJ, Hartley SE. Agrivoltaics in east Africa: opportunities and challenges. *AIP Conf Proc* 2021;2361:090001. <https://doi.org/10.1063/5.0055470>.
- [24] Marrou H, Dufour L, Wery J. How does a shelter of solar panels influence water flows in a soil–crop system? *Eur J Agron* 2013;50:38–51. <https://doi.org/10.1016/J.EJA.2013.05.004>.
- [25] Ravi S, Macknick J, Lobell D, Field C, Ganesan K, Jain R, et al. Colocation opportunities for large solar infrastructures and agriculture in drylands. *Appl Energy* 2016;165:383–92. <https://doi.org/10.1016/J.APENERGY.2015.12.078>.
- [26] Weselek A, Bauerle A, Hartung J, Zikeli S, Lewandowski I, Högy P. Agrivoltaic system impacts on microclimate and yield of different crops within an organic crop rotation in a temperate climate. *Agron Sustain Dev* 2021;41:1–15. <https://doi.org/10.1007/S13593-021-00714-Y/FIGURES/5>.
- [27] Adeh EH, Selker JS, Higgins CW. Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency. *PLoS One* 2018;13:e0203256. <https://doi.org/10.1371/JOURNAL.PONE.0203256>.
- [28] Elamri Y, Cheviron B, Lopez JM, Dejean C, Belaud G. Water budget and crop modelling for agrivoltaic systems: application to irrigated lettuces. *Agric Water Manag* 2018;208:440–53. <https://doi.org/10.1016/J.AGWAT.2018.07.001>.
- [29] Sekiyama T, Nagashima A. Solar sharing for both food and clean energy production: performance of agrivoltaic systems for corn, a typical shade-

- intolerant crop. *Environ. - MDPI* 2019;6. <https://doi.org/10.3390/environments6060065>.
- [30] Malu PR, Sharma US, Pearce JM. Agrivoltaic potential on grape farms in India. *Sustain Energy Technol Assessments* 2017;23:104–10. <https://doi.org/10.1016/j.seta.2017.08.004>.
- [31] Al-Agele HA, Proctor K, Murthy G, Higgins C. A case study of tomato (*Solanum lycopersicon* var. Legend) production and water productivity in agrivoltaic systems. *Sustainability* 2021;13:2850. <https://doi.org/10.3390/SU13052850>.
- [32] Gonocruz RA, Nakamura R, Yoshino K, Homma M, Doi T, Yoshida Y, et al. Analysis of the rice yield under an agrivoltaic system: a case study in Japan. *Environments* 2021;8:65. <https://doi.org/10.3390/ENVIRONMENTS8070065>.
- [33] Jo H, Asekova S, Bayat MA, Ali L, Song JT, Ha YS, et al. Comparison of yield and yield components of several crops grown under agro-photovoltaic system in Korea. *Agriculture* 2022;12:619. <https://doi.org/10.3390/AGRICULTURE12050619>.
- [34] Teng JWC, Soh CB, Devihsur SC, Tay RHS, Jusuf SK. Effects of agrivoltaic systems on the surrounding rooftop microclimate. *Sustainability* 2022;14:1–13. <https://doi.org/10.3390/su14127089>.
- [35] Dupraz C, Talbot G, Marrou H, Wery J, Roux S, Liagre F, et al. To mix or not to mix: evidences for the unexpected high productivity of new complex agrivoltaic and agroforestry systems. In: *Proceedings of the 5th world congress on conservation agriculture incorporating 3rd farming systems design conference*; 2011. p. 203–4.
- [36] Barron-Gafford GA, Pavao-Zuckerman MA, Minor RL, Sutter LF, Barnett-Moreno I, Blackett DT, et al. Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. *Nat Sustain* 2019;2(9):848–55. <https://doi.org/10.1038/s41893-019-0364-5>.
- [37] Zheng J, Meng S, Zhang X, Zhao H, Ning X, Chen F, et al. Increasing the comprehensive economic benefits of farmland with even-lighting agrivoltaic systems. *PLoS One* 2021;16:e0254482. <https://doi.org/10.1371/journal.pone.0254482>.
- [38] Santra P, Meena HM, Yadav OP. Spatial and temporal variation of photosynthetic photon flux density within agrivoltaic system in hot arid region of India. *Biosyst Eng* 2021;209:74–93. <https://doi.org/10.1016/j.biosystemseng.2021.06.017>.
- [39] Zhang J, Wang T, Chang Y, Liu B. A sustainable development pattern integrating data centers and pasture-based agrivoltaic systems for ecologically fragile areas. *Resour Conserv Recycl* 2023;188:106684. <https://doi.org/10.1016/J.RESCONREC.2022.106684>.
- [40] Ott EM, Kabus CA, Baxter BD, Hannon B, Celik I. Environmental analysis of agrivoltaic systems. *Compr Renew Energy* 2022;9:127–39. <https://doi.org/10.1016/b978-0-12-819727-1.00012-1>.
- [41] Walston LJ, Barley T, Bhandari I, Campbell B, McCall J, Hartmann HM, et al. Opportunities for agrivoltaic systems to achieve synergistic food-energy-environmental needs and address sustainability goals. *Front Sustain Food Syst* 2022;6:374. <https://doi.org/10.3389/FSUFS.2022.932018/BIBTEX>.
- [42] Gorjian S, Bousi E, Ozdemir OE, Trommsdorff M, Kumar NM, Anand A, et al. Progress and challenges of crop production and electricity generation in agrivoltaic systems using semi-transparent photovoltaic technology. *Renew Sustain Energy Rev* 2022;158:112126. <https://doi.org/10.1016/J.RSER.2022.112126>.
- [43] Schindele S, Trommsdorff M, Schlaak A, Obergfell T, Bopp G, Reise C, et al. Implementation of agrophotovoltaics: techno-economic analysis of the price-performance ratio and its policy implications. *Appl Energy* 2020;265:114737. <https://doi.org/10.1016/J.APENERGY.2020.114737>.
- [44] Campana PE, Stridh B, Amaducci S, Colauzzi M. Optimisation of vertically mounted agrivoltaic systems. *J Clean Prod* 2021;325:129091. <https://doi.org/10.1016/J.JCLEPRO.2021.129091>.
- [45] Thompson EP, Bombelli EL, Shubham S, Watson H, Everard A, D'Ardes V, et al. Tinted semi-transparent solar panels allow concurrent production of crops and electricity on the same cropland. *Adv Energy Mater* 2020;10:2001189. <https://doi.org/10.1002/AENM.202001189>.
- [46] Chae SH, Kim HJ, Moon HW, Kim YH, Ku KM. Agrivoltaic systems enhance farmers' profits through broccoli visual quality and electricity production without dramatic changes in yield, antioxidant capacity, and glucosinolates. *Agronomy* 2022;12:1415. <https://doi.org/10.3390/AGRONOMY12061415/S1>.
- [47] Marrou H, Guillon L, Dufour L, Dupraz C, Wery J. Microclimate under agrivoltaic systems: is crop growth rate affected in the partial shade of solar panels? *Agric For Meteorol* 2013;177:117–32. <https://doi.org/10.1016/j.agrformet.2013.04.012>.
- [48] Agostini A, Colauzzi M, Amaducci S. Innovative agrivoltaic systems to produce sustainable energy: an economic and environmental assessment. *Appl Energy* 2021;281:116102. <https://doi.org/10.1016/J.APENERGY.2020.116102>.
- [49] Casares de la Torre FJ, Varo-Martínez M, López-Luque R, Ramírez-Faz J, Fernández-Ahumada LM. Design and analysis of a tracking/backtracking strategy for PV plants with horizontal trackers after their conversion to agrivoltaic plants. *Renew Energy* 2022;187:537–50. <https://doi.org/10.1016/J.RENENE.2022.01.081>.
- [50] Imran H, Riaz MH. Investigating the potential of east/west vertical bifacial photovoltaic farm for agrivoltaic systems. *J Renew Sustain Energy* 2021;13:03502. <https://doi.org/10.1063/5.0054085>.
- [51] Katsikogiannis OA, Ziar H, Isabella O. Integration of bifacial photovoltaics in agrivoltaic systems: a synergistic design approach. *Appl Energy* 2022;309:118475. <https://doi.org/10.1016/J.APENERGY.2021.118475>.
- [52] Trommsdorff M, Vorast M, Durga N, Padwardhan S. Potential of agrivoltaics to contribute to socio-economic sustainability: a case study in Maharashtra/India. In: *AIP Conf Proc*, vol. 2361. AIP Publishing LLC/AIP Publishing; 2021, 040001. <https://doi.org/10.1063/5.0054569>.
- [53] Sato D, Yamada N. Design and testing of highly transparent concentrator photovoltaic modules for efficient dual-land-use applications. *Energy Sci Eng* 2020;8:779–88. <https://doi.org/10.1002/ESE3.550>.
- [54] Ketzler D, Schlyter P, Weinberger N, Rösch C. Driving and restraining forces for the implementation of the Agrophotovoltaics system technology – a system dynamics analysis. *J Environ Manag* 2020;270:110864. <https://doi.org/10.1016/J.JENVMAN.2020.110864>.
- [55] Chamara R, Beneragama C. Agrivoltaic systems and its potential to optimize agricultural land use for energy production in Sri Lanka: a Review. *J Sol Energy Res* 2020;5:417–31.
- [56] Trommsdorff M, Kang J, Reise C, Schindele S, Bopp G, Ehmann A, et al. Combining food and energy production: design of an agrivoltaic system applied in arable and vegetable farming in Germany. *Renew Sustain Energy Rev* 2021;140:110694. <https://doi.org/10.1016/J.RSER.2020.110694>.
- [57] Pulipaka S, Peparthy M. Agrivoltaics in India. New Delhi, India: National Solar Energy Federation of India (NSEFI); 2021.
- [58] Leon A, Ishihara KN. Assessment of new functional units for agrivoltaic systems. *J Environ Manag* 2018;226:493–8. <https://doi.org/10.1016/J.JENVMAN.2018.08.013>.
- [59] Macknick J, Hartmann H, Barron-Gafford G, Beatty B, Burton R, Seok-Choi C, et al. The 5 Cs of agrivoltaic success factors in the United States: lessons from the InSPIRE research study. 2022. <https://doi.org/10.2172/1882930>. Golden, CO (United States).
- [60] Dupraz C, Marrou H, Talbot G, Dufour L, Nogier A, Ferard Y. Combining solar photovoltaic panels and food crops for optimising land use: towards new agrivoltaic schemes. *Renew Energy* 2011;36:2725–32. <https://doi.org/10.1016/j.renene.2011.03.005>.
- [61] Cho J, Park SM, Reum Park A, Lee OC, Nam G, Ra IH. Application of photovoltaic systems for agriculture: a study on the relationship between power generation and farming for the improvement of photovoltaic applications in agriculture. *Energies* 2020;13:4815. <https://doi.org/10.3390/EN13184815>.
- [62] Lee HJ, Park HH, Kim YO, Kuk YI. Crop cultivation underneath agro-photovoltaic systems and its effects on crop growth, yield, and photosynthetic efficiency. *Agronomy* 2022;12:1842. <https://doi.org/10.3390/AGRONOMY12081842>.
- [63] Potenza E, Croci M, Colauzzi M, Amaducci S. Agrivoltaic system and modelling simulation: a case study of soybean (*Glycine max* L.) in Italy. *Horticulturae* 2022;8:1160. <https://doi.org/10.3390/HORTICULTURAE8121160/S1>.
- [64] Kim S, Kim S, Yoon CY. An efficient structure of an agrophotovoltaic system in a temperate climate region. *Agronomy* 2021;11:1584. <https://doi.org/10.3390/AGRONOMY11081584>.
- [65] Oleskiewicz K. The effect of gap spacing between solar panel clusters on crop biomass yields, Nutrients, and the Microenvironment in a Dual-Use Agrivoltaic System 2020. <https://doi.org/10.7275/15996616>.
- [66] Pulido-Mancebo JS, López-Luque R, Fernández-Ahumada LM, Ramírez-Faz JC, Gómez-Uceda FJ, Varo-Martínez M. Spatial distribution model of solar radiation for agrivoltaic land use in fixed PV plants. *Agronomy* 2022;12:2799. <https://doi.org/10.3390/AGRONOMY12112799>.
- [67] Yano A, Onoe M, Nakata J. Prototype semi-transparent photovoltaic modules for greenhouse roof applications. *Biosyst Eng* 2014;122:62–73. <https://doi.org/10.1016/J.BIOSYSTEMSENG.2014.04.003>.
- [68] Willock B, Herteleer B, Cappelle J. Combining photovoltaic modules and food crops: first agrovoltaic prototype in Belgium. *Renew Energy Power Qual J (RE&PQJ)* 2020;18:266–71.
- [69] Gorjian S, Ebadi H, Trommsdorff M, Sharon H, Demant M, Schindele S. The advent of modern solar-powered electric agricultural machinery: a solution for sustainable farm operations. *J Clean Prod* 2021;292:126030. <https://doi.org/10.1016/J.JCLEPRO.2021.126030>.
- [70] Gorjian S, Zadeh BN, Eltrop L, Shamshiri RR, Amanlou Y. Solar photovoltaic power generation in Iran: development, policies, and barriers. *Renew Sustain Energy Rev* 2019;106:110–23. <https://doi.org/10.1016/J.RSER.2019.02.025>.
- [71] Sánchez-Friera P, Lalaguna B, Montiel D, Gil J, Caballero LJ, Alonso J, et al. Development and characterisation of industrial bifacial PV module with ultra-thin screen-printed solar cells. In: *22nd European photovoltaic solar energy conference*; 2007. p. 3–7.
- [72] Riaz MH, Imran H, Younas R, Alam MA, Butt NZ. Module technology for agrivoltaics: vertical bifacial versus tilted monofacial farms. *IEEE J Photovoltaics* 2021;11:469–77. <https://doi.org/10.1109/JPHOTOV.2020.3048225>.
- [73] Pascaris AS, Schelly C, Pearce JM. A first investigation of agriculture sector perspectives on the opportunities and barriers for agrivoltaics. *Agronomy* 2020;10:1885. <https://doi.org/10.3390/AGRONOMY10121885>.
- [74] Amelia AR, Irwan YM, Safwati I, Leow WZ, Mat MH, Rahim MSA. Technologies of solar tracking systems: a review. *IOP Conf Ser Mater Sci Eng* 2020;767:012052. <https://doi.org/10.1088/1757-899X/767/1/012052>.
- [75] Das A, Durgaprasad S. Simulation and implementation of single Axis solar tracker. *Int Res J Eng Technol (IRJET)* 2020;7:756–61.
- [76] Ali Abaker Omer A, Liu W, Li M, Zheng J, Zhang F, Zhang X, et al. Water evaporation reduction by the agrivoltaic systems development. *Sol Energy* 2022;247:13–23. <https://doi.org/10.1016/J.SOLENER.2022.10.022>.
- [77] Zhang Z, Zhang F, Li M, Liu L, Liu W, Lv H, et al. Progress in agriculture photovoltaic leveraging CPV. *AIP Conf Proc* 2018;2012:110006. <https://doi.org/10.1063/1.5053554>.
- [78] Liu L, Guan C, Zhang F, Li M, Lv H, Liu Y, et al. A novel application for concentrator photovoltaic in the field of agriculture photovoltaics. *AIP Conf Proc* 2017;1881:080008. <https://doi.org/10.1063/1.5001446>.

- [79] Gorjian S, Jalili Jamshidian F, Gorjian A, Faridi H, Vafaei M, Zhang F, et al. Technological advancements and research prospects of innovative concentrating agrivoltaics. *Appl Energy* 2023;337:120799. <https://doi.org/10.1016/j.apenergy.2023.120799>.
- [80] Psaila P, Photo Library S. How to expand solar power without using precious land. *Proc Natl Acad Sci U S A* 2023;120. <https://doi.org/10.1073/pnas.2301355120>.
- [81] Zheng J, Zhang X, Ning X, Ingenhoff J, Liu W. An improved photovoltaic agriculture system with groove glass plate. *Opt Design Testing IX* 2019;11185: 241–9. <https://doi.org/10.1117/12.2538750>.
- [82] Trommsdorff M, Dhal IS, Özdemir OE, Ketzner D, Weinberger N, Rösch C. Agrivoltaics: solar power generation and food production. *Solar Energy Advancements in Agriculture and Food Production Systems* 2022:159–210. <https://doi.org/10.1016/B978-0-323-89866-9.00012-2>.
- [83] Uchanski M, Hickey T, Boussetot J, Barth KL. Characterization of agrivoltaic crop environment conditions using opaque and thin-film semi-transparent modules. *Energies* 2023;16:3012. <https://doi.org/10.3390/EN16073012>.
- [84] Cho J, Park SM, Reum Park A, Lee OC, Nam G, Ra IH. Application of photovoltaic systems for agriculture: a study on the relationship between power generation and farming for the improvement of photovoltaic applications in agriculture. *Energies* 2020;13:4815. <https://doi.org/10.3390/EN13184815>.
- [85] Wydra K, Vollmer V, Busch C, Prichta S, Wydra K, Vollmer V, et al. Agrivoltaic: solar radiation for clean energy and sustainable agriculture with positive impact on nature. In: *Solar radiation - enabling technologies, recent innovations, and advancements for energy transition*. IntechOpen; 2023. <https://doi.org/10.5772/intechopen.111728>.
- [86] Moswetsi G, Fanadzo M, Neube B. Cropping systems and agronomic management practices in smallholder farms in South Africa: constraints, challenges and opportunities. *J Agron* 2017;16:51–64. <https://doi.org/10.3923/ja.2017.51.64>.
- [87] Waghmare R, Jilte R, Joshi S, Tete P. Review on agrophotovoltaic systems with a premise on thermal management of photovoltaic modules therein. *Environ Sci Pollut Control Ser* 2023;30:25591–612. <https://doi.org/10.1007/S11356-022-23202-6/METRICS>.
- [88] Sirmik I, Sluijsmans J, Oudes D, Stremke S. Circularity and landscape experience of agrivoltaics: a systematic review of literature and built systems. *Renew Sustain Energy Rev* 2023;178:113250. <https://doi.org/10.1016/J.RSER.2023.113250>.
- [89] Cossu M, Yano A, Solinas S, Deligios PA, Tiloca MT, Cossu A, et al. Agricultural sustainability estimation of the European photovoltaic greenhouses. *Eur J Agron* 2020;118:126074. <https://doi.org/10.1016/J.EJA.2020.126074>.
- [90] Laub M, Pataczek L, Feuerbacher A, Zikeli S, Högy P. Contrasting yield responses at varying levels of shade suggest different suitability of crops for dual land-use systems. A meta-analysis. *AgriRxiv* 2021;2021. <https://doi.org/10.31220/AGRIRXIV.2021.00099>.
- [91] Willockx B, Uytterhae gen B, Ronsijn B, Herteleer B, Cappelle J. A standardized classification and performance indicators of agrivoltaic systems, vol. 2020. *Eu Pvsec*; 2020. p. 1–4.
- [92] Zainali S, Qadir O, Parlak SC, Lu SM, Avelin A, Stridh B, et al. Computational fluid dynamics modelling of microclimate for a vertical agrivoltaic system. *Energy Nexus* 2023;9:100173. <https://doi.org/10.1016/J.NEXUS.2023.100173>.
- [93] Kuo C-FJ, Su T-L, Huang C-Y, Liu H-C, Fulginei FR, Kuo C-FJ, et al. Design and development of a symbiotic agrivoltaic system for the coexistence of sustainable solar electricity generation and agriculture. *Sustainability* 2023;15:6011. <https://doi.org/10.3390/SU15076011>.
- [94] Francia G Di, Cupo P. A cost-benefit analysis for utility-scale agrivoltaic implementation in Italy. *Energies* 2023;16:2991. <https://doi.org/10.3390/EN16072991>.
- [95] Miao R, Khanna M. Harnessing advances in agricultural technologies to optimize resource utilization in the food-energy-water nexus. *Annu Rev Resour Econ* 2020; 12:65–85. <https://doi.org/10.1146/ANNUREV-RESOURCE-110319-115428>.
- [96] Kumar S, Saravaiya S, Pandey A. Precision farming and protected cultivation: concepts and applications. 2021.
- [97] Nam CH, Park MH, Yun AA, Ji HJ, Choi B ram, Sun SS. Study on forage production under agrivoltaic system. *J Korean Soc Grassland Forage Sci* 2021;41: 1–9. <https://doi.org/10.5333/KGFS.2021.41.1.1>.
- [98] Giri NC, Mohanty RC. Design of agrivoltaic system to optimize land use for clean energy-food production: a socio-economic and environmental assessment. *Clean Technol Environ Policy* 2022;24:2595–606. <https://doi.org/10.1007/S10098-022-02337-7>.
- [99] Giri N, Mohanty R. Traditional versus underneath farming of turmeric and ginger in Odisha. *India Int J Agricult Stat Sci* 2022;18:189–95.
- [100] Kumpanalaisatit M, Setthapun W, Sintuya H, Jansri SN. Efficiency improvement of ground-mounted solar power generation in agrivoltaic system by cultivation of Bok choy (*Brassica rapa* subsp. *chinensis* L.) under the panels. *Int J Renew Energy Dev* 2021;11:103–10. <https://doi.org/10.14710/ijred.2022.41116>.
- [101] Jiang S, Tang D, Zhao L, Liang C, Cui N, Gong D, et al. Effects of different photovoltaic shading levels on kiwifruit growth, yield and water productivity under "agrivoltaic" system in Southwest China. *Agric Water Manag* 2022;269: 107675. <https://doi.org/10.1016/J.AGWAT.2022.107675>.
- [102] Moon HW, Ku KM. Impact of an agriphotovoltaic system on metabolites and the sensorial quality of cabbage (*Brassica oleracea* var. *capitata*) and its high-temperature-extracted juice. *Foods* 2022;11:498. <https://doi.org/10.3390/FOODS11040498/S1>.
- [103] Qiu Y, Sheng J, He X. An analysis on urban land use efficiency based on super-efficiency DEA. *J Phys Conf Ser* 2021;1873:012051. <https://doi.org/10.1088/1742-6596/1873/1/012051>.
- [104] Population | United Nations n.d. <https://www.un.org/en/global-issues/population> (accessed August 3, 2023).
- [105] Mead R, Willey RW. The concept of a 'land equivalent ratio' and advantages in yields from intercropping. *Exp Agric* 1980;16:217–28. <https://doi.org/10.1017/S0014479700010978>.
- [106] Smith RG, Atwood LW, Warren ND. Increased productivity of a cover crop mixture is not associated with enhanced agroecosystem services. *PLoS One* 2014; 9:e97351. <https://doi.org/10.1371/JOURNAL.PONE.0097351>.
- [107] Polacco R. Master Thesis-Analysis of the agrivoltaic power plants and practical evaluations. Supervisors Spertino F., Ciocia A., Master of Science Program Energy and Nuclear Engineering Luglio 2022, Politecnico di Torino.
- [108] Dupraz C, Marrou H, Talbot G, Dufour L, Nogier A, Ferard Y. Combining solar photovoltaic panels and food crops for optimising land use: towards new agrivoltaic schemes. *Renew Energy* 2011;36:2725–32. <https://doi.org/10.1016/j.renene.2011.03.005>.
- [109] Bhandari SN, Schlüter S, Kuckshinrichs W, Schlör H, Adamou R, Bhandari R. Economic feasibility of agrivoltaic systems in food-energy nexus context: modelling and a case study in Niger. *Agronomy* 2021;11:1906. <https://doi.org/10.3390/agronomy11101906>.
- [110] Kostik N, Bobyl A, Rud V, Salamov I. The potential of agrivoltaic systems in the conditions of southern regions of Russian Federation. *IOP Conf Ser Earth Environ Sci* 2020;578:012047. <https://doi.org/10.1088/1755-1315/578/1/012047>.
- [111] Andrew AC, Higgins CW, Smallman MA, Graham M, Ates S. Herbage yield, lamb growth and foraging behavior in agrivoltaic production system. *Front Sustain Food Syst* 2021;5:659175. <https://doi.org/10.3389/FSUFS.2021.659175/BIBTEX>.
- [112] Kumpanalaisatit M, Setthapun W, Sintuya H, NarratJansri S. Design and test of agri-voltaic system. *Turk J Comput Math Educ (TURCOMAT)* 2021;12:2395–404. <https://doi.org/10.17762/TURCOMAT.V12I8.3728>.
- [113] Schweiger AH, Pataczek L. How to reconcile renewable energy and agricultural production in a drying world. *Plants People Planet* 2023;5:650–61. <https://doi.org/10.1002/PPP3.10371>.
- [114] Sinclair TR, Tanner CB, Bennett JM. Water-use efficiency in crop production. *Bioscience* 1984;34:36–40. <https://doi.org/10.2307/1309424>.
- [115] Zahoor SA, Ahmad S, Ahmad A, Wajid A, Khaliq T, Mubeen M, et al. Improving water use efficiency in agronomic crop production. *Agronomic Crops: Volume 2: Management Practices* 2019;2:13–29. https://doi.org/10.1007/978-981-32-9783-8_2/COVER.
- [116] Poonia S, Santra P, Jat NK, Jain D, Meena HM. Agri-voltaic system: A novel technology for doubling the farmer's income in hot arid ecosystem of western Rajasthan, India. *Indian Farmer* 2021;8:351–60.
- [117] Nordberg EJ, Julian Caley M, Schwarzkopf L. Designing solar farms for synergistic commercial and conservation outcomes. *Sol Energy* 2021;228:586–93. <https://doi.org/10.1016/J.SOLENER.2021.09.090>.
- [118] Gorjian S, Fakhraei O, Gorjian A, Sharafkhani A, Aziznejad A. Sustainable food and agriculture: employment of renewable energy technologies. *Curr Robotics Rep* 2022;(3):153–63. <https://doi.org/10.1007/S43154-022-00080-X>. 2022 3:3.
- [119] Weselek A, Bauerle A, Zikeli S, Lewandowski I, Högy P. Effects on crop development, yields and chemical composition of celeriac (*Apium graveolens* L. var. *rapaceum*) cultivated underneath an agrivoltaic system. *Agronomy* 2021;11: 733. <https://doi.org/10.3390/AGRONOMY11040733>.
- [120] Proctor KW, Murthy GS, Higgins CW. Agrivoltaics align with green new deal goals while supporting investment in the US' rural economy. *Sustainability* 2021;13: 137. <https://doi.org/10.3390/SU13010137>. 2020;13:137.
- [121] Mohamed ASA, Maghrabie HM. Techno-economic feasibility analysis of Benban solar Park. *Alex Eng J* 2022;61:12593–607. <https://doi.org/10.1016/J.AEJ.2022.06.034>.
- [122] Kumpanalaisatit M, Setthapun W, Sintuya H, Pattiya A, Jansri SN. Current status of agrivoltaic systems and their benefits to energy, food, environment, economy, and society. *Sustain Prod Consum* 2022;33:952–63. <https://doi.org/10.1016/J.SPC.2022.08.013>.
- [123] Abidin MAZ, Mahyuddin MN, Zainuri MAAM. Agrivoltaic systems: an innovative approach to combine agricultural production and solar photovoltaic system. *Lecture Notes Electr Eng* 2022;829(LNEE):779–85. https://doi.org/10.1007/978-981-8129-5_119/COVER.
- [124] Chowdhury K, Mandal R. Agrivoltaic: a new approach of sustainable development. *Lecture Notes Civil Eng* 2021;131(LNCE):513–22. https://doi.org/10.1007/978-981-33-6412-7_37/COVER.
- [125] Higgins CW, Hassanpour Adeh E, Good SP. The case for agrivoltaic systems. *AGUFM*, vol. 2018. Corvallis: Oregon State University; 2018H13M–1939.
- [126] Karim MohH, Diantoro M, Nasikhudin N, Lestari SR. Implementation of agricultural technology urban farming agrivoltaic based system to increase productivity and empowerment of farmer women's community. *J Community Service Empower* 2023;4:184–95. <https://doi.org/10.22219/JCSE.V4I1.25103>.
- [127] Maity R, Sudhakar K, Razak AA, Karthick A, Barbuiescu D. Agrivoltaic: a strategic assessment using SWOT and TOWS matrix. *Energies* 2023;16:3313. <https://doi.org/10.3390/EN16083313>.
- [128] Andrew AC, Higgins CW, Smallman MA, Graham M, Ates S. Herbage yield, lamb growth and foraging behavior in agrivoltaic production system. *Front Sustain Food Syst* 2021;5:659175. <https://doi.org/10.3389/FSUFS.2021.659175/BIBTEX>.
- [129] Reasoner M, Ghosh A. Agrivoltaic engineering and layout optimization approaches in the transition to renewable energy technologies: a review. *Challenges* 2022;13:43. <https://doi.org/10.3390/CHALLENGE13020043>.

- [130] Chalgynbayeva A, Mizik T, Bai A. Cost–benefit analysis of Kaposvár solar photovoltaic park considering agrivoltaic systems. *Cleanroom Technol* 2022;4: 1054–70. <https://doi.org/10.3390/CLEANTECHNOL4040064>.
- [131] Yajima D, Toyoda T, Kirimura M, Araki K, Ota Y, Nishioka K. Estimation model of agrivoltaic systems maximizing for both photovoltaic electricity generation and agricultural production. *Energies* 2023;16:3261. <https://doi.org/10.3390/EN16073261>.
- [132] Huang K, Shu L, Li K, Chen Y, Zhu Y, Valluru R. Sustainable and intelligent phytoprotection in photovoltaic agriculture: new challenges and opportunities. *Electronics* 2023;12:1221. <https://doi.org/10.3390/ELECTRONICS12051221>.
- [133] Riaz MH, Imran H, Alam H, Alam MA, Butt NZ. Crop-specific optimization of bifacial PV arrays for agrivoltaic food-energy production: the light-productivity-factor approach. *IEEE J Photovoltaics* 2022;12:572–80. <https://doi.org/10.1109/JPHOTOV.2021.3136158>.
- [134] Shukla A, Kumar M, Shukla A. A review of agri-voltaic system in India: opportunities and constraints. *Int J Environ Climate Change* 2022;12:1134–42. <https://doi.org/10.9734/IJECC/2022/V12I1030909>.
- [135] Ya'acob ME, Lu L, Nobilly F, Che'Ya NN, Aziz AA, Dupraz C, et al. Analysis of weed communities in solar farms located in tropical areas—the case of Malaysia. *Agronomy* 2022;12:3073. <https://doi.org/10.3390/AGRONOMY12123073>.
- [136] Cuppari RI, Higgins CW, Characklis GW. Agrivoltaics and weather risk: a diversification strategy for landowners. *Appl Energy* 2021;291:116809. <https://doi.org/10.1016/J.APENERGY.2021.116809>.
- [137] Irie N, Kawahara N, Esteves AM. Sector-wide social impact scoping of agrivoltaic systems: a case study in Japan. *Renew Energy* 2019;139:1463–76. <https://doi.org/10.1016/J.RENENE.2019.02.048>.
- [138] Rahman MM, Khan I, Field DL, Techato K, Alameh K. Powering agriculture: present status, future potential, and challenges of renewable energy applications. *Renew Energy* 2022;188:731–49. <https://doi.org/10.1016/J.RENENE.2022.02.065>.
- [139] Vollprecht J, Trommsdorff M, Hermann C. Legal framework of agrivoltaics in Germany. *Agrivoltaics2020 Conference: Launching Agrivoltaics World-wide* 2021;2361:020002. <https://doi.org/10.1063/5.0055133>. Perpignan, France.
- [140] Torma G, Aschemann-Witzel J. Social acceptance of dual land use approaches: stakeholders' perceptions of the drivers and barriers confronting agrivoltaics diffusion. *J Rural Stud* 2023;97:610–25. <https://doi.org/10.1016/J.JRURSTUD.2023.01.014>.
- [141] Yu Y, Ko Y. A review of the attributes of successful agriphotovoltaic projects. *APRU sustainable cities and landscapes hub PhD symposium*. 2020. p. 1–8.
- [142] Sultan M, Shamshiri RR, Shamim Ahamed M, Farooq M, Fadzlin Othman N, Effendy Ya M, et al. Advancement in agriculture approaches with agrivoltaics natural cooling in large scale solar PV farms. *Agriculture* 2023;13:854. <https://doi.org/10.3390/AGRICULTURE13040854>.
- [143] Koley S. Future perspectives and mitigation strategies towards groundwater arsenic contamination in West Bengal, India. *Environ Qual Manag* 2022;31: 75–97. <https://doi.org/10.1002/TQEM.21784>.



Research article

Ecological and environmental effects of global photovoltaic power plants: A meta-analysis

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ABSTRACT

The construction of photovoltaic power plants (PVPPs) globally not only mitigates climate change but also exerts various impacts on terrestrial ecosystems. A comprehensive exploration of the intensity of PVPPs on the ecological environmental elements of terrestrial ecosystems, as well as their regulatory mechanisms, is an urgent scientific issue that must be addressed within the context of carbon balance. In this study, we conducted a meta-analysis to investigate the soil, climate, and biological effects of PVPPs construction, as well as changes in ecosystem CO₂ fluxes. Our analysis synthesized data from 42 original studies encompassing over 4300 observations. Findings revealed that a significant reduction in wind speed and soil temperature within the photovoltaic field, with average changes of −63.55% (confidence intervals (CI): [−70.77, −56.32]) and −9.72%, CI [−18.51, −0.93], respectively. Concurrently, there was an average increase of 301.63%, CI [14.14, 589.13] in soil moisture content and gross primary productivity, and 28.52%, CI [14.29, 42.75], respectively. However, no significant effects were observed on other ecological environmental factors. Both the random forest model and mixed effects model highlighted key driving factors such as air temperature and humidity, location under the photovoltaic panel, monthly variations, geographical environment, and photovoltaic scale, which influenced the ecological responses to PVPPs. Furthermore, statistical cluster analysis demonstrated that the thresholds of key driving factors will significantly affect the response of ecological environment factors to PVPPs. This study enhances our comprehension of the ecological and environmental implications of PVPPs construction and offers valuable insights for policymakers aiming to implement 'photovoltaic + ecological' integrated management strategies.

1. Introduction

Against the backdrop of global climate change and the "carbon balance" goals, the development of "green energy" has become the fundamental approach to achieving carbon cycle balance (Shan et al., 2021). At the same time, as an important clean energy source, photovoltaics have experienced rapid development. The development and construction of large-scale photovoltaic power plants have played a crucial role in promoting regional socioeconomic development. However, they have altered local surface energy distribution and

microclimate (Chang et al., 2020), influencing the biogeochemical behavior of biogenic elements within the ecosystem and related material, energy, chemical, and biological domains (Lambert et al., 2021). This has inevitably impacted ecological hydrological processes, such as soil function regulation, microclimate adjustment, vegetation restoration, and reconstruction (Liu et al., 2019).

PVPPs plays a critical role in regulating the ecological environment elements of a region, including climate, soil, biological communities, and terrestrial ecosystem carbon sinks, through altering the spatial layout of the environment. The magnitude of their impact is influenced

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by a range of natural and human-induced factors (Zhang et al., 2023a), such as the size of the power plants, operational duration, and methods used for installing photovoltaic panels, collectively termed as ‘driving factors’ (see Fig. 1). Essentially, the installation of photovoltaic panels can impact surface water, heat exchange, and energy balance, leading to spatial and temporal variations in environmental effects within the photovoltaic field (Jiang et al., 2021). These environmental effects primarily manifest in climate, soil, biological communities, and terrestrial ecosystem carbon sinks (Kaldellis et al., 2014). Specifically, PVPPs can result in differences in temperature, air humidity, wind speed, soil particle size, physicochemical properties, temperature, evaporation, biomass, and species diversity across different areas within the photovoltaic field (Yavari et al., 2022). Furthermore, PVPPs may indirectly influence the carbon cycling balance in terrestrial ecosystems by modifying soil temperature, humidity, and organic carbon content (Zhou et al., 2018). As photovoltaic power plants continue to operate, these regulatory effects are expected to become more pronounced. Therefore, objectively and effectively assessing the ecological environmental effects of photovoltaic power plants (PVPPs), exploring their primary impact mechanisms, and transforming potential driving factors into future positive outcomes are urgent scientific issues that must be addressed in the context of carbon balance.

A substantial number of experiments have investigated the ecological and environmental effects associated with the construction of photovoltaic power plants. For instance, Elminshawy et al. (2024) examined the impact of photovoltaic support systems with varying tilt angles on evaporation and demonstrated that photovoltaic power generation can contribute to a reduction in carbon emissions. Additionally, research by Zhou et al. (2024) indicates that photovoltaic systems can lower surrounding temperatures during the summer while increasing them in the winter. Collectively, these studies provide valuable evidence for understanding the impact mechanisms of photovoltaic power plant construction on the ecological environment. However, individual experimental studies have limited scope and usually only focus on a certain type or category of ecological environmental effects of PVPPs. There is still a lack of comprehensive understanding of the global impact of photovoltaic power plant construction on ecological and environmental effects. For example, Wu et al., (2020) research shows that the construction of desert photovoltaic power plants mainly leads to a cooling effect on the nighttime temperature at 2.5 m and a warming effect on the daytime temperature at 2.5 m. However, the research conclusions obtained from Tucson, PSPS and PSA3 photovoltaic power plants contradict these results, with nighttime temperatures at 2.5 m being approximately 20% higher than the surrounding temperatures (Broadbent et al., 2019). This may be due to the thermal insulation effect of the PV panels influenced by the scale of PVPPs and the location of the observation points within PVPPs. This observation indicates that individual experimental studies may lead to highly variable and occasionally contradictory results (Guzzo et al., 1987). This variability may be influenced by the research methods employed and the limited number of comprehensive experiments conducted.

Meta-analysis, a statistical method for synthesizing the results of multiple experiments in a systematic and quantitative manner, provides more comprehensive and reliable conclusions than a single study by increasing the sample size (Guzzo et al., 1987) and can identify more universal laws and patterns. Additionally, meta-analysis can explore the heterogeneity among different studies through inter-group analysis and

sensitivity analysis, thereby enhancing our understanding of the impact of various driving factors on the results (Hedges and Tipton, 2010). Common analytical models used in meta-analysis include fixed-effects models and random-effects models. The fixed-effects model assumes that all studies share the same true effect, meaning that differences in effect values are solely attributed to sampling error. This model is relatively simple and is suitable for situations where the sample size is sufficiently large and evenly distributed. In contrast, the random-effects model can handle and explain variation among studies, making it applicable to a broader range of research types (Borenstein et al., 2010). For example, Beillouin et al. (2023) constructed a random effects model through meta-analysis to reveal the impact of land use types and climate change on global soil organic carbon. Similarly, Sang et al. (2022) employed a fixed effects model to demonstrate that wet-dry cycles increase greenhouse gas emissions in soil. However, there is relatively little research focused on applying meta-analysis to evaluate the impact of engineering development on terrestrial ecosystems. Furthermore, considering the variations in ecosystem type, soil texture, observation point location, observation time, geographical conditions, installation technology, and power plant scale, which contribute to significant heterogeneity among studies, a random effects model for meta-analysis was selected to analyze the ecological and environmental effects of photovoltaic power plant construction. This approach aims to comprehensively evaluate the ecological and environmental impacts of photovoltaic power plants (PVPPs) within the context of these complex scenarios.

In response to the impact of photovoltaic power plants construction on the ecological environment factors of the regional ecosystem, this study conducted a meta-analysis of 4369 paired comparison observations across 42 original studies. The analysis focused on four categories of factors that reflect the differences in the ecological environment inside and outside the photovoltaic field. Climatic elements examined include air temperature (AT), wind speed (WS), and air humidity (ARH). Soil elements assessed encompass soil temperature (ST), soil moisture content (SMC), soil particle size (SPS), soil evaporation (SE), and soil physical and chemical properties (SPCP). Biological factors considered include plant biomass (VB), plant diversity (VD), microbial biomass (MB), microbial diversity (MD), and arthropod diversity (AD). Additionally, ecosystem carbon flux elements were evaluated, including net ecosystem carbon exchange (NEE), ecosystem respiration (Re), and Gross primary productivity (GPP), which can reflect the important ecological processes of carbon exchange between terrestrial ecosystem vegetation and the atmosphere. GPP was utilized to characterize the ability of vegetation to absorb and fixed atmospheric CO₂. This study aimed to achieve the following objectives: (1) to determine the direction and intensity of the ecological and environmental effects of photovoltaic power plant construction and (2) to assess the effects of experimental variables (observation time, observation location, power plants scale, geographic conditions, soil texture, ecosystem type, and installation techniques) on ecological and environmental effects.

2. Materials and methods

2.1. Systematic literature search

A total of 1849 peer-reviewed publications from January 2010 to July 2023 were collected using the following databases: “Web of

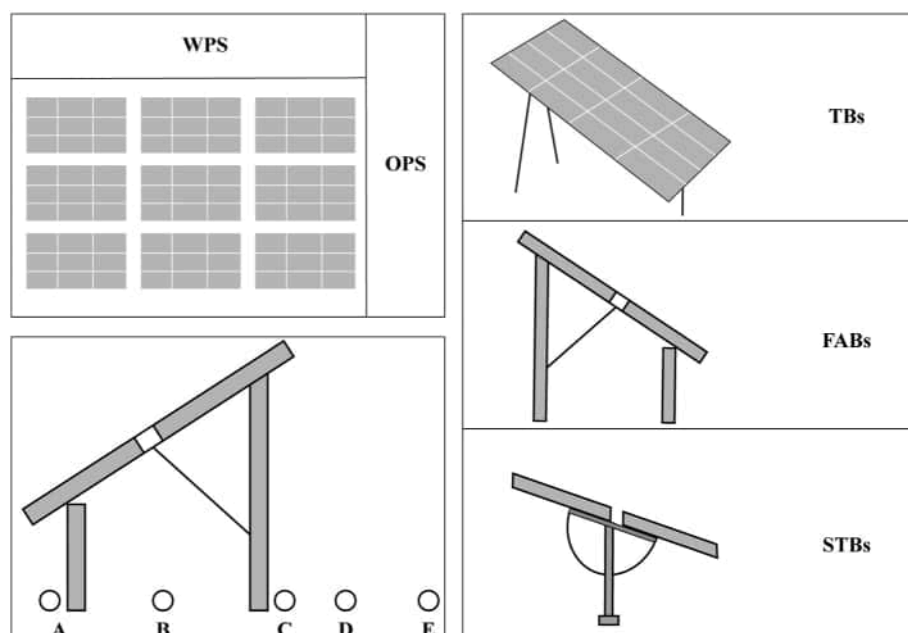


Fig. 1. Throughout the entire experimental process, the selected criteria for the studies (control group [OPS] and experimental group [WPS]) were based on the ecological and environmental effects of photovoltaic development. A (front edge), B (underneath the panels), C (rear edge), D (between panels), and E (outside the field) represent different photovoltaic panel locations. There are three main types of installation brackets for photovoltaic panels: fixed angle brackets (FABs), tracking brackets (TBs), and semitracking brackets (STBs).

Science Core Collection,” “Scopus,” “MEDLINE,” “China Science Citation Database,” “CNKI China Knowledge Resource Integrated Database,” “Engineering Village,” and “ProQuest Dissertations and Theses.” The search strings used were (“photovoltaic” OR “solar power plants” OR “solar park”) AND (“ecology” OR “environment” OR “microenvironment” OR “climatic” OR “microclimate” OR “temperature” OR “humidity” OR “wind speed” OR “wind” OR “soil” OR “sediment” OR “nutrients” OR “CO₂ fluxes” OR “carbon cycle” OR “carbon turnover” OR “biodiversity” OR “microorganism” OR “archaea” OR “microbial” OR “vegetation” OR “plant” OR “crop” OR “grass”). The collected articles were then screened based on the following criteria: (1) The differences in ecological environmental factors between the control group (the original ecological area outside the photovoltaic field) and the experimental group (the operational area inside the photovoltaic field) with the same underlying substrate conditions during the same observation period were analyzed, and assessed the impact of photovoltaic power plants on various ecological factors (Fig. 1); (2) analysis of the influence of different driving factors on the intensity and direction of ecological and environmental effects; and (3) direct reports of effect values (mean and standard error or confidence intervals) of environmental variables or calculated values based on the reported statistical samples. Ultimately, a total of 42 studies were included (see Supplementary Fig. S1 and Fig. 2). The detailed information of the selected studies is included in the appendix.

Existing research on the ecological environmental effects of photovoltaics is primarily concentrated in mainland China and Western Europe, with a smaller amount of studies distributed across South America, North America, and Southeast Asia. Among them, Western

Europe is mainly characterized by temperate continental climate and Mediterranean climate, with dry summers and mild and humid winters. The annual average temperature typically exceeds 10 °C, accompanied by relatively ample rainfall. Notably, vegetation phenology phenomenon is not significant in this region. PVPPs are predominantly established on abandoned farmland and unused grasslands, where perennial herbaceous plants constitute the dominant vegetation species. This has led to the development of a unique photovoltaic ecosystem influenced by the presence of these power plants. Furthermore, the scale of photovoltaic power plants in this region tends to be relatively small, and the photovoltaic supports employed are generally fixed-angle brackets, which effectively optimize space utilization.

PVPPs in mainland China are predominantly located in the arid and semi-arid regions of northwest China, characterized by a temperate continental climate. Rainfall distribution in this area is uneven throughout the year, featuring hot and rainy summers alongside cold and dry winters, which leads to sparse surface vegetation and significant phenological phenomena. PVPPs in northwest China are typically established in deserts, Gobi, and wastelands. These locations offer abundant solar energy resources and extensive areas of unused land, rendering them suitable for photovoltaic energy development. However, the ecological environment in these regions is relatively fragile. Most existing PVPPs continue to utilize fixed-angle brackets. Although a small number of power plants are experimenting with tracking and semi-tracking brackets to enhance light energy absorption efficiency, these technologies have not yet been deployed on a large scale due to spatial limitations.

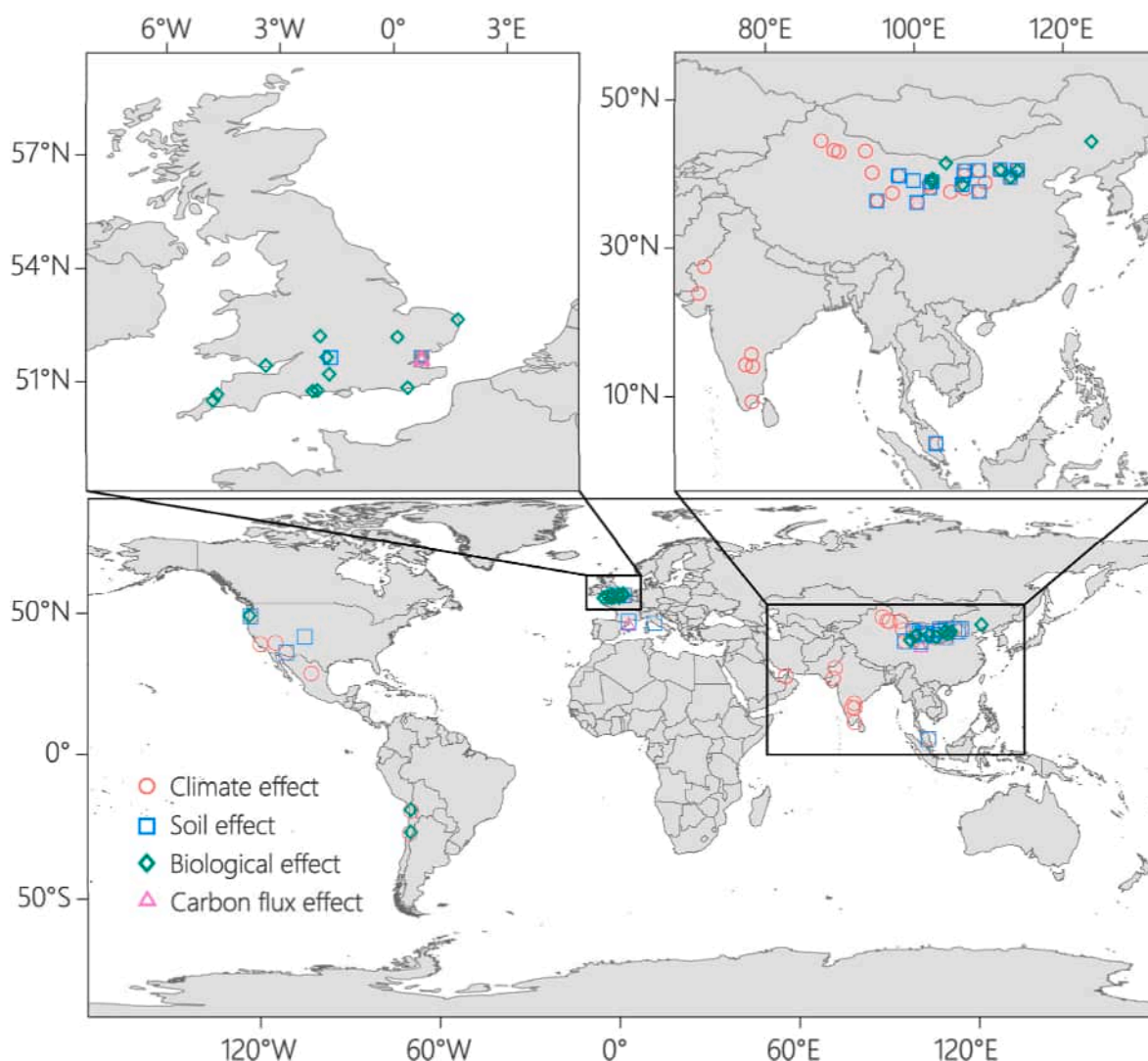


Fig. 2. Geographical distribution overview of the ecological and environmental effects of photovoltaic power plant construction considered in meta-analysis. Among them, the red circle represents research on climate effects, the blue box represents research on soil effects, the green diamond represents research on biological effects, and the pink triangle represents research on carbon flux effects.

2.2. Data extraction and coding

We extracted all the details of the photovoltaic ecological environmental effects included in this study from texts, tables, or charts (using the GetData Graph Digitizer, <http://getdata-graph-digitizer.com/version/2.26>) and recorded them in an Excel file. The ecological environmental effects associated with each statistical value were classified according to climate effects, soil effects, biological effects, and CO₂ flux. We also extracted indicators (such as ratios and percentage changes), possible transformations (such as logarithms), confidence intervals or other variability measures, as well as the original research data and observation numbers used to calculate the effect values (Beillouin et al., 2023). Ultimately, for this study, we extracted 1168 climate effect observations from 20 studies, 1364 soil effect observations from 28 studies, 682 biological effect observations from 14 studies, and 1171 CO₂ flux observations from 3 studies (Fig. 3).

Given the potential variability in the basic conditions of observational experiments among the collected studies, detailed information regarding the experiments was recorded. This information included the observed height of climate measurement points (MH), distance relative to the centre of the power plant (DWS), placement on the surface or backside of the photovoltaic panel (SBP), soil depth (SD), installation

technique for PV panels in the biological observation area (PPIT), elevation (ALT), air humidity (APH), soil properties in the CO₂ flux observation area (such as the clay content (Clay), bulk density (BD), total organic carbon content (TOC), soil temperature (ST), and soil pH. Additionally, the position of the observation points beneath the photovoltaic panel (UBP), differences observed between day and night (DN), differences observed between months (Mon), scale of the photovoltaic power plant (SPV), duration of operation of the power plant (PVOT), land use type (TLU), annual average temperature (MAT), annual precipitation (MAP), and topographical differences (TOP) were also recorded. If studies did not report MAT and MAP data, these data were obtained from NOAA and NCEI (National Centers for Environmental Information) (<https://www.ncei.noaa.gov/>) based on the geographic location of the observation points. If soil properties were not provided in the studies, missing data were obtained from the Harmonized World Soil Database (HWSD: http://www.fao.org/land-water/land/land-governance/land-resources-planning-toolbox/category/details/en/c/10_28,012/) (Fischer et al., 2000).

2.3. Data analysis

The natural logarithm transformation of the response ratio (RR) is

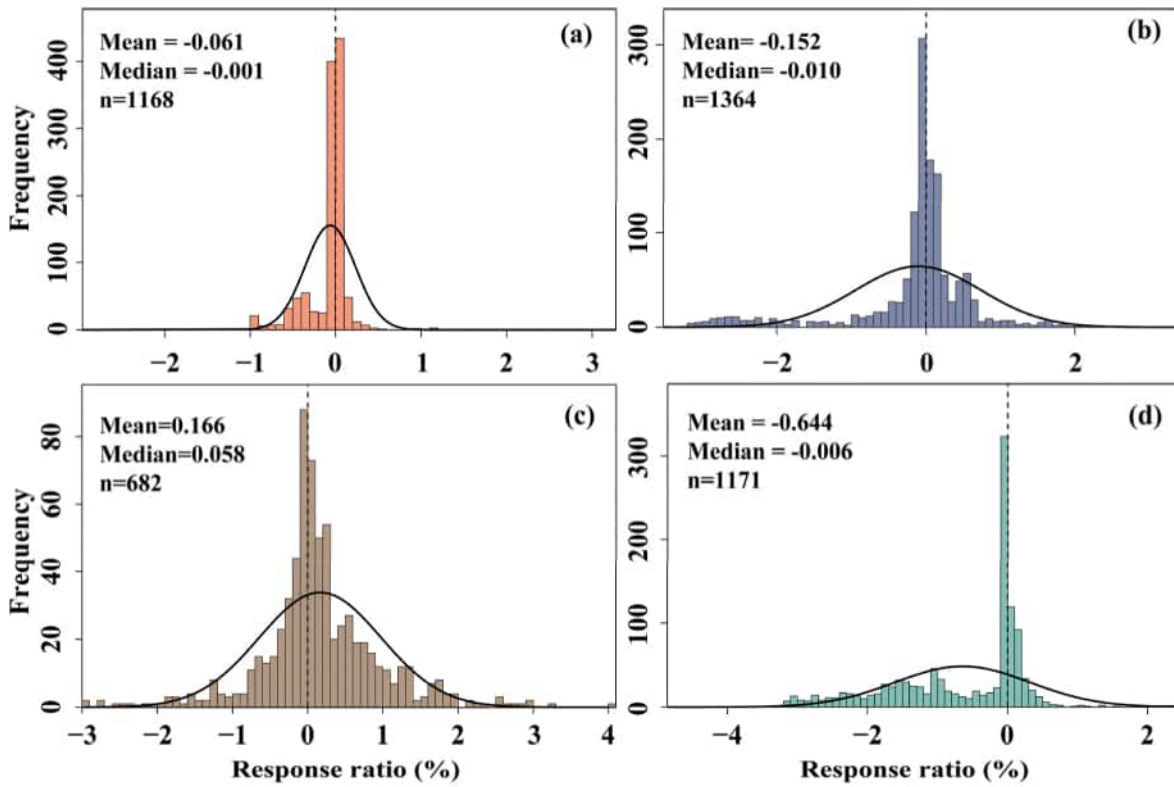


Fig. 3. The frequency distribution of the response rates of climate elements (a), soil elements (b), biological elements (c), and carbon flux elements (d) to the construction of photovoltaic power plants in the original research. The fitting curve is a Gaussian distribution estimated in frequency.

used to estimate the effects of photovoltaic power plant construction on ecological environmental variables (Osenberg et al., 1999), as shown below:

$$\ln RR = \ln\left(\frac{\bar{X}_T}{\bar{X}_C}\right) = \ln(\bar{X}_T) - \ln(\bar{X}_C) \quad (1)$$

with a variance of:

$$\text{var}(RR) = \frac{s.d._T^2}{n_T \bar{X}_T^2} + \frac{s.d._C^2}{n_C \bar{X}_C^2} \quad (2)$$

where $\bar{X}_T$, $s.d._T$ and n_T represent the mean, standard deviation, and sample size of the experimental group, respectively, and $\bar{X}_C$, $s.d._C$ and n_C represent the mean, standard deviation, and sample size of the control group, respectively (Lajeunesse, 2011). Based on a method developed in a previous study, for data extracted from experiments with multiple single-factor experimental groups and one multifactor control group, $\ln RR$ was separately calculated for each control-experimental group pair and treated as independent data during analysis (Song et al., 2019).

To obtain an overall measure of the response magnitude of the experimental group relative to the control group, we used the metafor package in R software to calculate the weighted response ratio ($\ln RR_{++}$) and bias-corrected 95% bootstrapped confidence intervals (CIs) by employing inverse variance weighted regression and random effects models (Nakagawa et al., 2017). Additionally, we used chi-square tests to determine whether there was heterogeneity in $\ln RR$ for the ecological environmental variables influenced by photovoltaic development (Q_{total}) and whether it significantly exceeded the expected sampling error (refer to Table S1). Funnel plots were utilized to assess publication bias, and if studies demonstrated a symmetrical “funnel” shape distribution around the average effect size, it indicated the absence of publication bias. Moreover, we performed Egger’s regression to further evaluate potential asymmetry in the funnel plot (Jennions et al., 2013) (refer to

Fig. S1).

The weighted response ratio (RR_{++}) is calculated using the individual natural logarithm-transformed response ratios RR_{ij} ($i = 1, 2, \dots, m; j = 1, 2, \dots, n$) (Hedges and Tipton, 2010):

$$RR_{++} = \frac{\sum_{i=1}^m \sum_{j=1}^n w_{ij} RR_{ij}}{\sum_{i=1}^m \sum_{j=1}^n w_{ij}} \quad (3)$$

where m and n represent the number of groups compared and the corresponding group, respectively, and w_{ij} represents the weighting factor ($w_{ij} = 1/(\text{var}(RR_{ij}) + \tau^2)$). The variance of RR_{++} is calculated using Formula (4) (Veroniki et al., 2016), with τ^2 estimated using restricted maximum likelihood estimation (REML).

$$\text{SE}(RR_{++}) = \sqrt{\frac{1}{\sum_{i=1}^m \sum_{j=1}^n w_{ij}}} \quad (4)$$

The 95% confidence interval (CI) is calculated using $RR_{++} \pm 1.96 \times \text{SE}(RR_{++})$, and it is worth noting that when the CI of the environmental variable is not equal to zero, it signifies a statistically significant response to photovoltaic development (Gurevitch and Hedges, 2001). Furthermore, if the 95% CI of the environmental variable has no overlap with zero, it indicates a significant effect of photovoltaic development on that variable (Schwarzer et al., 2015). Finally, the percentage change in the experimental and control groups is evaluated as follows:

$$\text{Percentage change} = (e^{\ln RR_{++}} - 1) \times 100$$

The data are grouped according to the types of ecological environmental effects, and the “ggstatsplot”, “palmerpenguins”, and “tidyverse” packages are used to construct boxplot-violin plots. Multiple pairwise t tests are performed for comparative analysis (Kassambara, 2020; Villanueva and Chen, 2019). The “randomForest” package is used to construct a random forest model to determine the importance of driving factors in the RRs of ecological environmental elements, such as climate,

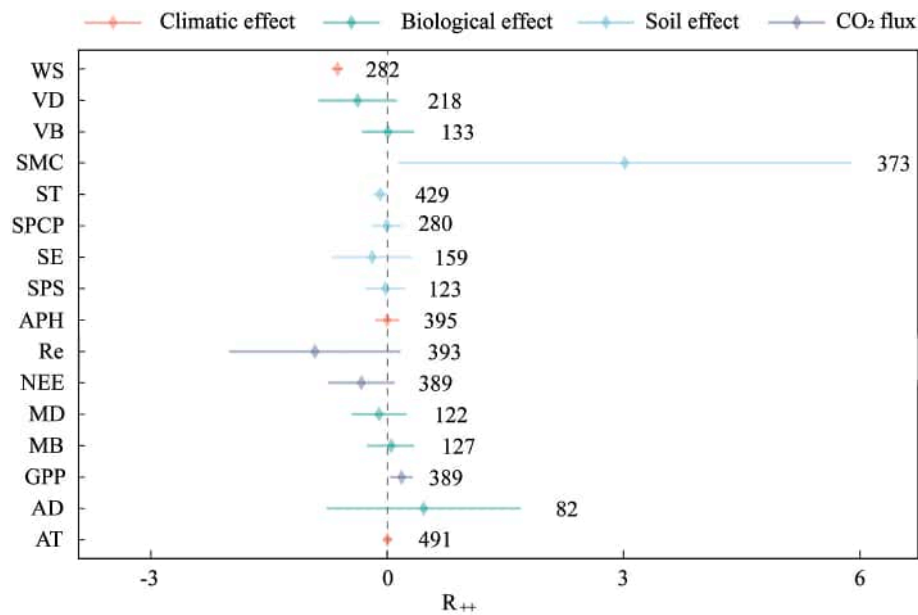


Fig. 4. The weighted response ratio (RR_{++}) of wind speed (WS), plant diversity (VD), plant biomass (VB), soil moisture content (SMC), soil temperature (ST), soil physiochemical properties (SPCP), soil evaporation (SE), soil particle size (SPS), air humidity (APH), ecosystem respiration (Re), net ecosystem carbon exchange (NEE), microbial diversity (MD), microbial biomass (MB), total primary productivity (GPP), arthropod diversity (AD), and temperature (AT) in response to PVPPs ($RR_{++} \pm 95\%$ confidence interval (CI)). The sample sizes for each group are given in the graph. 95% of CIs overlapping with zero or not represent significant or non-significant response ratios, respectively. $RR_{++} > 0$ represents a positive effect, while $RR_{++} < 0$ indicates a negative effect.

soil, biology, and CO_2 , under the influence of PVPPs (Grömping, 2009). The impact of important driving factors on the response ratio of ecological environmental elements in photovoltaic development is evaluated using the mixed-effects model in the “lme4” package (Bates et al., 2015). Statistical clustering methods in the “tidyverse”, “cluster”, and “factoextra” packages are used to determine the threshold of important driving factors (MH, SPV, month, etc.) on the impact of ecological environmental elements (Giordani et al., 2020). All the aforementioned packages are programmed in R software (version 4.2.3).

3. Results

3.1. Effects of PVPPs on ecological environmental elements

To evaluate the impact of large-scale photovoltaic power plants (PVPPs) on regional ecological elements, an analysis was conducted on changes in 16 ecological factors. The study revealed that PVPPs significantly reduced on-site wind speed (WS) and soil temperature (ST) compared to control areas, with RR_{++} values of 0.64, CI[-0.71, 0.56] and 0.10, CI[-0.18, 0.01] respectively (Fig. 4). This reduction is likely due to the shading effect of PV panels. In contrast, soil moisture content (SMC) within the PV fields increased by 301.63%, CI[14.14, 589.13], and total primary productivity (GPP) increased by 28.52%, CI [14.29, 42.75], indicating a notable impact on the regional carbon distribution pattern. However, other ecological elements did not exhibit significant changes under the influence of PVPPs, possibly due to variations in experimental locations and outcomes.

The analysis reveals significant differences in the response rates of climate effects, soil effects, and carbon flux effects to photovoltaic power plants (PVPPs). However, various biological indicators exhibit similar response rates to PVPPs, showing a slight increase overall (Fig. 5d), suggesting that the presence of photovoltaic power plants promotes biological activity. Fig. 5a illustrates that the average response rates of ARH and AT to PVPPs are 0.03 and 0.01, respectively. Notably, the response rate of WS to PVPPs is significantly higher than that of APH and AT ($p < 0.05$). The 25th and 75th percentiles of the average response rate to PVPPs are 0.41 and 0.17, respectively, indicating that PVPPs

primarily reduce wind speed in the site. Regarding the response of soil elements to PVPPs, the average response rate of ST is 0.10, signifying a decrease in soil temperature, which is significantly different from SE, SMC, and SPCP ($p < 0.05$). Among these, SMC and SPCP in the photovoltaic site both exhibit increases, with response rates of 0.24 and 0.08, respectively, while SE shows a significant decrease, with an average response rate of -1.80 (Fig. 5b). Meanwhile, PVPPs had a significant impact on the ecosystem carbon balance, leading to a notable increase in GPP, with an average response rate of 0.36. As illustrated in Fig. 5c, three indicators used to characterize regional ecosystem carbon exchange fluxes demonstrated a significant difference in response to PVPPs ($p < 0.05$). The response rates of Re and NEE to PVPPs were 1.72 and 0.01, respectively. It indicates that unlike other new energy technologies, the construction of PVPPs leads to a decrease in soil particle size, an increase in water content, and a reduction in temperature in the site. These changes contribute to a decrease in soil respiration intensity. Furthermore, a higher clay content in the soil promotes the formation of soil aggregates, which physically protects unstable dissolved organic matter from microbial decomposition, thereby reducing carbon emissions. Additionally, PVPPs influence environmental factors such as microclimate and soil conditions in the site, resulting in positive effects on plant and microbial communities (Fig. 5d), enhancing photosynthesis and chemical energy synthesis, indirectly improving the carbon absorption and fixation effects of regional ecosystems (i.e. $NEE < 0$).

3.2. Importance of driving factors on ecological environmental elements

Figs. 6 and 7 illustrate the relative importance of driving factors on various environmental elements. Specifically, Mon, SPV, and DN emerge as the most crucial driving factors influencing the response rates of WS, AT, and APH (RR_{WS} , RR_{AT} , and RR_{APH}) under the influence of PVPPs (Fig. 6a). The mixed effects model reveals that UBP, PVOT, and Mon are the primary driving factors for WS, APH, and AT, with significant correlation relationships among them ($p < 0.05$) (Fig. 7a). In Fig. 6b, the importance analysis of driving factors on soil element response rates highlights UBP, SPV, PVOT, and Mon as the key factors influencing the variation of soil element response rates to PVPPs. Furthermore, the

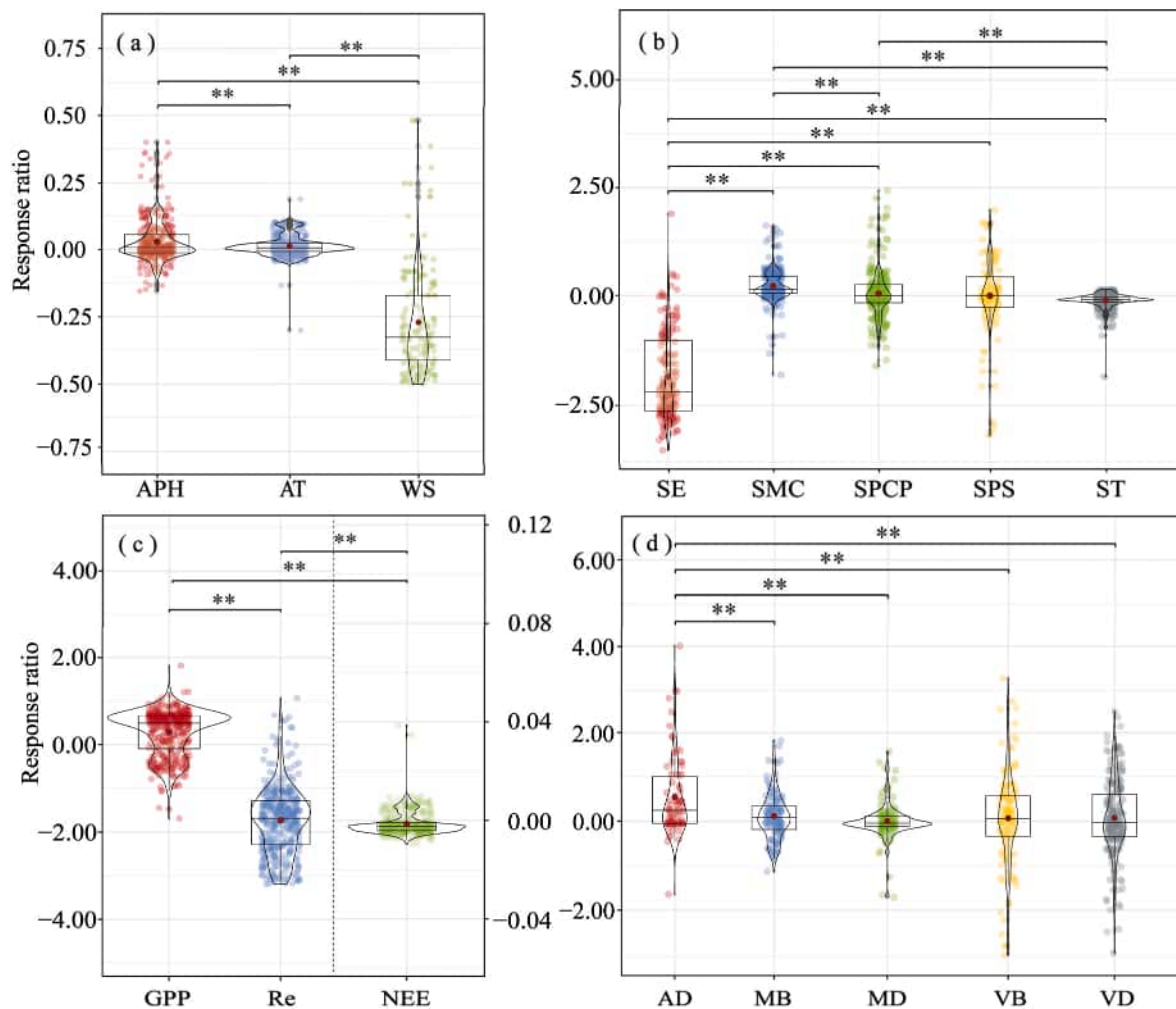


Fig. 5. An overview of the response ratio of different types of ecological environmental elements to PVPPs ((a) climate effect, (b) soil effect, (c) CO₂ flux, and (d) biological effect). The horizontal line and the red dot within each box indicate the median and mean values, respectively. The boundaries of the box represent the 25th and 75th percentiles. The vertical lines represent the 5th and 95th percentiles. The width of the curve indicates the density of the sample distribution. Please note the different scales between the charts. The significance of differences between different environmental variables within the same group is indicated by t tests: ** $p < 0.05$.

mixed effects model indicates a significant correlation between SE and Mon, DWS, with correlation coefficients of 0.55 and 0.37, respectively (Fig. 7c). Soil temperature and air humidity play a significant role in controlling the carbon cycling process in terrestrial ecosystems under the influence of PVPPs (Fig. 6c). Additionally, variations in months and changes in soil TOC content can impact the carbon balance of regional ecosystems (Fig. 7b). The results from the random forest model suggest that differences in MAT and TLU are the primary drivers for plant growth, with MAT also influencing the activities of microorganisms and arthropods (Fig. 7d). However, limitations in the number of observational experiments led to the mixed effects model not converging in the analysis of biological elements, resulting in this aspect of the analysis being omitted.

3.3. Effects of threshold values of driving factors on ecological environmental elements

A cluster analysis was performed to examine the impact of threshold values of key driving factors on the response rate of ecological environmental elements to PVPPs (Fig. 8). The results revealed that thresholds for SPV (40–70 MW), PVOT (3–5 years), and UBP (before the panel) influence the response of air temperature, air humidity, and wind speed to PVPPs (Fig. 8a–c). Similarly, UBP, DWS, SD, and Month also

significantly influenced the response rate of soil elements (PSP, SE, SMC, ST, and SPCP) to PVPPs (Fig. 8d–h). Among these, the threshold values of DWS causing variations in the response rates of SE and SPCP differed, with thresholds of 350 m and (1085–1200 m), respectively. In terms of regional ecosystem carbon cycling, differences in air humidity and month affected the response rate of carbon flux to PVPPs (Fig. 8i–k). The dual effect of PV panel cleaning and gradual vegetation recovery increased air humidity within the photovoltaic field, intensifying the response of GPP and NEE to PVPPs. Furthermore, ecosystem respiration weakened as winter temperatures decreased. The clustering results of biological variables indicated that threshold values of annual average temperature, annual average rainfall, and altitude influenced the response rate of biological variables to PVPPs. Annual average temperature emerged as the most significant driving factor (Fig. 8l–p), with specific temperature ranges causing notable changes in the response rate of microorganisms, plant communities, and arthropods to PVPPs.

4. Discussion

4.1. Changes in the ecological environmental response to PVPPs

- (1) Changes in the climate element response to PVPPs

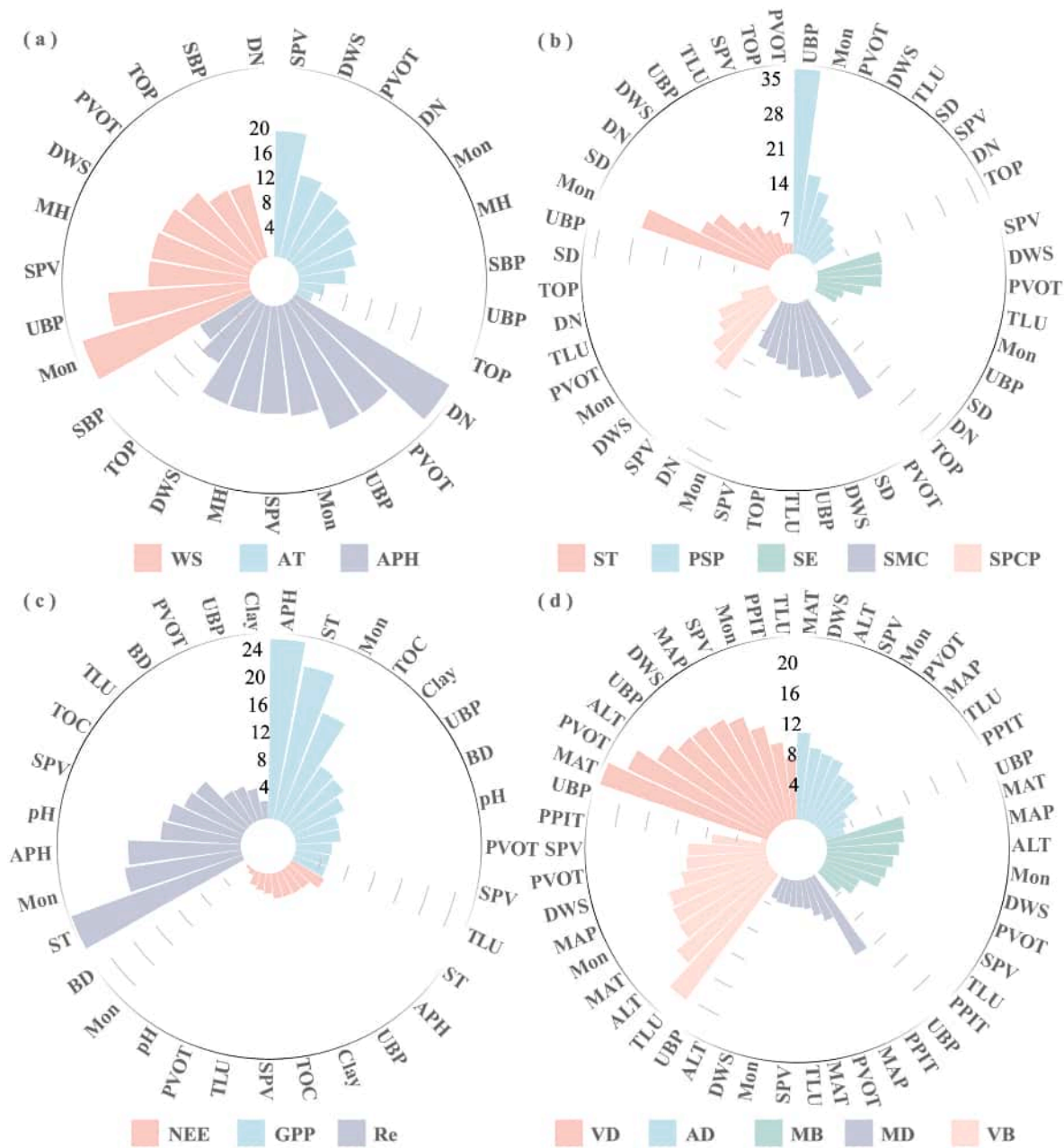


Fig. 6. The importance of driving factors affecting the response rate of Climate, Soil, CO₂, and Biology to PVPPs can be determined by the mean square error percentage (IncMSE%). A higher IncMSE% determined by the random forest model indicates greater importance of the driving factors. The length of the bars in the charts represent the magnitudes of the IncMSE% values, and the scales between the charts vary. For ease of calculation in the experiment, the following quantifications are applied to the categorical variables: i) setting “under the board,” “in front of the board,” “between the boards,” and “behind the board” in UBPP as 0, 1, 2, and 3, respectively; ii) setting “day” in DN as 0 and “night” as 1; iii) setting “PV board surface” and “PV board back” in SBP as 0 and 1, respectively; iv) setting “plain,” “hills,” “urban,” and “mountain” in TOP as 0, 1, 2, and 3, respectively; v) setting “saline-alkaline land,” “desert,” “grassland,” “forest,” and “farmland” in TOP as 0, 1, 2, 3, and 4, respectively; and vi) setting “fixed support” as 0, “tracking support” as 1, and “semitracking support” as 2 in PPIT.

PVPPs have changed the original land use and spatial layout of underlying surfaces, thus affecting the water, heat exchange, and energy balance at the land–atmosphere interface of terrestrial ecosystems (Chang et al., 2022) and leading to changes in ecological environmental elements, such as the microclimate, soil, biology, and carbon cycle (Choi et al., 2020; Luo et al., 2023). This meta-analysis shows that compared with the control area outside the photovoltaic field, PVPPs result in a 63.49% decrease in the average wind speed (Fig. 4). On the one hand, this is due to the increased surface roughness caused by the installation of PV panels, resulting in a barrier effect and strong attenuation of wind-sand energy (Chang et al., 2020; Etyemezian et al., 2017). On the other hand, this is due to the greater vegetation coverage inside the

photovoltaic field than outside (Fig. 5d), resulting in significant interception of airflow by vegetation (Grace, 1989; Yang et al., 2019). Moreover, PVPPs can significantly impact local thermal circulation, aiding in the transformation and consumption of potential wind-sand energy and thus reducing the intensity of airflow (Tian et al., 2023). In this study, the maximum and minimum reduction effects were observed at the 30 MW Kubeqi desert photovoltaic power plants in China (Chen et al., 2019) and the 1.40 MW Oregon agricultural photovoltaic power plants in the United States, respectively. When compared to the original ecological control area outside the photovoltaic site, the reduction rates of PVPPs on wind speed within the site were 238.21% and 2.75%, respectively. As airflow enters PVPPs, the reduction in wind

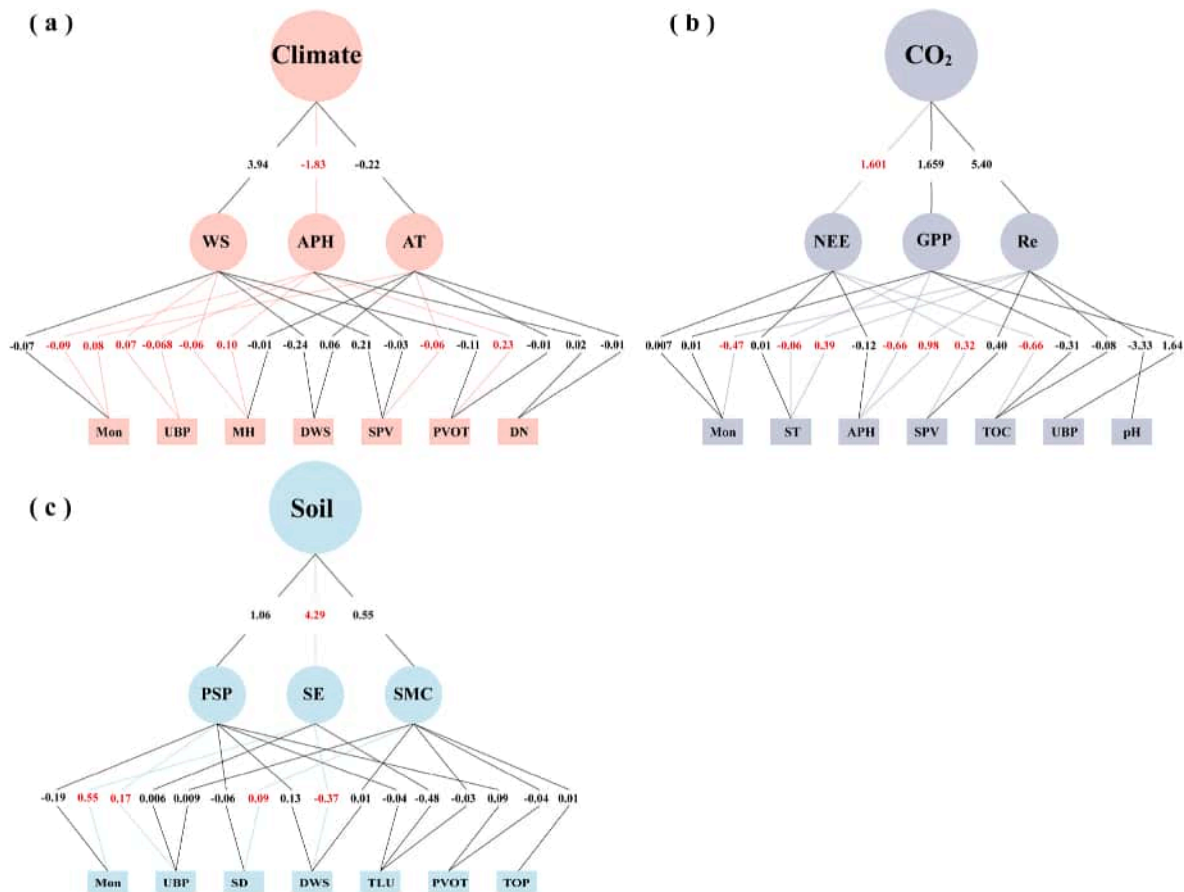


Fig. 7. Relationships between the response rate and driving factors of climate factor (a), carbon flux factor (b), and soil factor (c) to PVPPs. Values with a (-) imply a negative correlation, and values highlighted in red and bold indicate statistical significance at a p value of less than 0.05.

speed becomes more pronounced with increasing distance from the entry point. This observation suggests that larger PVPPs may exert a more significant influence on wind speed. These processes partially explain why the wind speeds inside the photovoltaic field are significantly lower than those outside the photovoltaic field (Fig. 5a). Notably, air temperature and humidity are also important climatic factors, and many studies have shown that the temperature under PV panels is relatively lower, while the air humidity is greater than that outside the panel area (Li et al., 2020). Previous observations in agricultural photovoltaic field areas have indicated that differences in observation heights can result in different warming and cooling effects, with significantly lower air humidity inside the field than outside (Hassanpour et al., 2018). However, in this study, due to the limited sample size and differences in driving factors, there are no significant changes in the response of air temperature or humidity to PVPPs.

(2) Changes in the soil element response to PVPPs

In addition to having a significant effect on the microclimate, our meta-analysis shows that compared to the control area outside the photovoltaic field, PVPPs increased the average soil moisture content in the site by 301.63% (Fig. 4). In addition, the geographical environment of the study area can significantly influence the soil wetting effect of PVPPs, with this effect being more pronounced in arid regions compared to humid ones. For example, Wu et al. (2022) conducted a study on photovoltaic power plants in the arid northwest region of China, revealing that the average soil moisture content within the plant ($0.15 \text{ m}^3\text{m}^{-3}$) was 1.79 times greater than that outside the site ($0.09 \text{ m}^3\text{m}^{-3}$). In contrast, research findings from the UiTM 50 MW photovoltaic power plants, situated in a humid area of Malaysia, indicated that the soil

moisture content beneath the PV panels was 10.87% higher than that outside the site (Noor and Reeza, 2022). Furthermore, the humidification effect varies depending on the specific location beneath the PV panel, primarily because PV panels alter the path of rainfall runoff, thereby increasing soil moisture in localized areas (Yue et al., 2021). In this process, the diversion effect of PV panels promotes an increase in soil moisture at points A and B, as shown in Fig. 1 (Choi et al., 2020). Additionally, the shading effect of PV panels greatly reduces soil moisture evaporation, indirectly affecting the soil moisture content (Li et al., 2016; Moscatelli et al., 2022). In a previous study conducted in southern France, three photovoltaic power plants with different vegetation types planted under PV panels were investigated. One study reported that the soil moisture content in areas with shrub vegetation was 2.50%–5.50% greater than that in pine and grapevine areas (Lambert et al., 2021). Due to the different water retention capacities of plant root systems, the presence of different vegetation types inside and outside the photovoltaic field may result in spatial heterogeneity in the soil moisture content (Leenaars et al., 2018; Stratton et al., 2000). Additionally, there is a feedback relationship between vegetation coverage and soil moisture content (Wang et al., 2018). Notably, as important soil parameters, soil temperature, particle size, physicochemical properties, and evaporation can also change due to PVPPs (Shang et al., 2023). Studies have shown that from the periphery to the interior of photovoltaic power plants, the proportion of fine soil particles gradually increases (Dang et al., 2019). This is mainly due to the blocking effect of PV panels, which slows the wind velocity and improves the sorting of soil particles, thus facilitating the storage of soil moisture and nutrients. However, due to significant soil disturbance during the PVPP construction process, nutrient loss in the soil is severe, resulting in relatively lower soil nutrient contents inside the field than outside (Fig. 4). Soil moisture not only sustains

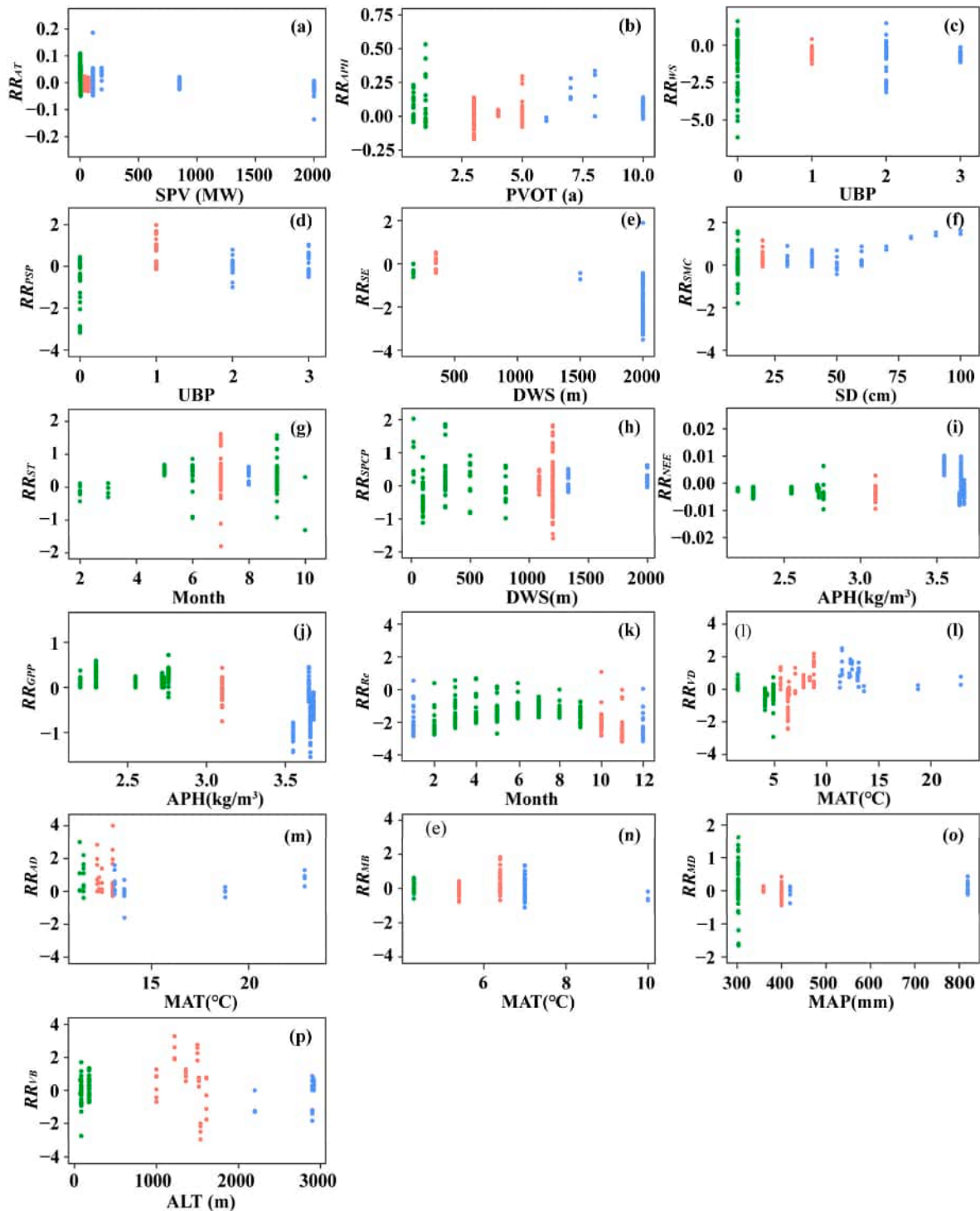


Fig. 8. Cluster analysis of key driving factors and environmental elements. Among them, the red, green, and blue points represent a type of data point in the clustering analysis results, and the red threshold interval divides the data point into two parts in reverse. Note the different scales among the graphs.

vegetation growth and nutrient storage but also regulates soil temperature (Wang et al., 2019). Therefore, under the influence of PVPPs, the soil temperature inside the field is lower than that outside, resulting in a decrease in soil evaporation (An et al., 2018). However, our meta-analysis revealed that the impact of PVPPs on soil temperature, particle size, physicochemical properties, and evaporation is not significant.

(3) Changes in the CO₂ flux response to PVPPs

PVPPs also lead to a decrease in gross primary productivity (GPP). Our meta-analysis shows that the GPP within the solar photovoltaic (PV) field is 28.52% higher than that outside the PV field (Fig. 4). However, the increase in GPP on site may also be closely related to the land use type of the study area. For example, Alona et al. (2016) conducted a study in Westmill, UK, revealing that the site was previously farmland before the construction of the photovoltaic power plant, but was subsequently managed as permanent grassland after construction. GPP within the site was found to be 0.11% higher than that outside the site.

In a separate study, Li (2023) investigated the northwest desert photovoltaic power plants in China and reported that the GPP inside the site was 29.77% higher compared to the control area outside. This increase is attributed to the enhanced photosynthesis of vegetation within the photovoltaic field (Xie et al., 2020). This study indicates that PVPPs reduce soil temperature, increase soil moisture content, and significantly enhance vegetation coverage, which is beneficial for promoting GPP growth (Ma et al., 2023; Shi et al., 2023). Furthermore, the construction of PVPPs has improved soil hydrothermal conditions and physicochemical properties, creating a favorable environment for microbial activity within the soil. This enhancement can promote the formation of mineral-bound organic matter and soil aggregates (Bünemann et al., 2016; Denef et al., 2001) and bolster carbon sequestration in ecosystems. Soil plays a crucial role in the carbon cycle of terrestrial ecosystems, and soil respiration is a primary contributor to the increase in atmospheric CO₂ concentration and the greenhouse effect (Barba et al., 2018; Čapek et al., 2019). The improvement of soil texture and physicochemical properties promotes the formation of soil aggregates, which physically protects organic matter in the soil, making it more difficult for microorganisms to decompose. This process further reduces CO₂ emissions from the soil to the atmosphere, resulting in a decrease in Re. Our study also reveals that under the influence of PVPPs, the overall net ecosystem carbon exchange (NEE) and ecosystem respiration (Re) also decrease, indicating that PVPPs increase carbon sequestration in terrestrial ecosystems, but the results are not significant (Fig. 4). This is consistent with previous observational experiments conducted in Northwest China (Li, 2023).

(4) Changes in the biological element response to PVPPs

Under the influence of PVPPs, changes in the flux and exchange processes of surface water, heat, and carbon in the ecosystem have led to differences in the distribution patterns of organisms. In the photovoltaic field, abundant sunlight and suitable temperature and humidity conditions are favorable for the growth of various vegetation types (Liu et al., 2019). Previous studies have shown that plant biomass between PV panels is 1.5 times greater than that outside the photovoltaic field, while plant biomass under PV panels is lower (Alona et al., 2016). The redistribution of rainfall runoff by PV panels leads to a lower soil moisture content under the panels, and weak annual light conditions result in reduced plant biomass under the panels. Due to interspecies competition, dominant species have a significant competitive advantage, which leads to a decrease in plant diversity in the photovoltaic field to some extent (Yue, 2022). Moreover, the biomass and diversity of microorganisms can also differ significantly due to differences in soil water, heat, and vegetation (Ding and Liu, 2021; Li et al., 2023). In addition, a study investigating arthropod diversity at 11 photovoltaic power plants in southwestern England indicated that PVPPs help increase arthropod diversity, possibly because vegetation recovery in the photovoltaic field provides ample food for arthropods (Montag et al., 2016). However, in our study, PVPPs do not have a significant impact on the behaviour of the organisms (Fig. 4). Generally, vegetation and microorganisms are affected by soil water, heat conditions, and light, which results in the response of biotic factors to PVPPs (Augé et al., 2015). This may be attributed to the small sample size of the observed data and significant climate differences (Figs. 4 and 6d).

4.2. Driving factors affecting the response of ecological environmental elements to PVPPs

The regulatory mechanism of PVPPs on ecological environmental elements is intricate. By altering spatial layout or implementing technology, the regulation of ecological environmental elements can be achieved. Research indicates that different types of ecological environmental elements respond diversely to driving factors (Zhang et al., 2023a). Notably, the regional ecosystem water, heat, carbon flux, and

exchange processes display spatiotemporal heterogeneity due to changes in ecological environmental elements within and outside PVPPs (Luo et al., 2023). This study identified MAT, APH, Month, DWS, and UBP as the most critical driving factors influencing the response of ecological environmental elements to PVPPs. Variations in their thresholds significantly impact the response rate of ecological environmental elements to PVPPs, primarily by indirectly constraining biological processes and carbon cycling processes through alterations in the distribution of traditional climate and soil elements. Similar research has also demonstrated that PVPPs can produce both direct and indirect effects (Zhang et al., 2023b).

During the operation of photovoltaic plants, various factors such as differences in months, plant scale, day-night variations, and the location of measurement points have a significant impact on the reduction of wind speed by photovoltaic plants (Fig. 6a). This aligns with a previous study in a semi-arid region, which found that wind speed reduction by PVPPs is 3.00%–5.00% lower in spring and summer compared to winter and autumn. The reduction rate increases exponentially with height, although the effect on wind speed at a 20 cm height has higher uncertainty (Yang et al., 2022). Furthermore, the operating duration and soil depth play a crucial role in the soil humidification effect of photovoltaic plants (Fig. 6b). As the PVPPs operates for longer periods, the soil humidification effect by PVPPs becomes more prominent (Li et al., 2016). Additionally, the impact of soil depth on this effect initially strengthens and then weakens with increasing depth (Wu et al., 2022). Notably, the study identified a turning point in the soil humidification effect at a depth of 20 cm (Fig. 8f). Moreover, air temperature and humidity influenced by PVPPs significantly impact the physicochemical properties of the soil, subsequently affecting soil respiration, plant photosynthesis intensity, and ultimately regulating the carbon cycling processes in the ecosystem (Yu et al., 2017).

5. Conclusions and limitations

This meta-analysis investigated the impact of photovoltaic power plants (PVPPs) construction on four ecological environmental elements: climate, soil, biological, and carbon flux, under composite scenarios of various geographical environments, ecosystem types, and photovoltaic system parameters. It elucidated the mechanisms through which key driving factors influence ecological environmental elements. The results indicated that PVPPs significantly reduced average wind speed by 63.55% (confidence intervals (CI): [70.77, 56.32]), increased soil moisture content by 301.63% (CI: [14.14, 589.13]), and enhanced gross primary productivity by 28.52% (CI: [14.29, 42.75]). The impact of PVPPs on ecological environment factors is mainly related to monthly variations, the scale of photovoltaic systems, geographical conditions, and soil characteristics. Changes in water and heat balance serve as the primary driving forces behind the heterogeneity of ecological environmental factors resulting from PVPPs, with this impact being more pronounced in larger and drier photovoltaic power plants. However, the effect of PVPPs on biological elements is not significant, which may be attributed to data scarcity and the high variability in observational results caused by complex driving factors. The construction of PVPPs not only generates clean energy but also enhances the regional ecological environment and promotes carbon sequestration. However, due to the heterogeneity of these impacts across ecosystems of varying scales and degrees of drought, the future development and management of PVPPs must be comprehensively considered in relation to the specific conditions of each region. This study aims to support the integrated development of photovoltaic energy development alongside ecological environment protection in the context of global climate change and carbon balance objectives.

Research results can support the comprehensive life cycle management of photovoltaic power plants. On one hand, ecological compensation measures, such as vegetation restoration and the construction of artificial ecosystems, can be developed in advance during the planning

stage to mitigate the ecological and environmental risks associated with photovoltaic engineering development. On the other hand, it can offer data support for the rational design of construction plans and the development of scientifically sound and effective ecological security protection strategies during the construction phase. For instance, by integrating the findings of biological effect research, appropriate protective measures can be implemented to mitigate the destruction of species habitats. Furthermore, the research results can offer a scientific foundation for optimizing the operation and maintenance methods of photovoltaic power plants during their operational phases. This includes the establishment of a long-term monitoring system for ecological environmental factors, as well as the evaluation of the sustainability of photovoltaic energy in relation to ecological synergy. This meta-analysis primarily examines the impact of PVPPs construction on terrestrial ecosystem climate elements, soil elements, biological elements, and carbon flux elements. However, the effects of PVPPs construction on terrestrial ecosystems extend beyond these aspects. In addition, the research on carbon flux observation in terrestrial ecosystems influenced by photovoltaic development is still in its early stages, resulting in a limited number of relevant studies. This scarcity may impact the reliability of the findings. Furthermore, the mechanisms by which PVPPs affect ecological environmental elements involve more than just the variables currently considered; they also encompass a broader range of environmental and human factors. Future research should incorporate additional variables, such as socioeconomic indicators and air quality metrics. Moreover, it is essential to evaluate more parameters related to photovoltaic systems, including PV panel types and layout densities, to enhance the representativeness of the results.

CRediT authorship contribution statement

Hang Chen: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Wei Wu:** Writing – review & editing, Project administration, Funding acquisition, Formal analysis, Data curation. **Chen Li:** Visualization, Software. **Gang Lu:** Software, Investigation. **Deli Ye:** Software. **Chao Ma:** Investigation. **Lei Ren:** Data curation. **Guodong Li:** Supervision, Investigation.

Consent to participate

Not applicable.

Ethics approval

Not applicable.

Consent to publication

Not applicable.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2024.123785>.

Data availability

Data will be made available on request.

References

- Alona, A., Nicholas, J.O., Jeanette, W., 2016. Solar park microclimate and vegetation management effects on grassland carbon cycling. *Environ. Res. Lett.* 11 (7), 074016. <https://doi.org/10.1088/1748-9326/11/7/074016>.
- An, N., et al., 2018. Effects of soil characteristics on moisture evaporation. *Eng. Geol.* 239, 126–135. <https://doi.org/10.1016/j.enggeo.2018.03.028>.
- Augé, R.M., Toler, H.D., Saxton, A.M., 2015. Arbuscular mycorrhizal symbiosis alters stomatal conductance of host plants more under drought than under amply watered conditions: a meta-analysis. *Mycorrhiza* 25 (1), 13–24. <https://doi.org/10.1007/s00572-014-0585-4>.
- Barba, J., et al., 2018. Comparing ecosystem and soil respiration: review and key challenges of tower-based and soil measurements. *Agric. For. Meteorol.* 249, 434–443. <https://doi.org/10.1016/j.agrformet.2017.10.028>.
- Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. *J. Stat. Software* 67 (1). <https://doi.org/10.18637/jss.v067.i01>.
- Beillouin, D., et al., 2023. A global meta-analysis of soil organic carbon in the anthropocene. *Nat. Commun.* 14 (1), 3700. <https://doi.org/10.1038/s41467-023-39338-z>.
- Borenstein, M., Hedges, L.V., Higgins, J.P., Rothstein, H.R., 2010. A basic introduction to fixed-effect and random-effects models for meta-analysis. *Res. Synth. Methods* 1 (2), 97–111. <https://doi.org/10.1002/jrsm.12>.
- Broadbent, A.M., Krayenhoff, E.S., Georgescu, M., Sailor, D.J., 2019. The observed effects of utility-scale photovoltaics on near-surface air temperature and energy balance. *J. Appl. Meteorol. Climatol.* 58 (5), 989–1006. <https://doi.org/10.1175/JAMC-D-18-0271.1>.
- Bünemann, E.K., Augstburger, S., Frossard, E., 2016. Dominance of either physicochemical or biological phosphorus cycling processes in temperate forest soils of contrasting phosphate availability. *Soil Biol. Biochem.* 101, 85–95. <https://doi.org/10.1016/j.soilbio.2016.07.005>.
- Čapek, P., Starke, R., Hofmockel, K.S., Bond-Lamberty, B., Hess, N., 2019. Apparent temperature sensitivity of soil respiration can result from temperature driven changes in microbial biomass. *Soil Biol. Biochem.* 135, 286–293. <https://doi.org/10.1016/j.soilbio.2019.05.016>.
- Chang, R., Luo, Y., Zhu, R., 2020. Simulated local climatic impacts of large-scale photovoltaics over the barren area of Qinghai, China. *Renew. Energy* 145, 478–489. <https://doi.org/10.1016/j.renene.2019.06.059>.
- Chang, R., et al., 2022. A coupled WRF-PV mesoscale model simulating the near-surface climate of utility-scale photovoltaic plants. *Sol. Energy* 245, 278–289. <https://doi.org/10.1016/j.solener.2022.09.023>.
- Chen, X., Gao, Y., Zhai, B., Liu, X.J., Cheng, B., 2019. The transport characteristics of wind and sand currents in photovoltaic fields in sandy areas. *Res. Arid Regions* 36 (03), 684–690. <https://doi.org/10.13866/j.azr.2019.03.20>.
- Choi, C., et al., 2020. Effects of revegetation on soil physical and chemical properties in solar photovoltaic infrastructure. *Front. Environ. Sci.* 8, 140. <https://doi.org/10.3389/fenvs.2020.00140>.
- Dang, M.J., Meng, Z.J., Siqing, B., Yang, S.R., 2019. Particle characteristics of surface sediment in the photovoltaic power plants in the South margin of the Kubuqi desert. *Chinese Journal of Soil Science* 50 (2), 260–266. <https://doi.org/10.19336/j.cnki.trtb.2019.02.02>.
- Denef, K., et al., 2001. Influence of dry–wet cycles on the interrelationship between aggregate, particulate organic matter, and microbial community dynamics. *Soil Biol. Biochem.* 33 (12), 1599–1611. [https://doi.org/10.1016/S0038-0717\(01\)00076-1](https://doi.org/10.1016/S0038-0717(01)00076-1).
- Ding, C.X., Liu, Y., 2021. Effects of solar photovoltaic park construction on soil microbial community in alpine desert of Qinghai Tibet plateau. *Acta Agrestia Sinica* 29 (5), 1061–1069. <https://doi.org/10.11733/j.issn.1007-0435.2021.05.023>.
- Elminshawy, N.A., Osama, A., Gagliano, A., Oterkus, E., Tina, G.M., 2024. A technical and economic evaluation of floating photovoltaic systems in the context of the water-energy nexus. *Energy* 131904. <https://doi.org/10.1016/j.energy.2024.131904>.
- Etyemezian, V., Nikolich, G., Gillies, J.A., 2017. Mean flow through utility scale solar facilities and preliminary insights on dust impacts. *J. Wind Eng. Ind. Aerod.* 162, 45–56. <https://doi.org/10.1016/j.jweia.2017.01.001>.
- Fischer, G., Shah, M., Velthuisen, H., Nachtergaele, F., 2000. *Global Agro-Ecological Zones Assessment*.

- Giordani, P., Ferraro, M.B., Martella, F., 2020. *Introduction to Clustering*. Springer Singapore, Singapore.
- Grace, J., 1989. *Measurement of Wind Speed Near Vegetation*. Springer Netherlands, Dordrecht, pp. 57–73.
- Grömping, U., 2009. Variable importance assessment in regression: linear regression versus random forest. *Am. Statistician* 63 (4), 308–319. <https://doi.org/10.1198/tast.2009.08199>.
- Gurevitch, J., Hedges, L.V., 2001. Meta-analysis: combining the results of independent experiments. *Design and analysis of ecological experiments* 2, 347–369.
- Guzzo, R., Jackson, S., Katzell, R., 1987. Meta-analysis analysis. *Res. Organ. Behav.* 9, 407–442.
- Hassanpour, A.E., Selker, J.S., Higgins, C.W., 2018. Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency. *PLoS One* 13 (11), e0203256. <https://doi.org/10.1371/journal.pone.0203256>.
- Hedges, L.V., Tipton, E., 2010. *Meta-Analysis*. Springer, New York, New York.
- Jennions, M.D., Lortie, C.J., Rosenberg, M.S., Rothstein, H.R., 2013. *Handbook of Meta-Analysis in Ecology and Evolution*. Princeton University Press, pp. 207–236.
- Jiang, J.X., Gao, X.Q., Lv, Q.Q., Li, Z.C., Li, P.D., 2021. Observed impacts of utility-scale photovoltaic plant on local air temperature and energy partitioning in the barren areas. *Renew. Energy* 174, 157–169. <https://doi.org/10.1016/j.renene.2021.03.148>.
- Kaldellis, J.K., Kapsali, M., Kavadias, K.A., 2014. Temperature and wind speed impact on the efficiency of PV installations. Experience obtained from outdoor measurements in Greece. *Renew. Energy* 66, 612–624. <https://doi.org/10.1016/j.renene.2013.12.041>.
- Kassambara, A., 2020. Package ‘ggpubr’. 6 (0).
- Lajeunesse, M.J., 2011. On the meta-analysis of response ratios for studies with correlated and multi-group designs. *Ecology* 92 (11), 2049–2055. <https://doi.org/10.1890/11-0423.1>.
- Lambert, Q., Bischoff, A., Cuff, S., Cluchier, A., Gros, R., 2021. Effects of solar park construction and solar panels on soil quality, microclimate, CO₂ effluxes, and vegetation under a mediterranean climate. *Land Degrad. Dev.* 32 (18), 5190–5202. <https://doi.org/10.1002/ldr.4101>.
- Leenaars, J.G.B., et al., 2018. Mapping rootable depth and root zone plant-available water holding capacity of the soil of sub-saharan Africa. *Geoderma* 324, 18–36. <https://doi.org/10.1016/j.geoderma.2018.02.046>.
- Li, C., Liu, J.X., Bao, J.B., Wu, T.H., Chai, B.F., 2023. Effect of light heterogeneity caused by photovoltaic panels on the Plant–Soil–Microbial system in solar park. *Land* 12 (2). <https://doi.org/10.3390/land12020367>.
- Li, G.Q., Armstrong, A., Liu, Z., 2020. Effect of solar photovoltaic power field on land surface temperature. *Acta Energaie Solaris Sin.* 41 (12), 117–123. <https://doi.org/10.19912/j.0254-0096.2012.017>.
- Li, J.T., 2023. Research on the characteristics and forecasting of carbon flux variation under the influence of large scale photovoltaic development based on SSA-SVR model. Xi'an University of Technology, MA, pp. 41–45. <https://doi.org/10.27398/d.cnki.gxalu.2023.001216>.
- Li, S.H., Gao, Q., Wang, X.Q., Lan, L., Yang, Z.W., 2016. Characteristics of vegetation and soil property changes by photovoltaic plant interference in alpine desert steppe. *J. Soil Water Conserv.* 30 (12), 325–329. <https://doi.org/10.13870/j.cnki.stbxb.2016.06.054>.
- Liu, Y., et al., 2019. Solar photovoltaic panels significantly promote vegetation recovery by modifying the soil surface microhabitats in an arid sandy ecosystem. *Land Degrad. Dev.* 30 (18), 2177–2186. <https://doi.org/10.1002/ldr.3408>.
- Luo, L.H., et al., 2023. Environmental impacts of photovoltaic power plants in Northwest China. *Sustain. Energy Technol. Assessments* 56, 103120. <https://doi.org/10.1016/j.seta.2023.103120>.
- Ma, D.J., et al., 2023. Detection, mapping, and interpretation of the main drivers of the arctic gpp change from 2001 to 2019. *Clim. Dynam.* <https://doi.org/10.1007/s00382-023-06935-z>.
- Montag, H., Parker, G., Clarkson, T., 2016. *The Effects of Solar Farms on Local Biodiversity: A Comparative Study*. Clarkson and Woods and Wychwood Biodiversity.
- Moscattelli, M.C., Marabottini, R., Massaccesi, L., Marinari, S., 2022. Soil properties changes after seven years of ground mounted photovoltaic panels in Central Italy coastal area. *Geoderma Regional* 29, e00500. <https://doi.org/10.1016/j.geodrs.2022.e00500>.
- Nakagawa, S., Noble, D.W.A., Senior, A.M., Lagisz, M., 2017. Meta-evaluation of meta-analysis: ten appraisal questions for biologists. *BMC Biol.* 15 (1), 18. <https://doi.org/10.1186/s12915-017-0357-7>.
- Noor, N.F.M., Reeza, A.A., 2022. Effects of Solar Photovoltaic Installation on Microclimate and Soil Properties in Uitm 50mwac Solar Park, Malaysia. *IOP Conf. Ser. Earth Environ. Sci.* 1059 (1), 012031. <https://doi.org/10.1088/1755-1315/1059/1/012031>.
- Sang, J., Lakshani, M.M.T., Deepagoda, T.C., Shen, Y., Li, Y., 2022. Drying and rewetting cycles increased soil carbon dioxide rather than nitrous oxide emissions: a meta-analysis. *J. Environ. Manag.* 324, 116391. <https://doi.org/10.1016/j.jenvman.2022.116391>.
- Schwarzer, G., Carpenter, J., Rücker, G., 2015. *Meta-Analysis with R*.
- Shan, S., Geng, S.Y., Kamran, H.W., Dinca, G., 2021. Role of green technology innovation and renewable energy in carbon neutrality: a sustainable investigation from Turkey. *J. Environ. Manag.* 294, 113004. <https://doi.org/10.1016/j.jenvman.2021.113004>.
- Shang, W., et al., 2023. Spatial heterogeneity of vegetation communities and soil properties in a desert solar photovoltaic power plants of the hexi corridor, northwestern China. *Pol. J. Environ. Stud.* 32 (3), 2795–2807. <https://doi.org/10.15244/pjoes/160205>.
- Shi, X.L., et al., 2023. Effects of climate change and human activities on gross primary productivity in the heihe river basin, China. *Environ. Sci. Pollut. Control Ser.* 30 (2), 4230–4244. <https://doi.org/10.1007/s11356-022-22505-y>.
- Song, J., et al., 2019. A meta-analysis of 1,119 manipulative experiments on terrestrial carbon-cycling responses to global change. *Nature Ecology & Evolution* 3 (9), 1309–1320. <https://doi.org/10.1038/s41559-019-0958-3>.
- Stratton, L., Goldstein, G., Meinzer, F.C., 2000. Stem water storage capacity and efficiency of water transport: their functional significance in a Hawaiian dry forest. *Plant Cell Environ.* 23 (1), 99–106. <https://doi.org/10.1046/j.1365-3040.2000.00533.x>.
- Tian, Z.Q., et al., 2023. Effects of photovoltaic power plants construction on terrestrial environment: retrospect and prospect. *Environmental Science* 44 (11). <https://doi.org/10.13227/j.hjke.202301152>.
- Veroniki, A.A., et al., 2016. Methods to estimate the between-study variance and its uncertainty in meta-analysis. *Res. Synth. Methods* 7 (1), 55–79. <https://doi.org/10.1002/jrsm.1164>.
- Villanueva, R.A.M., Chen, Z.J., 2019. *ggplot2: Elegant Graphics for Data Analysis*.
- Wang, C., Fu, B.J., Zhang, L., Xu, Z.H., 2019. Soil moisture–plant interactions: an ecohydrological review. *J. Soils Sediments* 19 (1), 1–9. <https://doi.org/10.1007/s11368-018-2167-0>.
- Wang, X.H., et al., 2018. Spatial and temporal variations in surface soil moisture and vegetation cover in the loess plateau from 2000 to 2015. *Ecol. Indic.* 95, 320–330. <https://doi.org/10.1016/j.ecolind.2018.07.058>.
- Wu, C.D., et al., 2022. Ecohydrological effects of photovoltaic solar farms on soil microclimates and moisture regimes in arid northwest China: a modeling study. *Sci. Total Environ.* 802, 149946. <https://doi.org/10.1016/j.scitotenv.2021.149946>.
- Wu, W., et al., 2020. Observational study on the impact of large-scale photovoltaic development in deserts on local air temperature and humidity. *Sustainability* 12 (8). <https://doi.org/10.3390/su12083403>.
- Xie, S.D., Mo, X.G., Hu, S., Liu, S.X., 2020. Contributions of climate change, elevated atmospheric CO₂ and human activities to ET and GPP trends in the three-north region of China. *Agric. For. Meteorol.* 295, 108183. <https://doi.org/10.1016/j.agrformet.2020.108183>.
- Yang, R.T., et al., 2022. Influence of fixed-stand photovoltaic array on wind field in gonghe Basin, Qinghai, China. *J. Desert Res.* 42 (5), 114–121. <https://doi.org/10.7522/j.issn.1000-694X.2022.00024>.
- Yang, S.R., et al., 2019. Wind speed fluctuation at Kubuqi desert ecological photovoltaic power plants. *Arid Zone Res.* 36 (5), 1309–1317. <https://doi.org/10.13866/j.azr.2019.05.29>.
- Yavari, R., Zaliwciw, D., Cibin, R., McPhillips, L., 2022. Minimizing environmental impacts of solar farms: a review of current science on landscape hydrology and guidance on stormwater management. *Environ. Res.: Infrastructure and Sustainability* 2 (3), 032002. <https://doi.org/10.1088/2634-4505/ac76dd>.
- Yu, G.R., et al., 2017. *Principles of Flux Measurement in Terrestrial Ecosystems, second ed.* China Higher Education Press, Beijing, pp. 349–357.
- Yue, S.J., 2022. Research on Eco-Environmental Effects of Large-Scale Photovoltaic Development in Qinghai Desert Area. Xi'an University of Technology. <https://doi.org/10.27398/d.cnki.gxalu.2022.000129>. PhD dissertation.
- Yue, S.J., Guo, M.J., Zou, P.H., Wu, W., Zhou, X.D., 2021. Effects of photovoltaic panels on soil temperature and moisture in desert areas. *Environ. Sci. Pollut. Control Ser.* 28 (14), 17506–17518. <https://doi.org/10.1007/s11356-020-11742-8>.
- Zhang, H.Y., et al., 2023a. Green or not? Environmental challenges from photovoltaic technology. *Environmental Pollution* 320, 121066. <https://doi.org/10.1016/j.envpol.2023.121066>.
- Zhang, Y., Tian, Z.Q., Liu, B.L., Chen, S.Y., Wu, J.H., 2023b. Effects of photovoltaic power plants construction on terrestrial ecosystems: a meta-analysis. *Frontiers in Ecology and Evolution* 11, 1151182. <https://doi.org/10.3389/fevo.2023.1151182>.
- Zhou, L., Qi, F., Yan, X., 2024. A review of research on the passive effect of building photovoltaic systems and analysis of influencing factors. *Sol. Energy* 278, 112766. <https://doi.org/10.1016/j.solener.2024.112766>.
- Zhou, Z.H., Wang, C.K., Luo, Y.Q., 2018. Effects of forest degradation on microbial communities and soil carbon cycling: a global meta-analysis. *Global Ecol. Biogeogr.* 27 (1), 110–124. <https://doi.org/10.1111/geb.12663>.

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Abstract

Increasing energy demands and the drive towards low carbon (C) energy sources has prompted a rapid increase in ground-mounted solar parks across the world. This represents a significant global land use change with implications for the hosting ecosystems that are poorly understood. In order to investigate the effects of a typical solar park on the microclimate and ecosystem processes, we measured soil and air microclimate, vegetation and greenhouse gas emissions for twelve months under photovoltaic (PV) arrays, in gaps between PV arrays and in control areas at a UK solar park sited on species-rich grassland. Our results show that the PV arrays caused seasonal and diurnal variation in air and soil microclimate. Specifically, during the summer we observed cooling, of up to 5.2 °C, and drying under the PV arrays compared with gap and control areas. In contrast, during the winter gap areas were up to 1.7 °C cooler compared with under the PV arrays and control areas. Further, the diurnal variation in both temperature and humidity during the summer was reduced under the PV arrays. We found microclimate and vegetation management explained differences in the above ground plant biomass and species diversity, with both lower under the PV arrays. Photosynthesis and net ecosystem exchange in spring and winter were also lower under the PV arrays, explained by microclimate, soil and vegetation metrics. These data are a starting point to develop understanding of the effects of solar parks in other climates, and provide evidence to support the optimisation of solar park design and management to maximise the delivery of ecosystem services from this growing land use.

Introduction

Increasing energy demands and the need to move to low carbon (C) energy sources has promoted the development of renewable sources of energy (BP 2014). Solar photovoltaics (PV) has the greatest potential for power generation amongst all renewables, and the growth rate has accelerated in recent years and this trend is expected to continue (Pogson *et al* 2013, EPIA 2014, REN21 2014). A substantial proportion of PV comprise solar parks—arrays of ground-mounted PV modules, generally tilted toward the equator and arranged in rows with gaps between to prevent shading of the subsequent row. In Europe solar parks are most often located in converted arable

and grasslands and represent a significant land use change given their relatively low energy density (MacKay 2013). Within the UK, Europe and globally land use change for ground-mounted solar PV in 2013 was approximately 15–79 km², 204–1019 km² and 554–2772 km², respectively. Further expansion of large-scale solar parks are predicted in Europe and countries within 35° of the equator (DOE 2004, EPIA 2014, Europe 2015).

Solar parks may have consequences for microclimate, C cycling, biodiversity, water, soil erosion, air quality and ecosystem energy balances (Armstrong *et al* 2014, Hernandez *et al* 2014), yet there has been little research effort to quantify impacts. These impacts may occur at the regional scale (Millstein and



Figure 1. (a) Aerial photograph of Westmill Solar Park (photo courtesy of Neil B. Maw), (b) an under plot, (c) a gap plot and (d) a control plot.

Menon 2011), but the physical presence of PV arrays may also promote within solar park variation in climate and ecosystem function. The physical presence of solar parks will impact solar radiation fluxes (and thus temperature), wind speed and turbulence (and thus the exchange of biogenic gases and water vapour) and the distribution of precipitation within the solar park (Armstrong *et al* 2014). Given the climate regulation of ecosystem processes (Gu *et al* 2002, Flanagan and Johnson 2005, Bond-Lamberty and Thomson 2010), resolving the impacts of PV arrays on the soil and near surface climate within solar parks is essential. The spatial and temporal dynamics of solar park-induced microclimates on ecosystem processes is likely to be different to projected climate change. Consequently, given the complex nature of terrestrial C cycling (Heimann and Reichstein 2008), implications for plant–soil processes are unknown. Further, solar park management, in particular that relating to the vegetation (i.e. seeding, mowing, grazing and fertiliser addition), will be a strong determinant of ecosystem response.

The aim of this research was to investigate the effect of PV arrays on the microclimate and plant–soil processes as a result of differences in the microclimate and grassland management within a typical solar park. We hypothesised that: (1) PV arrays promote differences in both seasonal and diurnal variation in microclimate metrics and (2) differences in microclimate and vegetation management together explain variance in plant diversity, above-ground biomass, and ecosystem CO₂ fluxes. We also discuss the potential implications of the variation in microclimate on some plant–soil ecosystem processes.

Materials and methods

This research was undertaken at Westmill Solar Park, UK (51°37′03″N 01°38′45″W), a 5 MW capacity solar park with 36 PV array rows covering 12.1 ha installed in 2011 (figure 1(a)). The PV array rows were 4.4 m wide, had a gap between the rows of 11.2 m, faced south, and were at an angle of 30°. The footprint under the PV arrays was 2.9 ha, the gap area was 5.8 ha and the designated control area (that which was greater than 7 m from a PV array row in the N–S direction) was 3.4 ha. Prior to conversion to a solar park, the field site was arable cropland and was sown with a species-rich meadow mixture prior to construction. After construction there was very limited germination and therefore the gap and control areas were re-seeded with the same seed mix. For three years prior to the study the site was managed as permanent grassland with winter sheep grazing and mowing of ~1.5 m wide strips in front of the PV arrays annually to prevent shading of the PV arrays (no sampling was undertaken in mown areas).

To determine effects of the solar park on plant–soil properties and C cycling, measurements were made at twelve 1.5 m² plots. Four of the plots were located in each of the three designated treatment areas: under the PV arrays, in the gaps between the PV arrays and in the control area, referred to as under, gap and control treatments (figure 1). The exact spatial location of the plots was randomly selected within the treatment areas and sheep exclusion fencing was erected. At each plot microclimate, soil properties, vegetation and greenhouse gas (GHG) metrics were measured.

Microclimate

At each plot soil and air microclimate metrics were sampled every minute and the average over each hour recorded from 27/06/13 13:00 to 27/06/14 12:00. At all plots, air (50 cm above the surface) and soil (10 cm below the surface) temperature, soil moisture (10 cm below the surface) and relative humidity (RH, 50 cm above the surface) were recorded (Tempcon, UK: HOBO Micro Station with S-TMB-M002, S-THB-M002 and S-SMD-M005). In addition, at one plot of each of the treatments, wind speed (150 cm above the surface), rainfall (120 cm above the surface) and photosynthetically active radiation (PAR, 130 cm above the surface) were recorded (Tempcon, UK: HOBO U30 data logger, S-LIA-M003, S-RGB-M002, S-WSA-M003, S-WDA-M003). At one under and one control plot, total and diffuse radiation were also recorded (Delta-T, UK: BF5 sunshine sensor and GP1 data logger, 130 cm above the surface); direct radiation was calculated by difference.

Absolute humidity (AH) and vapour pressure deficit (VPD) were derived from temperature, T , relative humidity, RH, and the saturated vapour pressure, e_s , following Ward and Trimble (2003):

$$e_s = \exp \left[\frac{16.78 T - 116.9}{T + 237.3} \right],$$

$$AH = \frac{2.17 e_s \frac{RH}{100}}{T + 273.15},$$

$$VPD = e_s - e_s \left[\frac{RH}{100} \right].$$

Growing degree days (GDD) were calculated using a threshold of 5.5 °C (MetOffice 2015). Growing season length was calculated as the time period from the first five consecutive days above 5 °C after 1st March and the first five consecutive days below 5 °C after 1st July following a modified version of the Met Office (2015).

Soil properties

The soil from the A horizon at each plot ($n = 12$, four under the PV arrays, four in the gaps between the PV array rows and four in control areas) was analysed for total C and N, bulk density, particle size distribution and microbial C and N. Soil surface bulk density was determined from an oven dried (105 °C) 5.3 cm diameter, 10 cm long soil core (Carter and Gregorich 2007). Total C and N were determined on a 30 mg homogenised and oven dried (60 °C) subsample of a 5.3 cm diameter, 10 cm long core (LECO Truspec CN Analyser, USA) and C:N was calculated (Carter and Gregorich 2007). A 5 g sub sample of the same core was used to derive the median particle size by analysing the primary soil particle size distribution in triplicate using MasterSizer 2000MU laser diffraction particle sizer (Malvern, UK), after the organics had been removed using a modified version of Gale and Hoare (1991). Soil microbial biomass C and N were

determined using an ethanol-free chloroform fumigation—potassium sulphate extraction procedure, as detailed in Ward *et al* (2007), using soil taken from each plot on 27/06/14 using a 5.5 cm diameter, 4.5 cm long core.

Vegetation

Species level percentage cover in each of the 30 cm diameter GHG collars (see below; $n = 12$, four under the PV arrays, four in the gaps between the PV array rows and four in control areas) was surveyed on 02/07/13, the number of species counted and the ratio of the number of non-grass to grass species calculated. Above-ground biomass was determined by harvesting all the vegetation from the GHG collars on 27/06/14 (after the last set of GHG measurements and at the time of peak biomass) and oven drying (60 °C) to constant weight.

Greenhouse gas fluxes

At each plot, GHG fluxes were monitored monthly from July 2013 to June 2014 using 30 cm diameter static chambers (Armstrong *et al* 2015). Net ecosystem exchange (NEE) and ecosystem respiration were measured using an EGM-4 infrared gas analyser (PP Systems, USA) attached to clear and opaque chambers, respectively. CH₄ and N₂O concentrations were determined from samples taken from opaque chambers and analysed in the laboratory using a Perkin Elmer Autosystem XL Gas Chromatograph (see Ward *et al* 2013). GHG concentrations were quality controlled and those affected by poor chamber seals, leaking vials or instrument malfunction removed. If the variation in CH₄ and N₂O concentrations in the field samples was less than two times the standard deviation of the standards the fluxes were considered to be below the limit of detection. Fluxes, as mg CO₂-C, CH₄-C or N₂O mg m⁻² h⁻¹, were calculated following Levy *et al* (2012). CO₂ assimilated through photosynthesis was estimated by subtracting ecosystem CO₂ respiration from NEE.

Statistical analysis

All statistics were undertaken using Stata 13 (Stata-Corp 2013) and p values <0.05 deemed significant. Differences in soil properties (C, N, C:N, median particle size, bulk density, microbial biomass C, microbial biomass N and microbial biomass C:N), GDD and growing season length between the treatments were tested for significance using a one way ANOVA with a Bonferroni multiple comparison posthoc test. The GHG data were analysed using a repeated measures linear mixed model with treatment, date and their interactions as fixed effects and site as a random effect and the significance of treatment, date and their interaction and the dates on which there was a significant difference between the treatments determined. The models were run for CH₄ and N₂O with all

the data (i.e. including that below the limit of detection) as the reduced dataset was too unbalanced for rigorous analysis. In order to establish the relative importance of biotic and abiotic controls over the GHG fluxes a two-step analysis was undertaken. Firstly, principal components analysis (PCA) was used to reduce dimensionality and avoid collinearity between the variables. The first three PCs and their interactions were entered into generalised linear models with a log link and Gaussian family to explain variation in respiration, calculated photosynthesis, NEE, CH₄ and N₂O. As the PCs are standardised the magnitude of the coefficients were used as an indication of effect size.

The seasonal variation in daily arithmetic average, minimum and maximum soil and air temperature, soil moisture, AH and VPD for each treatment were compared by fitting a linear mixed effects model with treatment, season (using day of the year sine and cosine functions) and their interactions as fixed effects and season and site as random effects. If the 95% confidence intervals from the fitted models did not overlap then the differences between the treatments were deemed significant.

Significant differences in the diurnal variation in daily arithmetic average soil and air temperature, soil moisture, AH and VPD between the treatments was determined using the same method as for seasonal variation but using the time of day sine and cosine functions. This was undertaken for each month separately to allow assessment of changing trends during the annual cycle. As sunrise and sunset times vary through the year, fraction of day was calculated, with sunrise as 0.0 (or 1.0), sunset as 0.5 and time linearly scaled between. The resulting fractions of day values were categorised into 24 pseudo-hourly bins and used in the analysis instead of time.

Least squares linear regression was used to determine the proportion of wind speed, rainfall, PAR, total, diffuse and direct radiation at the gap and under treatments compared with the control (using the gradient coefficient).

Results

In the following sections we outline the measured variation in microclimate, vegetation and soil properties, and greenhouse gas fluxes within the solar park.

Microclimate effects

There were clear differences in the microclimate due to the presence of the PV arrays at both seasonal and diurnal scales. From spring to autumn, soil under the PV arrays was significantly cooler (up to 5.2 °C daily average) compared to the control and gap treatments, with reductions of up to 3.5 °C and 7.6 °C for the daily minimum and maximum respectively (figures 2, S1

and table S1). These cooler average temperatures occurred throughout the diurnal cycle in spring and summer (figure 3). Also, the daily variation in air temperature was lower under the PV arrays; daily minimum and maximum temperatures were significantly warmer (up to 2.4 °C) and cooler (up to 6.0 °C) respectively, compared with control and gap treatments from spring to autumn (figures 2, S1 and table S1). These opposing trends resulted in no significant difference in the daily average air temperature; however, from April to September air was consistently cooler under the PV arrays during the day and warmer at night (figure 3).

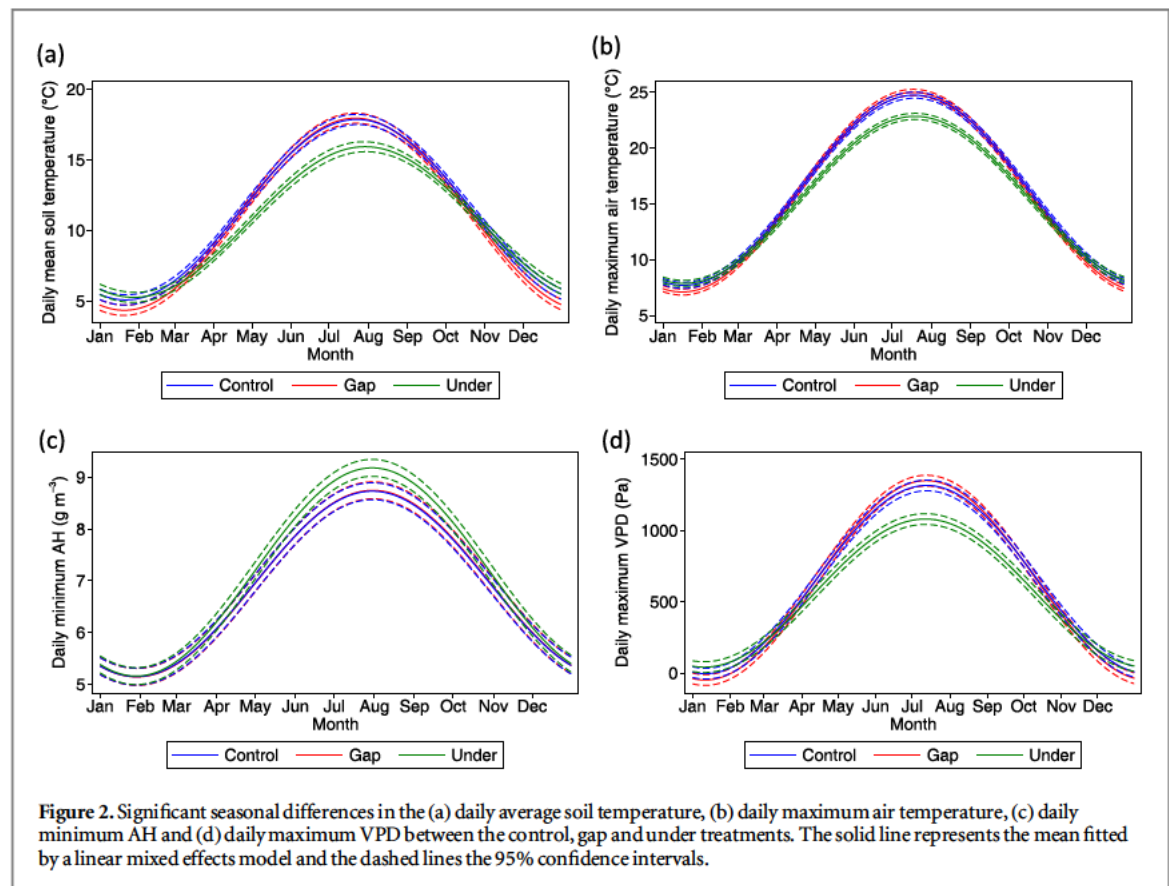
From spring to autumn, the daily average VPD was up to 337 Pa lower, the daily minimum AHs and VPDs were higher (up to 1.3 g m⁻³ and 1009 Pa respectively) and the daily maximums lower (up to 5.6 g m⁻³ and 108 Pa respectively) (figure 2, table S1). In terms of the diurnal variation, from spring to autumn VPD was lower under the PV arrays during the day and higher during the night compared to gap and control areas (figure 3).

During autumn and winter the soil in the gap treatments was, on average, 1.7 °C cooler than the control and under treatments throughout the diurnal cycle (figures 3, S1, table S1). Air temperature in the gaps was also significantly cooler (up to 2.5 °C) during the day but not during the night compared with the control and under treatments (figure 2, table S1).

Growing season length was the same for all treatments (6th March–19th November). However, the differences in air temperature led to significantly shorter annual GDDs under the PV arrays compared with the control treatment (2133 ± 22 °C; 2212 ± 32 °C 2186 ± 36 °C, for under, control and gap areas respectively). Microclimatic conditions under the PV arrays were significantly different to those of the control areas: PAR was 92% lower, with a greater proportion of diffuse radiation (90% compared to 79%); rainfall was on average three times higher; and the wind speed was only 14% of that in control areas, although the relationships were relatively weak (R^2 0.61 and 0.46 respectively). PAR receipts and rainfall in the gaps were similar to the control areas (figure 4), however, the wind speed in the gaps was notably slower (63% on average, R^2 0.88).

Vegetation and soil properties

Total above-ground plant biomass was four times higher in the gap and control areas compared with under the PV arrays (table 1) where there were also significantly fewer species (table 1). With the exception of *Achillea millefolium* the control and gap areas were more dominated by forbs and legumes compared with under the PV arrays (table 1). Soil properties did not vary between the treatments.



Greenhouse gas exchange

Ecosystem CO_2 fluxes were greatest during the summer and lowest during the winter (figure 5). We found significant differences in ecosystem respiration, NEE and photosynthesis rates between the treatments and with sampling date ($p < 0.05$), with monthly differences in treatment effects for photosynthesis and NEE (treatment*date, $p < 0.05$). However, differences between treatments did not occur throughout the year and were not consistent across fluxes (figure 5). Ecosystem respiration only differed between treatments in the first six months of the year and was generally lower from under areas (figure 5). Under areas also exhibited lower rates of photosynthesis but the differences occurred throughout the year (figure 5). As indicated by NEE, control and gap areas tended to be a sink of CO_2 whereas areas under the PV arrays were more often a source (figure 5). During the summer the gap areas were a significantly greater sink compared with under areas, but in spring and autumn control areas were a greater sink than both under and gap areas (figure 5).

A PCA-GLM model was developed to determine the relative importance of biotic and abiotic metrics in explaining the variation in CO_2 fluxes. PCA of all the microclimate, vegetation and soil metrics resulted in three PCs dominated by soil properties (except microbial biomass C:N), microclimate (except wind speed) and vegetation properties (including wind speed) respectively, as indicated by a correlation coefficient of

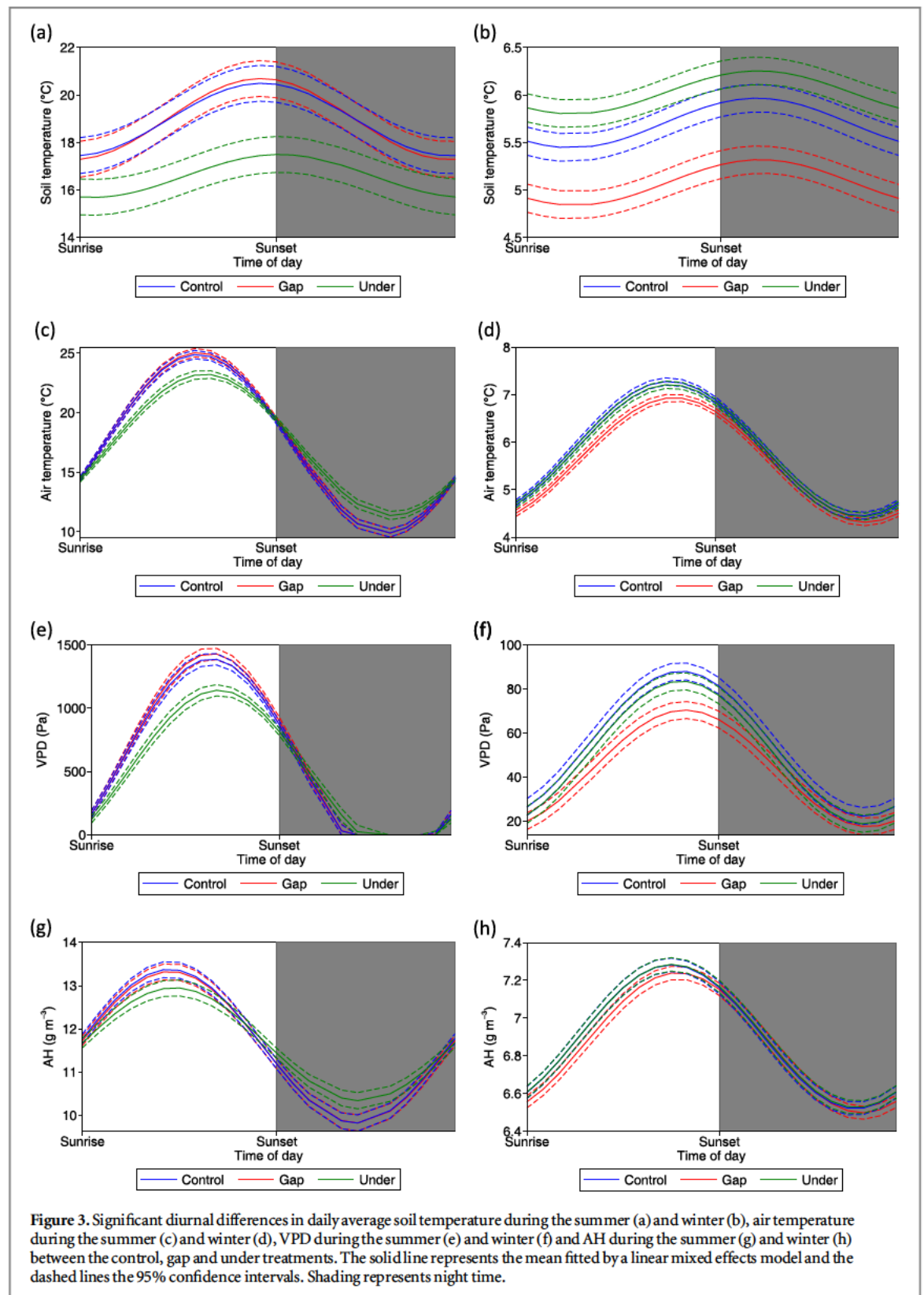
> 0.60 (table S2). Approximately 50% of the variation in ecosystem respiration and photosynthesis could be explained by the PCs, with most explained by the vegetation PC (table 2). A GLM model could not be fitted for NEE.

Discussion

Our results show, for the first time, the seasonal and diurnal variation in microclimate within a solar park and vegetation response to both the induced-microclimate and vegetation management. First, we discuss the mechanisms causing the microclimatic variability within the solar park. Given climate is a recognised key driver of ecosystem function and service provision, including biodiversity, productivity, GHG emissions, soil C storage and crop yields (Zavaleta *et al* 2003, Wu *et al* 2011), we also hypothesise potential impacts on plant–soil ecosystem processes. We then discuss the differences in measured vegetation metrics and greenhouse gas emissions in light of both microclimatic and vegetation management impacts.

Potential ecosystem consequences of solar park-induced microclimates

Our first hypothesis, that solar parks promote seasonal and diurnal variation in microclimate, was supported. At the solar park soil temperature was cooler under the PV arrays during the summer and between the PV arrays during the winter (figure 2, table S1),



attributable to the interception of shortwave radiation by the PV arrays (Weinstock and Appelbaum 2009). The shadow cast by the PV arrays varied from 1.72 m at the summer solstice (21/06/14) to 10.69 m on the winter solstice (21/12/14) (table S3 and figure S2). The cooling is likely to be significant in terms of

ecosystem function with temperature differences of this magnitude (up to 5.2 °C) observed to alter many key plant–soil processes, from productivity to decomposition (Feng *et al* 2008, Wu *et al* 2012). However, within this study we focus on soil and air temperature, but plant processes and productivity are often more

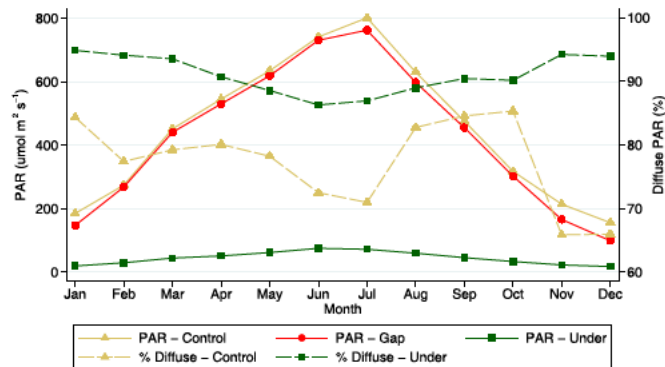


Figure 4. Average monthly daytime PAR receipts ($\mu\text{mol m}^{-2} \text{s}^{-1}$) at control, gap and under treatments and the proportion of diffuse radiation (%) at the control and under treatments.

Table 1. Differences in plant community composition and productivity in under, control and gap areas: percentage cover of plant species and bare ground, number of species, non-grass:grass, and above ground plant biomass (g dwt m^{-2}) between the treatment plots (mean $\pm$ SD). Different letters denote a significant difference ($p < 0.05$) in the number of species, non-grass:grass and biomass between treatments.

	Species	Control	Gap	Under
Forbs	<i>Leucanthemum vulgare</i>	0.8 ± 1.5	2.0 ± 2.4	0.0 ± 0.0
	<i>Plantago lanceolata</i>	7.5 ± 8.7	1.3 ± 2.5	0.0 ± 0.0
	<i>Achillea millefolium</i>	10.0 ± 8.2	18 ± 35.0	20.0 ± 26.0
	<i>Ranunculus acris</i>	0.8 ± 1.5	0.0 ± 0.0	0.0 ± 0.0
Legumes	<i>Trifolium repens</i>	24.0 ± 10.0	9.8 ± 4.1	0.0 ± 0.0
	<i>Lotus corniculatus</i>	1.3 ± 2.5	10.0 ± 17.0	0.0 ± 0.0
	<i>Onobrychis viciifolia</i>	1.0 ± 2.0	0.8 ± 1.5	0.0 ± 0.0
Grasses	<i>Phleum pratense</i>	6.3 ± 7.5	21.0 ± 27.0	15.0 ± 7.1
	<i>Poa spp. (pratensis or annua)</i>	24.0 ± 11.0	20.0 ± 15.0	41.0 ± 26.0
	<i>Brachypodium sylvaticum</i>	8.8 ± 12.0	0.0 ± 0.0	0.0 ± 0.0
	<i>Festuca rubra</i>	3.8 ± 4.8	1.3 ± 2.5	3.8 ± 7.5
Other	Dead/bare	13.0 ± 2.9	16.0 ± 7.5	20.0 ± 10.0
	Number of species	$4.8 \pm 1.0^{\text{ab}}$	$5.8 \pm 2.2^{\text{a}}$	$2.8 \pm 0.5^{\text{b}}$
	Non-grass:grass	$1.5 \pm 0.5^{\text{a}}$	$1.6 \pm 0.9^{\text{ab}}$	$0.3 \pm 0.3^{\text{b}}$
	Biomass	$511.1 \pm 102.8^{\text{a}}$	$599.5 \pm 143.1^{\text{a}}$	$131.6 \pm 46.5^{\text{b}}$

strongly correlated with plant temperature; differences in crop, soil and air temperature response has been observed under PV arrays (Marrou *et al* 2013).

During the winter, the cooler soil temperatures in the gaps (up to 1.7°C daily average), but similar temperatures in the control and under areas, may be attributed to: the lower solar zenith angle during the winter reducing solar radiation received by the gap plots (table S3 and figure S2) (Weinstock and Appelbaum 2009); the smaller sky view (i.e. the fraction of sky visible) under the arrays reducing net longwave radiation loss (and thus heat) from the surface (Oke 1987); and the impact of the arrays on air turbulence and thus heat transfer and soil temperature. This is an interesting finding that requires further research to establish the causes. The magnitude of these temperature differences may have limited significance for plant–soil processes given the generally lower biological activity during the winter period. However, in areas where temperatures are close to plant–soil process

thresholds, the impacts could be substantial. For example, in regions where warmer winter temperatures are slowing spring phenology (Yu *et al* 2010), where minimum temperatures affect vegetation survival (Kreyling 2010) or specific temperatures are required for seed dormancy and germination (Walck *et al* 2011).

Although the daily averages for air temperature did not vary between the treatments, under the PV arrays during the summer the diurnal variation in temperature was dampened, attributable to lower radiation receipts during the day and the reduced sky view minimising longwave radiation loss at night. Further, dew formation can be inhibited under PV arrays and thus temperatures may be higher compared to control and gap areas (evaporation of dew can reduce temperature) (Marrou *et al* 2013). Diurnal variation in temperature has direct and indirect impacts on plant–soil processes. For example, the reduced likelihood of frost occurrence under the PV arrays (given the warmer night time temperatures) could lead to greater risk

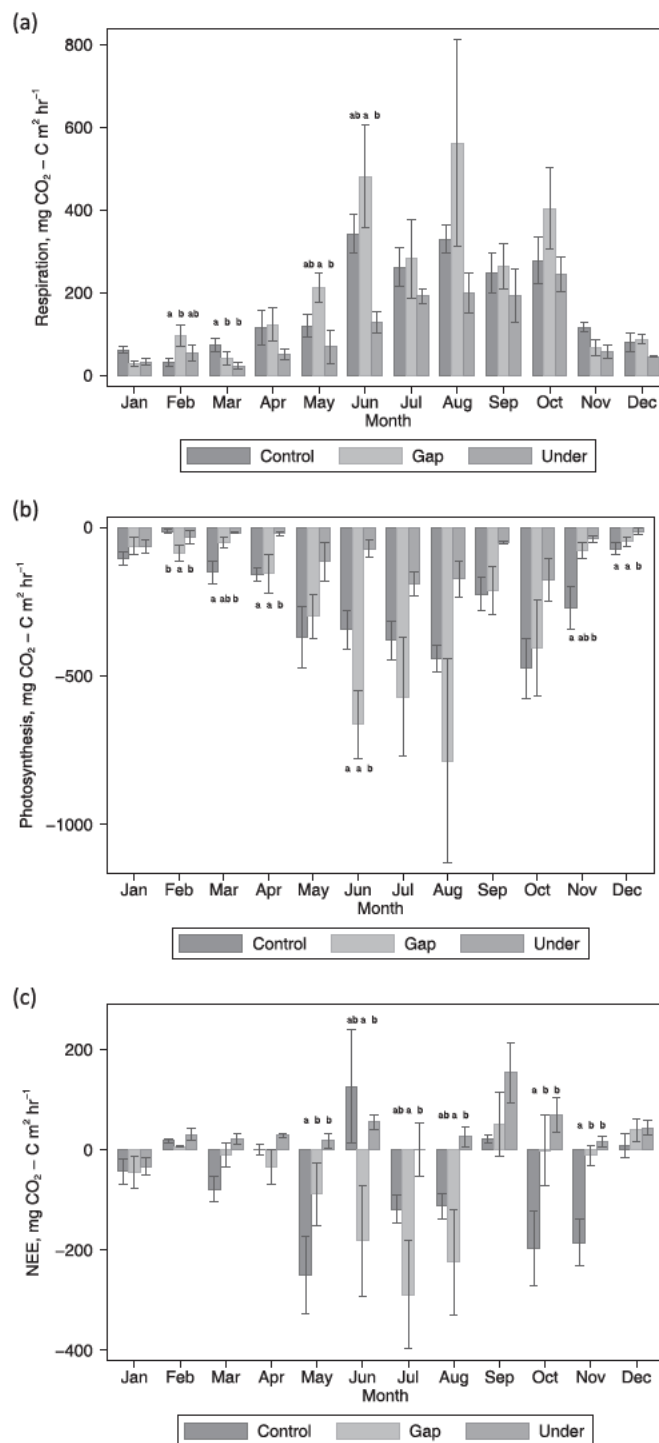


Figure 5. Differences in average (a) ecosystem respiration, (b) photosynthesis and (c) NEE between control, gap and under treatments during the year. Error bars represent the standard error. Only data over the limit of detection are included. On a month-by-month basis, bars with different letters had a significantly different flux.

of frost injury (Kreyling 2010); and there is some evidence that respiration may acclimate to night minimum temperatures (Covey-Crump *et al* 2002). Moreover, the dynamics between day and night temperatures also impact plant–soil processes, for example, asymmetric diurnal warming has led to a divergent response of vegetation growth and C sequestration in Northern Hemisphere vegetation (Peng *et al* 2013).

AH and VPD both varied significantly with treatment at the solar park, with the treatment effect varying seasonally and diurnally. Under the PV arrays, the lower daily maximum AH potentially indicates lower evapotranspiration rates, whilst lower daily average VPD under the PV arrays during the summer may indicate that transpiration rates were lower. This is consistent with the lower photosynthesis rates and plant biomass under the PV arrays.

Table 2. The pseudo- R^2 of the PCA-GLM models for ecosystem respiration and photosynthesis, with the correlation coefficients (measure of effect size) of the soil, climate, vegetation PCs and their interactions.

PC	Respiration	Photosynthesis
Soil	NS	NS
Climate	0.17	0.13
Vegetation	0.51	0.68
Soil*climate	0.03	0.03
Soil*vegetation	0.09	0.18
Climate*vegetation	NS	NS
R^2	0.51	0.44

PAR receipts were significantly lower under the PV arrays compared with control areas and this is reflected in the lower rates of photosynthesis and plant biomass under the PV arrays. Plants can be stressed by excessive radiation and can adapt and acclimatise to low PAR conditions, with shade plants reaching maximum photosynthesis rates at lower PAR levels (Lambers *et al* 2008). Consequently in higher radiation environments, such as Sub-Saharan Africa, reductions in PAR may increase productivity. In addition to affecting plant productivity, reduced PAR and the balance between direct and diffuse radiation can alter the processing of C, for example increasing soil C sequestration, within the plant–soil system (Mercado *et al* 2009, Bahn *et al* 2013).

Field observations revealed that the surprising result of higher precipitation under the PV arrays is due to rainfall flowing along the PV panel supporting frame and dripping into the rain gauge. This tendency for water to track along the supporting frame is supported by the soil moisture results; there were no significant differences with treatment.

Further to the direct impact of microclimate parameters on ecosystem processes, their interactions and indirect effects may also cause significant alterations to plant–soil processes. Some interactions, such as those between temperature and moisture have received much attention (Ise and Moorcroft 2006, Suseela *et al* 2012). However, others, such as the interaction between temperature and PAR are less well resolved but have been shown to be significant (Edwards *et al* 2004, Hartley *et al* 2007). The composite effect of reduced temperatures, increased humidity and shading, all factors observed under the PV arrays, have been shown to moderate plant response to macroclimatic warming as forest canopies close (De Frenne *et al* 2013). Consequently, resolution of the interactive and indirect effects of altered microclimatic conditions on plant–soil processes in solar parks requires further investigation.

Solar park effects on vegetation and greenhouse gas fluxes

Our second hypothesis that, differences in microclimate and vegetation management explain variance in

plant diversity, above-ground biomass, and ecosystem CO_2 fluxes was supported, with the areas under the PV arrays less diverse, dominated by grasses, and less productive compared with the control and gap areas. The re-seeding of the gap and control areas with a species-rich meadow mix after construction will have strongly influenced vegetation diversity, especially given the limited potential for seed dispersal as the field measurements were taken two years after seeding. However, the observed differences in microclimate between the treatments are of a magnitude known to affect vegetation composition and productivity (Zavala *et al* 2003, Wu *et al* 2011). Given the temperatures were similar during early spring, the lower diversity and domination of grasses under the PV arrays may have been influenced by grasses out-competing the forbs and legumes under the reduced PAR conditions. Further, the only non-grass species found under the PV arrays was *Achillea millefolium*, which is more shade tolerant than other forbs found at this site (Grime *et al* 2007). The lower biomass under the PV arrays also reflects reductions in the microclimatic drivers known to be positively associated with productivity: lower temperatures, VPD and radiation (Larcher 2003, Rogiers *et al* 2005).

GHG emissions are controlled by climate, vegetation and soil properties and the relative importance of these factors controls the response of plant–soil C cycling to environmental change (De Deyn *et al* 2008, Heimann and Reichstein 2008). Consequently, the observed differences in GHG fluxes between treatments may have been influenced by both the differences in vegetation due to the re-seeding of the gap and control areas and the varying microclimate between the treatments. The lack of consistent differences in CO_2 fluxes between treatments throughout the year, despite temperature differences of a scale known to impact CO_2 fluxes, indicates the ability of vegetation characteristics, both species composition and biomass, to compensate for climatic variability. When differences did occur, it was commonly the under areas that had lower flux rates, reflecting the lower biomass and lower temperatures. The PCA-GLM results indicated that vegetation metrics and wind speed (which governs CO_2 exchange between the leaf and atmosphere Oke 1987) were more strongly correlated with CO_2 fluxes than climate or soil factors. This indicates the pivotal role of vegetation, and thus the importance of vegetation management in the shorter term and vegetation change in response to the microclimate induced by the PV arrays in the longer term, in influencing C cycling at solar parks (Cornwell *et al* 2008, De Deyn *et al* 2008).

Our data highlights the potential significance of the impact of solar park-induced microclimates on ecosystem processes and quantifies the impact on some measures of ecosystem response (biomass, diversity and ecosystem CO_2 fluxes). The microclimatic impacts need to be assessed for different climatic

zones and solar park architectures to enable potential co-benefits, such as enhanced biodiversity or crop production, to be identified and any detrimental effects to be mitigated. Future research should establish the effects of the microclimatic impacts, focusing not only on the direct effects but also indirect and interactive effects, on ecosystem processes and plant physiological responses (Schlenker and Roberts 2009, Wan *et al* 2009, Wang *et al* 2014). Given thresholds in plant–soil processes, different microclimate metrics should be analysed, including averages, minimum and maximum temperatures (Jolly *et al* 2005, Craine *et al* 2012), along with seasonal variation, encapsulated by measures of growing season length, and diurnal variation (Piao *et al* 2007, Wan *et al* 2009).

Conclusion

Land use change for energy generation is accelerating, with the growth of solar parks predicted to continue globally. The effects of this growing land use change on plant–soil processes, which underpin key ecosystem services, is poorly understood. In this study we show that PV arrays can cause both seasonal and diurnal variation in the ground-level microclimate to a magnitude known to affect terrestrial C cycling. We also observed significant differences in above-ground biomass, plant diversity and ecosystem CO₂ fluxes which were associated with the vegetation management and microclimate. Given the quantifiable differences in plant–soil C cycling presented here, we argue that there is a critical need for a systematic assessment of the impact of solar parks on ecosystem functioning and the potential to exploit the induced-microclimate effects for co-benefits. For example, the production of crops under PV arrays in locations where solar radiation receipts currently prevent it. Solar parks contribute to climate change mitigation by providing low carbon energy, but the wider environmental costs and benefits need to be taken into account, to ensure they are deployed sustainably.

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References

- Armstrong A, Waldron S, Ostle N, Richardson H and Whitaker J 2015 Biotic and abiotic factors interact to regulate northern peatland carbon cycling *Ecosystems* **18** 1395–409
- Armstrong A, Waldron S, Whitaker J and Ostle N J 2014 Wind farm and solar park effects on plant–soil carbon cycling: uncertain impacts of changes in ground-level microclimate *Glob. Change Biol.* **20** 1699–706
- Bahn M, Lattanzi F A, Hasibeder R, Wild B, Koranda M, Danese V, Brüggemann N, Schmitt M, Siegwolf R and Richter A 2013 Responses of belowground carbon allocation dynamics to extended shading in mountain grassland *New Phytologist* **198** 116–26
- Bond-Lamberty B and Thomson A 2010 Temperature-associated increases in the global soil respiration record *Nature* **464** 579–82
- BP 2014 *BP Statistical Review of World Energy 2014*
- Carter M R and Gregorich E G 2007 *Soil Sampling and Methods of Analysis* (Boca Raton, FL: CRC)
- Cornwell W K *et al* 2008 Plant species traits are the predominant control on litter decomposition rates within biomes worldwide *Ecology Lett.* **11** 1065–71
- Covey-Crump E M, Attwood R G and Atkin O K 2002 Regulation of root respiration in two species of *Plantago* that differ in relative growth rate: the effect of short- and long-term changes in temperature *Plant, Cell & Environ.* **25** 1501–13
- Craine J M, Nippert J B, Elmore A J, Skibbe A M, Hutchinson S L and Brunsell N A 2012 Timing of climate variability and grassland productivity *Proc. Natl Acad. Sci.* **109** 3401–5
- De Deyn G B, Cornelissen J H C and Bardgett R D 2008 Plant functional traits and soil carbon sequestration in contrasting biomes *Ecology Lett.* **11** 516–31
- De Frenne P *et al* 2013 Microclimate moderates plant responses to macroclimate warming *Proc. Natl Acad. Sci. USA* **110** 18561–5
- DOE U 2004 PV FAQs: how much land will PV need to supply our electricity? *Energy* (Washington, DC: US DOE)
- Edwards E J, Benham D G, Marland L A and Fitter A H 2004 Root production is determined by radiation flux in a temperate grassland community *Glob. Change Biol.* **10** 209–27
- EPIA 2014 *Global Market Outlook for Photovoltaics 2014–2018* (Brussels, Belgium: European Photovoltaic Industry Association) (www.cleanenergybusinesscouncil.com/site/resources/files/reports/EPIA_Global_Market_Outlook_for_Photovoltaics_2014-2018_-_Medium_Res.pdf)
- Europe S 2015 *Global Market Outlook for Solar Power 2015–2019* (Brussels, Belgium: SolarPower Europe)
- Feng X, Simpson A J, Wilson K P, Dudley Williams D and Simpson M J 2008 Increased cuticular carbon sequestration and lignin oxidation in response to soil warming *Nat. Geosci.* **1** 836–9
- Flanagan L B and Johnson B G 2005 Interacting effects of temperature, soil moisture and plant biomass production on ecosystem respiration in a northern temperate grassland *Agric. Forest Meteorol.* **130** 237–53
- Gale S J and Hoare P J 1991 *Quaternary Sediments* (London: Belhaven)
- Grime J P, Hodgson J and Hunt R 2007 *Comparative Plant Ecology: A Functional Approach to Common British Species* (Dalbeattie: Castlepoint)
- Gu L, Baldocchi D, Verma S B, Black T A, Vesala T, Falge E M and Dwyer P R 2002 Advantages of diffuse radiation for terrestrial ecosystem productivity *J. Geophys. Res.* **107** 4050
- Hartley I P, Heinemeyer A and Ineson P 2007 Effects of three years of soil warming and shading on the rate of soil respiration: substrate availability and not thermal acclimation mediates observed response *Glob. Change Biol.* **13** 1761–70
- Heimann M and Reichstein M 2008 Terrestrial ecosystem carbon dynamics and climate feedbacks *Nature* **451** 289–92
- Hernandez R R *et al* 2014 Environmental impacts of utility-scale solar energy *Renew. Sustainable Energy Rev.* **29** 766–79
- Ise T and Moorcroft P R 2006 The global-scale temperature and moisture dependencies of soil organic carbon decomposition: an analysis using a mechanistic decomposition model *Biogeochemistry* **80** 217–31
- Jolly W M, Nemani R and Running S W 2005 A generalized, bioclimatic index to predict foliar phenology in response to climate *Glob. Change Biol.* **11** 619–32
- Kreyling J 2010 Winter climate change: a critical factor for temperate vegetation performance *Ecology* **91** 1939–48

- Lambers H, Chapin F S III and Pons T L 2008 *Plant Physiological Ecology* (New York: Springer)
- Larcher W 2003 *Physiological Plant Ecology* (Berlin: Springer)
- Levy P E *et al* 2012 Methane emissions from soils: synthesis and analysis of a large UK data set *Glob. Change Biol.* **18** 1657–69
- MacKay D J C 2013 Solar energy in the context of energy use, energy transportation and energy storage *Phil. Trans. R. Soc. A* **371** 20110431
- Marrou H, Guillioni L, Dufour L, Dupraz C and Wery J 2013 Microclimate under agrivoltaic systems: is crop growth rate affected in the partial shade of solar panels? *Agric. Forest Meteorol.* **177** 117–32
- Mercado L M, Bellouin N, Sitch S, Boucher O, Huntingford C, Wild M and Cox P M 2009 Impact of changes in diffuse radiation on the global land carbon sink *Nature* **458** 1014–7
- Metoffice 2015 *UKCP09: Annual data sets* (<http://metoffice.gov.uk/climatechange/science/monitoring/ukcp09/available/annual.html>) (accessed 12th June 2015)
- Millstein D and Menon S 2011 Regional climate consequences of large-scale cool roof and photovoltaic array deployment *Environ. Res. Lett.* **6** 034001
- Oke T R 1987 *Boundary Layer Climates* 2nd edn (London: Routledge)
- Peng S *et al* 2013 Asymmetric effects of daytime and night-time warming on Northern Hemisphere vegetation *Nature* **501** 88–92
- Piao S, Friedlingstein P, Ciais P, Viovy N and Demarty J 2007 Growing season extension and its impact on terrestrial carbon cycle in the Northern Hemisphere over the past 2 decades *Glob. Biogeochemical Cycles* **21** GB3018
- Pogson M, Hastings A and Smith P 2013 How does bioenergy compare with other land-based renewable energy sources globally? *GCB Bioenergy* **5** 513–24
- REN21 2014 *Renewables 2014 Global Status Report* REN21 Secretariat, France, Paris
- Rogiers N, Eugster W, Furger M and Siegwolf R 2005 Effect of land management on ecosystem carbon fluxes at a subalpine grassland site in the Swiss Alps *Theor. Appl. Climatol.* **80** 187–203
- Schlenker W and Roberts M J 2009 Nonlinear temperature effects indicate severe damages to US crop yields under climate change *Proc. Natl Acad. Sci.* **106** 15594–8
- StataCorp 2013 *Stata Statistical Software: Release 13* (Texas: Stata)
- Suseela V, Conant R T, Wallenstein M D and Dukes J S 2012 Effects of soil moisture on the temperature sensitivity of heterotrophic respiration vary seasonally in an old-field climate change experiment *Glob. Change Biol.* **18** 336–48
- Walck J L, Hidayati S N, Dixon K W, Thompson K E N and Poschlod P 2011 Climate change and plant regeneration from seed *Glob. Change Biol.* **17** 2145–61
- Wan S, Xia J, Liu W and Niu S 2009 Photosynthetic overcompensation under nocturnal warming enhances grassland carbon sequestration *Ecology* **90** 2700–10
- Wang X, Liu L, Piao S, Janssens I A, Tang J, Liu W, Chi Y, Wang J and Xu S 2014 Soil respiration under climate warming: differential response of heterotrophic and autotrophic respiration *Glob. Change Biol.* **20** 3229–37
- Ward A D and Trimble S W 2003 *Environmental Hydrology* (Boca Raton, FL: CRC)
- Ward S, Bardgett R, Mcnamara N, Adamson J and Ostle N 2007 Long-term consequences of grazing and burning on northern peatland carbon dynamics *Ecosystems* **10** 1069–83
- Ward S E, Ostle N J, Oakley S, Quirk H, Henrys P A and Bardgett R D 2013 Warming effects on greenhouse gas fluxes in peatlands are modulated by vegetation composition *Ecology Lett.* **16** 1285–93
- Weinstock D and Appelbaum J 2009 Optimization of solar photovoltaic fields *J. Solar Energy Eng.* **131** 031003
- Wu Z, Dijkstra P, Koch G W and Hungate B A 2012 Biogeochemical and ecological feedbacks in grassland responses to warming *Nat. Clim. Change* **2** 458–61
- Wu Z, Dijkstra P, Koch G W, Peñuelas J and Hungate B A 2011 Responses of terrestrial ecosystems to temperature and precipitation change: a meta-analysis of experimental manipulation *Glob. Change Biol.* **17** 927–42
- Yu H, Luedeling E and Xu J 2010 Winter and spring warming result in delayed spring phenology on the Tibetan Plateau *Proc. Natl Acad. Sci. USA* **107** 22151–6
- Zavaleta E S, Shaw M R, Chiariello N R, Mooney H A and Field C B 2003 Additive effects of simulated climate changes, elevated CO₂, and nitrogen deposition on grassland diversity *Proc. Natl Acad. Sci. USA* **100** 7650–4

RESEARCH ARTICLE

Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency

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Abstract

Power demands are set to increase by two-fold within the current century and a high fraction of that demand should be met by carbon free sources. Among the renewable energies, solar energy is among the fastest growing; therefore, a comprehensive and accurate design methodology for solar systems and how they interact with the local environment is vital. This paper addresses the environmental effects of solar panels on an unirrigated pasture that often experiences water stress. Changes to the microclimatology, soil moisture, water usage, and biomass productivity due to the presence of solar panels were quantified. The goal of this study was to show that the impacts of these factors should be considered in designing the solar farms to take advantage of potential net gains in agricultural and power production. Microclimatological stations were placed in the Rabbit Hills agrivoltaic solar arrays, located in Oregon State campus, two years after the solar array was installed. Soil moisture was quantified using neutron probe readings. Significant differences in mean air temperature, relative humidity, wind speed, wind direction, and soil moisture were observed. Areas under PV solar panels maintained higher soil moisture throughout the period of observation. A significant increase in late season biomass was also observed for areas under the PV panels (90% more biomass), and areas under PV panels were significantly more water efficient (328% more efficient).

1 Introduction

Global energy demand will be doubled by mid-century due to population and economic growth [1,2]. Renewable and environmental-friendly energies will play a vital role to meet this demand.

Among all renewable energies, solar power is the most abundant and available source [3]. Solar power is also becoming more affordable. The cost of solar panels has fallen by 10% per year for the past thirty years, while production has risen by 30% per year. If costs continue to be reduced based on this historic rate, solar energy will be less expensive than coal by 2020 [4]. The impact of wide-spread solar installations is an area of increasing interest. Regional

Competing interests: The authors have declared that no competing interests exist.

climatology may be influenced by large scale solar installations, but simulations have provided conflicting results: 3–4°C *increase* in air temperature over solar panels compared to wildlands at night [5], 0.1–0.5°C *decrease* in air temperature [6], 26°C *increase* in the shaded roof top temperature compared with unshaded roof top [7], 1–2.5°C *increase* in regional and global temperatures in urban area [8] and a 5.2°C *increase* in air temperature under solar panels [9].

Solar installations can occupy large land areas and sometimes compete with agriculture for the land resource [10]. Agrivoltaic systems are created when solar and agricultural systems are co-located for mutual benefit. The formal introduction of agrivoltaic systems is credited to Dupraz in 2011 [11]. Land demand for energy production decreases profoundly when agrivoltaics are used [10]. Not all agricultural crops are suitable, but plants with less root density and a high net photosynthetic rate are ideal candidates [11]. Agrivoltaic systems have been shown to increase land productivity by 60–70% [12], and increase the value of energy production system by 30% [13]. Very limited experimental research was found on the impacts of a solar arrays on agricultural production. Marrou et al. [14] measured soil water potential and soil water gradient (difference between uptake and drainage) in cucumber and lettuce and revealed lower soil water potential under the panels. This water potential led to an increase in harvested final fresh weight. Another experiment by Marrou et al. [15] found that plants cover soil faster under the shade of solar panels. An experimental study by Dupraz et al. demonstrated that summer crops benefited of solar shade more than winter crops such as pea and wheat crops [16]. Co-locating agave plant below solar panels increased yield per m³ of water used in the San Bernardino County in California [17]. Non-beneficial effects have also been observed in Welch onion fields where, photovoltaics reduced the fresh and dry matter harvest weight [18].

In this paper, a field study was performed to measure the effects of a six-acre agrivoltaic solar farm on the microclimatology, soil moisture and pasture production. The experimental setup included microclimatological and soil moisture measurements from May to August 2015 in Rabbit Hills agrivoltaic solar arrays, located on the Oregon State University campus. The field data for this study is accessible through Oregon State library system [19].

2 Material and methods

The field study was performed on a six acre agrivoltaic solar farm and sheep pasture near the Oregon State University Campus (Corvallis, Oregon, US.). The PhotoVoltaic Panels (PVPs) have been arranged in east–west orientated strips, 1.65 m wide and inclined southward with a tilt angle of 18°. PVPs have been held at 1.1 meters above ground (at lowest point) and the distance between panels is 6 meters as shown in Fig 1) e. The whole solar array system has a capacity of 1435 kilowatts (<http://fa.oregonstate.edu/sustainability/ground-mounted-photovoltaic-arrays>). As shown in Fig 1, the data were collected from localized zones (described hereafter) including areas below solar panels and a control area outside the agrivoltaic system. The pasture below the solar panels and the control areas were in the same paddock that was actively grazed by sheep. Exclusionary plots, to eliminate grazing pressure, were maintained with fencing. The total size of the fenced areas was limited by agricultural activities. The pasture was not irrigated, and typically experiences water stress mid-summer. The soil classification for >70% of the pasture area (control and agrivoltaic system) is Woodburn Silt clay [20]. The control and treatment plots were located within Woodburn Silt clay classification areas. The intent of the field measurements was to minimize uncontrollable differences between the treatments and control (e.g. solar forcing, soil types) and minimize impact on agricultural activities. Thus, the distance between the treatment site and the control site was kept minimum. The observations within the treatment site were further divided into three sub-treatments (Fig 2): (1) Sky Fully Open area between panels (SFO), (2) Solar Partially Open

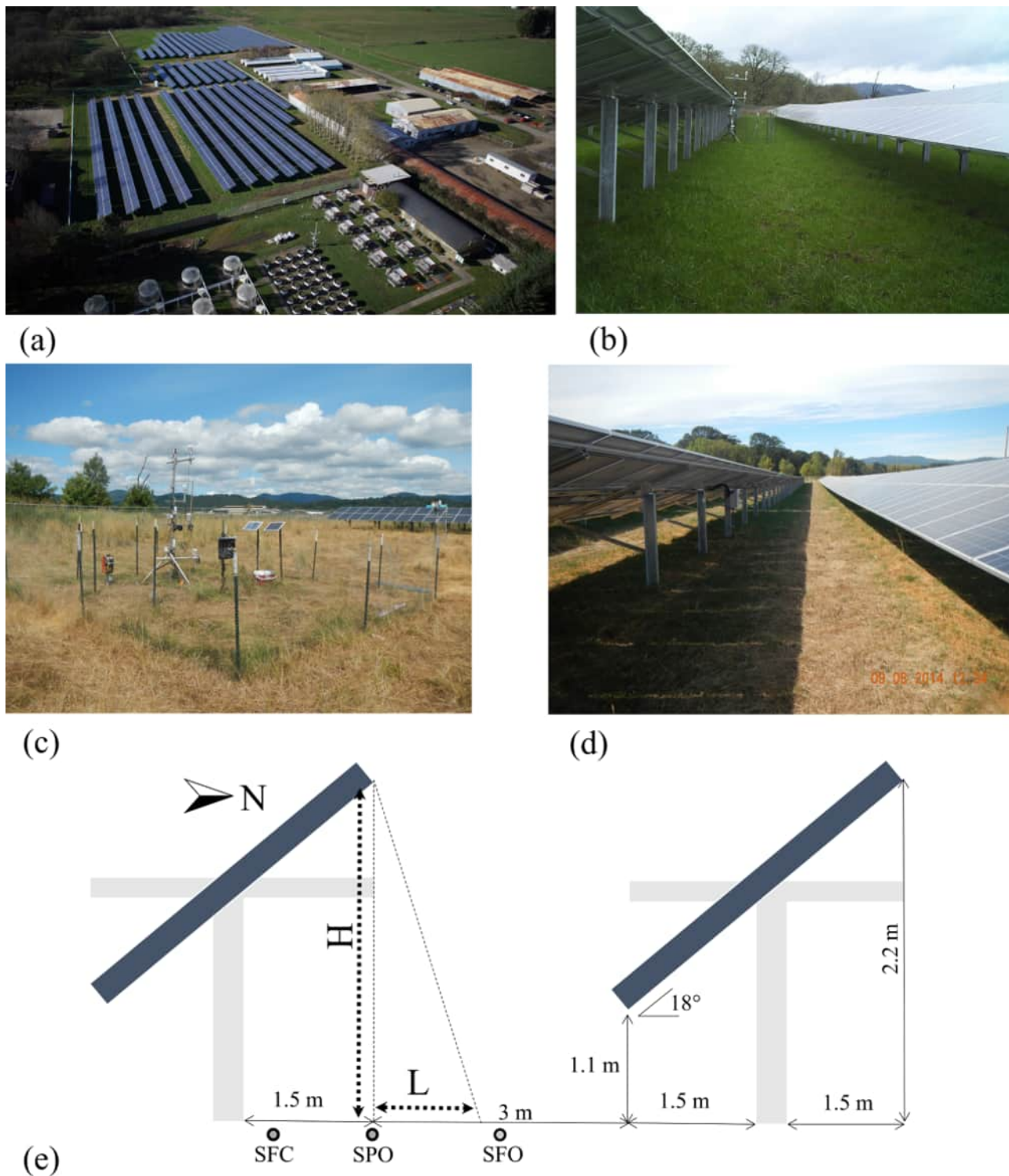


Fig 1. a) Aerial photo of 35th Street agrivoltaic solar array, Oregon State University Corvallis campus (this photo is taken in winter and shadow pattern is different from the measurements which held in summer) Copyright: Oregon State University, b) Solar panel set up, c) Control area set up, d) Shade zones in solar panel, e) Schematic drawing of shade zones (H is object height and L is shadow length).

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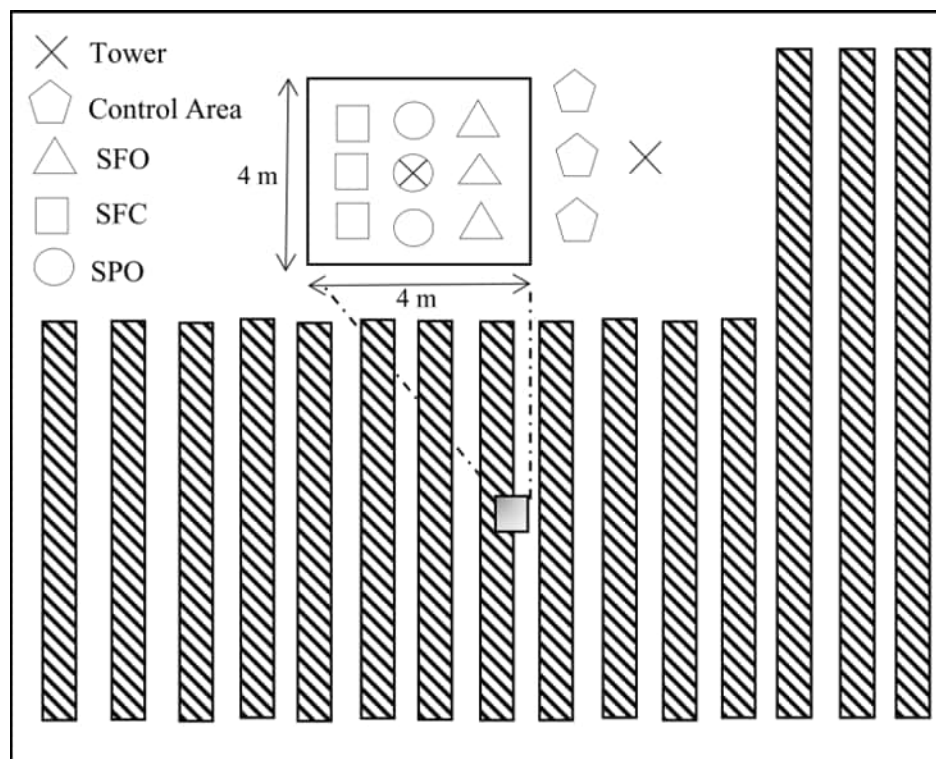


Fig 2. Plan view of experimental setup in solar array area showing locations of towers and neutron probe access tubes for: Solar Fully Covered (SFC), Solar partially open (SPO), Sky Fully Open (SFO), solar measurements are almost 70 meters apart from control area.

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between panels (SPO) and (3) Solar Fully Covered area under panels (SFC). SFO areas are between the edges of installed PV panels and experienced full sun. Shadow length calculation also confirms no shade covers the SFO zone [21]. SPO areas are in the penumbra and experienced episodic shade. SFC areas are directly beneath the PV panels and experienced full shade. Data from these sub-treatments were compared to the data collected from the control area outside the agrivoltaic array, where each measurement was replicated.

Shadow length (L) is calculated [20] based on the sun latitude, solar panel height, day and time of the year and it changes from 1.1 meters to 1.4 meters for May, June, July and August of 2015 which makes the SFO no shadow zone. Data were collected continuously in all areas from May–August 2015. Air temperature, relative humidity, wind speed and wind direction measurements were collected on 1 minute intervals. Soil moisture profiles were collected three times each week, and biomass samples were collected at the end of the observation period. Details associated with each set of measurements are explained in the following sub-sections.

2.1 Microclimatological measurements

Two atmospheric profiling stations were installed 70 meters apart: one in the control area and one near the center of the solar panel area. Micrometeorological variables were collected at four levels (0.5, 1.2, 2.0 and 2.7 m aboveground) in 1 minute intervals. The gathered variables were (1) air temperature (VP-3 Decagon Devices), (2) wind speed and directions (DS-2 Decagon Devices), (3) relative humidity (VP-3 Decagon Devices) and (4) net radiation (PYR

Decagon Devices). Data were logged on EM50 data loggers (Decagon Devices). Temperature and humidity devices were calibrated in a chamber, and wind sensors were calibrated in a wind tunnel prior to installation. A Kolmogorov Smirnov test was used to detect differences in *distributions* of temperature, humidity, wind speed, wind direction, and down welling radiation between the solar array area and the control area. A two tailed t-test was used to detect differences in the *mean* temperature, humidity, wind speed, wind direction, and down welling radiation between the solar array area and the control area and standard deviation results was measured to quantify the amount of dispersion of a set of data values.

2.2 Soil moisture measurement

The soil moisture was obtained using a neutron probe device (503 DR hydro-probe Campbell Pacific Nuclear International Inc. BoartLongyear Corporation (CPN), Concord, California, USA). These data were gathered at six depths for each sampling location (0.1 m to 0.6 m in 0.1 m intervals). Fig 2 shows a plan view where nine neutron probe access tubes for soil moisture measurements were installed in the solar area. Three access tubes were installed in each sub-treatment: SFO, SPO, and SFC respectively. Three access tubes were also installed in the control area. Neutron Probe readings were taken approximately every three days. A standard count was taken prior to sampling each day to calibrate data readings. Three neutron counts were averaged for each individual measurement (a single depth in a single tube). This count was normalized by the standard count, and the normalized count was calibrated to soil moisture. Within each sub-treatment, data at the same depths are averaged to determine the soil moisture profile and error-bars. The result is a soil moisture profile with measurements at 0.1, 0.2, 0.3, 0.4, 0.5, and 0.6 m for each sub-treatment and the control every three days. Neutron probe readings at the 0.1m depth for all sub-treatments and the control were adjusted to account for possible neutron losses to the atmosphere [22]. Two-way ANOVA was used to test the independence of the soil moisture measurements with respect to zoning (the control, SFO, SPO, and SFC) and depth.

2.3 Biomass measurements

Above-ground biomass was collected on the 28th of August. Six 1m by 1m quadrants were collected from within the fenced areas for each sub-treatment and the control. Harvested biomass was dried for 48 hours in a 105 °C oven and weighed. The Daubenmire method [11] was used to study grass species diversity at the end of July. Six transects in the control and one transect in the solar array were performed. For each transect, a random number was drawn (from 1–10) to determine the final location of each 1m x1m quadrant. Six quadrants were collected in each transect resulting in a total of 42 samples. In each quadrant, the coverage, by species, was determined visually.

3 Results and discussions

3.1 Micrometeorological variables

Using a Kolmogorov Smirnov test, a two tailed t-test, standard deviation and William Watson test[23] for wind direction showed subtle but statistically significant differences. Significant differences in mean temperature were found in readings taken closest to the PV panel surfaces at the 1.2 m and 2.0 m elevations. No significant differences were observed at the lowest (0.5 m) or highest (2.7 m) elevations. Note that the magnitude of these mean temperature differences are smaller than those reported from simulation studies [5–9]. Significant differences in mean relative humidity and wind speed were found for all measurement heights. Solar

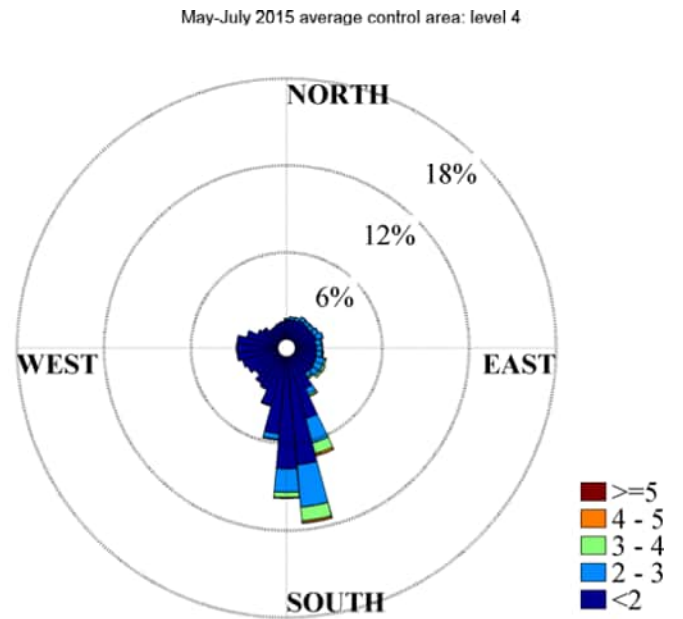
Table 1. Mean/Std and p-values from solar panel and control area Two-sample Kolmogorov-Smirnov, t tests and William Watson test.

Elevation (m)		0.5	1.2	2.0	2.7
Temperature (°C)	Mean/Std (solar panel area)	18.34/7.87	18.03/8.06	18.30/7.39	18.37/7.65
	Mean/Std (control area)	18.27/7.85	18.32/8.31	18.36/7.47	18.11/7.64
	p-values (KS test)	0.9964	0.9964	1.0000	1.0000
	p-values (t test)	0.1527	0.0000	0.0000	0.5996
Relative humidity (%)	Mean/Std (solar panel area)	65.62/0.226	64.17/0.252	64.29/0.209	64.92/0.230
	Mean/Std (control area)	66.23/0.234	66.38/0.242	64.89/0.222	65.37/0.223
	p-values (KS test)	0.0004	0.3611	0.7014	0.6703
	p-values (t test)	0.0000	0.0000	0.0000	0.0118
Wind speed (m/s)	Mean/Std (solar panel area)	0.5471/0.506	0.4880/0.427	1.3777/1.083	1.0889/0.909
	Mean/Std (control area)	0.8752/0.665	0.6384/0.520	1.1313/0.859	0.9726/0.757
	p-values (KS test)	0.9579	1.0000	0.8497	0.9964
	p-values (t test)	0.0000	0.0000	0.0000	0.0000
Solar radiation (W/m ²)	Mean/Std (solar panel area)	-	59.53/96.65	-	275.72/322.59
	Mean/Std (control area)	-	328.26/407.93	-	271.58/323.34
	p-values (KS test)	-	0.0099	-	0.9597
	p-values (t test)	-	0.0000	-	0.0054
Wind direction (°)	Mean/Std (solar panel area)	196.29/107.71	220.96/102.32	211.83/101.68	206.11/96.65
	Mean/Std (control area)	210.54/102.29	196.82/121.16	211.87/95.91	182.13/115.97
	p-values (WW test)	0.0000	0.0000	0.0000	0.0000

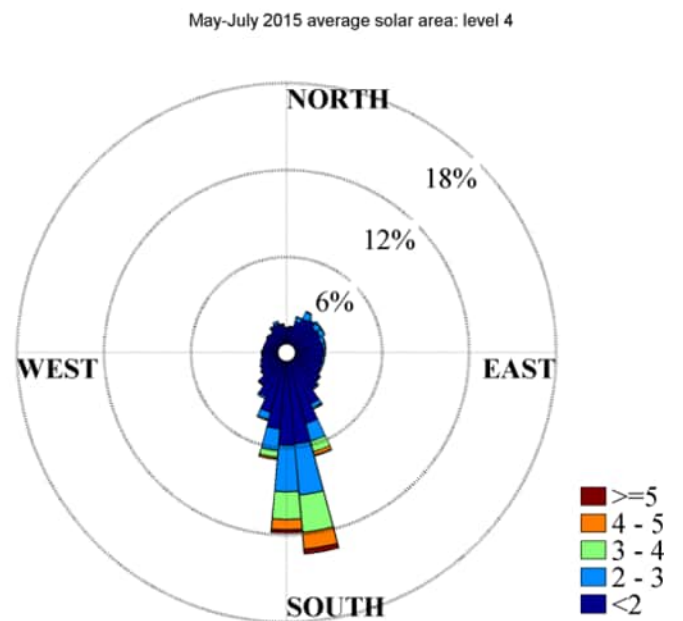
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radiation below the solar panel installation height was significantly reduced (as expected) and the incoming solar radiation measured at a height above the solar panels was found to be statistically significant (unexpected) but the difference relatively small. The distribution of wind direction was significantly altered at all heights, and the mean wind speed was significantly different at all heights. A summary of the p-values from all statistical tests is shown in Table 1. Standard deviation values were big due to diurnal changes of micro climate variables during the day.

Wind direction data at 2.7 m above ground level is shown in Fig 3 to illustrate the alterations in the wind direction. For the sake of brevity, only one height is presented in this manuscript, but all heights are shown in Supporting Information (Figure A in S1 Appendix). Fig 3 shows a histogram of incident wind direction plotted as a function of direction. Longer spokes indicate that that particular direction is more probable. Each spoke is divided and colored according to the strength of the wind (wind speed). For example, a long blue spoke would indicate that light winds from that direction are common. We can conclude from Fig 3 that the wind direction in the control area is distributed among many incident angles, while the wind direction within the treatment is oriented predominantly from the south. That is, the wind direction within the treatment area reorients with solar panels such that the wind is from south to north. The panels do not act as ‘canyons’ and orient the wind along their rows (a common occurrence in urban flows for example)[24]. Rather, the wind is reoriented perpendicular to the solar array’s rows. The authors believe that the local increase in temperature near the solar panel surface results in a buoyant force that causes local anabatic flow up the panel surfaces. Each anabatic flow on each PV row has a vector component perpendicular to the solar panel row orientation, and the entire solar farm acts like a ‘Fresnel slope’ that reorients the flow. The total buoyant force is enough to accelerate the flow directionally, and contributes the increase in wind speed above the panels. Flow acceleration around a bluff body (PV panel) also contributes to increased wind speed above the solar panels. Increased drag due to the



(a)



(b)

Fig 3. Wind rose plots for control (upper) and solar areas (lower) for May–August average wind directions. The data are for elevation 2.7 m.

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‘solar canopy’ is likely the cause of the reduced speed below the solar panels. Note that the most common wind speeds are weak ($<2\text{m/s}$), and it is unclear if this wind direction shift would be a robust result for windy locations. Higher wind speeds are also observed to reorient in Fig 3; however, the number of occurrences are limited.

3.2 Soil moisture data comparisons

The horizontal axis shows the Day of Year (DoY) of the data collection in 2015 and vertical axis is the volumetric soil moisture in vol/vol. Independence was determined with a p-value of less than 0.01 for all depths and zones by two-way ANOVA test. The soil moisture is near saturation for all depths and all treatments at the start of observation. That is, all areas had nearly identical initial soil moistures. The differing rates of soil water depletion in the three sub-treatments and the control led to dramatic differences in late season soil moisture.

The soil moisture in the SFO area is depleted more rapidly than the SPO, SFC or control areas. This result is intriguing since the SFO area and the control experience similar incident solar radiation. Thus, the SFO must have a different energetic balance despite similar exposure to direct solar energy. We hypothesize that this difference in rate of soil moisture loss is a result of the longwave radiation transfer. The SFO will experience incident long wave radiation from the adjacent PV panels. These PV panels would also reduce the sky view factor of the SFO area. In contrast, the sky view in the control area is unobstructed. Thus, we infer that the total net long wave and net shortwave radiation both play an important role in the energetics and evaporation in the SFO area. The complete long and short wave radiation budgets within an agrivoltaic system will be explored in future study.

Time series of the soil moisture at 0.2 m, 0.4 m and 0.6 m are presented in Fig 4 in subpanels a–c. Time series of soil moisture at 0.1 m, 0.3 m and 0.5 m can be found in Supporting Information (Figure A in S2 Appendix). Soil moisture is most persistent in the SFC area and remains available for a larger portion of the growing season. The soil moisture at 0.6 m depth remained close to saturation (0.3 vol/vol) for the entire season which implies that water is available at the bottom of the root zone over the period of observation Fig 4C. Overall the SFC area remained wetter than all other areas, including the control. This water availability is in stark contrast to the SFO area which was near saturation at the start of observation ($\sim 0.3\text{ vol/vol}$) and depleted to $\sim 0.2\text{ vol/vol}$ at the end of the season. This stark contrast in the moisture availability between the SFO and SFC creates an undesirable variability across the field and hints that shade uniformity may be an important consideration for the design of future agrivoltaic systems. The SPO area dries at a rate slower than the SFO but faster than the SFC and the control.

In other words, for most times and soil depths, the SFC had that highest soil moisture followed by the SPO, control and SFO respectively. It should be noted that the mean soil moisture across the SPO, SFO and SFC regions is similar to the control. But, the solar panels increase the local heterogeneity of soil water conditions, which results in some areas (SFC) having more persistent stores of soil water throughout the growing season.

The soil profiles at the beginning and end of the observation period are shown in Fig 5. All areas were near saturation for all depths initially. By the end of the observation period, the soil moisture in the SFC zone was nearly twice the SFO. These measurements are separated by less than two meters spatially. All measured soil moisture profiles are available in Supporting Information (Figure A in S3 Appendix).

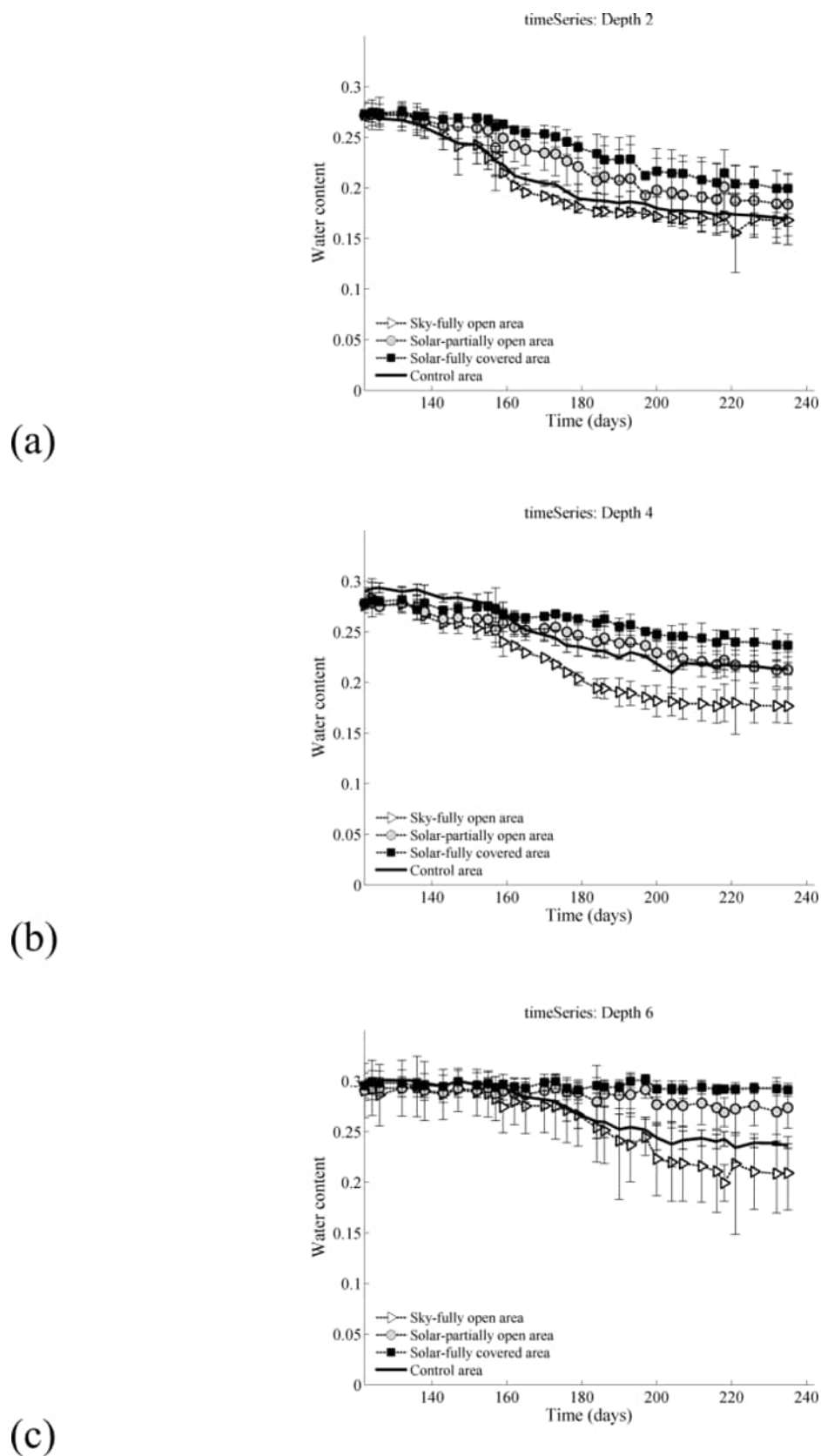
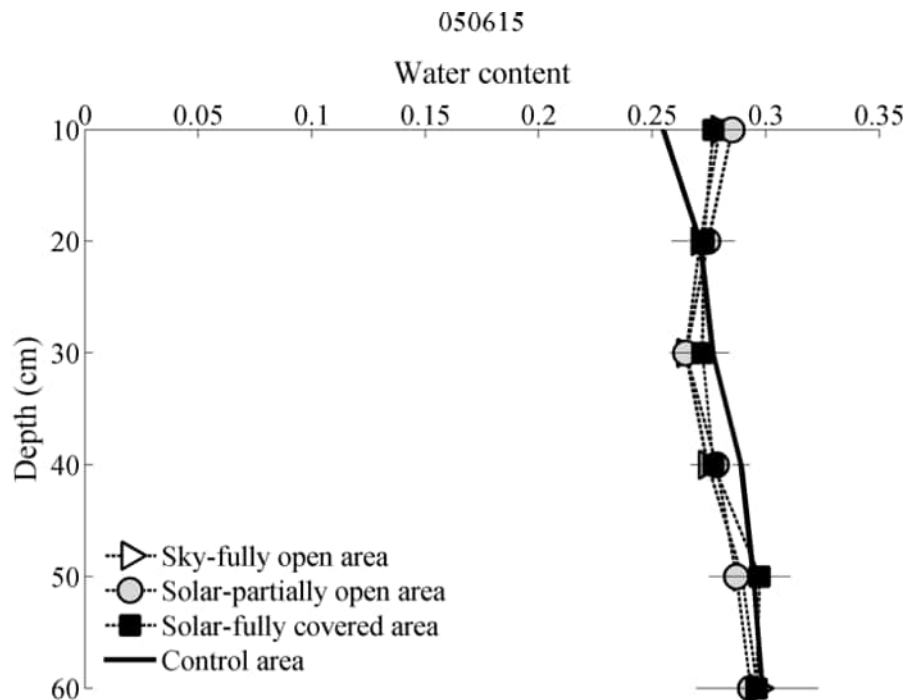
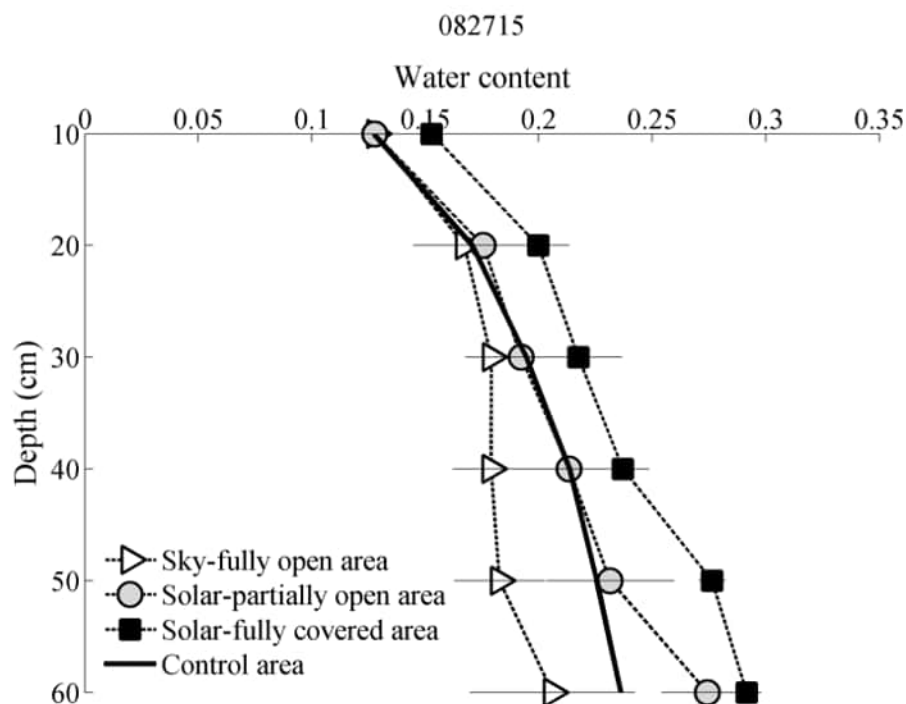


Fig 4. Soil moisture time series (a) 0.2m, (b) 0.4m and (c) 0.6m. For more information: there was 40 mm precipitation over the observation period, i.e. May-Aug 2015.

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(a)



(b)

Fig 5. Selected normalized soil moisture profiles from data sampling to show the change in soil moisture through growing season, (a) May 06–2015 and (b) August 27–2015.

<https://doi.org/10.1371/journal.pone.0203256.g005>

3.3 Vegetation

Eight grass types were identified in the control pasture and five were identified in the solar farm area. A summary of the results is presented in Table 2. The most common species in the solar panel area was *Alopecurus*, a long-lived perennial that thrives in moist conditions. *Alopecurus* provides a “succulent and palatable forage” [25]. The most prevalent grass type in control area is *Hordeum* that has spikelet clusters that can enter nostrils and ear canals in mammals. Three types of grasses *Calamagrostis*, *Cirsium* and *Dactylis* were observed only in the control area. These grasses are only favored by sheep and cattle in the early stage of the grass before spine develops [26]. The causal factor for the diversity change between control and treatment requires further investigation.

The harvested dry biomass at the end of the observation period is shown in Fig 6 Results show 126% more dry biomass in the SFC zone relative to the SFO zone and 90% more dry biomass in the SFC zone relative to the control. Although the sample size is small, difference between the SFC and the control were found to be significant, (p-value = 0.007). In addition, the difference between the SFC and the SFO were found to be significant, (p-value = 0.007).

3.4 Water usage

Water usage was calculated based on difference in depth averaged soil moisture between the beginning (Fig 5(A)) and end (Fig 5(B)) of the observation period. Averages are calculated by integrating soil moisture over soil depth from 10cm to 60cm. Water Use Efficiency (WUE) is then calculated as the biomass produced per unit of water used. Water use efficiencies in kg biomass/m³ of water against the biomass weight in control and SFO and SFC treatments are presented in Fig 7 ($\frac{WUE_{SFC}}{WUE_{Control\ area}}$). The higher producing SFC treatment was also significantly more water efficient (328%).

The seasonal climate pattern at the site produces an initially saturated pasture and a dry growing season. Initial water stores are depleted, through evapotranspiration (ET), and water scarcity occurs in the control and SFO areas. The shaded treatments (SFC and SPO) experience lower potential evapotranspiration (PET) due to decreased solar radiation throughout the observation period which resulted in a slower dry-down of the stored soil water. The decreased rate of dry-down in the SFC and SPO areas left soil water stores available throughout the observation period and allowed pasture grasses in the SFC and SPO to accumulate a significantly greater biomass. The reduced PET in the SFC and SPO treatments also contributed to

Table 2. The results of biomass monitoring for different grass types in solar and control area.

Grass scientific name (common name)	Solar area (%)	Control area (%)
<i>Hordeum</i> (Foxtail barely)	10	25
<i>Agrostis</i> (Redtop bentgrass)	30	20
<i>Alopecurus</i> (Meadow foxtail)	50	7
<i>Schedonorus</i> (Tall rye grass)	5	9
<i>Bromus</i> (Foxtailbrome)	5	22
<i>Calamagrostis</i> (Reed grass)	0	6
<i>Cirsium</i> (Thistle)	0	10.5
<i>Dactylis</i> (Orchard grass)	0	0.5

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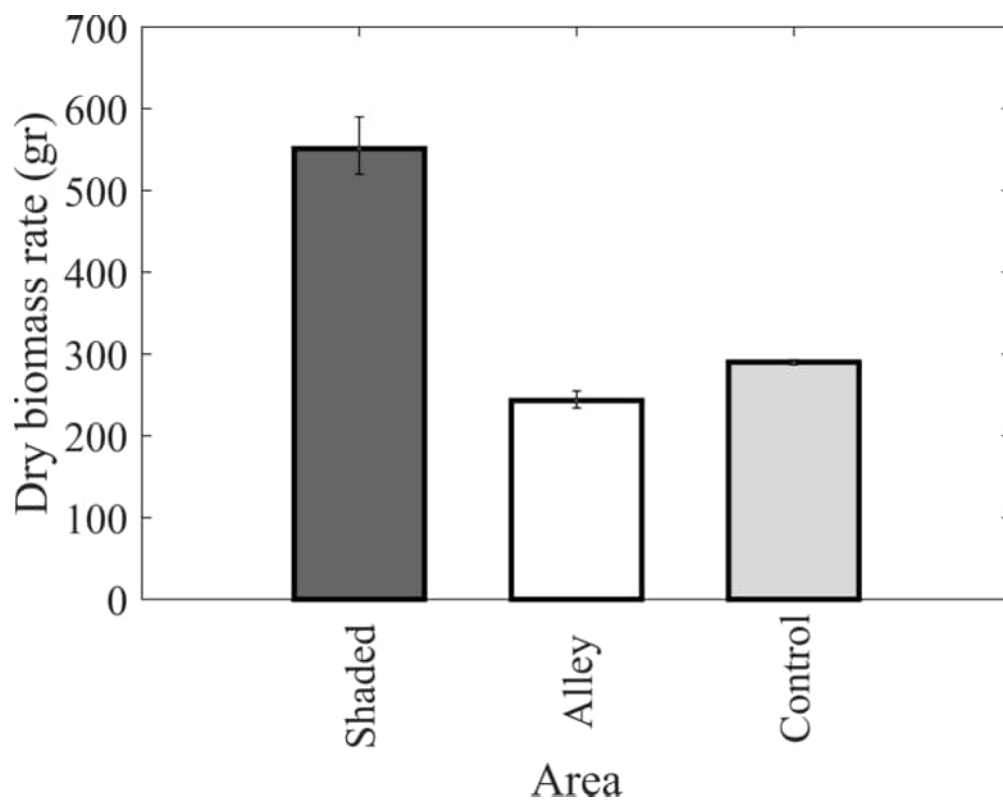


Fig 6. Dry biomass comparison in three places Solar Fully Covered (SFC), Sky Fully Open (SFO) and control area.

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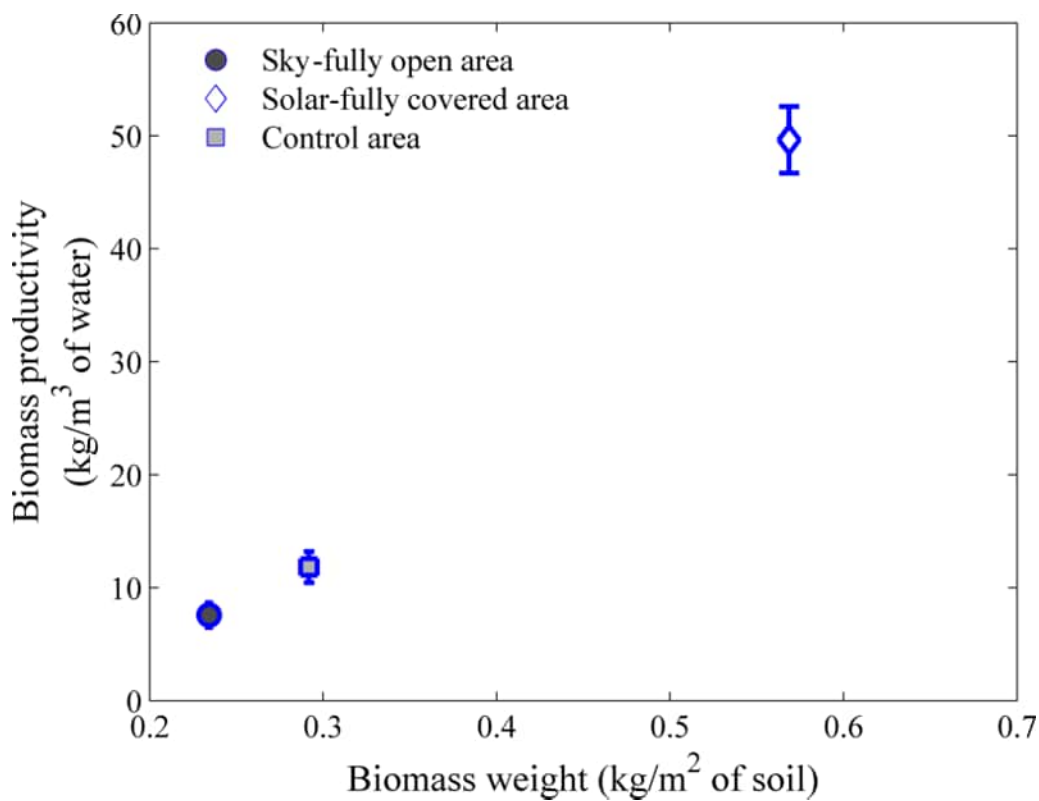


Fig 7. Biomass productivity in kg/ m³ of water.

<https://doi.org/10.1371/journal.pone.0203256.g007>

an increase in water use efficiency of the pasture grasses. That is, a ‘water limited’ area, in a Budyko [27] sense, could be considered as an area of ‘solar excess.’ By harvesting this solar excess with solar panels, PET is reduced. Taken to an extreme it is possible to shift the aridity such that the shaded area becomes energy limited. Thus there must exist a shading level, for a water limited area, where PET and AET would be in balance. We would not expect a similar outcome in ‘energy limited’ areas (Budyko sense) as observed by Armstrong et al. [8]. In this case, there is no solar excess and the PET is already equal to the AET. If solar arrays were placed above growing plants in ‘energy limited’ conditions we would expect that the total biomass production would decrease, consistent with the findings of Armstrong et al. [16].

4 Conclusion

Typical agricultural operations manage multiple on-farm resources including soil, nutrients and water. This study suggests that the on-farm solar resource management could also be implemented for productive benefits. Water limited areas are most likely to benefit as solar management reduces PET and consequently the water demand. Not all crops will be amenable to solar management, and the economics of active solar management with PV panels needs further study. But, semi-arid pastures with wet winters may be ideal candidates for agrivoltaic systems as supported by the dramatic gains in productivity (90%) observed over the May-Aug 2015 observation period at the Rabbit Hills agrivoltaic solar array. These net benefits were largely achieved through an increased water use efficiency in the shaded areas of the field which left water stored in the soil column available throughout the entire observation period. Extreme heterogeneity and spatial gradients in biomass production and soil moisture were observed as a result of the heterogeneous shade pattern of the PV array. Future agrivoltaic designs should eliminate this heterogeneity by optimizing PV panel placement to create a spatially uniform shadow pattern. A spatially uniform shadow pattern would foster uniform biomass accumulation benefits. The agricultural benefits of energy and pasture co-location could reduce land competition and conflict between renewable energy and agricultural production. Reduced or eliminated land competition would open new areas for PV installation. Local climatic effects of agrivoltaic installations were statistically significant but subtle, however the regional climatic impacts (e.g. rainfall patterns) of large scale agrivoltaic installations are still unclear and should be the subject of further study.

Supporting information

S1 Appendix. Figure A: Wind rose plots for four level heights.
(DOCX)

S2 Appendix. Figure A: Soil moisture time series (a) 0.1m, (b) 0.3m and (c) 0.5m. For more information: there was 40 mm precipitation over the observation period, i.e. May-Aug 2015.
(DOCX)

S3 Appendix. Figure A: Selected normalized soil moisture profiles from data sampling to show the change in soil moisture through growing season: May 06–2015 to August 27–2015. The dates are mentioned on top of each figure with mmddyy format.
(DOCX)

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References

- Lewis NS, Nocera DG. Powering the planet: Chemical challenges in solar energy utilization. *Proc Natl Acad Sci*. 2006; 103: 15729–15735. <https://doi.org/10.1073/pnas.0603395103> PMID: 17043226
- Rodman LC, Meentemeyer RK. A geographic analysis of wind turbine placement in Northern California. *Energy Policy*. 2006; 34: 2137–2149.
- Rogner HH, others. in *Global Energy Assessment—Towards a Sustainable Future* Ch. 7, 423–512. Cambridge University Press; 2012.
- Trancik JE. Renewable energy: Back the renewables boom. *Nature*. 2014; 507: 300–302. <https://doi.org/10.1038/507300a> PMID: 24654279
- Barron-Gafford GA, Minor RL, Allen NA, Cronin AD, Brooks AE, Pavao-Zuckerman MA. The Photovoltaic Heat Island Effect: Larger solar power plants increase local temperatures. *Sci Rep*. 2016; 6: srep35070. <https://doi.org/10.1038/srep35070> PMID: 27733772
- Millstein D, Menon S. Regional climate consequences of large-scale cool roof and photovoltaic array deployment. *Environ Res Lett*. 2011; 6: 034001.
- Scherba A, Sailor DJ, Rosenstiel TN, Wamser CC. Modeling impacts of roof reflectivity, integrated photovoltaic panels and green roof systems on sensible heat flux into the urban environment. *Build Environ*. 2011; 46: 2542–2551. <https://doi.org/10.1016/j.buildenv.2011.06.012>
- Hu A, Levis S, Meehl GA, Han W, Washington WM, Oleson KW, et al. Impact of solar panels on global climate. *Nat Clim Change*. 2016; 6: 290–294. <https://doi.org/10.1038/NCLIMATE2843>
- Armstrong A, Ostle NJ, Whitaker J. Solar park microclimate and vegetation management effects on grassland carbon cycling. *Environ Res Lett*. 2016; 11: 074016.
- Nonhebel S. Renewable energy and food supply: will there be enough land? *Renew Sustain Energy Rev*. 2005; 9: 191–201.
- Seidlova L, Verlinden M, Gloser J, Milbau A, Nijs I. Which plant traits promote growth in the low-light regimes of vegetation gaps? *Plant Ecol*. 2009; 200: 303–318. <https://doi.org/10.1007/s11258-008-9454-6>
- Dupraz C, Marrou H, Talbot G, Dufour L, Nogier A, Ferard Y. Combining solar photovoltaic panels and food crops for optimising land use: Towards new agrivoltaic schemes. *Renew Energy*. 2011; 36: 2725–2732. <https://doi.org/10.1016/j.renene.2011.03.005>
- Dinesh H, Pearce JM. The potential of agrivoltaic systems. *Renew Sustain Energy Rev*. 2016; 54: 299–308. <https://doi.org/10.1016/j.rser.2015.10.024>
- Marrou H, Dufour L, Wery J. How does a shelter of solar panels influence water flows in a soil–crop system? *Eur J Agron*. 2013; 50: 38–51. <https://doi.org/10.1016/j.eja.2013.05.004>
- Marrou H, Wéry J, Dufour L, Dupraz C. Productivity and radiation use efficiency of lettuces grown in the partial shade of photovoltaic panels. *Eur J Agron*. 2013; 44: 54–66.
- Dupraz C, Talbot G, Marrou H, Wery J, Roux S, Liagre F, et al. To Mix or Not to Mix: Evidences for the Unexpected High Productivity of New Complex Agrivoltaic and Agroforestry Systems. 2011. Available

Online Httpswww Res Netpublication230675951To Mix Andagroforestrysystems Accessed 9 Dec 2015.: 202–203.

17. Ravi S, Lobell DB, Field CB. Tradeoffs and Synergies between Biofuel Production and Large Solar Infrastructure in Deserts. *Environ Sci Technol*. 2014; 48: 3021–3030. <https://doi.org/10.1021/es404950n> PMID: 24467248
18. Kadowaki M, Yano A, Ishizu F, Tanaka T, Noda S. Effects of greenhouse photovoltaic array shading on Welsh onion growth. *Biosyst Eng*. 2012; 111: 290–297. <https://doi.org/10.1016/j.biosystemseng.2011.12.006>
19. Hassanpour Adeh E, Higgins CW, Selker JS. Remarkable solar panels Influence on soil moisture, micrometeorology and water-use efficiency. 2017; Available: <https://ir.library.oregonstate.edu/xmlui/handle/1957/60846>
20. Web Soil Survey—Home [Internet]. [cited 5 Jun 2017]. Available: <https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm>
21. Appelbaum J, Bany J. Shadow effect of adjacent solar collectors in large scale systems. *Sol Energy*. 1979; 23: 497–507.
22. Parkes ME, Siam N. Error associated with measurement of soil moisture change by neutron probe. *J Agric Eng Res*. 1979; 24: 87–93.
23. Berens P. CircStat: a MATLAB toolbox for circular statistics. *J Stat Softw*. 2009; 31: 1–21.
24. Pavageau M, Schatzmann M. Wind tunnel measurements of concentration fluctuations in an urban street canyon. *Atmos Environ*. 1999; 33: 3961–3971.
25. W.M. Murphy M. J. Grass varieties for central Oregon. 1976 Nov. Report No.: Special Report 468.
26. De Bruijn SL, Bork EW. Biological control of Canada thistle in temperate pastures using high density rotational cattle grazing. *Biol Control*. 2006; 36: 305–315.
27. Budyko MI (Mikhail I. Climate and life. 1971; Available: <http://agris.fao.org/agris-search/search.do?recordID=US201300494263>



Research Paper

Ecohydrological effects of photovoltaic solar farms on soil microclimates and moisture regimes in arid Northwest China: A modeling study



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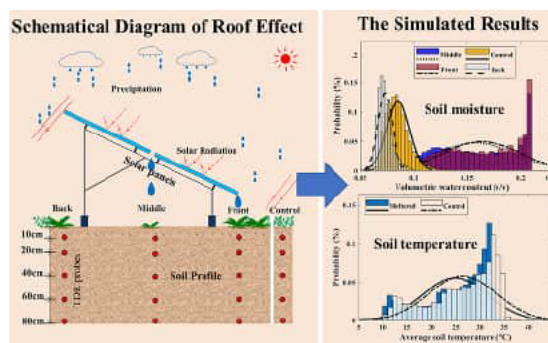
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HIGHLIGHTS

- A model was developed for detecting soil temperature and soil moisture dynamics in solar farms.
- Soil moisture content was increased by 59.8% to 113.6% in the Middle and Front zones.
- Soil temperature was decreased by 1.47 to 1.66 °C in the intermittent shade.
- Hydrological and biogeochemical processes in solar-farm management should be better studied.

GRAPHICAL ABSTRACT



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ABSTRACT

Photovoltaic technology plays an important role in the sustainable development of clean energy, and arid areas are particularly ideal locations to build large-scale solar farms, all over the world. Modifications to the energy balance and water availability through the installation of large-scale solar farms, however, fundamentally affect the energy budget, water, and biogeochemical cycles. In-situ field observations, though, fail to draw definitive conclusions on how photovoltaic panels (PVs) affect the ambient environment, or how microclimates and soil moisture evolve under the long-term, continuous, cumulative influence of PVs. Here, we designed a synthetic model, integrating processes of energy budget and water cycle, to quantify the ecohydrological effects of PVs on soil microclimate and moisture regimes at different locations (zones) near individual PVs. Simulations run with a stochastically generated 100-year climate time series were examined to capture the evolutionary trends of soil microclimate and soil moisture. The results indicate that soil moisture content was increased by 59.8% to 113.6% in the Middle and Front zones, and soil temperature was decreased by 1.47 to 1.66 °C in all the sheltered zones, mainly because there was 5–7 times more available water and ~27% less available radiation there, compared with the control zone. On the other hand, if the ground clearance of the PVs is too low, turbulence beneath hot PVs will have a significant influence on not only soil temperature but also soil moisture content. The innovative contribution of this study lies in reinforcing existing theoretical patterns for the development of soil microclimate and moisture dynamics influenced by PVs, and can be used to provide reliable insights into the hydrological and biogeochemical processes on Earth and the sustainable management of large-scale solar farms in arid ecosystems.

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1. Introduction

Growing environmental concerns and the increasing demand for energy are opening up new opportunities for the utilization of renewable energy resources. As one of the most promising candidates for low-carbon, non-fossil fuel energy production, solar photovoltaic (PV) technology is believed to have potential for shaping a clean, reliable, scalable and affordable electricity system for the future (Hosenuzzaman et al., 2015; Qerimi et al., 2020). According to the International Renewable Energy Agency (IRENA), the total installed capacity of solar power had reached 714 GW by 2020, and the growth rate of solar power generation continues to accelerate (IRENA, 2021). Arid and semiarid regions cover more than 40% of Earth's terrestrial surface (Liu et al., 2020a). These lands are of great interest for PV applications due to their high solar potential (Tanner et al., 2020): the climatic conditions can provide high rates of solar irradiation throughout the year, and the abundant land resources can support large solar-power generating stations (Adeh et al., 2019). However, these regions, because of their stressful conditions and sparse vegetation, are fragile and sensitive ecological environments and are vulnerable to any human activities that could exacerbate the stresses they are subjected to (Hassanpour Adeh et al., 2018; Yue et al., 2021). Thus, while establishing that solar PVs would clearly provide environmental benefits by reducing carbon emissions, it is obvious that these systems could also create new environmental problems—in other words, threats as well as untapped benefits. For instance, more vigorously growing vegetation has been frequently reported in solar farms established in dry climates (the biomass has sometimes increased by 22.7 times compared with their surrounding regions), due to the shading effects of the solar panels, which resemble natural ecotones that tend to generate greater plant coverage and biomass (Boussetot et al., 2017; Liu et al., 2019). Through significantly altering the water/energy availability, and thereby the interaction modes between soil and air, the expansion of ground-mounted solar farms might further affect soil carbon cycling and promote the growth of plants that can absorb greenhouse gas emissions (Jahanfar et al., 2019; Tanner et al., 2020; Thorne et al., 2015). Yet not enough is known about these effects.

Microclimates are known to influence the nature of local soil and its relationship with plants (Armstrong et al., 2014). Large-scale solar farms may incur unintended ecohydrological effects through modifications of the energy budget and water cycle (Boussetot et al., 2017; Liu et al., 2019), and thus change the temperature and moisture conditions of the surface soil (Armstrong et al., 2016; Chang et al., 2018). Indeed, the changed microclimate can have various and even opposing effects on the “under-PV” environment, depending on the climate, soil, vegetation, and PV system configuration (i.e., ground clearance, tilt angle, and PV materials) (Armstrong et al., 2016; Elamri et al., 2018; Liu et al., 2019; Onyshchenko et al., 2020). For example, besides transforming a substantial portion of incoming radiation into electricity, PVs also reflect and re-radiate solar radiation and cast heavy shade on the ground, thereby lowering soil temperatures and consequently reducing the rate of thermal-induced loss of water from soil underneath the PVs (surface soil evaporation) (Armstrong et al., 2016; Tanner et al., 2020; Yue et al., 2021). Conversely, however, PVs have low albedo and heat capacity, so that the air beneath the PVs may be heated more rapidly than in the open areas, resulting in potentially higher air temperature, lower relative humidity, and thus increased evapotranspiration water loss by both the soil and plants (Wu et al., 2014). Moreover, shifts in rainfall patterns caused by PV panels change the water inputs to the soil, resulting in both increased and reduced spatial water availability (Jahanfar et al., 2019; Tanner et al., 2020). Changes in wind patterns alter site-specific air-current regimes and evoke substantial changes in microclimates occurring over short distances as well. The above-mentioned complex effects of PVs on microclimate may in turn substantially affect local vegetation structure, biodiversity and carbon balance, resulting in changes in ecosystem services at multiple scales (Boussetot et al., 2017; Liu et al., 2019).

Since solar farms may potentially affect the patterns of local and even regional ecosystems through changed microclimates (Yang et al., 2018; Yue et al., 2021), these related ecological and environmental issues are becoming a matter of public and governmental concern, including whether solar farms suck up all the energy from the sun or become a photovoltaic heat island, and thus prevent plants from growing in the vicinity of the PV panels (Fthenakis and Yu, 2013; Zhe et al., 2019); whether solar farms can lead to greater ecological diversity when compared with equivalent undeveloped sites (Tanner et al., 2020); and so on (Montag et al., 2016). This is especially the case in arid and semiarid regions like northwestern China, where the climate is dry, ecosystems are being degraded, and solar farms are booming (Liu et al., 2019). Improved understanding of soil microclimate and moisture regimes is urgently needed to respond to these concerns, but only a few studies have been done so far on the ecohydrological effects of PVs for this region or other similar regions around the world (Nash et al., 2016; Yue et al., 2021). The available in-situ observations have suggested that PV panels reduce the available irradiance (Araki et al., 2017), lower the soil temperature (Armstrong et al., 2016), or elevate soil moisture content, at local scales (Yue et al., 2021). However, the existing measurements at PV-plant level and regional scales have disclosed that either heat- or cold-island effects could be found, depending on the scale of observation (Gao et al., 2016; Li et al., 2020). It is clear that PVs' effects on the local climate and how these in turn impact the vegetation and soil are still not certain. Due to the inherent limitation of field observation, a synthetic modeling approach is the only possible way to bridge the gap between observations at different sites and scales, but this type of research is still lacking to date (Elamri et al., 2018; Scherba et al., 2011). There are two major difficulties in developing such a model: 1) potential applicability for the varieties of solar farms in terms of climate, configuration and location, and 2) spatially explicit descriptions of the PV-affected ecohydrological processes (Nemet, 2009; Yang et al., 2018).

Here we designed a synthetic model based on field observations, with daily timestep, to quantify the ecohydrological effects of PVs on soil microclimate and moisture regimes for different ground zones in relation to PVs. The salient advantage of our model over existing models is the spatially explicit treatment of the processes of energy budget and the water cycle, which overcame the limitations involved in evaluating the ecohydrological effects of photovoltaic solar farms using limited field observations. Through modeling efforts, this work aimed 1) to explore the ecohydrological effects of PVs on soil microclimates and moisture regimes by using a synthetic model; 2) to provide a quantitative comprehension of how PVs affect the ambient environment, or how microclimates and soil moisture evolve under the long-term, continuous, cumulative influence of PVs; and 3) to identify the moisture regimes that may further affect the carbon cycle. In order to achieve these aims, a set of numerical experiments was designed, to provide a solid basis for understanding the ecohydrological processes of large-scale solar farms in an arid ecosystem over a stochastically generated 100-year climate time series, which is long enough to reasonably capture the evolutionary trends of soil microclimate and soil moisture.

2. Materials and methods

2.1. Site description and field data collection

This study was carried out at a solar farm (38°06'8"N, 102°19'47"E; 1702 m a.s.l.) located in the town of Wuwei in Gansu Province, in the eastern part of the Hexi Corridor in arid northwest China. This area has a typical temperate continental arid climate with an annual average temperature of 14.2 °C (maximum daily temperature of 35.3 °C and minimum daily temperature of -10.9 °C). The average annual precipitation is approximately 212 mm with 88% occurring during the growing season (from April 1 to September 30) based on the last 38 years of available meteorological records (1980–2017 inclusive). Just as for other arid and semiarid areas, the soil moisture content in the study

site is low, due to strong evapotranspiration, sterile soil and high-albedo surfaces, creating a harsh growing environment for vegetation (Liu et al., 2020a, 2020b). A large number of photovoltaic solar farms and concentrated solar plants have been built in this area. At the study site, the PVs are arranged in east–west orientated rows and inclined southward at a tilt angle of 37.5° , and the length and width of a single photovoltaic panel (which consists of two sub-panels with a 3-cm gap between them) are 4 m and 1 m, respectively. The underlying surface is typical of the Gobi Desert, and the soil contains gravel of varying sizes (Fig. 1c), making it difficult to install a time domain reflectometer (TDR). In order to facilitate the installation of TDR (Fig. 1a), the existing top 1 m of soil was replaced with sandy loam.

The meteorological data from 1980 to 2017 (daily maximum and minimum air temperature, sunshine duration, and total precipitation), observed at the Yongchang site—which is about 30 km away from the solar farm (Fig. 2a)—were obtained from the National Meteorological Science Data Center, China. The volumetric moisture content (VWC) was taken to be the average of vertical profiles where the probes were installed at five depths below the soil surface (10, 20, 40, 60, and 80 cm) in each plot, and data were collected at 10-min scan intervals. The soil moisture and soil temperature were measured at each point by the TDR probes (ECH2O, Decagon Devices, Inc.). Because of the high rainfall and solar radiation availability differences among experimental zones caused by the PVs, four experimental zones were set up in order to describe the variability of soil moisture at different positions in relation to the PVs (Fig. 1a): Front (rainfall interception zone), Middle (rainfall interception and shade zone), Back (shade zone), and Control (natural bare zone). The reference monitoring site (Control) was located in an open space approximately 100 m away from the PVs, so that it was not covered by PVs.

2.2. Model structures and simulation methods

The scheme of the synthetic model is shown in Fig. 2b. The edge effect is not considered in the model. The aim was to assess the long-term

effects of large-scale solar farms on moisture regimes and soil microclimates. A single-site daily stochastic weather generation model (WeaGet) (Chen et al., 2011; Chen et al., 2010; Chen et al., 2012)—a Richardson-based weather generator (Richardson, 1981)—was used to generate rainfall, maximum and minimum air temperature, and solar radiation over a 100-year period, as the inputs of the residual submodules. In the WeaGet, a first-order two-state Markov chain was used to generate the occurrence of wet or dry days. The probability of precipitation on a given day is based on the wet or dry status of the previous day with a two-parameter gamma distribution for precipitation amounts. We assume that rainfall is an instantaneous process because the duration of each rainfall event is short relative to the daily scale. One first-order linear autoregressive model was used to generate maximum and minimum air temperatures (T_{max} and T_{min}) and solar radiation at a daily scale. To obtain the most suitable soil parameters, a range of possible values of soil parameters were obtained from the literature (Laio et al., 2001b; Liu et al., 2020a, 2020b) and calibrated by in-situ observation results using the genetic algorithm method, and statistical analysis was employed to evaluate the performance of the parameters. Numerical experiments with different restrictive treatments were then designed to quantify the ecohydrological effects of PVs on soil microclimate and moisture regimes at different locations (zones) near individual PVs. The model structures are detailed as below and in Appendixes A and B.

2.2.1. Soil microclimate

Soil temperature, near-surface air temperature, and coupling heat and water transfer between land and atmosphere are important components of the energy balance in arid and semi-arid areas. Soil temperature is mainly affected by those factors, physical properties of the ground, land cover, and near-surface climate (Chow et al., 2011). Since there was a strong correlation between average soil temperature and air temperature ($R = 0.89$, $P < 0.001$), in this study, soil temperature is given by Eq. (1) (Chow et al., 2011) as a function of near-surface temperature, available solar radiation and soil depth.

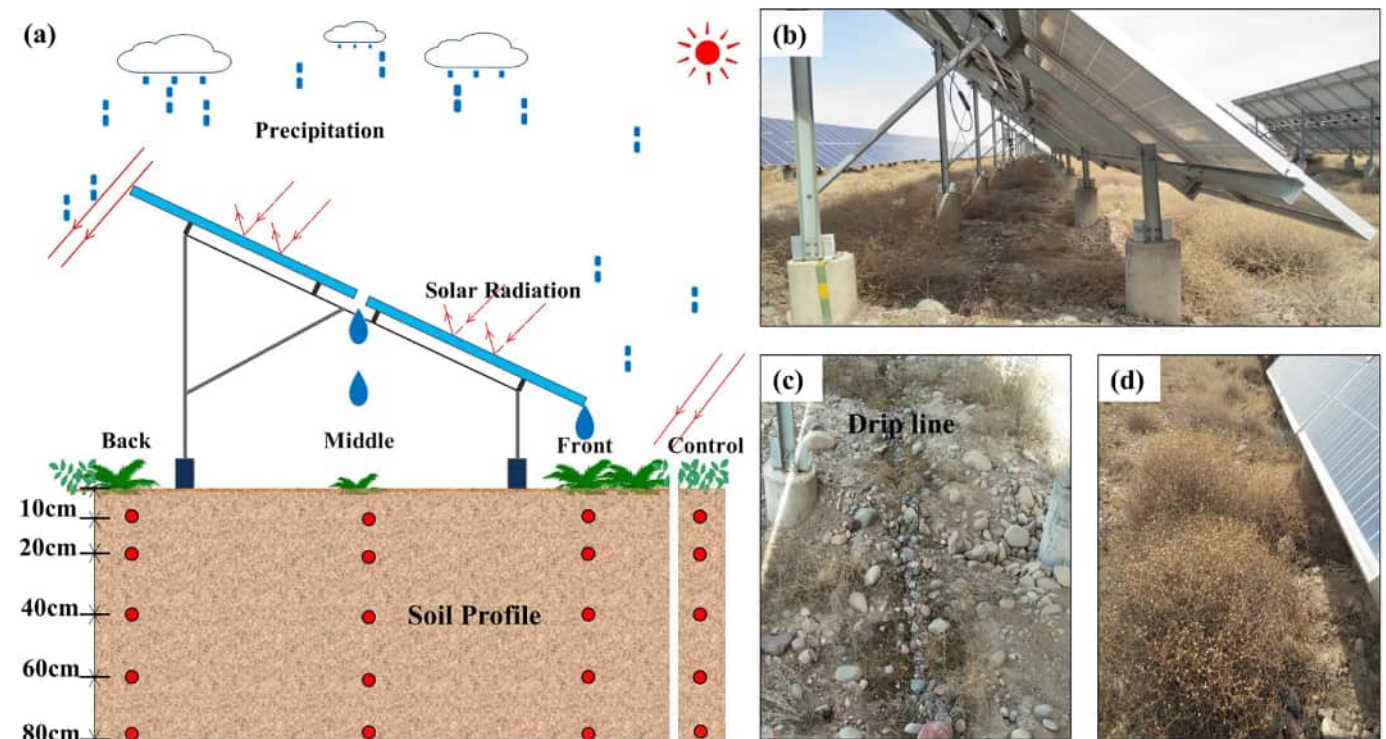


Fig. 1. (a) Roof effect caused by PVs and installation diagram of TDR (red dots); (b) photograph of single photovoltaic panel; (c) photograph of soil surface in the Middle zone, and drip line; (d) a vegetation plot in the Front zone.

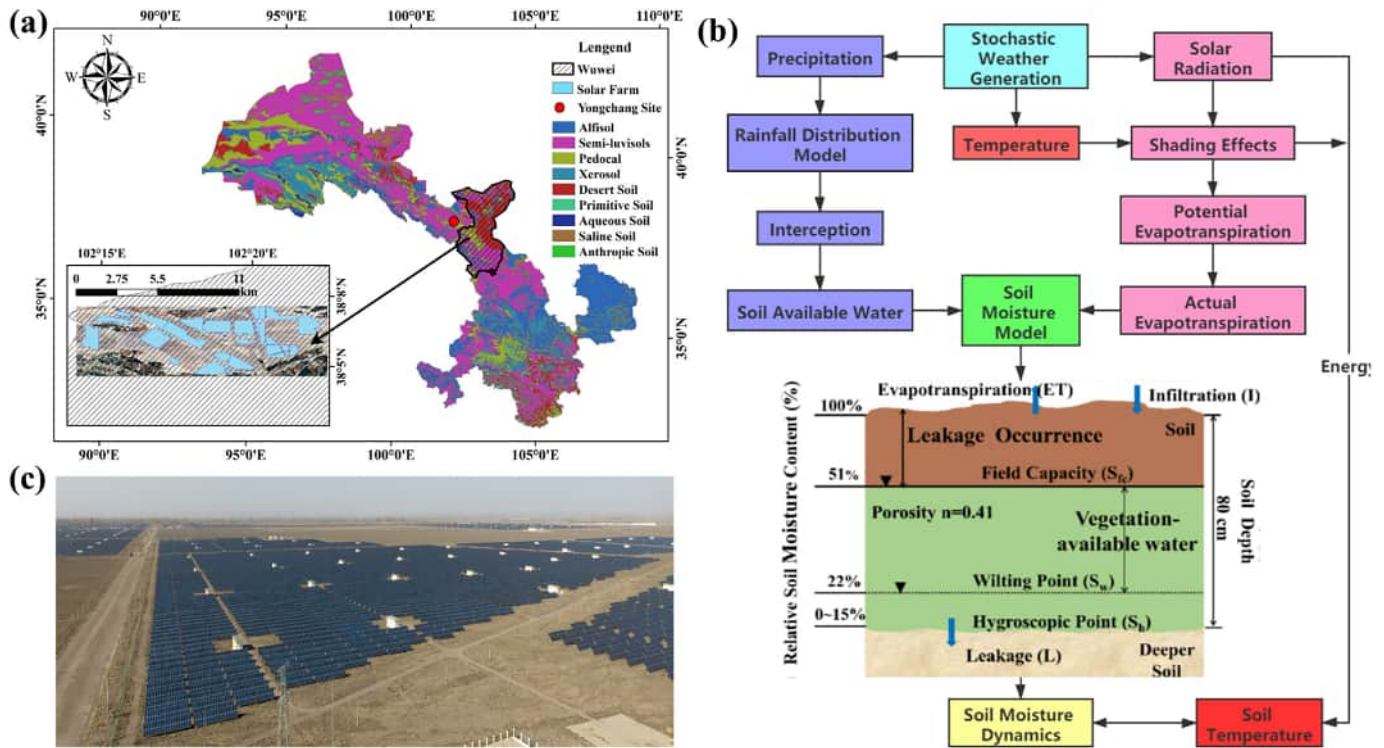


Fig. 2. (a) Location of the solar farm: Fengle town in Wuwei city; (b) schematic showing the relationships among the sub-models within the synthetic model; (c) photograph of the solar farm.

$$T_{si} = a_1 \exp(-a_2 x_i) T_{air} + b_1 \exp(-b_2 x_i) \sin\left(\frac{2\pi m}{365} + b_3 x_i + b_4\right) + c_1 \left(-\frac{2}{\pi}\right) \tan^{-1}(c_2 x_i) + d_1 + d_2 R_a \quad (1)$$

where T_{si} (°C) is the temperature of the i_{th} soil layer, T_{air} (°C) is near-surface temperature, x_i is simulated soil depth of the i_{th} soil layer (m), and R_a is the available solar radiation (MJ/m^2). The numerical coefficients for Eq. (1), a_1 - a_2 , b_1 - b_4 , c_1 - c_2 , and d_1 - d_2 are estimated as 15.79, 18.22, 12.52, -2.07, 17.65, 14.95, -1.68, 14.59, 12.52, and 5, respectively.

2.2.2. Solar radiation

Solar radiation is one of the most important factors controlling both the energy budget and the water cycle. Accurate estimation of solar radiation is essential for calculating potential evapotranspiration and soil temperature. Referencing algorithms are available for calculating solar radiation at any site if latitude, longitude, and date are given (Araki et al., 2017; Passias and Källbäck, 1984; Singh et al., 2020; Tong et al., 2005); actual local daily solar radiation (R_a) can be expressed as a function of solar incidence angle (i), solar elevation angle (h_c) (Passias and Källbäck, 1984), the azimuth angle of the PVs (γ), and the inclination angle of the PVs (β). For more details refer to Appendix A.

$$R_a = f(i, h_c, \gamma, \beta) \quad (2)$$

$$i = f(\varphi, \beta, \gamma, \delta, \omega) \quad (3)$$

$$h_c = f(\varphi, \delta, \omega) \quad (4)$$

where φ is latitude, β is the inclination angle of the PVs, γ is the azimuth angle of the PVs—which is considered equal to zero, solar declination δ in range of $\pm 23.45^\circ$ is a function of date, and ω is the angle subtended by the sun at a particular hour.

2.2.3. Shading effects

The available solar radiation of the area beneath the PVs has been reduced because the PVs are intercepting a portion of the solar radiation. This shading effect has an influence on not only PET but also air and soil temperature. The amount of radiation beneath the PVs depends on the reflectivity and electricity transform efficiency of the PVs. In order to simplify the model, the shade effect of the PVs was not calculated by the mechanism model specifically. Rather, we assumed the reflectivity and electricity transform efficiency to be 10% and 18%, respectively, as those are the global average levels (Hu et al., 2016). Therefore, the residual (90%) can be divided into 18% (of the remaining 90%) absorbed by the PVs and converted to electricity, and the other 82% (of the remaining 90%) transmitted through the panels and absorbed by the underlying surface. Thus, the available solar radiation underneath the PVs is equal to 73.8% ($90\% \times 82\%$) of the incoming solar radiation on the surface of the PVs.

2.2.4. Rain redistribution effects

When rainfall occurs, the PVs intercept some of it, and most of the intercepted rainfall flows down to the edge of the PVs and drips down forming a narrow drip line (Fig. 1b and c). After the vegetation intercepts a small portion of the dripped water, the residual will infiltrate downward through pores of soil or generate Hortonian overland flow, depending on the rainfall intensity. When the soil reaches its field capacity (i.e., the volume of water able to be retained in the soil against gravity drainage), deep drainage occurs and begins to dominate the water losses from soil. This process is explicitly described by Jahanfar et al. (2019). In more detail and more specifically, the impervious surface of the solar panels produces a roof effect that delineates a sheltered area (Fig. 1a).

Rainfall usually does not vertically drip onto the surface of the ground, as it is under the effect of the velocity of wind and raindrops. Instead, it arrives at the ground with the incidence angle (α) of rainfall with respect to the vertical direction. The model adopted to estimate

the intercepted rainfall by the PVs is the AVrain model (Agrivoltaic Plot Rain Redistribution Model) proposed by Elamri et al. (2018). For the sake of simplicity, the model assumes the irregular flow of water above the PVs is homogeneous downward flow, and the output rainfall concentrates on an area of 0.15 m width covering the edge of the PVs. These simplifications are valid due to the relatively smooth surfaces and moderate incline angles of PV panels. The incidence angle (α) and the interception of rainfall are given by

$$\tan(\alpha) = \frac{V_W}{V_D} \quad (5)$$

$$I_{PVs} = I[\cos(\beta) - \tan(\alpha) \sin(\beta)]K_p \quad (6)$$

where V_W (m/s) is the velocity of the wind, V_D (m/s) is the velocity of the raindrops, I_{PVs} (mm) is the amount of water intercepted by the PVs, I (mm) is the daily precipitation, and parameter K_p is a rainfall interception coefficient, which is the ratio between the area of the PVs and the area of the narrow drip zone.

2.2.5. Soil moisture dynamics

Soil moisture regimes influenced by the PVs were analyzed by using a single-bucket model (Rodriguez-Iturbe et al., 1999). This model has been widely used to evaluate the spatial-temporal dynamics of soil moisture (Li et al., 2013; Liu et al., 2020a; Srivastava et al., 2021).

$$nZ_r \frac{\partial S}{\partial t} = I - I_c - R - E(S) - L(S) \quad (7)$$

where n is the soil porosity, Z_r is average root depth, S is the vertically averaged relative soil moisture content (the ratio of volumetric water content, θ , to the porosity, n), t (d) is time, I_c (mm/d) is the canopy interception loss, R (mm) is the drainage runoff, E is the evapotranspiration loss rate, including soil evaporation and plant transpiration, and L is the leakage loss rate.

The soil moisture is controlled mainly by the available water and solar radiation. As Fig. 1a shows, a PV acts like a roof, changing the microclimate conditions beneath it. Before performing a quantitative analysis of the soil moisture dynamics, daily potential evapotranspiration (PET , mm/d) must be calculated; this is a function of daily solar radiation and temperature (Bourletsikas et al., 2017; Hargreaves, 1975; Hargreaves and Samani, 1985). A modified Hargreaves-Samani (Droogers and Allen, 2002) equation was adopted to estimate PET where only daily maximum and minimum air temperature, precipitation, and extraterrestrial radiation are required; this is given by

$$PET = 0.0018 \times 0.408 R_a (T_{avg} + 18.36)(TD - 0.0123P)^{0.74} + 1.5 \quad (8)$$

where R_a (MJ/m²) is incident radiation, T_{avg} (°C) is daily average temperature defined as the average of daily maximum temperature and minimum temperature, TD (°C) is the temperature range, estimated as the difference between mean daily maximum and mean daily minimum temperature, P (mm/d) is the daily precipitation amount, and the constant 0.408 is used to convert the radiation to evaporation equivalents in mm: 0.018, 18.36, 0.0123 and 1.5 are the empirical parameters optimized by the genetic algorithm.

The total losses from the system include actual total evapotranspiration and leakage loss. The piecewise relationships of normalized losses (Laio et al., 2001a; Rodriguez-Iturbe et al., 1999) are given by:

$$\rho(S) = \frac{E(S)}{nZ_r} + \frac{L(S)}{nZ_r} = \begin{cases} 0, & 0 \leq S < S_h \\ K_W \frac{S - S_h}{S_w - S_h}, & S_h \leq S < S_w \\ \left[K_W + K_C(K_{max} - K_W) \frac{S - S_w}{S^* - S_w} \right], & S_w \leq S < S^* \\ K_C K_{max}, & S^* \leq S < S_{fc} \\ K_C K_{max} + K_X, & S_{fc} \leq S \leq 1 \end{cases} \quad (9)$$

where S_h is the hygroscopic point, S_w is the wilting point, S_{fc} is the field capacity, and S^* is the soil moisture threshold level where a plant reduces transpiration under water stress (Srivastava et al., 2021). K_C , evapotranspiration coefficient, is the sum of two factors—the plant's natural coefficient and the soil evaporation coefficient—accounting for crop transpiration and soil evaporation, respectively. K_W , K_{max} , and K_X are normalized minimum evapotranspiration, maximum evapotranspiration, and leakage loss, respectively, as defined in the study by (Laio et al., 2001b). For more details, please refer to Appendix B.

2.3. Statistical analysis

The statistical indices—the Nash–Sutcliffe efficiency coefficient (NSE) and the root mean square error (RMSE)—were calculated for assessment of the accuracy of the synthetic model:

$$NSE = 1 - \frac{\sum_i^n (Q_o^i - Q_s^i)^2}{\sum_i^n (Q_o^i - \bar{Q}_o)^2} \quad (10)$$

$$RMSE = \left[\frac{1}{n} \sum_i^n (T_s^i - T_o^i)^2 \right]^{1/2} \quad (11)$$

where Q_o^i and Q_s^i are observed and simulated daily soil moisture content, respectively, i is the number of days in the growing season, $\bar{Q}_o$ is the average observed soil moisture content, and T_o^i and T_s^i are observed and estimated daily soil temperature, respectively.

3. Results

3.1. Model validation and evaluation metrics

Parameter calibration was carried out for the Front zone, where the magnitudes of soil moisture pulses are of the most concern to us. Meanwhile, the change of meteorological elements in the Front zone is relatively simple: only water availability changed. The simulated soil depth at the site is about 80 cm where groundwater does not have active impacts on the soil moisture. The soil porosity (n) and field capacity (S_{fc}) were estimated as 0.41 and 0.21, respectively. The corresponding values of S_w and S^* were estimated as 0.09 and 0.16, respectively. Other parameters are given in Table 1, and these soil physical parameters are within the reasonable range of the values reported in the literature for sandy loam. Different values of K_C were adopted for the early growing season (from Apr 1rd to Jun 30rd) and late growing season (from Jul 1rd to Sep 30rd), as the evapotranspiration rate is related to the leaf area. The observed and simulated processes of soil responding to the rainfall and the soil-drying process at the four different zones for the year 2016 are shown in Fig. 3a, and there was no significant difference between the observed and simulated values in the Front zone, with $NSE = 0.68$ and $RMSE$ of the observed and simulated soil moisture content of the Middle zone equal to 0.02 v/v. The simulated average soil temperature calculated by Eq. (1) (Fig. 3b) is similar to the observed value, with $RMSE = 2.45$ v/v. The average soil temperature appears to have been slightly underestimated in the summer. But since Eq. (1) successfully simulates the trend of soil temperature, the errors generated by the model are within acceptable limits.

Table 1
Model parameter definitions and values estimated for the Front zone.

Parameter	Unit	Definition	Eq.	Value	Method
β	°	Incline angle of photovoltaic panel	(2)	37.5	Measured
ϕ	°	Latitude	(3)	38.1	Measured
n	v/v	Soil porosity	(7)	0.41	Estimated
Z_r	mm	Average soil depth	(7)	800	Observation
t	d	Time step	(7)	1	–
I_c	mm	Canopy interception loss	(7)	3	Estimated
S_h	v/v	Hygroscopic point	(9)	0.06	(Liu et al., 2020a, 2020b)
S_w	v/v	Wilting point	(9)	0.09	(Laio et al., 2001b)
S^*	v/v	Soil moisture threshold level for plants' reduced transpiration under water stress	(9)	0.16	(Laio et al., 2001b)
S_{fc}	v/v	Field capacity	(9)	0.21	(Laio et al., 2001b)
K_c	–	Vegetation coefficient for early growing season	(9)	0.75	Estimated
		Vegetation coefficient for later growing season	(9)	1.32	Estimated
K_s	cm/d	Saturated hydraulic conductivity	(B.5)	80	(Laio et al., 2001b)
b	–	Empirical parameter	(B.5)	4.38	(Laio et al., 2001b)

3.2. Soil microclimate features affected by the PVs

In order to avoid uncertainties attributable to the initial start-up operation of the solar farm, the model was run for a study period of 100 years—by which time the meteorological and soil microclimate elements in the solar farm would have stabilized enough to capture climatic fluctuations—to study the difference in soil temperature between the PV-sheltered zone and natural bare soil. Annual average soil temperature in the sheltered zone is 1.47–1.66 °C lower than in the natural bare soil (Fig. 4). Meanwhile, the soil temperature does not show strong variability, for either the sheltered zone or the control; the corresponding values of the coefficient of variation are equal to 0.0032 and 0.0039, respectively. Although the reduction of surface radiation is a long-term, continuous, cumulative process, the simulated results indicate that soil temperature beneath the PVs is not gradually becoming cooler, but is rather relatively stable, with normal fluctuations. Furthermore, no obvious difference in probability of daily average soil temperature was found (Fig. 4b), although the probability was that daily average soil temperature in the sheltered zone is in the range of 25 to 32 °C—higher than in the control; this difference might be attributed to the warming effect of PVs because of their low albedo and heat capacity. In general, the control zone was warmer than the sheltered zone. This phenomenon will be discussed in Section 4.2.

3.3. Soil moisture regimes affected by the PVs

The average annual soil moisture in the rainfall interception zones, for the Front and Middle zones, were 16.3% and 15.8%, respectively, about twice as high as in the Control zone, where it was only 8%

(Fig. 5a). Soil moisture content of the rainfall interception zones was distributed in a range of 7% to 20%. However, the values in the Control zone only varied from 6% to 13% (Fig. 5b), and the number of days when soil moisture content was less than the wilting point came to about 72% of the growing season. Compared with the Control, the water stress tended to be more severe in the Back zone (Fig. 5). Since lower soil moisture content is usually accompanied by lower soil moisture variability, this result simply and intuitively reflects the influence of PVs on the soil moisture dynamics. During the 100-year time series, soil moisture variability in the rainfall interception zones was higher than in the Control or Back zones, with the corresponding values of the coefficient of variation equaling 0.24, 0.22, 0.12, and 0.09, respectively. There is an obvious soil moisture content gradient: the highest soil moisture is located at the Front and the lowest at the Back instead of the Control. In general, the areas beneath the PVs were wetter, and the PVs could raise the local soil moisture content by 59.8% to 113.6%.

4. Discussion

4.1. Model and parameter performance

At the site, soil temperature is strongly correlated with air temperature and slightly related to solar radiation. Therefore, an empirical equation (Eq. (1)) was adopted to estimate average soil temperature based on air temperature and solar radiation. The soil moisture dynamics are significantly influenced by rainfall pulses—not only the amounts of rainfall but also the duration of adjacent rainfall events. Therefore, the soil moisture response to rainfall events is more rapid in the model compared with the observed response, because the temporal characteristic

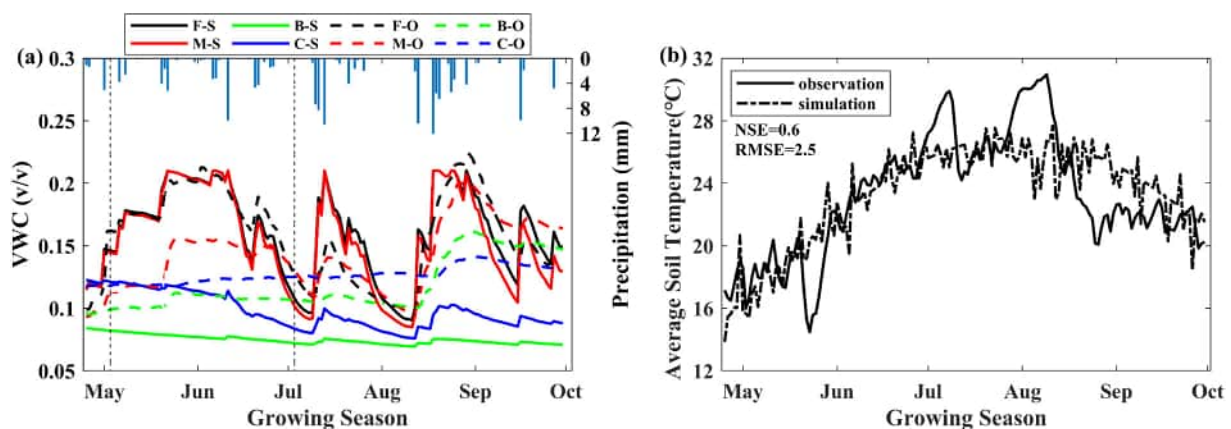


Fig. 3. Observed and simulated soil moisture dynamics (a) and observed and simulated average soil temperature (b). F, M, B, and C represent different experimental zones: Front, Middle, Back, and Control, respectively, and ‘S’ and ‘O’ mean simulated and observed results, respectively. The blue bars indicate observed daily precipitation.

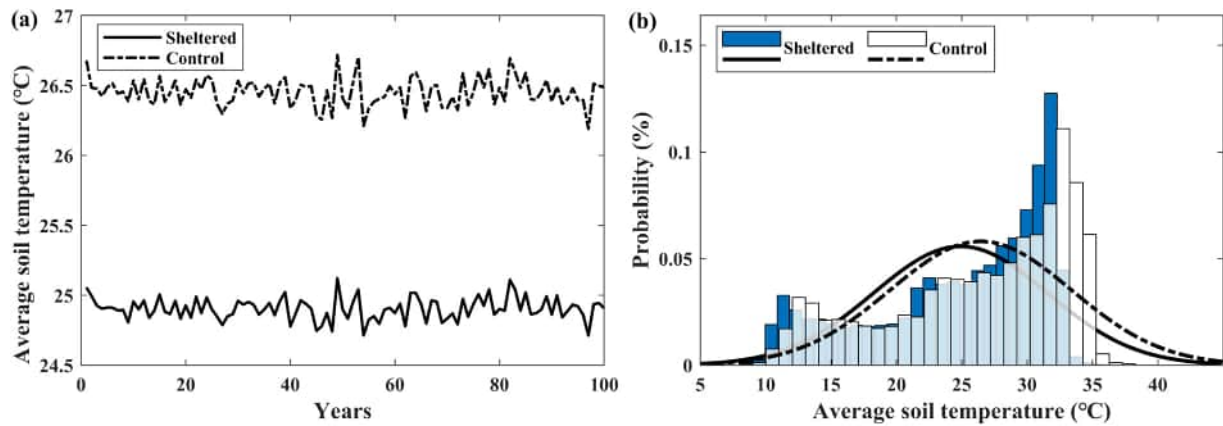


Fig. 4. Model results of average soil temperature after a 100-year simulation run for the sheltered zone and the control zone (a). Probability density curve of soil temperature shows the difference of soil temperature between the control and the sheltered zone (b).

of each rainfall event is not considered and water redistribution in soil is not considered in the model. The model captures the magnitudes of soil moisture pulses and the shapes of the soil-drying process in the Front and Middle reasonably well (Yetemen et al., 2015), although it underestimates the soil moisture in the summer as it overestimates evapotranspiration. However, the model performed less satisfactorily at the Back and the Control zones, possibly because the real meteorological conditions at these two zones are more complicated than are considered in the model, and there are obvious soil crusts in the Control which might raise the rainfall interception loss. Also, for the sake of simplification, we assumed a 'saturation from below' mechanism for run-off generation in this model, with no lateral distribution and excluding Hortonian overland flow, and the soil was also considered as isotropic and homogeneous in terms of physical characteristics (e.g., porosity, saturated hydraulic conductivity, etc.). However, in the real situation, this simplification could result in significant inaccuracies for soil moisture modeling, especially in areas where the ground is not as flat or homogeneous as assumed in the model. Furthermore, diffuse radiation can come from various directions, especially as PVs also reflect radiation. However, we only considered the portion of diffuse radiation along the direction of the sun's rays, in the model, possibly adding another influence on the simulated results. Despite those limitations, the model fits the data well and behaves as expected (Figs. 4–5).

Aside from the limitations involved in model structures, parameters adopted in the present work could also be a source of error in the simulation experiments. For example, previous studies have suggested

that apart from the effects of a PV's incline angle and the astronomical angle of the sun (Passias and Källbäck, 1984), the available solar radiation of a sheltered zone is significantly affected by the electricity transformation efficiency of the PV. Compared with an area without PVs, the average annual illumination decreased by 80–90% (Armstrong et al., 2016; Tanner et al., 2020), and Liu et al. (2019) found the available solar radiation decreased by 67.3%. Those inconsistent results may be caused by both differing regional climatic conditions and differing PV system configurations in the different study areas. The magnitude and spatio-temporal variations of available solar radiation directly or indirectly affect the energy and matter exchanges among the atmosphere, the vegetation, and the soil (Gueymard, 2004), and thus it is crucial to accurately estimate the radiation interception efficiency of the PVs. The radiation interception efficiency of the PVs was calibrated by limited field observations and was estimated as 0.27 in the model, meaning that the available solar radiation in the sheltered zones is 73% of the total solar radiation the PVs received. In order to not underestimate the radiation interception efficiency of the PVs, a control treatment was adopted, which reduced the available radiation of the soil beneath the PVs by another 20% (Fig. 6b). Therefore, available solar radiation beneath the PVs is equal to 59% ($73.8\% \times 80\%$), which is in the range of the observed results. Compared with Fig. 3a, the soil moisture in the Middle zone was overestimated, and there was little change in the Back zone. Based on the simulated results, we think a radiation interception coefficient of 0.27 is reasonable for the site. Furthermore, diffuse radiation can come from various directions, especially since PVs also reflect radiation.

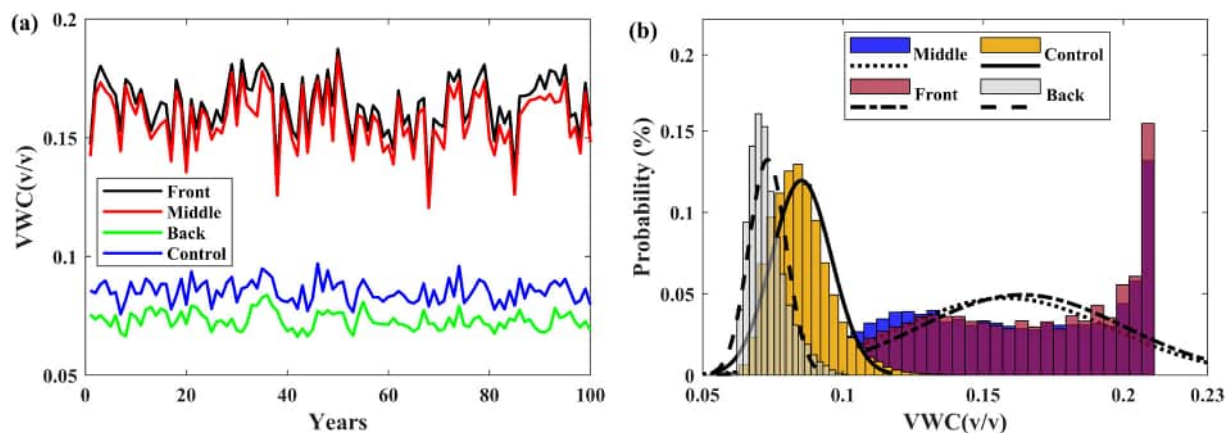


Fig. 5. Model results of soil moisture content after a 100-year simulation run for three different zones under the PVs and for the Control zone (a). Probability density curve of soil moisture shows the difference of soil moisture content in different zones (b).

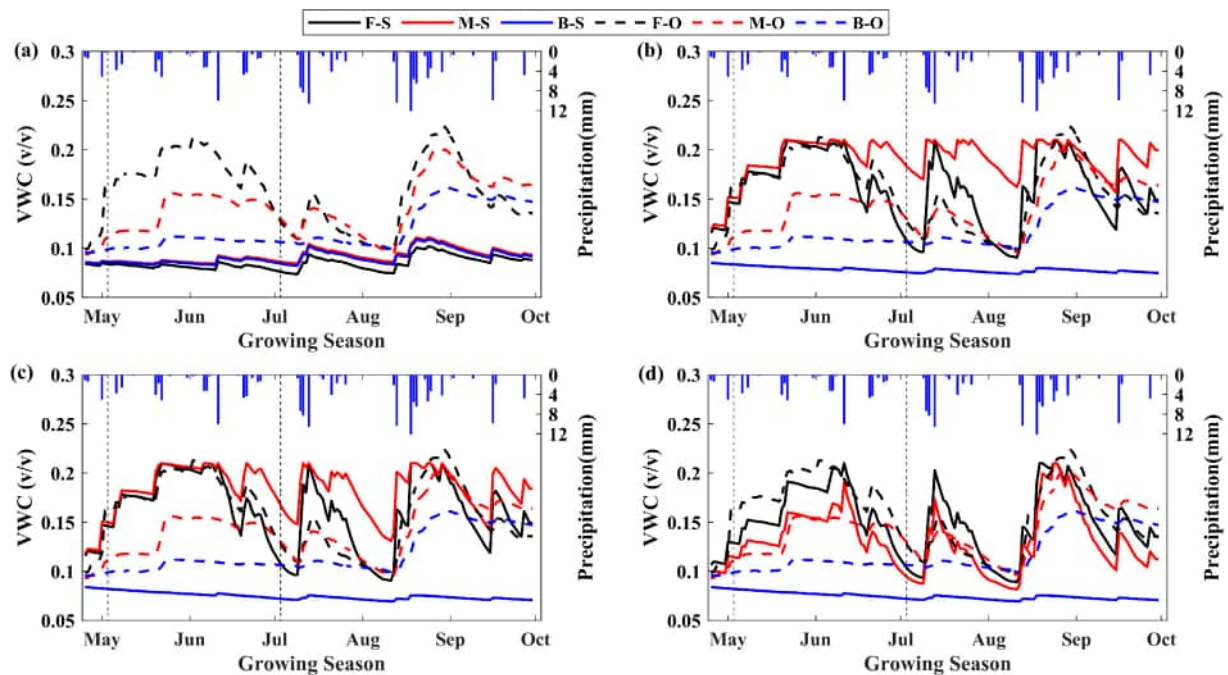


Fig. 6. Results of numerical experiments for soil moisture dynamics under the influence of photovoltaic panels: (a) without considering the “roof effect” of photovoltaic panels; (b) another 20% decrease in the amount of solar radiation the sheltered zones received; (c) without considering the effects of turbulence on soil; (d) considering the rainwater interception efficiency of the PVs. The blue bars indicate observed daily precipitation.

However, we only considered the portion of diffuse radiation along the direction of the sun's rays in the model, possibly influencing the simulated results.

4.2. How do PVs change the soil microclimate features?

Less net radiation compared with natural bare soil leads to lower soil temperature, as was proved in our simulated results (Fig. 4) and by the observed results reported in the literature (Jahanfar et al., 2016; Suuronen et al., 2017; Tanner et al., 2014). In this context, one concern is whether a large-scale solar farm, usually built in a short time, will rapidly and significantly modify soil temperature, and cause a “cool island” effect that makes the soil beneath the PVs become cooler and cooler over time. However, this concern was not confirmed by the simulated results in this work. From an energy-balance point of view, the net radiation the soil accepts can be divided into three components: latent heat flux between the soil and the atmosphere, sensible heat flux between upper and lower soil boundaries, and soil sensible heat storage which directly controls soil temperature (Heitman et al., 2008a; Heitman et al., 2008b). The latter two mainly depend on the thermodynamic properties of the soil (Seneviratne et al., 2017; Tanaka et al., 2001). Therefore, soil temperature is mainly influenced by available net radiation, evapotranspiration rate, and soil thermodynamic properties. These are also the ways in which PVs most likely affect soil temperature. In theory, whether the net radiation beneath PVs rises or falls depends on the albedo difference between the PVs and the natural land surface. In arid desert areas, the amount of net radiation tends to be reduced because PVs reflect a portion of the incoming radiation to the atmosphere and convert a small amount (~20%) of residual energy into electricity (Barron-Gafford et al., 2016).

Coupled energy and water exchange processes occurring in the land-atmosphere boundary are principally linked by evapotranspiration, which is an expenditure of both energy and soil moisture (Brubaker and Entekhabi, 1996; Heitman et al., 2008a). As a result, evapotranspiration intensity and soil temperature tend to be positively correlated. In a warm/dry anomaly, elevated temperature will stimulate increased evaporation in order to cool the surface, and vice versa

(Brubaker and Entekhabi, 1996). Therefore, PVs can change evaporation or evapotranspiration intensity to influence soil temperature. Furthermore, soil volumetric heat capacity is also one of the controlling factors of soil temperature. It is affected by all three components — air, liquid, and soil (Sakai et al., 2011). As the effect of air on soil volumetric heat capacity is usually ignored, soil volumetric heat capacity depends mainly on soil water content and solid components. Although there have been no reports that PVs obviously change soil physicochemical properties, PVs can change the spatial distribution of rainfall and increase soil moisture at their edges (Fig. 5). Higher soil water content will increase the amount of heat required for the soil temperature to rise, which benefits soil by maintaining a relatively lower temperature compared with dry soil.

4.3. How do PVs control the moisture regimes beneath them?

In an arid environment, PVs' roof effect increases water availability (Hernandez et al., 2020), which is a restrictive environmental factor for the survival of vegetation, insects, and small animals (Jacobs et al., 2000; P.Mckay et al., 2003), and affects the moisture regimes beneath the PVs (P.Mckay et al., 2003; Vale and Brito, 2015). Although observed results can provide clarity and reinforce intuitive expectations of soil moisture regimes affected by PVs, the mechanisms of how PVs influence soil moisture regimes are still not revealed through short-term observation alone. As is well known, the evapotranspiration rate depends on soil moisture content and energy availability. As mentioned in Section 4.2, there is a negative relationship between soil moisture and evapotranspiration rate (Brubaker and Entekhabi, 1996); hence, changes in evapotranspiration intensity caused by PVs also have an effect on soil moisture regimes. Because there are so many confounding factors, predictions of the effects of PVs are best conducted using ecological models (Nouvellon et al., 2000). Different restrictive treatments are input to the model (Fig. 6), with the aim of providing a comprehensive quantitative view of how PVs influence soil moisture regimes through their effects on coupled energy and water processes occurring at the land-atmosphere boundary.

We assumed that PVs do not intercept natural precipitation or change the spatial distribution of precipitation; they only shade the surface beneath them (Fig. 6a). The simulated soil moisture results from this shading effect were about 33%–44% lower than the observed results in the Middle and Front zones, showing that the roof effect does have a significant influence on soil moisture content. As discussed in Section 4.1, available radiation has a significant influence on soil moisture, so we compared the effects of different radiation interception efficiencies on soil moisture (Figs. 3 and 6b). NSE decreased from -0.8 to -3, and annual average soil moisture increased from 0.15 to 0.18 when available solar radiation decreased 20% in the sheltered zone. These results indicate that there is a negative correlation between available radiation and soil moisture, a result consistent with previous conclusions about the effects of available radiation on soil moisture.

Even when solar radiation was correctly estimated, the simulation of soil moisture dynamics in the Middle zone still did not fit well with the observations, with NSE = -2 (Fig. 6c), because evapotranspiration in the Middle zone was underestimated. The surface temperature of a PV is usually ~20 °C higher than the nearby air temperature (Fthenakis and Yu, 2013)—a temperature so hot that the PV will re-radiate the energy as longwave radiation, and the air beneath the PV will be heated by the PV itself. Consequent wind velocity reduction has been reported in the literature (Yuan et al., 2016). Such hot and low-velocity turbulence might have a strong influence on evapotranspiration. In other words, the higher air temperature and lower wind velocity under PVs (as in the Middle zone here) can cause evaporation intensity to be significantly stronger than in other zones. In order to reflect the effect of air turbulence on soil moisture regime, the daily maximum temperature was increased by 50% in the simulation (Fig. 3a). Although the Middle zone has the same water availability as the Front, and less radiation, soil moisture in the Middle was even lower than in the Front because turbulence increases evapotranspiration intensity (Fig. 3a). The result indicates that turbulence has a significant effect on soil moisture. Yet there is another uncertain factor that might have an even stronger influence on soil moisture regime: the PVs' rainfall harvesting efficiency. In the model, we assumed that water flow on the PVs' surfaces is homogeneous without redistribution, but this assumption is not true. Water might flow out of the longitudinal slit, or through the cross gap between the two sub-panels when the intensity of the rain is above a certain threshold. In order to test that conjecture, the rainfall harvesting efficiencies in the Front and Middle zones were set to 0.8 and 0.65, respectively (Fig. 6d), enabling the model to capture the magnitudes of soil moisture pulses and the shapes of the soil-drying process better than is indicated in Fig. 3a, with NSE equal to 0.67 and 0.13, respectively. In a word, PVs affect the soil moisture regime mainly through changing available radiation and water. Furthermore, turbulence and rainfall in homogeneous flow might also have a significant influence on the soil moisture regimes.

4.4. Broad application and implications

Precipitation promotes germination and supplies food and water for vegetation and animals, especially in arid environments, and a change in water availability might have even more dramatic impacts on biodiversity compared with other ecosystems (Vale and Brito, 2015). Large-scale solar farms might provide another way to mitigate water restriction in arid environments, as one 50 MWp solar farm can collect about 23,000 m³ water per year due to the PVs' roof effect in extremely arid zones where the average annual precipitation is less than 100 mm. Intermingling solar panels with agriculture is known as an agrivoltaic system (Brown, 2018), and these systems have been widely studied in large-scale solar farms (Adeh et al., 2019; Cossu et al., 2014; Marrou et al., 2013). Application of agrivoltaic systems in an arid environment tends to improve land utilization, rainfall use efficiency, and crop yields (Amaducci et al., 2018; Ravi et al., 2016), because the intermittent shade provided by PVs is better for crops where microclimates are more

moderate (as discussed above), and the stronger evapotranspiration is balanced by the additional precipitation intercepted by the PVs (Adeh et al., 2019). Maize (Amaducci et al., 2018), aloe vera (Ravi et al., 2016), Goji berries (Wu et al., 2014), and other crops (Adeh et al., 2019) have been studied in agrivoltaic systems. Besides the agrivoltaic systems, other solar photovoltaic types—including aquavoltaics (the combination of PVs with aquaculture), floatovoltaics (floating solar PVs on open water), and building-attached or -integrated PVs—have been widely deployed, not only sparing land needed for the installation of solar farms, but also reducing evaporation losses substantially, providing vital water savings for drought-stricken areas (Cagle et al., 2020). These PV systems, when operating in conjunction with other traditional electricity sources (e.g., floatovoltaics with hydropower), can further improve energy efficiency and reduce external evaporation (Kuriqi et al., 2021; Kuriqi et al., 2020).

In contrast to the booming development of PV power systems (Exley et al., 2021), few researches have been conducted on their ecohydrological effects on their surrounding environments. The effects of large-scale solar farms on the ecological environment have been studied mostly at the local scale, but whether large-scale solar farms will change atmospheric circulation and whether they will mitigate or intensify global warming as a result of their modification of land surface properties (e.g., surface albedo, roughness) is still not known (Hu et al., 2016; Millstein and Menon, 2011; Nemet, 2009; Yang et al., 2018). The carbon sequestration potential of a large-scale solar farm is also important to research, as solar farms are clearly beneficial for vegetation restoration, as this study has found. As for a holistic view of solar farms; although they are not free of non-renewable resource use because their manufacturing process consumes considerable non-renewable energy and materials, they are still much cleaner and have lower carbon emissions compared with coal-based or other fossil-fuel energy sources. For example, Ye et al. (2021) pointed out that over 90% of carbon emissions can be avoided with solar energy, compared with fossil-based energy. However, these researches have usually concentrated on the benefits of solar farms that have been substituted for fossil-based energy, and fail to consider the additional carbon emission reductions caused by the changes solar farms make to the ecosystem. Furthermore, the ecohydrological effects of large-scale solar farms may be different, or even contrary, when comparing daily, seasonal or interannual scales, or site, regional, or continental scales. Therefore, studies should also be conducted, on how scale can impact the ecohydrological effects of large-scale solar farms.

5. Conclusions

Soil microclimates and moisture regimes affected by PVs were analyzed using a synthetic model. Our study provides a solid basis for understanding the ecohydrological effects of large-scale solar farms on an arid ecosystem, and can also provide evidence to support previously observed results and maximize the ecosystem services of large-scale solar farms in arid areas. The results indicate that PVs can improve soil moisture content in the middle and front zones, by about 59.8% to 113.6%, and that an obvious soil moisture gradient exists in solar farms where the highest soil moisture is located at the front zone and the lowest at the back. Average soil temperature beneath PVs is about 1.47–1.66 °C lower than on the ground outside the PVs, but there was no evidence that the soil becomes continuously cooler and wetter; in fact, it may be that PVs have the opposite effect on soil temperature and moisture at night, reversing the daytime effect (Armstrong et al., 2016). Turbulence associated with the ground clearance of PVs also has an influence on soil temperature and soil moisture content. In the future, agrivoltaic systems should be studied, and the sites and installation methods for solar farms should be carefully selected to avoid some of the adverse effects. Furthermore, more work is needed, to evaluate the carbon sequestration capabilities of solar farms, taking into account how they can change ecosystems, and to better understand how scale

impacts the ecohydrological effects of large solar farms. In general, however, the simulation results of this study indicate that large-scale solar farms benefit arid environments, as they can mitigate heat and water stress in arid areas and facilitate vegetation restoration.

CRediT authorship contribution statement

Chuandong Wu: Investigation, Data Curation, Writing- Original draft preparation. **Hu Liu:** Conceptualization, Writing, Supervision. **Yang Yu, Wenzhi Zhao, Jintao Liu, Hailong Yu and Omer Yetemen:** Writing – Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Method of calculating solar radiation

Here, one simple algorithm was adopted to calculate the incidence angle (i) (the angle of incidence of the radiation beam on the tilted PVs) and the elevation angle (h_c). Both are key parameters for calculating the solar radiation intercepted by PVs and the solar radiation on the horizontal ground surface.

The solar declination δ and angle ω are given by

$$\delta = 23.45 \sin\left(360 \frac{284 + n}{365}\right) \quad (\text{A.1})$$

$$\omega = (\tau - 12) \times 15^\circ \quad (\text{A.2})$$

where n is the day of the year, and the solar time τ is given by

$$\tau = T + \frac{E - 4 \times (12 - \varphi)}{60} \quad (\text{A.3})$$

where T (h) is Beijing time, φ is the local longitude, and E (min), meaning the corrected time difference due to the change in the speed of the earth's motion around the sun, is given by

$$E = 9.87 \sin(2B) - 7.53 \cos(B) - 1.5 \sin(B) \quad (\text{A.4})$$

$$B = \frac{360(n - 81)}{365} \quad (\text{A.5})$$

The solar beam radiation (MJ/m^2) and diffuse radiation (MJ/m^2) of the horizontal ground surface are respectively given by Eqs. (A.7) and (A.9), and the total solar radiation available on the ground is the sum of the beam radiation and the diffuse radiation.

$$I_n = 1353 \times \left[1 + 0.034 \cos\left(\frac{2\pi n}{365}\right)\right] \times \frac{\sin(h_c)}{\sin(h_c) + C} \quad (\text{A.6})$$

$$I_{nG} = I_n \sin(h_c) \quad (\text{A.7})$$

$$\sin(h_c) = \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \cos(\omega) \quad (\text{A.8})$$

$$I_{sG} = I_{nG} \frac{1 - p^m}{2(1 - 1.4 \ln p)} \quad (\text{A.9})$$

where I_n is the solar beam radiation of the surface perpendicular to the solar sunshine, m is a function of elevation angle, and p is a constant index of atmospheric transparency ($p = 0.8$). Analogously, the solar beam radiation (MJ/m^2) and diffuse radiation (MJ/m^2) of PVs are respectively given by

$$I_{n\beta} = I_n \cos(i) \quad (\text{A.10})$$

$$I_{s\beta} = I_{sG} \frac{1 + \cos(\beta)}{2} \quad (\text{A.11})$$

Because the daily solar radiation from 1980 to 2017 was not observed at the Yongchang site, only daily sunshine duration (SSD) could be found. Another alternative algorithm was adopted: that the daily solar radiation is equal to SSD multiplied by daily average solar radiation, which is the average of all the per-hour solar radiation values. The model assumes that every growing season has the same average solar radiation on a daily scale, which is produced on the basis of 12 h of SSD, so that daily solar radiation can be calculated from SSD records. The total available solar radiation on the horizontal ground surface and PVs can be calculated by

$$I_G = \frac{\sum_j^{12} (I_{nG,j} + I_{sG,j})}{12} \quad (\text{A.12})$$

$$I_{PV} = \frac{\sum_j^{12} (I_{n\beta,j} + I_{s\beta,j})}{12} \quad (\text{A.13})$$

Appendix B. Method of calculating K_w , $K_{\max}$ and K_x

$$K_w = \frac{ET_{\min}}{nZ_r} \quad (\text{B.1})$$

$$K_{\max} = \frac{ET_{\max}}{nZ_r} \quad (\text{B.2})$$

$$K_x = \frac{K_s S^{2b+3}}{nZ_r} \quad (\text{B.3})$$

where $ET_{\max}$ (mm) and $ET_{\min}$ (mm) are the maximum and minimum rate of evapotranspiration from a composite soil-vegetation surface, respectively. K_s (cm/d) is the saturated hydraulic conductivity.

$$ET_{\max} = K_{et} PET \quad (\text{B.4})$$

$$ET_{\min} = K_2 ET_{\max} \quad (\text{B.5})$$

where K_{et} and K_2 are the empirical coefficients. Different values are adopted for the early growing season (from Apr 1st to Jun 30th) and late growing season (from Jul 1st to Sep 30th)—0.09, 0.81, 0.88, and 0.13, respectively, as the evapotranspiration rate is related to the leaf area.

References

- Adeh, E.H., Good, T.P., Calaf, M., Higgins, C.W., 2019. Solar PV power potential is greatest over croplands. *Sci. Rep.* 9 (1), 11442. <https://doi.org/10.1038/s41598-019-47803-3>.
- Amaducci, S., Yin, X., Colauzzi, M., 2018. Agrivoltaic systems to optimise land use for electric energy production. *Appl. Energy* 220, 545–561. <https://doi.org/10.1016/j.apenergy.2018.03.081>.

- Araki, K., Nagai, H., Lee, K.-H., Yamaguchi, M., 2017. Analysis of impact to optical environment of the land by flat-plate and array of tracking PV panels. *Sol. Energy* 144, 278–285. <https://doi.org/10.1016/j.solener.2017.01.021>.
- Armstrong, A., Waldron, S., Whitaker, J., Ostle, N.J., 2014. Wind farm and solar park effects on plant-soil carbon cycling: uncertain impacts of changes in ground-level microclimate. *Glob. Chang. Biol.* 20 (6), 1699–1706. <https://doi.org/10.1111/gcb.12437>.
- Armstrong, A., Ostle, N.J., Whitaker, J., 2016. Solar park microclimate and vegetation management effects on grassland carbon cycling. *Environ. Res. Lett.* 11 (7), 074016. <https://doi.org/10.1088/1748-9326/11/7/074016>.
- Barron-Gafford, G.A., Minor, R.L., Allen, N.A., Cronin, A.D., Brooks, A.E., Pavao-Zuckerman, M.A., 2016. The photovoltaic Heat Island effect: larger solar power plants increase local temperatures. *Sci. Rep.* 6, 35070. <https://doi.org/10.1038/srep35070>.
- Bourletsikas, A., Argyrokastritis, I., Proutsos, N., 2017. Comparative evaluation of 24 reference evapotranspiration equations applied on an evergreen-broadleaved forest. *Hydrol. Res.* 49 (4), 1028–1041. <https://doi.org/10.2166/nh.2017.232>.
- Bousselot, J., Slabe, T., Klett, J., Koski, R., 2017. Photovoltaic array influences the growth of green roof plants. *J. Living Archit.* 4 (3), 9–18. <https://doi.org/10.6084/m9.figshare.11977782>.
- Brown, A., 2018. Photovoltaic win-win. *Nat. Clim. Chang.* 9 (1), 7. <https://doi.org/10.1038/s41558-018-0381-9>.
- Brubaker, K.L., Entekhabi, D., 1996. Analysis of feedback mechanisms in land-atmosphere interaction. *Water Resour. Res.* 32 (5), 1343–1357. <https://doi.org/10.1029/96WR00005>.
- Cagle, A.E., Armstrong, A., Exley, G., Grodsky, S.M., Macknick, J., Sherwin, J., Hernandez, R.R., 2020. The land sparing, water surface use efficiency, and water surface transformation of floating photovoltaic solar energy installations. *Sustainability* 12 (19), 8154. <https://doi.org/10.3390/su12198154>.
- Chang, R., Shen, Y., Luo, Y., Wang, B., Yang, Z., Guo, P., 2018. Observed surface radiation and temperature impacts from the large-scale deployment of photovoltaics in the barren area of gonghe, China. *Renew. Energy* 118, 131–137. <https://doi.org/10.1016/j.renene.2017.11.007>.
- Chen, J., Brissette, F.P., Leconte, R., 2010. A daily stochastic weather generator for preserving low-frequency of climate variability. *J. Hydrol.* 388 (3–4), 480–490. <https://doi.org/10.1016/j.jhydrol.2010.05.032>.
- Chen, J., Brissette, F., Leconte, R., 2011. Assessment and improvement of stochastic weather generators in simulating maximum and minimum temperatures. *Trans. ASABE* 54, 1627–1637. <https://doi.org/10.13031/2013.39851>.
- Chen, J., Brissette, F.P., Leconte, R., Caron, A., 2012. A versatile weather generator for daily precipitation and temperature. *Trans. ASABE* 55 (3), 895–906. <https://doi.org/10.13031/2013.41522>.
- Chow, T.T., Long, H., Mok, H.Y., Li, K.W., 2011. Estimation of soil temperature profile in Hong Kong from climatic variables. *Energy Buildings* 43 (12), 3568–3575. <https://doi.org/10.1016/j.enbuild.2011.09.026>.
- Cossu, M., Murgia, L., Ledda, L., Deligios, P.A., Sirigu, A., Chessa, F., Pazzona, A., 2014. Solar radiation distribution inside a greenhouse with south-oriented photovoltaic roofs and effects on crop productivity. *Appl. Energy* 133, 89–100. <https://doi.org/10.1016/j.apenergy.2014.07.070>.
- Droogers, P., Allen, R.G., 2002. Estimating reference evapotranspiration under inaccurate data conditions. *Irrig. Drain. Syst.* 16 (1), 33–45. <https://doi.org/10.1023/A:1015508322413>.
- Elamri, Y., Cheviron, B., Mange, A., Dejean, C., Liron, F., Belaud, G., 2018. Rain concentration and sheltering effect of solar panels on cultivated plots. *Hydrol. Earth Syst. Sci.* 22 (2), 1285–1298. <https://doi.org/10.5194/hess-22-1285-2018>.
- Exley, G., Armstrong, A., Page, T., Jones, I.D., 2021. Floating photovoltaics could mitigate climate change impacts on water body temperature and stratification. *Sol. Energy* 219, 24–33. <https://doi.org/10.1016/j.solener.2021.01.076>.
- Fthenakis, V., Yu, Y., 2013. Analysis of the potential for a heat island effect in large solar farms. *Proceedings of the 2013 IEEE 39th Photovoltaic Specialists Conference (PVSC)*, pp. 3362–3366.
- Gao, X., Yang, L., Lyu, F., Ma, L., Li, H., Hui, X., Hou, X., 2016. Observational study on the impact of the large solar farm on air temperature and humidity in desert areas of Golmud. *Acta Energiae Solaris Sin.* 37 (11), 2909–2914.
- Gueymard, C.A., 2004. The sun's total and spectral irradiance for solar energy applications and solar radiation models. *Sol. Energy* 76 (4), 423–453. <https://doi.org/10.1016/j.solener.2003.08.039>.
- Hargreaves, G.H., 1975. Moisture availability and crop production. *Trans. ASAE* 18 (5), 0980–0984. <https://doi.org/10.13031/2013.36722>.
- Hargreaves, G.H., Samani, Z.A., 1985. Reference crop evapotranspiration from temperature. *Appl. Eng. Agric.* 1 (2), 96–99. <https://doi.org/10.13031/2013.26773>.
- Hassanpour Adeg, E., Selker, J.S., Higgins, C.W., 2018. Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency. *PLoS One* 13 (11), e0203256. <https://doi.org/10.1371/journal.pone.0203256>.
- Heitman, J.L., Horton, R., Sauer, T.J., DeSutter, T.M., 2008a. Sensible heat observations reveal soil-water evaporation dynamics. *J. Hydrometeorol.* 9 (1), 165–171. <https://doi.org/10.1175/2007jhm963.1>.
- Heitman, J.L., Xiao, X., Horton, R., Sauer, T.J., 2008b. Sensible heat measurements indicating depth and magnitude of subsurface water evaporation. *Water Resour. Res.* 44 (4), W00D05. <https://doi.org/10.1029/2008wr006961>.
- Hernandez, R.R., Tanner, K.E., Haji, S., Parker, I.M., Pavlik, B.M., Moore-O'Leary, K.A., 2020. Simulated photovoltaic solar panels Alter the seed Bank survival of two desert annual plant species. *Plants-Basel* 9 (9), 1125. <https://doi.org/10.3390/plants9091125>.
- Hosenuzzaman, M., Rahim, N.A., Selvaraj, J., Hasanuzzaman, M., Malek, A.B.M.A., Nahar, A., 2015. Global prospects, progress, policies, and environmental impact of solar photovoltaic power generation. *Renew. Sustain. Energy Rev.* 41, 284–297. <https://doi.org/10.1016/j.rser.2014.08.046>.
- Hu, A., Levis, S., Hu, A., Levis, S., Meehl, Gerald A., Han, W., Washington, Warren M., Oleson, Keith W., van Ruijven, Bas J., He, M., Strand, Warren G., 2016. Impact of solar panels on global climate. *Nat. Clim. Chang.* 6 (3), 290–294. <https://doi.org/10.1038/nclimate2843>.
- IRENA, 2021. *International Renewable Energy Agency*.
- Jacobs, A.F.G., Heusinkveld, B.G., Berkowicz, S.M., 2000. Force-restore technique for ground surface temperature and moisture content in a dry desert system. *Water Resour. Res.* 36 (5), 1261–1268. <https://doi.org/10.1029/2000wr900016>.
- Jahanfar, A., Drake, J., Sleep, B., Margolis, L., 2016. Shading effects of photovoltaic panels on the evapotranspiration process in extensive green roofs. *Novatech* 1–6.
- Jahanfar, A., Drake, J., Sleep, B., Margolis, L., 2019. Evaluating the shading effect of photovoltaic panels on green roof discharge reduction and plant growth. *J. Hydrol.* 568, 919–928. <https://doi.org/10.1016/j.jhydrol.2018.11.019>.
- Kuriki, A., Pinheiro, A.N., Sordo-Ward, A., Garrote, L., 2020. Water-energy-ecosystem nexus: balancing competing interests at a run-of-river hydropower plant coupling a hydrologic-ecohydraulic approach. *Energy Convers. Manag.* 223, 113267. <https://doi.org/10.1016/j.enconman.2020.113267>.
- Kuriki, A., Pinheiro, A.N., Sordo-Ward, A., Bejarano, M.D., Garrote, L., 2021. Ecological impacts of run-of-river hydropower plants—Current status and future prospects on the brink of energy transition. *Renew. Sust. Energy Rev.* 142, 110833. <https://doi.org/10.1016/j.rser.2021.110833>.
- Laio, F., Porporato, A., Fernandez-Illescas, C.P., Rodriguez-Iturbe, I., 2001a. Plants in water-controlled ecosystems: active role in hydrologic processes and response to water stress: IV. Discussion of real cases. *Adv. Water Resour.* 24 (7), 745–762. [https://doi.org/10.1016/S0309-1708\(01\)00007-0](https://doi.org/10.1016/S0309-1708(01)00007-0).
- Laio, F., Porporato, A., Ridolfi, L., Rodriguez-Iturbe, I., 2001b. Plants in water-controlled ecosystems: active role in hydrologic processes and response to water stress: II. Probabilistic soil moisture dynamics. *Adv. Water Resour.* 24 (7), 707–723. [https://doi.org/10.1016/S0309-1708\(01\)00005-7](https://doi.org/10.1016/S0309-1708(01)00005-7).
- Li, G., Alona, A., Liu, Z., 2020. Effect of solar photovoltaic power field on land surface temperature. *Acta Energiae Solaris Sin.* 41 (12), 117–123.
- Li, X.-Y., Zhang, S.-Y., Peng, H.-Y., Hu, X., Ma, Y.-J., 2013. Soil water and temperature dynamics in shrub-encroached grasslands and climatic implications: results from Inner Mongolia steppe ecosystem of North China. *Agric. For. Meteorol.* 171–172, 20–30. <https://doi.org/10.1016/j.agrformet.2012.11.001>.
- Liu, H., Wu, C.D., Yu, Y., Zhao, W.Z., Yang, Q.Y., Wang, S.J., Liu, J.T., 2020. Modeling the physiological responses of a desert shrub to rainfall pulses in an arid environment in northwestern China. *J. Arid Environ.* 183, 104277. <https://doi.org/10.1016/j.jaridenv.2020.104277>.
- Liu, Y., Zhang, R., Huang, Z., Cheng, Z., Lopezvicente, M., Ma, X., Wu, G., 2019. Solar photovoltaic panels significantly promote vegetation recovery by modifying the soil surface microhabitats in an arid sandy ecosystem. *Land Degrad. Dev.* 30 (18), 2177–2186. <https://doi.org/10.1002/ldr.3408>.
- Liu, Y., Zhang, R., Ma, X., Wu, G., 2020. Combined ecological and economic benefits of the solar photovoltaic industry in arid sandy ecosystems. *J. Clean. Prod.* 262, 121376. <https://doi.org/10.1016/j.jclepro.2020.121376>.
- Marrou, H., Dufour, L., Wery, J., 2013. How does a shelter of solar panels influence water flows in a soil-crop system? *Eur. J. Agron.* 50, 38–51. <https://doi.org/10.1016/j.eja.2013.05.004>.
- Mckay, C.P., Friedmann, E.I., Gomez-Silva, B., Caceres-Villanueva, L., Andersen, D.T., Landheim, R., 2003. Temperature and moisture conditions for life in the extreme arid region of the Atacama desert: four years of observations including the El Nino of 1997–1998. *Astrobiology* 3 (2), 393–406. <https://doi.org/10.1089/153110703769016460>.
- Millstein, D., Menon, S., 2011. Regional climate consequences of large-scale cool roof and photovoltaic array deployment. *Environ. Res. Lett.* 6 (3), 034001. <https://doi.org/10.1088/1748-9326/6/3/034001>.
- Montag, H., Parker, G., Clarkson, T., 2016. *The Effects of Solar Farms on Local Biodiversity: A Comparative Study*. Clarkson and Woods and Wychwood Biodiversity.
- Nash, C., Clough, J., Gedge, D., Lindsay, R., Newport, D., Ciupala, M.A., Connop, S., 2016. Initial insights on the biodiversity potential of biosolar roofs: a London Olympic Park green roof case study. *Isr. J. Ecol. Evol.* 62 (1–2), 74–87. <https://doi.org/10.1080/15659801.2015.1045791>.
- Nemet, G.F., 2009. Net radiative forcing from widespread deployment of photovoltaics. *Environ. Sci. Technol.* 43 (6), 2173–2178. <https://doi.org/10.1021/es801747c>.
- Nouvellon, Y., Rambal, S., Seen, D.L., Moran, M.S., Lhomme, J.P., Begue, A., Chehbouni, A.G., Kerr, Y., 2000. Modelling of daily fluxes of water and carbon from shortgrass steppes. *Agric. For. Meteorol.* 100, 137–153. [https://doi.org/10.1016/S0168-1923\(99\)00140-9](https://doi.org/10.1016/S0168-1923(99)00140-9).
- Onyshchenko, V.F., Karachevtseva, L.A., Karas, M.I., 2020. Photoconductivity relaxation time in macroporous silicon. *Emerg. Sci. J.* 4 (3), 192–204. <https://doi.org/10.28991/esj-2020-01223>.
- Passias, D., Källbäck, B., 1984. Shading effects in rows of solar cell panels. *Solar Cells* 11 (3), 281–291. [https://doi.org/10.1016/0379-6787\(84\)90017-6](https://doi.org/10.1016/0379-6787(84)90017-6).
- Qerimi, D., Dimitrieska, C., Vasilevska, S., Rrecaj, A.A., 2020. Modeling of the solar thermal energy use in urban areas. *Civil Eng. J.* 6 (7), 1349–1367. <https://doi.org/10.28991/cej-2020-03091553>.
- Ravi, S., Macknick, J., Lobell, D., Field, C., Ganesan, K., Jain, R., Elchinger, M., Stoltenberg, B., 2016. Colocation opportunities for large solar infrastructures and agriculture in drylands. *Appl. Energy* 165, 383–392. <https://doi.org/10.1016/j.apenergy.2015.12.078>.
- Richardson, C.W., 1981. Stochastic simulation of daily precipitation, temperature, and solar radiation. *Water Resour. Res.* 17 (1), 182–190. <https://doi.org/10.1029/WR017i001p00182>.
- Rodriguez-Iturbe, I., Porporato, A., Ridolfi, L., Isham, V., Cox, D.R., 1999. Probabilistic modelling of water balance at a point: the role of climate, soil and vegetation. *Proc. R. Soc. London, Ser. A* 455 (1990), 3789–3805. <https://doi.org/10.1098/rspa.1999.0477>.

- Sakai, M., Jones, S.B., Tuller, M., 2011. Numerical evaluation of subsurface soil water evaporation derived from sensible heat balance. *Water Resour. Res.* 47 (2), W02547. <https://doi.org/10.1029/2010wr009866>.
- Scherba, A., Sailor, D.J., Rosenstiel, T.N., Wamser, C.C., 2011. Modeling impacts of roof reflectivity, integrated photovoltaic panels and green roof systems on sensible heat flux into the urban environment. *Build. Environ.* 46 (12), 2542–2551. <https://doi.org/10.1016/j.buildenv.2011.06.012>.
- Seneviratne, S.I., Hirschi, M., Schwingshackl, C., 2017. Quantifying spatiotemporal variations of soil moisture control on surface energy balance and near-surface air temperature. *J. Clim.* 30 (18), 7105–7124. <https://doi.org/10.1175/jcli-d-16-0727.1>.
- Singh, S.K., Lohani, B., Arora, L., Choudhary, D., Nagarajan, B., 2020. A visual-inertial system to determine accurate solar insolation and optimal PV panel orientation at a point and over an area. *Renew. Energy* 154, 223–238. <https://doi.org/10.1016/j.renene.2020.02.107>.
- Srivastava, A., Saco, P.M., Rodriguez, J.F., Kumari, N., Chun, K.P., Yetemen, O., 2021. The role of landscape morphology on soil moisture variability in semi-arid ecosystems. *Hydrol. Process.* 35, e13990. <https://doi.org/10.1002/hyp.13990>.
- Suuronen, A., Muñoz-Escobar, C., Lensu, A., Kuitunen, M., Guajardo Celis, N., Espinoza Astudillo, P., Ferrú, M., Taucare-Ríos, A., Miranda, M., Kukkonen, J.V.K., 2017. The influence of solar power plants on microclimatic conditions and the biotic community in Chilean desert environments. *Environ. Manag.* 60 (4), 630–642. <https://doi.org/10.1007/s00267-017-0906-4>.
- Tanaka, K., Ishikawa, H., Hayashi, T., Tamagawa, I., Ma, Y., 2001. Surface energy budget at amdo on the tibetan plateau using GAME/Tibet IOP98 data. *J. Meteorol. Soc. Jpn.* 79 (1B), 505–517. <https://doi.org/10.1002/cbic.201500519>.
- Tanner, K., Moore, K., Pavlik, B., 2014. Changes to shade and water regimes imposed by solar development affect desert plant performance and community attributes. *Esa Convention* 42 (2), 15–16.
- Tanner, K.E., Moore-O'Leary, K.A., Parker, I.M., Pavlik, B.M., Hernandez, R.R., 2020. Simulated solar panels create altered microhabitats in desert landforms. *Ecosphere* 11 (4), e03089. <https://doi.org/10.1002/ecs2.3089>.
- Thorne, J.H., Boynton, R.M., Flint, L.E., Flint, A.L., 2015. The magnitude and spatial patterns of historical and future hydrologic change in California's watersheds. *Ecosphere* 6 (2), 24. <https://doi.org/10.1890/ES14-00300.1>.
- Tong, C., Zhang, W., Tang, Y., Wang, H., 2005. Estimation of daily solar radiation in China. *Chin. J. Agrometeorol.* 26 (03), 165–169.
- Vale, C.G., Brito, J.C., 2015. Desert-adapted species are vulnerable to climate change: insights from the warmest region on earth. *Glob. Ecol. Conserv.* 4, 369–379. <https://doi.org/10.1016/j.gecco.2015.07.012>.
- Wu, Z., Hou, A., Chang, C., Huang, X., Shi, D., Wang, Z., 2014. Environmental impacts of large-scale CSP plants in northwestern China. *Environ Sci Process Impacts* 16 (10), 2432–2441. <https://doi.org/10.1039/C4EM00235K>.
- Yang, L., Eugenia, K., Safa, M., Jorge, R., Fred, K., Daniel, K.D., Eviatar, B., Ning, Z., 2018. Climate model shows large-scale wind and solar farms in the Sahara increase rain and vegetation. *Science* 361, 1019–1022. <https://doi.org/10.1126/science.aar5629>.
- Ye, B., Jiang, J., Liu, J., 2021. Feasibility of coupling PV system with long-distance water transfer: a case study of China's "South-to-north water diversion". *Resour. Conserv. Recycl.* 164, 105194. <https://doi.org/10.1016/j.resconrec.2020.105194>.
- Yetemen, O., Istanbuloglu, E., Flores-Cervantes, J.H., Vivoni, E.R., Bras, R.L., 2015. Ecohydrologic role of solar radiation on landscape evolution. *Water Resour. Res.* 51 (2), 1127–1157. <https://doi.org/10.1002/2014wr016169>.
- Yuan, F., Zhang, Z., Bu, C., Yang, Y., Yuan, S., 2016. Wind speed flow field and wind erosion control measurement at photovoltaic power plant project area in mu us sandy land. *J. Desert Res.* 36 (2), 287–294.
- Yue, S., Guo, M., Zou, P., Wu, W., Zhou, X., 2021. Effects of photovoltaic panels on soil temperature and moisture in desert areas. *Environ. Sci. Pollut. Res.* 28 (12), 1–13. <https://doi.org/10.1007/s11356-020-11742-8>.
- Zhe, L., Hua, Y., Xingyu, C., Guoqun, L., Biaoqun, S., 2019. Impact analysis of solar park on land surface temperature. *Geospatial Inf.* 17 (10), 20–23. <https://doi.org/10.3969/j.issn.1672-4623.2019.10.006>.



Effects of Revegetation on Soil Physical and Chemical Properties in Solar Photovoltaic Infrastructure

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Solar photovoltaic (PV) technology is being deployed at an unprecedented rate. However, utility-scale solar energy development is land intensive and its large-scale installation can have negative impacts on the environment. In particular, solar energy infrastructure can require extensive landscape modification that transforms soil ecological functions, thereby impacting hydrologic, vegetative, and carbon dynamics. However, reintroducing native vegetation to solar PV sites may be a means of restoring their soils. To this end, we investigated critical soil physical and chemical parameters at a revegetated photovoltaic array and an adjacent reference grassland in Colorado, United States. Seven years after revegetation, we found that carbon and nitrogen remained lower in the PV soil than in the reference soil and contained a greater fraction of coarse particles. We also found that the PV modules introduced heterogeneity in the soil moisture distribution, with precipitation accumulating along the lower edges of panels. The redistribution of soil moisture by panel arrays could potentially be used in concert with planting strategies to maximize plant growth or minimize soil erosion, and should be considered when evaluating the potential to co-locate vegetation with solar infrastructure.

Keywords: land use change, infiltration, soil moisture, renewable energy, agrivoltaics, co-location

INTRODUCTION

Solar photovoltaic (PV) technologies have been among the fastest growing energy technologies in recent years due to technological advancements and favorable government policies (U. S. Department of Energy, 2012; Breyer et al., 2017). Further, solar power has the greatest technical potential among renewable energy technologies (Jacobson, 2009; Edenhofer et al., 2011; De Marco et al., 2014; Ellabban et al., 2014) and is expected to fulfill 20–29% (32,700–133,000 GW) of global electrical demand by 2100 (Breyer et al., 2017). Although solar generation of electricity has many advantages, including low emission rates, an ability to reclaim degraded land, and an ability to improve quality of life in off-grid rural areas, deploying large-scale solar PV infrastructure can have negative impacts on ecological functions including carbon sequestration (Ravi et al., 2014; Hernandez et al., 2019). Moreover, solar PV is space-intensive, with the large-scale, non-integrated deployment of solar PV estimated to require more land area than coal,

nuclear, or natural gas technologies (Fthenakis and Kim, 2009). Under an optimistic scenario for global solar energy deployment by 2050 (8500 GW_p) (IRENA-International Renewable Energy Agency, 2018) and assuming utility-scale PV installations require 3 ha per MW_p of capacity-weighted average direct land use (Ong et al., 2013), around 25 million hectares of land will be transformed in the next 30 years if all arrays are ground-mounted. Further, requirements for access roads, transmission lines, etc. can raise the total land area transformed by solar PV installations substantially (Ravi et al., 2014).

Conventional, utility-scale solar energy infrastructure modifies landscapes extensively through the site preparation process: native vegetation is removed, the ground surface is graded, and fill is added and compacted (Hernandez et al., 2014). Such modifications transform soil physical, chemical, and biological properties, thereby impacting moisture and nutrient dynamics, and thus soil's ability to support vegetation and perform a host of associated ecological processes. Strategies to mitigate the cumulative impacts of solar PV installation and operation on landscape function have therefore been the focus of recent research (Turney and Fthenakis, 2011; Phillips, 2013; Hernandez et al., 2014, 2015; Armstrong et al., 2016; Walston et al., 2016). One promising strategy is to integrate other, vegetated land cover types (e.g., crop cultivation or native grassland) into PV facilities, as these may increase their ability to support ecosystem services like pollination and carbon sequestration (Dupraz et al., 2011; Macknick et al., 2013; Hernandez et al., 2014; Ravi, 2015; Hoffacker et al., 2017; Walston et al., 2018). The concept of co-locating solar PV and agriculture (i.e., "agrivoltaics") was first suggested by Goetzberger and Zastrow (1982). Since then, a number of modeling (Dupraz et al., 2011; Ravi et al., 2014, 2016) and field studies (Marrou et al., 2013b,c; Beatty et al., 2017; Barron-Gafford et al., 2019) have investigated the technological, economic, and environmental feasibility of co-location approaches.

Assessing the impacts of PV deployment on land surface characteristics can inform guidelines for site preservation and help determine the optimum environmental and financial outcomes co-location strategies could bring about. Ultimately, such information could be used to determine if proposed co-located PV installations are likely to be successful. Prior studies of the environmental impacts of solar infrastructure have been focused on modeling runoff and monitoring microclimatic impacts (Cook, 2011; Marrou et al., 2013a; Barron-Gafford et al., 2016). For example, one review found that site preparation for PV arrays typically remove vegetation and degrade soil, resulting in significant increases in onsite runoff and soil erosion (Cook, 2011). Further, changes in structure of the terrain, vegetation cover, and albedo can raise air temperatures over PV arrays relative to surrounding natural areas (Barron-Gafford et al., 2016). However, other studies have identified effects of PV infrastructure that are likely to be favorable for co-located vegetation; these include increases in soil moisture content, biomass, and plant water use efficiency (Marrou et al., 2013a; Hassanpour Adeg et al., 2018; Barron-Gafford et al., 2019). In addition, lower PV panel temperatures have been observed in arrays with underlying agricultural crops vs. those without

(attributed to greater evapotranspiration rates), highlighting the potential of co-location to increase electrical generation in arid regions (Barron-Gafford et al., 2019).

Despite the above-mentioned advances, it is unclear if reintroducing native vegetation at existing solar PV sites can successfully mitigate changes to soil hydrology and ecology. In cases where natural land is leased for solar projects, leases typically span 20–30 years; during this time soil hydrological and ecological processes may be negatively impacted or made spatially heterogeneous. In addition to diminishing the landscape's ability to support ecosystem services during the solar facility's lifespan, these changes may leave legacy effects that persist long after the installation is removed. Although many studies have quantified the environmental footprints of photovoltaic facilities (Fthenakis and Kim, 2010, 2011; Sherwani et al., 2010; Turney and Fthenakis, 2011; Fthenakis et al., 2012; Perez and Fthenakis, 2012; Leccisi et al., 2016), there have been few field-based investigations of the impacts of PV arrays and co-location strategies on soil properties (e.g., hydrology, geomorphology, and chemistry) (Armstrong et al., 2014; Hassanpour Adeg et al., 2018). Given this, we investigated whether revegetation of a PV facility is able to engender soil physical and chemical properties similar to those at an undisturbed reference site and, further, if the PV modules introduce spatial variation in soil properties. We did this at a PV installation that had been experimentally revegetated with native grasses. Soil properties at the PV site were compared (a) to those in an adjacent, undisturbed grassland characteristic of the region's native land cover and (b) spanning the range of location types under and between PV modules.

MATERIALS AND METHODS

Site Description

This study took place at a 1.1 MW solar PV facility in the National Renewable Energy Laboratory's National Wind Technology Center. This facility is located on the eastern slope of the Front Range in northern Jefferson County, Colorado, USA and has a mean annual precipitation of 374 mm (Beatty et al., 2017). When the site was constructed in 2009, the topsoil was largely removed and the site was graded, leveled to < 1% slope, and compacted (Beatty et al., 2017). Surficial soils at the site are paleosols derived from unsorted alluvial/colluvial deposits; soil-forming processes have extensively oxidized native iron and leached clay minerals (Beatty et al., 2017). The area encompassing the site was historically a xeric tallgrass prairie dominated by big bluestem grass (*Andropogon gerardii*). Grazing and other activities have altered the region's vegetation while leaving the paleosols and clay-enriched subsoils intact (Beatty et al., 2017). Following the construction of the solar PV array, a portion of the disturbed area was revegetated with a variety of native grasses (e.g., *Bouteloua gracilis* and *Poa compressa*) to determine, in part, if soil alteration could be mitigated (Beatty et al., 2017). Revegetation occurred in 2010, 7 years prior to the activities described below.

Study Design

A campaign to collect soil samples and take field measurements was carried out in the revegetated portion of the solar PV facility and in a nearby grassland in July 2017. This portion of the PV facility had four rows of PV modules, each 49 m in length (**Supplementary Figures S1A,B**). PV panels were mounted on single-axis solar-tracking systems 1 m above ground-level (Beatty et al., 2017). Soil measurements and samples were taken along three transects in the revegetated portion of the solar PV site (hereafter, solar transects/soils) and along a fourth transect in an adjacent, undisturbed grassland (hereafter, reference transect/soil) that is representative of the area's vegetation (**Supplementary Figure S1A**). Solar transects ran perpendicular to the rows of PV modules, spanning four rows and the adjacent interspaces. The reference transect was 50 m east of the nearest point in the PV array, across an unpaved road (**Supplementary Figure S1A**). Soil measurements and sampling took place at four locations on solar transects: below the east edge of each panel (EE), beneath the center of each panel (BP), below the west edge of each panel (WE), and in the uncovered interspace adjacent to each panel (IS) (**Supplementary Figure S1C**). Transects thus consisted of 16 sampling locations, spaced ~2.5 m apart, and were ~10 m in length. Sampling/measurement locations on the reference transect were likewise spaced 2.5 m apart, with the transect extending 10 m. In total there were 48 solar PV sampling locations and 16 reference locations.

Field Measurements

Volumetric soil moisture (VSM) content and infiltration rates were measured at each sampling location. VSM was measured using a 15-cm long soil water content reflectometer (HydroSense II, Campbell Scientific, Logan, United States). In addition to the primary set of VSM measurements, a second set of measurements was made the next day, after an overnight rainfall event. This event delivered 6.6 mm of rainfall and the wind direction ranged from southwesterly to northwesterly. Precipitation and wind data were collected from a meteorological station located ~200 m northwest of the PV array. The solar array was facing west at the end of the field campaign and during the precipitation event that evening.

Infiltration rates were measured along two of the three solar transects, as well as the reference transect, with two measurements made per sampling location. This modification to

the sampling design was deemed appropriate given the spatial variability of infiltration in combination with the limited period of access to the site. A mini disk infiltrometer (METER, Pullman, United States) was used for measurements; it had an adjustable suction (1 cm was used) and a small footprint (5-cm diameter disk). The mini disk infiltrometer exerts a negative tension on the soil surface, thereby excluding macropores and only measuring flow in the soil matrix; the resulting data better represent properties of the soil itself. Infiltration data were used to calculate unsaturated hydraulic conductivity (K_{unsat}) for each sample following Zhang (Zhang, 1997).

Laboratory Measurements

Surficial soil samples (0–5 cm) were taken at all sampling locations along the four transects. After air-drying, soil samples were sieved to 2 mm, passed through a riffle sampler, and sub-sampled. One sub-sample per sample was used to characterize the particle size distribution (PSD) while another was used for chemical analysis. PSDs were measured with a laser diffraction particle size analyzer (LS 13-320 with a tornado dry powder module; Beckman Coulter, Brea, United States); the dynamic grain size ranged from 0.4 to 2000 μm . Total soil carbon (C) and nitrogen (N) were determined by Brookside Labs (New Bremen, United States) using the combustion method (McGeehan and Naylor, 1988; Nelson and Sommers, 1996).

Statistical Analysis

Data were analyzed using mixed- or fixed-effects linear models (**Table 1**). Separate models were generated for each response variable, which included VSM before and after the precipitation event, K_{unsat} , total carbon, total nitrogen, mean particle diameter, and the coarse particle fraction ($> 2 \text{ mm}$). In all models, the location category (EE, BP, WE, IS, and Reference) was the only fixed explanatory variable. When likelihood ratio tests indicated that it was warranted (**Table 1**), random effects were included to account for the spatial clustering of samples along transects and/or beneath panels. *F*-tests, based on Type II sums of squares, were used to determine if response means differed across location categories. When they differed, pairwise comparisons were made using estimated marginal means with Tukey adjustments applied to *P*-values. All analyses were carried out in R 3.6.1 (R Core Team, Vienna, Austria) with $P < 0.05$ considered statistically significant.

TABLE 1 | Statistical models and results for evaluations of whether soil properties differed by location type.

Response	Fixed effect			Random effects		R^2 Fixed	R^2 Full
	Location type	<i>F</i>	<i>P</i>	Transect	Panel		
Moisture before	•	13.1	< 0.001	•	•	0.48	0.82
Moisture after	•	108.1	< 0.001	•	•	0.84	0.93
K_{unsat}	•	5.1	0.001			0.18	0.18
Mean particle diameter	•	23.9	< 0.001			0.61	0.61
Coarse fraction	•	13.8	< 0.001			0.54	0.54
Carbon	•	28.5	< 0.001			0.64	0.64
Nitrogen	•	10.3	< 0.001		•	0.74	0.83

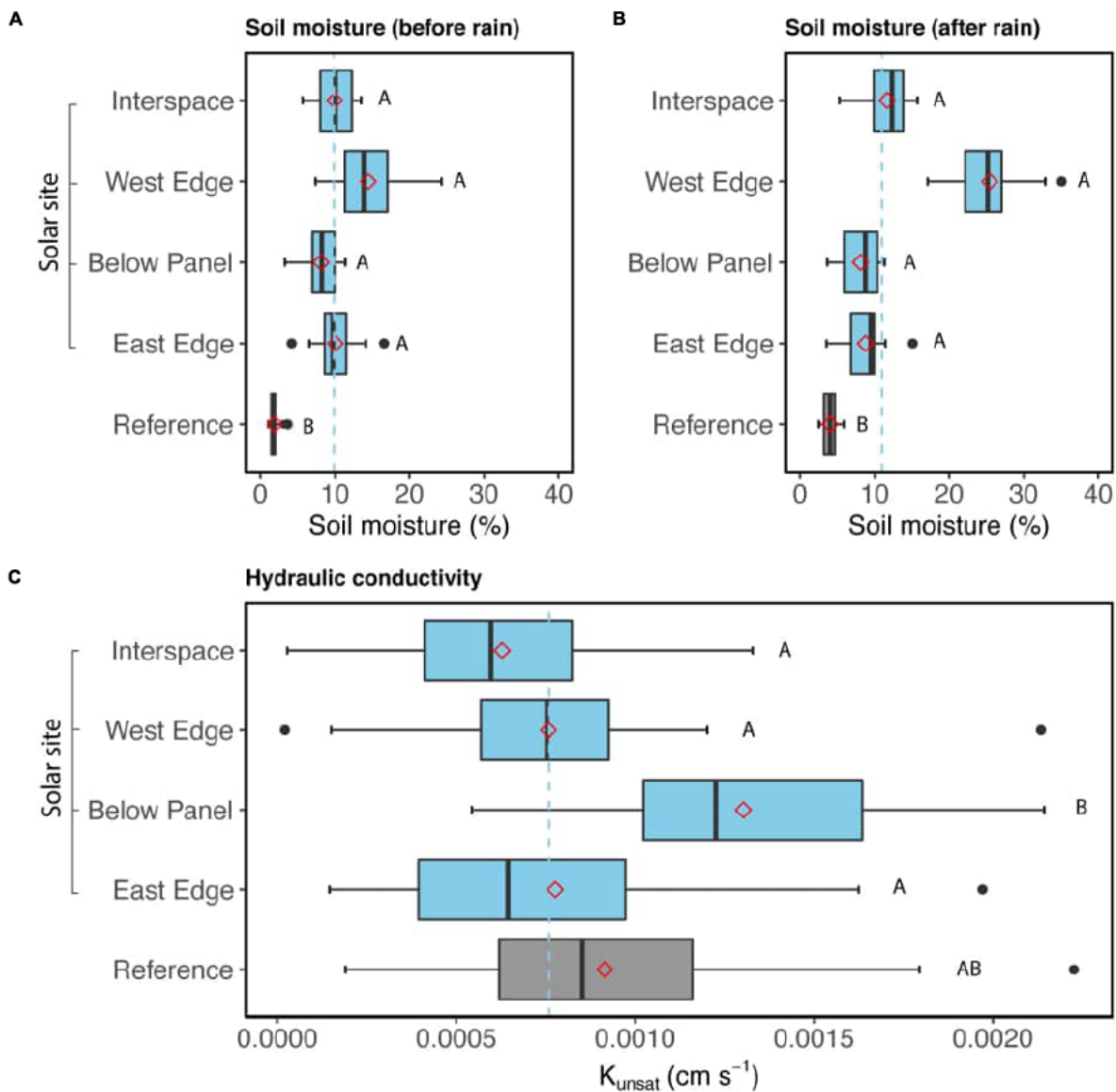


FIGURE 1 | Soil moisture (A) before and (B) after a precipitation event in the reference grassland and in locations beneath solar modules. (C) Unsaturated hydraulic conductivity (K_{unsat}) in the reference soil and in locations beneath solar modules. Box plots show medians (solid lines) and interquartile ranges (box enclosures), with whiskers extending to the most extreme observation $\leq 1.5 \times$ the interquartile range beyond the box. Also shown are means (red diamonds) and individual observations beyond whiskers (black circles). Location categories share letters if pairwise comparisons did not identify significant differences between means.

RESULTS

Soil Moisture

The reference soil had the lowest sample mean during both measurement periods, though population means were not statistically differentiable between the reference and nearly any PV location; the exception was west edges after the rain event. Soil moisture was elevated in west edge locations in PV soils, both before (Figure 1A) and after (Figure 1B) the rain event (Table 1). Moreover, mean moisture levels increased from 14.5 to 25.4% at these locations following the rain event, whereas they increased from 9.4 to 9.5%, on average, in other soils at the PV site.

Hydraulic Conductivity

Mean K_{unsat} was highly variable, ranging from 0.2×10^{-4} to $21.4 \times 10^{-4} \text{ cm s}^{-1}$ in the PV array and 1.9×10^{-4} – $22.3 \times 10^{-4} \text{ cm s}^{-1}$ in the reference. Given the substantial overlap, K_{unsat} was not significantly different in reference vs. PV soils but was greater beneath panels than at edge locations or in interspaces (Figure 1C and Table 1).

Particle Size

Soil at the PV site had a greater coarse-particle ($> 2 \text{ mm}$) mass fraction than did the reference soil (Figure 2A); the fraction was similar across the four PV location categories. Correspondingly,

mean particle diameter was greater in soils (< 2 mm) from the PV site than those at the reference site (Figure 2B). Moreover, the reference soil had a more heterogeneous grain size distribution than did soil from the solar site, with the degree of sorting roughly proportional to the mean particle diameter [ϕ size-scale = $-\log_2$ (diameter in mm)] (Figure 2C). No difference in particle size characteristics were observed among locations in the PV site.

Carbon and Nitrogen

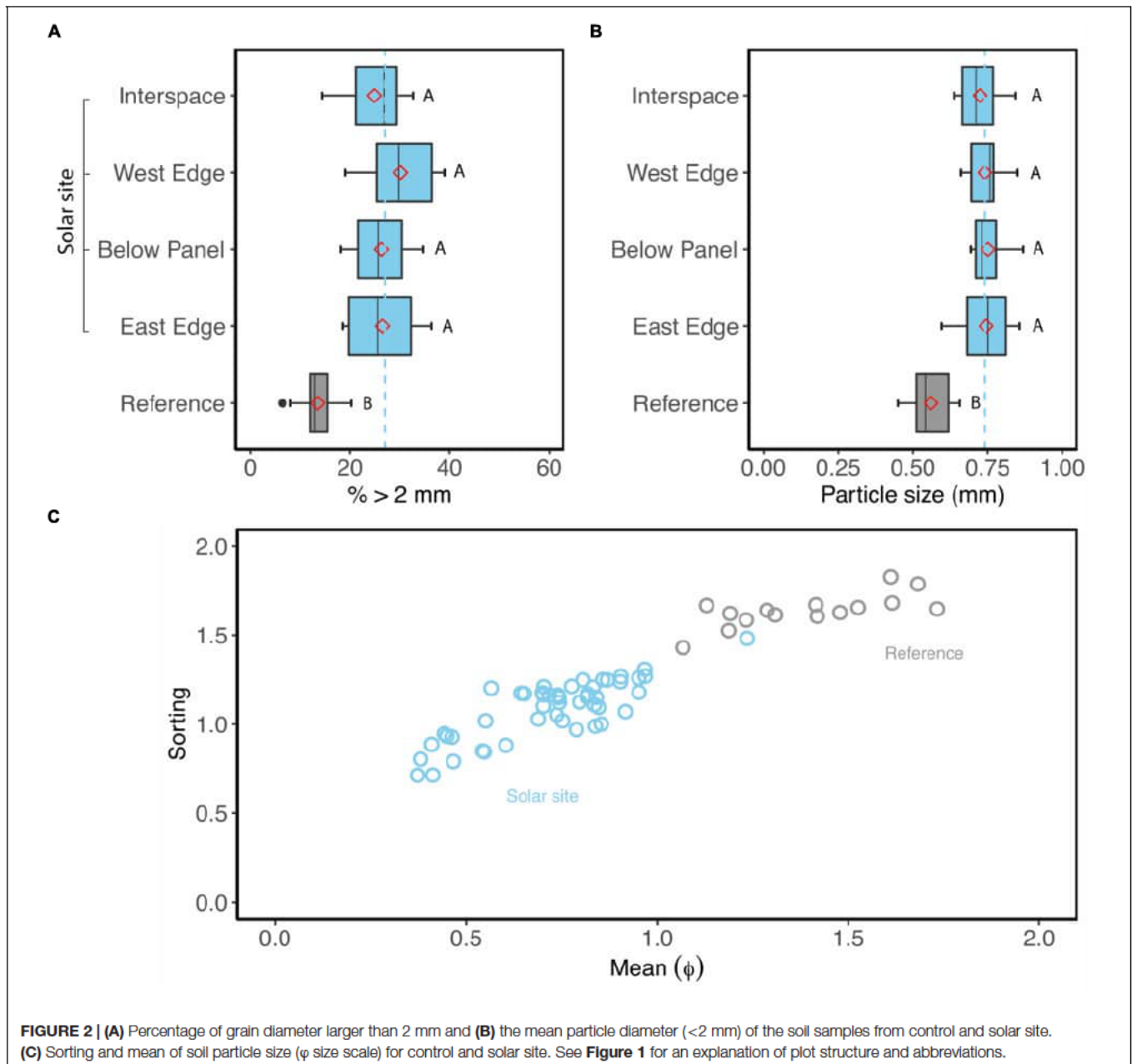
Soils at the solar PV site contained significantly less carbon (38%) and nitrogen (50%) than did the reference soil (Figure 3 and Table 1). However, there was no evidence of

differences in mean carbon or nitrogen content among location categories at the PV site.

DISCUSSION

Soil Moisture

Although statistically equivocal, our results suggested that soil moisture may have been greater at the solar PV site compared to the reference soil. If real, this could have been due to shading and wind sheltering by the PV array, as these have been found to decrease actual evapotranspiration by 10–40% (Marrou et al., 2013a). Our results also demonstrate that



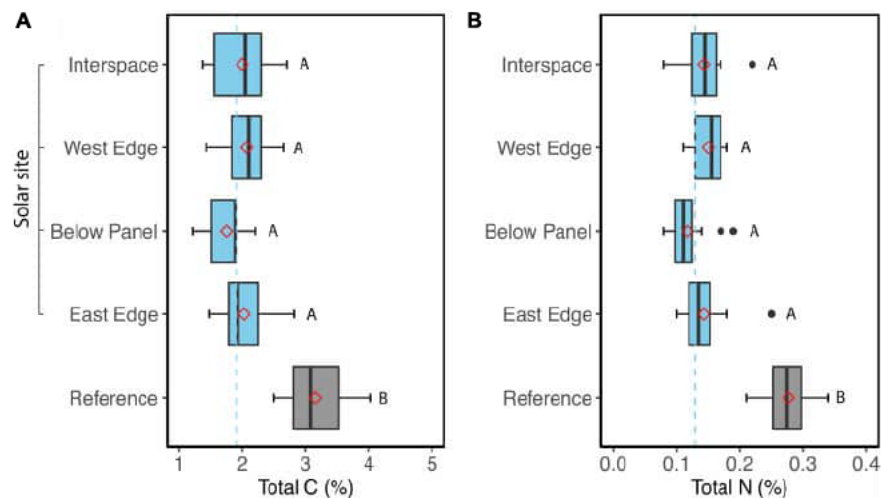


FIGURE 3 | (A) Total carbon and **(B)** total nitrogen for the reference soil and in locations beneath solar modules. Also shown are means (red diamonds) and individual observations beyond whiskers (black circles). See **Figure 1** for an explanation of plot structure and abbreviations.

PV arrays can introduce considerable heterogeneity in the spatial distribution of soil moisture. Specifically, the presence of PV modules can concentrate moisture along their low-lying edges, which were to the west in this study. While this spatial pattern was greatest following a rain event, it was also evident before the event, which was 3 days after the prior (5.6 mm). There may be important implications of soil moisture heterogeneity for plant growth in PV arrays co-located with crop or forage plants; these would be especially magnified in arid regions, where small variations in water availability could have large effects on plant growth (Noy-Meir, 1973; D'Odorico et al., 2007).

Hydraulic Conductivity and Particle Size

Even though soil grain size distribution is one of the determinants of infiltration rates (Mazaheri and Mahmoodabadi, 2012), the difference in grain size distribution did not result in measurable differences in K_{unsat} between the solar PV site and reference soils (Figure 1C). However, when comparing K_{unsat} among the location types within the solar site, K_{unsat} was elevated immediately below panels, even though the particle size distribution in these locations were similar to those at other locations (Arya et al., 1999). This discrepancy between expected and observed hydraulic conductivity below panels may be attributable to reduced exposure to site maintenance activities that cause compaction, as compaction decreases hydraulic conductivity (Vomocil and Flocker, 1961). Differences in compaction may likewise explain the lack of difference in K_{unsat} despite the difference between particle size distributions between PV and reference soils (Figures 2A,B).

It is likely that the disparity in particle size between reference and PV soils arose during the PV facility's construction phase. As documented by other studies (Mohammad and Adam, 2010; Hernandez et al., 2014), disturbance to topsoil, the addition of

fill, and the removal of native vegetation during construction can accelerate the erosion of fine particles, both by wind and water action. In the long-term absence of vegetation – a major soil erosion control – accelerated erosion results in loss of soil carbon, nutrients, and water holding capacity, leading to an overall decrease in the ability of soil to sustain vegetation (Lal, 2003; Li et al., 2008). Dust particles resulting from wind erosion can be transported long distances (Field et al., 2010; Ravi et al., 2011) or even deposited locally on solar PV panel surfaces, resulting in significant losses in solar power generation and additional operational costs for cleaning panels (Mani and Pillai, 2010; Mejia and Kleissl, 2013).

Carbon and Nitrogen

The significantly lower total carbon and nitrogen levels in the solar PV soil vs. in the reference soil (Figure 3) was likely caused by the removal of topsoil during the array's construction. This is consistent with prior studies showing reduced soil organic matter and plant production in experiments simulating topsoil erosion by artificially removing it (Larney et al., 2000, 2016; Hölzel and Otte, 2003). Reduced C and N levels suggest that nutrient cycling had not fully reestablished 7 years after PV construction and, further, that the PV soil's ability to sequester carbon was diminished relative to the native soil. In order to minimize the loss of these key soil functions, appropriate site preservation practices should be adopted to minimize topsoil disturbance during construction. Total N and C content for the reference site were similar to those reported by prior studies in the region (e.g., Golubiewski, 2006).

Implications

The revegetation of our study site was intended, in part, to render the soil at a solar PV facility similar to those of the

region's grasslands. A number of the investigated soil characteristics differed between reference and PV array, indicating that this was not fully achieved in 7 years. Further, the presence of photovoltaic arrays induced spatial heterogeneity in soil moisture and K_{unsat} , specifically coupling soil moisture to the position and orientation of the PV modules. Despite these persistent changes to soil properties, other studies indicate that co-location can restore certain ecological functions. For example, a previous study at our site indicated that the revegetation was sufficient to suppress erosion and provide wildlife habitat (Beatty et al., 2017).

The environmental heterogeneity introduced by PV modules may have some advantages, even if soil properties differ from those of native grasslands. For instance, it may be possible for co-located PV panels to be strategically oriented in a manner that would direct intercepted rain to or away from the adjacent soil, depending on the irrigation requirements of the plants. This control over rainfall distribution could benefit vegetation types with specific watering requirements, like many agricultural crops. Further, the rapidly-draining soils beneath PV modules could be suitable for cultivating drought-resistant crops (Ravi et al., 2016). Co-locating vegetation would also suppress dust emissions, reducing rates of dust deposition on panels (Ravi et al., 2016; Elamri et al., 2018a,b). Conversely, crops that require protection from excessive rainfall at the seedling stage could be placed under the PV panels during the seedling stage and replanted on the side of the lower edge of the PV array in their adult stage to receive more water (Choi, 2019). Thus, understanding the timing and direction of rainfall is crucial to placing and orienting PV panels in order to bring about a controlled and favorable soil moisture distribution.

The effects of panel orientation on precipitation redistribution by solar panels indicate that solar arrays could be used to manipulate soil moisture distribution, an important factor when evaluating the potential to co-locate crops with solar infrastructure. Further, the environmental consequences of PV installation like those identified here should be quantified and modeled to inform site preservation, to evaluate long-term impacts of onsite management strategies, and to optimize soil

moisture, nutrient, and sunlight availability when co-locating natural vegetation or crops with photovoltaic arrays.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

AUTHOR CONTRIBUTIONS

CC, AC, JM, and SR conceived and planned the study. CC, AC, and JM carried out the field data collection. CC, SR, JC, and DB conducted the laboratory and data analyses. CC, SR, JC, and JM interpreted the results. CC, SR, and JC wrote the manuscript. All authors provided critical feedback and helped shape the research, analysis, and manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenvs.2020.00140/full#supplementary-material>

REFERENCES

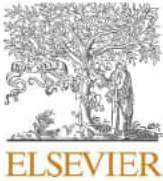
- Armstrong, A., Ostle, N. J., and Whitaker, J. (2016). Solar park microclimate and vegetation management effects on grassland carbon cycling. *Environ. Res. Lett.* 11:074016. doi: 10.1088/1748-9326/11/7/074016
- Armstrong, A., Waldron, S., Whitaker, J., and Ostle, N. J. (2014). Wind farm and solar park effects on plant-soil carbon cycling: uncertain impacts of changes in ground-level microclimate. *Glob. Chang. Biol.* 20, 1699–1706. doi: 10.1111/gcb.12437
- Arya, L. M., Leij, F. J., Shouse, P. J., and van Genuchten, M. T. (1999). Relationship between the hydraulic conductivity function and the particle-size distribution. *Soil Sci. Soc. Am. J.* 63, 1063–1070. doi: 10.2136/sssaj1999.6351063x
- Barron-Gafford, G. A., Minor, R. L., Allen, N. A., Cronin, A. D., Brooks, A. E., and Pavao-Zuckerman, M. A. (2016). The photovoltaic heat island effect: larger solar power plants increase local temperatures. *Sci. Rep.* 6:35070. doi: 10.1038/srep35070
- Barron-Gafford, G. A., Pavao-Zuckerman, M. A., Minor, R. L., Sutter, L. F., Barnett-Moreno, I., Blackett, D. T., et al. (2019). Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. *Nat. Sustain.* 2, 848–855. doi: 10.1038/s41893-019-0364-5
- Beatty, B., Macknick, J., McCall, J., Braus, G., and Buckner, D. (2017). *Native Vegetation Performance Under a Solar PV Array at the National Wind Technology Center*. Washington, DC: U.S. Department of Energy, doi: 10.2172/1357887
- Breyer, C., Bogdanov, D., Gulagi, A., Aghahosseini, A., Barbosa, L. S. N. S., Koskinen, O., et al. (2017). On the role of solar photovoltaics in global energy transition scenarios. *Prog. Photovoltaics Res. Appl.* 25, 727–745. doi: 10.1002/pip.2885
- Choi, C. S. (2019). *Combined Land use of Solar Infrastructure and Agriculture for Socioeconomic and Environmental Co-Benefits*. Masters Thesis, Temple University, Philadelphia, PA.
- Cook, P. (2011). Infrastructure, rural electrification and development. *Energy Sustain. Dev.* 15, 304–313. doi: 10.1016/j.esd.2011.07.008
- De Marco, A., Petrosillo, I., Semeraro, T., Pasimeni, M. R., Aretano, R., and Zurlini, G. (2014). The contribution of Utility-scale solar energy to the global climate regulation and its effects on local ecosystem

- services. *Glob. Ecol. Conserv.* 2, 324–337. doi: 10.1016/j.gecco.2014.10.010
- Dupraz, C., Marrou, H., Talbot, G., Dufour, L., Nogier, A., and Ferard, Y. (2011). Combining solar photovoltaic panels and food crops for optimising land use: towards new agrivoltaic schemes. *Renew. Energy* 36, 2725–2732. doi: 10.1016/j.renene.2011.03.005
- D'Odorico, P., Caylor, K., Okin, G. S., and Scanlon, T. M. (2007). On soil moisture-vegetation feedbacks and their possible effects on the dynamics of dryland ecosystems. *J. Geophys. Res. Biogeosci.* 112:G4. doi: 10.1029/2006JG000379
- Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Eickemeier, P., Matschoss, P., et al. (2011). “IPCC, 2011: summary for policymakers,” in *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*, (Cambridge: Cambridge University Press), doi: 10.5860/CHOICE.49-6309
- Elamri, Y., Cheviron, B., Lopez, J. M., Dejean, C., and Belaud, G. (2018a). Water budget and crop modelling for agrivoltaic systems: application to irrigated lettuces. *Agric. Water Manag.* 208, 440–453. doi: 10.1016/j.agwat.2018.07.001
- Elamri, Y., Cheviron, B., Mange, A., Dejean, C., Liron, F., and Belaud, G. (2018b). Rain concentration and sheltering effect of solar panels on cultivated plots. *Hydrol. Earth Syst. Sci.* 22, 1285–1298. doi: 10.5194/hess-22-1285-2018
- Ellabban, O., Abu-Rub, H., and Blaabjerg, F. (2014). Renewable energy resources: current status, future prospects and their enabling technology. *Renew. Sustain. Energy Rev.* 39, 748–764. doi: 10.1016/j.rser.2014.07.113
- Field, J. P., Belnap, J., Breshears, D. D., Neff, J. C., Okin, G. S., Whicker, J. J., et al. (2010). The ecology of dust. *Front. Ecol. Environ.* 8:423–430. doi: 10.1890/090050
- Fthenakis, V., and Kim, H. C. (2009). Land use and electricity generation: a life-cycle analysis. *Renew. Sustain. Energy Rev.* 13, 1465–1474. doi: 10.1016/j.rser.2008.09.017
- Fthenakis, V., and Kim, H. C. (2010). Life-cycle uses of water in U.S. electricity generation. *Renew. Sustain. Energy Rev.* 14, 2039–2048. doi: 10.1016/j.rser.2010.03.008
- Fthenakis, V. M., Betita, R., Shields, M., Vinje, R., Blunden, J., Shields, M., et al. (2012). “Life cycle analysis of high-performance monocrystalline silicon photovoltaic systems: energy payback times and net energy production value,” in *27th European Photovoltaic Solar Energy Conference*, Frankfurt, 4667–4672.
- Fthenakis, V. M., and Kim, H. C. (2011). Photovoltaics: life-cycle analyses. *Sol. Energy* 85, 1609–1628. doi: 10.1016/j.solener.2009.10.002
- Goetzberger, A., and Zastrow, A. (1982). On the coexistence of solar-energy conversion and plant cultivation. *Int. J. Sol. Energy* 1, 55–69. doi: 10.1080/01425918208909875
- Golubiewski, N. E. (2006). Urbanization increases grassland carbon pools: effects of landscaping in Colorado's front range. *Ecol. Appl.* 16, 555–571. doi: 10.1890/1051-0761
- Hassanpour Adeg, E., Selker, J. S., and Higgins, C. W. (2018). Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency. *PLoS One* 13:e0203256. doi: 10.1371/journal.pone.0203256
- Hernandez, R. R., Armstrong, A., Burney, J., Ryan, G., Moore-O'Leary, K., Diédhiou, I., et al. (2019). Techno-ecological synergies of solar energy for global sustainability. *Nat. Sustain.* 2, 560–568. doi: 10.1038/s41893-019-0309-z
- Hernandez, R. R., Easter, S. B., Murphy-Mariscal, M. L., Maestre, F. T., Tavassoli, M., Allen, E. B., et al. (2014). Environmental impacts of utility-scale solar energy. *Renew. Sustain. Energy Rev.* 29, 766–779. doi: 10.1016/j.rser.2013.08.041
- Hernandez, R. R., Hoffacker, M. K., Murphy-Mariscal, M. L., Wu, G. C., and Allen, M. F. (2015). Solar energy development impacts on land cover change and protected areas. *Proc. Natl. Acad. Sci. U.S.A.* 112, 13579–13584. doi: 10.1073/pnas.1517656112
- Hoffacker, M. K., Allen, M. F., and Hernandez, R. R. (2017). Land-sparing opportunities for solar energy development in agricultural landscapes: a case study of the great central valley. CA, United States. *Environ. Sci. Technol.* 51, 14472–14482. doi: 10.1021/acs.est.7b05110
- Hölzel, N., and Otte, A. (2003). Restoration of a species-rich flood meadow by topsoil removal and diaspore transfer with plant material. *Appl. Veg. Sci.* 6, 131–140. doi: 10.1111/j.1654-109X.2003.tb00573.x
- IRENA-International Renewable Energy Agency (2018). *Global Energy Transformation: A Roadmap to 2050*. Abu Dhabi: IRENA.
- Jacobson, M. Z. (2009). Review of solutions to global warming, air pollution, and energy security. *Energy Environ. Sci.* 2, 148–173. doi: 10.1039/B809990C
- Lal, R. (2003). Soil erosion and the global carbon budget. *Environ. Int.* 29, 437–450. doi: 10.1016/S0160-4120(02)00192-7
- Larney, F. J., Li, L., Janzen, H. H., Angers, D. A., and Olson, B. M. (2016). Soil quality attributes, soil resilience, and legacy effects following topsoil removal and one-time amendments. *Can. J. Soil Sci.* 96, 177–190. doi: 10.1139/cjss-2015-0089
- Larney, F. J., Olson, B. M., Janzen, H. H., and Lindwall, C. W. (2000). Early impact of topsoil removal and soil amendments on crop productivity. *Agron. J.* 92, 948–956. doi: 10.2134/agronj2000.925948x
- Leccisi, E., Rauei, M., and Fthenakis, V. (2016). The energy and environmental performance of ground-mounted photovoltaic systems - A timely update. *Energies* 9:622. doi: 10.3390/en9080622
- Li, J., Okin, G. S., Alvarez, L., and Epstein, H. (2008). Effects of wind erosion on the spatial heterogeneity of soil nutrients in two desert grassland communities. *Biogeochemistry* 88, 73–88. doi: 10.1007/s10533-008-9195-6
- Macknick, J., Beatty, B., and Hill, G. (2013). *Overview of Opportunities for Co-Location of Solar Energy Technologies and Vegetation*. Golden, CO: National Renewable Energy Laboratory.
- Mani, M., and Pillai, R. (2010). Impact of dust on solar photovoltaic (PV) performance: research status, challenges and recommendations. *Renew. Sustain. Energy Rev.* 14, 3124–3131. doi: 10.1016/j.rser.2010.07.065
- Marrou, H., Dufour, L., and Wery, J. (2013a). How does a shelter of solar panels influence water flows in a soil-crop system? *Eur. J. Agron.* 50, 38–51. doi: 10.1016/j.eja.2013.05.004
- Marrou, H., Guilioni, L., Dufour, L., Dupraz, C., and Wery, J. (2013b). Microclimate under agrivoltaic systems: is crop growth rate affected in the partial shade of solar panels? *Agric. For. Meteorol.* 177, 117–132. doi: 10.1016/j.agrformet.2013.04.012
- Marrou, H., Wery, J., Dufour, L., and Dupraz, C. (2013c). Productivity and radiation use efficiency of lettuces grown in the partial shade of photovoltaic panels. *Eur. J. Agron.* 44, 54–66. doi: 10.1016/j.eja.2012.08.003
- Mazaheri, M. R., and Mahmoodabadi, M. (2012). Study on infiltration rate based on primary particle size distribution data in arid and semiarid region soils. *Arab. J. Geosci.* 5, 1039–1046. doi: 10.1007/s12517-011-0497-y
- McGeehan, S. L., and Naylor, D. V. (1988). Automated instrumental analysis of carbon and nitrogen in plant and soil samples. *Commun. Soil Sci. Plant Anal.* 19, 493–505. doi: 10.1080/00103628809367953
- Mejia, F. A., and Kleissl, J. (2013). Soiling losses for solar photovoltaic systems in California. *Sol. Energy* 95, 357–363. doi: 10.1016/j.solener.2013.06.028
- Mohammad, A. G., and Adam, M. A. (2010). The impact of vegetative cover type on runoff and soil erosion under different land uses. *Catena* 81, 97–103. doi: 10.1016/j.catena.2010.01.008
- Nelson, D. W., and Sommers, L. E. (1996). “Total carbon, organic carbon, and organic matter,” in *Methods of soil Analysis: Part 3 Chemical Methods*, eds M. E. S. D. L. Sparks, J. M. Bartels, D. L. Sparks, A. L. Page, P. A. Helmke, R. H. Loeppert, et al. (Madison, WI: Soils Science Society of America, Inc. and American Society of Agronomy, Inc), 961–1010.
- Noy-Meir, I. (1973). Desert ecosystems: environment and producers. *Annu. Rev. Ecol. Syst.* 4, 25–51. doi: 10.1146/annurev.es.04.110173.000325
- Ong, S., Campbell, C., Denholm, P., Margolis, R., and Heath, G. (2013). *Land-use Requirements for Solar Power Plants in the United States*. Golden, CO: National Renewable Energy Laboratory.
- Perez, M. J. R., and Fthenakis, V. (2012). Façade-integrated photovoltaics?: a life cycle and performance assessment case study. *Prog. Photovolt. Res. Appl.* 20, 975–990. doi: 10.1002/ppv.1167
- Phillips, J. (2013). Determining the sustainability of large-scale photovoltaic solar power plants. *Renew. Sustain. Energy Rev.* 27, 435–444. doi: 10.1016/j.rser.2013.07.003
- Ravi, S. (2015). Resources: partner crop plants with solar facilities. *Nature* 524:161. doi: 10.1038/524161a
- Ravi, S., D'Odorico, P., Breshears, D. D., Field, J. P., Goudie, A. S., Huxman, T. E., et al. (2011). Aeolian processes and the biosphere. *Rev. Geophys.* 49:RG3001. doi: 10.1029/2010RG000328
- Ravi, S., Lobell, D. B., and Field, C. B. (2014). Tradeoffs and synergies between biofuel production and large solar infrastructure in deserts. *Environ. Sci. Technol.* 48, 3021–3030. doi: 10.1021/es404950n

- Ravi, S., Macknick, J., Lobell, D., Field, C., Ganesan, K., Jain, R., et al. (2016). Colocation opportunities for large solar infrastructures and agriculture in drylands. *Appl. Energy* 165, 383–392. doi: 10.1016/j.apenergy.2015.12.078
- Sherwani, A. F., Usmani, J. A., and Varun. (2010). Life cycle assessment of solar PV based electricity generation systems: a review. *Renew. Sustain. Energy Rev.* 14, 540–544. doi: 10.1016/j.rser.2009.08.003
- Turney, D., and Fthenakis, V. (2011). Environmental impacts from the installation and operation of large-scale solar power plants. *Renew. Sustain. Energy Rev.* 15, 3261–3270. doi: 10.1016/j.rser.2011.04.023
- U. S. Department of Energy (2012). *SunShot Vision Study*. doi:SunShot, *Energy Efficiency and Renewable Energy*. NREL Report No. BK5200-47927. Washington, DC: U.S. Department of Energy.
- Vomocil, J. A., and Flocker, W. J. (1961). Effect of soil compaction on storage and movement of soil air and water. *Trans. ASAE* 4, 0242–0246. doi: 10.13031/2013.41066
- Walston, L. J., Mishra, S. K., Hartmann, H. M., Hlohowskyj, I., McCall, J., and Macknick, J. (2018). Examining the potential for agricultural benefits from pollinator habitat at solar facilities in the United States. *Environ. Sci. Technol.* 52, 7566–7576. doi: 10.1021/acs.est.8b00020
- Walston, L. J., Rollins, K. E., LaGory, K. E., Smith, K. P., and Meyers, S. A. (2016). A preliminary assessment of avian mortality at utility-scale solar energy facilities in the United States. *Renew. Energy* 92, 405–414. doi: 10.1016/j.renene.2016.02.041
- Zhang, R. (1997). Determination of soil sorptivity and hydraulic conductivity from the disk infiltrometer. *Soil Sci. Soc. Am. J.* 61:1024. doi: 10.2136/sssaj1997.03615995006100040005x

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Research papers

Quantifying soil moisture and evapotranspiration heterogeneity within a solar farm: Implications for stormwater management

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ABSTRACT

As solar energy becomes a cheap source of renewable energy, the number of major utility-scale ground solar panel installations, often called 'solar farms,' are growing. With these solar farms often covering hundreds of acres, there is potential for impacts on natural hydrologic processes, including runoff generation and erosion. There is still limited research in this area, and best management practices to address these impacts are variable and not well understood. To fill this gap, we conducted a field investigation of soil moisture patterns, solar radiation, and vegetation at two solar farms in central Pennsylvania, USA that are representative of the complex terrain in the region (e.g., high or variable slopes). Both solar farms also included engineered infiltration basins or trenches that were investigated. Analysis of soil moisture patterns reveals redistribution of water relative to panels, with dripline soil moisture 19 % higher than the reference, and underpanel moisture 25 % lower than the reference, on average at both solar farms over a year. There are also the greatest periods of saturation and runoff generation at the panel driplines. However, an open interspace between panel rows and existing infiltration basins and trenches are playing a critical role in managing runoff. Micrometeorological monitoring indicates reduced evapotranspiration (ET) under panels, with potential underpanel ET 37–67 % lower in summer, and minimal difference in winter. However, a survey of vegetation revealed almost complete ground coverage under panels, which is critical for supporting infiltration and reducing erosion. As solar farms expand to meet important renewable energy goals, it is essential that care be taken to design the landscape to minimize runoff generation and erosion. This work demonstrates that healthy vegetation and well-draining soils can help manage runoff on solar farms; where necessary on more challenging landscapes, engineered stormwater controls can manage any unmitigated runoff.

1. Introduction

1.1. The expansion of solar farms

Technologies to harvest solar energy have rapidly expanded in recent decades due to technological advancements and favorable government policies that make it more affordable, along with goals for reducing the carbon footprint of energy (Gunerhan et al., 2008; Shorabeh et al., 2019). Ground mounted solar arrays are one of the methods used for harnessing solar energy. Utility-scale ground-mounted solar arrays generating at least 1 MW of electricity are commonly referred to as 'solar

farms'. As of 2023, there are approximately 6440 existing major solar projects across the US, with existing installations generating 104 GW, and projects under construction or in development generating 111 GW (Solar Energy Industries Association, 2023). The area covered by solar farms can vary between 1 acre (0.40 ha) to hundreds of acres (Aman et al., 2015; Jacobson and Delucchi, 2011). Historically, many of these projects were developed in areas most abundant in solar radiation. However, there is increasing development of solar energy infrastructure across a variety of landscapes and climatic regions (US Energy Information Administration (EIA), 2023).

Solar farms present a unique land use transition, where impervious

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solar panels are mounted on metal supports above pervious land. There is the potential for negative impacts on the environment, depending on the way that the solar farm is built and maintained (Hernandez et al., 2014). For example, vegetation type and management and solar panel height and spacing could all impact the ecosystem functions on a solar farm (Yavari et al., 2022). With respect to hydrology, there is the potential for impacts to hydrologic processes, as panels intercept precipitation and route it to a concentrated drip zone, as well as intercept solar radiation, which is a major influence on evapotranspiration. However, there is very limited existing research characterizing how solar farms may change environmental characteristics and function.

1.2. Existing research on solar farm hydrology and soils

1.2.1. Soil physical properties and soil moisture

Field measurements on solar farms have often been made at specific locations relative to solar panels- these have included the interspace area open to sun between panels, under the lower edge of the panel or 'dripline', and underneath the center of the panels. Sometimes measurements may also be made at a control or reference area outside the main array of panels.

Physical, chemical, and biological soil indicators have been found to be lower or unchanged on solar farms compared to reference land cover types. No change in bulk density has been observed at multiple solar farms (Armstrong et al., 2016; Lambert et al., 2021). Reductions in soil carbon and nitrogen content have been documented (Choi et al., 2020; Lambert et al., 2021), in addition to lack of difference in soil nutrients (Choi et al., 2023). There is also evidence of the impacts of land management choices; no significant changes in soil physical and chemical properties were observed at a solar farm on reclaimed cropland sown with meadow grasses (Armstrong et al., 2016).

Some soil properties may also vary within the solar farm. Hydraulic conductivity was found to be higher beneath solar panels than in the interspace area between panels. The reason for this difference may be the reduced exposure to maintenance activities beneath the panel, which could induce compaction and reduce hydraulic conductivity (Choi et al., 2020).

Substantial variation in soil moisture has also been observed within solar farms. In multiple solar farms, particularly those in more arid environments, relatively higher moisture has been observed under panels (Barron-Gafford et al., 2019; Hassanpour Adeh et al., 2018; Yue et al., 2021). These patterns are presumably driven by reduced evapotranspiration (ET). At multiple sites, the dripline has had relatively higher soil moisture compared to the reference, under panel, or interspace, particularly following rain events (Choi et al., 2020, 2023; Elamri et al., 2018b; McCall et al., 2023).

1.2.2. Micro-meteorology and evapotranspiration

The presence of solar panels can alter meteorological characteristics. Because they may interrupt the movement of air, reduced wind speed and altered wind direction has been observed under solar panels (Choi et al., 2023; Hassanpour Adeh et al., 2018). Solar panels can also impact the balance of incoming solar radiation and emitted radiation, in turn altering soil temperature and ET. Reduced solar radiation has been consistently observed under solar panels (Armstrong et al., 2016; Hassanpour Adeh et al., 2018; Kannenberg et al., 2023; Marrou et al., 2013b). Changes in these variables also manifest in changes in ET, where reductions in ET have been observed under panels in multiple solar farms (Elamri et al., 2018a; Marrou et al., 2013a). However, recent work has demonstrated that these ET reductions can be much less than solar radiation reductions under the panels, thanks to strategic changes in photosynthetic traits by plants (Kannenberg et al., 2023).

1.2.3. Runoff

The soil and hydrologic variables discussed above have implications for runoff generation, but there has been almost no direct study of runoff

on solar farms. Two recent plot-scale field studies have investigated runoff from ground-mounted solar panels. While one study found no measurable impact on runoff volume or velocity from solar panels over bare soil as compared to bare soil alone (Wang and Gao, 2023), the second study observed increased peak discharge (Baiamonte, Gristina, & Palermo, 2023). Because these studies did not compare other land covers, it is unclear how addition of solar panels may affect vegetated landscapes. Increased roughness under the panels did lead to reduced sediment fluxes compared to the control (Wang and Gao, 2023) but it is important to again note that this was without the presence of vegetation. Because this study did not compare other land covers, it is unclear how addition of solar panels may affect other soils or vegetated landscapes. Several published modeling studies have evaluated the impacts of solar farms on runoff. Their results have varied from no net impact on runoff to net increases in runoff from solar farms, as compared to pre-development conditions (Cook and McCuen, 2013; Edalat, 2017; Gullotta et al., 2023; McCall et al., 2023; Nair et al., 2023; Pisinaras et al., 2014). However, most hydrologic modeling approaches for solar farms did not explicitly represent the impervious solar panels over pervious land, and thus the results may not reflect reality. Recently, EPA Stormwater Management Model (SWMM) and Hydrus have been used to represent solar farm runoff generation, in a way where there is both the impervious surface of the panel, and underlying pervious surface (Gullotta et al., 2023; McCall et al., 2023; Nair et al., 2023). The two SWMM modeling studies found that solar farms had minimal impact on runoff for smaller storm events, but could increase runoff volume and peak flow for larger storm events (Gullotta et al., 2023; Nair et al., 2023).

1.3. Objectives of this study

As the rapid development of solar farms continues to meet renewable energy goals, it is critical that we understand their potential impacts on landscape hydrology, and how to best manage and minimize these impacts. It is important to understand how redistribution of soil moisture may manifest in changes in runoff generation.

In this research, we focus on the hydrological impacts of solar farms by quantifying various hydrologic parameters including soil moisture, runoff, and evapotranspiration. We specifically focus on two solar farms that have more complex terrain than those previously investigated, specifically higher slopes. These two solar farms have many similar characteristics (e.g. soil type, slope magnitude, managed meadow vegetation); despite these similarities, the ability to study two sites allows consideration of inevitable heterogeneities of natural landscapes.

The first objective is to understand how solar farm implementation in a humid continental climate changes soil moisture patterns and resulting potential for runoff generation. We hypothesize that the under panel area does not receive direct precipitation, and thus we expect it to be driest. However, the dripline receives runoff from the solar panel surface; therefore, higher soil moisture and incidence of saturation is expected at the dripline. Our second objective is to understand the performance of stormwater management strategies on these solar farms, including impervious disconnection and structural stormwater management (e.g. infiltration trenches). By characterizing changes in soil moisture and the potential for resulting runoff generation, as well as understanding whether existing stormwater management strategies are able to manage generated runoff, we can support the sustainable development of solar farms on more marginal landscapes.

2. Materials and methods

2.1. Solar farm research sites

The two solar farm research sites are located in the State College area in central Pennsylvania, USA. This region is at the edge of the ridge and valley landscape and is characterized by variable topography and karst geology. The average annual temperature in State College is 9.3 °C.

Annual average rainfall is 1088 mm (State College Climate (2023)).

Solar farm 1 is located adjacent to Penn State University- University Park campus (Fig. 1; Fig. 2a). It was developed in 2019, generates 2 MW, and covers 2.6 ha. The pre-development conditions in this site were a combination of mostly meadow and pasture. The soil type is mapped as Opequon-Hagerstown complex, which is predominantly silty clay loam. The solar farm has a consistent slope of about 25 % directed down towards an adjacent road. The solar panels are oriented in the same direction as the land slope. There are three linear infiltration basins at the base of the slope (Fig. 2c). The basins vary in length based on the width of the upslope solar panel rows, but the basin that was instrumented is 75 m. Each basin is approximately 1 m depth. These basins were designed on the basis of Pennsylvania's solar-specific stormwater management guidance, which requires more detailed consideration of runoff calculations when the slope is greater than 10 % (Pennsylvania Department of Environmental Protection, 2022). In this case, runoff calculations were based on a modified Curve Number to factor in the potential effect of solar panels, where stormwater design targets were no net increase in runoff volume for a 2 year-24 hour event, and no net increase in peak flows for a 100 year event (Minnesota Pollution Control Agency, 2019). During solar farm development, the site was seeded with a low-growth native perennial seed mixture. Mowing is conducted several times per year.

Solar farm 2 is located at a wastewater treatment authority to the northeast of State College, PA and covers a total of 7 ha (Fig. 1). Soils at this site are Hagerstown silt loam or Opequon-Hagerstown complex, primarily silty clay loam. There are also small sections of rock outcrops.

The solar farm was constructed over multiple years, where Phase 1 was constructed in 2018 and produces 2.6 MW of electricity, and Phase 2 was completed in spring 2021 and produces 3.5 MW of electricity. Slopes at the solar farm are variable, ranging from a few percent to over 30 %. Due to the local township stormwater ordinance, Phase 2 has gravel infiltration trenches that are implemented along the topographic contours of the landscape (Fig. 2b). Each trench is 30 cm wide, 20 cm deep, and filled to the surface with gravel. The entire site was grazed by sheep starting in June 2022. Field measurements were made in multiple areas of the farm, with a cluster of soil moisture sensors located around a row on the north side/ phase 1, and an infiltration trench monitored on the south part of the solar farm. Fig. 2d shows the location of the sensors around the panels.

The width of panels in both solar farms is 4 m. The width of the interspace zone between the panels at both sites is 3 m. The vertical height of the lower edge of the panel is 1.5 m in solar farm 1. In solar farm 2 the vertical height of the lower panel edge varies between 0.8 to 1.5 m. At both sites, panels are fixed tilt, and are mounted towards the south at approximately a 40 degree angle, given the location in central Pennsylvania.

2.2. Continuous measurements

2.2.1. Soil moisture

To investigate the effects of solar panels on the soil moisture distribution around the panels, we implemented several clusters of soil moisture sensors at depth of 10 cm at different locations relative to the

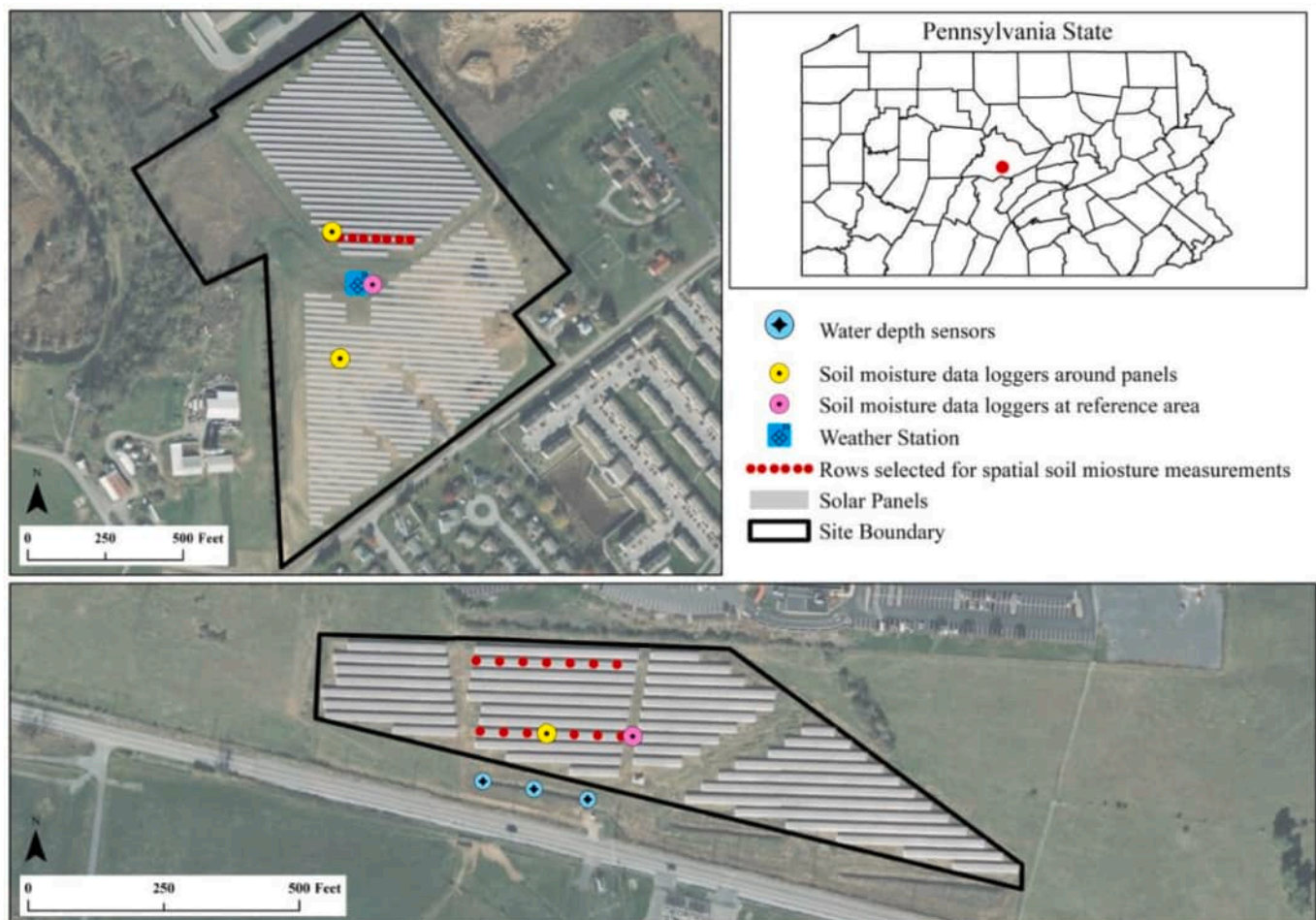


Fig. 1. Map of two studied solar farms with location of sensors, including solar farm 2 (top left) and solar farm 1 (bottom). At the top right, the location of these sites within Pennsylvania USA is indicated.

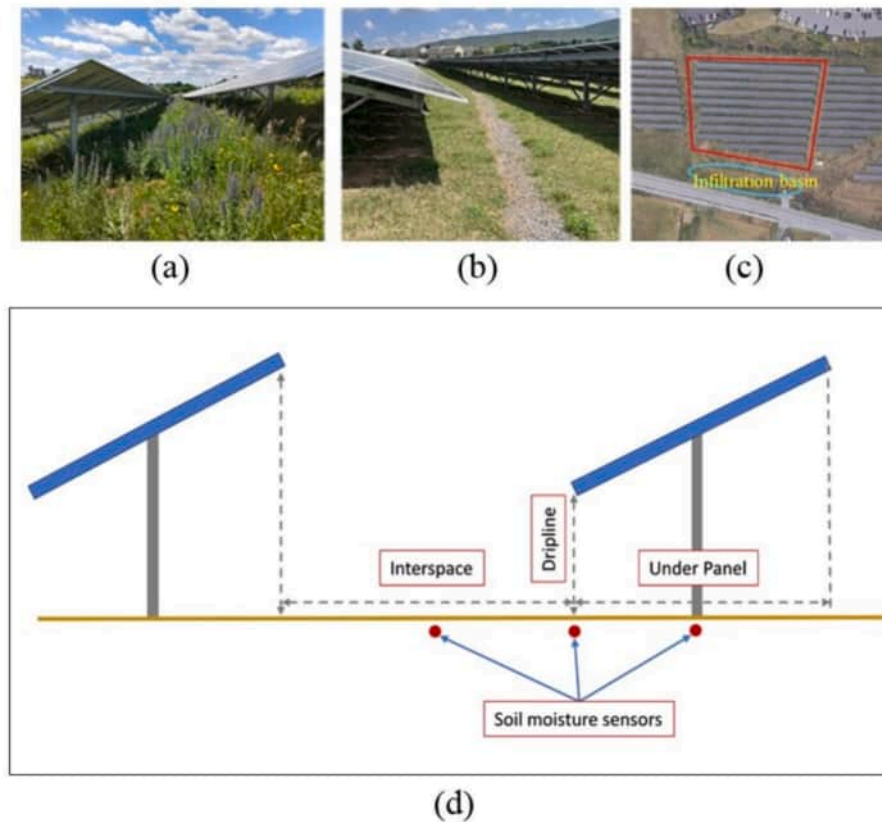


Fig. 2. Photos and Schematic of the solar farms: (a) solar farm 1 (steep site); (b) solar farm 2 with infiltration trench; (c) infiltration basin at base of solar farm 1, and (d) schematic of key monitoring locations relative to solar panels.

panels (Fig. 2d). These clusters were located away from the edges of the solar farm to be as representative as possible. Three METER TEROS 12 sensors were implemented around the panels during summer and fall 2021 at the following locations: interspace, under panel and dripline. Each detects volumetric water content (VWC; vol/vol). We implemented one cluster of sensors around one of the panel rows in solar farm 1, and one sensor at the reference point off to the side of the row where other sensors were implemented (Fig. 1). The sensor implemented in the reference site is not affected by the panels (there is not any panel upslope of the reference point). Each sensor records VWC, temperature, and soil electrical conductivity at 15-minute intervals. The data is recorded automatically with the installed METER ZL6 data loggers. We also added one cluster of sensors around a panel row in solar farm 2; also at solar farm 2, we added TEROS 12 sensors on either side of an infiltration trench. In addition to using soil moisture timeseries to evaluate changes in time and space, we also leveraged this data to evaluate patterns of saturation (i.e., plateau at a maximum value for a given location), and presumed runoff generation.

2.2.2. Meteorology and ET

Meteorological data is available for both solar farms. For solar farm 1, a weather station was already located nearby (~2 km) to the solar farm. The HOBO RX3000 weather station logs data on rainfall, air temperature, wind speed, solar radiation, humidity, and barometric pressure at 5-minute intervals. At solar farm 2, a METER ATMOS 41 weather station was installed at the site, several meters away from any panels. This station collects the same variables as solar farm 1, at 15-minute intervals. To compare the solar radiation under the solar panels with the reference points, we installed additional pyranometers (METER PYR). The pyranometers were located at the underpanel location at solar farm 1 and solar farm 2.

We assessed daily potential evapotranspiration beneath solar panels

in comparison to the reference point (not affected by solar panels). For underpanel ET computations, we utilized the same dataset collected from the weather stations, with the sole exception being solar radiation; in this case, data from the underpanel pyranometers was used. Potential ET was then calculated for both under panel and reference point conditions at each solar farm using the Penman-Monteith method, facilitated by the 'evapotranspiration' R package (Guo et al., 2016).

2.2.3. Runoff

To measure the runoff that reaches the base of the slope at solar farm 1, we installed three Onset HOBO U20L water level loggers along the infiltration basin of the selected watershed. Three loggers were installed, given the length of the infiltration basin (Fig. 1), to capture any heterogeneity in runoff or the basin; ultimately the middle logger is used for presented data analysis in this paper. Water level data was logged at 5-minute intervals between fall 2021 and summer 2023; however, the loggers were removed during winter periods, and data was not available for other selected periods of time for other reasons.

2.3. Manual field measurements

Soil hydraulic conductivity was measured using a METER SATURO infiltrometer at multiple sites in each solar farm. In addition, soil samples were taken in close proximity to the soil moisture sensor clusters using a bulk density corer as well as a cylindrical push probe for a 10 cm deep sample; two soil samples for all analyses were taken at each sensor location and properties of the two samples were averaged. Samples were analyzed for bulk density, soil texture, and organic matter content via loss-on-ignition.

To complement the continuous soil moisture measurements made at discrete locations, and to understand larger-scale variability of moisture patterns, we also measured the soil moisture manually along selected

rows and transects at the sites. For this purpose, we used handheld Campbell Scientific Hydrosense II probes. For these measurements, we selected two rows in solar farm 1 (one row upslope and one row downslope) with a length of 85 m, and one row in solar farm 2 with length of 92 m, where the selected row was in the vicinity of the soil moisture sensor clusters. For the solar farm 1 measurements, one of the rows is located upslope of the soil moisture cluster, while the second row is located at the same row which we added the sensor cluster (Fig. 1). Measurements were conducted at 1–2 m intervals along each row. For each row, measurements were conducted at the three key locations relative to the panels: interspace, underpanel and dripline. These manual measurements were made on four selected dates throughout the year that represented a range of hydrologic conditions.

An additional set of manual soil moisture data was collected to investigate the soil moisture patterns in fine scale with respect to the panels. The first type of manual fine scale measurements was conducted to check if the patterns in the three key locations are consistent. For this purpose, we considered four blocks (1 m × 1 m) under a panel, four blocks (1 m × 1 m) in the interspace and four blocks in the dripline (Fig. S1). In the underpanel and interspace blocks, we conducted nine soil moisture measurements and in each dripline block, we made three soil moisture measurements. We conducted one set of these fine-scale measurements for solar farm 1, and one set for solar farm 2.

In a second series of fine-scale measurements, we surveyed the soil moisture patterns around the dripline (Fig. S2). The dripline is one of the locations which is focused on by different researchers when doing soil moisture related measurements in solar farms and is likely a critical area of runoff generation. Therefore, fine scale investigation of soil moisture around the dripline is crucial. In this approach, we considered three lines around the dripline- one line exactly under the dripline, a second line 0.3 m toward the interspace and a third line 0.3 m toward the interspace. We conducted these measurements along the solar panel rows. We conducted this type of measurement at both solar farms.

Basic vegetation characteristics were also surveyed near the soil moisture sensor clusters at both solar farms. Two-meter plastic quadrats were used at three locations in the underpanel, interspace, and reference zones. For underpanel and interspace, we gathered data in four locations along the panels. For the reference, we randomly selected four locations around the reference location which are not affected by panels. The dripline was not surveyed because its width is narrower than the quadrat. In each quadrat, percent coverage of vegetation by species, bare soil, or rock were noted, as well as maximum height of each species.

2.4. Data analysis

For soil moisture time series data, initial quality control was performed where moisture values were removed where soil temperatures were recorded as below freezing. Statistical analysis was conducted using R Statistical Computing Software, version 4.3.1, and graphical evaluation was carried out with Tableau. For manual soil moisture measurements at each solar farm and each date, we employed a Kruskal-Wallis test. When the test statistic was significant, indicating variations among the groups, we conducted post-hoc comparisons to pinpoint the groups with significant differences. Due to a relatively limited number of samples per site for selected soil and vegetation properties, statistical analysis was not conducted on these parameters.

To assess variations in soil moisture saturation times across different locations, we used soil moisture time series for saturation time comparisons. We conducted two distinct types of saturation time comparisons, leveraging Tableau. The first set of calculations revolved around comparing saturation times at key locations: dripline, underpanel, interspace, reference. We conducted this type of calculation from June to September 2022. The second comparison entailed assessing saturation times at solar farm 2 both before and after the location of the infiltration trench. For this type of analysis, we considered the period of September and October 2022 (note that a different period was used for

the trench analysis due to some missing data during summer 2022). For these saturation time comparisons, our approach began by identifying the maximum volumetric soil moisture content at each solar farm and each key location (e.g. interspace). Subsequently, we identified the periods during which the soil moisture content remained at its maximum level. We also calculated key summary statistics (e.g. mean, standard deviation) for a year-long period of soil moisture for each sensor location. To characterize variability of soil moisture, we used coefficient of variation, but also adapted the flashiness metric commonly used in streamflow analysis (Baker et al., 2004).

$$\text{SoilMoistureFlashiness} = \frac{\sum_{i=1}^n |VWC_i - VWC_{i-1}|}{\sum_{i=1}^n VWC_i} \quad (1)$$

This proposed flashiness index (Eq. (1)) can provide different insight than coefficient of variation. This is because the point-to-point variability characterized by flashiness can differ from the overall variance over a certain time period, relative to the mean, that is characterized by coefficient of variation.

For the water depth calculations in the infiltration basin of solar farm 1, considerable noise in the data was observed around low/baseline values. To address this, we applied a de-noising technique using the moving average method in Tableau. Our findings were then presented in the form of daily rain data versus maximum water depth in the infiltration trench comparison.

3. Results and discussion

3.1. Vegetation and soil properties

A summary of some soil properties and vegetation height are demonstrated in Table 1. Similar to the results of research in solar farms in France, bulk density does not show any specific patterns across the measured key locations (Lambert et al., 2021). In both solar farms, the height of vegetation was higher in the interspace and lower under the panels (Table 1). Vegetation height in the interspace was similar to the reference locations, and even taller in some instances. There was also good coverage of vegetation in the entire solar farm. Areas of rock or bare soil were limited to less than 5 %; however, in the underpanel area, there was more dead vegetation (i.e. duff) than in other areas- over a third of the area at solar farm 1. The duff still provides benefits of soil cover like erosion protection. These vegetation characteristics were consistent with research on solar farms in the United Kingdom, which documented taller grasses in the interspace (Armstrong et al., 2016). In a Colorado, USA solar farm, there was also greater aboveground plant biomass in the interspace, but underpanel biomass was less than 25 % lower (Kannenberg et al., 2023). At solar farm 2, organic matter was higher at the reference in comparison to the other locations. However, at solar farm 1, there was no noticeable difference between the organic matter content of the different locations, similar to the results of the research on UK solar farms which did not show any significant differences in soil physical properties, as compared to a reference location (Armstrong et al., 2016).

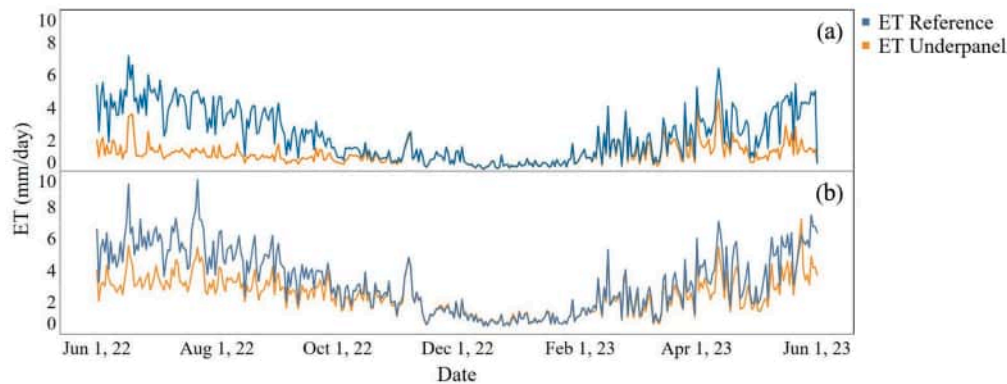
3.2. Evapotranspiration

At both solar farms, we documented consistent differences in solar radiation (Fig. S3) and potential ET (PET) (Fig. 3) between the under panel and reference locations (Table S3 and Table S4). At solar farm 1, the under panel solar radiation was 87 % lower than reference in summer, while in winter it was 60 % lower. In solar farm 2, the under panel solar radiation was lower than the reference by 88 % in summer and 87 % in winter. Despite these similar magnitudes of difference across seasons, there is an overall trend of both the reference and under panel locations to have substantially reduced ET in winter months. The differences across parts of the solar farm align with observations at solar

Table 1

Selected vegetation and soil properties of the solar farms. Samples or measurements were taken in the vicinity of the soil moisture sensor locations at each solar farm.

Site/Location	Solar farm 1				Solar farm 2			
	Dripline	Interspace	Under panel	Reference	Dripline	Interspace	Under panel	Reference
Soil texture	Silty clay loam	Silty clay loam	Silty clay loam	Clay loam	Silty clay loam	Silty clay loam	Silty clay loam	Silty clay loam
Bulk density (g/cm ³)	1.27	1.13	1.3	1.12	1.23	1.41	1.50	1.53
Average vegetation height (cm)		27.9	12.7	25.4		43.1	17.87	33
Saturated hydraulic conductivity (cm/s)		0.0118	0.0074	0.0129		0.006	0.0072	0.0132
Organic matter as % of soil mass	5.7	5.8	5.3	5.8	5.2	5.3	5	7
% live veg/ duff/bare soil or rock		82/ 14.6/ 3.3	58.5/ 39/ 2.5	92.5/ 7.5/ 0		100/ 0/ 0	93.5/ 6.5/ 0	100/ 0/ 0

**Fig. 3.** Potential evapotranspiration patterns in under panel and reference location at (a) solar farm 1 and (b) solar farm 2. The period of June 1, 2022, to June 1, 2023, is shown.

farms in France where lower solar radiation was noticed under panel in comparison to the reference location (Marrou et al., 2013a)

Calculated PET at the reference location was consistently higher than under the solar panels (Fig. 3). In solar farm 1, under panel PET is lower than the reference by 67 % in summer and only 1 % winter. At solar farm 2, under panel PET is lower than the reference by 37 % in summer, while there was no difference in under panel and reference PET in winter. It is important to note that these PET calculations only incorporated differences in solar radiation between underpanel and reference areas and did not directly incorporate changes in wind or other factors, due to lack of data on these parameters. Given that other field research has identified decreases under panel for these other factors, they could lead to further decreases in PET calculations as well (Hassanpour Adeh et al., 2018).

3.3. Continuous soil moisture patterns

Various factors, including precipitation, evapotranspiration, and soil or geological features, exert influence over soil moisture patterns within solar farms. Over the course of a year, average volumetric water content at solar farm 1 was 0.33, 0.28, 0.27 and 0.20 for dripline, reference, interspace and underpanel, respectively.

For solar farm 2, the average VWC was 0.36, 0.35, 0.29, and 0.23 for interspace, dripline, reference and underpanel, respectively. At solar farm 1, the annual average soil moisture of the dripline is 18 % higher than the reference, while the underpanel contains 29 % lower soil moisture than the reference. For solar farm 2, average soil moisture at the dripline is 21 % higher than the reference, while average underpanel soil moisture is 20 % lower than the reference. Thus, the dripline area often exhibits high volumetric water content (VWC), while the underpanel area is relatively drier. Average annual interspace soil moisture is similar to average soil moisture at the reference site at solar farm 1, but is 23 % higher than the reference over the course of the year at solar farm 2. Thus soil moisture at the reference locations and interspace areas are often similar, with the interspace at solar farm 2 periodically being wetter. Both the reference and interspace locations are directly impacted by both evapotranspiration and interception of precipitation. The wetter conditions at the solar farm 2 interspace may be due to more shading and less ET relative to the reference; unfortunately, solar radiation was not directly measured in the interspace in this study.

Precipitation emerges as the primary driver impacting soil moisture

Table 2

Summary statistics for soil moisture time series, as calculated for the June 1, 2022–May 31, 2023 time period.

Site	Location w/in a site	Summary statistics for volumetric water content (vol/vol) data				
		Median	Mean	Standard deviation	Coefficient of variation	Flashiness
Solar farm 1	Dripline	0.35	0.33	0.068	0.21	0.00088
	Under panel	0.20	0.20	0.043	0.22	0.00063
	Interspace	0.30	0.27	0.082	0.30	0.00085
	Reference	0.31	0.28	0.069	0.25	0.00070
Solar farm 2	Dripline	0.36	0.35	0.050	0.14	0.0013
	Under panel	0.21	0.23	0.046	0.20	0.00037
	Interspace	0.40	0.36	0.073	0.20	0.00076
	Reference	0.31	0.29	0.074	0.25	0.00054

levels along the dripline, while the interactions of precipitation and ET appear to be more important at other locations. During rain events, there is a rapid surge in dripline soil moisture, which may temporarily reach its peak value (Fig. 4). This extended duration of elevated soil moisture serves as an indicator of soil saturation periods, indicating the potential for runoff generation during such saturation intervals. This rain-driven response also drives relatively higher flashiness values at the dripline (Table 2). The dripline has considerable variability in spring, summer and fall in comparison to winter, which is likely because of the dominance of rain-driven rapid responses in spring through fall, but decreased ET and dominance of snow precipitation and snow ground cover change patterns in winter.

Looking across the year, there are some slow shifts in soil moisture at the underpanel, reference, and interspace between warmer and cooler months. Thus, while the dripline has the highest flashiness (point-to-point variability) from rain-driven responses, the other locations still have relatively high coefficients of variation from these slow seasonal shifts. The underpanel area does consistently have a lower coefficient of variation than the reference (Table 2). During some dry periods of the summer, the soil moisture of interspace and reference locations gets lower than underpanel, while underpanel soil moisture remains relatively constant, due to more limited ET. For example, during July and August 2022, soil moisture of the interspace at solar farm 1 gets lower than under the panel and at solar farm 2, the reference soil moisture is lower than the underpanel (Fig. 4). Research in solar farms in more arid regions (Barron-Gafford et al., 2019; Yue et al., 2021), shows similar results to these summer patterns at these sites, with the underpanel zone often having higher soil moisture. Consequently, in more arid climates, the increased soil moisture under the panels area could be beneficial for plant growth by reducing water limitation. In the winter months, there is an increase in the underpanel soil moisture. In general, soil moisture patterns are more similar between locations in winter, likely due to the more similar ET patterns between the interspace or reference areas and under panel zones in winter months.

To determine the soil moisture saturation time, we examined soil moisture patterns from June 1, 2022, to September 1, 2022, in both solar farms. In this period, at solar farm 1, there was a total of 205 min when the dripline remained at saturation. In this same period, no saturation was detected in the underpanel and interspace areas, but there were 10

min of saturation at the reference location. At solar farm 2, the dripline remained at saturation for a total of 130 min. The interspace remained saturated for a total of 15 min. No soil saturation was detected under the panel and reference locations. Thus, there is clearly a much longer period of time in which the dripline may be generating runoff, and very limited or no time in which the other areas are likely to be generating runoff.

3.4. Spatial soil moisture variability in the solar farms

Manual soil moisture measurements made along entire solar panel rows demonstrate similar patterns to those from the continuous sensors (Fig. 5a and b). In the upslope row of solar farm 1 on all dates, there were significant differences between the dripline, under panel and interspace (Table S1). On all measurement dates, the dripline had highest soil moisture, followed by interspace and under panel. In the downslope row of solar farm 1 on all four measurement dates, there were significant differences between the dripline with other locations (Table S1). On three dates, the dripline had higher soil moisture, followed by the interspace and under panel. On Feb 23, 2022, the interspace had higher soil moisture followed by the dripline and under panel. The potential explanation may stem from the absence of ET and wet soil conditions due to the presence of snow cover in the days preceding the measurements. At solar farm 2 on all dates, there were significant differences between all measurement locations, and dripline consistently had highest soil moisture. Overall, in 11 out of 12 manual measurement campaigns, the dripline contained higher soil moisture and the under panel had the least soil moisture.

Results of fine-scale soil moisture investigation indicate that at both solar farms, there is not any significant difference between under panel blocks, dripline blocks and interspace blocks (Table S2). This indicates that the time series measurements made at a few discrete locations are representative of the entire rows (Figure S1).

Results of fine-scale moisture investigation around the dripline indicate that there are significant differences between the selected locations around the dripline (Fig. 5c, Table S2). At both solar farms, there is a significant difference between the selected location, with the portion of the dripline zone located slightly behind the panel edge containing the lowest soil moisture, and the portion of the dripline located towards

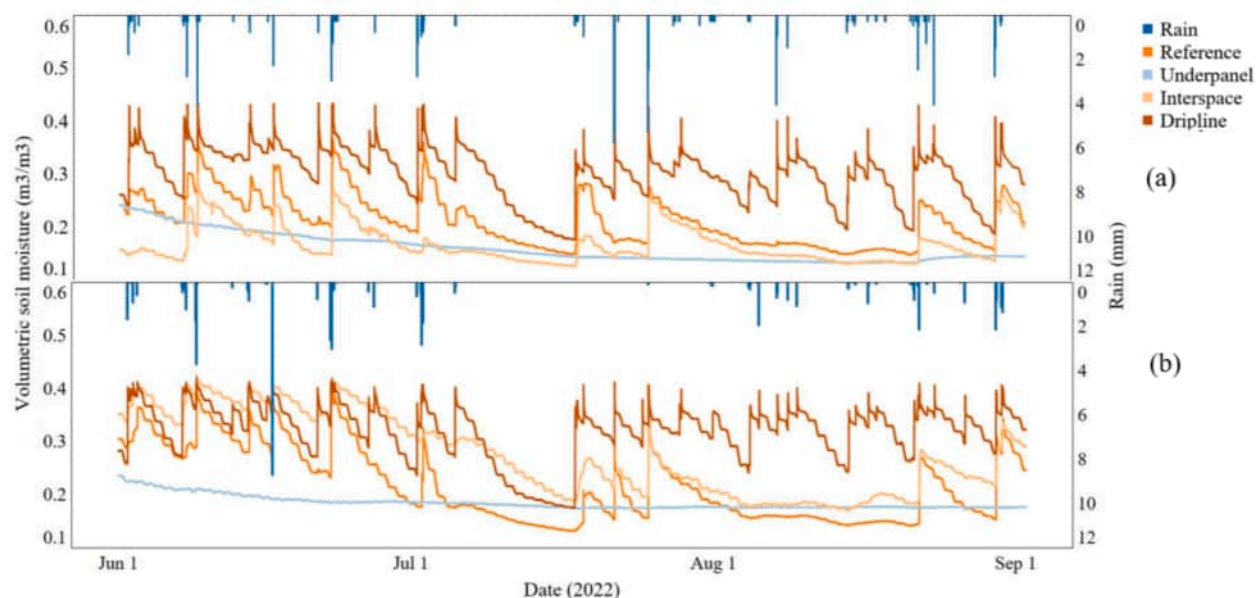


Fig. 4. Soil moisture timeseries at four key locations relative to solar panels at (a) solar farm 1 and (b) solar farm 2, phase 1. The period of June 1, 2022, to Sept 1, 2022 (late spring to late summer) is shown.

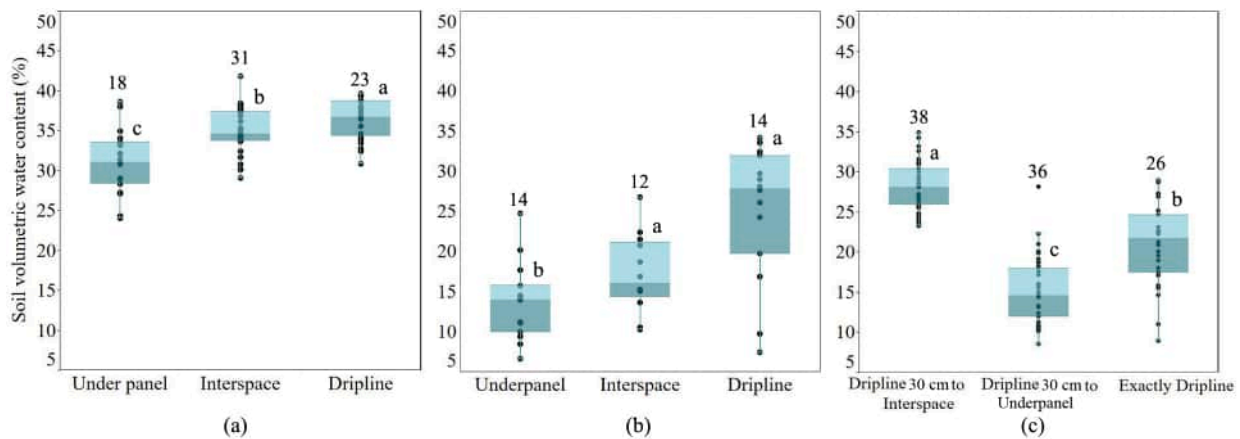


Fig. 5. Soil moisture data taken manually along entire rows of solar panels at three key locations relative to panels in (a) downslope row of solar farm 1 (date: 8.12.2021) and; (b) solar farm 2 (date: 6.17.2022). Fine-scale spatial soil moisture patterns are also indicated around the dripline (c). Numbers reported above each boxplot correspond to the number of measurements made.

the interspace being wettest. This makes sense, given the slope of the panels and landscape, and the fact that water falling from the dripline would be likely to hit the ground just beyond the panel edge and then run downslope. These major changes in moisture occurring over a total of 0.6 m indicate the importance of accurately considering this zone in field and modeling investigation of solar farms.

3.5. Function of stormwater management practices

Comparison of precipitation data and water level in the infiltration basin at solar farm 1 indicates multiple occurrences of runoff generation and conveyance to the infiltration basin (Fig. 6). We evaluated the data over 247 days, in which time there were 84 rain events. The rain events are calculated as the accumulated daily rain. There were 55 rain events that led to maximum daily water level of more than 10 mm in the center of the infiltration basin. The maximum daily rainfall was 67.2 mm, which was less than the 2 year, 24 h design event of 69 mm. The maximum water level in the infiltration basin during this period was 110 mm and thus never came close to exceeding the actual maximum basin depth of 1 m. Comparison of the water depth in the infiltration basin at the base of solar farm 1 to the dripline saturation patterns indicates some correlation. There is generally some measurable water in the basin, and detectable saturation on days with rain. However, there is not a strong relationship between the magnitude of saturation time and the infiltration basin water level, indicating influence of other factors such as antecedent soil moisture or season (Table S5). It is also important

to note that while runoff was detected in the infiltration basin, we cannot conclude whether the runoff captured in the infiltration basin is significantly more than runoff magnitude for comparable storm events prior to solar farm development, due to lack of pre-development monitoring.

At solar farm 2, we investigated the soil saturation time before and after an infiltration trench by evaluating the soil moisture time series. During September and October 2022, there were two rain events in which the sensor located before the trench reached its maximum volumetric water content. At the sensor located before the trench, in two out of the four rain events that before trench reached to its max VWC, soil saturation was indicated. The total duration that the sensor located before the trench remained at saturation was 9 h. While there were observable spikes in soil moisture at these rain events at the sensor located after the trench, no saturation happened during these 2 months (Fig. 7). Though there was not direct measurement of runoff generation at solar farm 2, the lack of any detected saturation during the quantified period indicates that the infiltration trench is adequately managing any generated runoff.

3.6. Implications

This field investigation shows that there is indeed re-routing of water on solar farms that results in unique, spatially heterogeneous soil moisture patterns. The dripline of the solar panel is clearly the area with highest moisture, and greatest incidence of saturation, and associated

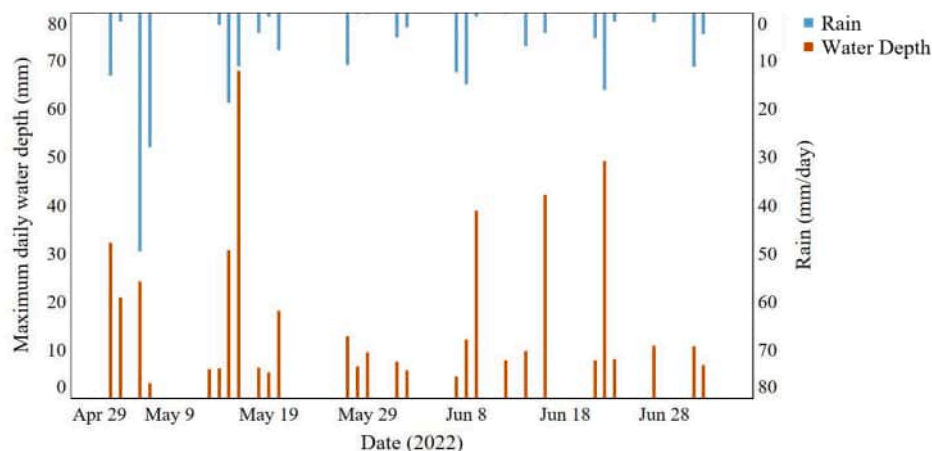


Fig. 6. Rainfall depth, and water depth in the infiltration basin at the base of solar farm 1.

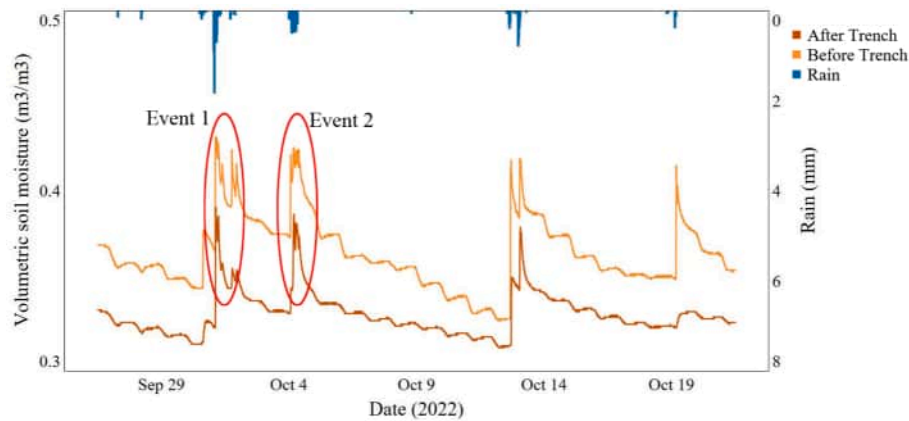


Fig. 7. Continuous soil moisture patterns before and after infiltration trench (BMP) in solar farm 2. Two rain events are highlighted.

potential for runoff reduction. However, we also observe substantial soil moisture reduction from the dripline to the center of the interspace, and minimal occurrence of saturation at the interspace. Frequently, moisture patterns in the interspace are indistinguishable from the reference site; even where average soil moisture is higher in the interspace, there is still little evidence of saturation relative to the dripline. Thus, this interspace disconnection zone between the rows of impervious solar panels is critical. While this study did not directly investigate the impact of vegetation, there was high coverage of well-established perennial vegetation at both solar farms, and other work has demonstrated the role that this can play in maintaining soil health, particularly infiltration capacity. Healthy vegetation is also particularly important at the dripline area, in order to minimize the effects of concentrated runoff, and the associated potential for splash erosion. However, some observations point to the need for some engineered structural stormwater management at certain types of sites. These observations include the presence of some differences in soil moisture and saturation patterns between the interspace and reference site, along with reduced incidence of saturation before and after an infiltration trench. The types of landscapes most in need of structural stormwater management are those most prone to runoff generation in undisturbed conditions- those with steep slopes and poorly draining soils.

Our research also reveals substantial variations in ET in space and time. These patterns are important for stormwater management, but also for considering the implications for agrivoltaics – an increasingly popular combination of agriculture (via grazing or cropping) and solar farms. The implications of spatial variation in ET also differs by climatic region. In humid continental regions like where our work was conducted, the underpanel zone had much lower ET than away from solar panels, but this zone was often still drier due to lack of intercepted precipitation. This was reflected in much shorter vegetation, and presence of vegetation is important for managing runoff. In warm arid regions which have much higher solar radiation and reference ET, shading of under panel areas and associated ET reduction can facilitate higher crop production (Barron-Gafford et al., 2019; Hassanpour Adeh et al., 2018).

3.7. Innovations, limitations, and opportunities

There is a dearth of work understanding the changes in hydrology on solar farms. Though there has been some investigation of soil moisture changes (Choi et al., 2023), no previously published work to our knowledge has focused on saturation timing and associated potential for runoff generation, or directly evaluated function of stormwater management practices on solar farms. The only existing field research (to our knowledge) directly evaluating runoff quantity and erosion was focused on a limited set of scenarios on bare soils (Baiaumont et al., 2023; Wang and Gao, 2023). This type of first-hand measurement is critical as we

understand how to best implement and manage solar farms. It is also important for this work to occur across a range of landscapes. While many solar farms are implemented in landscapes with lower slopes and better draining soils, it is more marginal types of landscapes – some of which were focused on in this work – that need further consideration. As solar farms expand and there is increasing pressure on the most arable and ideal lands, it will be important to understand how to appropriately implement solar farms on marginal lands, with minimal impact on the landscape.

While field measurements are important for capturing the true response of hydrologic systems, we are still limited in some of the insights we can derive. This and other field data can be used to generate further insight through use in modeling scenarios. Solar farms present a unique landscape transition, and it is important to determine how to best represent the hydrologic changes in modeling programs, particularly to inform stormwater management considerations in the development process (Nair et al., 2023). In this work, it is clear that different parts of the landscape have different potential for runoff generation. Fine-scale soil moisture measurements around the dripline also indicate the importance of accurately representing this zone at which precipitation is concentrated.

This work demonstrated the need for stormwater management considerations on solar farms, particularly those in more runoff-prone landscapes like high slopes. In the two examined solar farms, two different types of structural practices were used (infiltration basins and trenches), in addition to low impact development approaches of impervious disconnection. However, previous review of guidelines for stormwater management on solar farms demonstrates many inconsistencies and variability in solar-specific stormwater management guidance (Yavari et al., 2022). Additional field evaluation combined with further development of hydrologic models customized for solar farms can help determine the best way of representing the unique semi-impervious nature of solar farms along with the appropriate options and sizing of stormwater management strategies.

It is clear that there are many opportunities and needs for additional field and modeling research on solar farms. While this work introduced some new insights in potential for runoff generation on solar farms, there is still a need for direct measurements of runoff on various parts of solar farms, and at catchment outlets. In many cases, such measurements can be very challenging, depending on the management of the landscape (i.e. avoiding regular mowing that can destroy monitoring setups), and identifying sites where topography facilitates such measurements. Additionally, there is a need to make pre-development measurements in advance of solar farm implementation, rather than relying on space-for-time substitutions (i.e. using a reference location in another nearby location, which may not be a perfect reference).

4. Conclusions

The rising adoption of solar energy as a renewable resource underscores the importance of assuring that it is being implemented in the most sustainable way. Solar panels introduce impervious surfaces to the landscape and alter land use in their ground-mounted form, highlighting the necessity for effective stormwater management within solar farms. Ground-mounted solar panels differ from conventional impervious surfaces due to the permeable nature of the underpanel area. To prevent adverse environmental outcomes such as erosion and runoff, but to also prevent overestimation of the size and cost of stormwater management practices, thorough and accurate assessment of the landscape impacts of ground-mounted solar panels is essential.

This work provided new insights on the hydrological phenomena on solar farms, through first-hand field measurements. It provides some of the first interpretation of saturation and runoff potential on solar farms, in particular on steep and complex landscapes, and the first assessment of structural stormwater management practices on solar farms. While our observations document clear alteration in natural hydrologic patterns, they also demonstrate that adequately sized vegetated spaces between solar panel rows, and in some cases, structural stormwater management, can manage these changes. These types of insights, along with investigation of how land management on solar farms can affect other ecosystem services, can allow us to facilitate this critical transition to renewable energy with minimal ecosystem impact.

CRedit authorship contribution statement

Rouhangiz Yavari Bajehbaj: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Raj Cbin:** Writing – review & editing, Methodology, Funding acquisition. **Jonathan M. Duncan:** Writing – review & editing, Methodology. **Lauren E. McPhillips:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Co-Author L. McPhillips is a current Associate Editor for Journal of Hydrology. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data generated during this research is available via CUAHSI Hydroshare at <https://www.hydroshare.org/resource/57f374bfc33c4c449d136f790730c3de/> (Yavari Bajehbaj & McPhillips, 2023)

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jhydrol.2024.131474>.

References

- Aman, M.M., Solangi, K.H., Hossain, M.S., Badarudin, A., Jasmon, G.B., Mokhlis, H., et al., 2015. A review of Safety, Health and Environmental (SHE) issues of solar energy system. *Renew. Sustain. Energy Rev.* 41, 1190–1204. <https://doi.org/10.1016/j.rser.2014.08.086>.
- Armstrong, A., Ostle, N.J., Whitaker, J., 2016. Solar Park Microclimate and Vegetation Management Effects on Grassland Carbon Cycling. *Environ. Res. Lett.* 11 (7), 074016. <https://doi.org/10.1088/1748-9326/11/7/074016>.
- Baiaumont, G., Gristina, L., Palermo, S., 2023. Impact of solar panels on runoff generation process. *Hydrological Processes* 37 (12), e15053.
- Baker, D.B., Richards, R.P., Loftus, T.T., Kramer, J.W., 2004. A new flashiness index: characteristics and applications to midwestern rivers and streams. *J. Am. Water Resour. Assoc.* 40 (2), 503–522. <https://doi.org/10.1111/j.1752-1688.2004.tb01046.x>.
- Barron-Gafford, G.A., Pavao-Zuckerman, M.A., Minor, R.L., Sutter, L.F., Barnett-Moreno, I., Blackett, D.T., et al., 2019. Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. *Nat. Sustainability* 2 (9), 848–855. <https://doi.org/10.1038/s41893-019-0364-5>.
- Choi, C.S., Cagle, A.E., Macknick, J., Bloom, D.E., Caplan, J.S., Ravi, S., 2020. Effects of revegetation on soil physical and chemical properties in solar photovoltaic infrastructure. *Front. Environ. Sci.* 8, 140. <https://doi.org/10.3389/fenvs.2020.00140>.
- Choi, C.S., Macknick, J., Li, Y., Bloom, D., McCall, J., Ravi, S., 2023. Environmental co-benefits of maintaining native vegetation with solar photovoltaic infrastructure. *Earth's Future* 11 (6), e2023EF003542.
- Cook, L.M., McCuen, R.H., 2013. Hydrologic response of solar farms. *J. Hydrol. Eng.* 18 (5), 536–541. [https://doi.org/10.1061/\(ASCE\)HE.1943-5584.0000530](https://doi.org/10.1061/(ASCE)HE.1943-5584.0000530).
- Edalat, M.M., 2017. Remote sensing of the environmental impacts of utility-scale solar energy plants. Doctoral dissertation. University of Nevada, Las Vegas.
- Elamri, Y., Cheviron, B., Lopez, J.-M., Dejean, C., Belaud, G., 2018a. Water budget and crop modelling for agrivoltaic systems: application to irrigated lettuce. *Agric. Water Manag.* 208, 440–453. <https://doi.org/10.1016/j.agwat.2018.07.001>.
- Elamri, Y., Cheviron, B., Mange, A., Dejean, C., Liron, F., Belaud, G., 2018b. Rain concentration and sheltering effect of solar panels on cultivated plots. *Hydrol. Earth Syst. Sci.* 22 (2), 1285–1298. <https://doi.org/10.5194/hess-22-1285-2018>.
- Solar Electricity Net Generation, 2023. Solar Electricity Net Generation. Energy Information Administration (EIA). <https://www.eia.gov/totalenergy/data/brower/index.php?tbl=T10.06#/f=M&start=200001>.
- Gullotta, A., Aschale, T.M., Peres, D.J., Sciuto, G., Cancelliere, A., 2023. Modelling stormwater runoff changes induced by ground-mounted photovoltaic solar parks: a conceptualization in EPA-SWMM. *Water Resour. Manag.* 37 (11), 4507–4520. <https://doi.org/10.1007/s11269-023-03572-3>.
- Gunerhan, H., Hepbasli, A., Giresunlu, U., 2008. Environmental impacts from the solar energy systems. *Energy Sources Part A* 31 (2), 131–138. <https://doi.org/10.1080/15567030701512733>.
- Guo, D., Westra, S., Maier, H.R., 2016. An R package for modelling actual, potential and reference evapotranspiration. *Environ. Model. Softw.* 78, 216–224. <https://doi.org/10.1016/j.envsoft.2015.12.019>.
- Hassanpour Agh, E., Selker, J.S., Higgins, C.W., 2018. Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency. *PLoS One* 13 (11), e0203256.
- Hernandez, R.R., Easter, S.B., Murphy-Mariscal, M.L., Maestre, F.T., Tavassoli, M., Allen, E.B., et al., 2014. Environmental impacts of utility-scale solar energy. *Renew. Sustain. Energy Rev.* 29, 766–779. <https://doi.org/10.1016/j.rser.2013.08.041>.
- Jacobson, M.Z., Delucchi, M.A., 2011. Providing all global energy with wind, water, and solar power, Part I: technologies, energy resources, quantities and areas of infrastructure, and materials. *Energy Policy* 39 (3), 1154–1169. <https://doi.org/10.1016/j.enpol.2010.11.040>.
- Kannenberg, S.A., Sturchio, M.A., Venturas, M.D., Knapp, A.K., 2023. Grassland carbon-water cycling is minimally impacted by a photovoltaic array. *Commun. Earth Environ.* 4 (1), 1–8. <https://doi.org/10.1038/s43247-023-00904-4>.
- Lambert, Q., Bischoff, A., Cluchier, A., Cuffe, S., Gros, R., 2021. Effects of solar parks on soil quality, CO₂ effluxes and vegetation under Mediterranean climate. *Authorea Preprints*.
- Major Solar Projects List, 2023. Major Solar Projects List. Solar Energy Industries Association. <https://www.seia.org/research-resources/major-solar-projects-list>.
- Marrou, H., Dufour, L., Wery, J., 2013a. How does a shelter of solar panels influence water flows in a soil–crop system? *Eur. J. Agron.* 50, 38–51. <https://doi.org/10.1016/j.eja.2013.05.004>.
- Marrou, H., Guillioni, L., Dufour, L., Dupraz, C., Wery, J., 2013b. Microclimate under agrivoltaic systems: is crop growth rate affected in the partial shade of solar panels? *Agric. For. Meteorol.* 177, 117–132. <https://doi.org/10.1016/j.agrformet.2013.04.012>.
- McCall, J., Daw, J., Day, M., Galzki, J., Hanson, A., Mulla, D., Ross, B., 2023. PV Stormwater Management Research and Testing (PV-SMaRT): Final Technical Report (No. NREL/TP-6A20-87555). National Renewable Energy Laboratory (NREL), Golden, CO (United States).

- Minnesota Stormwater Manual, 2019. Minnesota Stormwater Manual: stormwater management for solar projects and determining compliance with the NPDES construction stormwater permit. Minnesota Stormwater Manual. https://stormwater.pca.state.mn.us/index.php/Stormwater_management_for_solar_projects_and_determining_compliance_with_the_NPDES_construction_stormwater_permit.
- Nair, A.A., Rohith, A.N., Cibir, R., McPhillips, L.E., 2023. A Framework to model the hydrology of solar farms using EPA SWMM. *Environ. Model. Assess.* <https://doi.org/10.1007/s10666-023-09922-0>.
- Pennsylvania Department of Environmental Protection, 2022. <https://www.dep.pa.gov/Pages/default.aspx>.
- Pisinaras, V., Wei, Y., Barring, L., Gemitzi, A., 2014. Conceptualizing and assessing the effects of installation and operation of photovoltaic power plants on major hydrologic budget constituents. *Sci. Total Environ.* 493, 239–250. <https://doi.org/10.1016/j.scitotenv.2014.05.132>.
- Shorabeh, S.N., Firozjaei, M.K., Nematollahi, O., Firozjaei, H.K., Jelokhani-Niaraki, M., 2019. A risk-based multi-criteria spatial decision analysis for solar power plant site selection in different climates: a case study in Iran. *Renew. Energy* 143, 958–973. <https://doi.org/10.1016/j.renene.2019.05.063>.
- State College Climate, 2023, October 3. State College Climate (United States of America). Climate Data. <https://en.climate-data.org/north-america/united-states-of-america/pennsylvania/state-college-18494/>.
- Wang, F., Gao, J., 2023. How a photovoltaic panel impacts rainfall-runoff and soil erosion processes on slopes at the plot scale. *J. Hydrol.* 620, 129522 <https://doi.org/10.1016/j.jhydrol.2023.129522>.
- Yavari Bajehbaj, R., McPhillips, L.E., 2023. Solar farm hydrology data. *HydroShare* <http://www.hydroshare.org/resource/57f374bfc33c4c449d136f790730c3de>.
- Yavari, R., Zaliwciw, D., Cibir, R., McPhillips, L., 2022. Minimizing environmental impacts of solar farms: a review of current science on landscape hydrology and guidance on stormwater management. *Environ. Res. Infrastruct. Sustainability* 2 (3), 032002. <https://doi.org/10.1088/2634-4505/ac76dd>.
- Yue, S., Guo, M., Zou, P., Wu, W., Zhou, X., 2021. Effects of photovoltaic panels on soil temperature and moisture in desert areas. *Environ. Sci. Pollut. Res.* 28 (14), 17506–17518. <https://doi.org/10.1007/s11356-020-11742-8>.

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Minimizing environmental impacts of solar farms: a review of current science on landscape hydrology and guidance on stormwater management

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Keywords: utility-scale solar, stormwater management, ground-mounted solar, renewable energy, sustainable solar development

Abstract

As solar energy becomes an increasingly cheap source of renewable energy, major utility-scale ground solar panel installations, often called ‘solar farms’, are rapidly growing. With these solar farms often covering hundreds of acres, there is the potential for impacts on natural hydrologic processes, including runoff generation and erosion. Here we review the current state of scientific research on the hydrology and water quality impacts of solar farms, as well as management recommendations for minimizing any impacts. The limited field measurements indicate the redistribution of soil moisture around solar farms, but the net impacts on runoff and erosion are less clear. Research focused on coupling solar farms with agriculture as ‘agrivoltaics’ demonstrates reduced evaporative water losses and associated crop stress, particularly in more arid regions. With regards to land and the stormwater management associated with solar farms, most US states currently do not have solar farm-specific recommendations and instead defer to standard stormwater management permits and guidance. In states with solar farm-specific guidance, typical recommendations include minimizing construction-related compaction, ensuring a high cover of perennial vegetation with minimal maintenance, and designing with pervious space between solar panel rows to promote infiltration of any runoff; in some cases, structural stormwater management like infiltration basins may be required. In general, solar farms can be designed to minimize the impact on landscape ecohydrological processes, but more research is needed to determine whether current recommendations are adequate. In particular, there is a need for more field research on less ideal sites such as those with higher slopes.

1. Introduction

The advancement of human civilization depends on energy. Societies are growing, and the standard of living is rising, resulting in a growing demand for energy. The use of fossil fuels as a major energy source has led to environmental pollution and global warming. In addition, fossil fuels are not renewable. In recent decades, there has been a search for cheaper, affordable and more environmentally friendly and sustainable energy sources (Gunerhan *et al* 2008, Shorabeh *et al* 2019).

Amongst sustainable energy sources, solar energy is favored, owing to its plenitude and increasing affordability. It is more abundantly distributed in nature than any other renewable energy source. Solar energy has widely and exponentially grown in the last couple of decades (US Energy Information Administration (EIA) 2020). Solar photovoltaic (PV) technology converts the Sun’s energy to environment-friendly electricity (Solangi *et al* 2011). This has been one of the most booming forms of renewable energy in recent years, due to technological advancements and favorable government policies that have made it increasingly affordable and accessible (Gunerhan *et al* 2008, Hassanpour Adeg *et al* 2018, Shorabeh *et al* 2019). PV development can also

be beneficial in terms of potentially supporting the reclamation of degraded land, economic opportunities, and rural electricity access. (Ravi *et al* 2016). It also avoids the greenhouse gas impacts, air quality concerns, and other sources of pollution caused by fossil fuels (Aman *et al* 2015, Hernandez *et al* 2014, Grigorescu *et al* 2019, Lambert *et al* 2021, Shorabeh *et al* 2019, Taha 2013, Vrinceanu *et al* 2019).

PV technology is deployed in various ways. One popular approach leverages the rooftops of residential or commercial buildings for solar panel installation, where solar panels are impervious panels of PV cells. Solar panel arrays mounted on the ground are another way of harvesting solar energy, particularly at a larger scale compared to residential rooftop solar. Utility-scale ground solar panel installations used for electricity generation of 1 MW or greater are commonly referred to as ‘solar farms’ (US Energy Information Administration (EIA) 2020). On solar farms, solar panels are mounted on metal supports, with panels arranged in long rows. The area under and between the panels could be paved, covered with gravel, bare soil, or vegetated. The interspace between the rows, as well as access paths or roads between clusters of rows, allows for maintenance as well as possible infiltration of water (Barnard *et al* 2017a, Gunerhan *et al* 2008, Zhu *et al* 2019).

Utility-scale solar energy development needs a lot of space, and its large-scale installation could potentially have some negative impacts on the environment, but this depends on the way that the solar farm is built and maintained (Hernandez *et al* 2019, 2014, Moore-O’Leary *et al* 2017). The area covered by solar farms can vary between 1 acre (0.40 ha) to several hundred acres, depending on the power generation capacity. The construction process of solar farms can require extensive landscape modification that could result in the modification of soil properties and vegetation (Aman *et al* 2015, Jacobson and Delucchi 2011). The addition of an impervious surface, as solar panels, could alter the site’s hydrology and impact erosion. Changes in vegetation and ongoing maintenance of the site can also impact soil carbon dynamics and habitat provision (Barnard *et al* 2017a, Choi *et al* 2020a, Gunerhan *et al* 2008, Moore-O’Leary *et al* 2017, Walston *et al* 2021). There is increasing interest in leveraging solar farms for the provision of additional ecosystem services or benefits beyond solar power generation. This could include planting of certain vegetation to create pollinator habitats (Blaydes *et al* 2021, Graham *et al* 2021, Walston *et al* 2021, 2018). The concept of ‘agrivoltaics’ involves leveraging the solar farm for agriculture, such as sheep grazing or crop cultivation (Weselek *et al* 2019).

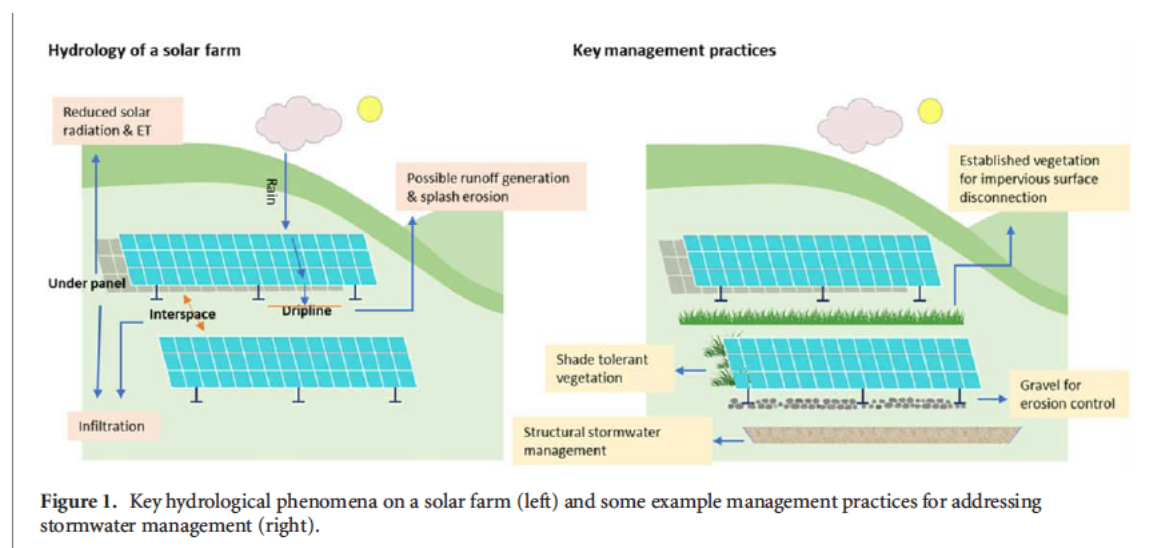
As solar energy becomes an increasingly cheap source of renewable energy, the number of solar farms is rapidly growing. As of 2022, there are approximately 5500 major solar projects across the US, with existing installations generating 55 GW, and projects under construction or in development generating 110 GW (Solar Energy Industries Association 2020). Thus, it is critical to ensure that these projects are implemented in the most sustainable way.

There is a small but growing body of scientific research seeking to understand the impacts of solar farms, specifically on landscape ecohydrology in a range of environmental and land conditions. Similarly, there are rapidly evolving guidance and/or regulations on best land development practices related to solar farm implementation. Thus, we seek to synthesize the current state of scientific knowledge and management recommendations, as well as to identify gaps. We review the current science on how solar farms impact landscape hydrology and related soil and vegetation characteristics, as well as review the current state of land and stormwater management guidance in US states with respect to solar farms.

2. Methods

In order to review the current science on solar farm hydrology, in mid-2022 we sought relevant scientific literature using Google Scholar and Web of Science to perform searches with the following key words: (solar farm, PV, or agrivoltaic) and (hydrology, stormwater management, soil moisture, runoff, or evapotranspiration). We have also followed references cited in these articles to identify additional relevant articles. This yielded 18 usable articles which are reviewed.

In addition, we reviewed available information on land and stormwater management recommendations from US states. In the US, most states have authority delegated from the US Environmental Protection Agency to oversee permitting processes related to land development under the National Pollutant Discharge Elimination System (NPDES). States may also choose to enact their own regulations relating to solar farm development and/or stormwater management. We searched the websites of US state agencies with jurisdiction over stormwater management regulations, in order to summarize the available rules and guidelines specific to stormwater management on solar farms. If we could not find stormwater management information specific to solar farms for a given state, we also attempted to contact the agency directly for information.



3. Review of scientific research on solar farm hydrology

Research on the landscape hydrology of solar farms is comprised of field-based and computational modeling studies. Field-based studies primarily address hydrologic components and landscape biophysical attributes, including soil moisture patterns, evapotranspiration, soil properties, and vegetation characteristics (table 1). Field studies span multiple continents and climatic zones, including Asia, North America and Europe. Modeling studies focus on simulating soil moisture, runoff generation, and erosion (table 2).

3.1. Solar farms and soil properties

Given that solar farms involve major construction activities during the site development process, there is potential for them to have impacts on soil properties and vegetation. Soil physical and chemical properties directly impact hydrologic processes, and thus we begin our review with understanding these impacts.

Some physical, chemical, and biological soil indicators can be lower on solar farms compared to semi-natural land cover types, depending on solar farm management strategies. Research on a solar farm in southern France with silty clay soils did not find differences in soil bulk density on solar farms as compared to semi-natural pinelands and shrublands, but did find a reduced water holding capacity (Lambert *et al* 2021). Research on a solar farm in Colorado, USA observed a greater coarse particle fraction on the solar farm as compared to an adjacent native grassland reference. The reason for the difference in particle size is likely the soil disturbance and vegetation removal during the construction phase of the solar farm, which causes erosion of the fine particles (Choi *et al* 2020a).

Some studies have found the carbon and nitrogen content to be lower in the soil on solar farms than in reference soils (Choi *et al* 2020a, Lambert *et al* 2021). Basal respiration and microbial biomass have also been measured at lower quantities on solar farms compared to reference land covers (Lambert *et al* 2021). However, at a solar farm on reclaimed cropland with meadow grasses, there were no significant differences in soil physical and chemical properties, as compared to a reference site (Armstrong *et al* 2016). There were some differences in soil biological indicators such as respiration, but the differences were not consistent throughout the year.

Some soil properties may also vary within the solar farm. Unsaturated hydraulic conductivity was found to be higher beneath solar panels on a solar farm in Colorado than at the edge or interspace area between panels (see the schematic of example solar farm in figure 1). The reason for this difference may be the reduced exposure to maintenance activities beneath the panel, which could induce compaction and reduce hydraulic conductivity (Choi *et al* 2020a). This in turn can impact patterns of soil moisture distribution, which is discussed later in section 3.4.

3.2. Solar farms, micrometeorology, and evapotranspiration

The presence of solar panels has the potential to alter multiple meteorological properties. They may change the balance of incoming solar radiation and emitted radiation, in turn altering soil temperature and evapotranspiration. The fact that they are typically mounted some distance above the ground and inclined may also affect wind dynamics. Additionally, the type and health of vegetation affects actual evapotranspiration (AET) rates, where vegetation may be influenced by the solar panels as well as by human management decisions.

Reduced solar radiation from shading has been documented beneath solar panels on solar farms in France, the United Kingdom, and Oregon and Nevada, USA. This results in lower mean daily soil and air temperatures

Table 1. Summary of the reviewed field-based studies on solar farm hydrologic phenomena, highlighting the basic study location and types of measurements made on hydrologic and related variables. An 'x' indicates that measurements were made for variables in the given category.

Source	Site characteristics			Types of measurements				
	Location	Climate zone	Solar farm info	Micro-meteorology	Soil Phys/Chem/Bio properties	Veg-etation	Soil moisture	Runoff
AL-agele <i>et al</i> 2021	Corvallis, Oregon USA	Mediterranean warm, cool summer climates	0.8 ha agrivoltaic vegetable farm with 18 degree panel tilt. Silty clay loam soil	x	—	x	x	—
Armstrong <i>et al</i> 2016	Swindon, United Kingdom	Oceanic climate	Land cover prior to construction: the field site was arable cropland and was sown with a species-rich meadow mixture After construction: the control and interspace of the solar farm were re-seeded with species-rich meadow mixture	x	x	x		
Barron-Gafford <i>et al</i> 2019	Tucson, Arizona, USA	Arid climate, hot desert	Agrivoltaic site with crops (tomatoes, jalapenos, and chiltepin plants). Native soil was replaced with an organic garden blend (organic compost and sandy soil) Age of the solar site: less than one year	x	—	x	x	—
Choi <i>et al</i> 2020a	Northern Jefferson County, Colorado, USA	Cold semi arid	The treatment site is revegetated with native grasses similar to the undisturbed condition (control point) Surficial soils at the solar site are paleosols with clay-enriched subsoil Age of the solar site: 8 years	x	x	—	x	—
Elamri <i>et al</i> 2018a, 2018b	Montpellier, France	Mediterranean hot summer	Agrivoltaic system (lettuce) with varying panel density and tilt. oil type is loamy clay deep alluvial soil (same site as Marrou <i>et al.</i> with updated ability for variable panel tilt)	x	—	—	x	—
Hassanpour Adeh <i>et al</i> 2018	Corvallis, Oregon USA	Mediterranean warm, Oregon USA	Agrivoltaic site with pasture. The soil classification for both the control and agrivoltaic systems is Woodburn silt clay Age of the solar site: 2 years	x	—	x	x	—
Lambert <i>et al</i> 2021	Southern France	Mediterranean hot summer climates	Soil type of solar farms are carbonatic pedofeatures Different control points with a land cover of pinewood, shrubland and abandoned vineyards were selected	—	x	x	x	—

(continued on next page)

Table 1. Continued Summary of the reviewed field-based studies on solar farm hydrologic phenomena, highlighting the basic study location and types of measurements made on hydrologic and related variables. An 'x' indicates that measurements were made for variables in the given category.

Source	Site characteristics			Types of measurements				
	Location	Climate zone	Solar farm info	Micro-meteorology	Soil Phys/Chem/Bio properties	Veg-etation	Soil moisture	Runoff
Marrou 2013b <i>et al</i> 2013a ,	Montpellier, France	Mediterranean hot summer climates	Agrivoltaic system (lettuce and cucumber) with varying panel density and a fixed 25 degree tilt. The soil type is loamy clay deep alluvial soil (same site as Elamri <i>et al</i> 2018a)	x	—	x	x	—
Uldrijan <i>et al</i> 2021	South Moravian Region, Czech Republic	Oceanic climate	The soil has textures of loamy-sand to clay-loam, vegetated with perennial grass mixture Age of the solar site: 7 years	—	—	x	—	—
Wu <i>et al</i> 2022	Northwestern China	Arid climate, cold desert	Solar farm with a panel tilt of 37.5 degrees, where a panel row is comprised of two adjoining sub panels with a 3 cm gap. Mixed gravel and sand soil substrate	—	—	—	x	—
Yue <i>et al</i> 2021	Western China	Arid climate, cold desert	The soil material is loess or gravel, soil texture is mainly sandy loam and light silt loam The main plant species are shallow-rooted plants Some of panels are fixed and some are rotating	x	—	—	x	—

Table 2. Summary of reviewed studies performing hydrological modeling of solar farms.

Source	Solar farm info	Modeling approach	Target variable(s)
Barnard <i>et al</i> 2017a	Three solar farm sites in west Texas and one solar site in Georgia USA (humid subtropical climate)	Flo-2D/HEC-HMS maps of maximum flow depth and velocity	The final products are
Cook and McCuen 2013	No specific geographic location Different scenarios: • Slope 1%–5% • Soil type B and C • Panel angle 30, 45 and 70 • Vegetation type: bare ground	Custom model in MATLAB (Water balance, Manning's Eqn)	Runoff depth, peak flow, erosion potential
Edalat 2017	Two solar farms in Nevada USA (arid climate) • Urban • Outside urban area	HEC-HMS	Runoff depth/peak flow
Elamri <i>et al</i> 2018b	Agrivoltaic solar farm in Montpellier, France (mediterranean hot summer)	Hydrus 2D with custom AVrain module to simulate rain redistribution of panels	Solar panel rain redistribution /runoff, soil moisture
Pisinaras <i>et al</i> 2014	Low, medium, and high intensity solar the farm scenarios for sub-basins in 1%–5% of Vosvozis River watershed in northern Greece (Mediterranean hot summer climate) Solar farm scenarios replaced existing agricultural land use	SWAT	Surface runoff, infiltration, evapotranspiration
Walston <i>et al</i> 2021	Midwest United States (hot summer, continental climate) land use scenarios: • Agriculture scenario • Solar-turfgrass scenario • Solar-native grassland scenario	InVEST ecosystem services model	Sediment retention, water retention
Wu <i>et al</i> 2022	Solar farm in northwestern China (arid, cold desert climate)	Custom model using energy balance, AVrain and single bucket water balance	Soil moisture and temperature

below the panels in comparison to full sun reference sites during the spring and summer (AL-agele *et al* 2021, Armstrong *et al* 2016, Hassanpour Adeh *et al* 2018, Marrou *et al* 2013b, Yue *et al* 2021). Remote sensing of land surface temperature at a solar farm has also indicated overall reductions in soil temperature across the site as compared to pre-development data, though this approach could not explicitly evaluate changes below the panels (Edalat 2017). Wind and humidity changes were not as consistent. Wind speed and vapor pressure deficit did not change relative to solar panels at a solar farm in France (Marrou *et al* 2013b). However, wind speed, direction, and relative humidity were all altered around solar panels, as compared to the reference site at a solar farm in Oregon (Hassanpour Adeh *et al* 2018), and vapor pressure deficit decreased under solar panels on solar farms located in the United Kingdom and Arizona USA (Armstrong *et al* 2016, Barron-Gafford *et al* 2019).

There can be temporal variability in how solar farms affect meteorological properties and resulting soil dynamics. For example, solar panels decreased the soil temperature beneath the panels compared to reference sites, but these differences were more substantial in spring versus summer (Lambert *et al* 2021). Increases in soil temperature beneath solar panels relative to reference sites have also been observed during autumn and winter periods at solar farms located in the United Kingdom and western China, when solar panels may help prevent loss of longwave radiation (Armstrong *et al* 2016, Yue *et al* 2021). Remote sensing observations of the land surface temperature in Nevada found temperature differences to be greatest in winter when the Sun was lower and the shadows from solar panels were larger (Edalat 2017).

Reductions in solar radiation generally translate into reduced potential evapotranspiration (PET) under solar panels (Elamri *et al* 2018a, Hassanpour Adeh *et al* 2018). Solar farm impacts on evapotranspiration dynamics have been investigated in depth on prototypes of agrivoltaic systems in France, testing two crops (cucumber and lettuce) and two solar panel configurations (full panel density vs half density (Marrou *et al* 2013a). Results show that PET and AET were higher in the full Sun reference locations compared to the solar farm agrivoltaic sites. The reduction in AET was slightly more at the full density solar farm as opposed to the half density site, and differences also varied by crop type. For the lettuce agrivoltaics site, AET over the measured growing period was 103 mm at the full Sun reference, but reduced to 81 and 79 mm for the half density and full

density solar farm sites, respectively. Similarly, at the cucumber agrivoltaics site, AET was 178 mm at the full Sun reference, but reduced to 153 and 145 mm at the half density and full density solar farm sites, respectively. In general, ET fluxes were more affected in spring than in summer, indicating temporal variability in the solar panel influence (Marrou *et al* 2013a). The ratio of transpiration to evaporation also changed, increasing 3 – 4 times in the shaded area of the solar farm sites.

Additional research at this same agrivoltaic site explored the impact of variable panel tilting/tracking on solar radiation and ET (Elamri *et al* 2018a). While there was still a net reduction in solar radiation and ET under panels with panel tracking, it led to much less heterogeneity than at the sites with a fixed panel orientation.

3.3. Solar farms and vegetation

As with soil properties, vegetation on solar farms is a function of both initial human management decisions regarding the initial solar farm development, and ongoing operations and maintenance decisions on the solar farm. It is also affected by interactions with site soil properties and hydrology. Vegetation is explicitly leveraged as a stormwater management practice, as described later in this review, and is a critical managed element of agrivoltaics operations where solar farms are leveraged for the additional co-benefits of crop production. Thus we feel it is important to review what is known about changes in vegetation on solar farms.

Existing field research has focused on the assessment of vegetation coverage, biomass, and diversity, as well as on interactions with hydrologic processes via water use efficiency or water productivity. Findings are quite variable in these limited studies. Surveys of a solar farm (non-agrivoltaic site) in France largely found no major differences in plant community composition and coverage, relative to nearby reference shrubland and pineland sites. There was a slight increase in the relative abundance of shadow-tolerant plant types under solar panels (Lambert *et al* 2021). At a reclaimed brownfield site in the Czech Republic, where the land was sown with a meadow grass mixture during solar farm development, differences in plant composition within the solar farm were observed in a survey eight years after the initial development (Uldrijan *et al* 2021). A greater abundance of taller native perennial grasses was documented in the interspace between panel rows, where more shade-tolerant species and sometimes invasive grasses were observed beneath panels. At a solar farm in the United Kingdom, reduced plant species diversity was observed under solar panels, with reference and panel interspace areas dominated by forbs and legumes (Armstrong *et al* 2016).

Both increases and decreases in vegetation biomass have been documented under solar panels, depending on the climatic zone. In the areas with lower solar radiation (solar farms in the United Kingdom and the Czech Republic), reduced vegetation coverage and reduced biomass (up to four times lower) have been documented beneath solar panels, relative to panel interspace or reference areas (Armstrong *et al* 2016, Uldrijan *et al* 2021). However, the results of research in the solar farm located in Oregon show 126% more dry biomass beneath solar panels relative to the interspace zone and 90% more dry biomass relative to the reference site (Hassanpour Adeg *et al* 2018). This site is less energy-limited. Thus, the shading of solar panels helps to reduce ET losses and in turn to maximize the water use efficiency of plants, as well as to increase biomass. At crop agrivoltaic sites in Oregon and France, some reduction in crop yield and biomass has been observed under panels relative to nearby reference sites (AL-agele *et al* 2021, Elamri *et al* 2018a). At sites with solar panel tracking, biomass was only 16% less than the reference, compared to 30% or greater reductions at fixed panel sites (Elamri *et al* 2018a).

More efficient water use has been observed under solar panels in multiple cases, mainly because of the shading and reduced solar radiation and PET under the panels. This is particularly evident in locations abundant in solar radiation. In an agrivoltaics solar farm in Arizona, USA, the shade of the solar panels reduced plant drought stress and led to greater crop and food production (Barron-Gafford *et al* 2019). More efficient water use was also observed for lettuce crops in an agrivoltaics solar farm in France. Coverage of soil by crops was found to be important in reducing soil evaporation and maximizing the availability of water for transpiration and biomass production (Marrou *et al* 2013a). Water productivity also improved in the shade of panels at a tomato agrivoltaic site located in Oregon (AL-agele *et al* 2021). Modeling of water and vegetation dynamics at agrivoltaic sites in France successfully reproduced field data on rain and soil water redistribution, and allowed for the additional scenario exploration of plant-water interactions and optimization. The modeled scenarios indicated that the tilting of solar panels could help to minimize water interception and the associated redistribution of water. The scenarios also indicated that agrivoltaics could improve water productivity relative to more traditional agriculture, with only small reductions in crop yield (Elamri *et al* 2018a, 2018b).

3.4. Impact of solar panels on soil moisture distribution

On solar farms, the impervious surface of solar panels intercepts precipitation and drains the water into the interspace between panels. Previously discussed changes in evapotranspiration and soil physical and chemical properties can interact with this altered surface hydrology to cause some heterogeneity in the soil moisture content on solar farms.

Field measurements of the soil moisture on solar farms have often been focused on key locations relative to the solar panels. These have included the interspace area fully open to the sun between panels, under the lower front edge of the panel or ‘dripline’, underneath the center of the panels, and at the back (higher) edge of the panels where there is partial Sun (figure 1). Sometimes measurements may also be made at a control or reference area outside the main array of panels. At a solar farm in western Oregon, USA on silt clay soils, the soil beneath the center of solar panels was consistently wettest, followed by soil under the back edge of solar panels, and nearby reference soils, with the interspace soils being driest. At a 0.6 m depth, soil under the center of the panels remained near saturation ($\sim 30\%$ volumetric water content (VWC)), whereas the interspace area depleted from $\sim 30\%$ to $\sim 20\%$ VWC by the end of the growing season (Hassanpour Adeg *et al* 2018). Similar patterns have been observed at solar farms in China (Wu *et al* 2022, Yue *et al* 2021). Soil moisture at a northwest China site was wettest (10% – 20% VWC) at the main dripline at the front of panels as well as under the center of the panel row where a small gap in panels was located; soils at the back edge of panels and nearby reference soils were driest (5% – 10% VWC; Wu *et al* 2022). At an arid western China solar farm, soil moisture was consistently higher under panels— 14.7% higher under fixed tilt panels compared to 11% higher under variable tilt panels (Yue *et al* 2021). Soil moisture was also consistently higher under solar panels at an agrivoltaics site located at Arizona, USA, as compared to an agricultural control site (Barron-Gafford *et al* 2019). At a solar farm in Colorado, USA (cold semi-arid climate) with paleosols and clay subsoil, some soil moisture variability was observed. Dripline soils were consistently higher (up to 20% – 30% VWC), especially following rain events (Choi *et al* 2020a). However, substantial variability in soil moisture at all locations relative to solar panels led to a lack of statistically significant differences. The reference site at nearby native grassland was consistently lower in moisture ($\sim 5\%$). At an agrivoltaic site in France, higher soil moisture was observed at panel driplines, while soil moisture was lower under the panels and in the interspace (Elamri *et al* 2018b). Another solar farm in France did not demonstrate differences in soil moisture under solar panels compared to the interspace, but did observe overall reduced soil moisture at the solar farm sites as compared to a shrubland reference (Lambert *et al* 2021). Overall, the main panel dripline at the front of solar panel rows is consistently wetter, and interspace zones tend to be drier. However, under panel soil moisture may vary depending on the balance of evapotranspiration and runoff contributions, due to the climate and panel design.

There have also been some efforts to model soil moisture dynamics on solar farms. These studies have created or leveraged models of rain redistribution from solar panels, and then combined this with various approaches of water and energy balance representation to simulate soil moisture (Elamri *et al* 2018b, Wu *et al* 2022). In both cases, there was reasonable agreement between observed and simulated soil moisture. Suspected causes of inaccuracy included challenges in representing the complex energy dynamics under solar panels that influence evapotranspiration (Wu *et al* 2022) as well as challenges in the accurate representation of water redistribution (Elamri *et al* 2018b).

3.5. Solar farms and runoff

To our knowledge, at the time of the writing of this review, the evaluation of runoff generation has occurred only in published modeling-based studies. Many of these studies leverage existing modeling programs, with certain modifications used to represent the unique land cover type of the solar panels. None of these published studies, to our knowledge, have validated their models with field data specific to solar farms.

HEC-HMS (US Army Corps of Engineers 2021) has been leveraged in multiple studies. In one study, the runoff on a solar farm was simulated using a linked model which used a combination of Flo-2D and HEC-HMS (which uses a one-dimensional approach). To simulate the flow from upgradient catchments to the solar farm catchment, HEC-HMS was used. USDA Natural Resource Conservation Service Curve Number methods and shallow water equations were used to predict and route stormwater runoff across FLO-2D grids. The results were reported as maps of maximum flow depths and velocities (Barnard *et al* 2017a). HEC-HMS has also been used to study hydrologic dynamics in a Nevada, USA (arid climate) solar farm (Edalat 2017). It is shown that regardless of the orientation and tilt angles, runoff volume increases after solar panel installation. Impacts on peak flow are more variable, with the orientation of panels either increasing or decreasing peak flow rates. The results indicate that the panels also noticeably change the rain distribution onto the land surface. Therefore, panel orientation and tilt angles are important factors that need to be considered in stormwater channel design to carry runoff peak flow. One major limitation of this study was that solar panels were represented as an impervious surface on the ground, and infiltration could not be permitted under the panels, as would occur at an actual site; thus this approach likely overestimates runoff (Edalat 2017).

SWAT has also been leveraged for assessing the impact of solar farms on watershed hydrology (Pisinaras *et al* 2014). For a watershed in northern Greece, scenarios were implemented that induced land use change from agriculture to solar farms in 1 or 5% of the watershed area. Solar farm implementation was represented using soil physical property changes, curve number increase associated with imperviousness, ground cover change from cultivated to bare soil, and reduced solar radiation. The model demonstrated increased surface runoff

and percolation, and decreased ET due to solar panel implementation, but these changes were not significant at the watershed scale. However, there is the potential for local-scale impacts. For example, there were increases of ~ 100 mm in surface runoff for a given sub-basin, even for a low impact scenario of solar farm implementation (Pisinaras *et al* 2014).

Other research has relied on custom-built models for representing solar farms (Cook and McCuen 2013). A model written in MATLAB was based on the creation of NRCS type II storms for precipitation (hyetograph) inputs. A simple water balance for each land surface cell was used to allocate precipitation to storage or loss (runoff). Manning's equation was used to estimate runoff velocity and the associated kinetic energy relating to splash erosion. Model scenarios were constructed for a 30 cell grid solar farm, where each cell could have a portion allocated as wet, dry, or interspace. A variety of characteristics were manipulated to simulate changes in soil types, solar panel spacing, vegetation roughness, etc. The results indicated that the addition of solar panels over a grassy field does not change the volume of runoff, the peak discharge, nor time to peak. In general, it was not anticipated that structural stormwater management would be required to prevent adverse impacts (Cook and McCuen 2013).

Some US states, such as Minnesota, have recommended a simple modification to the calculation of impervious surface used in typical runoff modeling approaches for stormwater management planning. Minnesota's recommendation for the modification of runoff calculations leverages the ratio of impervious to pervious surface, where the pervious surface considers both the interspace area as well as the area directly below the panels. Runoff depth associated with this impervious to pervious ratio, as well as soil type, is determined using an Excel tool that leverages the output of an extensive series of models generated in XP-SWMM (Minnesota Pollution Control Agency 2019).

3.6. Solar farms and erosion

Research on the impacts of solar farms on erosion is quite limited. Some modeling results suggest solar panels can increase erosion. The energy and velocity of water draining from the panels is higher, which could cause erosion in soil below the base of the panels, especially if the interspace is bare. Increases (up to 10 times) of kinetic energy were simulated, which could lead to erosion and the need for erosion control measures, but this modeling effort was not validated by field measurements (Cook and McCuen and 2013).

A larger-scale modeling assessment has quantified changes in erosion and associated sediment loss, along with multiple other ecosystem services for hypothetical solar farms in the Midwestern US. These solar farm scenarios focused on vegetation, comparing hypothetical solar farms with native grassland or turfgrass with baseline agricultural land use. Modeling with InVEST, which leverages the revised universal soil loss equation, estimated sediment export under the solar-native grassland scenario to be 0.007 tons/ha/year, which was a reduction of over 95% and 77% compared to the agriculture and solar-turfgrass scenarios, respectively (Walston *et al* 2021). However, erosion estimates were based largely on landscape characteristics such as vegetated cover or slope and did not explicitly represent the fact that solar panels are elevated off the ground.

This existing work largely focuses on the potential for erosion on solar farms after initial construction. However, construction of solar farms can require substantial land manipulation. Thus, it is also important to consider this in erosion estimates, and manage this impact appropriately (see discussion in section 4). In addition to erosion associated with runoff, aeolian erosion is a concern in more arid environments, particularly when presence of vegetation is limited (Ravi *et al* 2016).

4. Review of guidance from US states on solar farm development and stormwater management

In our review of the guidelines and rules of different US states regarding stormwater management on solar farms, a major finding was that most states (close to 30) do not have any guidance for stormwater management specific to solar farms. For ten states, no definitive information was found online and no answer was received to email inquiries, and it is assumed that there is no solar farm specific guidance. In general, these states without specific guidelines defer to their standard rules regarding construction and stormwater management. This typically means that for construction that disturbs a certain area of land (often specified as 1 acre), the solar farm developer would need to follow requirements under the construction general permit for stormwater management. There also may be post-construction stormwater management requirements. The management of construction-related stormwater impacts is required to be managed by states or the US Environmental Protection Agency (US EPA) under the EPA's National Pollution Discharge Elimination System (NPDES) (US EPA 2015).

Twelve US states currently have solar farm-specific guidance relating to managing stormwater (table 3). These states are largely located in the north-central, eastern, and northwestern US. Guidelines from these states rely heavily on 'low impact development' practices (Davis 2005). This involves minimizing initial impacts on

the site during the construction process, as well as strategically planned development and site operations that maintain the natural characteristics of the land to mitigate stormwater. The stormwater management functions desired involve runoff volume reduction via infiltration and, to a lesser degree, evapotranspiration; these processes are in turn dependent on soil properties and vegetation. The reduction of erosion and/or retention of sediment relies on reducing the velocity of runoff through infiltration and enhanced surface roughness, particularly from vegetation (Davis *et al* 2012).

Some guidance relates to the initial site selection process for the solar farm. It is recommended to avoid soils with a slip potential, and well-draining soil types are ideal. Lesser sloped sites are ideal, though there is substantial variability in the recommended slope thresholds (e.g. Maryland recommends 5% or less, while other states recommend less than 10%). With considerations such as the slope or soil hydrologic class, certain categories (e.g. poorly draining soils or higher slopes) are generally permissible for solar farms, but would require additional structural stormwater management to be added (discussed further below).

During the construction process, it is recommended that soil compaction and disturbance be minimized, in order to maintain the soil's natural ability to infiltrate runoff. It is also critical to implement temporary erosion and sediment controls to prevent any impacts during the construction process. This may include erosion control socks, temporary sedimentation basins, or mulching the bare soil surface.

Another group of recommendations relates to how the solar farm site is designed. A key stormwater management practice mentioned by most states with specific guidance is to maintain a certain interspace distance between rows of solar panels. This leverages the 'low impact development' principle of disconnecting impervious surfaces. The pervious interspace between solar panel rows serves to promote infiltration of any runoff and the retention of eroded sediment. In this interspace, as well as under the panels, it is often recommended to maintain a certain proportion of vegetation cover on the site, at least 85% – 90%. A deep-rooted perennial vegetation cover, typically grasses, forbs, or legumes is recommended to facilitate infiltration and assist with erosion control. This may be satisfied by minimizing the impact to existing vegetation, or may be facilitated by seeding. Crop production may also occur, but additional considerations may be needed to ensure that harvesting does not facilitate increased runoff or erosion. It is also important to promote the establishment of more shade-tolerant vegetation under the panels. Minimal mowing, pesticide, or herbicide application is recommended.

The additional practice recommended in some cases is structural stormwater management. As noted above, these sorts of structural practices may be required for specific cases where a site has a high slope or poorly draining soils. Some structural practices are focused on runoff volume reduction via enhanced infiltration, and include features like infiltration basins or infiltration trenches. Other structural practices may be focused on erosion prevention and sediment control and involve stone drip or splash pads near the dripline area under solar panel rows.

5. Discussion and conclusions

5.1. Insights from ecohydrologic research on solar farms

There is a small but growing body of work characterizing how solar farm development changes soil properties, vegetation, and hydrologic processes. Most existing work focuses on soil properties, vegetation, soil water, and micrometeorological characteristics or evapotranspiration; there is no published work yet in the academic literature, to our knowledge, documenting the direct measurement of runoff on solar farms.

The results of scientific research vary from findings of no net impact of solar farms on these ecohydrological properties to detection of some impacts. Field soil moisture measurements often demonstrated variability with respect to the solar panels. These changes in soil moisture relative to panels demonstrate the impact of panels on solar radiation, runoff redistribution, and the corresponding evapotranspiration. Particularly in regions where evapotranspiration is not energy-limited (e.g. warm arid regions), there is a climatic sweet spot where the shading of solar panels can help reduce evapotranspiration and maximize water efficiency and facilitate enhanced crop production in association with solar farms (Barron-Gafford *et al* 2019, Hassanpour Adeg *et al* 2018). Results from agrivoltaic systems indicate that crops can still achieve high yield under the fluctuating shade of these systems (Marrou *et al* 2013a). However, more extensive research is merited in agrivoltaic systems across a range of climate settings and crop types.

In wetter climates, there is an interest in keeping soils from reaching sustained levels of saturation and the associated runoff generation. Solar panels introduce heterogeneity in the soil moisture distribution, with precipitation accumulating along the dripline at the lower edge of the panels. It is essential that appropriate management practices are implemented to prevent this heterogeneity from manifesting in increased runoff and erosion generation. Variable panel tilting may also be considered to reduce the redistribution of water.

Table 3. Example guidelines from US states regarding stormwater management on solar farms. The table is not comprehensive of every guideline for all listed states, but provides examples of the range of guidelines currently available.

Category	Recommendation	Source of example
Site conditions		
Site slope	Ideally <5%; >5% requires various additional management considerations. For slopes >8%, additional management needed to maintain sheet flow and prevent erosion. <10% is favorable; additional management considerations if >10%.	Maryland (MA DOE 2021) North Carolina (NC DEQ 2018), Rhode Island (RI DEM 2021) Pennsylvania (PA DEP, 2019)
Soils	For soils with a depth to bedrock of 12" or less, plans must show that soil will be enhanced by the addition of at least 4" of top soil. Sites with soils having a slip potential should be more closely evaluated for any geotechnical issues—especially in areas with moderate to steep slopes. 2. Soil compaction should be avoided.	New Hampshire (NH DES 2020) Pennsylvania
Considerations during construction		
Considerations during construction	To minimize disturbance and compaction, construction vehicles and equipment should avoid interspace areas during installation of the solar panels to effectively use interspace later for impervious disconnection/infiltration. Erosion and sediment control practices are needed. Temporary erosion control, such as mulch, must be put on exposed soil at the site to prevent erosion during rain events until vegetation is established. Avoid soil compaction and/or topsoil removal. If the soil is compacted or removed, it should be amended to return to its pre-development condition.	Maryland Massachusetts (Mass DEP 2017), Minnesota (MN PCA, 2021), New Hampshire Massachusetts, New Hampshire, North Carolina
Post-construction stormwater management		
Modeling runoff from impervious area	The calculation of water quality volume depends on the slope (if >15%, then panels are an effective impervious area, if not then the evaluation of vegetated areas is emphasized). For water quality and water quantity calculations, solar panels are considered disconnected impervious surfaces. Curve number adjustment is permitted to account for infiltration under impervious panels. With certain steeper slope + soil drainage classes, there cannot be the assumption that infiltration will occur under panels. Solar panels are not considered impervious surfaces, so they do not need to be considered in the calculation of impervious cover at a site.	Connecticut (CT DEEP 2020) Minnesota, Virginia (VA DEQ 2022) New Hampshire New Jersey (New Jersey Legislature 2021)
Panel orientation	Parallel orientation of the solar panels is recommended with respect to slope, in order to prevent flow concentration. If not, runoff should be directed to infiltration practices. The orientation of panels should be considered with respect to drainage pattern, flow concentration, drainage area, and velocity.	Rhode Island Connecticut
Vertical clearance of panels	< 10 feet in order to minimize erosion at the dripline.	Connecticut, Massachusetts, North Carolina, Ohio (OH EPA 2019), Pennsylvania
Impervious disconnection	In general, all states with solar-specific stormwater guidance leverage the disconnection of the impervious surface (i.e., solar panel rows) with well-established vegetation as a key stormwater management strategy, under certain site conditions. More details are noted in the examples below. The vegetated interspace area receiving runoff must be equal to or greater in length than the disconnected surface (e.g., the width of the row of solar panels). Runoff must sheet flow onto and across vegetated areas to maintain the disconnection. Solar panel rows are spaced in a manner to allow sunlight penetration sufficient to support vegetation between the solar panel rows. Pervious space is required between rows of panels. This allows for the use of the 'disconnected impervious credit method', which often results in a reduction in the water treatment volume required. Under some conditions such as the existence of an uncompacted soil profile, dense and healthy vegetation maintenance, it is possible to easily manage the runoff from panels by disconnection. The disconnection length depends on the soil type, where well-draining soils require a shorter interspace (e.g. 1:1 solar panel to interspace distance along the slope) compared to more poorly draining soils.	Maryland, North Carolina, Pennsylvania, Rhode Island Massachusetts, Rhode Island Minnesota Ohio

(continued on next page)

Table 3. Continued Example guidelines from US states regarding stormwater management on solar farms. The table is not comprehensive of every guideline for all listed states, but provides examples of the range of guidelines currently available.

Category	Recommendation	Source of example
Site conditions		
Vegetation	In areas receiving disconnected runoff, groundcover vegetation must be maintained in good condition and should be protected from future compaction (e.g., by planting shrubs or trees along the perimeter). Include cool-season, warm-season, shade-resistant, and legumes as necessary to develop a dense, year-round groundcover that accounts for differences in the temperature and shading from panels.	Maryland
	Utilize low- and slow-growing grass varieties to reduce compaction and damage from frequent mowing. Low maintenance grass mixture recommended. The use of fertilizers, pesticides, and herbicides should be minimized.	North Carolina, Ohio, Rhode Island
	>90% deep-rooted perennial vegetative cover with a density capable of resisting accelerated erosion and sedimentation is required. If mowed, do not cut to < 4 in. In agrivoltaic applications, this may include hand-harvested or small machine-harvested crops.	North Carolina, Ohio, Rhode Island
	There should be at least 85% coverage. Maintain the vegetation height that maximizes sheet flow - no shorter than 4" and not taller than 12" (grass) or 18" (meadow).	Pennsylvania
		Rhode Island
Post-construction structural stormwater management	When the slope >5%, spreaders, terraces, or berms may be used to prevent concentrated flow and promote infiltration. When the slope >10%, more extensive stormwater management is required.	Maryland
	If the disconnected interspace is not adequate for the volume reduction of runoff or other site conditions merit it, other types of permanent stormwater management for non-erosive conveyance of runoff must be constructed, such as infiltration trenches or berms, wet sedimentation basins, or sand filters.	Connecticut, Massachusetts, Minnesota, Pennsylvania
	A stone drip pad to prevent erosion at the dripline, if panels have a fixed inclination.	Ohio
	Where panels are not oriented generally parallel with the slope and/or where slopes are >8%, runoff needs to be either intercepted by stone trenches for infiltration and/or directed non-erosively to an infiltration practice. Add scour control if instances of erosion/scour develop. Regular inspection and maintenance of infiltration practices is required, and to look for erosion	Rhode Island
	For a solar array in an open field, it is expected that the designer will show compliance with flow control related requirements by using infiltration and/or dispersion type management practices	Washington (Washington State Department of Ecology 2021)

At the time of this review, we were unable to find any study that directly evaluated runoff generation on solar farms through field measurement. Thus, we are still lacking critical insight into whether solar farms change runoff generation, and whether existing site and stormwater management practices are adequate to prevent adverse impacts. As a result, existing hydrologic models of solar farms are largely uncalibrated. There is also a bias in the sort of sites being evaluated. In general, existing environmental research on solar farms has focused on more ideal sites, i.e. those on sites with lower slopes and well-draining soils. Thus, we are neglecting sites that could be more vulnerable to changes in hydrologic processes with solar farm development.

In general, there is still also a need for simultaneous evaluation of multiple environmental co-benefits from solar farm land management, considering how certain vegetation or crop choices could help manage runoff, but also provide habitat or food.

5.2. Connecting observed phenomena to management decisions

While there are some environmental conditions that are linked to the inherent characteristics of ground-mounted solar panels (e.g. that there will be at least some level of shading and interception of water from an inclined panel above the ground), many phenomena can be influenced strongly by specific decisions in how the solar farm is constructed and managed.

Changes in certain soil properties (e.g. the reduction in soil organic matter) between solar farms and reference sites indicate the impacts of initial solar farm development, such as some removal of soil and/or vegetation and regrading of soil. This is something that can be changed by a more careful development process. Other soil property changes in different parts of the solar farm (under panel versus interspace) indicate the impacts of continued maintenance between the panels, such as mowing, that may induce some compaction. Thus, these observed detrimental impacts should be addressed as solar farm development guidance is developed. There are opportunities to select management practices that minimize adverse impacts (e.g. soil compaction) and maximize additional benefits- for example, leveraging sheep grazing for vegetation management in lieu of frequent mowing.

5.3. Key gaps in regulatory/management approaches and scientific knowledge

Most states in the US currently rely on construction general permits for guiding solar farm development, which may not be adequate for the unique design of solar farms (Great Plains Institute 2021). Only 12 of 50 US states had solar-specific stormwater management guidance, as of the writing of this review. The management practices currently recommended largely leverage low impact development practices of disconnection of the solar panel impervious surface, well-developed shade-tolerant vegetation, and minimal impact of construction practices on soil properties. Where necessary, given site conditions or solar panel configuration, structural stormwater practices such as infiltration practices are recommended. These recommendations are an important start, but validation is needed to confirm that these current practices are adequate, and appropriately tailored to the site conditions. There is a particular lack of guidance relating to appropriate stormwater management practices for solar farms in arid environments (table 3).

Given that runoff volume and quality are key metrics in the stormwater regulatory realm, it is a major gap that there is a lack of field research studying runoff on solar farms. It is also critical that hydrologic modeling approaches be improved to appropriately represent the unique design of solar panels, in that there is an impervious surface with the ability to infiltrate water underneath. In particular, approaches are needed that are simple enough to be widely implemented by those personnel preparing runoff calculations and associated permits for proposed solar farm development.

Though this review focused on hydrology and stormwater management, it is critical that future research and management consider simultaneous evaluation of some of the many other ecosystem services (or dis-services) that could be provided by solar farms (Moore-O'Leary *et al* 2017). The role of solar farms (and how precisely they are developed) can also be explored further within the food-energy-water nexus (Lee *et al* 2021). Hernandez *et al* recently proposed a framework of 'techno-ecological synergy' which pushes us to think more broadly about how to implement renewable energy technologies where they will minimize ecological impact and maximize additional co-benefits (Hernandez *et al* 2019). Thus, instead of simply considering how to minimize the environmental impacts for an already proposed solar farm, we need to also think more broadly about what are the most optimal sites for this type of development. This includes considering how to leverage existing impervious surface for the implementation of utility-scale solar energy, such as parking lots or warehouses. With these multi-criteria and system frameworks, we can ensure that solar farms are developed in the most sustainable manner.

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Data availability statement

No new data were created or analysed in this study.

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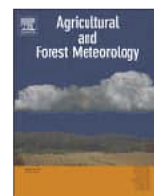
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References

- AL-agele H A, Proctor K, Murthy G and Higgins C 2021 A case study of tomato (*Solanum lycopersicon* var. Legend) production and water productivity in agrivoltaic systems *Sustainability* **13** 2850
- Aman M M, Solangi K H, Hossain M S, Badarudin A, Jasmon G B, Mokhlis H, Bakar A H A and Kazi S N 2015 A review of safety, health and environmental (SHE) issues of solar energy system *Renew. Sustain. Energy Rev.* **41** 1190–204
- Armstrong A, Ostle N J and Whitaker J 2016 Solar park microclimate and vegetation management effects on grassland carbon cycling *Environ. Res. Lett.* **11** 074016
- Barnard T, Agnaoui M and Barbis J 2017 Two dimensional modeling to simulate stormwater flows at photovoltaic solar energy sites *J. Water Manage. Model.* **25**
- Barron-Gafford G A *et al* 2019 Agrivoltaics provide mutual benefits across the food-energy-water nexus in drylands *Nat. Sustain.* **2** 848–55
- Blaydes H, Potts S G, Whyatt J D and Armstrong A 2021 Opportunities to enhance pollinator biodiversity in solar parks *Renew. Sustain. Energy Rev.* **145** 111065
- Choi C S, Cagle A E, Macknick J, Bloom D E, Caplan J S and Ravi S 2020a Effects of revegetation on soil physical and chemical properties in solar photovoltaic infrastructure *Front. Environ. Sci.* **8** 140

- Connecticut Department of Energy and Environmental Protection (CT DEEP) 2020 *Guidance regarding solar arrays and the general permit for the discharge of stormwater and dewatering wastewaters from construction activities* Connecticut guidance for construction of solar array projects https://portal.ct.gov/-/media/DEEP/water_regulating_and_discharges/stormwater/construction/200108GuidanceforConstructionofSolarArrayProjects.pdf
- Cook L M and McCuen R H 2013 Hydrologic response of solar farms *J. Hydrol. Eng.* **18** 536–41
- Davis A P 2005 Green engineering principles promote low-impact development *Environ. Sci. Technol.* **39** 338A–44A
- Davis A P, Stagge J H, Jamil E and Kim H 2012 Hydraulic performance of grass swales for managing highway runoff *Water Res.* **46** 6775–86
- Edalat M M 2017 *Remote Sensing of the Environmental Impacts of Utility-Scale Solar Energy Plants* (Las Vegas: University of Nevada)
- Elamri Y, Cheviron B, Lopez J-M, Dejean C and Belaud G 2018a Water budget and crop modelling for agrivoltaic systems: application to irrigated lettuces *Agric. Water Manag.* **208** 440–53
- Elamri Y, Cheviron B, Mange A, Dejean C, Liron F and Belaud G 2018b Rain concentration and sheltering effect of solar panels on cultivated plots *Hydrol. Earth Syst. Sci.* **22** 1285–98
- Graham M, Ates S, Melathopoulos A P, Moldenke A R, DeBano S J, Best L R and Higgins C W 2021 Partial shading by solar panels delays bloom, increases floral abundance during the late-season for pollinators in a dryland, agrivoltaic ecosystem *Sci. Rep.* **11** 7452
- Great Plains Institute 2021 *Photovoltaic Stormwater Management Research and Testing (PV-SMaRT) Potential Stormwater Barriers and Opportunities* (Great Plains Institute) <https://betterenergy.org/wp-content/uploads/2021/10/PV-SMaRT-Potential-Stormwater-Barriers-and-Opportunities.pdf>
- Gunerhan H, Hepbasli A and Giresunlu U 2008 Environmental impacts from the solar energy systems *Energy Sources A* **31** 131–8
- Hassanpour Adeb E, Selker J S and Higgins C W 2018 Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency *PLoS One* **13** e0203256
- Hernandez R R *et al* 2019 Techno-ecological synergies of solar energy for global sustainability *Nat. Sustain.* **2** 560–8
- Hernandez R R *et al* 2014 Environmental impacts of utility-scale solar energy *Renew. Sustain. Energy Rev.* **29** 766–79
- Grigorescu I, Vrinceanu A, Vrinceanu A, Dumitraşcu M, Mocanu I, Dumitrică C, Mitrică B, Kuscicsa G and Şerban P 2019 Regional differences in the spatial distribution and environmental consequences of PV farms in southern Romania *Ukrainian Geogr. J.* **3** 60–9
- Jacobson M Z and Delucchi M A 2011 Providing all global energy with wind, water, and solar power: I. Technologies, energy resources, quantities and areas of infrastructure, and materials *Energy Pol.* **39** 1154–69
- Lambert Q, Bischoff A, Cluchier A, Cuff S and Gros R 2021 Effects of solar park construction and solar panels on soil quality, microclimate, CO₂ effluxes and vegetation under a Mediterranean climate *Land Degradation and Development* **32** 5190–5202
- Lee K, Khanal S and Bakshi B R 2021 Techno-ecologically synergistic food-energy-water systems can meet human and ecosystem needs *Energy Environ. Sci.* **14** 3700–16
- Marrou H, Dufour L and Wery J 2013a How does a shelter of solar panels influence water flows in a soil-crop system? *Eur. J. Agron.* **50** 38–51
- Marrou H, Guilioni L, Dufour L, Dupraz C and Wery J 2013b Microclimate under agrivoltaic systems: is crop growth rate affected in the partial shade of solar panels? *Agric. For. Meteorol.* **177** 117–32
- Maryland Department of the Environment (MA DOE) 2021 *Maryland Stormwater Design Guidance—Solar Panel Installations* (Maryland Department of the Environment) <https://mde.maryland.gov/programs/Water/StormwaterManagementProgram/Documents/ESDMEP%20Design%20Guidance%20Solar%20Panels.pdf>
- Massachusetts Department of Environmental Protection (Mass DEP) 2017 *MassDEP Wetlands Program Policy 17-1: Photovoltaic System Solar Array Review* (Massachusetts Department of Environmental Protection) <https://mass.gov/guides/massdep-wetlands-program-policy-17-1-photovoltaic-system-solar-array-review>
- Minnesota Pollution Control Agency 2019 *Stormwater Management for Solar Projects and Determining Compliance with the NPDES Construction Stormwater Permit (Minnesota Stormwater Manual)* (Minnesota Pollution Control Agency) https://stormwater.pca.state.mn.us/index.php/Stormwater_management_for_solar_projects_and_determining_compliance_with_the_NPDES_construction_stormwater_permit
- Moore-O'Leary K A, Hernandez R R, Johnston D S, Abella S R, Tanner K E, Swanson A C, Kreidler J and Lovich J E 2017 Sustainability of utility-scale solar energy—critical ecological concepts *Front. Ecol. Environ.* **15** 385–94
- New Hampshire Department of Environmental Services (NH DES) 2020 *New Hampshire Guidance for Large Solar Arrays* (New Hampshire Department of Environmental Services) https://sulloway.com/wp-content/uploads/2020/09/NHDES-Solar-Stormwater-Guidance_2.28.20.pdf
- New Jersey Legislature 2021 *Bill S291: Exempts Solar Panels from Impervious Surface or Impervious Cover Designation* (New Jersey Legislature) <https://njleg.state.nj.us/bill-search/2010/S921>
- North Carolina Department of Environmental Quality (NC DEQ) 2018 *NCDEQ Stormwater Design Manual: Solar Farms* (North Carolina: North Carolina Department of Environmental Quality) <https://deq.nc.gov/about/divisions/energy-mineral-and-land-resources/stormwater/stormwater-program/stormwater-design>
- Ohio Environmental Protection Agency (OH EPA) 2019 Ohio guidance on post-construction storm water controls for solar panel arrays <https://epa.ohio.gov/static/Portals/35/storm/Guidance+on+Post-Construction+Storm+Water+Controls+for+Solar+Panel+Arrays.pdf>
- Pennsylvania Department of Environmental Protection (PA DEP) 2019 Pennsylvania Department of Environmental Protection (PA DEP) 2021 Chapter 102 Permitting for Solar Farms: Frequently Asked Questions (FAQ) https://files.dep.state.pa.us/Water/BPNPSM/StormwaterManagement/ConstructionStormwater/Solar_Panel_Farms_FAQ.pdf
- Pisinaras V, Wei Y, Barring L and Gemitzi A 2014 Conceptualizing and assessing the effects of installation and operation of photovoltaic power plants on major hydrologic budget constituents *Sci. Total Environ.* **493** 239–50
- Ravi S, Macknick J, Lobell D, Field C, Ganesan K, Jain R, Elchinger M and Stoltenberg B 2016 Colocation opportunities for large solar infrastructures and agriculture in drylands *Appl. Energy* **165** 383–92
- Rhode Island Department of Environmental Management (RI DEM) 2021 *Rhode Island Freshwater Wetlands Program and Stormwater Construction Permitting Ground-Mounted Solar Array Guidance* (Rhode Island Department of Environmental Management) <http://dem.ri.gov/programs/benviron/water/permits/ripdes/stwater/pdfs/solar-guidance.pdf>
- Shorabeh S N, Firozjaei M K, Nematollahi O, Firozjaei H K and Jelokhani-Niaraki M 2019 A risk-based multi-criteria spatial decision analysis for solar power plant site selection in different climates: a case study in Iran *Renew. Energy* **143** 958–73
- Solangi K H, Islami M R, Saidur R, Rahim N A and Fayaz H 2011 A review on global solar energy policy *Renew. Sustain. Energy Rev.* **15** 2149–63
- Solar Energy Industries Association 2020 Major solar projects list <https://seia.org/research-resources/major-solar-projects-list>

- Taha H 2013 The potential for air-temperature impact from large-scale deployment of solar photovoltaic arrays in urban areas *Sol. Energy* **91** 358–67
- Uldrijan D, Kováčiková M, Jakimiuk A, Vaverková M D and Winkler J 2021 Ecological effects of preferential vegetation composition developed on sites with photovoltaic power plants *Ecol. Eng.* **168** 106274
- US Army Corps of Engineers 2021 HEC-HMS <https://hec.oce.army.mil/software/hec-hms/>
- US Energy Information Administration (EIA) 2020 *U.S. Energy Information Administration (EIA)—Data. Monthly Energy Review* (US Energy Information Administration) <https://eia.gov/totalenergy/data/browser/index.php?tbl=T10.06#/?f=M%start=200001>
- US EPA 2015 *Stormwater Discharges from Construction Activities [Overviews and Factsheets]* (US EPA) <https://epa.gov/npdes/stormwater-discharges-construction-activities>
- Virginia Department of Environmental Quality (VA DEQ) 2022 *Virginia Guidance for Solar Farms* (Virginia Department of Environmental Quality) <https://deq.virginia.gov/home/showpublisheddocument/13985/637842474433400000>
- Vrinceanu A, Grigorescu I, Dumitraşcu M, Mocanu I, Dumitrică C, Micu D, Kucsicsa G and Mitrică B 2019 Impacts of photovoltaic farms on the environment in the Romanian plain *Energies* **12** 2533
- Walston L J, Li Y, Hartmann H M, Macknick J, Hanson A, Nootenboom C, Lonsdorf E and Hellmann J 2021 Modeling the ecosystem services of native vegetation management practices at solar energy facilities in the Midwestern United States *Ecosyst. Serv.* **47** 101227
- Walston L J, Mishra S K, Hartmann H M, Hlohowskyj I, McCall J and Macknick J 2018 Examining the potential for agricultural benefits from pollinator habitat at solar facilities in the United States *Environ. Sci. Technol.* **52** 7566–76
- Washington State Department of Ecology 2021 *Washington Stormwater Requirements for Solar Farms* (Washington State Department of Ecology) <https://ecology.wa.gov/>
- Weselek A, Ehmann A, Zikeli S, Lewandowski I, Schindele S and Högy P 2019 Agrophotovoltaic systems: applications, challenges, and opportunities. A review *Agron. Sustain. Dev.* **39** 35
- Wu C, Liu H, Yu Y, Zhao W, Liu J, Yu H and Yetemen O 2022 Ecohydrological effects of photovoltaic solar farms on soil microclimates and moisture regimes in arid northwest China: a modeling study *Sci. Total Environ.* **802** 149946
- Yue S, Guo M, Zou P, Wu W and Zhou X 2021 Effects of photovoltaic panels on soil temperature and moisture in desert areas *Environ. Sci. Pollut. Res.* **28** 17506–18
- Zhu Z, Chen Z, Chen X and Yu G 2019 An assessment of the hydrologic effectiveness of low impact development (LID) practices for managing runoff with different objectives *J. Environ. Manage.* **231** 504–14
- Minnesota Pollution Control Agency (MN PCA) 2021 *Stormwater management for solar projects and determining compliance with the NPDES construction stormwater permit* Minnesota Pollution Control Agency https://stormwater.pca.state.mn.us/index.php?title=Stormwater_management_for_solar_projects_and_determining_compliance_with_the_NPDES_construction_stormwater_permit



Microclimate under agrivoltaic systems: Is crop growth rate affected in the partial shade of solar panels?



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ABSTRACT

Agrivoltaic systems are mixed systems that associate, on the same land area at the same time, food crops and solar photovoltaic panels (PVPs). The aim of the present study is to assess whether the growth rate of crops is affected in the specific shade of PVPs. Changes in air, ground and crop temperature can be suspected due to the reduction of incident radiation below the photovoltaic shelter. Soil temperature (5 cm and 25 cm depth), air temperature and humidity, wind speed as well as incident radiations were recorded at hourly time steps in the full sun treatment and in two agrivoltaic systems with different densities of PVPs during three weather seasons (winter, spring and summer). In addition, crop temperatures were monitored on short cycle crops (lettuce and cucumber) and a long cycle crop (durum wheat). The number of leaves was also assessed periodically on the vegetable crops.

Mean daily air temperature and humidity were similar in the full sun treatments and in the shaded situations, whatever the climatic season. On the contrary, mean daily soil temperature significantly decreased below the PVPs compared to the full sun treatment. The hourly pattern of crop temperature during day-time (24 h) was affected in the shade. In this experiment, the ratio between crop temperature and incident radiation was higher below the PVPs in the morning. This could be due to a reduction of sensible heat losses by the plants (absence of dew deposit in the early morning or reduced transpiration) in the shade compared to the full sun treatment. However, mean daily crop temperature was found not to change significantly in the shade and the growth rate was similar in all the treatments. Significant differences in the leaf emission rate were measured only during the juvenile phase (three weeks after planting) in lettuces and cucumbers and could result from changes in soil temperature. As a conclusion, this study suggests that little adaptations in cropping practices should be required to switch from an open cropping to an agrivoltaic cropping system and attention should mostly be focused on mitigating light reduction and on selection of plants with a maximal radiation use efficiency in these conditions of fluctuating shade.

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1. Introduction

Agrivoltaic systems (AVS) were defined by Dupraz et al. (2010) as “mixed systems associating solar panels and crop at the same time on the same land area”. They may contribute to conciliate food security and green energy supply. In these mixed production systems, photovoltaic panels (PVPs) partially shelter the crop growing below. PVPs create intermittent shading and reduce the average available light for the crop. Marrou et al. (2013) showed that light reduction had a significant impact on final crop yield of spring and

summer lettuces in AVS. Biomass accumulation was mainly driven by the capture of light resource while other resources such as water and nitrogen were not limiting. By using a light driven prediction of plant biomass accumulation (Monteith, 1977), it was showed that high crop productivities can be expected from these dual purpose systems (food and electricity) (Marrou et al., 2013). Marrou et al. (2013) found that light reduction was not necessarily detrimental for crop production. Indeed, an experiment conducted on spring and summer lettuces in AVS showed that lettuce yield was maintained, despite shading, by an improved radiation interception efficiency (RIE) in the shade. Enhanced RIE was explained by an increase in total leaf area per plant despite a decrease in the number of leaves.

The aim of the present study is to determine if other climatic variables are significantly modified in the shade of solar panels and

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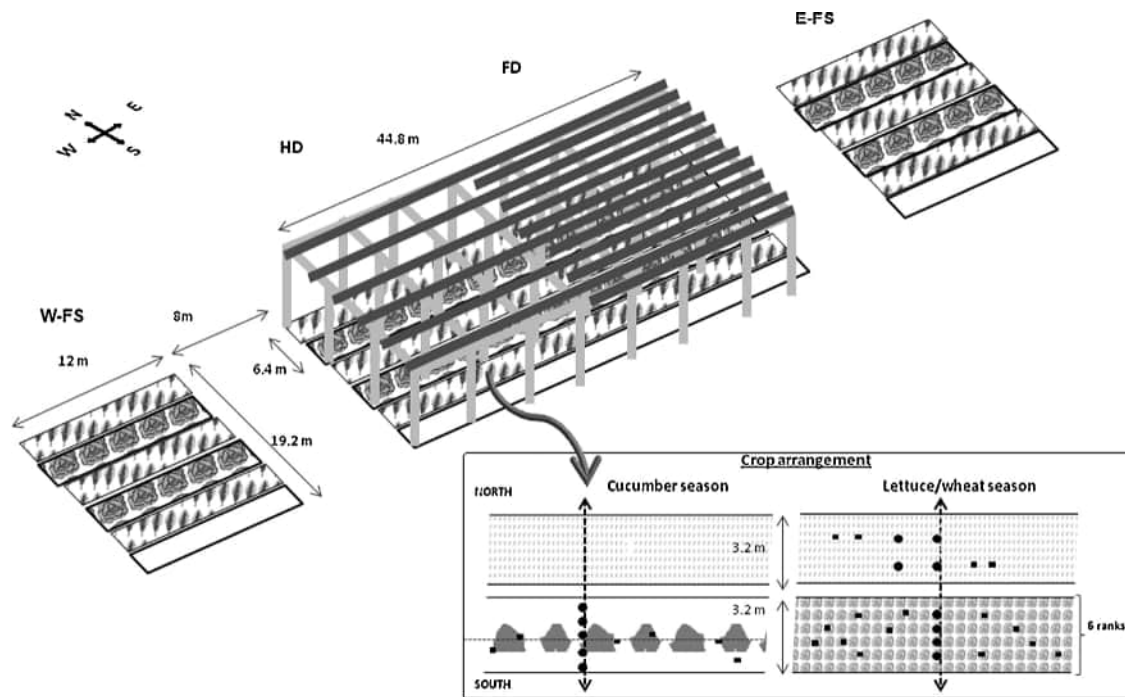


Fig. 1. General map of the experimental device during the wheat/lettuce season. In the bottom right frame, a zoom on the two central crop strips during wheat/lettuce season and cucumber season is represented. Closed circles represent radiation sensors, located on North-to-South transects; closed square symbols represent thermocouples or microthermistances. FD represents the shaded plot with PVPs at full density whereas HD represents the shaded plot with PVPs at half density. W-C and E-C stand respectively for Western control plot and Eastern control plot.

to what extent this could affect crop temperature and plant development rates in AVS. Former work on shaded glasshouses (Baille et al., 2001; Kittas et al., 2003) or agroforestry systems (Lott et al., 2009; Monteith et al., 1991) suggested that air temperature and vapor pressure deficit at crop level are reduced by shading. Effects of shading on crop temperature and growth rate were also reported. Lott et al. (2009) showed that, under 50% of available radiation, the meristem temperature of shaded maize plants was reduced by 2–9 °C (depending on the climatic seasons). At the same time, they noticed a significant delay in flowering date. Moreover, in the case of AVS, the shade pattern under PVPs varies from one season to another and among different latitudes as the limits between shade and light move with sun elevation. For this reason, the effect of the PVP shelter may have a different impact on the productivity of winter crops compared to summer crops, or on short cycle crops compared to long cycle crops. We therefore analyze in this study the impact of PVPs on the microclimate at crop level (air temperature, air vapour pressure deficit (VPD) and wind) as well as crop and soil temperature. The experiment was conducted on three crop species and cropping seasons: durum wheat (winter to summer), lettuces (spring and summer), and cucumbers (summer).

2. Materials and methods

2.1. Experimental device

Data were collected on an experimental prototype of agrivoltaic systems, in Montpellier, France (43.15° N; 3.87° E) from July 2010 to September 2011 (Marrou, 2012; Marrou et al., 2013). In this experimental prototype, photovoltaic panels (PVPs) were arranged in East–West orientated strips, 0.8 m wide and inclined southward with a tilt angle of 25°. PVPs were held at 4 m above-ground by wooden pillars spaced on a 6.4 m × 6.4 m grid, in order to allow mechanical cropping of the plants below, using tractors (Fig. 1).

The experimental design enabled to compare three shading intensities, corresponding to two densities of solar panels and a full sun control (FS): (1) the full density treatment (FD), which corresponds to the PVPs density optimized for electricity production. In this treatment the distance between 2 strips of PVPs is 1.6 m, which lets an average of 50% of the incident radiation to the crop, (2) the half density treatment, which is obtained from FD by removing one strip of PVPs out of two (distance between 2 PVPs strips: 3.2 m) and thus letting through an average of 70% of incident radiation available to the crop, and (3) the full sun control plot (100% of incident radiation available) (Marrou, 2012). Shading treatments were applied on four land plots. They were aligned from East to West as following: eastern full sun control plot (E-FS), FD plot, HD plot, and western full sun control plot (W-FS). Each plot is 12 m wide in the East–West direction and separated from each other by a buffer zone of 8 m (between control plots and shaded plots) or 6 m (between FD and HD plots). In the North–South direction, each control plot is 19 m long. In FD and HD plots, plant and meteorological measurements were taken only in the first 15 m in the Northern part of the plots to avoid a border effect due to the higher incident light in the southern side of the prototype. The total area covered by PVPs (including FD and HD plots as well as the surrounding buffer zones) is 860 m² (19.2 m × 44.8 m) and corresponds to the minimum standard size of an agrivoltaic system adapted for vegetable production. Due to the large size of any agrivoltaic system required to avoid unwanted border effects and the cost of work and material to build an experimental agrivoltaic system, it was not possible to replicate FD and HD plots and design a complete randomized experimental device. However, as E-FS and W-FS were the two most distant plots in the experimental field, they controlled the environmental variability in the East–West direction. Moreover, environmental variability in the North–South was assessed during the first experimental season (2010) and controlled by subdividing both control and shaded plots into three blocks in the North–South. Variance analysis showed that

there was no significant difference in lettuces' dry matter, neither between blocks within the same full sun plot, nor between the W-FS and the E-FS. Identical soil type (loamy clayish deep alluvial soil) and field history (10 years of homogenous non tillage cropping) also contributed to homogenous soil conditions between treatment plots. Moreover, the homogeneity of soil properties was checked across the treatment plots using soil hygrometry measurements on samples evenly collected over the area of the experimental field (Marrou, 2012).

2.2. Crop management

Three different species were tested on the prototype for various cropping seasons spanning from July 2010 to September 2011: lettuces – *Lactuca sativa* spp. (two cropping cycles, five subspecies), durum wheat (*Triticum durum* L.), and cucumbers (*Cucumis sativus* L.). Thus, a wide range of growing conditions in terms of temperature, VPD, and sun elevation was covered.

Lettuces were planted during one summer and one spring season. Firstly, lettuces were grown from July 21, 2010 (day of the year, DOY 202) to September 6, 2010 (DOY 249). Two varieties were then planted at the same time: one variety of crisphead lettuce, called “Kiribati” (noted FC+), and one butterhead lettuce, called “Tourbillon” (noted B0). Secondly, lettuces were planted on March 22, 2011 (DOY 81) and harvested on May 24, 2011 (DOY 144). For this second cropping season, two varieties of crisphead lettuces (FC+, and a second one called “Bassoon” and noted FC–) and two new varieties of butterhead lettuces (variety “Model” noted B+ and variety “Emocion” noted B–) were tested simultaneously. Cucumbers (variety “Marketmore”) were planted on June 25, 2011 (DOY 178) and fruits were picked from August 8, 2011 (DOY 220) to August 31, 2011 (DOY 239), twice a week. Durum wheat (variety “Claudio”) was sown at a density of 150 kg/ha on November 26 (DOY 331), 2010, and harvested at maturity on June 17, 2011 (DOY 168) (Fig. 2).

Lettuces and cucumbers were planted in lines. Planting rows were parallel to PVP strips. The distance between two planting rows was 0.33 m for lettuces and 3 m for cucumbers. To allow simultaneous cultivation of wheat and vegetable crops in 2011, the entire experimental field was divided into 3.2 m wide block strips in the North–South direction. Blocks were dedicated alternatively to the cultivation of cereals or vegetables. In spring 2011, three blocks of wheat were intercalated with two strips of 6 rows of lettuces. Each block of lettuces was replaced by one row of cucumber in June 2011.

Vegetables were irrigated with sprinklers (summer 2010) or drip lines (spring and summer 2010), in the day-time. Irrigation was monitored with tensiometers (SDEC, Reignac sur Indre, France). In order to avoid plant water stress, soil water potential at 0.3 m depth was kept above -0.02 MPa (Gay, 2002).

2.3. Plant development rate

Development rate of vegetable crops was assessed by counting the number of leaves, over 1 cm long, that were emitted every 3 weeks for lettuces and twice a week for cucumbers. For lettuces, the number of leaves per plant was assessed through destructive sampling at three dates (DOY 223, 236, and 249 in summer 2010, and DOY 104, 125, and 144 in spring 2011). 12–15 plants per treatment and per variety were collected at each sampling date. Samples were stratified to warrant that each sample contained the same number of plants collected from each planting rank, and to explore the intra-treatment variability. Leaf emission rates (τ) were calculated by fitting linear models between the number of leaves measured on each sampled lettuce plant and the thermal time (calculated from air temperature at 2 m above-ground with a base temperature of 3°C , Thicoïpé, 1997) for each period between two sampling

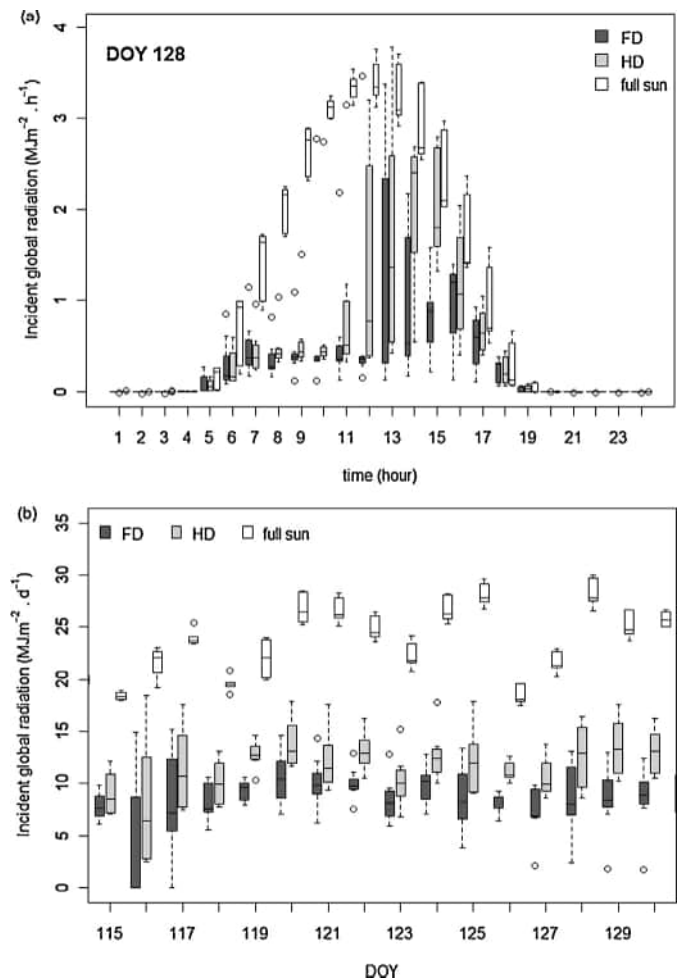


Fig. 2. Hourly (a, for DOY 128) and daily (b, from DOY 115 to DOY 230) incident radiation in the FS treatment (white background boxes), in HD (gray background boxes) and FD (dark gray background boxes). The boxes feature the spatial variability of the incident radiation (radiation was recorded at the same time by sensors settled at different locations on the North–South axis).

dates. Analysis of covariance (ANCOVA), using shading treatment as a factor, was performed to determine whether a single linear model could be fit for all the treatments. If not, development rate were considered as significantly different between treatments, for the corresponding time period.

Concerning cucumbers, the number of leaves on the main stem and on each secondary branch was counted in the field twice a week on 16 plants. These plants had been randomly chosen at planting date (3 plants both in E–C and in W–C and 5 plants in FD and in HD). After plotting the dynamic of the total number of leaves per plant over the entire cropping period, three time periods with nearly constant τ were identified, and a mean τ was calculated in the three treatments for each period. To do so, we applied the same methodology as for lettuces: linear models were fitted to predict the number of leaves as a function of thermal time (calculated from air temperature at 2 m above-ground with a base temperature of 15°C , Perry et al., 1986) for each time period. Shading effect on τ was tested with ANCOVAs.

For wheat, phenological stages such as tillering, flowering, and maturity were determined according to the Zadoks scale (Zadoks et al., 1974) in each plot. A given phenological stage was reported as attained when 50% of the plant population had reached this stage (visual assessment).

2.4. Microclimate monitoring

2.4.1. Air temperature, air humidity and wind speed at standard height

Air temperature ($\pm 0.2^\circ\text{C}$) and air relative humidity ($\pm 2\%$) at 2 m above-ground were measured respectively with a capacitive thermohygrometer (HMP 45, Vaisala, Helsinki, Finland) placed in radiation screens with natural ventilation (MET20, Campbell Scientific, Inc., USA) and connected to dataloggers (CR1000 Campbell Scientific, Inc., USA). Three probes were set in the middle of each treatment plot from DOY 222 to 249 in 2010 (for second half of the summer season for lettuces) and from DOY 36 to 239 in 2011 (for the complete cycle of summer lettuces and cucumber, and from “3 leaves” stage to maturity for the wheat cycle). Wind speed (u , m s^{-1}) was measured at 2 m above-ground with a mechanical wind monitor (05103-5, Young, Traverse City, MI, USA), in the E-FS plot and in the FD treatment from DOY 36 to 239 in 2011. All these data were collected every 5 s on a datalogger (CR1000, Campbell Scientific Inc., Logan, UT, USA) and averaged over 1 h.

Analyses of variance (ANOVA) and least significant difference (LSD) tests were performed successively on T_A and VPD, using the shading level as treatment to determine the effect of the shading treatments on mean daily air temperature and VPD. These statistical analyses were done over the whole the measurement period at a daily (to compare mean daily values) or hourly (to compare daily microclimatic patterns) time-step.

2.4.2. Soil temperature

Soil temperature ($\pm 0.4^\circ\text{C}$) was measured below the wheat crop in 2011 (from DOY 36 to 165) at 0.05 m (T_{S5}) and 0.25 m (T_{S25}) below the ground surface with thermistors (107 thermistors, Campbell Scientific, Inc., USA) at 2 positions along a North South transect between two strips of solar panels. Soil temperature at 0.25 m depth was also measured in irrigated soil during the crop cycle of summer lettuce (from DOY 220) until after the harvest of the lettuces (DOY 279). 6 probes were dug both in the FD and in the HD plots, at different positions on North South transects, and 3 probes were dug in the control plots. All probes were connected to dataloggers (CR1000, Campbell Scientific, Inc., USA), and data were recorded with a time step of 5 s, and then averaged over 1 h for storage in the datalogger memory. Soil temperature was not collected during the spring lettuce cycle, because it would have required a higher number of probes as the crop was irrigated with drip lines.

2.4.3. Crop temperature

Crop temperatures (T_L) were measured on spring lettuces from DOY 117 to 149 in 2011, with copper-constantan thermocouples, inserted between the lettuces leaves, close to the central axis of the plant. Leaf temperatures were measured on cucumber (DOY 178–244) and durum wheat (DOY 36–168) with microthermistors taped on the bottom side of the leaves (Thorpe and Butler, 1977). Thermistors were moved from one leaf to another during the crop cycle so that they would measure the temperature of a non-senescent leaf. We chose leaves that were located in the middle of the main stem for cucumber, or at mid-height of the plant cover for wheat. Measurements from thermocouples and microthermistors were recorded on dataloggers (CR10X and CR1000, Campbell Scientific, Inc., USA) with the same time steps as mentioned above. The precision of the data was estimated at $\pm 0.4^\circ\text{C}$ in the worst case.

2.4.4. Incident radiation

2.4.4.1. Incident global radiation received on an horizontal surface at crop height. Incident solar radiation (R_s , W m^{-2}) was measured during the wheat and cucumber cycles with pyranometers (SKS 1110, Skye Instruments, Powys, UK) set horizontally at the height of the crop. For lettuces, photosynthetically active radiation (R_p ,

W m^{-2}) was measured with PAR sensors (spring and summer). R_s and R_p measurements were treated equally after conversion, as R_p/R_s is constant, equal to 0.48 in outdoors conditions, provided all measurements are taken above plant foliage.

In the FD and the HD treatments, several sensors were set along North–South transects, perpendicularly to the PVP strips. We thus captured the hourly and daily intra-treatment variations below the panels. One sensor acquired data above each row of lettuce, while 5 sensors were regularly placed (spacing of 40 cm) on a diagonal transect centered on the cucumber rows. As for the wheat experiments, two pairs of sensors were set on a transect perpendicular to the crop strip: one was just below a PVP strip and the other was in-between two PVP strips. All sensors were connected to dataloggers (CR1000 Campbell Scientific, Inc., USA), and data were recorded with a time step of 5 s, and then averaged over 1 h.

2.4.4.2. Spatial distribution of the incident beam rays. The spatial distribution of the incident radiation was assessed through modeling and field measurements in the FS treatment as well as in the two shaded treatments (FD and HD) in order to test whether there were significant scattering effects below the PVPs and to characterize the proportion of diffuse and direct radiation in the different treatments.

2.4.4.2.1. Field measurements. Complementary measurements were conducted in spring 2012, from DOY 124 to 134 to quantify incoming radiation from different directions, using a turtle PAR sensor. This device has been described by Chenu et al. (2008). It is made of six faces with equal solid angles, so that the entire sky hemisphere is covered without overlapping. Each face of the turtle sensor is a pentagonal PAR sensor. Face 1 was horizontal, while faces 2–6 were inclined with a tilt angle of 63.4° , and directed to 5 different azimuth directions. Face 4 was oriented northwards. The directional measurement of incident radiation was repeated for different locations within the FD and HD plots: the sensor was set for 2 days of acquisition at each location where the PAR sensors had been placed in 2011 above each lettuce planting row. The sensors were connected to a datalogger (CR10X Campbell Scientific, Inc., USA), and data were recorded with a time step of 5 s, then averaged over 10 min.

2.4.4.2.2. Simulation of the light captured by an inclined surface. The spatial distribution of incoming radiation measured below the PVPs needed to be compared that in the full sun conditions (FS). To do so, the solar energy that would have been captured by each face of the turtle PAR sensor in full sun conditions (FS) for the same days of the year was simulated. The spatial distribution of solar energy, in the absence of sheltering, abides to astrological laws and can be predicted with precision according to existing models (Liu and Jordan, 1960; Spitters et al., 1986; Allen et al., 1998; Bindi et al., 1992; Anderson, 1966). A model was coded, and implemented with the R-cran software (<http://cran.r-project.org/>), to simulate the energy captured by each face of the turtle sensor in FS, with a time step of 10 min, for a given day of the year (DOY). Model algorithm uses astrology equations currently in use in existing astrological models (Marrou et al., 2013), with a few adaptations. Firstly, extraterrestrial radiation was calculated with the De Jong formula (Bindi et al., 1992), which is more suitable at infra-daily time steps. Secondly, the calculation step integrating the incident radiation over one day was removed. Inputs of the model were latitude of the site, orientation of the sensor and incident global radiation measured on a horizontal surface at the model time step. Radiation data were collected at an hourly time step from a weather station located 400 m from the experimental field (INRA, Lavalette weather station). Linear interpolation was performed between hourly data in order to get a dataset with a time step of 10 min that can be used as an input for the radiation model. Model quality was verified by comparing

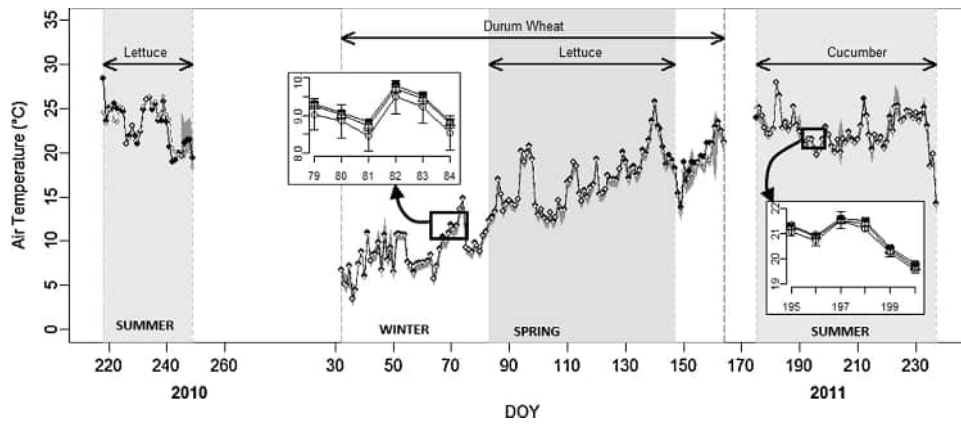


Fig. 3. Mean daily temperature (T_A) measured at 2 m above-ground during every cropping cycles from July 2010 to August 2011. Zooms on 6-day periods (6 days in winter and 6 days in summer) are provided. FS is represented with shaded intervals on the main graph (95% confidence interval for T_A measured in FS with three different probes) and with open circles (○) in the zoom areas, while FD and HD are represented respectively with open triangles (Δ) and closed squares (■). In the zoom areas, vertical error bars feature standard errors for all the treatments.

simulation with measurements taken in FS from DOY 196 to 199 in 2012. A linear model was fitted for each sensor face with a correction coefficient higher than 0.94, and the slope coefficient was always between 0.88 and 1. It was concluded that the model was a good predictor and that simulated data in FS needed no correction coefficient to match measured values. More details on the model specifications and validation are given in [Appendix A](#).

2.4.4.3. Long wave radiations. In spring 2012 (DOY 174–202) upwards ($R_{\ell\uparrow}$) and downwards ($R_{\ell\downarrow}$) longwave radiation, and upward ($R_{s\uparrow}$) and downward ($R_{s\downarrow}$) short wave radiation were measured for each treatments. The four types of radiations were measured successively in the FD, HD, and FS treatments with two net radiometers (Q-7.1, Campbell Sci, USA) and 2 pyranometers (SKS 11110, Skye Instruments, Powys, UK). All the sensors were set on an East–West orientated line, below a PVP strip, for FD and HD. The ground was then covered with spring barley sown on DOY 89, with an almost closed canopy.

2.5. Theoretical background: crop energy balance and consequences on crop temperatures

The temperature of any plant organ results from the balance between incoming energy and energy loss. The energy balance of a plant organ (or a canopy) can be written as:

$$R_n - H - \lambda E - G = 0 \quad (1)$$

where R_n is the net radiation, H and λE are the sensible and latent heat fluxes between the considered vegetation and the surrounding air, and G is the rate of heat storage in the vegetation and soil.

During daylight, the main energy input is radiation, both solar and longwave radiation (Eq. (2)). If crop or leaf temperature is different from air temperature at the same height ($T_A(z)$), energy may be absorbed or released as sensible heat by convection (Eq. (3)). Part of this energy can also be released by evaporation through stomata (Eq. (4a)). Moreover, energy may be transferred to and from storage in plant canopies and in the soil by conduction (Eq. (5)). During the night, the sign of most fluxes change to the opposite. The radiation balance is negative then, and water vapor may condense on plants (Eq. (4b)).

$$R_n = (1 - \alpha) \cdot R_s + \varepsilon \cdot R_{\ell} - \varepsilon \cdot \sigma \cdot T_L^4 \quad (2)$$

$$H = \frac{\rho \cdot C_p}{r_a} (T_L - T_A(z)) \quad (3)$$

$$\begin{cases} \lambda \cdot E = \frac{\rho \cdot C_p}{\gamma \cdot (r_a + r_s)} (e^*(T_L) - e_a(z)) & \text{for transpiration} \\ \lambda \cdot E = \frac{\rho \cdot C_p}{\gamma \cdot r_a} (e^*(T_L) - e_a(z)) & \text{for dew deposition or evaporation} \end{cases} \quad (4)$$

$$G = \frac{\rho \cdot C_p}{r_0} (T_0 - T_{z_0}) \quad (5)$$

where R_{ℓ} is the downwards incoming longwave radiation, e_a is the vapor pressure of the air surrounding the plant organ, $e^*(T_L)$ is the saturated vapor pressure at leaf temperature, r_a is the aerodynamic resistance to water vapor and sensible heat mainly function of wind speed, r_s the stomatal resistance, ρ is the air density, C_p is the specific heat of air at constant temperature, γ is the psychrometric constant, T_0 is the soil surface temperature, and T_{z_0} is the soil temperature at depth z_0 .

The organ or plant temperature balances the energy budget equation (Eq. (1)). For certain sets of environmental conditions (air temperature, solar radiation, vapor pressure and wind speed), only one surface temperature that balances the energy budget equation exists.

Net radiation is influenced by the PVPs through (1) the reduction of the solar incident radiation during day-time only (R_s), (2) the modification of downwards long wave radiation (R_{ℓ}) coming from the sky and from the PVPs in the case of agrivoltaic systems. Latent heat flux H could change under PVPs if air temperature or wind speed were modified by the PVPs (leading to variations in the aerodynamic resistance of the crop). Heat storage is negligible for leaves or small canopies. For the wheat crop, there is no heat conduction between leaves and ground as the crop stands at a sufficient height (more than 50 cm) above-ground in the second part of the crop cycle. In the case of short or creeping plants (lettuce and cucumber), conduction occurs and the intensity of this flux depends on the vertical gradient of soil temperature. Any change in soil temperature could result in a modified G flux under PVPs. Finally, energy can be released as latent heat (λE) through crop transpiration or dew evaporation in the morning, which are monitored by aerodynamic and stomatal (for transpiration only) resistances. PVPs could modify the latent heat exchanges between the plant and the surrounding air by a change in leaf stomatal resistance or air vapor pressure.

2.6. Statistical analysis

All statistical analyses were performed with the R software. Analyses of variance (ANOVA) and covariance (ANCOVA) were realized with the 'lm' procedure and boxed linear models were

Table 1
Sum of T_A calculated for the totality or a part of each cropping season. Differences in crop cycle length between the shaded situations and FS are expressed in thermal time ($^{\circ}\text{C d}$) and in equivalent number of leaves, according to the literature. Sums of temperature are calculated with a base temperature of 3°C for lettuces, 0°C for wheat, and 15°C for cucumbers.

From planting to harvest		FS	FD	HD
<i>Spring lettuces (2011)</i>				
Crop cycle length ($^{\circ}\text{C d}$)	Sum of T_A ($^{\circ}\text{C d}$)	797	819	812
	Difference ($^{\circ}\text{C d}$)	0	22.8	15.6
Equivalent NB of leaves	Min development rate 0.052 leaves ($^{\circ}\text{C d}^{-1}$)	0	1.18	0.81
	Max development rate leaves ($^{\circ}\text{C d}^{-1}$)	0	2.96	2.03
From mid-cycle to harvest		FS	FD	HD
<i>Summer lettuces (2010)</i>				
Crop cycle length ($^{\circ}\text{C d}$)	Sum of T_A ($^{\circ}\text{C d}$)	465	465	471
	Difference ($^{\circ}\text{C d}$)	0	0.00	5.5
Equivalent NB of leaves	Min development rate 0.052 leaves ($^{\circ}\text{C d}^{-1}$)	0	0.00	0.29
	Max development rate 0.130 leaves ($^{\circ}\text{C d}^{-1}$)	0	0.00	0.72
From planting to harvest		FS	FD	HD
<i>Cucumbers</i>				
Crop cycle length ($^{\circ}\text{C d}$)	Sum of T_A ($^{\circ}\text{C d}$)	467	474	469
	Difference ($^{\circ}\text{C d}$)	0	7.4	1.5
Equivalent NB of leaves	Min development rate 0.069 leaves ($^{\circ}\text{C d}^{-1}$)	0	0.51	0.10
	Max development rate 0.083 leaves ($^{\circ}\text{C d}^{-1}$)	0	0.61	0.12
From tillering to harvest		FS	FD	HD
<i>Durum wheat</i>				
Crop cycle length ($^{\circ}\text{C d}$)	Sum of T_A	1820	1872	1845
	Difference ($^{\circ}\text{C d}$)	0	52.98	24.54
Equivalent NB of leaves	Min development rate 0.0014 leaves ($^{\circ}\text{C d}^{-1}$)	0	0.07	0.03
	Max development rate 0.0147 leaves ($^{\circ}\text{C d}^{-1}$)	0	0.78	0.36

compared according to the maximum of likelihood ratio ('anova' procedure). Mean comparison between treatments was performed using Student tests (t -test procedure) and least significant differences test (LSD-test procedure). Sigmoid adjustments were fitted for the number of cucumber leaves using the nls procedure.

3. Results

3.1. Incident radiation

The average proportion of daily radiation transmitted below the PVPs (FD and HD treatments) compared to the FS treatment ranged around 32% in FD, and 48% in HD during the lettuce crop cycle (DOY 117–143), 52% in FD and 68% in HD during the wheat crop cycle (DOY 35–168) and 37% in FD and 62% in HD during the cucumber crop cycle (DOY 181–240) (Fig. 2). The average proportion of radiation transmitted daily below the PVPs varied from one day to another one with a coefficient of variation equal to 37% in FD and 46% in HD over the whole measurement period (DOY 35–240). The fraction of transmitted variation also varied within day-time (C_p = 57% in FD and 60% in HD, between 09:00 and 18:00, in average over all the days with means).

For a given day of the year, the proportion of transmitted radiation over 24 h varies depending on the position of the plants on the North–South axis. The coefficient of spatial variation of the transmitted radiation equals 29% in FD and 38% in HD, in average over the measurement period (DOY 35–244).

3.2. Aerial microclimate

A wide range of climatic conditions was explored over the four crop cycles: air temperature (T_A) varied from 3 to 28°C and daily incident solar radiation varied from 1 to $31 \text{ MJ m}^{-2} \text{ d}^{-1}$ in FS. However, T_A in the shaded treatments (both FD and HD) remained nearly

equal to that in the FS during all cropping cycles, from July 2010 to August 2011 (Fig. 3), according to ANOVAs. ANOVAs were repeated for every day, using shading treatments as an explicative factor of mean daily T_A . Only 12 days were found to have a risk p -value below 5% (i.e. with a significant effect of shading on air temperature). During days with low wind speed ($u < 1.2 \text{ m s}^{-1}$ and $u_{\text{max}} < 6 \text{ m s}^{-1}$) or high global radiation ($R_s > 24 \text{ MJ m}^{-2} \text{ d}^{-1}$), air temperature below the solar panels tended to be higher than in FS.

Variations in daily T_A between shade treatments resulted in variations of the crop cycle length in thermal time that never exceeded 23°C d for lettuces, 8°C d for cucumber and 53°C d for wheat. According to literature references, these differences were too small to allow the production of even one more leaf in the case of cucumber (Horie et al., 1979) and wheat (Porter and Gawith, 1999). For lettuces, in 2011 only, two to three extra leaves (on a total of 80 leaves in average, Marrou et al., 2013) could have been emitted in FD as mean air temperatures tended to increase in average over the second part of the cropping cycle. However, as the thermal time required for lettuce leaves to reach the length of 1 cm is over 200°C d at 20°C in FS (Bensink, 1971), this increase in the number of leaves may have little impact on lettuce size or dry weight. Results are summed up in Table 1. When carrying the same type of analysis at an hourly time step over the measurement period, differences in hourly records of air temperature were never found between the shaded (FD or HD) and unshaded treatments at the same time of the day.

Similarly, no significant effect of shading was found on air relative humidity or VPD, neither at a daily nor at an hourly time step. The maximal increase in VPD in shaded treatments compared to FS was 0.11 kPa , while the mean VPD over the measurement period is 0.91 kPa , in FS.

Besides, the horizontal wind speeds measured at an hourly time step in FS and in each of the shaded treatments (FD and HD) were found to be similar, regarding the precision of measurements

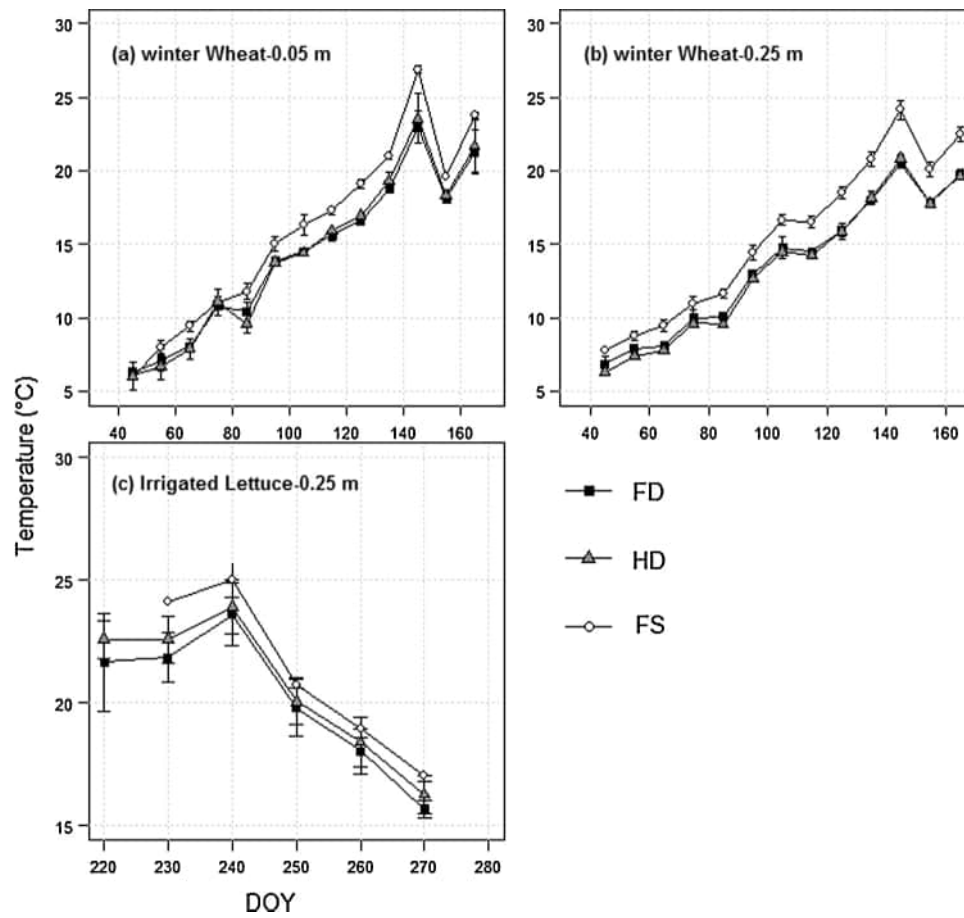


Fig. 4. Mean daily ground temperature measured in non-irrigated winter wheat at (a) 0.05 m and (b) 0.25 m depth; and in sprinkler irrigated summer lettuce at (c) 25 cm depth.

($\pm 0.3 \text{ m s}^{-1}$). However, the significance of differences between treatments could not be tested due to the lack of replications.

3.3. Soil temperature

During the wheat cycle, soil temperature at 0.05 m depth (T_{S5}) decreased by 1.9°C in FD and 1.8°C in HD compared to FS (Fig. 4).

A covariance analysis using shade treatment as a factor and LSD comparison tests on mean values showed that these differences were significant ($p\text{-value} < 5\%$). The temperature at 25 cm depth (T_{S25}) was also significantly reduced in the shade, both for non-irrigated wheat (-2.1°C in FD and -2.3°C in HD) and irrigated lettuces (-0.5°C in HD and -0.6°C in FD), according to ANCOVA and LSD tests. These daily differences resulted in a decrease of T_S

Table 2

Number of days when significant differences were detected in the hourly pattern of T_L for at least one hour or for at least 4 h. The mean variation in T_L in the shaded treatments (FD or HD) compared to FS was calculated over the times when T_L is significantly higher or lower than in FS, as well as the number of days during which these significant increases/decreases were observed.

Number of days when ...	Wheat		Spring lettuces		Cucumbers	
	FD	HD	FD	HD	FD	HD
<i>TL significantly different from FS for at least 1 h</i>						
Number of days	119	116	26	26	40	60
% of the crop cycle	98%	95%	100%	100%	65%	97%
<i>TL significantly different from FS for at least 4 h</i>						
Number of days	117	114	25	25	26	43
% of the crop cycle	96%	93%	96%	96%	42%	69%
<i>TL significantly decreased compared to FS</i>						
Number of days	109	106	26	26	40	60
Mean decrease	3.04	2.9	5.66	5.03	4.96	5.71
Time in the day	09:00 → 18:00	08:00 → 23:00	11:00 → 18:00	15:00 → 18:00	11:00 → 17:00	08:00 → 17:00
<i>TL significantly increased compared to FS</i>						
Number of days	117	115	26	18	0	0
Mean decrease	2.26	1.93	4.34	5.76	–	–
Time in the day	18:00 → 09:00	18:00 → 08:00	20:00 → 01:00	11:00 → 13:00	–	–
Length of the measurement period (in days)	122	122	26	26	62	62

by 214–278 °C d for wheat (with a basal temperature of 0 °C) over the measurement period (for HD and FD, 5 or 25 cm depth). In 2010, in the lettuce crop, the cumulated soil surface temperatures were reduced by 73 °C d in FD and 48 °C d in HD.

3.4. Crop temperature

3.4.1. Pattern of the crop temperature (T_L) at hourly time step

When looking at crop temperature (T_L) with an hourly time step, daily pattern appears to be affected by shading for all the tested crops. The results of the LSD tests performed with p -value < 5% for every hour and every day are summarized in Table 2. In the case of wheat, crop thermal pattern was significantly affected by shading every day, from tillage to flowering. Wheat T_L significantly increased during night (+2 °C, both in FD and in HD, in average, between 18:00 and 09:00). On the contrary day-time temperatures significantly decreased by 3 °C in FD and in HD (from 18:00 to 09:00). For vegetables, T_L was also significantly cooler in the shade than in FS during day-time along most of the crop cycle. In the case of spring lettuces, significant reduction of temperature below the PVPs occurred earlier in the day in FD (before noon) than in HD where significant reduction of T_L started later in the afternoon than in FD. On the contrary, T_L significantly increased in HD compared to FS, between 11:00 and 12:00. However, this event lasted for only 1–2 h and was detected as significant only for 13 days over the cropping season. For cucumbers, no significant decrease of T_L was detected during night in the shaded treatments (FD and HD). However the power of the ANOVA (i.e. the probability to find a difference when it does exist) was below 40% during night-time, for cucumbers.

As an example, patterns of T_L evolution at an hourly time step are presented (Fig. 5) for a sunny day (DOY 128 for wheat and spring lettuce, DOY 202 for cucumber), for the three crops.

3.4.2. Day/night-time steps

Significant differences were found between shaded and unshaded treatments (Fig. 6) when comparing mean night-time (19:00–05:00 Universal Time) and mean day-time (06:00–18:00 Universal Time) crop temperatures, which confirm the results of Section 3.4.1. Mean day-time temperature was significantly lower in the shade (FD and HD) for every crop, during at least 25% of the crop cycle duration (LSD test). Mean crop temperature averaged over night-time ($T_{L,N}$) increased significantly for wheat in the shade (FD and HD) and for lettuce in FD compared to FS during 80% of the cycle (LSD test). No significant difference in $T_{L,N}$ was found for cucumbers in the shade compared to FS, but no conclusion can be drawn because the statistical power of the ANOVA was of 27% in average at night for cucumbers (mean power equal to 27%).

3.4.3. Daily time steps (24 h)

The temperature increases in the shade during night-time and decrease during day-time tended to compensate each other on a 24 h cycle. Consequently, differences between mean daily (24 h) T_L occurred more seldom, for all the tested crops.

Significant differences in the mean daily crop temperature (T_L , 24 h average) between FS on the one hand, and FD and HD treatments on the other hand were detected for the wheat crop with LSD tests (p -value < 5%) for 40 days in FD and 30 days in HD, out of a measurement period of 122 days (Fig. 6). No particular weather conditions were noted for those days, but they correspond to time periods with a high variability between records from the thermistors in FS. For lettuces, significant differences from FS occurred only in HD (8 days out of 26), and for cucumbers, significant differences were detected only for 2 days in FD and 5 days in HD, over a crop cycle of 62 days, as the spatial variability in T_L records (from one

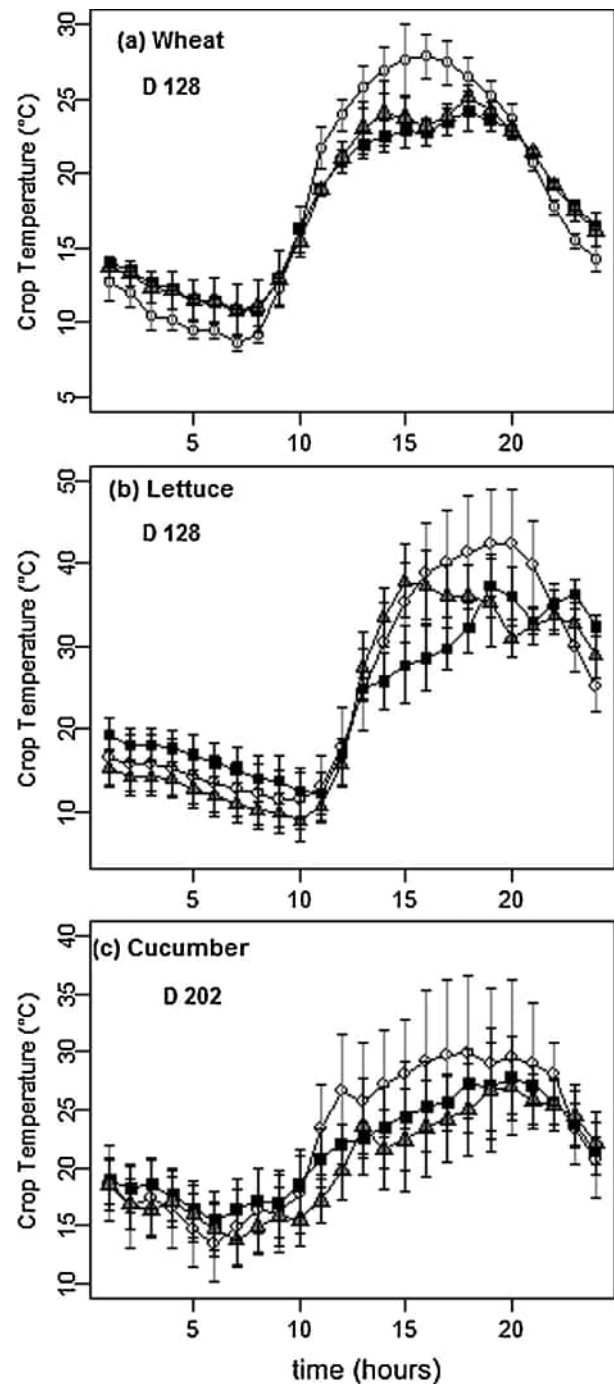


Fig. 5. Thermal pattern of hourly T_L measured on (a) wheat crop, (b) lettuce crop, and (c) cucumber crop, during a sunny day (DOY 128 for wheat and lettuce, DOY 202 for cucumber). Symbols ■ ▲ ○ stand respectively for treatments “FD”, “HD”, and “FS”. Vertical error bars represent standard deviation.

plant to another), for every treatment, was higher for cucumbers and lettuces compared to wheat.

3.5. Radiative drivers of crop temperatures

3.5.1. Photothermal patterns of shaded and un-shaded plants within day

As the plant temperature is directly and indirectly (through net radiation and stomatal aperture) influenced by the incident global radiation (R_s) (De Boeck et al., 2012; Jones, 1992), we compared the photothermal trajectory ($T_L - T_A$ as a function of R_s) in the shaded

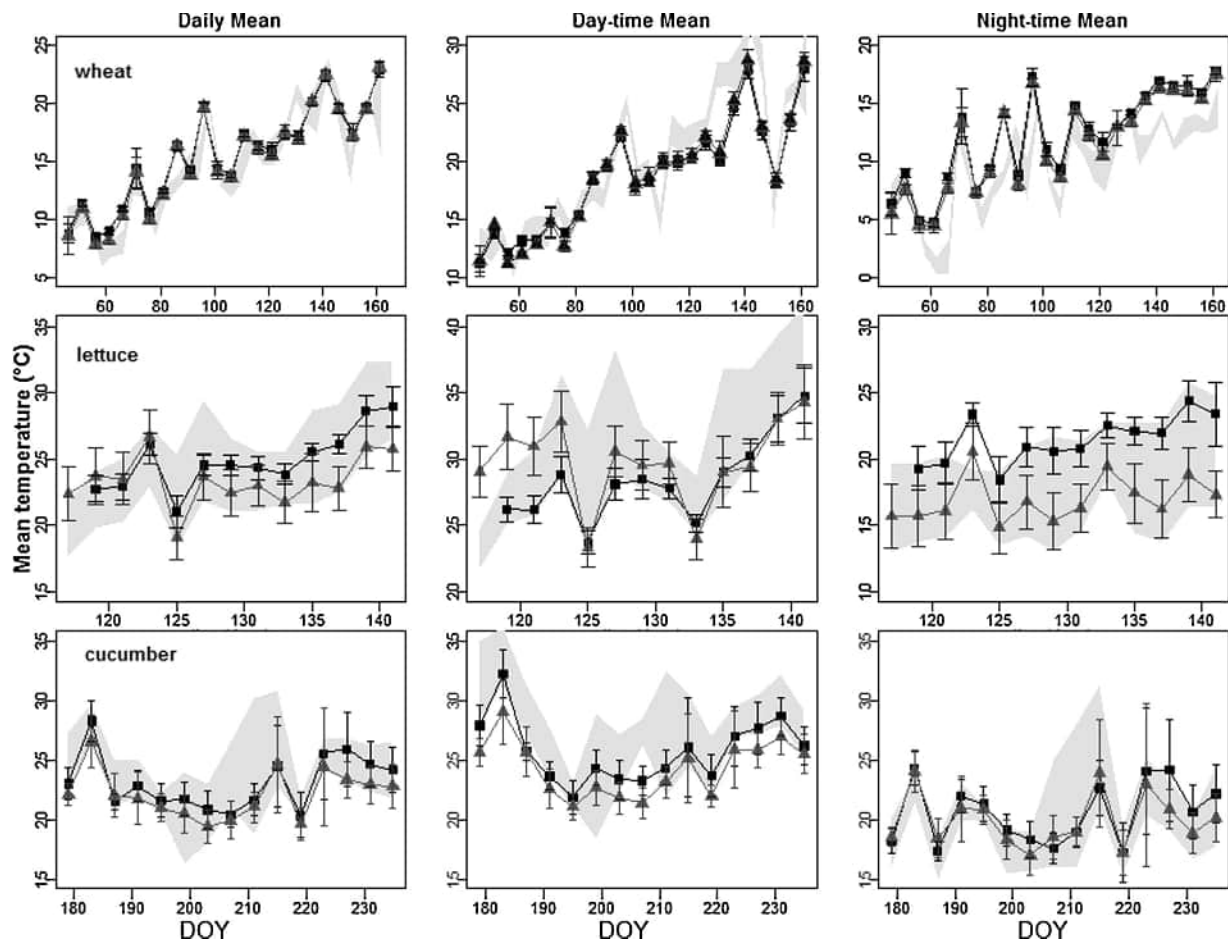


Fig. 6. Mean daily (24 h) crop temperature (T_L), mean day-time temperature (T_{LD}), and night-time temperature (T_{LN}) measured for each crop monitored in 2011. Shaded intervals represent mean values $\pm$ standard error for T_L , T_{LD} , and T_{LN} in FS. The line with gray triangles (▲) features the average of T_L , T_{LD} , and T_{LN} records (4–13 probes depending on the crop) in HD, while the line with closed squares (■) features the average of T_L , T_{LD} , and T_{LN} records (4–13 probes depending on the crop) in FD. Vertical error bars represent standard deviation.

treatments for a sunny day in the late spring (wheat and lettuces) or in midsummer (cucumber). The purpose of this analysis was to determine to which extent the variation of incoming shortwave radiations explain the differences observed on crop temperature T_L in the shade compared to FS, at hourly time step. In order to compare crop temperature measured on different days, the difference between crop temperature and air temperature ($T_L - T_A$) was considered for each treatment. In FD and HD, the photothermal trajectory did not follow the same pattern as in FS. In FS, from sunrise to 14:00, the $(T_L - T_A)/R_s$ ratio was nearly constant and equal to $0.0124^\circ\text{C m}^2 \text{W}^{-1}$ for wheat, $0.0232^\circ\text{C m}^2 \text{W}^{-1}$ for lettuces, and $0.0086^\circ\text{C m}^2 \text{W}^{-1}$ for cucumbers (Fig. 7). In the shade, lettuce temperatures increased more rapidly: the $(T_L - T_A)/R_s$ ratio was equal to 0.047 both in HD and FD. In the case of wheat and cucumber, $(T_L - T_A)/R_s$ was lower in the shade (FD and HD) compared to FS. Maximal temperatures were reached around midday in all the treatments and were similar in the shade and in FS, except in the case of lettuces in HD, where the maximal temperature of shaded plants exceeded that of the lettuces grown in FS.

3.5.2. Long wave radiation and radiative balance of shaded and un-shaded plants

In order to compare radiative balance assessed from data collected on different days for the three treatments, all radiation measurements were normalized by the maximal $R_{s\downarrow}$ of the day in the full sun. During day-time, the main effect of the PVP cover was a reduction of the downwards shortwave radiation ($R_{s\downarrow}$) (Fig. 8) while, the

downward longwave radiation ($R_{\ell\downarrow}$) remained similar in the three treatments (respectively 43%, 41%, and 44% in FS, HD, and FD). Thus, the PVPs did not contribute consistently to the long wave radiation input and did not compensate the loss of $R_{s\downarrow}$ in the radiative balance.

During night-time, no clear modifications were observed in downwards radiations, while the radiative losses were lower under the PVPs (41% both in FD and HD) than in FS (46%).

3.5.3. Spatial distribution of photosynthetically active shortwave radiations in the shade

For each face of the sensor, the amount of radiation received every 10 min in the shaded treatments never exceeded the one received by the same face at the same time in FS (data not shown). Thus, the hypothesis according to which PVPs could be responsible for radiation scattering, resulting in a significant increase of radiation reaching the crops with low elevation angle under the PVPs can be discarded.

However, the proportion of the radiation incoming from the different directions changed in the shade of the PVPs (Fig. 9). It seems that incident radiation distribution was more homogenous in the shade of PVPs than in FS, especially in the morning. In FS, the model predicted that the proportion of radiation incoming from North-East and North directions (F3 and F4 faces) dramatically decreased between 8:00 am and 14:00 ($C_v = 53\%$ for F3 and 48% for F4). In the shade (FD or HD), the proportion of radiation measured on inclined faces F3 and F4 varied less than in FS ($C_v = 36\%$ for F3 and 29% for F4) between 8:00 and 14:00. This different spatial balance

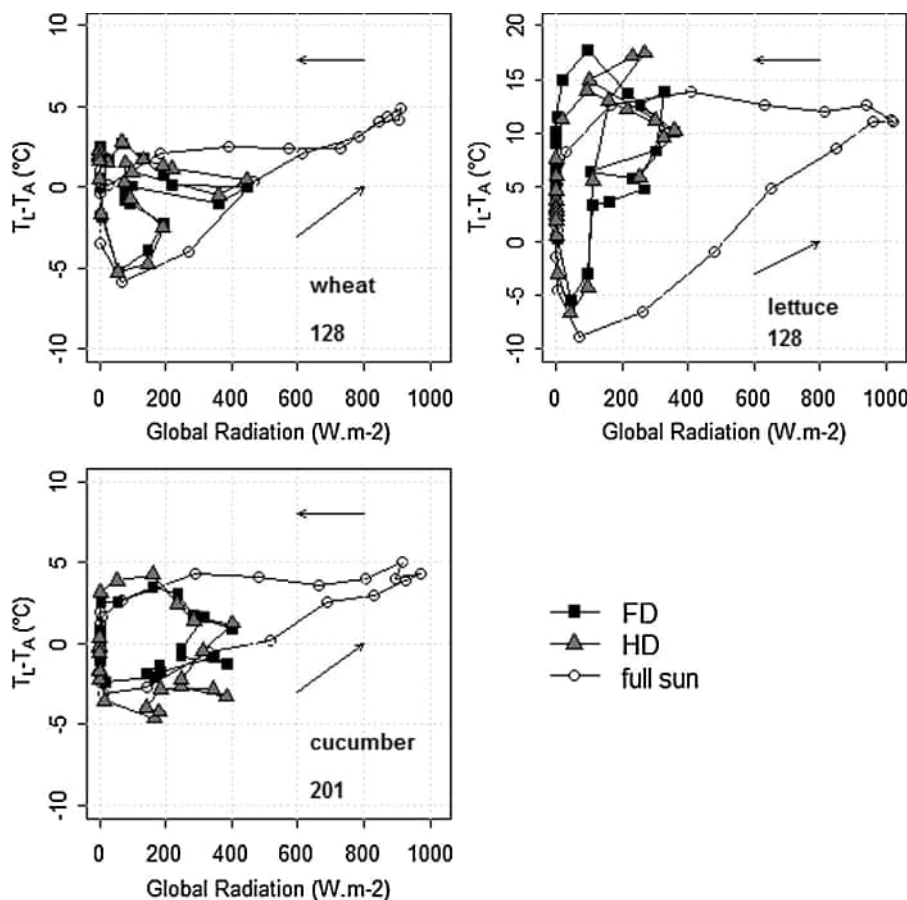


Fig. 7. Photothermal paths measured on sunny days for (a) wheat and (b) lettuce on DOY 128, and for (c) cucumber on DOY 201. The line with open symbols (○) represents FS situation, while lines with closed symbols feature the FD (■) and the HD situations (▲). Arrows indicate the direction of the trajectory in the morning (upward orientated arrow) and in the afternoon (horizontal arrow).

of radiation direction also highlights the increase of diffuse radiation proportion in the incident radiation at the crop level below the PVPs.

3.6. Plant development rate

3.6.1. Lettuce

Leaf numbers were plotted separately for the two varieties cropped in summer 2010 as this dataset was not collected for variety FC+ at the final harvest. For the two cropping seasons and the three shade levels, the leaf apparition rate was constant or increased from planting to harvest date (Fig. 10), which is consistent with former observations (Gay, 2002; Horie et al., 1979). In 2010, the analysis of covariance (ANCOVA) on leaf number, as a function of the thermal time and the shade treatment, showed that the leaf apparition rate was significantly reduced in FD and HD compared to FS during the first 3 weeks after planting (0–418 °Cd), for both varieties. After DOY 223, differences in development rate were evidenced for variety FC+ only. In 2011, the ANCOVA showed that leaf apparition rate was significantly reduced in FD and in HD compared to FS, only during the first three weeks after planting (0–336 °Cd). Afterwards, the leaf apparition rate was the same in all treatments, when considering all the varieties pooled together or individually (except variety B– for which apparition rates were significantly different between treatments up to 6 weeks after planting).

3.6.2. Cucumbers

Cucumber leaf apparition rate (leaf emitted on the main stem only or both on the main stem and on secondary branches

pooled together) followed a sigmoid dynamic in the three shading treatments (Fig. 11). Consequently, development dynamic was decomposed into three successive phases: (P1) from DOY 180 (planting, 0 °Cd) to 192 (196.5 °Cd), (P2) from DOY 192 to 214 (404.1 °Cd), (P3) from DOY 214 to 229 (567 °Cd). Phase 1 (P1) corresponds to the juvenile development phase, also called “initial lag phase” by Horie et al. (1979), Phase 2 (P2) corresponds to the maximum vegetative development (also called “stationary phase” by Horie et al., 1979), while Phase 3 (P3) corresponds to fruit development and plant senescence. The dates of transition from one phase to another were not affected by shading (Marrou, 2012).

The ANCOVA showed that the leaf apparition rate on the main stem (Fig. 11a) was not affected by the shade during P2; however, leaf emission rate was significantly reduced in FD and HD compared to FS during P1, and P3. On the opposite, when considering the total pool of leaves (Fig. 11b), the ANCOVA showed that the leaf apparition rate was reduced significantly only during P2. Considering the whole cropping season, the dynamics of the total number of leaves was more affected by shading than that of the number of leaves on the main stem, although it is also much more variable within treatments.

3.6.3. Wheat

Heading was reported on DOY 109 in FS, DOY 111 in the HD plot and DOY 115 in the FD plot (visual determination at 50% of heading). On DOY 157, wheat grain was in stage 89 in FS, while it was in stages 85–87 in FD and HD according to Zadock's phenological scale (Zadoks et al., 1974). The grains maturity was reached on DOY 168 in HD and FD while it was 2–3 days earlier in FS. These observations

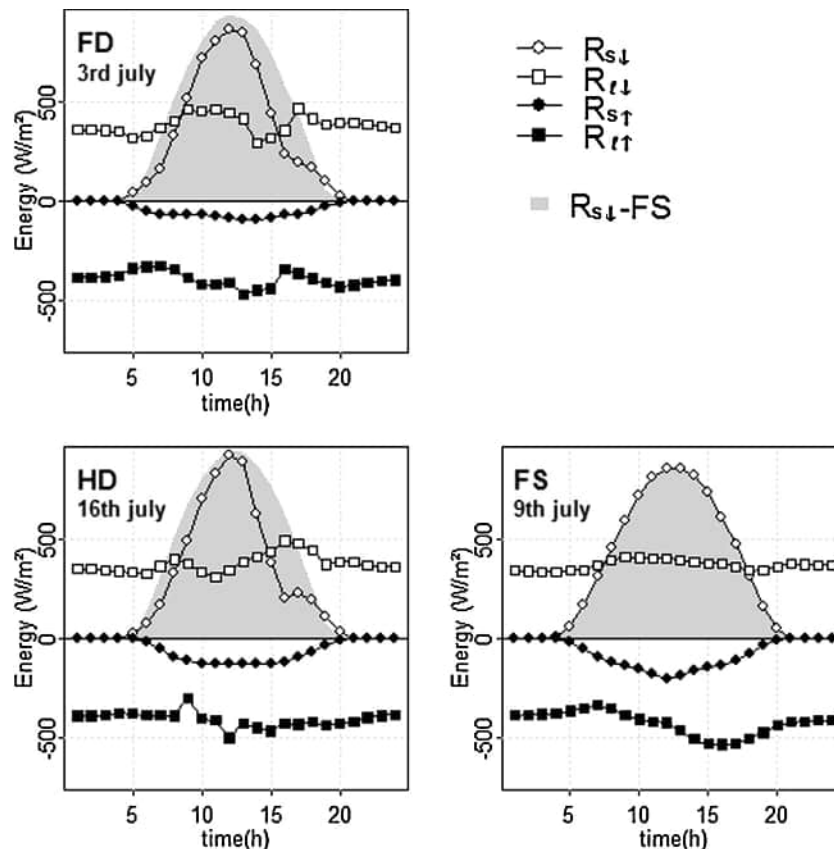


Fig. 8. Evolution of upward ($R_{l\uparrow}$) and downward ($R_{l\downarrow}$) longwave radiations and upward ($R_{s\uparrow}$) and downward ($R_{s\downarrow}$) shortwave radiations in the three treatments for three close sunny days. The shaded area represent the shortwave downwards radiation (global radiation) in the full sun for the day of the measurement.

are consistent with phenological delays reported by Sudmeyer and Speijers (2007) on wheat cropped under wind breaks.

4. Discussion

4.1. Unchanged air masses characteristics in agrivoltaic systems (AVS)

The comparison of air temperature at reference height (2 m) showed that there was no significant difference between partially shaded treatments and FS, neither at daily time step nor at hourly or infra hour time steps at the latitude of the experimental site (43° N). Similarly, no significant difference was found between treatments for VPD and wind speed at 2 m: the maximal increase in VPD in shaded treatments compared to FS corresponds for cereals to (1) a decrease in CO_2 assimilation rate of $0.5 \mu\text{mol m}^{-2} \text{s}^{-1}$ according to Dai et al. (1992), and (2) to a decrease in water use efficiency of $1.4 \text{ g m}^{-2} \text{mm}^{-1}$ according to literature (Abbate et al., 2004; Tanner and Sinclair, 1983). This result indicates that our prototype of AVS (around 45 m length and 860 m^2) with PVPs far above-ground (4 m) is a highly aerated system where air masses are in equilibrium with the outside environment. We could have expected significant differences in air temperatures or humidity on no wind days, but this was proved not to be true. Convection air movements seem therefore to be powerful enough to homogenize air characteristics across the system. However, our prototype was small compared to AVS that could be used for crop production. The mean average standard size for an AVS could be reasonably – on a technical point of view – comprised between 0.5 and 2 ha. Under such extensive devices, some changes in air temperature and wind speed profiles could be observed. It is difficult to know in which extent because AVS

combine numerous sources of variation in T_A and wind speed profiles such as shading, windbreak effects, development of boundary layers, changes in plant and soil temperature. Further experiments should be conducted to explore the impact of PVPs on air characteristics and heat exchanges in case of bigger size AVS. Nevertheless, agrivoltaic system are not closed system and should not be assimilated to photovoltaic greenhouses, as described by Carlini et al. (2012), Kadowaki et al. (2012), and Poncet et al. (2010). Therefore air temperature cannot be monitored in AVS as in greenhouses and crop adapted to outdoor conditions should be more suitable for AVS. One of the main negative effects of shading on crops is usually the increase of fungal diseases, as reported by Roberts and Paul (2006) and Wu et al. (2005). Fungus development is directly enhanced in confined environments with increased air humidity and reduced air circulation (Sudmeyer and Speijers, 2007). Therefore we can expect that pest and diseases will not be stimulated in AVS, compared to similar cropping systems and genotypes in FS, thanks to the maintenance of air circulation below the structure.

4.2. Variability of crop temperature at infra-daily time steps

Crop temperature solves the energy balance equation (Eq. (1)) which is dominated by the radiant exchanges (Chelle, 2005; Jones, 1992). Consequently, we analyzed the variation of crop temperature in the shade compared to the full sun regarding the modification of the radiative climate.

4.2.1. Crop temperature decreases

Unlike the air temperature and humidity, the crop temperature pattern within a day was affected by shading. We showed that day/night amplitude tends to decrease in the shade of solar panels

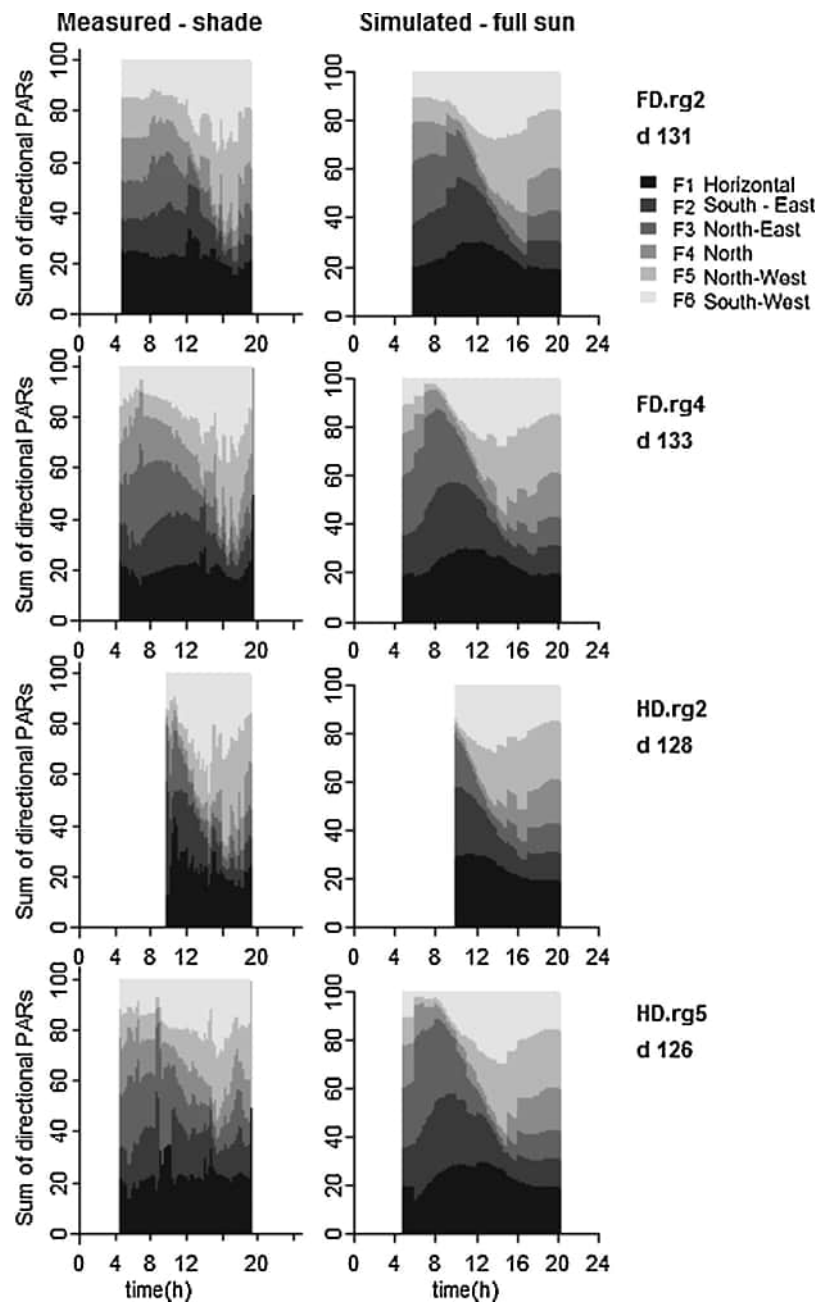


Fig. 9. Distribution of the proportion of incident photosynthetically active radiation captured by each face of the turtle sensor when placed at two locations in the HD plot (HD.rk2 and HD.rk4) and in the FD plot (FD.rk2 and FD.rk5), corresponding to different planting row positions during the lettuce cropping season in spring 2011, and in FS, on the same day. Incident radiation distribution in FS has been simulated using the model of radiation parameterized with the latitude of the site and the same orientation for the sensor as it was recorded on the day of measurement in the shaded treatment.

at the latitude of the experimental site (43° N). Crop temperature around midday decreased significantly for each tested crop in the three seasons.

T_L was found to have higher spatial variability (from one plant to another within the same treatment plot), for every treatment, for cucumbers and lettuces compared to wheat. This result is probably due to (1) the fact that wheat temperature was measured in the center of the plant cover, at mid plant height, and was consequently less affected by variations of the incident global radiation, (2) the influence of soil temperature variations that should be higher on small crops close to the ground surface (lettuces, cucumbers) than on tall crops such as wheat, (3) the number of plant positions where measurements were taken that was higher for lettuces than for

wheat (5 planting ranks on a North South transect in the case of lettuces compared to 2 locations on a transect for wheat).

Decrease in crop temperature under PVPs was mainly due to the reduction in the incoming shortwave radiations as variations in long wave radiations between shaded and unshaded treatments were found to remain small (Section 3.5.2) compared to variation in net shortwave radiation ($(1 - a) \cdot R_s$, with a the crop albedo).

4.2.2. Crop temperature increases

During night-time, crop temperature increased under PVPs (FD and HD treatments) compared to FS, which could be partly explained by reduced radiative losses under PVPs as shown in Section 3.5.2. Heat conduction from the soil could also contribute to

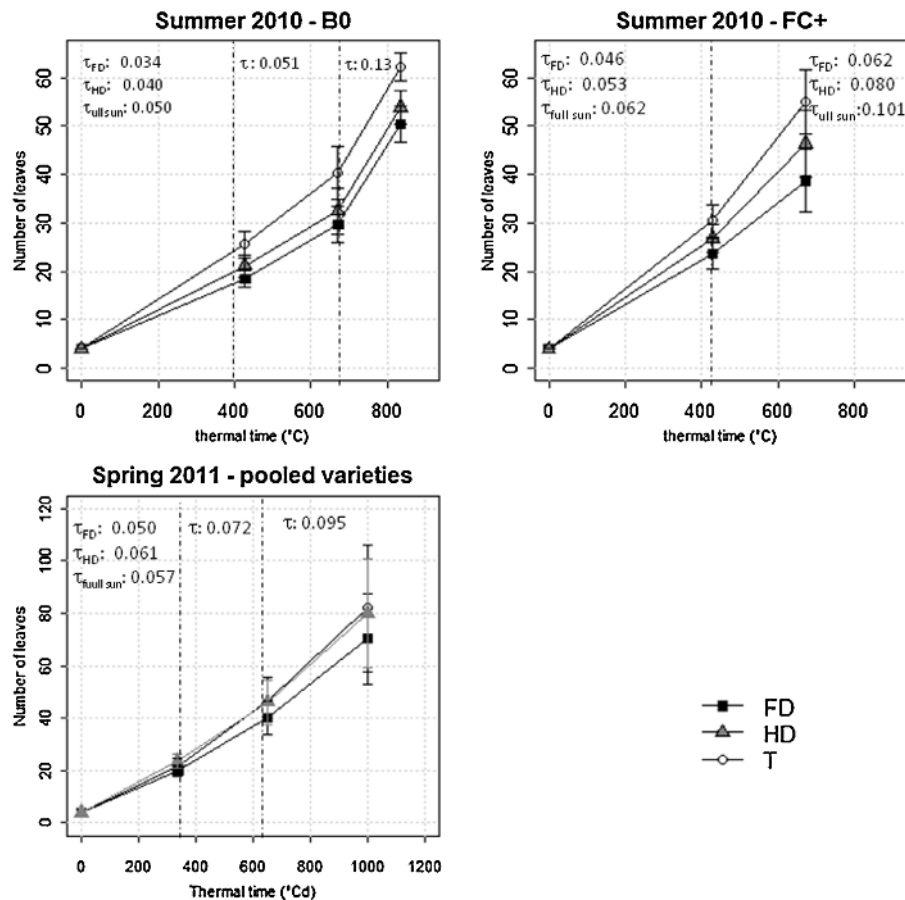


Fig. 10. Number of leaves measured on (a) summer lettuce variety B0, and (b) variety FC+ in 2010, and (c) spring lettuce (all varieties pooled together) in 2011. Lines with symbols ○, ■, ▲ refers respectively to measurements in FS, FD plot and HD plots. Vertical error bars feature standard errors. Leaf emission rate (τ , leaves °C d⁻¹) is represented for each period between two sampling dates.

modify crop temperature. Further measurements to quantify the radiative balance and heat fluxes from the soil are required to quantify and rank the main drivers of crop temperature increases during night-time.

During day-time, we observed a rapid increase of T_l in the morning in the case of lettuce in the HD treatment, whereas the radiative balance is lower under the PVPs compared to FS. Considering lettuce as hemispherical object, scattering effects increasing plant

irradiance in the morning could be suspected. Turtle measurements as well as FS simulation showed that the proportion of radiation incoming from different sky directions changed in the partially shaded situations compared to FS. Differences in the light distribution were mainly significant in the morning, during sunny days: whereas most of the incident radiation comes from the sun direction in FS, it is homogeneously distributed among the sky sectors in the shaded situation. However, the total amount of energy received

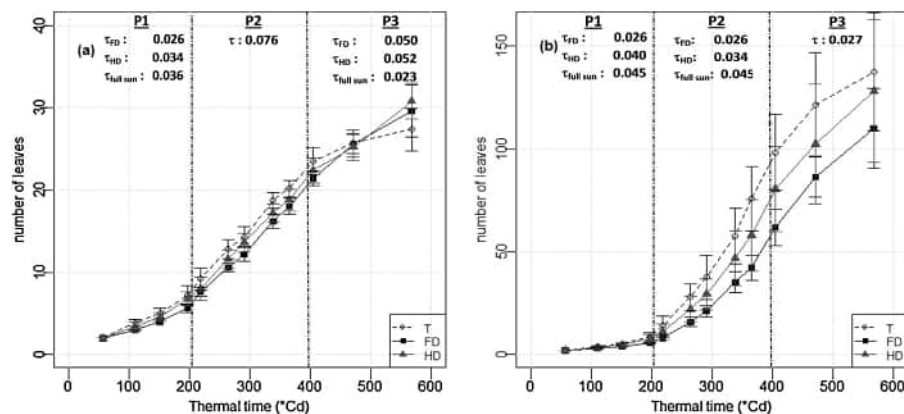


Fig. 11. Number of leaves measured on cucumbers, in 2011. (a) Accounted for leaves on the main stem only. (b) The total number of leaves (main stem, as well as secondary and tertiary branches). ○, ■, ▲ refers respectively to measurements in FS, FD plot and HD plots. Vertical error bars feature standard errors. Leaf emission rates (τ) are given for each development phase.

from any direction was always smaller below the PVPs compared to FS treatment. Consequently, strong scattering effects are unlikely to happen in agrivoltaic system, and do not explain that the plant temperature tends to increase more rapidly between 7:00 and 12:00 TU in the shaded situations compared to FS.

It is also important to notice that the more homogenous repartition of the spatial distribution of incident radiation below the PVPs is related to an increase of the diffuse/direct ratio of incident light. This characteristic of the radiative environment of agrivoltaic systems could be favorable to plant growth. Indeed, several authors already reported an increase of the radiation use efficiency when the proportion of diffuse radiation increases (Gu et al., 2002; Sinclair et al., 1992).

A comprehensive assessment of the energy balance, including the measurement of leaf transpiration at an hourly time step (Guilioni et al., 2000) would be necessary to determine the cause of the lettuce temperature elevation under HD treatment. The stomatal aperture is under the control of crop surface incident net radiation and has been reported to be sensitive to shade (Turner, 1991). However, the stomatal aperture/closure effect is expected to moderate changes in incident light, due to the quickness of the response of stomata conductance to shade (Fay and Knapp, 1996) and to be of a small order of magnitude compared to radiation fluxes (Baille et al., 2001). On the contrary, differential dew formation at night and evaporation in the morning could explain the different pattern of evolution of crop temperature in the morning in FD, HD, and FS treatments. Indeed, T_L is significantly lower in FS than in FD and in HD at night, and was checked to be less than dew point temperature during clear night. Consequently dew formation is expected (and was observed) in FS while it is not the case in the shaded treatment. In the morning, dew evaporation participate in the reduction of leaf temperature in the full sun and could lead to smaller rate if T_L increase than in shaded situations, even if incident radiation is higher.

4.3. Consequences on plants development rate in the agrivoltaic systems (AVS)

Although crop temperature in the shade of PVPs was reduced at infra-daily time step (Fig. 5), mean daily crop temperature remained close to the one in FS (Fig. 6). This result is consistent with the only slightly reduced leaf emission rate for partially shaded plants (Figs. 10 and 11a). Lettuces as well as cucumbers (considering the main stem only) were shown to grow at the same rate during the period of maximal vegetative growth (Figs. 10 and 11) whereas growth rates were reduced under PVPs at the beginning of the plant life cycle. This is likely to be caused by the reduction of ground temperature in the shade of the solar panels (explanation 1). Indeed, the development rate is monitored by the meristem temperature which is close to soil surface at the beginning of the plant life cycle and becomes to some distance to the soil surface when plant height further increases (Ritchie and NeSmith, 1991).

Several complementary explanations can be proposed for the reduction of growth at the beginning of each crop cycle and should be explored in further research and should be discriminated with further experimentation under controlled conditions (with potted plants or in growth chamber for example): (explanation 2) the increase of the crop temperature during night-time could entail an increase of the night respiration rate in shaded plants (Hüve et al., 2011; Vries et al., 1979), thereby reducing the carbon assimilates available for the plant development. A recent study showed that a reduction of the day-night temperature amplitude decreased the biosynthesis of vegetative structure from carbon reserves (Buono et al., 2012). Consequently leaf emission could be delayed below the PVPs through a C limitation of the leaf and stem development.

However, the increase of the crop temperature during night-time was significant only for wheat and night-time temperature remained below 20 °C during the first part of the cycle, which cannot entail a dramatic increase of respiration (explanation 3). The reduction of light resource could be directly responsible for the slower development of young plants in the shade. As the leaf area of a young plant is small, its light capture ability is limited, and shade can be more detrimental to young plants than to mature plants with wide light harvesting organs as suggested by Bensink (1971) for lettuces (explanation 4). Another possibility, relating directly the light reduction to the development rate decrease is that, at that stage of development, plant reserves are insufficient to overpass periods of light resource shortage. Young plants have smaller carbohydrates pool. So, when seedlings are punctually shaded during day-time, their non-structural pool of carbon may be emptied more rapidly through respiration as less carbon input would be provided by photosynthesis, as suggested by the Seginer's model (Seginer et al., 1994) (explanation 5). Low shoot/root ratio was reported as a plant adaptation to shade (Seidlova et al., 2009). During the first phase of development, biomass is preferentially allocated to root production: this could also explain why young plants have a reduced leaf emission rate in the shade, while older plants grow at the same rate in FS as in the shade. A new experiment with a monitoring of underground dry matter on plants grown in FS, in the FD and in the HD would be necessary to conclude on that point. Regarding our results, it seems that development rate decrease in the first plant stage should be attributed to light reduction, more than to temperature changes. Interaction between plant age and shade sensibility has already been reported (Niinemets, 2010; Valladares and Niinemets, 2008). It is likely that, for young lettuces and cucumbers in the shade of PVPs, light influence is predominant on temperature one and is the main limiting resource (as defined in Kho, 2000) for biomass accumulation. In accordance with this finding, a particular attention should be paid to juvenile stages of the plant development for the optimization of AVS. At these stages, not only biomass accumulation can be reduced but plant development can be delayed too.

5. Conclusion

This study shows small agrivoltaic systems can be handled as open field production systems, and not as closed greenhouse, because their main specificity is in the mean daily reduction of light availability for plant without significant modification of the other parameters of the microclimate at canopy level. Due to a sufficient air circulation below the open structure, air temperature and VPD were not significantly affected by the PVP shelters. Over the whole cropping season, and even for a long cycle crop, the crop temperature was marginally modified in the shade compared to FS, with regards to the impact on the plant development. This finding which was unexpected, as the energy balance was suspected to be impacted by the shelter, would make easy the establishment of agrivoltaic systems on farm. It suggests that little adaptation in cropping practices should be required to switch from open cropping to agrivoltaic cropping and attention should mostly be paid to light reduction mitigation (Marrou et al., 2013). Nevertheless, these results should be confirmed under larger AVS where air temperature and wind speed profiles could be modified under PVPs. Juvenile crop stages should be looked after with caution as strong shading at the beginning of the cycle could delay development for the whole cycle but may also have positive effects on vegetable plants establishment during warm season. A solution would be to use mobile panels that could be set in a direction that allows the maximal light penetration at the crop level at the plant setting time. Panels could be set back to an optimal position for energy production afterwards

(Marrou, 2012). Furthermore, AVS and light reduction are not necessary detrimental for crop production as Radiation Interception Efficiency (RIE) was showed to be increased in the shade (Marrou et al., 2013).

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Appendix A. Diagram of the simulated geometrical scene

See Fig. A1.

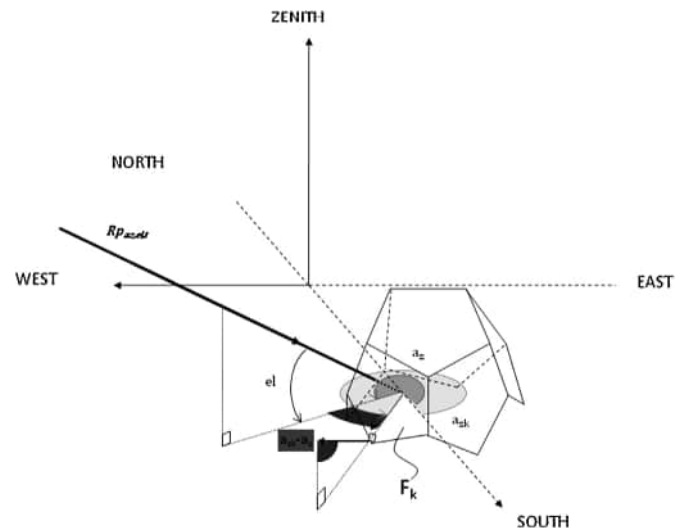


Fig. A1. geometric representation of the interception of light by the turtle sensor, as simulated by the radiation model. a_z : azimuth of the incident beam; el : elevation of the incident beam.

Appendix B. Model validation

See Fig. B2.

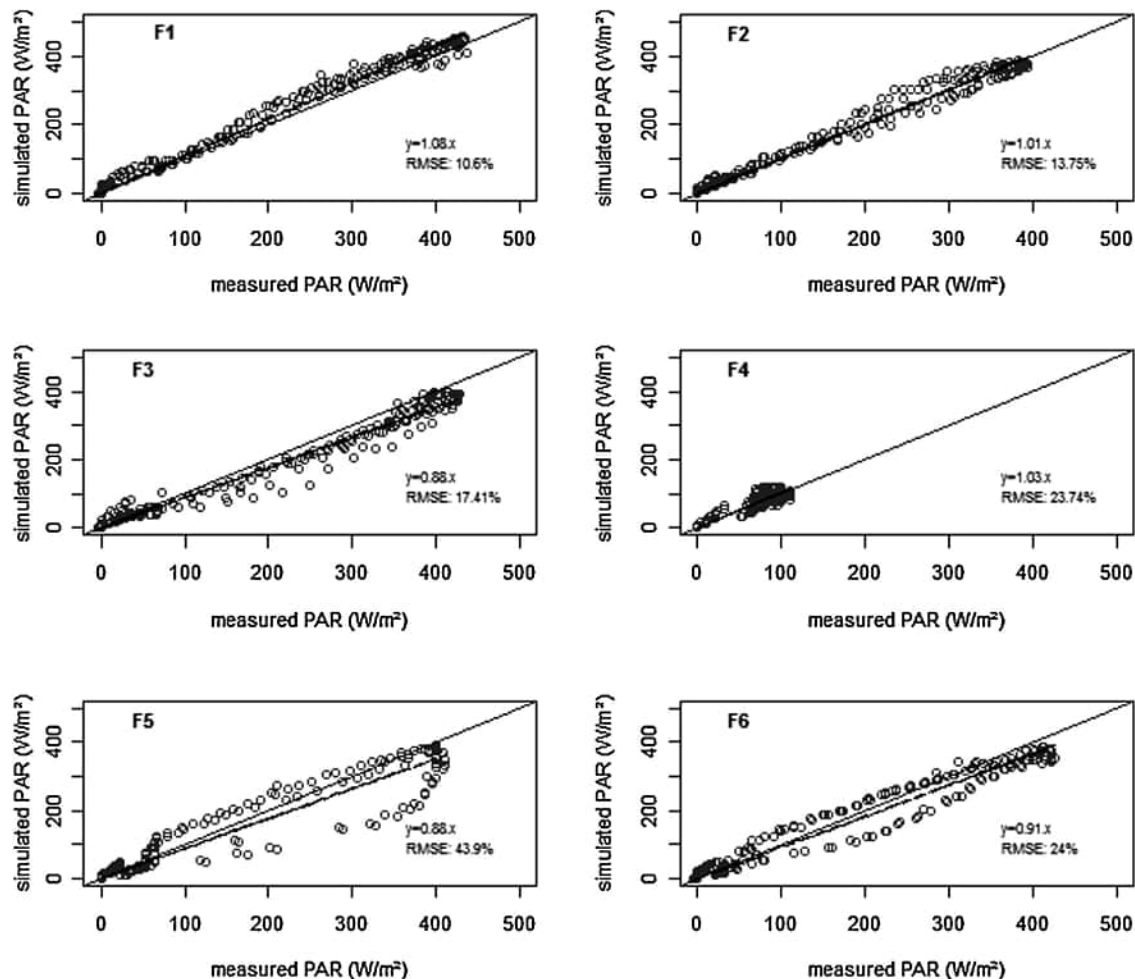


Fig. B2. simulated versus measured incident PAR radiation, for the measurement period (from DOY 196 to DOY 199, in 2012). Each graph corresponds to a different face of the turtle sensor – F1 (horizontal face) to F6. Equation of the regression line between simulated and measured data as well as RMSE calculated on the hypothesis that simulated data = measured data for each face of the sensor are plotted on the graph areas.

References

- Abbate, P.E., Dardanelli, J.L., Cantarero, M.G., Maturano, M., Melchiori, R.J.M., Suero, E.E., 2004. Climatic and water availability effects on water-use efficiency in wheat. *Crop Sci.* 44 (2), 474–483.
- Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration – Guidelines for computing crop water requirements. FAO Irrigation and Drainage Papers 56. FAO – Food and Agriculture Organization of the United Nations, Rome.
- Anderson, M., 1966. Some problems of simple characterization of the light climate in plant communities. In: Bainbridge, R., Evans, G.C., Rackham, O. (Eds.), *Light as an Ecological Factor*. Blackwell Science Publisher, Oxford, pp. 77–90.
- Baille, A., Kittas, C., Katsoulas, N., 2001. Influence of whitening on greenhouse microclimate and crop energy partitioning. *Agric. Forest Meteorol.* 107 (4), 293–306.
- Bensink, J., 1971. On morphogenesis of lettuce leaves in relation to light and temperature. Proefschrift Wageningen. Thesis. Veenman, Wageningen.
- Bindi, M., Miglietta, F., Zipoli, G., 1992. Different methods for separating diffuse and direct components of solar radiation and their application in crop growth models. *Clim. Res.* 2, 47–54.
- Bueno, A., Prudente, D., Machado, E., Ribeiro, R., 2012. Daily temperature amplitude affects the vegetative growth and carbon metabolism of orange trees in a rootstock-dependent manner. *J. Plant Growth Regul.* 31 (3), 309–319.
- Carlini, M., Honorati, T., Castellucci, S., 2012. Photovoltaic greenhouses: comparison of optical and thermal behaviour for energy savings. *Math. Prob. Eng.* 2012, Article ID 743764, 10 pages.
- Chelle, M., 2005. Phylloclimate or the climate perceived by individual plant organs: What is it? How to model it? What for? *New Phytol.* 166 (3), 781–790.
- Chenu, K., Rey, H., Dauzat, J., Lydie, G., LecAur, J., 2008. Estimation of light interception in research environments: a joint approach using directional light sensors and 3D virtual plants applied to sunflower (*Helianthus annuus*) and *Arabidopsis thaliana* in natural and artificial conditions. *Funct. Plant Biol.* 35 (10), 850–866.
- Dai, Z.Y., Edwards, G.E., Ku, M.S.B., 1992. Control of photosynthesis and stomatal conductance in *Ricinus-Communis* L. (Castor Bean) by leaf to air vapor–pressure deficit. *Plant Physiol.* 99 (4), 1426–1434.
- De Boeck, H.J., De Groote, T., Nijs, I., 2012. Leaf temperatures in glasshouses and open-top chambers. *New Phytol.* 194 (4), 1155–1164.
- Dupraz, C., Marrou, H., Talbot, G., Dufour, L., Nogier, A., Ferard, Y., 2010. Combining solar photovoltaic panels and food crops for optimising land use: towards new agrivoltaic schemes. *Renew. Energy* 36 (10), 2725–2732.
- Fay, P.A., Knapp, A.K., 1996. Photosynthetic and stomatal responses to variable light in a cool-season and warm-season prairie forb. *Int. J. Plant Sci.* 157 (3), 303–308.
- Gay, F., 2002. Elaboration d'une méthode d'évaluation des risques de pollution nitrique et de pertes de rendement en parcelles agricoles. Ecole Nationale Supérieure Agronomique de Montpellier, Montpellier.
- Gu, L., Baldocchi, D., Verma, S.B., Black, T.A., Vesala, T., Falge, E.M., Dowty, P.R., 2002. Advantages of diffuse radiation for terrestrial ecosystem productivity. *J. Geophys. Res.: Atmos.* 107 (D6), ACL 2-1–ACL 2-23.
- Guilioni, L., Cellier, P., Ruget, F.O., Nicoulaud, B., Bonhomme, R., 2000. A model to estimate the temperature of a maize apex from meteorological data. *Agric. Forest Meteorol.* 100 (2–3), 213–230.
- Horie, T., de Wit, C.T., Goudriaan, J., Bensink, J., 1979. A formal template for the development of cucumber in its vegetative stage. *Proceedings of the Nederlandse Akademie van Wetenschappen (Amsterdam, the Netherlands). Series C. Biol. Med. Sci.* 82 (4), 433–479.
- Hüve, K., Bichele, I., Ivanova, H., Keerberg, O., Pärnik, T., Rasulov, B., Tobias, M., Niinemets, Ü., 2011. Temperature responses of dark respiration in relation to leaf sugar concentration. *Physiol. Plant.* 144 (4), 320–334.
- Jones, H.G., 1992. *Plants and Microclimate: A Quantitative Approach to Environmental Plant Physiology*. Cambridge University Press, Cambridge.
- Kadowaki, M., Yano, A., Ishizu, F., Tanaka, T., Noda, S., 2012. Effects of greenhouse photovoltaic array shading on Welsh onion growth. *Biosyst. Eng.* 111 (3), 290–297.
- Kho, R.M., 2000. On crop production and the balance of available resources. *Agric. Ecosyst. Environ.* 80 (1–2), 71–85.
- Kittas, C., Bartzanas, T., Jaffrin, A., 2003. Temperature gradients in a partially shaded large greenhouse equipped with evaporative cooling pads. *Biosyst. Eng.* 85 (1), 87–94.
- Liu, B.Y.H., Jordan, R.C., 1960. The interrelationship and characteristic distribution of direct, diffuse and total solar radiation. *Solar Energy* 4 (3), 1–19.
- Lott, J.E., Ong, C.K., Black, C.R., 2009. Understorey microclimate and crop performance in a Grevillea robusta-based agroforestry system in semi-arid Kenya. *Agric. Forest Meteorol.* 149, 1140–1151.
- Marrou, H., 2012. Conception and Optimisation of Agrivoltaic Systems. PhD Thesis. Montpellier SupAgro, Montpellier.
- Marrou, H., Wery, J., Dufour, L., Dupraz, C., 2013. Productivity and radiation use efficiency of lettuces grown in the partial shade of photovoltaic panels. *Eur. J. Agron.* 44 (0), 54–66.
- Monteith, J.L., 1977. Climate and the efficiency of crop production in Britain. *Philos. Trans. R. Soc.* 281, 277–294.
- Monteith, J.L., Ong, C.K., Corlett, J.E., 1991. Microclimatic interactions in agroforestry systems. *Forest Ecol. Manage.* 45 (1–4), 31–44.
- Niinemets, U., 2010. A review of light interception in plant stands from leaf to canopy in different plant functional types and in species with varying shade tolerance. *Ecol. Res.* 25 (4), 693–714.
- Perry, K.B., Wehner, T.C., Johnson, G.L., 1986. Comparison of 14 methods to determine heat unit requirements for cucumber harvest. *Hortscience* 21 (3), 419–423.
- Poncet, C., Muller, M.M., Brun, R., Fatnassi, H., 2010. Photovoltaic greenhouses, non-sense or a real opportunity for the greenhouse systems? *Acta Horticult. Int. Soc. Horticult. Sci. (ISHS)*, 75–79.
- Porter, J.R., Gawith, M., 1999. Temperatures and the growth and development of wheat: a review. *Eur. J. Agron.* 10 (1), 23–36.
- Ritchie, J.T., NeSmith, D.S., 1991. Temperature and crop development. In: Hanks, J., Ritchie, J.T. (Eds.), *Modeling Plant and Soil Systems*. ASA, CSSA, SCAA, Madison, Wisconsin, USA, pp. 5–29.
- Roberts, M.R., Paul, N.D., 2006. Seduced by the dark side: integrating molecular and ecological perspectives on the influence of light on plant defence against pests and pathogens. *New Phytol.* 170 (4), 677–699.
- Seginer, I., Gary, C., Tchamitchian, M., 1994. Optimal temperature regimes for a greenhouse crop with a carbohydrate pool: a modelling study. *Sci. Horticult.* 60 (1–2), 55–80.
- Seidlova, L., Verlinden, M., Gloser, J., Milbau, A., Nijs, I., 2009. Which plant traits promote growth in the low-light regimes of vegetation gaps? *Plant Ecol.* 200 (2), 303–318.
- Sinclair, T.R., Shiraiwa, T., Hammer, G.L., 1992. Variation in crop radiation-use efficiency with increased diffuse radiation. *Crop Sci.* 32, 1281–1284.
- Spitters, C.J.T., Toussaint, H.A.J.M., Goudriaan, J., 1986. Separating the diffuse and direct component of global radiation and its implications for modeling canopy photosynthesis. Part I. Components of incoming radiation. *Agric. Forest Meteorol.* 38 (1–3), 217–229.
- Sudmeyer, R.A., Speijers, J., 2007. Influence of windbreak orientation, shade and rainfall interception on wheat and lupin growth in the absence of below-ground competition. *Agroforestry Syst.* 71 (3), 201–214.
- Tanner, C.B., Sinclair, T.R., 1983. Efficient water use in crop production: research or re-search? *Limitations to Efficient Water Use in Crop Production*, pp. 1–27.
- Thicoïpé, J.P., 1997. *Laitues. Monographie*, Paris, 281 pp.
- Thorpe, M.R., Butler, D.R., 1977. Heat transfer coefficients for leaves on orchard apple trees. *Boundary-Layer Meteorol.* 12 (1), 61–73.
- Turner, N.C., 1991. Measurement and influence of environmental and plant factors on stomatal conductance in the field. *Agric. Forest Meteorol.* 54, 137–154.
- Valladares, F., Niinemets, U., 2008. Shade tolerance, a key plant feature of complex nature and consequences. *Ann. Rev. Ecol. Evol. Syst. (Palo Alto)*, 237–257.
- Vries, F.W.T.P.D., Witlage, J.M., Kremer, D., 1979. Rates of respiration and of increase in structural dry matter in young wheat, ryegrass and maize plants in relation to temperature, to water stress and to their sugar content. *Ann. Bot.* 44 (5), 595–609.
- Wu, B.M., Subbarao, K.V., van Bruggen, A.H.C., 2005. Analyses of the relationships between lettuce downy mildew and weather variables using geographic information system techniques. *Plant Dis.* 89, 90–96.
- Zadoks, J.C., Chang, T.T., Konzak, C.F., 1974. A decimal code for the growth stages of cereals. *Weed Res.* 14 (6), 415–421.



How does a shelter of solar panels influence water flows in a soil–crop system?



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ABSTRACT

Associating on the same land area an upper layer of solar panels together with a crop layer at the ground level has been shown to allow significant saving of land resource compared to separate energy and food productions (Marrou et al., 2013a). Indeed, crops can achieve high yield under the fluctuating shade of these agrivoltaic systems. Moreover, under dry Mediterranean climate, microclimate measurements at crop level below these panels suggest that these systems could contribute to alleviate climatic stress and to save water. On two experimental prototypes of these agrivoltaic systems, we combined two complementary approaches to assess the impact of the solar panels cover on crop water use. First we calculated the bulk actual evapotranspiration (AET) of irrigated lettuces and cucumbers grown in agrivoltaic systems and in the full sun, from field measurements using the water balance equation for a crop–soil system. Then, we proposed a conceptual framework to analyze AET modifications in the partial shade and assess the contribution of identified drivers to this change. This conceptual framework breaks AET into two components (plant transpiration and soil evaporation) and four drivers: climatic demand at canopy level (ET_0), fraction of radiation intercepted by the vegetation, plant stomatal conductance, and soil surface hydraulic conductance. From specific field measurements, we assessed the contribution of each driver to the variations of evapotranspiration below the photovoltaic panels (PVP), in comparison with the full sun. Crop AET calculated with the first approach (water balance) was reduced in agrivoltaic systems by 10–30% when available light was equal to 50–70% of full sun radiation, with variations according to the weather season. The second approach showed that reduction of evapotranspiration was mainly driven by the reduction of the climatic demand below the solar panels and did not result systematically in an increase of the water use efficiency, depending on the genotypic plant sensibility of dry matter accumulation to shade. The conceptual framework suggest that water use efficiency in agrivoltaic systems could be increased by selecting crop species and varieties with a rapid soil covering, which contributes to increased light capture and to decreased soil evaporation, leaving more water for plant transpiration and thereby for biomass production.

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1. Introduction

Agrivoltaic systems are mixed production systems associating, on the same land area at the same time, crops (at ground level) and solar panels (above layer), as described in Dupraz et al. (2010). In such systems, plants are submitted to the fluctuating shading of the solar panels, resulting in an heterogeneous radiative environment below the solar panels.

We showed in a previous study (Marrou et al., 2013a) that high yield can be achieved by lettuce and other horticultural crops in the

partial shade of solar panels within agrivoltaic systems. Besides, an exhaustive assessment of the microclimatic variables in such systems suggested that the evapotranspiration of crops grown in agrivoltaic systems could be affected by the shade of agrivoltaic systems. Indeed, although the daily air temperature and vapour pressure deficit (VPD) at reference level were not significantly modified below the solar panels compared to the full sun, the radiative balance was modified by the photovoltaic shelter (Marrou et al., 2013b). Several studies have shown that crop evapotranspiration and stomatal conductance of drip irrigated vegetables were positively correlated to available light (Alves and Santos Pereira, 2000; Damour et al., 2010; Medrano et al., 2005).

In the context of global warming and water resource shortage, reducing water demand by shading plants could represent a consistent advantage in the near future (Wallace, 2000). Indeed, water use

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efficiency may increase if the yield is little affected or unchanged as shown by Marrou et al. (2013a) in these agrivoltaic systems.

In the following study we calculate evapotranspiration of two drip irrigated crops (lettuces and cucumbers), with soil water stock and flows measurements and a water balance equation of the rooting zone applied to two prototypes of agrivoltaic systems resulting in two levels of shade.

In a second step, we propose a theoretical framework of soil evaporation and plant transpiration, in order to carry a functional analysis of these modifications of water consumption in the shade of the solar panels. From literature references (Allen et al., 1998; Shuttleworth and Wallace, 1985), four variables can be identified as drivers of soil evaporation and plant transpiration fluxes: (1) the climatic demand, (2) the proportion of ground covered by plants (3) the plant stomatal conductance, (4) the bare soil hydraulic conductance. Despite the wide range of approaches and models developed formerly for crop evapotranspiration, no attempt of proposing a non empirical multiplicative model separating explicitly these drivers was successful so far (Rana et al., 1997; Shuttleworth, 2006). In this study, we arrange these four drivers into an equation to be used as a theoretical framework for data interpretation, and not as a predictive model, as it is not mathematically exact and relies on simplification hypothesis. However, it provides an efficient tool to analyze, with specific measurement of the four drivers, how solar panels influence soil evaporation and plant transpiration components, and how these drivers could be managed to improve water use efficiency and plant production in these agrivoltaic systems.

2. Materials and methods

2.1. Field experiments

2.1.1. Prototype device

The experiments were carried out during spring and summer 2011 (from March 22nd, 2011 to August 31st, 2011) on an experimental prototype of agrivoltaic system (Fig. 1) in Montpellier France (43.6°N, 3.9°E).

In this experimental prototype, photovoltaic panels (PVPs) were arranged in East–West orientated strips, 0.8 wide and inclined southward with a tilt angle of 25°. PVPs were held at 4 m above ground by wooden pillars spaced on a 6.4 m × 6.4 m square grid, in order to allow mechanical cropping of the plants below, using tractors.

The experimental design allowed to compare three shading intensities corresponding to different densities of solar panels: (1) the full density treatment (FD), which corresponded to the optimal PVPs density for electricity production and which transmitted in average 50% of the incident radiation to the crop, (2) the Half density treatment that was obtained from FD by removing one strip of PVPs out of two and which left in average 70% of incident radiation available to the crop, and (3) the full sun control plot (100% of incident radiation available) (Marrou et al., 2013a). The experimental field was composed of four 12 m × 19.2 m plots aligned from East to West in the following order: Full sun control plot (E-C plot), FD plot, HD plot, Full sun control plot (W-C plot) (Fig. 1).

Buffer zones were provided between each treatment plot (at least 6 m) and a 6 m wide land strip in the southern edge of the shaded plots was left un-used for the experiment to avoid border effects due to mutual shading between treatments or higher incident light penetrating below the PVPs in the southern side of the prototype.

Due to the large size of any agrivoltaic system required to avoid unwanted border effects and the cost of building an experimental agrivoltaic system, it was not possible to replicate FD and HD plots to get a complete experimental device. However, as E-C and W-C were the two more distant plots in the experimental field, they

controlled the environmental variability in the East–West direction. In addition, during a previous experimental season (2010), both control and shaded plots were subdivided into three blocks in the North–South direction. Variance analysis showed that there was neither block nor plot effect on dry matter accumulation in the full sun plots (Marrou et al., 2013a). Moreover, the homogeneity of environmental factors such as soil properties was checked across treatment plots through soil water content measurements on samples evenly collected over the area of the experimental field. The type of soil (loamy clayish deep alluvial soil), as well as the field history (10 years of homogenous non tillage cropping) were also in favor of homogenous soil conditions between treatment plots.

2.1.2. Plant material

Lettuces were planted on March, 22nd 2011 and harvested on May, 24th 2011. Four varieties of lettuces were tested at the same time: two crisphead lettuces (Varieties “Emocion” and “Model”), and two cutting lettuces (varieties “Kiribati” and “Bassoon”). Cucumbers (variety “Marketmore”) were planted at the same place after lettuces harvest and soil deep tilling, on June 24th 2011 and were cropped without trellis. Fruits were harvested from August 8th to August 31st 2011.

Each treatment plot was subdivided into blocks arranged as 3.2 wide strips in the North–South direction. Two blocks were planted with lettuces, then cucumbers, in between the three other blocks cropped with cereals (Fig. 1).

Lettuces were planted in East–West orientated rows (parallel to the PVP strips). The spacing between two rows was 0.33 m and the distance between two lettuce heads on the same row was 0.27 m. Each of the two blocks had six rows of lettuces numbered from one to six, from North to South. Cucumbers were planted on a single East West orientated row, in the middle of each 3.2 m wide block. The distance between two plants on the same row was 0.5 m.

2.1.3. Crop management: water and nitrogen supply

Crops were irrigated with flexible drip lines of 17 mm diameter with a dripper every 0.33 m. In the case of lettuces, one drip line was laid every two lettuce rows, in the middle of the inter-row. For cucumber, one drip line was laid 10 cm apart of the planting row (Fig. 1).

The water flow provided by the drip lines was kept constant, equal to 0.08 mm/min for lettuces and to 0.05 mm/min for cucumber. The drippers flow was checked to be homogenous in each drip line, and each plot. To do so, water was collected at the exit of a dripper at the beginning and the end of each drip line during ten minutes, at the beginning of each irrigation cycle out of two.

Irrigation cycles were launched during daytime. Lettuces were irrigated every two days while cucumbers were irrigated twice a week. The length of the irrigation cycle was decided according to tensiometer readings in order to maintain the soil water potential around -20 kPa in the rooting zone (see Section 2.1.4). This threshold is considered to correspond to the absence water stress for lettuces (De Tournonnet, 1998; Gay, 2002; Thicoipé, 1997) and for cucumbers (Suojala-Ahlfors and Salo, 2005).

No plastic mulching film was used, and both lettuces and cucumber were grown on bare soil.

Plants were fertilized according to soil nitrogen analysis so that nitrogen was not limiting in any treatment, both during lettuce and cucumber cycles. Fertilizer were applied before planting lettuces (52 kg N ha^{-1} , 2 kg P ha^{-1} , 9 kg K ha^{-1}), during the lettuce cycle (0.5 kg N ha^{-1} from urea spray), and before cucumber planting (136 kg N ha^{-1} , 68 kg P ha^{-1} , 182 kg K ha^{-1} , $190 \text{ kg MgO ha}^{-1}$.) according to soil mineral nitrogen analysis and plant N requirements.

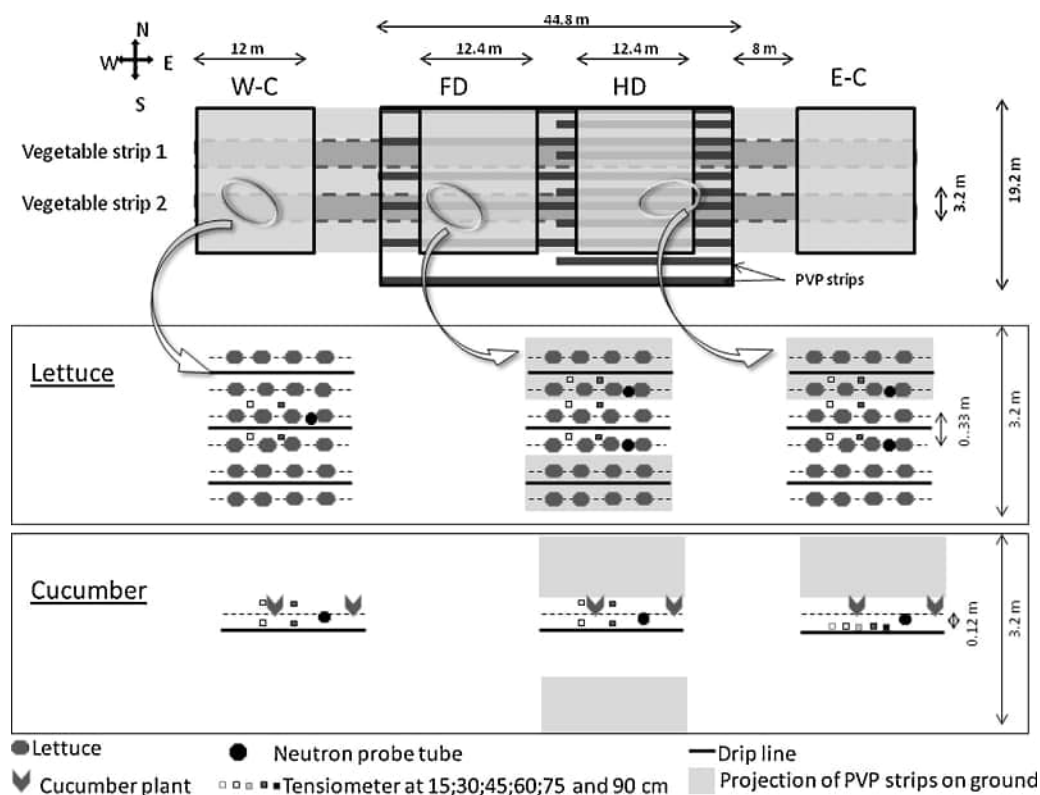


Fig. 1. Map of the experimental field. The top part of the figure represents a general view of the field map with the two shaded plots (FD and HD) and the two full sun controls (E-C and W-C). The bottom part corresponds to zooms featuring the location of tensiometers and neutron probe access tubes in the lettuce and cucumber crops.

2.1.4. Soil water content monitoring

Soil water content and soil water potential were monitored on the field from April 28th 2011 to lettuces harvest (24th May 2011), and during the whole cropping cycle for cucumbers (June 28th 2011 to August 31st 2011).

The soil water potential was measured in the rooting zone and below the maximal rooting front with tensiometers (SDEC, Reignac sur Indre, France). For lettuces, tensiometers were installed at 25 cm (zone of maximal root density, Thicoipé, 1997) and 40 cm in each treatment. In order to cover the spatial variability of soil water potential due to (1) the position of the drip lines (2) the discontinuity of the PVP shelter in FD and HD, three pairs of tensiometers were installed on a North South transect across a block of lettuces in FD and HD, and two pairs in W-C (Fig. 1). For cucumbers, tensiometers were installed at 30 cm, 60 cm and 90 cm depth in FD, HD and W-C. As there was only one planting row per block, exploring soil water availability would have been more complex. Thus, only a set of tensiometers was installed in each treatment between the planting row and the drip line in order to assess the soil water deficit experienced by the plants in their rooting zone (Fig. 1). Tensiometers were checked at least every two days, at solar noon, before each irrigation cycle.

Soil water content was measured weekly, at noon, before irrigation cycle, with a neutron probe (503DR, VECTRA, La Verrière, France) in aluminum access tubes (43–45 mm) to a depth of 1 m (lettuces) and 1.30 m (cucumbers). During the lettuces cycle, two tubes were set in FD and HD: one on planting row no. 2 (between two PVP strips), and one on planting row no. 4 (just below a PVP strip), and one tube was installed in E-C (Fig. 1). During the cucumber cycles, one tube was set in FD, HD, and W-C plots, on the planting row.

2.1.5. Radiation and other microclimate monitoring

Microclimate variables (air temperature and humidity, wind speed at 2 m above ground) were measured on the experimental field, in the full sun control plot as well as in FD and HD. In addition, meteorological data for the full sun situation were available from the Meteo France – INRA weather station, at 400 m from the field.

Daily rain in the full sun treatment was obtained from the weather station. In the FD and the HD treatments, water input from rain was distributed heterogeneously: more water may penetrate into the soil just below the southern edge of the PVP strips due to the water run-off on the PVP. On the contrary, one can expect that the water input was lower in the middle position below each PVP strip compared to between PVP strips positions. However, the total amount of water received on the total area of the FD and HD plots should be the same as in the full sun as there is no gutters nor drain pipes collecting the rain on the PVPs and exporting it out of the system on the prototype. Therefore, rain water inputs in the FD and HD treatments were assumed to be similar and equaled to that measured in the full sun by the weather station.

Incident radiation at crop height was measured in the full sun and in the shaded treatments with pyranometers (Campbell Scientific, Inc., USA) during the cucumber cycle and with photosynthetically active radiation (PAR) sensor during the lettuce cycle. PAR sensors and pyranometers were used indifferently to measure incident radiation above the crops as PAR/global radiation ratio is the same as long as it does not go through a plant canopy. In addition, PAR measurements and global radiation measurements were checked to be proportional at hourly time step, and the ratio between the two measurements was found to be equal in the shade and in the full sun. In the shaded treatments, incident radiation was measured above each lettuce planting row (except above external

rows). For cucumbers, incident radiation was measured at 0.4 m above the ground surface on a North–South transect centered on a planting row (5 sensors with a distance of 0.4 m between each).

In the following year (2012) at the same climatic season (April to July), net radiation was measured along with global radiation using radiometers (Q-7 Net Radiometer, Campbell Sci., Inc., USA) in every treatments. Linear regressions were fitted for each treatment and showed that daily net radiation could be predicted from daily global radiation with Root Mean Squared Errors (RMSE) equal to 64 W m^{-2} in FD, 69 W m^{-2} in HD and 48 W m^{-2} in the full sun.

2.1.6. Plant measurements

2.1.6.1. Dry matter accumulation. Lettuce productivity was assessed by destructive sampling in the field at DOY 125 and 144. Sampling and measurement methodology are detailed in Marrou et al. (2013a). Similarly, the total accumulation of dry matter by cucumbers was measured on DOY 241. To do so, four groups of four plants were tagged in each treatment. All along the productive phase, mature fruits were picked twice a week on the tagged plants, they were counted, weighted and their water content was assessed on a subsample. At final harvest (DOY 241), the whole plant were harvested (aerial part) and dried up.

2.1.6.2. Fraction of soil covered by the crop (f). The fraction of soil covered by the crop (f) was assessed in the field continuously both on lettuces and on cucumbers.

For lettuces, the percentage of soil covered by plants was obtained following the procedure described in Marrou et al. (2013a). Three lettuces plants were tagged just after planting in each variety and each radiative treatment. These tagged plants were photographed every week and cover rate was calculated after processing the pictures with Image J (NHI, MA, USA). For cucumbers, f was estimated from the fraction of intercepted PAR (Gay, 2002), directly measured in the field. In each treatment, PAR sensors were set on a diagonal transect centered on the cucumber planting row (5 sensors, 40 cm apart from each other) at ground level (below the plant). The percentage fraction of PAR that was not intercepted by the cucumber canopy ($1 - f$) was calculated daily as the ratio between the average of the records from the sensors at ground level and the mean incident radiation at crop height (average of the sensors at 40 cm above ground surface).

2.1.6.3. Stomatal conductance (G_s). Stomatal conductance G_s was measured on lettuces with a ventilated gaz exchange chamber (LI6200, Li-cor, Lincoln, NE, USA) on two sunny days (April 20th 2011 and May 17th 2011). Measurements were performed at solar noon, in situ, on the same plants for the two dates (12 plants in each treatment). One measurement by plant was taken on one leave chosen at random among the largest leaves of the plant (mid-aged leaves).

The measured values of stomatal conductance were plotted versus the incident PAR recorded just above the measured lettuce at the measurement time. When there is no other environmental factor than light limiting the stomatal aperture, the relation between the maximal stomatal conductance $G_s(\text{PAR})$ and the incident PAR can be described with Eq. (1) (Guilioni et al., 2000; Oliso et al., 1996).

$$G_s(\text{PAR}) = g_{\min} + (g_{\max} - g_{\min}) \times \left(1 - e^{-\frac{\text{PAR}}{K_{\text{PAR}}}}\right) \quad (1)$$

with $g_{\min}$ set at $0 \mu\text{mol m}^{-2} \text{s}^{-1}$.

An envelope curve corresponding to Eq. (1) was adjusted from the highest records of G_s obtained at the two dates, with a RMSE equal to 0.19. Estimates of the parameters of Eq. (1) were $1.02 \text{ mol m}^{-2} \text{s}^{-1}$ for $g_{\max}$, and $350 \mu\text{mol m}^{-2} \text{s}^{-1}$ for K_{PAR} . These estimates are in the same order of magnitude as those reported

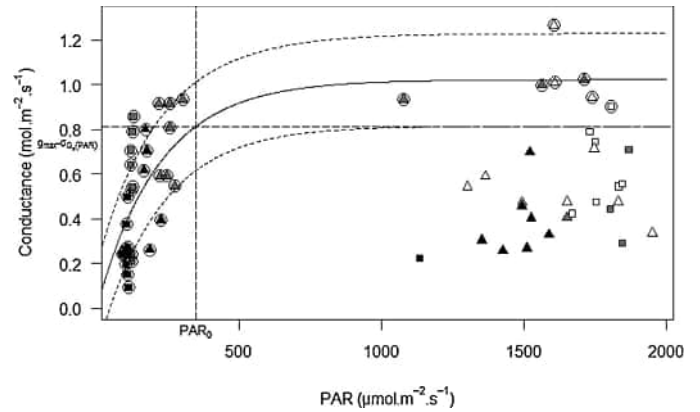


Fig. 2. Stomatal conductance measured on lettuces on DOY 110 (square symbols) and DOY 134 (triangle symbols) in the FD (black symbols), HD (gray symbols), and full sun (open symbols). Solid line represents the prediction of the maximum (i.e. light limited) conductance $G_s = f(\text{PAR})$ (when there is no environmental stress, except light reduction) as a function of PAR. Dotted lines represent the standard error interval of the model. Circle symbols correspond to the points selected to adjust the model of G_s as a function of PAR.

for K_{PAR} in soybean ($380 \mu\text{mol m}^{-2} \text{s}^{-1}$ Oliso et al., 1996) and for $g_{\max}$ in lettuces ($0.897 \text{ mol m}^{-2} \text{s}^{-1}$, He et al., 2001).

The threshold value PAR_0 above which $G_s = f(\text{PAR})$ reached the asymptotic value ($g_{\max}$) was $350 \mu\text{mol m}^{-2} \text{s}^{-1}$. It was determined from Fig. 2 as the PAR value for which $G_s(\text{PAR})$ equals $g_{\max}$ modulo the standard error of the model. At solar noon, all the lettuces in the full sun treatment received a higher PAR than the PAR_0 threshold. On the contrary, some of the lettuces in the FD and HD treatments were shaded and others were in the full sun at the measurement time, depending on the planting row they were picked on, and on their position toward the projected shade of the pillars supporting the PVPs cover.

2.2. Theoretical background for the calculation and analysis of water flows

The analysis of the impact of the PVPs shelter on water flows in the soil–crop system was carried out in two steps: Firstly, we calculated the actual evapotranspiration (AET) with a water balance equation and soil water measurements in each treatment. Secondly we proposed a theoretical model that breaks AET into plant transpiration and soil evaporation, and specify the four biophysical drivers that monitor evapotranspiration rate: (1) the climatic demand, (2) the proportion of ground covered by plants (3) the plant stomatal conductance, (4) the bare soil hydraulic conductance. From independent field measurements of each driver, we analyzed how PVP shade have modified plant and soil water losses, in order to explain the observed modification of AET and to derive hypothesis on how these drivers can be further manipulated to improve water use efficiency and plant production in these agrivoltaic systems.

2.2.1. Water balance

Water balance for a soil–plant system between two dates t_1 and t_2 is described in Eq. (2).

$$\text{AET}_{t_1 \rightarrow t_2} = -\Delta S_{t_1 \rightarrow t_2} + \sum_{t=t_1}^{t_2} P_t + \sum_{t=t_1}^{t_2} I_t + F_{t_1 \rightarrow t_2} \quad (2)$$

where $\Delta S_{t_1 \rightarrow t_2}$ is the variation of the water stock in the plant rooted zone of the soil between days t_1 and t_2 , P_t is the rain on day t , I_t is irrigation supply for day t , $F_{t_1 \rightarrow t_2}$ represents the vertical water fluxes below the rooted zone (capillary rises or drainage), and

$AET_{t_1 \rightarrow t_2}$ is the system (soil + plant) evapotranspiration between days t_1 and t_2 (one week).

Actual evapotranspiration (AET) was calculated weekly with Eq. (2) from field data (between each measurement of soil water content) for lettuces from May 4th 2011 May 24th 2011, and for cucumbers during all the cropping cycle (from June 28th to August 31st 2011).

The system was a soil parallelepiped of 1 m^2 of basal area and which height depends on the estimated maximal root depth (z_r) of the plant. For lettuce, z_r was set at 0.3 m according to literature (Thicoipé, 1997) and root profiles realized on the same experimental field in 2010 (Marrou, 2012). For cucumbers, z_r was set at 0.25 m for juvenile plants (from planting to July 19th 2011); then to 0.6 m (Chartzoulakis and Michelakis, 1990).

P_t was obtained from microclimate records on the experimental field.

The irrigation input I_t was calculated as the product of the mean drippers flow measured on the field, the number of drippers per square meter and the duration of the irrigation cycle for day t .

$\Delta S_{t_1 \rightarrow t_2}$ was calculated from soil water content measured in the rooting zone at depth z at $t_1, \theta(z, t_1)$ and at $t_2, \theta(z, t_2)$ according to Eq. (3). In the case of lettuces in FD and HD, where θ was measured at two locations (two neutron probe tubes), the soil water stock between the soil surface and the maximal plant rooting depth (z_r) was first calculated for each tube then averaged over the two locations. $\Delta S_{t_1 \rightarrow t_2}$ was then calculated as the variation of the mean water stock between t_1 and t_2 for the whole treatment plot. The coefficient of variation of the soil water content between two tubes in the same treatment plot never exceeded 5.7% at a given date for the lettuce crop. It was checked afterwards that the values of $\Delta S_{t_1 \rightarrow t_2}$ did not change significantly for any date or treatment, whether spatial average between the two tubes was calculated before or after the variation of water stock between t_1 and t_2 .

$$\Delta S_{t_1 \rightarrow t_2} = 1000 \times z_r \times \left[\int_{z=0}^{z=z_r} \theta(z, t_2) \cdot dz - \int_{z=0}^{z=z_r} \theta(z, t_1) \cdot dz \right] \quad (3)$$

$F_{t_1 \rightarrow t_2}$ was calculated as the average of capillary rises (or drainage) at day t_1 and t_2 . According to Darcy's law (Hillel, 1998) the water flow F_t (Eq. (4)) between two points in the soil at time t is the product of: (1) the gradient of soil water potential measured just below z_r . For cucumber the values given by the tensiometers at 60 cm and 90 cm were used whereas the gradient was calculated between 25 and 40 cm for lettuces. In the case of lettuces, where there were two sites of measurement at each depth, the average of the gradient measured on each site, was considered for further calculation. (2) The soil water conductivity $K(\theta)$ just below z_r . $K(\theta)$ was estimated from soil texture and water content between the two tensiometer cup depths according to Saxton et al. (1986) (Eq. (5)). Fluxes were calculated at t_1 and t_2 then averaged together to estimate the mean flux in between these two dates $F_{t_1 \rightarrow t_2}$.

$$F_t = \frac{\psi_{z_1}(t) - \psi_{z_2}(t)}{z_2 - z_1} \times K(t) \quad (4)$$

where $\psi_{z_1}(t)$ is the soil water potential at depth z , on day t .

$$K(t) = A \times \exp \left(B + \frac{C}{(1/z_2 - z_1) \int_{z_1}^{z_2} \theta(z, t) dz} \right) \quad (5)$$

where A , B and C depends on soil clay and sand contents measured on the experimental field, according to Saxton et al. (1986) and θ is the soil water content at depth z , on day t .

2.2.2. Framework for the decomposition of the AET

Lettuces and cucumber are crops with sparse cover. Thus, it is more relevant to decompose the system's actual evapotranspiration (AET) as the sum of two components: the transpiration by plants (T) and the evaporation from the surface of bare soil (E) (Eq. (6)). Moreover, these two components refer respectively to serviceable water uptake by the plant and useless water losses by the soil. The former is the only water loss to contribute to biomass production as it keeps the stomata open and contributes to heat stress avoidance with leaf cooling.

$$AET = T + E \quad (6)$$

Each component of AET can be considered as a water flux controlled by three drivers: (1) a climatic demand (ET_0), (2) applied on the surface area (of plant for T and of soil for E), (3) itself characterized by its conductance to water (Eq. (7)). We propose a multiplicative decomposition of both E and T based on the hypothesis that climatic demand ET_0 can be assimilated to a driving force and that the resulting flux can be calculated as the product between this force, the relative surface bulk resistance (compared to the bulk resistance of Penman reference surface) and the area of the conductive surface (Rana et al., 1997).

$$AET = (ET_0 \times f \times K_V) + (ET_0 \times (1 - f) \times K_S) \quad (7)$$

where f is the fraction of ground covered by the crop; K_V is the plant transpiration coefficient, related to the stomatal conductance and the aerodynamic conductance to water vapour through the cover. In the case of sparse cover, aerodynamic conductivity does not depend on cover characteristic (Guilioni et al., 2000). Therefore, variations of K_V between light treatments can be considered to be mainly explained by stomatal conductance and is equal to G_s/G_{s0} where G_{s0} represents the surface conductance of a well watered reference crop ($G_{s0} = 0.595 \text{ mol m}^{-2} \text{ s}^{-1}$, Allen et al., 1998). K_S is the soil evaporation coefficient. K_S represents the ground surface hydraulic conductivity, expressed as the ratio between the actual hydraulic conductance and the maximal conductance of the reference surface ($0 < K_S < 1$).

According to this framework, changes in AET, as previously measured in the fluctuating shade of the PVPs compared to the full sun, can result from a relative variation of the climatic demand and/or of the proportion of ground covered with vegetation and/or of the conductivity of soil or vegetation surfaces. The ratios between T in the shade and in the full sun and between E in the shade and in the full sun can be decomposed as the product of their relative determinants (Eq. (8)).

$$\frac{T_{\text{shade}}}{T_{\text{full sun}}} + \frac{E_{\text{shade}}}{E_{\text{full sun}}} = \left(\frac{ET_{0\text{shade}}}{ET_{0\text{full sun}}} \times \frac{f_{\text{shade}}}{f_{\text{full sun}}} \times \frac{G_{s\text{shade}}}{G_{s\text{full sun}}} \right) + \left(\frac{ET_{0\text{shade}}}{ET_{0\text{full sun}}} \times \frac{1 - f_{\text{shade}}}{1 - f_{\text{full sun}}} \times \frac{K_{S\text{shade}}}{K_{S\text{full sun}}} \right) \quad (8)$$

From the field data, we assessed each term of Eq. (8) in the full sun and in the shaded conditions, for each time period (6–7 days) for which AET was previously calculated with the water balance (Section 2.2.1). It is important to notice that our aim is not to use Eqs. (7) and (8) as a model to predict AET but rather as a conceptual model to analyze how the two components of AET (Eq. (6)) were modified by PVPs and which of the three drivers (see Eq. (7)) has an influence, in comparison with full sun (Eq. (8)). Actually, the predictive quality of Eq. (7) used as a model would be rather poor: the corresponding root mean square error is 16 mm, i.e. 23% of the mean AET measured for lettuces with the soil water balance.

2.2.2.1. ET_0 . Daily reference evapotranspiration ET_0 in the full sun was calculated from meteorological data according to Penman

Monteith equation (Eq. (9)) (Allen et al., 1998; Monteith and Unsworth, 1990).

$$ETO = \frac{0.408 \times \Delta \times (R_N - G) + \gamma \times (900/T_A + 278) \times u_2 \times (e_a - e_s)}{\Delta + \gamma \times (1 + 0.34 \times u_2)} \quad (9)$$

where R_N is the daily net radiation ($\text{MJ m}^{-2} \text{d}^{-1}$), G is the soil heat flux ($\text{MJ m}^{-2} \text{d}^{-1}$) estimated as $0.2 R_N$ (Jones, 1992), Δ is the slope of

$$K_s(t) = \begin{cases} 1 & \text{if } \left(\sum_{i=\text{last irrigation}}^t ETO_i \right) < \beta \\ \frac{\beta}{ETO(t)} \left(\left[\sum_{i=\text{last irrigation}}^t ETO_i \right]^{1/2} - \left[\sum_{i=\text{last irrigation}}^{t-1} ETO_i \right]^{1/2} \right) & \text{if } \left(\sum_{i=\text{last irrigation}}^t ETO_i \right) > \beta \end{cases} \quad (11)$$

the vapour pressure curve ($\text{kPa } ^\circ\text{C}^{-1}$), γ is the psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$), T_A is the air temperature at 2 m above ground ($^\circ\text{C}$), e_s and e_a are the saturation and the actual vapour pressure (kPa), and u_2 is the wind speed (m s^{-1}).

A previous detailed analysis of microclimate below the PVPs (Marrou et al., 2013b) showed that neither the mean daily air temperature nor the VPD, nor the wind speed were significantly affected in the shade of the PVPs compared to the full sun. Consequently, the variation of ETO between the full sun (ETO_{sun}) and the shade (ETO_{shade}) can be considered as proportional to the reduction of net radiation in the shade, for every day (Eq. (10)). ETO in the shade is then obtained from Eq. (10).

For day t :

$$ETO_{shade} = ETO_{sun} + C(t) \times (R_{Nshade} - R_{Nsun}) \quad (10)$$

where R_{Nshade} is the daily net radiation in the shade (FD or HD) and R_{Nsun} is the net radiation in the full sun, calculated from global radiation in the same light conditions, and $C(t)$ is a coefficient calculated every day as $C(t) = ((0.408 \times \Delta) / (\Delta + \gamma \times (1 + 0.34 \times u_2)))$ with the daily values of Δ and u_2 measured in the full sun (see Eq. (10)). Then ETO over a period of 7 days is calculated as the sum of daily ETO .

2.2.2.2. Fraction of soil covered by the crop (f). The fraction of soil covered by the crop (f) was assessed weekly in the field for the two crops (see Section 2.1.6). Daily evolution of f was then obtained by fitting models to field data to predict the fraction of soil covered by plants as a function of thermal time, with a base temperature of 3°C for lettuces (Thicoïpé, 1997) and 15°C for cucumbers (Perry et al., 1986).

In the case of lettuces, the model equation was a logistic sigmoid varying between 0 and 1. Two separated models were adjusted: one for lettuces grown in the shade (FD and HD pooled together, $\text{RMSE} = 0.147$), and one for lettuces in the full sun ($\text{RMSE} = 0.095$) (Marrou et al., 2013a). All lettuce varieties grown in the same light environment followed the same cover rate dynamic (Marrou et al., 2013a).

For cucumbers, the cover rate dynamic was described by the difference between two sigmoids: one for the dry matter accumulation phase and one for the senescence phase (Hay and Porter, 2006; Medany et al., 1996). Three different models were adjusted with respective root mean square error equal to 0.095 (FD), 0.059 (HD), and 0.056 (full sun).

For the two crops, model errors were estimated for every day by derivation of the model equation (Marrou et al., 2013a; Seber and Wild, 2003).

2.2.2.3. Soil evaporation coefficient (K_s). K_s was calculated for each day t as a function of the square root of the cumulated ETO in the same shading treatment from the last irrigation or the last heavy rain ($>4 \text{ mm}$ in one day) (Eq. (11)), according to the Gallardo model (Gallardo et al., 1996).

The threshold parameter β below which $K_s = 1$ was taken equal to 1.68 according to literature (Gallardo et al., 1996; Stroosnijder, 1987). A sensitivity analysis was carried out to assess the impact of the uncertainty on β on soil evaporation. When β varies between 1.3 and 2, the impact on daily soil evaporation averaged over the experiment duration is lower than 10% for the three light treatments.

2.2.2.4. Plant transpiration coefficient (K_v). K_v was estimated from measurements of stomatal conductance (G_s) of lettuce leaves in the field, at solar noon on two sunny days (see Section 2.1.6). K_v estimates are not available for cucumber as stomatal conductance measurements could not be achieved in the field. The daily evolution of mean G_s was estimated in each treatment from the envelop curve $G_s(\text{PAR})$ (Eq. (1)) fitted on the field measurement and the mean incident radiation recorded for that day in each treatment. If $\text{PAR} > \text{PAR}_0$, then G_s was assumed to have reached a plateau and was set equal to the mean conductance measured in each treatment when PAR is above PAR_0 . Otherwise, it was predicted from the equation of $G_s = f(\text{PAR})$.

Then the daily values of K_v were estimated as G_s/G_{s0} .

2.3. Water use efficiency of the system (WUE)

Relative water use efficiency in the shade compared to the full sun situation can be assessed as the ratio between the relative variation of Dry Matter (DM) and relative AET (Tanner and Sinclair, 1983) in the shade compared to the full sun. Relative water use efficiency between shaded treatment and the full sun control was calculated for lettuces (from DOY 124 to DOY 134) and cucumber (from DOY 175 to DOY 241) using DM measured in the field and AET calculated from Eq. (2) over the same period.

3. Results

3.1. Assessment of the irrigation strategy

The evolution of the soil water potential in the rooting zone indicates whether water stress was experienced by the plant, when and which plant process is affected (Wery, 2005). Thresholds levels for leaf growth in lettuce were taken from Gay (2002).

For lettuces, the soil water potential in the rooting zone (25 cm) was maintained below 50 kPa during the whole cropping season, in the three light treatments, except for the full sun where the soil water potential reached 65 kPa during the five last days before final harvest. But this was a too late and too short stress to have an influence on the final number and size of the major leaves of the plants and so on their final fresh weight (Gay, 2002; Thicoïpé, 1997). Thus,

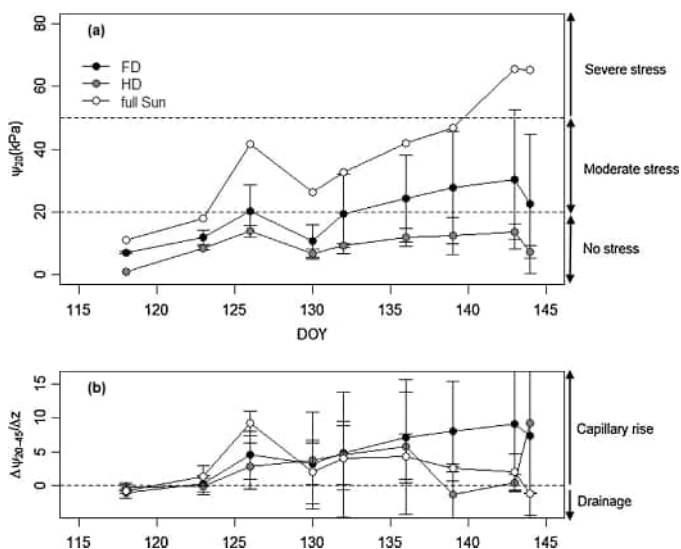


Fig. 3. Soil water potential (in kPa) in the rooting zone during the lettuce cycle (a) and gradient of soil water potential (m water/m soil) between the maximal rooting depth zone (25 cm) and below the root zone (40 cm) (b). Positive values of the gradient correspond to upward fluxes.

we can conclude that lettuces never experienced a sufficient water stress to reduce their leaf production in none of the treatments. For cucumber, soil water potential in the rooting zone (30 cm and 60 cm) remained below 20 kPa during the first 30 days after planting (Fig. 4). However, after DAY 220, at the beginning of the fruit production phase, the soil water potential at 30 cm rose up to 80 kPa (Fig. 4). Thus, moderate stress was possibly experienced by cucumber plants at that time, but this is typically the type of stress (its intensity and position in the plant cycle) which is considered as optimal to increase fruit production in indeterminate plants (Wery,

2005). The soil water gradient below root depth is an indicator of the water fluxes directions in depth (Cuny et al., 1998). For lettuces, soil water gradients were positive from DOY 126 to 144 in all the treatments, indicating the absence of drainage and a significant uptake of water by the plant through capillary rise below the maximal rooting depth (Fig. 3). For cucumbers, after the first 15 days following the plantation when seedlings were irrigated every day, soil water gradient below the rooting depth remained positive (Fig. 4). Consequently, for both crops, there was no consistent water loss by drainage below the plant rooting zone. On the contrary capillary rises (calculated from Eq. (4)) contributed to water inputs in the system.

Therefore, soil water potentials and gradients showed that the irrigation scheduled with tensiometers (cf; Section 2.1.4) was optimized for the two crops in order to minimize water inputs without causing significant water stress all along the two crop cycles.

3.2. Soil water losses by the agrosystem

For lettuces, actual evapotranspiration (AET) estimated from water balance measurements using Eq. (2) in the FD shade was 76% of AET calculated in the full sun during the period between DOYS 110 and 144 (final harvest). In the HD shade also, it was 78% of AET in the full sun during the same period. When considering the weekly dynamic of AET from DOY 110 to DOY 144, significant reduction of AET were found both in FD and HD compared to the full sun (Student test with minimum degree of freedom). The variations of the different water fluxes in the system are reported for lettuces in Table 1 for the three treatments.

For cucumber, AET was also reduced compared to the full sun: in FD, AET was 86% of the full sun and in HD, AET was 91% of the full sun. However, differences were not significant. Considering weekly AET calculated from Eq. (2), significant differences were found after DOY 188 only. Indeed, the standard errors of weekly AETs were higher in the cucumber crop than in lettuce, which can be explained

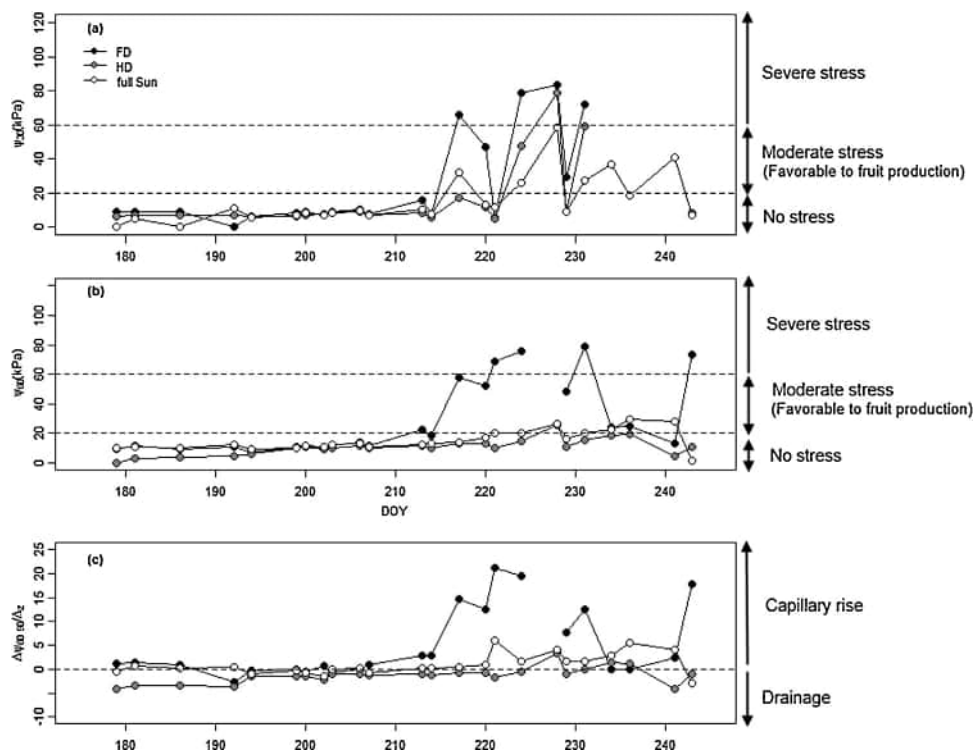


Fig. 4. Soil water potential (in kPa) in the middle of the rooting zone (a, 30 cm) and at the bottom of the rooting zone (b, 60 cm), and (c) gradient of soil water potential (m water/m soil) around the maximal rooting depth (60–90 cm). Positive values correspond to upward fluxes.

Table 1

Actual water fluxes (mm) and water stock variations (mm) in the agrosystem calculated for the lettuce crop from field measurements during three weeks before harvest. Deep fluxes refer to capillary rises (positive values) or drainage losses (negative values).

Treatment	From DOY	To DOY	DeltaStock	Deep fluxes	Irrigation	Rain	AET
FD	124	130	0.57	0.13	30.80	0.00	30.36**
FD	130	137	−0.79*	0.41	14.40	0.00	15.60**
FD	137	144	−1.49	0.53*	14.70	16.00	32.72**
HD	124	130	1.69*	0.32	30.50	0.00	29.13*
HD	130	137	−2.09	0.55	14.40	0.00	17.04**
HD	137	144	−2.80*	0.94	14.70	16.00	34.44*
Full sun	124	130	−0.56	0.14	33.70	0.00	34.40
Full sun	130	137	−2.75	0.12	23.10	0.00	25.97
Full sun	137	144	−0.41	0.01*	26.40	16.00	42.82
FD	Total		−1.71	1.07**	59.90	16.00	78.67**
HD	Total		−3.20	1.81**	59.60	16.00	80.61**
Full sun	Total		−3.71	0.27	83.20	16.00	103.18

* Figures corresponding to a significant difference between shade (FD or HD) and the full sun are marked with ($p < 5\%$).

** Figures corresponding to a significant difference between shade (FD or HD) and the full sun are marked with ($p < 1\%$).

by the poorer quality of soil water measurements during the first three weeks after planting, when irrigation was applied more often to ensure full hydration of the peats with plantlets. During that period, calculations with Eq. (2) lead to weekly AET exceeding ET_0 for the three light treatments, which suggests that some water drainage below the root zone occurred during this period but cannot be taken into account in our calculation. Consequently, we will focus only on the second part of the cycle in the following analysis. From DOY 208 to final harvest, AET was reduced to 71% of the full sun in FD (significant) and to 86% of the full sun in HD (non significant).

3.3. Analysis of the components and drivers of water losses

3.3.1. Potential evapotranspiration (ET_0)

In average over the two cropping seasons, ET_0 was reduced to 70% of full sun ET_0 in FD and to 78% of full sun ET_0 in HD (Fig. 5). ET_0 was more affected by shading in spring than in summer: during the lettuce cropping season (April–May) ET_0 decreased to 62% and 70% of the full sun ET_0 , in FD and HD respectively. During the cucumber cropping season (July–August), ET_0 was equal to 73% of the full sun in FD and to 81% of the full sun in HD.

3.3.2. Fraction of ground covered by plants (f)

For lettuces, different sigmoid models were adjusted for plants in the shade (FD and HD pooled together), and in the full sun following the method of Marrou et al. (2013a). Indeed the test of maximum likelihood showed that fitting two separate cover rate

models for FD and HD would not increase the quality of the adjustment (Fig. 6 a). In the second part of the cycle, when water balance was carried out (after 124 DOY), the plant cover rate was significantly higher in the shaded treatments than in the full sun. For each week between DOY 124 and 144, f in the shade was 150% of that in the full sun. According to Marrou et al. (2013a), increased cover rate in the shade can be explained by the morphological adaptation of lettuce heads (leaf size and arrangement) observed below the solar panels.

For cucumbers, three significantly different models were fitted to the field data (Fig. 6b). From planting to day 209, cucumber showed similar evolutions of f in the three treatments. It corresponds to the juvenile phase, during which plants cover rate was lower than 33% of the ground surface in every treatment. On the contrary, from DOY 209 to 243, the fraction of ground covered by the cucumber crop was significantly higher in the full sun than in the shade. In average for that period, f was 75% of that in the full sun in FD and 57% in HD. It corresponds to the time period during which, significant differences between treatments were also found in AET (Table 2).

3.3.3. Soil evaporation coefficient (K_s)

Between two irrigation cycles or rainy events, soil evaporation coefficient K_s tended to remain closer to its potential ($K_s = 1$) in the shaded treatments compared to the full sun (Fig. 7a and b). However, no significant differences between treatments were detected in the evolution of daily K_s , neither during the lettuce cycle, nor during the cucumber cycle. The proportion of days with maximal

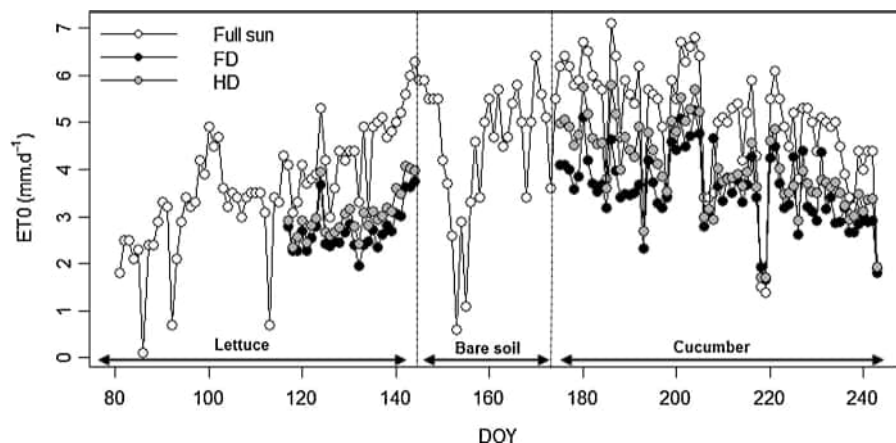


Fig. 5. Potential evapotranspiration calculated over the lettuce canopy (DOY 81 to 144) and the cucumber canopy (DOY175 to 244).

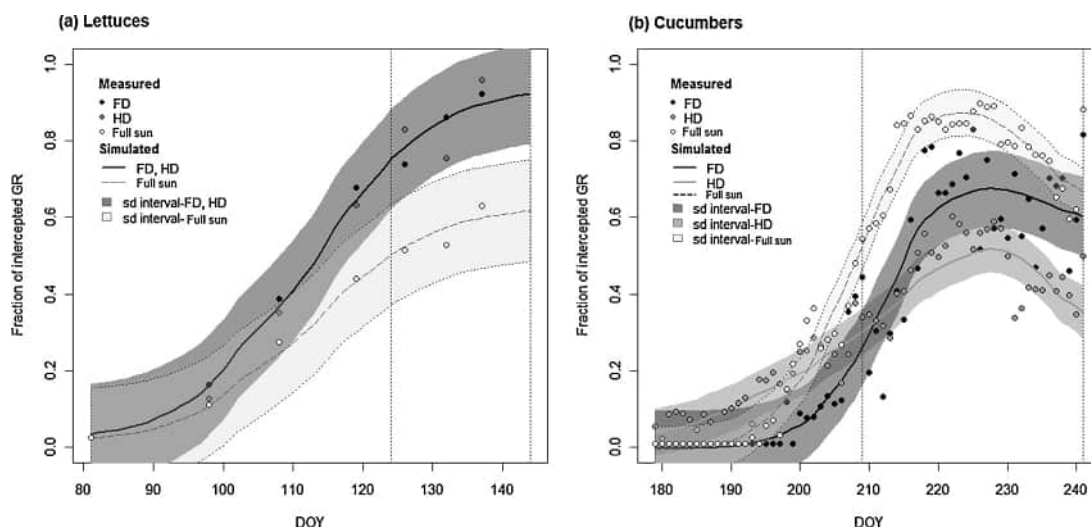


Fig. 6. evolution of the fraction of soil covered by the crop (f) during the lettuce (a) and cucumbers (b) cycles. Closed and open circles feature f values measured in the shade (black points for FD, gray points for HD). Shaded areas represent the standard error of the sigmoid adjustment fitted for f as a function of thermal time (solid and dashed line for shaded and full sun treatments, respectively).

soil evaporation (i.e. ET_0) was 38% for lettuce and 46% for cucumbers and was not significantly different between FD, HD and the full sun, according to the Chi squared test of homogeneity. Considering only the days when K_s was lower than 1, no significant difference between the value of K_s in the full sun and in the shaded treatments was detected between treatments, using the Newman–Keuls test.

3.3.4. Crop transpiration coefficient (K_V)

Variations in the stomatal conductance, and consequently in the K_V coefficient, under the solar panels can result from (1) the reduction of the incident radiation below the saturating threshold PAR_0 , or (2) the reduction of the maximal conductance g_{max} , even when solar radiation is saturating (i.e. higher than PAR_0), below the PVPS. According to radiation sensors data, the time during which the lettuce received a level of light limiting stomatal conductance was significantly higher in FD than in HD, and in HD compared to the full sun. Considering hourly radiation records (at each measurement location, or averaged over each treatment plot area), the

proportion of time (excluding night time) when PAR is higher than PAR_0 was 39% in FD, 49% in HD and 75% in the full sun (Fig. 8b). These proportions were significantly different according to the Chi squared test.

Within daytime, the time when lettuce were under saturating radiation significantly varied between treatments: the lettuce in the FD treatment spent in average 42% of day time under saturating PAR (with variations between 36 and 48% depending on the planting row), while, the lettuce in HD stayed in average 49% of daytime (with variations between 43 and 58% depending on the planting row) under saturating light, while the lettuce in the full sun stayed 75% of daytime under saturating PAR. Saturation did not occur at the same time of the day in all treatments. In the full sun, lettuce were exposed to saturating light from 7:00 am to 17:00 pm during most of the cropping cycle (at least 80% of the days). On the contrary, light reached the saturation threshold (PAR_0) later in the day for shaded treatments (at 16:00 pm in FD, and from 14:00 to 16:00 in HD), during the main part of the cropping cycle (80% of the days).

Table 2
Actual water fluxes (mm) and water stock variations (mm) calculated weekly (from DOY 208 to harvest) for the cucumber crop in the 0–60 cm soil layer, from field measurements.

From DOY	To DOY	Treatment	DeltaStock	Deep fluxes	Irrigation	Rain	AET
208	217	FD	−1.5	−6.9	21.1	21.5	37.1*
217	218	FD	−28.5	−2.3**	10.6	0.0	36.8
218	230	FD	21.5	−10.3**	46.4	6.5	21.2*
230	236	FD	−12.2	−3.4**	24.3	0.0	33.1
236	241	FD	−2.8*	−8.0	16.2	5.8	16.7
208	217	HD	−2.4*	−4.8	21.0	21.5	40.2
217	218	HD	−5.9*	−1.5**	10.6	0.0	14.9*
218	230	HD	−6.2**	−6.4**	46.4	6.5	52.8**
230	236	HD	−1.2	0.5*	24.3	0.0	26.0**
236	241	HD	4.2**	1.0	16.2	5.8	18.8
208	217	Full sun	−6.4	−2.2	23.4	21.5	49.1
217	218	Full sun	−22.8	0.4	11.9	0.0	35.1
218	230	Full sun	23	6.4	46.4	6.5	36.2
230	236	Full sun	−4.8	8.4	21.6	0.0	34.8
236	241	Full sun	−2.5	0.5	14.4	5.8	23.1
From DOY 208 to 241		FD	−23.5	−30.9**	118.6	33.8	144.9*
From DOY 208 to 241		HD	−11.5	−11.2	118.5	33.8	152.6
From DOY 208 to 241		Full sun	−13.5	13.4	117.7	33.8	178.3

* Figures corresponding to a significant difference between shade (FD or HD) and the full sun are marked with ($p < 5\%$).

** Figures corresponding to a significant difference between shade (FD or HD) and the full sun are marked with ($p < 1\%$).

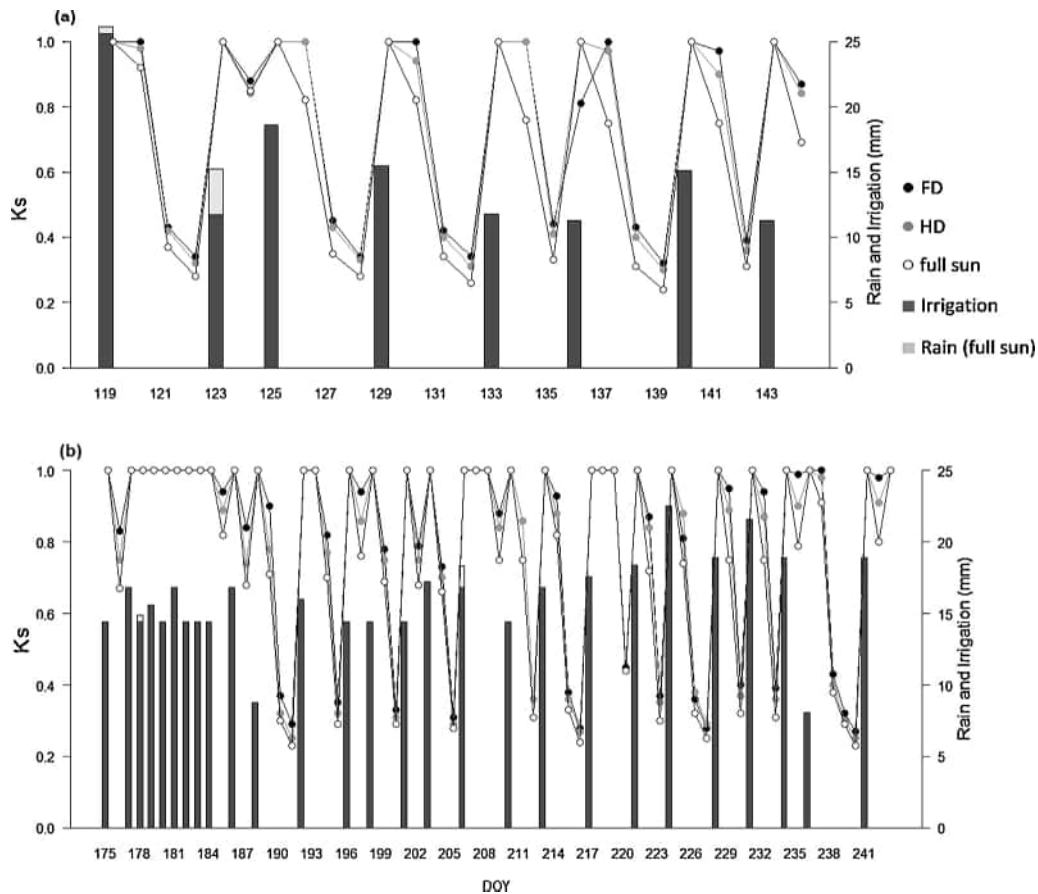


Fig. 7. Evolution of the soil evaporation coefficient K_s calculated according to the Gallardo et al.'s (1996) model in the three light treatments, during lettuce (a) and cucumber (b) crop cycles. Bars represent water input from irrigation (dark gray, the same amounts for the three treatments), or rain (soft gray, rain measured in uncovered (full sun) treatment).

Moreover, the ANOVA performed on measured values of G_s when the incident PAR was higher than PAR_0 (points in the right part of Fig. 2) showed that in conditions of non limiting light resource, G_s was significantly lower in FD than in the full sun. On the contrary, G_s was nearly the same under moderate shade (HD) as in the full sun. The mean G_s when PAR was above PAR_0 ($G_{s,sat}$) were respectively equal to $0.37 \mu\text{mol m}^{-2} \text{s}^{-1}$ in FD, $0.69 \mu\text{mol m}^{-2} \text{s}^{-1}$

in HD, and $0.66 \mu\text{mol m}^{-2} \text{s}^{-1}$ in the full sun (whereas the G_{sMAX} plateau value was equal to $1.38 \mu\text{mol m}^{-2} \text{s}^{-1}$).

Daily values of G_s estimated from the mean daily radiation and G_s (PAR) equation (Eq. (1)) were respectively $0.57 \mu\text{mol m}^{-2} \text{s}^{-1}$ both in the full sun and in HD, and $0.43 \mu\text{mol m}^{-2} \text{s}^{-1}$ in the FD (74% of the full sun) (Fig. 8a). The corresponding values of the crop coefficient transpiration (K_v) were 0.715 in FD, 0.958 in HD and

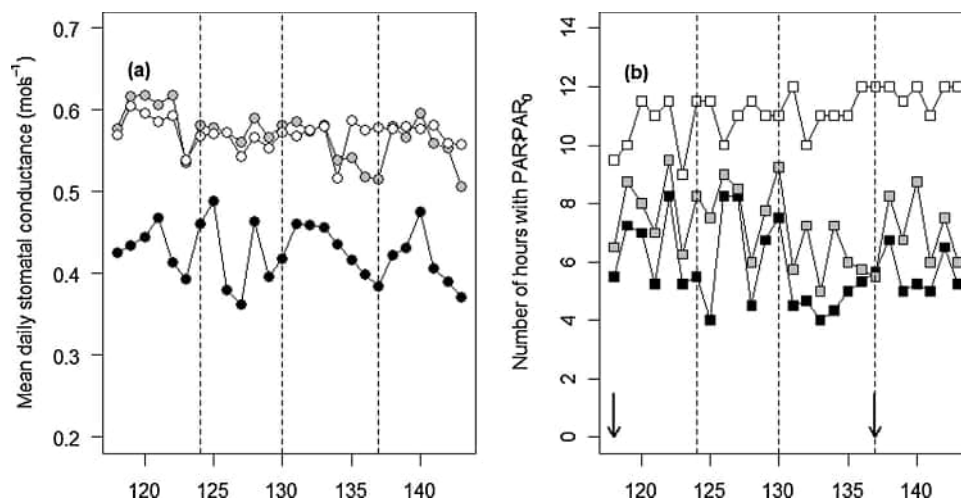


Fig. 8. Estimated daily day-time stomatal conductance (a) in full sun (○), FD (●), and HD (●) treatments, and number of hour per day when PAR was higher than the saturating threshold $PAR_0 = 350 \mu\text{mol m}^{-2} \text{s}^{-1}$ (b) in the full sun (□), the FD (■), and the HD (■) treatments.

Table 3

Evolution of lettuces AET in PVPs shade (% of the full sun) as calculated in Eq. (2) and its determinants as calculated from Eq. (7).

Lettuces Eq. (2)	FD AET 71%						HD AET 75%					
Eq. (7)	T 69%			E 21%			T 104%			E 25%		
	ETO	f	K _V	ETO	(1 – f)	K _S	ETO	f	K _V	ETO	(1 – f)	K _S
	62%	150%	74%	62%	33%	101%	69%	150%	100%	69%	33%	109%

0.960 in the full sun. The reduction of K_V in the shade compared to the full sun was only significant for FD.

3.3.5. Contribution of the system's components to water losses

The respective contribution of variations in evaporation (E) and in transpiration (T) to the reduction of the total evapotranspiration by solar panels was calculated from field data only in the case of lettuces (for cucumbers, stomatal conductance was not measured and K_V could not be calculated therefore). While soil evaporation was reduced consistently both in FD (21% of the full sun) and in HD (25% of the full sun), changes in plant transpiration were significant in FD only. In FD, transpiration was reduced by 31% compared to the full sun, whereas in HD it slightly increased and was 4% higher (non significant) than in the full sun (Table 3). The ratio T/E was significantly increased in the shade (multiplied by 3.3 in FD and by 4.2 in HD compared to the full sun) as the proportion of ground covered with plants increased and reached 150% of the full sun. Soil evaporation increased significantly in the shade of FD whereas it remained close to that of the full sun in HD. In HD, the reduced climatic demand (ETO) was compensated by an increase of the fraction of bare soil, whereas in FD the increase of the bare soil overpassed the decrease of ETO . In both case the contribution of the soil evaporation coefficient K_S was not significantly affected by shading, compared to full sun (Table 4).

3.4. Water use efficiency

For lettuces, between DOY 124 and final harvest (DOY 144), the accumulation of dry matter reached 67% of that in the full sun in FD, and 84% in HD, with strong variation between varieties (Table 5). Varieties “Kriribati” and “Emocion” were the most productive in the shade; relative yield for these varieties was above 80% of the full sun, in FD, and even above 91% in HD. For these two varieties, the water use efficiency of the system (WUE) increased in the shade both in FD and in HD compared to the full sun (+12 to +35% in FD and +21% to +42% in HD, depending on the variety). On the contrary, for varieties “Model” and “Bassoon”, the yield was decreased down to 47% of the full sun in FD and to 61% in HD. Consequently WUE was reduced for these two varieties (Table 5). In average, when pooling all varieties together, WUE between DOY 124 and 144 was reduced by 5% in FD and increased by 12% in HD.

Cucumbers were more sensitive to shade and the total dry matter accumulation was reduced to 42% of that of the full sun in FD and

79% in HD. For that species, thus, WUE was reduced by the PVPs; the mean value of WUE in the shade was 49% of that in the full sun in FD and 86% in HD.

4. Discussion

4.1. Effect of fluctuating shade on crop evapotranspiration, its components, and its drivers

Under the PVPs, the water losses through evapotranspiration are reduced: AET in the shade varies between 71% of the full sun (FD, lettuces) and 86% of the full sun (HD, cucumbers) depending on the level of shade and on the crop.

The evaporation (E) and transpiration (T) components are affected differently below the solar panels depending on the level of shade and the type of crops. Transpiration is reduced in most of the cases (except in HD, for lettuces where it remains close to 100% of the full sun, and even tends to increase slightly). Evaporation varies in the opposite direction for the two crops: it is dramatically reduced for lettuces in the shade as the fraction of soil covered by the vegetation increases in the shade; on the contrary, evaporation increases to at least 113% of the full sun for cucumbers as cucumber plants cover less efficiently the ground surface in the shade.

The reduction of Total evapotranspiration (AET) is mainly driven by the reduction of the climatic demand under the solar panels, itself mainly driven by light reduction. The linear regression model between weekly AET and ETO calculated from experimental data for both crops pooled together showed that the variations of ETO explained 50% of the variations of AET within and between treatments.

The second half of AET variability would result from adjustments through physical (soil surface) and physiological (plant canopy characteristics) modifications of the system. This part of the reduction of AET in the shade results from the interactions between: (1) the change in the fraction of bare soil, (2) the change of transpiration rate of 1 m² of plant canopy driven by $ETO \times K_V$, (3) the change of soil evaporation rate of a given unit area of bare soil monitored by $ETO \times K_S$ (Fig. 9).

The ratio K_V/K_S in the shade and in the full sun determines whether an increase or a decrease of the fraction of ground covered by plant may result in an increase or a decrease of the global crop transpiration. K_V was shown to decrease for shaded lettuces, provided the level of shading is severe enough (FD treatment).

Table 4

Evolution of cucumbers AET in shade (% of the full sun) as calculated in Eq. (2) and its determinants as calculated from Eq. (7).

Cucumbers Eq. (2)	FD AET 81%						HD AET 86%					
Eq. (7)	T –			E 158%			T –			E 113%		
	ETO	f	K _V	ETO	(1 – f)	K _S	ETO	f	K _V	ETO	(1 – f)	K _S
	73%	75%	–	73%	186%	116%	81%	57%	–	81%	126%	111%

Table 5

Relative dry matter accumulation (DM), Actual evapotranspiration (AET) and water use efficiency (WUE) expressed in % of the full sun for lettuces (between DOY124 to 144) and cucumbers (from DOY175 to 241).

	FD			HD		
	DM (%)	AET (%)	WUE(%)	DM (%)	AET (%)	WUE (%)
Lettuces						
Emocion	80	71	112	107	75	142
Model	47	71	66	81	75	108
Bassoon	56	71	89	61	75	82
Kiribati	96	71	135	90	75	121
All varieties	67	71	95	84	75	112
Cucumbers	42	79	53	79	82	96

Previous studies on the response of stomatal conductance (Damour et al., 2010; Medrano et al., 2005) confirm that K_V may decrease non linearly with incident radiation, under constant CO_2 atmospheric concentration and water potential. Plant specific maximal conductance and stomatal sensitivity to light may have an impact on the evolution of evapotranspiration in response to shade. The evolution of K_S in a shaded system, as calculated according to Gallardo et al. (1996) depends on soil water content (and therefore on the irrigation frequency) and soil properties (texture and structure). K_S may remain unchanged in the shade if the soil is watered enough to maintain soil evaporation at its maximum.

4.2. Determinants and levers for improvement of WUE in agrivoltaic systems

Water use efficiency can be enhanced through two levers of actions (Passioura et al., 2010). (1) The reduction of the ratio between water losses that are useless for the plant (e.g. not passing through the plant) and transpired water which contributes to stomatal opening and therefore biomass production. In the case where irrigation is accurately monitored so that there is little run-off or drainage, water losses are mainly due to soil evaporation and E/T ratio should be reduced in order to enhance WUE. (2) The

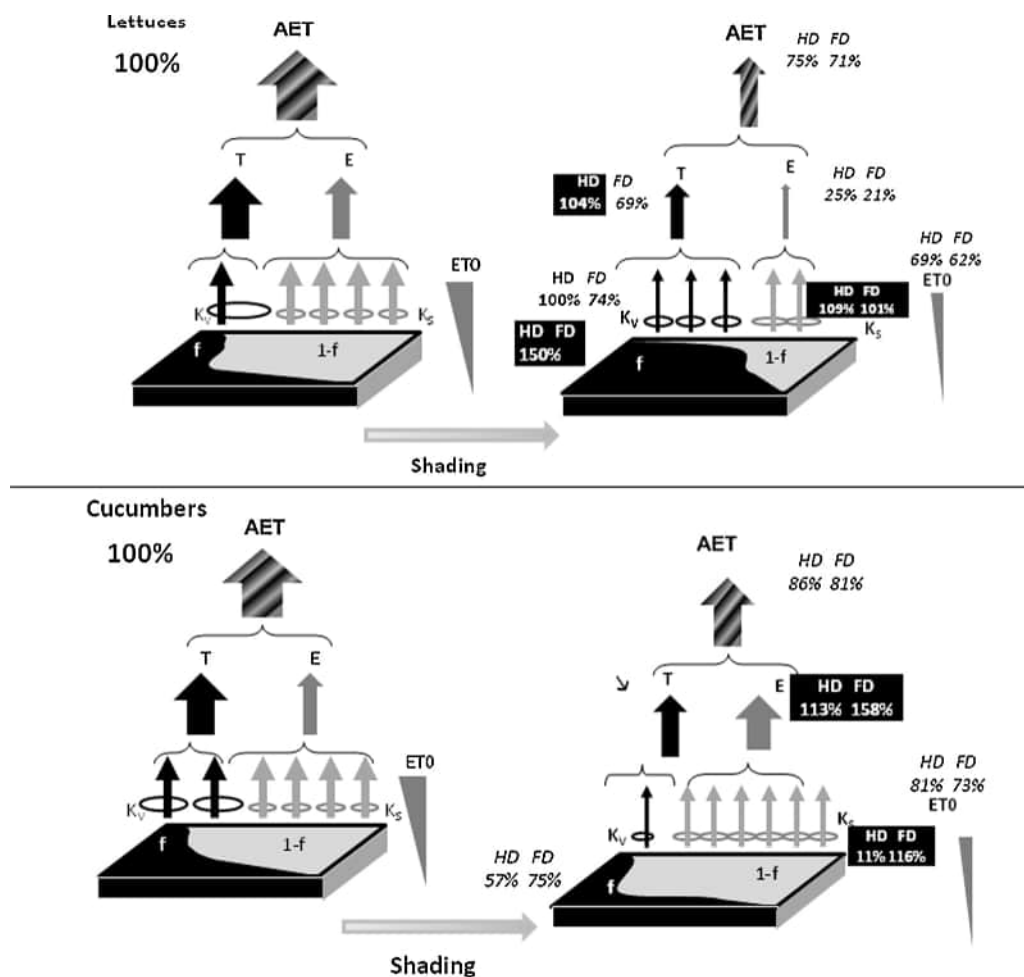


Fig. 9. Summary of the water losses from a lettuce and a cucumber crop and their drivers. Numbers with black background indicate an increase of the value of the corresponding determinants when shading compared to the full sun (100%). Numbers in italic indicate a decrease of the corresponding determinants under shading. The black area of the system represents the area covered with plant while the gray area represents bare soil. The thickness of water flux arrows just above the system surface represents the intensity of the flux (driven by ET_0), and the size of the ellipsoid they are going through represent the conductance for water of the surface (plant or soil) from which they are released.

improvement of transpiration use efficiency – calculated as the ratio between net photosynthesis (A) and transpired water (T): this can be achieved by making the exchange of transpired water for CO_2 input through the stomata more efficient for biomass production.

These two levers of action are highlighted when calculating water use efficiency (WUE) of a crop according to Eq. (12).

$$\frac{1}{\text{WUE}} = \frac{E}{A} + \frac{T}{A} = \frac{T}{A} \cdot \left(1 + \frac{E}{T}\right) \quad (12)$$

where T/A is the inverse of transpiration use efficiency.

4.2.1. Reduction of the E/T ratio

According to the formalism used to decompose AET (Eq. (7)) E/T ratio can be expressed as the product of (1) the ratio between the proportions of bare soil and soil covered by the crop, (2) the ratio between the surface resistances for water evaporation (soil) and water transpiration (crop) (Eq. (13)).

$$\frac{E}{T} = \frac{1-f}{f} \times \frac{K_s}{K_v} \quad (13)$$

Soil covering with a mulch or selecting crops with a dense canopy is already a widely recognized mean to reduce water loss through ground surface evaporation (Huang and Wu, 2007; Passioura et al., 2010; Wallace, 2000) and therefore WUE for the same amount of AET. We showed that the fraction of ground cover by the plant canopy was significantly increased in the shade compared to the full sun in the case of lettuces. However lettuce and cucumber cover rate differ significantly between the full sun and the shaded conditions only when the plants are old enough to cover at least 25% of the ground surface. On the opposite, E/T ratio is more sensitive to cover rate (f) variation when f is close to 0 (hyperbolic form of $(1-f)/f$). Therefore the reduction of the E/T ratio may contribute to increased WUE in the shade of the PVPs compared to the full sun mainly for middle aged crops, when crop cover rate is in between 20% and 40%. For that reason, to enhance WUE in agrivoltaic systems, we would recommend to use preferentially crops with rapid ground coverage and a high plasticity of cover rate in response to shade. Moreover, plants with a high soil cover rate would also benefit from a higher ability to capture light in shaded conditions (Condon et al., 2004; Marrou et al., 2013a; Valladares and Niinemets, 2008) and therefore partially maintain photosynthesis even if light resource is reduced. Indeed, it was already shown, in the same agrivoltaic system, that plant radiation interception efficiency in the shade was the main compensation mechanism to reach high yield (Marrou et al., 2013a).

Considering the second term of Eq. (12), reduction of the E/T ratio in the shade may be moderated by the evolution of the K_s/K_v in the shade compared to the full sun. In the present case study, it was shown that for irrigated crops, the soil hydraulic conductivity may remain equal to its maximum between two irrigation cycles, both in shaded and unshaded situations, whereas K_v tends to decrease in the shade. For non irrigated crop K_s could be significantly higher below the PVPs compared to the full sun as the ground surface dries less rapidly. Therefore AVS are more likely to improve WUE compared to the full sun for irrigated crop with frequent irrigation cycles. However, the PVPs may allow decreasing the frequency of irrigation without creating water stress and biomass reduction.

4.2.2. Improvement of transpiration use efficiency (TUE)

According to the formalism used to decompose AET (Eq. (7)), the inverse of transpiration use efficiency ($1/\text{TUE} = T/A$) can be expressed as the product of ET_0 and the ratio between the surface

resistance to transpiration (K_s) and the net photosynthesis (per unit of canopy area) of the crop (A_s) (Eq. (14)).

$$\frac{T}{A} = \frac{ET_0 \times f \times K_v}{A_s \times f} = ET_0 \times \frac{K_v}{A_s} \quad (14)$$

Stomatal conductance is a key parameter for crop transpiration use efficiency (TUE), as it monitors at the same time photosynthetic assimilation of CO_2 per unit of leaf area (A_s) and the plant transpiration (T). Under fluctuating light, the time lag between the reduction/increase of CO_2 assimilation rate and stomatal opening/closure can impact the dynamic of WUE (Knapp and Smith, 1987).

In the case of lettuces under PVPs, the maximum conductance measured on plant submitted to severe shading (FD) when they were exposed to saturating light ($\text{PAR} > \text{PAR}_0$) was significantly lower than for plants in the full sun (Fig. 2). This result can be explained either by (1) “dynamic effects” due to the fact that lettuce were sampled for the measurement of stomatal conductance without taking into account the time for which they had been exposed to light or to shade before the measurement, or by (2) a long term physiological or morphological adaptation of plant in response to the level of shade they have been exposed to since planting.

On the first hand, stomatal aperture when plant switch from shade to light can last for five to several dozens of minutes (Fay and Knapp, 1996; Knapp and Smith, 1987; Mojzes and Kalapos, 2008). Moreover, Allen and Percy, 2000 showed that the induction time for photosynthesis (time necessary for photosynthesis to recover its maximum once stomata are widely opened in response to light) depends on the duration of the period that plant had spent in the shade before that: the longer they stay in the shade, the longer is the induction period.

A closer analysis of Fig. 2 revealed that measurements corresponding to low G_s when incident PAR is above PAR_0 , were taken mainly on lettuces in FD in planting rows 2, 3 and 5 on May 17th 2011, and, to a lower extent, in HD in row 2 on April 20th 2011 and in rows 4 and 5 on May 17th 2011. According to pyranometers records on May 17th 2011, planting rows 2 and 5 in FD were in the shade of the solar panels and switched to the lightened zone in the hour when G_s measurement was taken. Thus, low G_s measured in that planting position can be attributed to the time lag necessary for stomata to recover steady state opening rate after return to full light.

On the other hand, reduction of the stomatal conductance has already been observed as a long term response to shade. When plants are grown in the shade, stomatal density decreases together with mesophyll thickness while leaf area increases (Fay and Knapp, 1995; Gay and Hurd, 1975; Lichtenthaler et al., 1981; Murphy et al., 2012).

As a consequence, another way to increase water use efficiency in the fluctuating shade conditions of agrivoltaic system would be to select species and varieties that are able to maintain a high Photosynthesis/transpiration ratio (TUE, transpiration Use Efficiency) during the transition period between shade and light period. According to Knapp and Smith, 1987, this objective can be achieved through different plant strategies. In the case of broad leaves species, high TUE could be obtained with plants having a stomatal conductivity that is relatively insensitive to radiation variations and with a high maximal value.

5. Conclusion

We showed in this experiment that shading irrigated vegetable crop with PVPs panels allowed saving 14–29% of evapotranspired water, depending of the level of shade created and the crop grown in the system. Using a theoretical framework according to which AET is monitored by four drivers, we identified and ranked the

biophysical processes responsible for that water saving in the shade of the PVPs. AET reduction was achieved thanks to (1) the reduction of the climatic demand as incident radiation is reduced compared to full light, (2) for lettuces the increase of the fraction of soil covered by the plant and of their stomatal conductance as a response to shade. In addition, this study highlights that soil evaporation was more sensitive to shading than plant transpiration. However the water use efficiency was found to increase only for some lettuce varieties (2 varieties out of 4) in the level of shade HD, compared to the full sun. WUE may be enhanced in these systems by selecting crops with ability to cover the ground rapidly thereby maximizing the T/E ratio for a given amount of water lost. This strategy, already recognized in conventional growing may contribute more efficiently to increase both biomass production and WUE in the shade of PVPs as, not only soil evaporation would be reduced, but plants with a high cover rate would be able to intercept light and photosynthesize more efficiently when light resource is reduced. Nevertheless, WUE efficiency is quite stable and possibilities for improvement are small when irrigation allows evapotranspiration and biomass production being close to their potential (Tanner and Sinclair, 1983) as it is the case in our experiment. For that reason PVPs are expected to be more beneficial regarding water use efficiency in case of crops submitted to water stress. More experiments are needed to explore further this hypothesis.

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References

- Allen, M.T., Pearcy, R.W., 2000. Stomatal behavior and photosynthetic performance under dynamic light regimes in a seasonally dry tropical rain forest. *Oecologia* 122 (4), 470–478.
- Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements. FAO irrigation and drainage papers 56. FAO – Food and Agriculture Organization of the United Nations, Rome.
- Alves, I., Santos Pereira, L., 2000. Modelling surface resistance from climatic variables? *Agricultural Water Management* 42 (3), 371–385.
- Chartzoulakis, K., Michelakis, N., 1990. Effects of different irrigation systems on root growth and yield of greenhouse cucumber. *Acta Horticulturae* (ISHS) 244, 237–244.
- Condon, A.G., Richards, R.A., Rebetzke, G.J., Farquhar, G.D., 2004. Breeding for high water-use efficiency. *Journal of Experimental Botany* 55 (407), 2447–2460.
- Cuny, H., Wery, J., Gaufres, F., 1998. A simple indicator for diagnosing nitrate leaching risk below the root zone using the Tensionic tensiometers. *Agronomy* 18 (8–9), 521–535.
- Damour, G., Simonneau, T., Cochard, H., Urban, L., 2010. An overview of models of stomatal conductance at the leaf level. *Plant, Cell and Environment* 33 (9), 1419–1438.
- De Tourdonnet, S., 1998. Maîtrise de la Qualité et de la Pollution Nitrique en Production de Laitues Sous Abris Plastique: Diagnostic et Modélisation des Effets des Systèmes de Culture. Institut National Agronomique de Paris-Grignon, Paris-Grignon, pp. 191.
- Dupraz, C., Marrou H., Dufour L., Talbot G., Ferard Y., Nogier A. (2010). Combining solar photovoltaic panels and food crops for optimising land use: Towards new agrivoltaic schemes. *Renewable Energy* 36(10): 2725n–2732.
- Fay, P.A., Knapp, A.K., 1995. Stomatal and photosynthetic responses to shade in sorghum, soybean and eastern gamagrass. *Physiologia Plantarum* 94, 613–620.
- Fay, P.A., Knapp, A.K., 1996. Photosynthetic and stomatal responses to variable light in a cool-season and warm-season prairie forb. *International Journal of Plant Sciences* 157 (3), 303–308.
- Gallardo, Snyder, R., Schulbach, K., Jackson, 1996. Crop growth and water use model for lettuce. *Journal of Irrigation and Drainage Engineering* 122 (6), 354–359.
- Gay, A.P., Hurd, R.G., 1975. The influence of light on stomatal density in the tomato. *New Phytologist* 75 (1), 37–46.
- Gay, F., 2002. Elaboration D'une Méthode D'évaluation des Risques de Pollution Nitrique et de Pertes de Rendement en Parcelles Agricoles. Ecole Nationale Supérieure Agronomique de Montpellier, Montpellier.
- Guilioni, L., Cellier, P., Ruget, F.O., Nicoulaud, B., Bonhomme, R., 2000. A model to estimate the temperature of a maize apex from meteorological data. *Agricultural and Forest Meteorology* 100 (2–3), 213–230.
- Hay, R.K.M., Porter, J.R., 2006. The Physiology of Crop Yield. John Wiley & Sons, Ames, IA Sons.
- He, J., Lee, S.K., Dodd, I.C., 2001. Limitations to photosynthesis of lettuce grown under tropical conditions: alleviation by root-zone cooling. *Journal of Experimental Botany* 52 (359), 1323–1330.
- Hillel, D., 1998. Environmental Soil Physics: Fundamentals, Applications, and Environmental Considerations. Elsevier Science, San Diego CA.
- Huang, Y.H., Wu, J.H., 2007. Technological system and renewable energy policy: a case study of solar photovoltaic in Taiwan. *Renewable and Sustainable Energy Reviews* 11 (2), 345–356.
- Jones, H.G., 1992. Plants and Microclimate: a Quantitative Approach to Environmental Plant Physiology. Cambridge University Press, New-York, NY.
- Knapp, A.K., Smith, W.K., 1987. Stomatal and photosynthetic responses during sun/shade transitions in subalpine plants: influence on water use efficiency. *Oecologia* 74 (1), 62–67.
- Lichtenthaler, H., et al., 1981. Photosynthetic activity, chloroplast ultrastructure, and leaf characteristics of high-light and low-light plants and of sun and shade leaves. *Photosynthesis Research* 2 (2), 115–141.
- Marrou, H., 2012. Conception et Optimisation of Agrivoltaic Systems. Montpellier SupAgro, Montpellier (Ph.D. Thesis).
- Marrou, H., Wery, J., Dufour, L., Dupraz, C., 2013a. Productivity and radiation use efficiency of lettuces grown in the partial shade of photovoltaic panels. *European Journal of Agronomy* 44 (0), 54–66.
- Marrou, H., Guilioni, L., Dufour, L., Dupraz, C., Wery, J., 2013b. Microclimate under agrivoltaic systems: is crop growth rate affected in the partial shade of solar panels? *Agricultural and Forest Meteorology* 177, 117–132.
- Medany, M.A., Abou-Hadid, A.F., Short, T.H., 1996. Cucumber models in relation to radiation and temperature. In: Hassan II, I.A.V. (Ed.), Protected Cultivation in the Mediterranean Region. Cahiers Options Méditerranéennes, Agadir, pp. 167–176.
- Medrano, E., Lorenzo, P., Sánchez-Guerrero, M.C., Montero, J.L., 2005. Evaluation and modelling of greenhouse cucumber–crop transpiration under high and low radiation conditions. *Scientia Horticulturae* 105 (2), 163–175.
- Mojzes, A., Kalapos, T., 2008. Leaf gas exchange responses to abrupt changes in light intensity for two invasive and two non-invasive C-4 grass species. *Environmental and Experimental Botany* 64 (3), 232–238.
- Monteith, J.L., Unsworth, H., 1990. Principles of Environmental Physics. Edward Arnold, Woburn MA.
- Murphy, C.M.R., Jordan, G.J., Brodribb, T.J., 2012. Differential leaf expansion can enable hydraulic acclimation to sun and shade. *Plant, Cell and Environment* 38 (8), 1407–1418.
- Olioso, A., Carlson, T.N., Brisson, N., 1996. Simulation of diurnal transpiration and photosynthesis of a water stressed soybean crop. *Agricultural and Forest Meteorology* 81 (1&2), 41–59.
- Passioura, J.B., Angus, J.F., Donald, L.S., 2010. Chapter 2 – Improving Productivity of Crops in Water-Limited Environments, *Advances in Agronomy*. Academic Press, Newkark, USA, pp. 37–75.
- Perry, K.B., Wehner, T.C., Johnson, G.L., 1986. Comparison of 14 methods to determine heat unit requirements for cucumber harvest. *Hortscience* 21 (3), 419–423.
- Rana, G., Katerji, N., Mastroianni, M., ElMoujabber, M., Brisson, N., 1997. Validation of a model of actual evapotranspiration for water stressed soybeans. *Agricultural and Forest Meteorology* 86 (3–4), 215–224.
- Saxton, K.E., Rawls, W.J., Romberger, J.S., Papendick, R.I., 1986. Estimating generalized soil–water characteristics from texture. *Soil Science Society of America Journal* 50 (4), 1031–1036.
- Seber, G.A.F., Wild, C.J., 2003. Nonlinear Regression. Wiley-Interscience, Hoboken New Jersey.
- Shuttleworth, W.J., 2006. Towards One-step Estimation of Crop Water Requirements. 49. American Society of Agricultural Engineers, St. Joseph, MI, ETATS-UNIS, pp. 11.
- Shuttleworth, W.J., Wallace, J.S., 1985. Evaporation from sparse crops – an energy combination theory. *Quarterly Journal of the Royal Meteorological Society* 111 (469), 839–855.
- Stroosnijder, L., 1987. Soil evaporation – test of a practical approach under semiarid conditions. *Netherlands Journal of Agricultural Science* 35 (3), 417–426.
- Suojala-Ahlfors, T., Salo, T., 2005. Growth and yield of pickling cucumber in different soil moisture circumstances. *Scientia Horticulturae* 107 (1), 11–16.
- Tanner, C.B., Sinclair, T.R., 1983. Efficient water use in crop production: research or re-search? Limitations to efficient water use in crop production (in press).
- Thicoipé, J.P., 1997. Laitues, Monographie, Paris, p. 281.
- Valladares, F., Niinemets, U., 2008. Shade tolerance, a key plant feature of complex nature and consequences. In: Annual Review of Ecology Evolution and Systematics, Annual Reviews, Palo Alto, pp. 237–257.
- Wallace, J.S., 2000. Increasing agricultural water use efficiency to meet future food production. *Agriculture, Ecosystems and Environment* 82 (1&2), 105–119.
- Wery, J., 2005. Differential effects of soil water deficit on the basic plant functions and their significance to analyse crop responses to water deficit in indeterminate plants. *Australian Journal of Agricultural Research* 56 (11), 1201–1209.



Conceptualizing and assessing the effects of installation and operation of photovoltaic power plants on major hydrologic budget constituents



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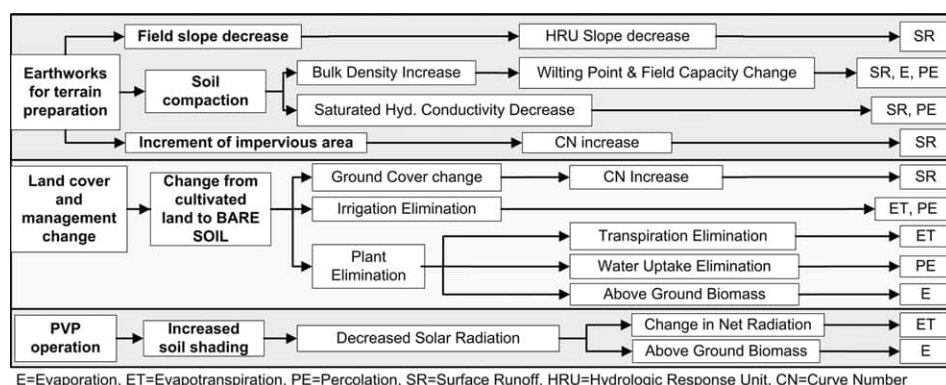
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HIGHLIGHTS

- Photovoltaic power plants effects on major hydrologic budget constituents are identified, conceptualized and simulated with SWAT model.
- Spatially, the effects are analyzed in basin and local (sub-basin) scale.
- The long-term effects of land use change from agricultural to photovoltaic power plants were investigated by applying downscaled climate projection data from a Regional Climate Model driven by 5 different General Circulation Models.

GRAPHICAL ABSTRACT



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ABSTRACT

This study addresses the effects of land use change from agricultural to photovoltaic parks (PVPs) on the hydrology of an area. Although many environmental effects have been identified and analyzed, only minor attention has been given to the hydrologic effects of the installation and operation of PVPs. The effects of current PVP installation and operation practices on major hydrologic budget constituents (surface runoff, evapotranspiration and percolation) were identified, conceptualized, quantified and simulated using SWAT model. Vosvozis river basin located in north Greece was selected as a test site. Additionally, long-term effects were simulated using dynamically downscaled climate projections by a Regional Climate Model (RCM) driven by 5 different General Circulation Models (GCMs) for the period 2011–2100. Results indicate that surface runoff and percolation potential are significantly increased at the local scale and have to be considered during PVP siting, especially when sensitive and protected ecosystems are involved.

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1. Introduction

As global greenhouse gas emissions cause an increasing concern on human community regarding climate change, alternative energy sources are substituting for the use of fossil fuel. Solar power plants are among those energy sources which are considered to be environmentally friendly, in terms of emission reduction of greenhouse gases

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(Pehnt, 2006) and other hazardous substances, such as mercury, cadmium or even particulates. However, there are other environmental impacts which have not yet been investigated. Turney and Fthenakis (2011) conducted a thorough review on the environmental effects related to the large scale solar power plants and pointed out that hydrology is one of the fields in which impact study is needed. Photovoltaic parks (PVPs) require large land portions to be covered with solar panels, ranging between 20 and 40 m²/kW_{peak}, which absorb a high amount of the incoming solar radiation; therefore, they reduce the earth's albedo. Nemet (2009) conducted a study on the radiative forcing due to the installation of widespread PVPs. He concluded that the overall radiative forcing from substitution of PV for fossil fuels is much larger than the one caused by the local reduction of earth's albedo. Moreover, the installation of a PVP causes changes to the physical nature of soil, by changing the preexisting vegetation and by converting to impervious a significant portion of the land occupied for this purpose in order to construct concrete footings for the solar panels to be mounted onto. Turney and Fthenakis (2011) list many interventions related to the installation and operation of PVPs that alter the hydrology of an area, such as: alteration of ground slopes if necessary to less than 5%, periodical mowing of vegetation, installation of inverters, transformers and collector boxes, trenching for electrical and communications cables, construction of access roads, maintenance vehicles moving in the area, and water consumption for washing the panels. Nevertheless, their effects on the

hydrology of an area occupied by photovoltaic installations have not yet been investigated.

Climate change is expected to significantly affect hydrological processes, especially in semi-arid and arid regions (IPCC, 2007) and Mediterranean region (Erol and Randhir, 2012). De Paola et al. (2014) analyzed the Intensity–Duration–Frequency rainfall curves for three cities in Africa and concluded that a rise of frequency of extreme events is expected and therefore flood risk is increasing. Luo et al. (2013) simulated climate change impacts on hydrology and water quality in northern Coastal Ranges and western Sierra Nevada, USA using SWAT model and concluded that the sensitivity of both hydrologic cycle and water quality to the projected climate change is high.

Within the present work, it is attempted to identify and analyze the effects of installation and operation of PVPs in the major hydrologic components. Furthermore, a generalized conceptualization of those effects is proposed with a view to a wider application in other climate and land uses change studies. Finally, the hydrologic effects are quantified and simulated in a medium sized basin in northern Greece, i.e., Vosvozis river basin (Fig. 1). For this purpose the widely applied hydrologic model SWAT (Neitsch et al., 2011) was calibrated and verified for the period 2008–2012 and various scenarios of impacts extent and land occupation by PVPs were tested. Moreover, dynamically downscaled projected climate data driven by 5 GCMs under SRES-A1B scenario were used as input to the developed model in order to assess the

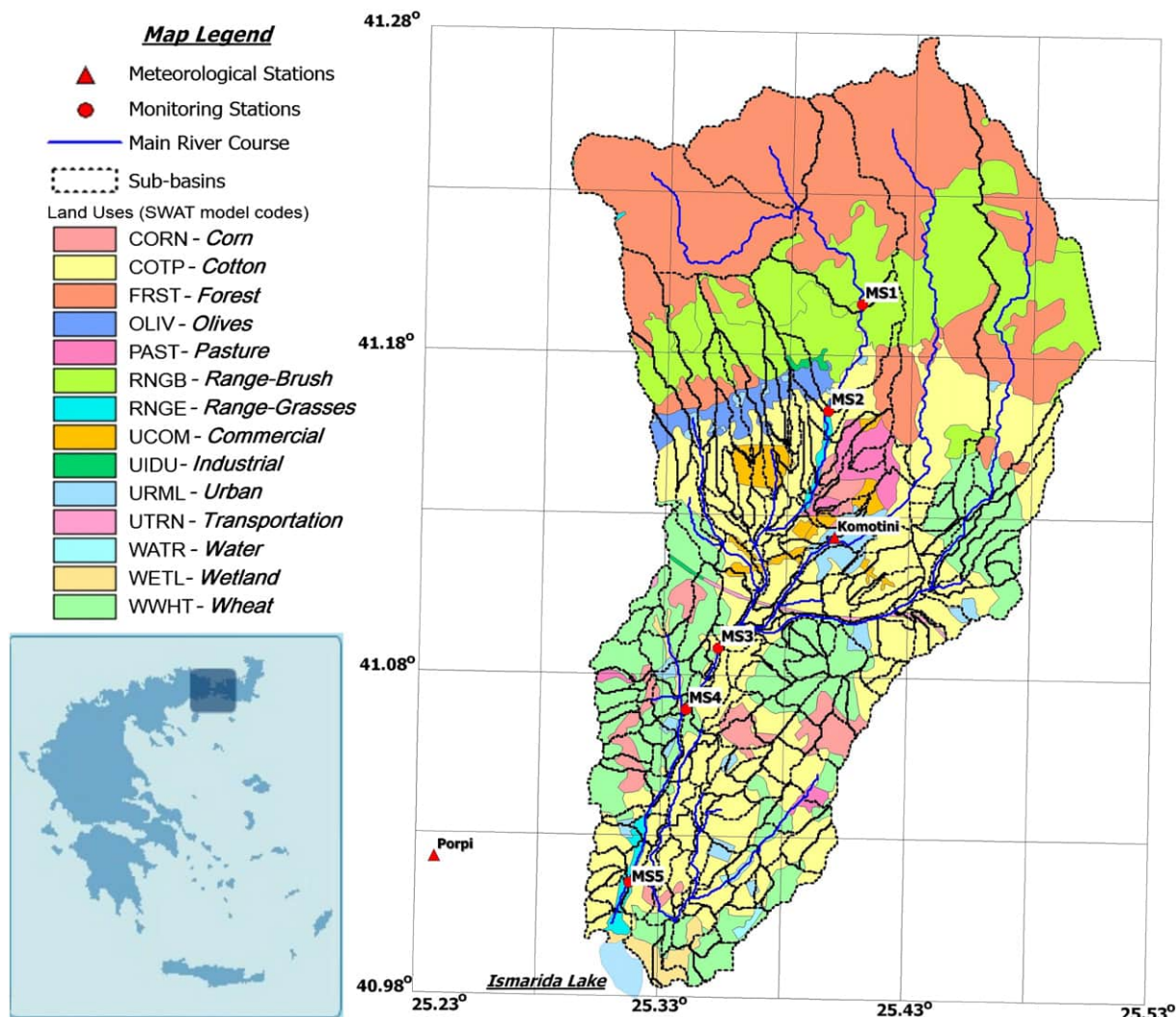


Fig. 1. Location and land use map of the study area.

long-term effects of PVPs on the hydrology of the test site for the period 2011–2100.

2. Materials and methods

2.1. Study area description

Vosvozis river basin in Thrace (Northern Greece) (Fig. 1) constitutes a typical Mediterranean watershed, especially suitable for the installation of PV systems due to the abundance of sunlight, its rural character and the presence of a large proportion of plain land. The catchment size is 340 km², extending from the Greek–Bulgarian borders down to the Thracian sea. Vosvozis river discharges into Ismarida Lake, which is an important ecosystem, protected by the Ramsar Treaty, it is designated as Natura 2000 area and it is part of the National Park of Eastern Macedonia and Thrace. Ismarida Lake is an ecosystem where complex interactions among surface waters, groundwaters and sea waters are taking place. Previous research in the area has proved the hydraulic connection of Ismarida Lake and Vosvozis river with the groundwater system. Gemitzi and Stefanopoulos (2011) and Gemitzi et al. (2013) have shown that Ismarida Lake recharges the groundwater system and therefore it should be considered as a groundwater dependent ecosystem. Therefore, any changes on land uses in Vosvozis catchment area are expected to affect Ismarida Lake and the associated aquifer system.

The climate of the area is characterized as Mediterranean with dry hot summers and mild winters. The average annual precipitation is 628 mm and the average annual temperature is 15 °C. The area is characterized by intense agriculture, cattle breeding and urban land uses. The main cultivations are corn, cotton and wheat, as illustrated in Fig. 1. Water is used mainly for irrigation and urban supply. During the last years, several legislative frameworks have been established in Greece which aims to promote the development of renewable energy sources, including photovoltaic power systems. One of the most recent legislative regulations with regard to renewable energy sources is the Law 3851/10 (Official Government Gazette of Greece, 2010), which motivates farmers to install small scale PVPs in agricultural areas, thus promoting land use change and activity modification from agricultural to energy production.

2.2. Model development

2.2.1. Data set and model parameterization

The SWAT model (SWAT2009 version) (Neitsch et al., 2011) was used for the purposes of this study. SWAT model has been widely used for the assessment of climate and land use change effects at the catchment hydrologic regime (Wu et al., 2012; Kim et al., 2013; Luo et al., 2013). SWAT model basic data requirements include topography, land use, soil and weather data. It is calibrated and validated using simulated against observed river discharge data. Thus, five monitoring stations were established in Vosvozis river basin (Fig. 1), in which river flow measurements were performed on a weekly or biweekly basis for the period October 2008 to April 2012. River flow was determined by in-stream wading measurements using a Hydrological Services Pty OSS-B1 current meter. The monitoring process resulted in 580 river flow measurements in total for the five monitoring stations.

Land use distribution for the study basin was defined using a hybrid approach of CORINE data and general crop pattern data derived from Apostolakis (2009). The appropriate SWAT land cover/plant codes were assigned to each land use and a reclassified land use map was produced (Fig. 1), which was used as input to SWAT model. Soil data were obtained by the local authorities and were enriched with recent soil data from Misopolinos (2009), which were incorporated into SWAT soil database.

Digital Elevation Model (DEM) quality can strongly influence the hydrologic simulation results (Defourny et al., 1999). For the mountainous

area, DEM was constructed by digitization of the 1:50,000 scale topographic map of the Hellenic Military Geographical Service. For the low-land area, where low slopes are observed, that were not sufficiently represented by the 1:50,000 scale topographic map, 1:5000 topographic maps of the Hellenic Military Geographical Service were digitized. The resolution of the final DEM was 50 × 50 m. Due to the fact that some parameters included in land use change scenarios, such as solar radiation, are assigned at the sub-basin level and not at the Hydrologic Response Unit (HRU) level, the agricultural part of Vosvozis river basin was densely subdivided into small sub-basins in order to be able to develop low PVP coverage scenarios. This does not affect the validity of model performance, as indicated by the results provided by Cho et al. (2010), showing that watershed subdivision did not affect streamflow prediction stability. Vosvozis river basin was subdivided into 211 sub-basins and 265 Hydrologic Response Units (HRUs). Weather data were collected from two meteorological stations shown in Fig. 1, including daily values of precipitation, maximum/minimum temperature, wind speed, solar radiation and relative humidity for the period October 2008 to April 2012.

Two methods are available within SWAT model for surface runoff simulation: the SCS runoff method (USDA-SCS, 1972) and the Green & Ampt infiltration method (Green and Ampt, 1911). Despite the fact that infiltration is directly simulated in Green & Ampt method, it requires sub-daily meteorological data. Hydrologic simulation in a sub-daily time step is not the case for the current study and therefore the widely applied SCS method was used for the purposes of this study. The parameter that controls surface runoff potential in SCS method is the curve number (CN) which ranges between 30 and 100. Lower CN values indicate low runoff potential, while higher values correspond to increasing runoff potential.

SWAT model interface offers several methods for the calculation of potential evapotranspiration. As solar radiation changes are crucial for the purposes of this study, a method which incorporates solar radiation in evapotranspiration calculations should be used. Between Penman–Monteith (Monteith, 1965) and Priestley and Taylor (1972) methods, the former was chosen, as the latter tends to underestimate potential evapotranspiration in semi-arid and arid areas (Neitsch et al., 2011).

2.2.2. Model calibration/verification

Calibration and validation processes are critical for model reliability, as there are parameters, which are difficult to be measured or estimated, thus increasing the degree of uncertainty in simulation. Model calibration could be either manual or automatic. As there are no continuous streamflow time series available, manual calibration was used for the purposes of this study.

Model calibration was based on daily streamflow data for the period October 2008 to October 2010. Several statistical methods and indices have been proposed and assessed for hydrological model evaluation. Legates and McCabe (1999) indicate that, not only correlation-based criteria, but also summary statistics and absolute error criteria have to be used in order to maintain a sufficient hydrological model evaluation. Krause et al. (2005) investigated the performance of several criteria used for the assessment of hydrological models and concluded that, unlike R^2 , weighted R^2 (wR^2) is capable to reveal systematic model errors. They also found that the most sensitive criteria to low flow conditions are the logarithmic Nash–Sutcliffe Efficiency (Nash and Sutcliffe, 1970) (lnNSE) and the modified NSE. Moriasi et al. (2007) reviewed several model performance evaluation criteria used in a wide range of watershed models applications. They concluded that NSE, percent bias (PBIAS) and the ratio of the root mean square error to the standard deviation of measured data (RSR), in combination with graphical methods, should be used for model performance evaluation.

According to the above, the SWAT model application within this study was initially evaluated through a visual inspection of calibration results in the form of scattergrams, in which simulated streamflows are plotted versus observed ones and a linear regression line is fitted

to (regression line gradient b and coefficient of determination R^2 are also calculated). Then wR^2 , NSE, lnNSE, PBIAS, RSR and mean absolute error (MAE) were calculated. The same evaluation criteria were used for model validation assessment with streamflow data for the period November 2010 to April 2012.

2.3. PVP installation and operation effect identification and conceptualization

Based on the current practices applied in PVP siting, installation and operation, three interventions performed in a PVP terrain, which can potentially affect the local hydrology, were recognized. Hydrologic cycle components within a watershed are interacting in a complex way. Therefore, within the present work it is attempted to conceptualize the assessment process by identifying and assigning the PVP installation and operation effects that directly affect the fundamental hydrologic budget components. Indirectly, almost every hydrological component will be affected, as they are in constant interaction. Moreover, SWAT model parameters that describe the specific impact of the affected hydrological process were identified and properly adjusted in order to develop short-term and long-term impact scenarios. The three interventions identified and the subsequent conceptualization of their effects in the major hydrologic budget components are presented in Fig. 2 and described in detail below, while the corresponding equation relating the affected hydrologic budget components to SWAT model parameters is presented in Section A1 of Supplementary Material.

2.3.1. Earthworks for terrain preparation and PV mounting

The first intervention includes the earthworks for field flattening and related equipment installation (PV mounting systems, cables,

inverters etc.). In general, low slope areas (<5%) are preferable for the construction of PVPs due to the fact that they are easier approached and the optimum orientation of photovoltaic panels is easier to be obtained, while less earthworks are required. Nevertheless, PVPs can be constructed in relatively high slope terrains. Any changes made in the slope of the PVP terrain will directly affect surface runoff potential. When applying SCS method for surface runoff simulation within SWAT model, CN is properly adjusted according to the slope of the corresponding HRU. Therefore, any changes in the slope of the HRU in which PVP is constructed will affect CN and subsequently surface runoff.

Depending on the case, earthworks may be required in order to eliminate the geomorphological anomalies of the installation terrain. Due to the fact that earthworks and related equipment installation are conducted using heavy machinery, soil compaction is likely to be observed, which refers to the packing effect of mechanical forces on soils (Ozgoz et al., 2006). Alaoui et al. (2011), in their review article, indicated that in most studies investigating the effects of soil compaction, bulk density (BD) was found to be increased in the upper soil layer, while the decrement in pore volumes of compacted upper soil layer, resulted in significantly lower saturated hydraulic conductivity (KSAT) values. The degree to which those soil hydraulic properties are affected by soil compaction depends on several factors, including soil type, moisture content and mechanical force amount load. Despite the fact that during the cultivation process, tractors and harvesting machines contribute to soil compaction, soil compaction effects are relieved by processes such as freezing/thawing, wetting/drying and tillage (Hakansson, 2005). Thus, the extent of recovering for PVP compacted soils is expected to be lower, since these soils are not tilled. Any change in BD affects wilting point and subsequently field capacity of the soil layer. Field capacity is related to retention parameter used in daily CN

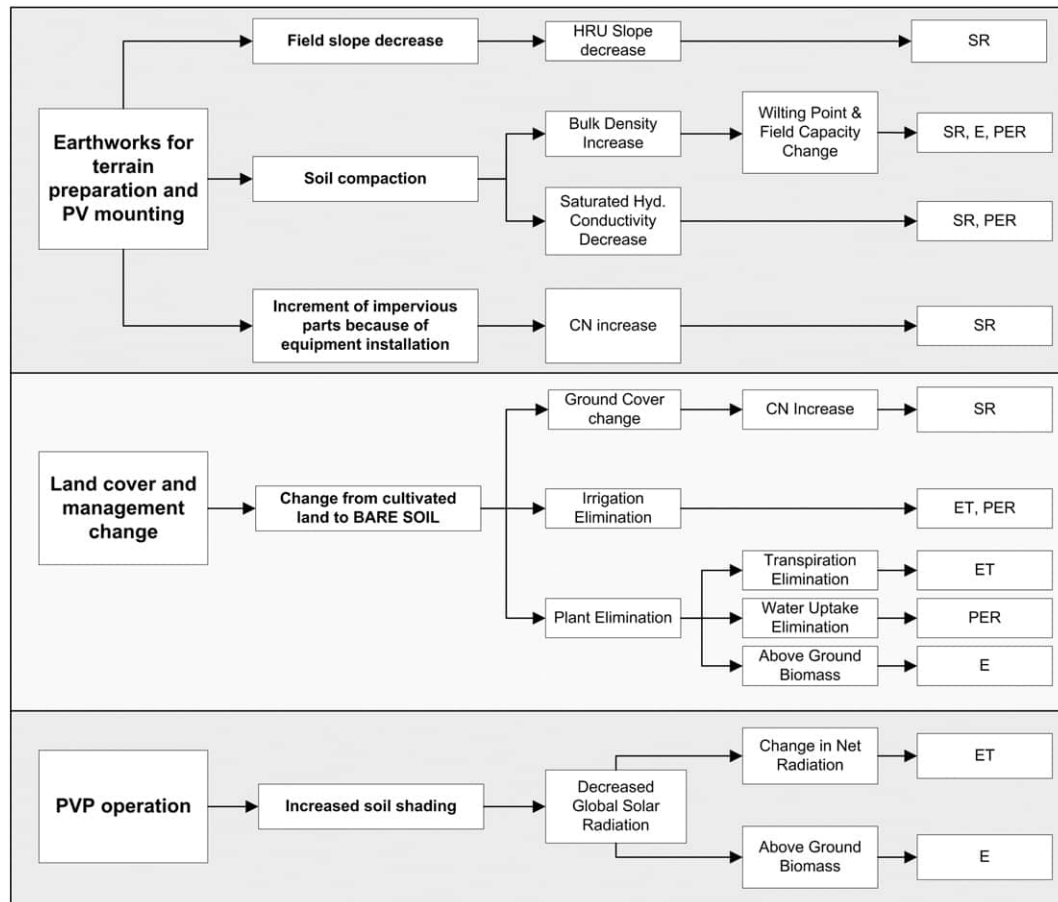


Fig. 2. Conceptualization scheme of PVP installation and operation impacts on major hydrologic components. (E = evaporation, ET = evapotranspiration, PER = percolation, SR = surface runoff, HRU = hydrologic response unit, CN = curve number).

calculation, when the daily CN is calculated as a function of water content and therefore surface runoff is affected. Moreover, soil water evaporation is affected, as field capacity constitutes the threshold water content value below which the evaporative demand of a soil layer decreases. Finally, percolation is affected by soil compaction, as field capacity and KSAT are related to travel time for percolation.

When concrete footings are constructed for PV panel mounting purposes and little prefab buildings are installed, a part of the PVP terrain is substituted by impervious areas. This will directly increase the potential of surface runoff, which is reflected in the modeling process by CN increment in SWAT model.

2.3.2. Land cover and management operations change from agricultural to PVP

The second significant intervention expecting to affect the hydrologic regime of an area is the land use change from agricultural to energy production. Cultivation includes several processes that directly affect the hydrologic regime of the agricultural field, such as plant growth and irrigation, which are eliminated when agricultural land is converted to PVP. Surface runoff is directly related to land cover. Peng and Wang (2012) measured surface runoff for six different land use covers, including forestland, cropland and pastureland using the large runoff field method. Their results indicated that the annual surface runoff can vary significantly with regard to land use type. The effects of land cover change from agricultural to energy production in surface runoff are reflected by changes in CN values, which are higher for bare soil when compared to CN values for the dominant crops of the study area (cotton, wheat and corn). These variations of CN values indicate a significant potential of land use change to affect surface runoff.

Depending on climate conditions and crop type, irrigation could constitute a significant component of the hydrologic budget. When agricultural irrigated land is substituted by PVPs, changes are expected for all the components of the hydrologic budget as irrigation ceases. The most significant change however, is expected to be observed in evapotranspiration due to changes in both transpiration and evaporation processes.

2.3.3. PVP operation

One of the fundamental principles concerning PVP construction is the orientation of photovoltaic panels in the way that they provide the maximum absorption of solar radiation. Within a PVP, several factors have to be taken into account for the definition of energy budget, as there are shaded surfaces of PVP terrain located under the PV panels and unshaded surfaces existing between the PV arrays, which serve to avoid PV panels shading from each other. Concerning the shaded surfaces of a PVP, from the total short-wave radiation, only short-wave diffuse radiation received from the ground should be taken into account. Therefore, significant changes are expected to be observed in ground's energy budget, which will affect evapotranspiration, as according to Penman–Monteith equation, evapotranspiration is directly related to solar radiation.

Studies investigating the energy budget and heat fluxes within a PVP are absent. Therefore, the ground energy balance was simulated with Autodesk Ecotect Analysis software for a typical PVP in order to estimate the shading effects of fixed mounting systems in solar radiation amounts reaching the ground. Despite the fact that Autodesk Ecotect software is mainly used for building energy analysis, for the purposes of this study, it was used in order to identify the extent of decrease in incident (direct and diffuse) solar radiation approaching the ground surface of a PVP. The incident solar radiation was simulated for a hypothetical PVP of 100 kWp, which is constructed in a zero slope terrain. Fixed mounting systems were assumed, whose characteristics are similar to those used in the study of Bakos (2009). South orientation of PV arrays was assumed with an inclination of 25° in order to maintain maximum electricity production during the year, while the appropriate row-to-row PV panel spacing was estimated to 6 m according to

Macomber et al. (1981), in order to avoid shading effects of adjacent rows. More details can be found in Section A2 of Supplementary Material.

2.4. PVP installation and operation impact scenarios development

The conceptualization of PVP installation and operation impacts on the hydrologic regime revealed a large amount of parameters influenced, while the degree of influence for some parameters, such as BD, KSAT and solar radiation (SLR) is highly uncertain. For this reason, three scenarios were developed based on intensity and extent of interventions. The first scenario, referred as low impact scenario, incorporates mild interventions, both during PVP construction and operation. According to low impact scenario, earthworks are limited as there is no need for field flattening and mounting systems are installed through pile driving and consequently, there is no need for concrete footing. Therefore, no changes in field slope are anticipated, while soil compaction is expected to be recovered because of drying/wetting and freezing/thawing processes; thus, bulk density and saturated hydraulic conductivity do not change. Agricultural land is substituted with bare soil, while the mounting system type and installation height are expected to cause a low decrease (20%) in solar radiation amount reaching the ground.

The second scenario, referred as medium impact scenario, involves medium interventions during the construction and operation of a PVP. Despite the fact that there is no need for concrete footing for PV mounting, earthworks are more intensive for field flattening, resulting in soil compaction that cannot be recovered by the drying/wetting and freezing/thawing processes. So, bulk density increases by 15%, while saturated hydraulic conductivity decreases by 50%. Similar to the previous scenario, agricultural land is substituted with bare soil, but mounting system setting and installation height cause higher reduction in solar radiation (40%).

The last scenario, referred as high impact scenario, incorporates serious interventions during PVP installation, as well as, during operation. Extensive earthworks are required for field flattening and mounting systems are installed in concrete footing. The extensive earthworks resulted in substitution of agricultural land with bare soil, significant increase in bulk density (30%) and decrease in saturated hydraulic conductivity (the original values were multiplied by 0.1). Moreover, PV mounting systems are closely installed to each other and the installation height is low, resulting in significant decrease in solar radiation reaching the ground (60%). Those three scenarios were tested for 1% and 5% coverage of the study basin. Each coverage, either 1% or 5%, was spatially distributed in five different ways in the catchment site, with PVP replacing different parts of the agricultural area, as illustrated in Fig. 3.

In order to predict the long-term impacts of the above mentioned land-use change scenarios, climate scenarios for the future have to be used as climate input to the SWAT model. For the purposes of the present study, data from the Rossby Centre regional climate model, RCA3 (Samuelsson et al., 2011) were used, which were driven by the following 5 Global Circulation Models (GCMs): a) CCSM3, b) CNRM, c) ECHAM5-r3, d) HADCM3-Q0 and e) IPSL. Nikulin et al. (2011) provided technical details and an evaluation of these regional scenarios and the driving GCMs. Despite the fact that the application of Regional Climate Models (RCMs) offers a much higher spatial resolution in meteorological variables simulation when compared to GCMs, a systematic bias is typically noticed in the hydro-meteorological variables produced by the RCM. This bias originates from either the driving GCM or parameterizations in RCMs (Kotlarski et al., 2005; Kay et al., 2006; Graham et al., 2007). Therefore, the primary hydrological variables such as precipitation and temperature need to be adjusted to get realistic time series for use in local impact studies (Graham et al., 2007; Yang et al., 2010).

In this work, Distribution-Based Scaling (DBS) approach was used in order to further correct RCM precipitation and minimum and maximum temperature for impact model applications. Details about DBS can be found in Yang et al. (2010). The DBS approach aims to maximize

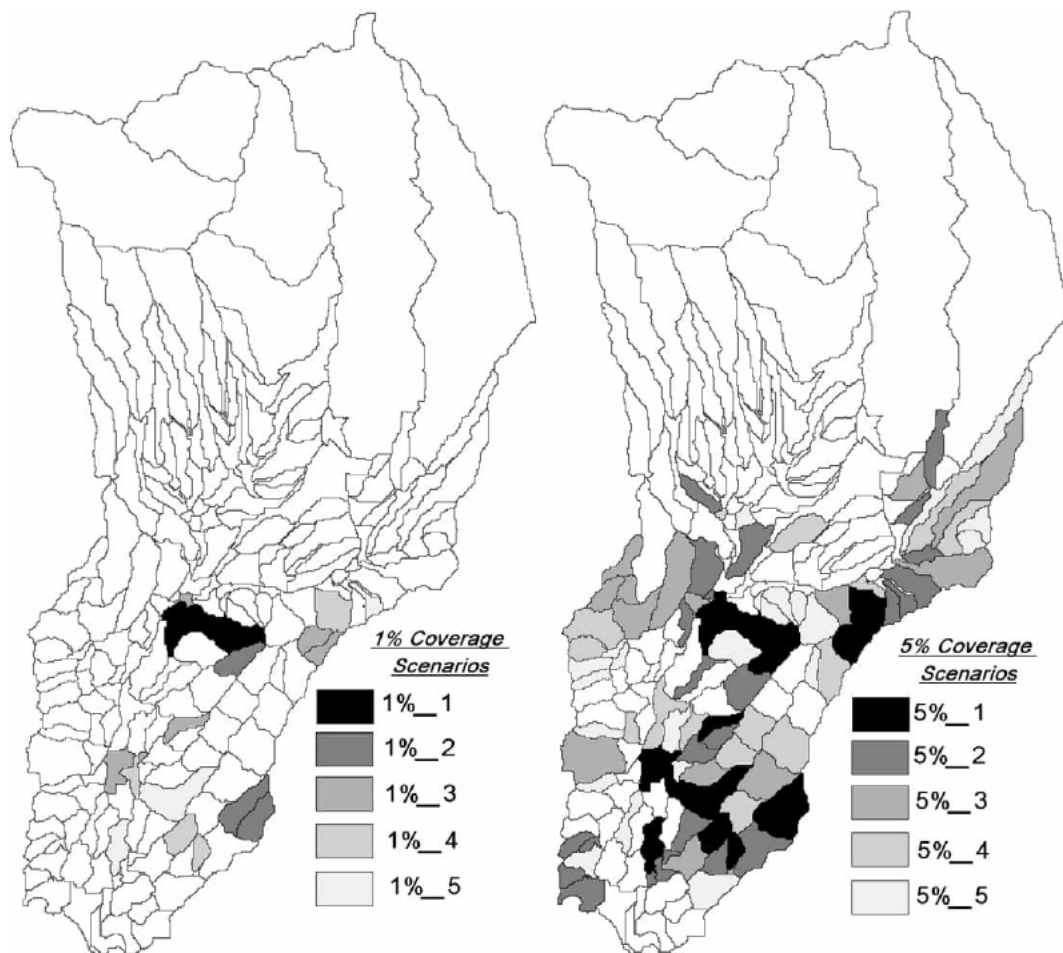


Fig. 3. Spatial distribution of scenarios with 1% and 5% coverage of agricultural land with PVPs.

utilization of RCM outputs to get more realistic input data for hydrological studies. With the DBS approach, statistical properties such as daily mean, standard deviation of temperature as well as distribution and frequency of precipitation days are much improved compared to direct RCM output. Relative humidity, solar radiation and wind speed RCM data were corrected using the widely used linear scaling approach, according to which daily RCM data are corrected by calculating a monthly correction factor for each parameter.

3. Results and discussion

3.1. Global radiation simulation results

The simulation results indicated a significant decrease of incident solar radiation reaching the ground surface of the hypothetical PVP, in relation to the incident solar radiation reaching the ground surface of the same terrain, when it is not covered by PVs. The decrease of average daily radiation in monthly basis ranges between 40% and 47.6% for panel inclination 25°, row-to-row spacing distance of 6 m (Fig. 4, line 25°, 6 m), while on the annual basis the decrease is 43.4%. Lower decreases were observed during summer months, while higher insolation decreases were observed during winter months, which depend mainly on differences of the sun path.

In order to test the influence of PV panel arrays density in insolation, the row-to-row spacing was decreased to 4 m. Moreover, the influence of PV panel inclination on insolation was tested by increasing inclination from 25° to 30° for both row-to-row spacing distances of 4 and 6 m. Thus, three more insolation simulations were performed and their results are presented in Fig. 4. Row-to-row spacing strongly influences the

insolation reaching ground surface of a PVP, as decreasing row-to-row spacing from 6 m to 4 m was found to further decrease insolation by 7.3 to 13.5% for 25° inclination and by 6.3 to 13.1% for 30° inclination. With regard to PV panel inclination, the increment from 25° to 30° presented lower insolation decrease during the whole year when row-to-row spacing is 6 m, while insolation was decreased during May and summer months when row-to-row spacing is 4 m and remained almost stable for the other months of the year. Significant changes in energy budget have also been reported in studies investigating the effects of PV panel installation on roofs. Scherba et al. (2011), concluded that adding PV panels to a black roof reduced the daily sensible heat flux by 11%, while for PV-covered white and green roofs the daily sensible heat flux reduction was up to about 50%.

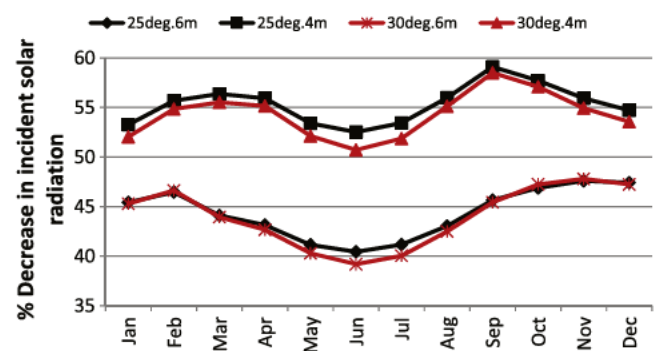


Fig. 4. Monthly decrease of ground surface incident solar radiation for several combinations of PV panels inclination and row-to-row spacing.

3.2. SWAT model calibration and validation

The statistical assessment results of SWAT model calibration and validation in Vosvozis river watershed are presented in Table 1, while the corresponding scattergrams of observed versus simulated streamflow are presented in Section A3 of Supplementary Material. Moriasi et al. (2007) indicate that SWAT model calibration for streamflow is satisfactory when $NSE > 0.50$, $RSR < 0.70$ and $-25\% < PBIAS < 25\%$. Based on this, both calibration and validation results were satisfactory, as indicated in Table 1, according to which NSE ranged from 0.86 to 0.97 for calibration and from 0.82 to 0.90 for validation, while the corresponding ranges for RSR was 0.19–0.38 for calibration and 0.04–0.387 for validation and for PBIAS is -6.12% – 3.14% for calibration and -2.68% – 9.13% for validation. The most widely used model performance assessment index (R^2) ranged between 0.87 and 0.98, thus indicating satisfactory model performance. $\lnNSE$ variation range was much lower than NSE variation range. Due to the fact that $\lnNSE$ is sensitive to low flow conditions, it is indicated that model response in low river flows observed during summer (less than $0.1 \text{ m}^3/\text{s}$) was worse than the overall model response. This does not significantly affect model performance, as those low river flows are not contributing significantly to the water budget. Except from MS1, the regression line gradient b in all monitoring stations is higher than 1, indicating that the model overestimated river flows. This overestimation (or underestimation for MS1) does not significantly affect model performance as wR^2 values in which b is incorporated, were satisfactory. As expected, calibration results are better than validation results, but validation results were also satisfactory.

3.3. Short-term land use change scenarios results

The short-term (2008–2012) effects of land use change from agricultural to PVP as described in the scenarios presented above were investigated at the basin scale, in order to assess the effects of 1% and 5% coverage of agricultural areas with PVP, and also at the sub-basin scale, in order to assess the local effects of land use change. The results for basin scale are presented in Fig. 5, while the corresponding results for sub-basin scale are presented in Fig. 6. The general trend observed both in basin and sub-basin scale is that surface runoff and percolation increase, while evapotranspiration decreases. These trends became more intense, as land use change impact increases from low to medium and high impact scenarios. Also, as impact intensity increased, a small increment in surface runoff was observed, while further decrement of evapotranspiration mostly contributed to increment of percolation. This fact indicates that after the allocation of precipitation water in surface runoff, more water is available to enter and remain in the soil profile, as evaporation decreases because of the shadowing effects.

The highest impact of land use change at the basin scale was presented for evapotranspiration, while the lowest impact was presented for percolation, both for 1% and 5% coverage. The decrement of soil permeability, as well as transpiration elimination, is a key process affecting

the major hydrologic budget constituents, as illustrated by the significant increase in surface runoff and the significant decrease in evapotranspiration, even from the low impact scenario.

The coverage of 1% basin area with PVPs does not significantly affect the hydrologic budget of the basin, as surface runoff changes ranged between 0.9 and 1.27 mm, while the corresponding ranges for evapotranspiration and percolation were -2.3 to -5.2 mm and 0.17 to 0.52 mm, respectively (Fig. 5). Significantly higher, but not important at the basin scale was the impact for 5% basin coverage with PVPs (Fig. 5). The wide range of variation of the major hydrologic constituents change illustrated both at the basin and sub-basin scale indicates that the spatial distribution of PVP coverage and the corresponding spatial variability in soil profile composition and properties are key parameters for the assessment of land use change from agricultural to PVPs. This is more obvious in the box-plots presenting the variation of change at the sub-basin scale for 5% coverage (Fig. 6). Especially for evapotranspiration and percolation, the variation range exceeded 100 mm and 300 mm, respectively.

At the sub-basin scale, the results illustrated a significant potential for surface runoff to be locally increased, even in low impact scenario, by more than 100 mm on the median, which subsequently increases the local flood risk. One could expect that surface runoff should not be increased due to the fact that the major part of the study area is cultivated with summer crops (cotton and corn), which are not active during winter, while during summer, their water needs are satisfied by irrigation. However, the fact that crop water requirements during the summer cultivation period are satisfied not only from irrigation but also from soil water implies that water in the soil profile at the end of the cultivation period is significantly decreased and has to be replenished before surface runoff is generated. For the same reason, an increasing trend was presented for percolation and subsequently for groundwater recharge (Fig. 6). Especially for the Mediterranean region, this is a favorable impact, as groundwater constitutes the most significant resource for the satisfaction of water needs and its role is important for the regional and local economies (Aureli et al., 2008). Furthermore, due to the fact that agrochemicals used for crop cultivation purposes will no longer be applied when land use changes from agricultural to PVPs, lower groundwater pollution risk is expected.

When irrigation of an agricultural field is made from groundwater, the groundwater availability in the aquifer is expected to be increased due to irrigation elimination. However, some amounts of water are required during PVP operation for PV panels washing. The water consumption for PV panel washing is highly uncertain, as it varies by site and developer and washing rates are not well documented. Based on Aspen Environmental Group studies (2011a, 2011b) and industry knowledge an estimate of $0\text{--}18.93 \times 10^{-3} \text{ m}^3/\text{MWh}$ is reported by US-DOE (2012). Even when considering the highest consumption rate of $18.93 \times 10^{-3} \text{ m}^3/\text{MWh}$, it is negligible when compared to water consumption for irrigation in semi-arid areas. For a PVP like the one presented by Bakos (2009) of 60 kWp, which is estimated to produce 74 MWh/y and covers an area ranging between 1200 and 2400 m^2 , the

Table 1

Statistical assessment results of SWAT model calibration and validation using river discharge data from the 5 monitoring stations located in Vosvozis river basin. (NSE = Nash–Sutcliffe efficiency, $\lnNSE$ = logarithmic NSE, b = regression line gradient, R^2 = coefficient of determination, wR^2 = weighted R^2 , PBIAS = percent bias, RMSE = root mean squared error, RSR = RMSE–observations standard deviation ratio).

	Calibration					Validation				
	MS1	MS2	MS3	MS4	MS5	MS1	MS2	MS3	MS4	MS5
NSE	0.86	0.90	0.94	0.96	0.97	0.86	0.90	0.83	0.88	0.82
$\lnNSE$	0.70	0.66	0.57	0.81	0.74	0.62	0.67	0.64	0.63	0.78
b	0.96	1.03	1.00	1.05	1.06	0.94	0.99	1.00	0.99	1.03
R^2	0.87	0.91	0.95	0.97	0.98	0.88	0.91	0.86	0.90	0.86
wR^2	0.83	0.89	0.95	0.93	0.92	0.83	0.90	0.86	0.89	0.83
PBIAS (%)	3.14	6.15	0.97	0.53	3.88	9.31	0.40	2.45	1.23	2.68
RMSE (m^3/s)	0.13	0.14	0.22	0.17	0.18	0.07	0.07	0.20	0.17	0.19
RSR	0.38	0.32	0.24	0.19	0.19	0.33	0.29	0.04	0.04	0.39

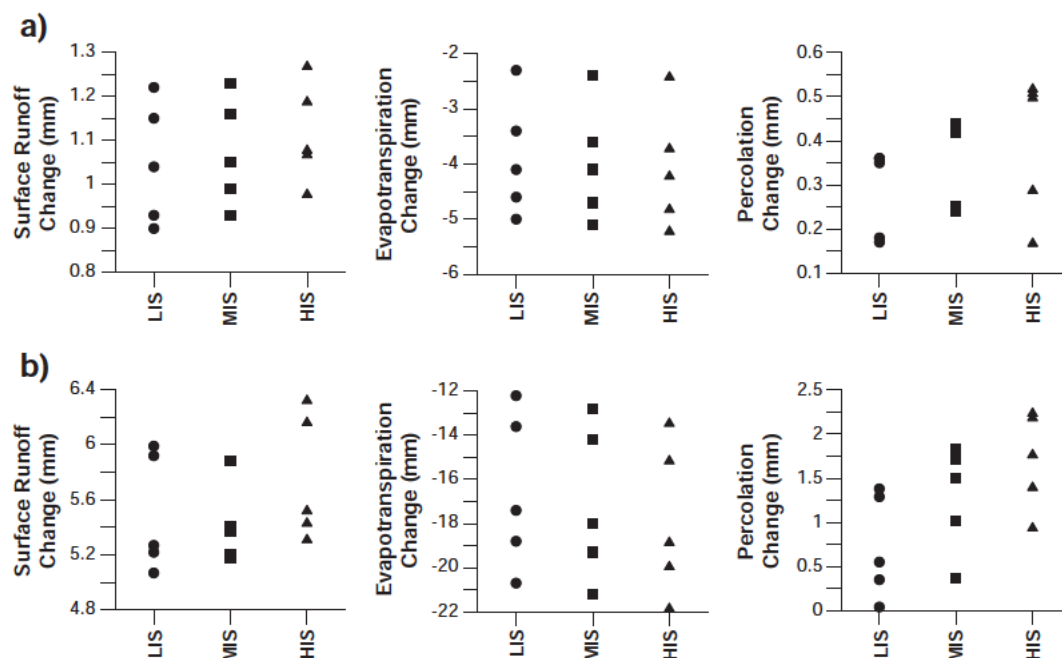


Fig. 5. Basin scale effects of land use change from agricultural to PVP on annual surface runoff, evapotranspiration and percolation for a) 1% PVP coverage and b) 5% basin coverage with PVPs for the period 2008–2012. LIS, MIS and HIS correspond to low, medium and high impact scenarios, respectively.

maximum water consumption is 1.4 m^3 or $0.58\text{--}1.16 \text{ mm}$ per year. This water amount is low compared to water needs of crops like corn and cotton, which require more than $500 \text{ mm H}_2\text{O}$ per growing season, mostly provided by irrigation in the Mediterranean region.

3.4. Long-term land use change scenarios results

Before the presentation and assessment of long-term effects of land use change from agricultural to PVP, future trends of precipitation and temperature resulted from the bias-correction process are analyzed

and compared to historical data for the period 1954–2010 from Porpi meteorological station (Fig. 1) and are representative of the lowland climate conditions. In terms of precipitation projection, except from downscaled IPSL and downscaled HADCM3 projected data which demonstrate increased average annual precipitation (5% and 13%, respectively) for the period 2011–2100 compared to period 1954–2010, all other projections indicated a decrease of average annual precipitation, ranging between 4 and 10%. IPSL projection indicated periods in which precipitation is well above the historical annual average, while there was no significant drought period signal observed. According to

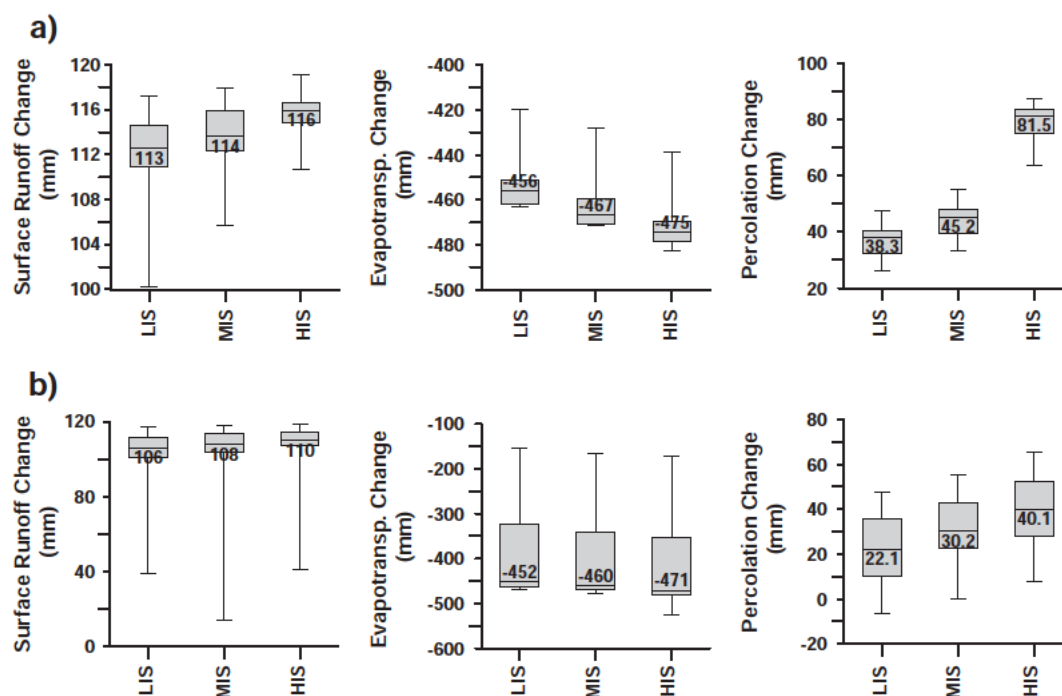


Fig. 6. Sub-basin scale effects of land use change from agricultural to PVP on annual surface runoff, evapotranspiration and percolation for a) 1% PVP coverage and b) 5% basin coverage with PVPs for the period 2008–2012. LIS, MIS and HIS correspond to low, medium and high impact scenarios, respectively.

downscaled CCSM3 data, annual precipitation demonstrated small variation for the period 2011–2070, while for the period 2070–2100, it was significantly decreased. For the same periods, annual precipitation according to downscaled HADCM3 projection was presented increasing and decreasing, respectively. Downscaled ECHAM5 projected precipitation data indicate two significant drought periods, the intensity and duration of which are similar or higher to the drought period observed during 1981–1994. In the same way, downscaled CNRM precipitation data indicated 3 significant drought periods and the strongest decreasing precipitation trend of all projections. Precipitation projection from downscaled CNRM, CCSM and ECHAM data are presented to be more realistic when compared to precipitation data variation for the period 1954–2010. Both annual maximum dry and wet spells demonstrate an increasing trend for all projections, compared to historical period. This fact indicates that after the extended dry spells, extended wet spells are expected to be observed. Also, extreme precipitation event frequency is expected to be increased. Concerning temperature, all projections demonstrated increasing trend, as illustrated in Fig. 7, and average temperature for the study area is presented to be increased from 3.5 °C (downscaled CCSM3 projection) to more than 5 °C (downscaled HADCM3 projection). In terms of solar radiation, it was found to be almost stable, while relative humidity indicated a decreasing trend which is more intense for downscaled HADCM3 projection. Finally, wind speed indicated increasing trend for all downscaled climate projections, except from IPSL, which indicated decreasing trend.

PVP coverage combinations 1_5 and 5_2 presented in Fig. 3 were chosen in order to assess the long-term effects of 1% and 5% land use change from agricultural to PVP, respectively. Those PVP coverage combinations were found to have the highest overall impact among the several PVP coverage distributions tested in short-term scenarios. At the basin scale, long-term impacts of land use change from agricultural to PVP presented in Fig. 8 are comparable to the corresponding results of short-term impacts both for 1% and 5% coverage, except from percolation, whose change was found to be negative under the low impact scenario, both for 1% and 5% coverage. In terms of surface runoff, the strongest increasing trend was observed for IPSL climate projection, thus reflecting the effects of higher precipitation simulated by this

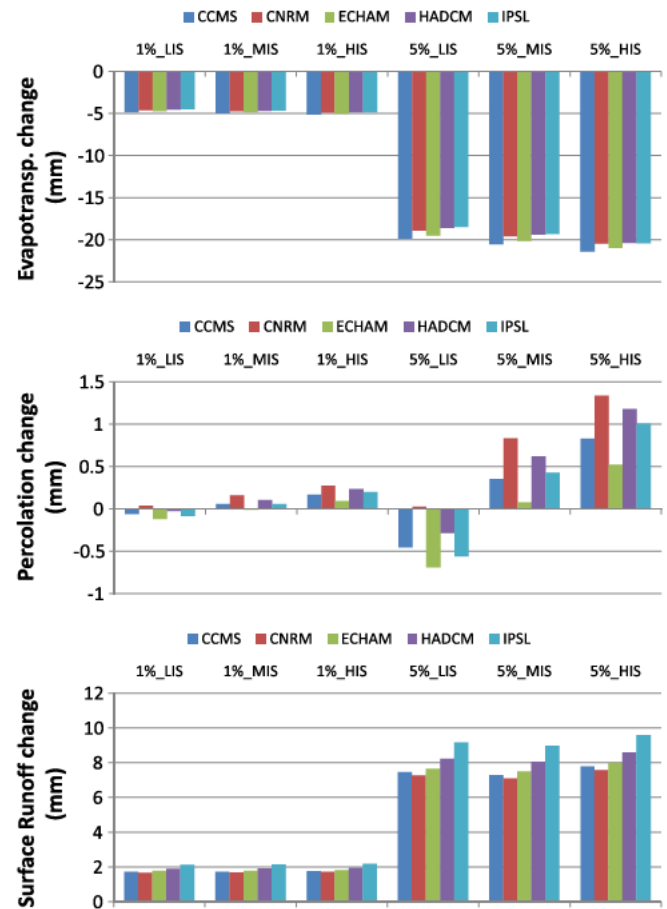


Fig. 8. Basin scale effects of land use change from agricultural to PVP on annual surface runoff, evapotranspiration and percolation for 1% and 5% PVP coverage during the period 2011–2100. LIS, MIS and HIS correspond to low, medium and high impact scenarios, respectively.

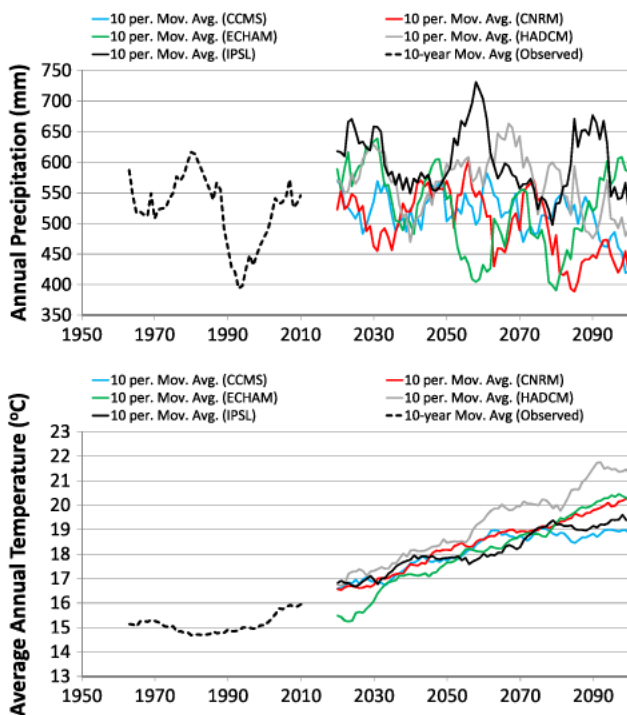


Fig. 7. 10-year moving average of historical (1954–2010) and projected (2011–2100) annual total precipitation and annual average temperature in Porpi (Fig. 1).

model, compared to the other four models. In contrast, the weakest increasing trend was observed for CNRM climate projection, which is consistent to the lowest average precipitation simulated by this model for the period 2011–2100. Concerning evapotranspiration, the strongest decreasing trend was observed for CCSM climate projection, whereas the weakest decreasing trend was observed for IPSL and HADCM climate projections. CCSM climate projection indicates the lowest temperature increase among the 5 climate projections and therefore the lowest temperature stress for the cultivated crops in the basin. This fact results in higher transpiration amounts and consequently higher evapotranspiration values simulated with CCSM climate projection data, which further produced higher change in evapotranspiration (Fig. 8), when transpiration was eliminated. Taking into account the findings of Nemet (2009), according to which PVPs may cover up to 0.39% of land by 2100 in case of high-diffusion of PVPs, the effects of PVP installation and operation are expected to be insignificant at the basin scale.

The results of long-term assessment land use change from agricultural to PVP at the sub-basin scale are illustrated in Fig. 9. The effects of temperature stress in evapotranspiration mentioned above are reflected in evapotranspiration change at the sub-basin scale, indicating higher evapotranspiration change for CCSM projection compared to evapotranspiration change simulated with the other climate projections, while the most wide inter-quartile range is presented for IPSL projection, reflecting the significantly different precipitation variation pattern compared to the other climate projections. The evapotranspiration change simulated for 1% coverage was about 15 to 20 mm higher than evapotranspiration change simulated for 5% coverage, thus indicating the importance of local soil profile properties and composition.

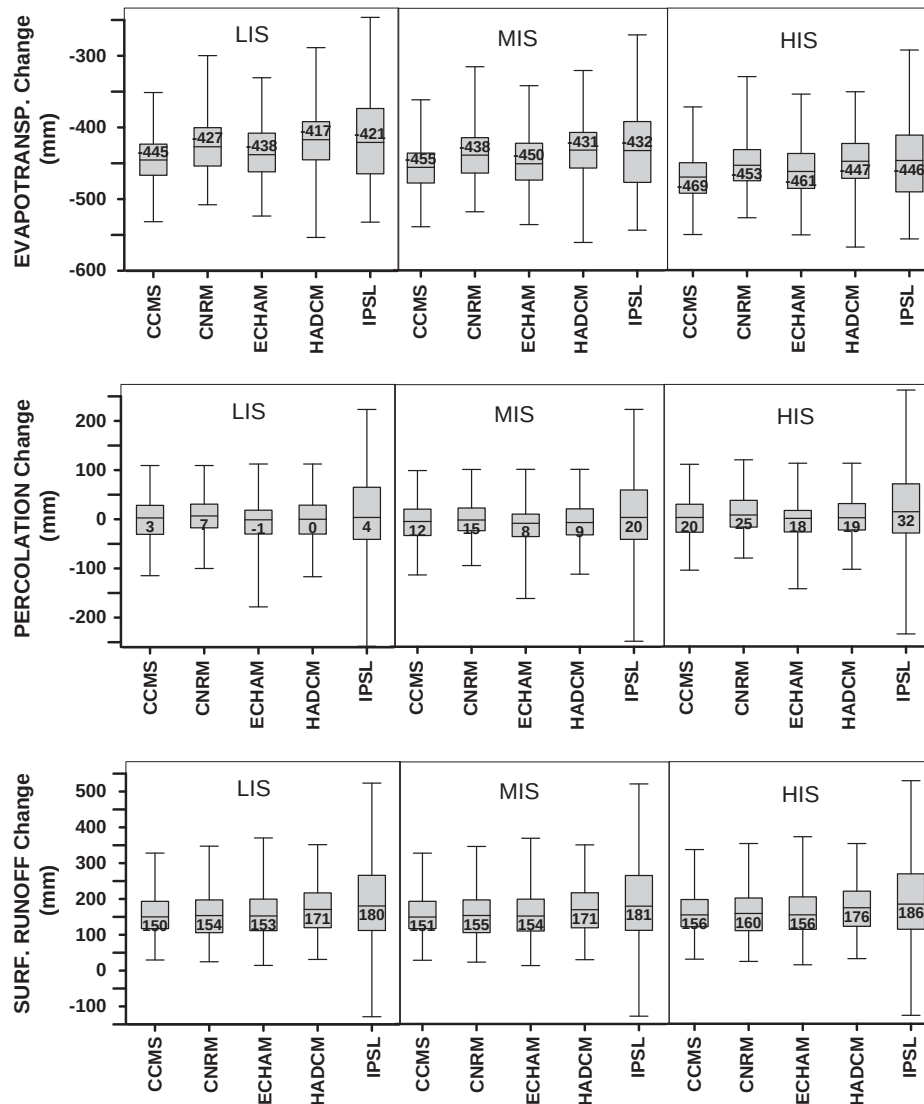


Fig. 9. Sub-basin scale effects of land use change from agricultural to PVP in annual surface runoff, evapotranspiration and percolation for 1% PVP coverage during the period 2011–2100. LIS, MIS and HIS correspond to low, medium and high impact scenarios, respectively.

Evapotranspiration was found to be further decreased from low to high impact scenarios, both for 1% and 5% coverage and all climate projections. For 5% coverage the decrement of evapotranspiration between the impact scenarios was found to be higher, demonstrating once again the effects of local conditions.

The clear increasing trend observed for percolation in the short-term assessment results for both 1% and 5% coverage presented in Fig. 6 was not observed in long-term assessment of land use change from agricultural to PVP, especially under low impact scenario. Median percolation change for ECHAM and HADCM climate projections under low impact scenario and both 1% and 5% coverage was negative, while interquartile range for all projections included both negative and positive percolation change values. The variation trend of percolation became clearer for medium and high impact scenarios, as interquartile range of percolation change included almost only positive values, but median percolation change increase was significantly smaller when compared to the corresponding results from short-term assessment. It is indicated that local soil water balance, part of which is percolation, may vary significantly according to local soil profile composition and properties and therefore resulted in high variation of percolation. Higher percolation increase was observed for IPSL climate projection, while lowest percolation increase was observed for ECHAM climate projection results.

Runoff potential presented a significant increasing trend at the sub-basin scale, as indicated by the significant increase in surface runoff for all climate projections (Figs. 9, 10). Higher runoff increase was indicated for IPSL projection, reflecting the higher projected precipitation amounts compared to the other four projections. Also, a wider interquartile range was presented for surface runoff change under this climate projection, indicating higher precipitation variability and extremes. Overall, surface runoff increase at the sub-basin level was significantly higher for the long-term assessment compared to the results of short-term assessment presented in Fig. 6. When comparing medium and high impact scenarios to low impact scenario, surface runoff was not significantly increased, indicating that further decrease of soil permeability by further increasing the corresponding CN did not significantly affect surface runoff.

4. Conclusions

Taking into account the anticipated climate change effects, the present work demonstrated that the effects of land use change from agricultural to PVPs do not significantly affect surface runoff, evapotranspiration and percolation at the basin scale, even for large coverage of the basin with PVPs. However, the effects of land use change from agricultural to

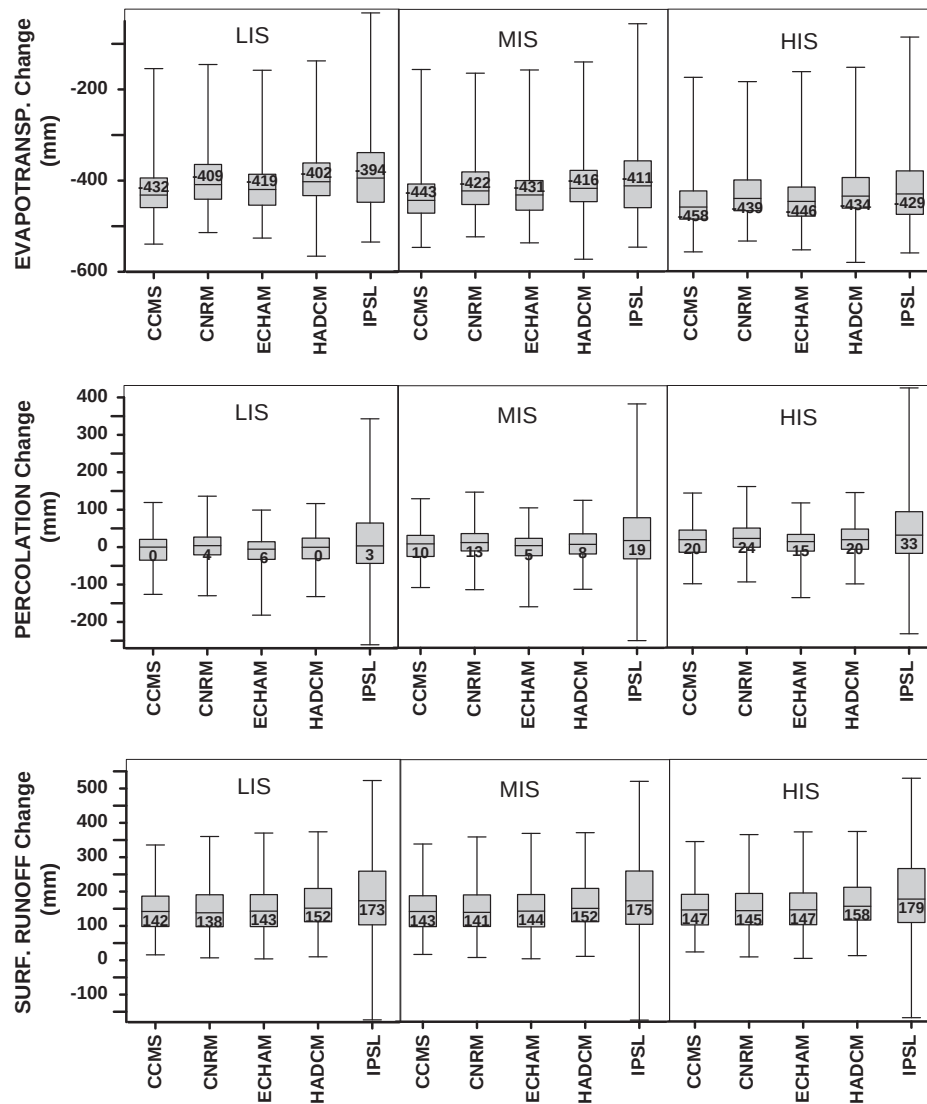


Fig. 10. Sub-basin scale effects of land use change from agricultural to PVP on annual surface runoff, evapotranspiration and percolation for 5% PVP coverage during the period 2011–2100. LIS, MIS and HIS correspond to low, medium and high impact scenarios, respectively.

PVPs were presented to be potentially significant at the local (sub-basin) scale, depending on the local hydrological conditions, which have to be addressed by the decision makers when allocating land for such uses. PVPs installation and operation may have both favorable and unfavorable impacts on the local hydrology of an area. A significant potential for surface runoff to be increased was indicated which has to be taken into account when siting PVPs. Therefore, special attention should be paid when allocating land for PVPs in flood prone areas and policy makers should be aware of the fact that increasing PVPs coverage in such areas may result in increased flood risk. On the other hand, the increasing trend of percolation and subsequently of groundwater recharge may be favorable for areas such as Mediterranean region. Moreover, taking into account the fact that PVP installation and operation minimize the use of fertilizers and pesticides involved in agricultural land uses, it may be assessed that a positive effect is to be anticipated both for surface water and groundwater quality.

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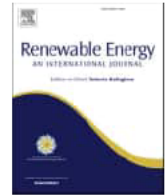
Appendix A. Supplementary information

Supplementary information to this article can be found online at <http://dx.doi.org/10.1016/j.scitotenv.2014.05.132>.

References

- Alaoui A, Lipiec J, Gerke HH. A review of the changes in the soil pore system due to soil deformation: a hydrodynamic perspective. *Soil Tillage Res* 2011(115–116):1–15. <http://dx.doi.org/10.1016/j.still.2011.06.002>.
- Apostolakis ADB1.1. Technical Report—Volume I: “Crop pattern of the year 2009 in the Prefecture of Rodopi”. Athens, Greece: Greek Biotope-Wetland Centre; 2009.
- Aspen Environmental Group. California valley solar ranch conditional use permit, and Twisselman reclamation plan and conditional use permit. Final Environmental Impact Report (DRC2008-00097, DRC2009-00004); 2011a [San Francisco, USA].
- Aspen Environmental Group. Topaz solar farm conditional use permit. Final Environmental Impact Report (DRC2008-00009); 2011b [San Francisco, USA].

- Aureli A, Ganoulis J, Margat J. Groundwater resources in the Mediterranean region: importance, uses and sharing. Paris: UNESCO International Hydrological Programme (IHP); 2008. p. 96–105.
- Bakos GC. Distributed power generation: a case study of small scale PV power plant in Greece. *Appl Energy* 2009;86:1757–66. <http://dx.doi.org/10.1016/j.apenergy.2008.12.021>.
- Cho J, Lowrance RR, Bosch DD, Strickland TC, Her Y, Vellidis G. Effect of watershed subdivision and filter width on SWAT simulation of a coastal plain watershed. *J Am Water Resour Assoc* 2010;46(3):586–602. <http://dx.doi.org/10.1111/j.1752-1688.2010.00436.x>.
- De Paola F, Giugni M, Topa MA, Buccignani E. Intensity–duration–frequency (IDF) rainfall curves, for data series and climate projection in African cities. *SpringerPlus* 2014; 3:133. <http://dx.doi.org/10.1186/2193-1801-3-133>.
- Defourny P, Hecquet G, Philippart T. Digital terrain modeling: accuracy assessment and hydrological simulation sensitivity. In: Lowell K, Jatón A, editors. *Spatial accuracy assessment: land information uncertainty in natural resources*. Michigan: Ann Arbor Press; 1999. p. 61–70.
- Erol A, Randhir TO. Climatic change impacts on the ecohydrology of Mediterranean watersheds. *Clim Chang* 2012;114:319–41. <http://dx.doi.org/10.1007/s10584-012-0406-8>.
- Gemitzi A, Stefanopoulos K. Evaluation of the effects of climate and man intervention on ground waters and their dependent ecosystems using time series analysis. *J Hydrol* 2011;403(1–2):130–40. <http://dx.doi.org/10.1016/j.jhydrol.2011.04.002>.
- Gemitzi A, Stefanopoulos K, Schmidt M, Richnow HH. Seawater intrusion into groundwater aquifer through a coastal lake—complex interaction characterised by water isotopes ^2H and ^{18}O . *Isot Environ Health Stud* 2013;50(1):74–87. <http://dx.doi.org/10.1080/10256016.2013.823960>.
- Graham LP, Hagemann S, Jaun S, Beniston M. On interpreting hydrological change from regional climate models. *Clim Chang* 2007;81:97–122. <http://dx.doi.org/10.1007/s10584-006-9217-0>.
- Green WH, Ampt GA. Studies on soil physics, 1. The flow of air and water through soils. *J Agric Sci* 1911;4:11–24. <http://dx.doi.org/10.1017/S0021859600001441>.
- Hakansson I. Machinery-induced compaction of arable soils. Incidence—consequences—counter-measures. Sweden: Department of Soil Sciences, Division of Soil Management, Swedish University of Agricultural Sciences; 2005.
- IPCC. The physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL, editors. *Climate change 2007: the physical science basis*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2007. p. 996.
- Kay AL, Jones RG, Reynard NS. RCM rainfall for UK flood frequency estimation. I. Method and validation. *J Hydro* 2006;318(1–4):151–62.
- Kim J, Choi J, Choi C, Park S. Impacts of changes in climate and land use/land cover under IPCC RCP scenarios on streamflow in the Hoeya River Basin, Korea. *Sci Total Environ* 2013;452–453:181–95. <http://dx.doi.org/10.1016/j.scitotenv.2013.02.005>.
- Kotlarski S, Block A, Böhm U, Jacob D, Keuler K, Knoche R, et al. Regional climate model simulations as input for hydrological applications: evaluation of uncertainties. *Adv Geosci* 2005;5:119–25. <http://dx.doi.org/10.5194/adgeo-5-119-2005>.
- Krause P, Boyle DP, Båse F. Comparison of different efficiency criteria for hydrological model assessment. *Adv Geosci* 2005;5:89–97. <http://dx.doi.org/10.5194/adgeo-5-89-2005>.
- Legates DR, McCabe GJ. Evaluating the use of “goodness-of-fit” measures in hydrologic and hydroclimatic model validation. *Water Resour Res* 1999;35(1):233–41. <http://dx.doi.org/10.1029/1998WR900018>.
- Luo Y, Ficklin D, Liu X, Zhang M. Assessment of climate change impacts on hydrology and water quality with a watershed modeling approach. *Sci Total Environ* 2013;450–451: 72–82. <http://dx.doi.org/10.1016/j.scitotenv.2013.02.004>.
- Macomber HL, Ruzek JB, Costello FA. Photovoltaic stand-alone systems. DOE/NASA/0195–1; 1981.
- Misopolinos N. The soil map of Eastern Macedonia-Thrace Region, Greece: Aristotle University of Thessaloniki, School of Agriculture, Lab of Applied Soil Sciences; 2009.
- Monteith JL. *Evaporation and Environment*, 19th Symposia of the Society for Experimental Biology. Cambridge: University Press; 1965 [p. 205–234].
- Moriassi DN, Arnold JG, Van Liew MW, Bingner RL, Harmel RD, Veith TL, et al. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans ASABE* 2007;50(3):885–900. <http://dx.doi.org/10.13031/2013.23153>.
- Nash JE, Sutcliffe JV. River flow forecasting through conceptual models. Part I. A discussion of principles. *J Hydrol* 1970;10(3):282–90. [http://dx.doi.org/10.1016/0022-1694\(70\)90255-6](http://dx.doi.org/10.1016/0022-1694(70)90255-6).
- Neitsch SL, Arnold JG, Kiniry JR, Williams JR. *Soil and water assessment tool, theoretical documentation*. Version 2009. Texas Water Resources Institute Technical Report No. 406. Texas, USA: Texas A&M University System College Station; 2011.
- Nemet GF. Net radiative forcing from widespread deployment of photovoltaics. *Environ Sci Technol* 2009;43(6):2173–8. <http://dx.doi.org/10.1021/es801747c>.
- Nikulin G, Kjellström E, Hansson U, Jones C, Strandberg G, Ullerstig A. Evaluation and future projections of temperature, precipitation and wind extremes over Europe in an ensemble of regional climate simulations. *Tellus A* 2011;63(1):41–55. <http://dx.doi.org/10.1111/j.1600-0870.2010.00466.x>.
- Official Government Gazette of Greece. Law 3851, Volume 85, Issue A, 1753 – 1780, 4/6/2010.
- Ozgoz E, Oztekin T, Günel H. Assessment of wheel traffic effect on soil compaction using a soil core sampler. *N Z J Agric Res* 2006;49(3):299–306. <http://dx.doi.org/10.1080/00288233.2006.9513720>.
- Pehnt M. Dynamic life cycle assessment (LCA) of renewable energy technologies. *Renew Energy* 2006;31(1):55–71. <http://dx.doi.org/10.1016/j.renene.2005.03.002>.
- Peng T, Wang SJ. Effects of land use, land cover and rainfall regimes on the surface runoff and soil loss on karst slopes in southwest China. *Catena* 2012;90:53–62. <http://dx.doi.org/10.1016/j.catena.2011.11.001>.
- Priestley CHB, Taylor RJ. On the assessment of surface heat flux and evaporation using large-scale parameters. *Mon Weather Rev* 1972;100:81–92. [http://dx.doi.org/10.1175/1520-0493\(1972\)100<0081:OTAOSH>2.3.CO;2](http://dx.doi.org/10.1175/1520-0493(1972)100<0081:OTAOSH>2.3.CO;2).
- Samuelsson P, Jones CG, Willén U, Ullerstig A, Gollvik S, Hansson U, et al. The Rossby Centre Regional Climate model RCA3: model description and performance. *Tellus A* 2011;63(1):4–23. <http://dx.doi.org/10.1111/j.1600-0870.2010.00478.x>.
- Scherba A, Sailor DJ, Rosenstiel TN, Wamser CC. Modeling impacts of roof reflectivity, integrated photovoltaic panels and green roof systems on sensible heat flux into the urban environment. *Build Environ* 2011;46(12):2542–51. <http://dx.doi.org/10.1016/j.buildenv.2011.06.012>.
- Turney D, Fthenakis V. Environmental impacts from the installation and operation of large-scale solar power plants. *Renew Sust Energ* 2011;15(6):3261–70. <http://dx.doi.org/10.1016/j.rser.2011.04.023>.
- USDA-SCS. *National engineering handbook. Hydrology section 4, chap. 4–10*. Washington, DC, USA: US Dept. of Agriculture, Soil Conservation Service; 1972.
- US-DOE. *SunShot vision study. Chapter 7: solar power environmental impacts and siting challenges*. Washington D.C., USA: United States Department of Energy; 2012.
- Wu Y, Liu S, Gallant AL. Predicting impacts of increased CO₂ and climate change on the water cycle and water quality in the semiarid James River Basin of the Midwestern USA. *Sci Total Environ* 2012;430:150–60. <http://dx.doi.org/10.1016/j.scitotenv.2012.04.058>.
- Yang W, Andréasson J, Graham PL, Olsson J, Rosberg J, Wetterhall F. Distribution-based scaling to improve usability of regional climate model projections for hydrological climate change impacts studies. *Hydrol Res* 2010;41:211–29. <http://dx.doi.org/10.2166/nh.2010.004>.



Observed impacts of utility-scale photovoltaic plant on local air temperature and energy partitioning in the barren areas

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ABSTRACT

Rapid progress of solar photovoltaic (PV) technology has caused growing interest in understanding interactions between large scale PV plants and near-surface atmosphere. However few attempts have been made to quantify the impact of PV modules on surface radiative forcing and energy partitioning process. Here, this issue is explored experimentally and analytically in the two adjacent sites located at the PV plant and the natural barren field respectively in Wujiaqu in Xinjiang of China. The results showed that the physical effect of PV panels is not symmetrical in the whole day. During the daytime, compared with the reference site, net shortwave radiative forcing increases 8%, a warming effect on the integrated underlying surface (0.1 K) and a cooling effect (~ 2.6 K) on the ground surface were found in the PV plant. 9.2% of the net radiation (NR) was converted into electric energy (PE), sensible heat flux (H) increased by 30.6% hence resulted in the convection heating effects of 0.64 K and 0.32 K on the near-surface air temperature at the height of 2 m and 10 m respectively, while latent heat flux (LE) and ground surface heat flux (GS) decreased by 49% and 3% respectively related to the reference site. At night, PV panels produce a cooling effect of -0.2 K and -2.3 K on the ground and integrated underlying surface respectively, and less GS is released in the PV plant which contribute to the cooling effects of -0.24 K and -0.08 K on the air temperature at the height of 2 m and 10 m respectively related to the reference site. In the whole day, in the PV plant, H increased by 27.6%, LE and GS decreased by 47.4% and 6.7% respectively, air temperature increased by 0.16 K and 0.1 K at 2 m and 10 m respectively.

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1. Introduction

Excessive consumption of traditional energy has not only accelerated the reduction of fossil fuel reserves and increased greenhouse gas emissions, but also led to global climate change and ecological imbalance, hindering sustainable development [1,2]. The development of environmentally friendly resources such as renewable energy is considered an effective way to alleviate this problem. Solar energy is considered to be the most promising renewable energy and is expected to play a central role in the global energy transition due to its ubiquitous and predictable nature [3–5]. Further, technological advancements, cost reduction, and government policy support [6,7] have promoted the unprecedented

development of photovoltaics (PV). In the past ten years, the average annual compound growth rate of the global PV industry has exceeded 35% [5]. At the end of 2019, the global cumulative PV installed capacity exceeded 600 GW [8] and is expected to reach 8519 GW in 2050 [9].

Although PV generation has many advantages, including low emission of CO₂ and pollutants, reduce traditional energy consumption and reclaim degraded land [10–12], large-scale deployment of solar PV may have negative impacts on ecological functions including soil erosion and compaction, environment degradation [13–15]. In particular, space-intensive solar PV infrastructure require a large amount of land [13,16]. On the one hand, darker-colored PV panels change the radiative forcing on Earth's surface by reducing the surface albedo [17,18], and alter the heat transfer in the exchange of energy and water fluxes between the surface and atmosphere. Changing in radiation and heat transfer would further regulate the partitioning of available energy into

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sensible, latent and ground heat fluxes, and ultimately reflected in the indirect impact on the local microclimate [19–23]. On the other hand, large-scale solar PV infrastructure in desert areas usually increase surface roughness [24], which may increase the efficiency of sensible heat transfer from surface to atmosphere [25,26]. Giving the development rate of PV industry and the changes to the surface properties, resolving the impacts of large-scale PV panels on the regional and local climate is essential.

In the previous studies, most simulations have shown that BIPV (Building Integrated Photovoltaic) can reduce the urban heat island effect, for instance, a cooling effect of 0.01–0.15 K was found in Los Angeles, USA when the conversion efficiency of PV panel is more than 25% [27]; some simulations in different cities also showed that BIPV produce a cooling effect of 0.2–2.1 K during the day and of 0.3–1 K at night [28–31]. Moreover, PV panels incorporated in urban pavements are proposed by researchers and can reduce the pavement surface temperature by 5–13 K and the ambient temperature by nearly 1 K [32,33]. However, due to the complexity of the underlying surface, the albedo disturbance signal caused by the PV panel is also different [34]. The simulation in the desert found that the average temperature of the PV area increased by 0.4–1.9 K [35,36], and some field observations for utility-scale PV plants in the barren areas also showed that PV modules increase the ambient air temperature by 2–4 K [37–39]. A recent study using MODIS (Moderate Resolution Imaging Spectroradiometer) data showed that the cooling effect of PV plants on the ground surface temperature is 0.81 K and 0.24 K during the day and night respectively [40]. Observed surface parameters such as albedo of the PV plant in Gonghe of China were introduced into the climate model for representing the PV array, and the simulated temperature decreased by 1 K and 2 K for January and July respectively [41]. For the energy partitioning in the PV plant in desert area, the ground surface heat flux decreased while the sensible heat flux increased, resulting in higher temperature at 1.5 m during the day [42]. Moreover, PV systems may generate a feedback of increased precipitation [43,44] and soil water content, biomass, and plant water utilization rate by reducing evaporation [45–47].

While the impact of PV infrastructure on climatic factors such as air temperature was quantified in the above-mentioned studies, the external forcing and internal feedback of PV system on local climate system are still unclear. In cases where natural land is used for solar projects, the net shortwave radiation as external forcing and energy partitioning process as internal feedback, may likely be changed. The primary goal of this paper is to investigate the effect of PV arrays on the local microclimate principally in terms of air temperature, and to further advance the understanding of the changes induced by PV arrays in the radiative forcing, surface longwave radiation, and energy balance process as reasons of differences in the microclimate. Given this, we compared and analyzed the land surface process observations including wind and air temperature, radiation, and turbulence measurements between a utility-scale PV plant and an adjacent reference site in Wujiaqu barren area in Xinjiang of China during the summer and autumn of 2020. Meanwhile, the present study seeks to explore the nature, dynamics and thermodynamics of atmosphere driven by air-panels-ground interaction and its potential for wind speed and air temperature and provide useful features for characterizing PV panels in numeric models.

2. Experiments and methods

2.1. Site description

This study took place at a utility-scale PV plant in the Wujiaqu barren area in Xinjiang. Wujiaqu is located at the northern foot of

the Tianshan mountains and southeast of the Junggar Basin, a typical continental temperate arid climate. It is hot and dry with the highest temperature above 40 °C in summer, and cold and long with the lowest temperature of 40 °C below zero in winter. The area has sufficient sunlight and abundant radiation resources with the annual total solar radiation of about 268.3 kJ/cm², and the annual accumulated sunshine hours of 2800–3000 h, and the annual average precipitation and evaporation are about 150 mm and 2000 mm, respectively.

The PV plant is of a distance of 1120 m from north to south and 1030 m from east to west, covering an area of about 1.15 km², and with an installed capacity of about 70 MW. The orientation of PV array is south with the tilt angle of 37°, the row spacing of PV array is 7.5 m, and the top and bottom edges of PV panels are 2.5 m and 0.5 m above the ground respectively. The panel material is polycrystalline silicon, and the maximum power is 250 W.

The two adjacent observation systems were setup in and out of the PV plant, respectively. The site in the PV plant is located at 44.406°N and 87.656°E, with a surface elevation of 439 m above sea level. The reference site (44.409°N, 87.667°E, 437 m alt) is located 910 m northeast of the PV site (Fig. 1). Additionally, the distances between the reference site and the northeast corner and the southeast corner of the PV array are about 400 m and 780 m respectively, and the horizontal distance between the reference site and the east edge of the PV array is about 280 m. The surface of the two sites is Gobi with sparse vegetation, and the soil type is sandy soil with good air permeability, but difficult to maintain water and has poor nutrients.

2.2. Study design

The observation systems in the PV plant and the reference site contained two meteorological observation towers of 11 m high respectively, and the observation items mainly include mean field, radiation fluxes, and turbulence field as shown in Fig. 2. The mean field observation system, mainly composed of three layers of wind sensors (Gill WindSonic) that have precisions of ±2% for wind speed and of ±3° for wind direction, air temperature and humidity sensors (Campbell HC2S3) with an accuracy of ±1°C, and pressure sensors (Vaisla CS106) with an accuracy of less than ±1.5 hPa, were installed at the height of 2, 4, 10 m on the towers in the PV plant and the reference site respectively.

The radiometers are all from Holland with type of Kipp&Zonen CNR4 net radiometer whose non-linear error is within 1%, and radiation observations include total solar radiation (DSR), reflected radiation (USR), sky long-wave radiation (DLR) and ground long-wave radiation (ULR). Two layers of radiometers were installed at the height of 1.5 m and 10 m in the PV plant and the reference site, respectively. With the field angle of downward sensors of 150°, the diameters for field of view of the downward radiation sensors at the height of 10 m above the PV panels and 1.5 m below the PV panels are 75.6 m and 11.2 m, respectively. Because of the observation tower in the PV plant is located between two rows of PV panels, the observation at the height of 10 m can reasonably characterize the PV integrated underlying surface (composed of PV panels of about 31% and exposed ground surface of about 69%), while the observation at the height of 1.5 m represents the radiation balance characteristics of the ground (consisting of the shaded ground surface of about 26% and exposed ground surface of about 74%). Before the formal observation, a parallel comparison of the radiometers was performed on the flat underlying surface at the height of 10 m, to ensure the consistency of results.

The ultrasonic open-path eddy covariance (EC) systems used for turbulence observation, were installed at the heights of 5.5 m level in the PV plant and 3 m level in the reference site, respectively. The

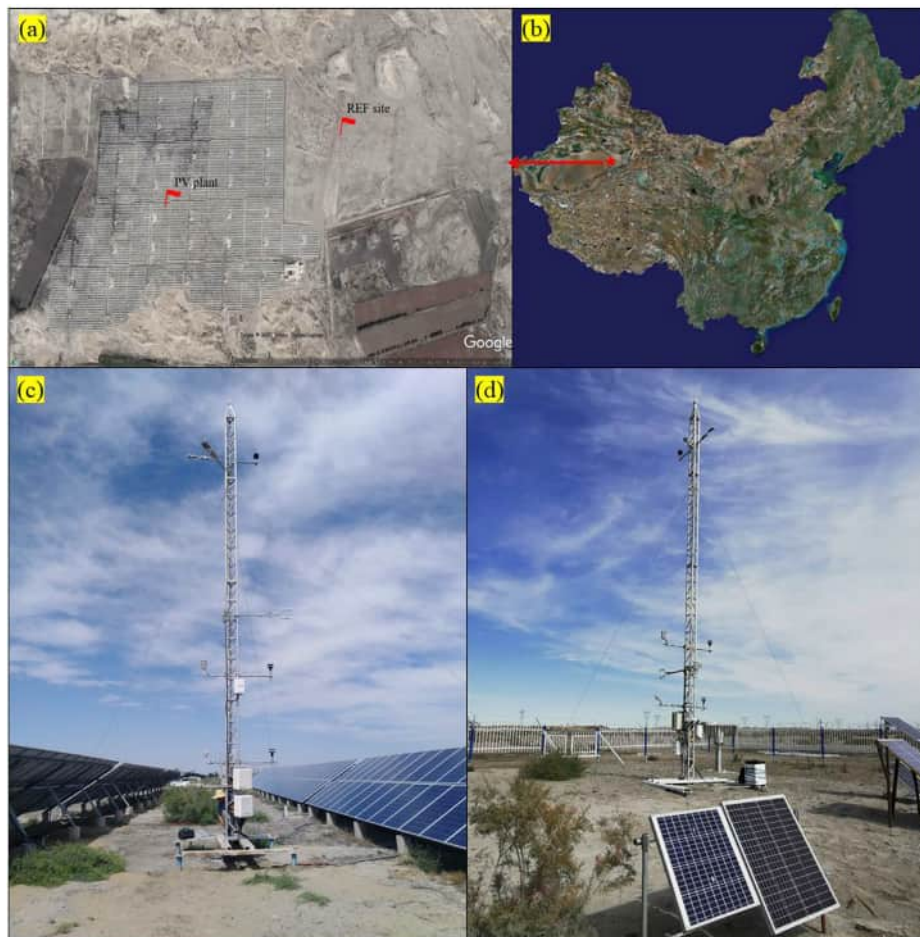


Fig. 1. The map shows the spatial distribution of the PV site and the reference site as extracted from Google Earth by the end of 2018(a), location of the utility-scale PV plant in Wujiaqu barren area in Xinjiang, northwest of China (b); Photos of the monitoring sites for the PV plant (c) and the reference site (d).

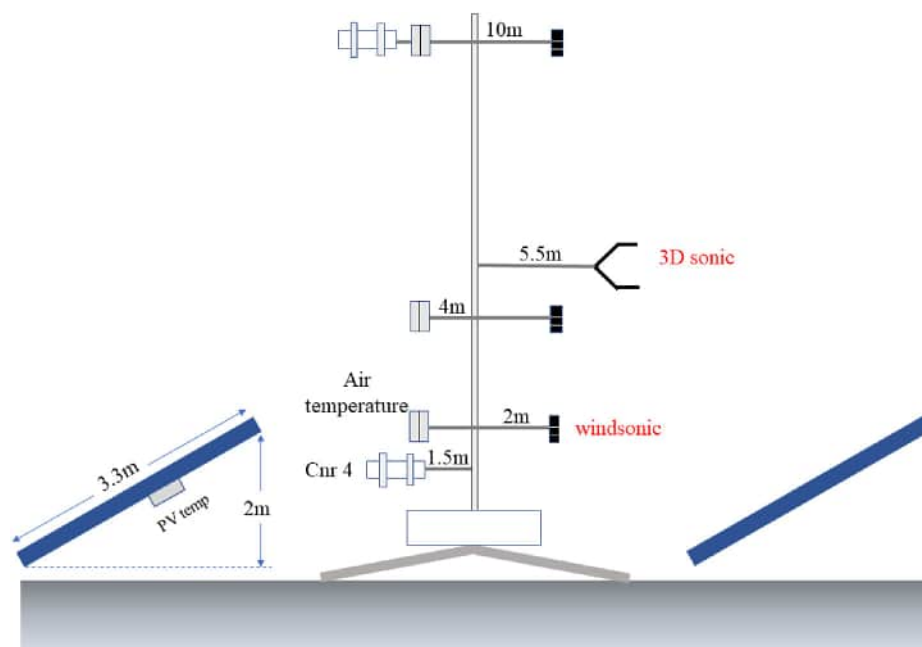


Fig. 2. Schematic diagram of instrumentation in the PV plant, it should be noted that the CNR4 net radiometer at the height of 1.5 m and 10 m characterize the radiation balance of the ground surface and the integrated underlying surface of the PV plant.

equipment of EC system is IRGASON-IC-BB by Campbell, USA. It combines an open-circuit infrared gas analyzer and a three-dimensional ultrasonic anemometer, was designed to measure the vertical flux of heat and water vapor in the atmosphere and various pulsations. The drift error is less than ± 8 cm/s for wind speed.

The collection and sampling frequency of mean field and radiation data is 10 min, and the bandwidth frequency of EC system is 10 Hz. The data used in this paper include 56 days from summer (20 days from 25 June to 14 July, 36 days from 23 July to 27 August 2020), and 90 days from autumn (from Sep 1 to 29 Nov 2020) from centralized observations. The time system used in this paper is Beijing time.

2.3. Data process

To account for accuracy of results, the data quality control was performed before analyzing the observation data. We removed outliers data that were obviously unreasonable, caused by instrument failure, and bad weather. The short-wave radiation at night was set to zero according to the solar altitude angle. EC data of the original observations were processed by the EasyFlux online processing program, and the main correction procedures implemented into the program are listed below: filter 10 Hz data using sonic and gas analyzer diagnostic algorithms, coordinate rotation using double rotation and planar fit method [48], frequency response corrections [49], ultrasonic virtual temperature correction [50] and WPL correction (proposed by E. K. Webb, G. I. Pearman and R. Leuning) for air density changes [51]. Fluxes were calculated by taking a block average of the covariance and other related variables over a 30-min.

2.4. Main methods

The surface temperature can be calculated from the absorbed and emitted long wave radiation by the surface [38,39]:

$$T_0 = \left[\frac{ULR - (1 - \varepsilon_g) DLR}{\varepsilon_g \sigma} \right]^{\frac{1}{4}} \quad (1)$$

where ULR and DLR are the long wave radiation emitted and absorbed by the surface ($W \cdot m^{-2}$), ε_g is the specific emissivity of the earth's surface, in this paper 0.95 is taken for the ground surface of the sand Gobi, and 0.89 is taken for the integrated underlying surface of the PV plant, which is calculated by the emissivity of the bared ground (0.95) and the emissivity of the upper surface of PV panels (0.83) [42] according to the proportion of area between the upper surface of PV panels and the bared ground. σ is Stefan-Boltzmann constant with the value of $5.67 \times 10^{-8} W \cdot m^{-2} \cdot K^{-4}$. In this paper, the temperature of ground surface and the integrated underlying surface for the PV plant were calculated by using the long wave radiation at the height of 1.5 and 10 m respectively.

The net radiation (NR) is the consequence of a balance between the amount of downward shortwave radiation (DSR) absorbed by Earth's surface and atmosphere and the amount of infrared long-wave radiation emitted by the system. The former related to the reflected shortwave radiation (USR) governed by the albedo of the surface and the latter concerns with the long wave radiation absorbed and emitted by the surface depending on the temperature and the emissivity of the surface. After processing the shortwave radiation at night as mentioned above, the NR can be calculated as:

$$R_n = DSR - USR + DLR - ULR \quad (2)$$

The energy budget of the underlying surface is an important part of near-surface observation research. In the PV plant, part of the absorbed solar radiation is converted into electrical energy (PE), and the remaining energy is distributed as sensible heat (H), latent heat (LE) and soil heat flux (GS), and its energy balance can be described as follows:

$$R_n - Pe = H + LE + GS \quad (3)$$

The turbulent fluxes are calculated by the following formulae:

$$H = \rho_a C_p \overline{w'T'} \quad (4)$$

$$LE = \lambda \rho_a \overline{w'q'} \quad (5)$$

where ρ_a is air density, C_p is the specific heat at constant pressure ($1.005 \text{ kJ/kg} \cdot K$), $\overline{w'T'}$ is the covariance between vertical turbulent wind components and temperature fluctuations. λ is the latent heat of water evaporation related to temperature and generally takes 2.45 kJ/kg , $\overline{w'q'}$ is the covariance between vertical turbulent wind components and humidity fluctuations.

2.5. Footprint analysis

Flux footprint is usually used to evaluate the contribution of upwind region of EC system, and is an important step to study the spatial representativeness of flux measurement [52]. In this study, we calculated flux source range of the PV site and the reference site with the flux footprint analysis models proposed by Kljun et al. [53] and Kormann and Meixner [54], for evaluating the representativeness of the measured physical parameters. Fig. 3 shows the aggregate of distance between upwind location of sources that contributes mostly to the measured fluxes and the observation sites of EC system in the PV plant and the reference site. The maximum weights of the measured flux source in the PV plant and the reference site are mainly concentrated within 300 m and 200 m of the observation sites, respectively. While satellite image shows that the minimum distances between the observation site in the PV plant and the eastern and western edges of PV array are about 700 m and 330 m respectively, and the minimum distances between the observation site in the PV plant and the northern and southern edges of PV array are about 490 m and 630 m respectively. Hence the observations are capable to characterize the turbulent fields of the PV underlying surface and the natural barren area.

3. Results and discussion

3.1. The attenuation and redirection effect on wind and heating effect on near-surface air

The prevailing wind is west and southwest wind (according to the direction of wind blowing) during the observation (Fig. 4). In the PV plant, the wind speed and direction in the PV site all have significant changes at different heights, the frequency of westerly wind increased from 21.6% at 10 m to 34.6% at 2 m, and the easterly wind increased from 18.3% at 10 m to 28.3% at 2 m, while winds with a southerly component decreased from 37.8% at 10 m to 31% at 2 m and winds having a northerly component decreased from 22.4% at 10 m to 5.9% at 2 m, the wind speed below 2 m/s increased from 39.4% at 10 m to 78% at 2 m. The second row of Fig. 4 indicates the wind speed also attenuated with the height decreases in the reference site, however the degree of attenuation is lower than that in the PV plant, and the wind directions at different heights remain nearly constant.

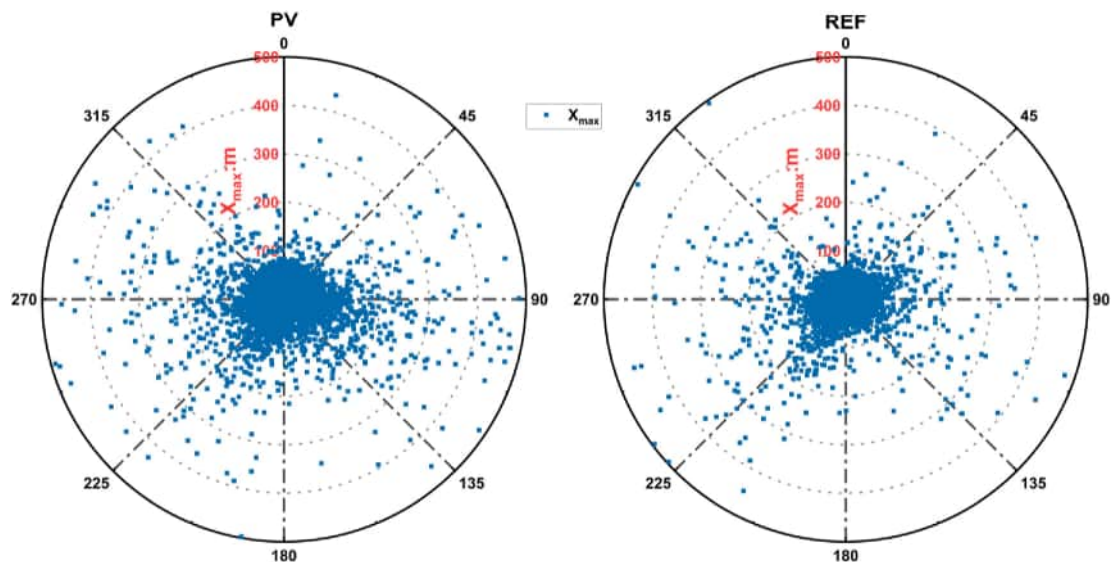


Fig. 3. Schematic diagram of distance aggregate between upwind location of sources that contributes most to the measured fluxes and the observation sites of EC system in the PV plant and the reference site, X_{max} represent the location of sources that contributes most to the measured fluxes, and the center represents the observation site.

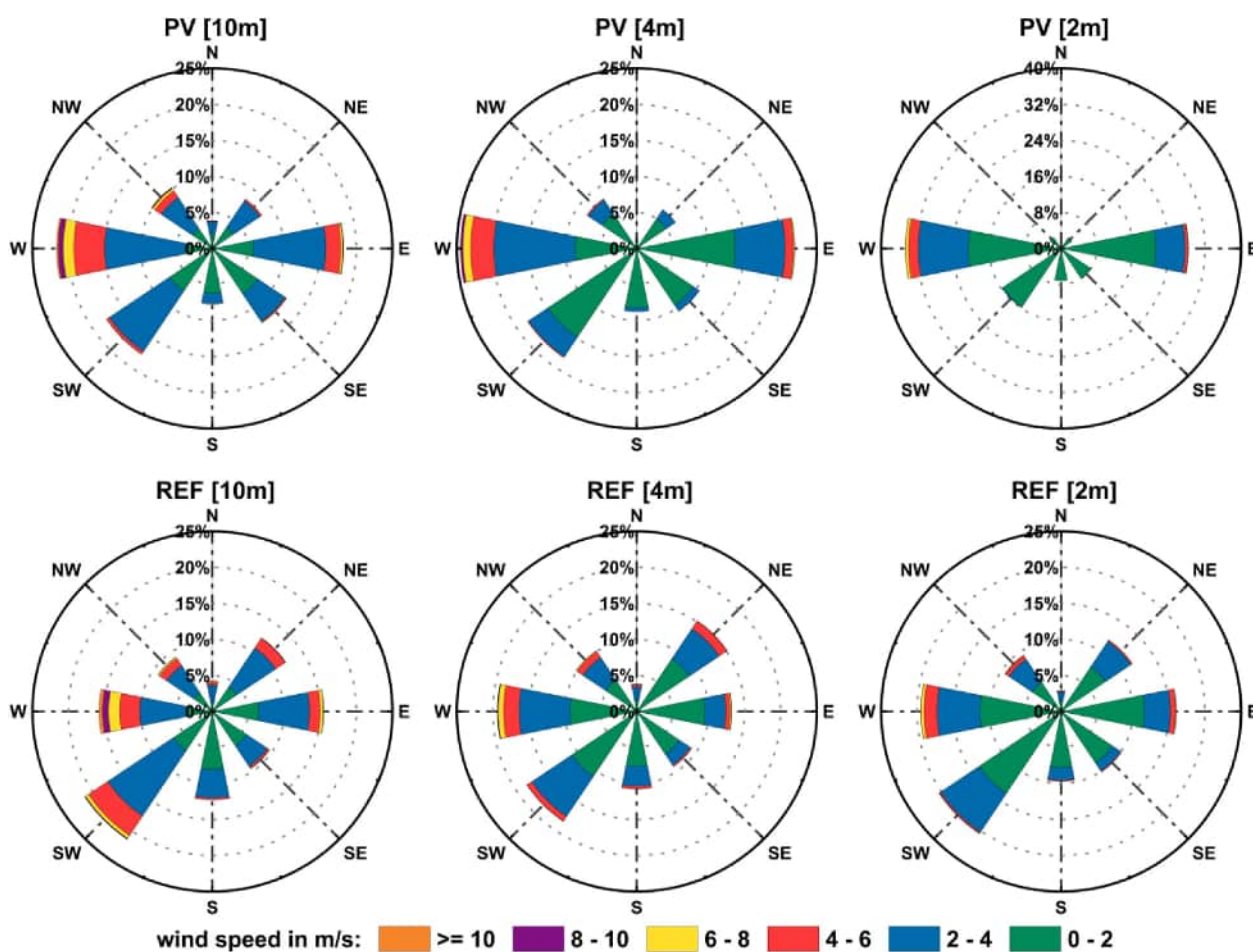


Fig. 4. Wind roses at different heights for the PV site and REF site during observational period from 25 Jun-29 Nov 2020. The columns show wind roses for the height of (left) 10 m, (center) 4 m, (right) 2 m. These data of wind direction and wind speed were collected at a frequency of 10 min.

The difference in the distribution of wind speed and direction with height in the PV plant is on the one hand related to the prevailing wind during the observation, and on the other hand related to the installation height and orientation of the PV panels. The top edge of PV panels is about 2.5 m above ground-level and placed facing south, impeding the airflow in the north-south direction. When the airflow reaches at the height of 2 m, the airflow flowing through the panel is affected by the retardation, resulting in the larger decrease of the wind speed and airflow separation from south and north to west and east.

Fig. 5(a) shows the average daily variation of 2-m air temperature in the PV plant and the reference site. During the daytime from 9:00 to 19:00, the air temperature in the PV plant is higher than the reference site, indicating that the PV panels generate a heating effect on the ambient temperature. The magnitude of this daily maximum heating effect varies from 0.2 to 2.6 K and tends to be increase with the increase of the daily maximum temperature difference between PV panel and 2-m air temperature (Fig. 5(b)).

Due to the failure of the air temperature and humidity detector at 4 m in the PV plant, the air temperature obtained by EC system at a height of 5.5 m was used in the average vertical profile of air temperature which was applied to investigate the height range of the heating effect (Fig. 6). The near-surface air temperature in the PV plant is 0.64 K and 0.32 K higher than the reference site at the height of 2 m and 10 m, respectively. One obvious reason is the temperature of PV panels is much higher than the ambient air temperature resulting in the convection heat dissipation to improve the conversion efficiency of PV panels (Fig. 5(b)). In addition, compared to the reference site, PV panels increase the surface area and aerodynamic roughness in the PV site, which may generate a higher efficiency of dissipate heat to the near-surface atmosphere through enhance vertical turbulent mixing. This “convection heating effect” can reach a height of more than 10 m. Our daytime heating effect of PV array is consistent with the findings of previous studies, they have also found local daytime air temperature heating ranges from 0.1 K to 1.9 K from both the field data and the simulations for the desert or barren areas [35,36,38,39,42].

For nocturnal hours from 20:00 to 8:00 overnight, the 2-m air temperature in the PV plant is lower than the reference site, and the

average difference of air temperature between the PV site and the reference site is 0.24 K and 0.08 K at the height of 2 m and 10 m respectively, suggesting that PV panels generate cooling effect for the near surface air temperature due to PV panels have the lower temperature compared to the ambient air and impede long wave radiative cooling of the ground surface at night. Even though this nocturnal cooling effect was very small at 10 m and within the bounds of instrument accuracy, these temperature differences imply that the PV array does cool air temperature at night. This nocturnal air temperature result is consistent with Fthenakis et al. who also found the PV panels are completely cooled and unlikely to produce a heating effect at night [36]. However, a significant nocturnal heating effect (3–4 K) at the height of 2.5 m was observed in a utility-scale PV array in southern Arizona [37], this contrary result may be resulted from the difference of the size of the PV array and local topographic structure [42].

The heating effect of PV panels on near-surface air temperature during the daytime is stronger than the cooling effect at night, hence in the whole averaged diurnal cycle, the PV panels eventually have a heating effect on the near-surface air temperature, making the near-surface air temperature in the PV plant increase by 0.16 K and 0.1 K related to the reference site at the height of 2 m and 10 m, respectively.

3.2. The effect of PV panels on the ground and the integrated underlying surface

In order to understand the impact of PV panels on the integrated underlying surface and the ground surface, the average diurnal variations of various of surface temperature were investigated (Fig. 7(a)). During the daytime, PV panels have a high temperature of up to 45 °C at 14:00 as increase of the absorbed solar radiation while prevent part of solar radiation reaching the ground and form part of physical shade on the ground, which resulting in the lower temperature of the ground surface in the PV plant compared to the reference site. However, there is of slightly difference between temperature of the integrated underlying surface in the PV plant and the ground surface in the reference site, which may be caused by the lower emissivity of front-side of PV panels and the lower temperature of the bared surface compared to the reference site

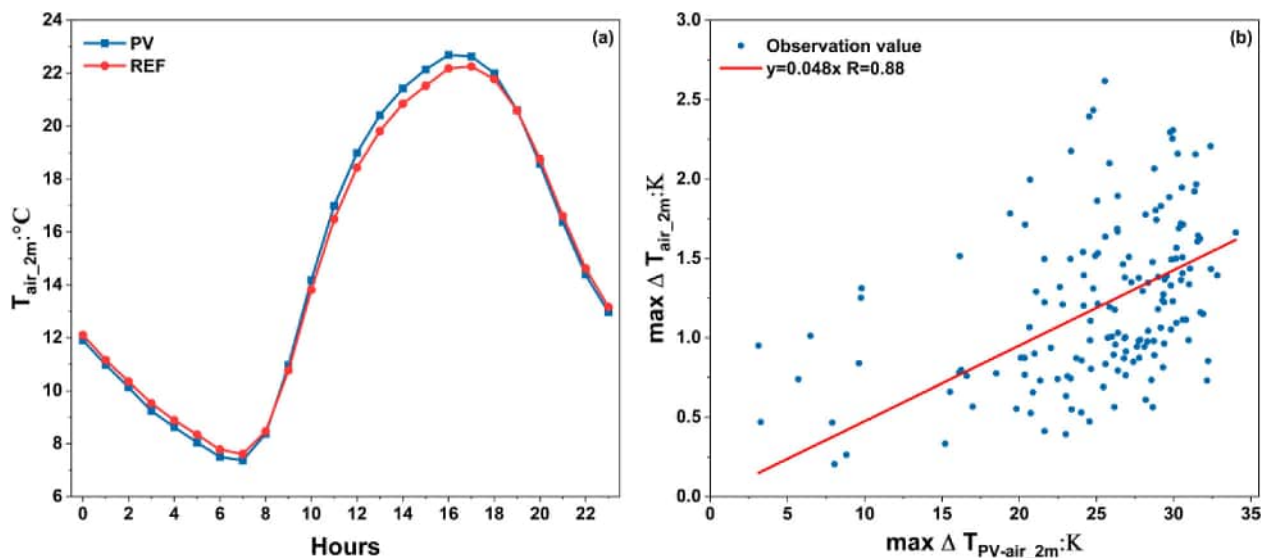


Fig. 5. The average diurnal variation of 2-m air temperature of the PV plant (blue) the reference site (red) for the period from 25 Jun–29 Nov 2020 (a); and the daily maximum temperature difference between the rear-side of PV panels and 2-m air vs the daily maximum 2-m air temperature difference between the PV plant and the reference site, R is the correlation coefficient (b). The temperature of PV panels is the average of four thermocouples adhered to the rear-side of PV panels.

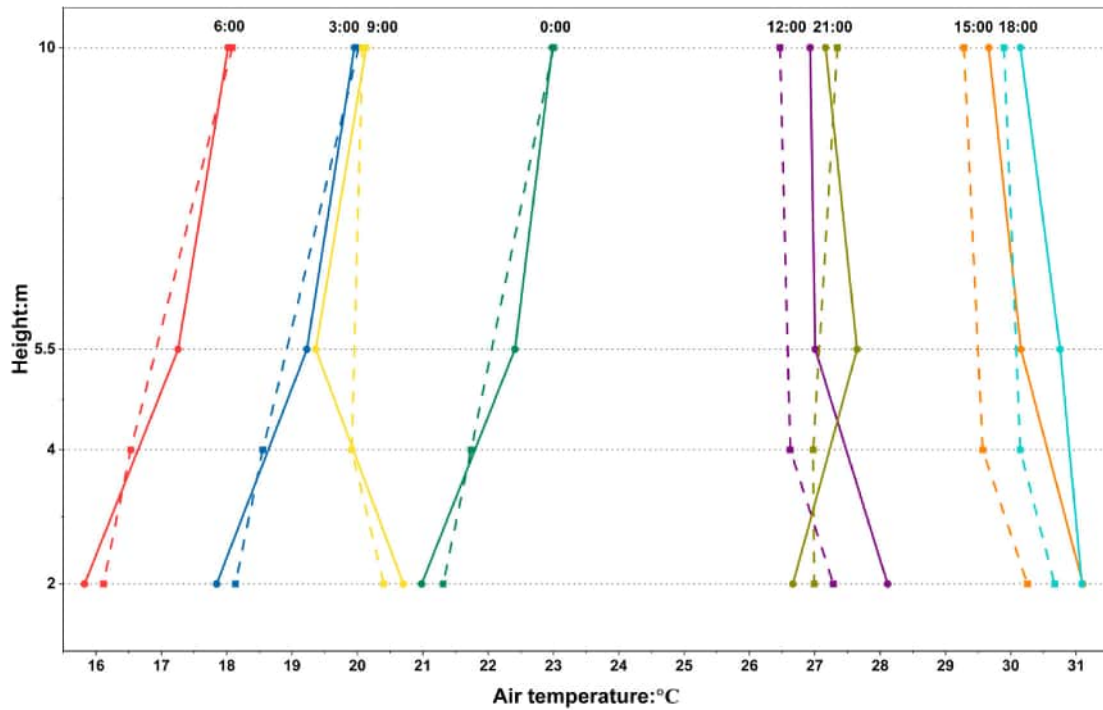


Fig. 6. Vertical profiles of near-surface air temperature throughout the average diurnal cycle during the observational period from 25 Jun–29 Nov 2020. The solid lines correspond to the PV plant, and the dashed lines correspond to the reference site. Due to instrument failure in the PV site, the air temperature at the height of 4 m is only taken from the reference site and use the temperature at 5.5 m measured by the eddy covariance system for the PV plant.

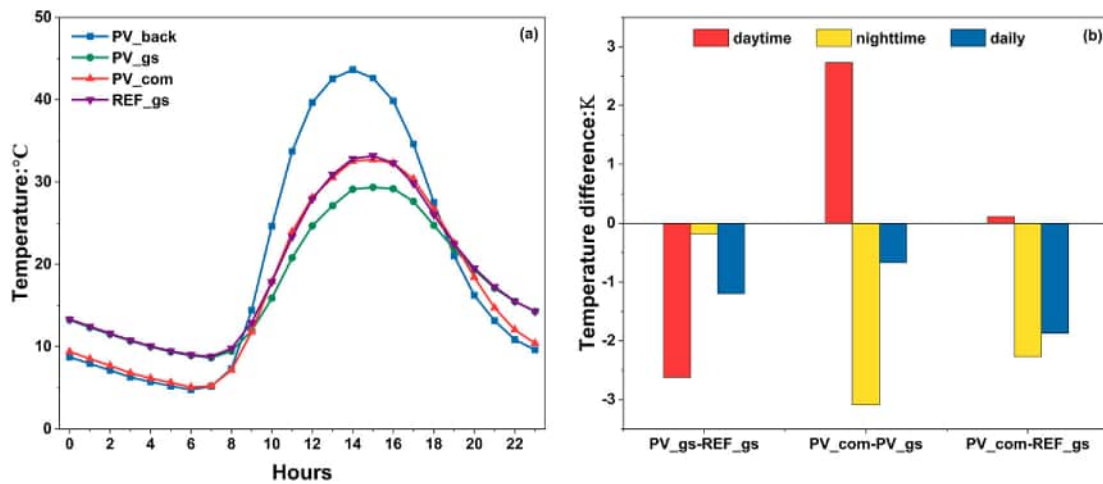


Fig. 7. Averaged diurnally variation of temperatures for the ground surface (green line), comprehensive surface (red line), the back surface of PV panels (blue line) in the PV plant and the ground surface in the reference site (purple line) (a) and differences in averaged temperatures during the daytime (red bars), nighttime (yellow bars) and the whole day (blue bars) (b) during the observational period from 25 Jun–29 Nov 2020.

[42]. On the contrary, after 19:00, the temperature of PV panels decreases rapidly, which was much lower than the surface temperature of the reference site, resulting in much lower temperature of the integrated underlying surface and slightly lower temperature of the ground surface in the PV plant compared to the ground surface temperature in the reference site at night. In the previous studies, the warming effect was found for the shaded ground surface largely caused by the impediment effect of the PV panels to long wave radiative cooling of the ground surface at night in the PV plant [39,42]. Our results indicate no warming effect for the ground surface in the PV plant mainly due to the radiometer was placed in the middle of the two rows of PV panels.

Generally, compared with the surface temperature of the reference site, during the daytime the PV panels have a cooling effect on the ground below (~ 2.6 K), and a slightly warming effect on the integrated underlying surface (~ 0.1 K). For nocturnal hours a significant cooling effect (~ 2.3 K) for the integrated underlying surface and the weaker cooling effect (~ 0.2 K) for the ground surface were observed in the PV plant (Fig. 7(b)). In the whole day, we found cooling effects of PV panels on the ground surface (~ 1.2 K) and the integrated underlying surface (~ 1.9 K).

Both the impact on temperature of near-surface air and various surface suggests the physical effect of PV panels is not symmetrical through the course of the day and the diurnal asymmetry resulted

from the following reasons. The first reason is the change of net shortwave radiative forcing induced by the PV panels which only occurs in the daytime; another reason comes from the change of the surface temperature due to the lower heat capacity, physical shading effect of PV panels, and energy redistribution near the ground. To further investigate the mechanisms of diurnal asymmetry of PV panels on air temperature and surface temperature we next present detailed results from radiative forcing and energy partitioning.

3.3. Radiation balance above and below the PV panels

From the above discussion, it can be found that the impact of PV panels on the temperature of the near-surface air and various surface presents a daily asymmetry, so the radiation components of the two sites at the height of 10 m (Fig. 8) and 1.5 m (Fig. 9) are further investigated for the daytime and nighttime respectively. At the height of 10 m, the daily average cumulative NR is higher 1.14 MJ/m² and the proportion of increased NR is 15.3% in the PV plant compared with the reference site, which is caused by the two reasons. The first reason of the difference comes from the change of

the net shortwave radiation as the external forcing item of the system. Due to the lower albedo of PV panels, less shortwave radiation reflected to the atmosphere USR in the PV plant and the daily average cumulative USR is lower 0.86 MJ/m² than the reference site, correspondingly the net shortwave radiation of PV site (13.07 MJ/m²) is significantly higher than the reference site (12.1 MJ/m²). Here the increased proportion of net shortwave radiation in the PV plant compared to the reference site is presented as 8%, which is calculated by subtracting the NR of the reference site from the NR in the PV plant and dividing it by the NR in the reference site, to describe the radiative forcing increase caused by PV panels more intuitively.

The second reason is related to the change of the long-wave radiation as an internal feedback mechanism. Although the ground temperature in the PV site is lower than the reference site during the daytime (Fig. 7) and the emissivity of the upper surface of the PV module (~0.83) is lower than that of the sandy soil (0.94) [42], however the temperature of PV panels is much higher than the surface of the reference site, resulting in a slightly higher temperature of the integrated underlying surface than that of the reference site during the daytime (Fig. 7), which may cause ULR of

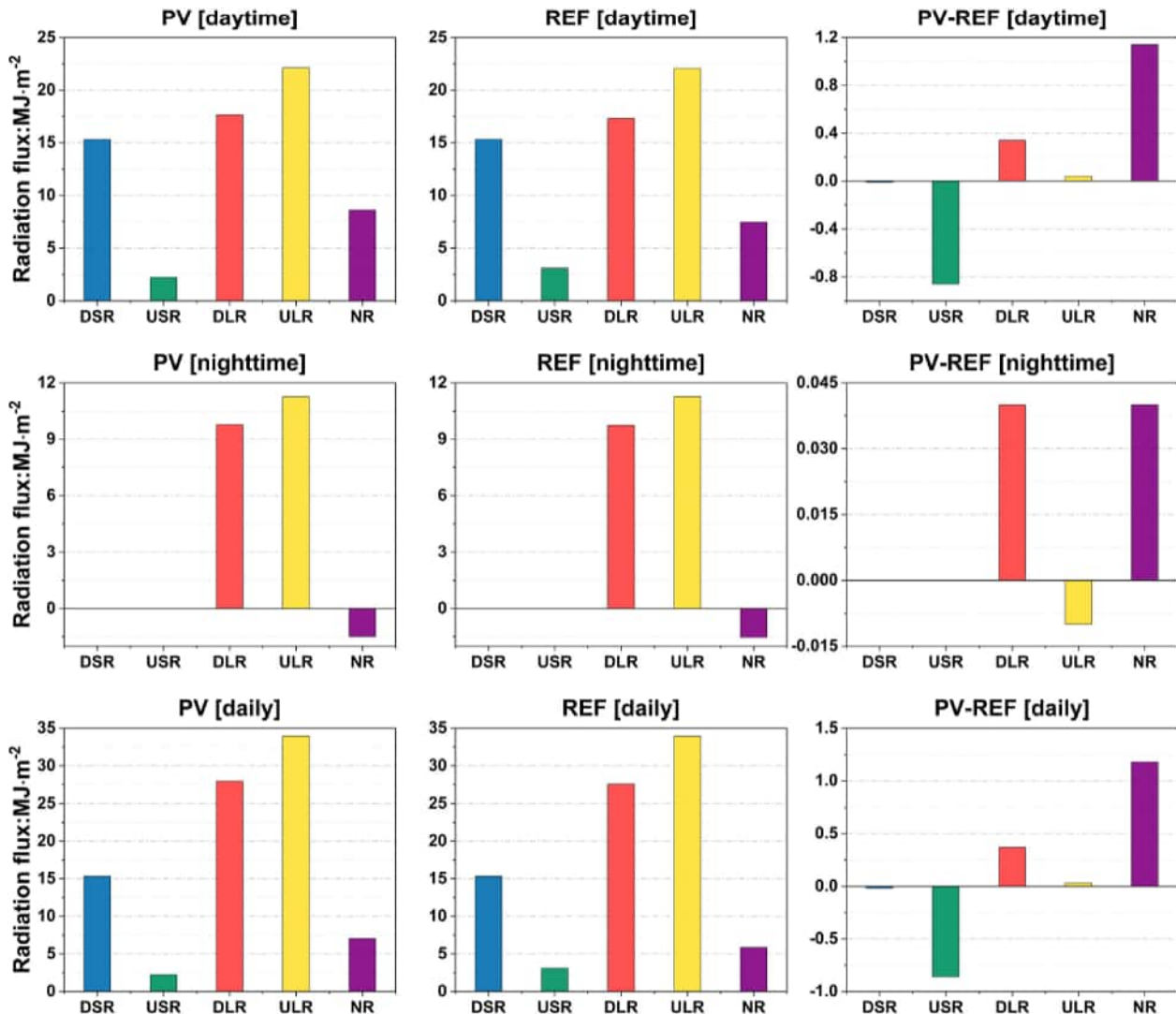


Fig. 8. Diurnally averaged total radiative fluxes at the height of 10 m during the daytime (top), nighttime (second row) and the whole day (bottom) in the PV site and the reference site.

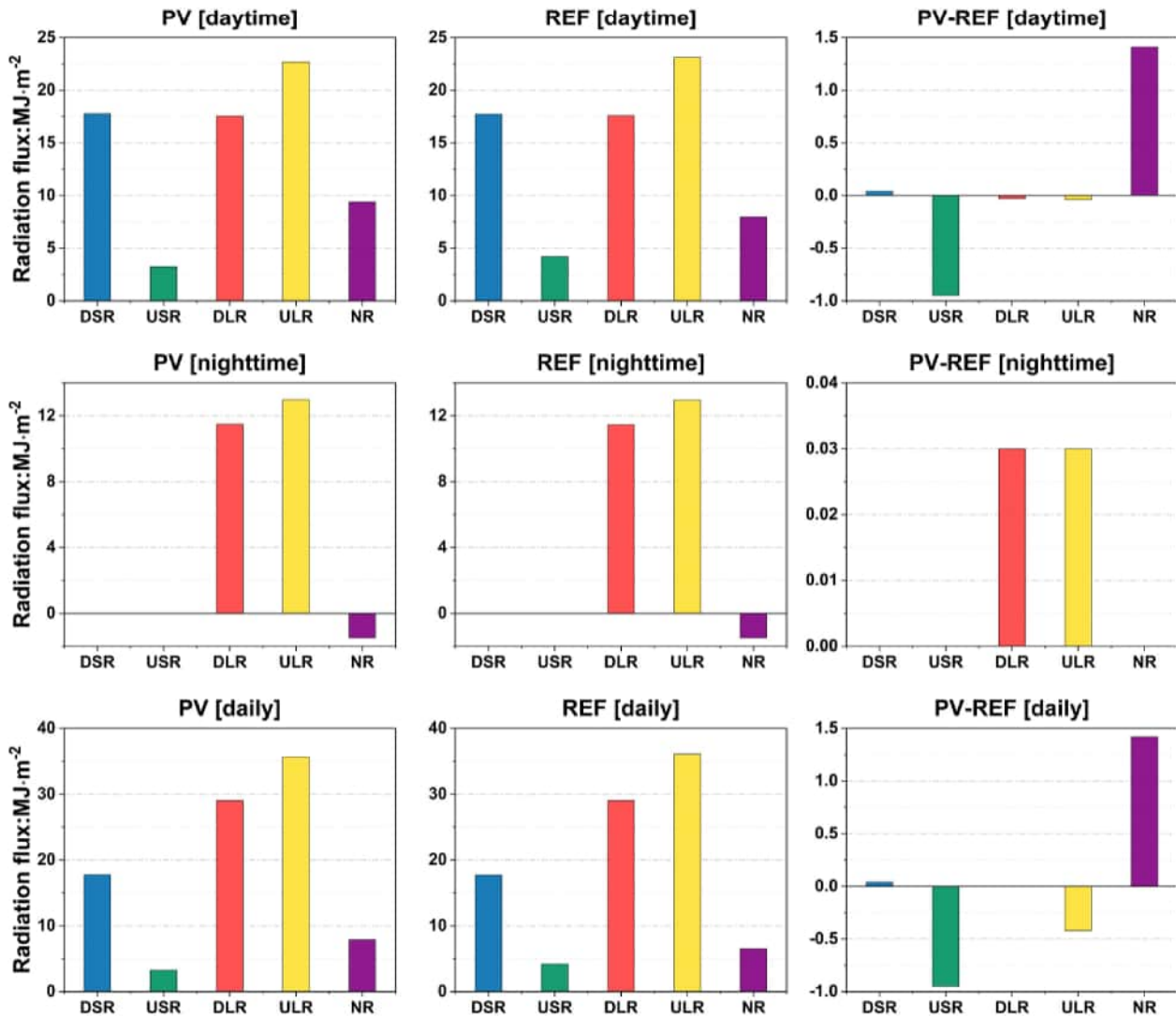


Fig. 9. The same as Fig. 8, at the height of 1.5 m.

the PV site to be slightly higher than the reference site by 0.04 MJ/m^2 . This is contrary to the results of previous studies and may be related to the experimental design, because the reported installation heights of the radiometers were 10 m and 3 m above the ground for the PV site and the reference site respectively in the literature [38], while in another study the reported heights of the radiometers were 5.7 m and 2.8 m for the PV site and the reference site respectively [42]. With regard to DLR, the PV site is 0.34 MJ/m^2 higher than the reference site. The possible explanation is that the high temperature of the PV panel during the day leading to the dryer air in the PV plant than that of the reference site.

At night, the negative NR of the PV plant is slightly higher (0.04 MJ/m^2) than the reference site, indicating that the heat release of the integrated underlying surface is less than that of the reference site. Due to the radiative forcing vanish at night, the difference mainly concerns with the decreased ULR, which resulted from the lower temperature of PV modules and the integrated underlying surface than the reference site. Over all, the cumulative NR in the PV plant is 1.18 MJ/m^2 higher than the reference site at 10 m during the whole day. The impact of PV panels on the radiation component is mainly from the reduced USR during the daytime and the longwave radiation response caused by the change of the surface temperature is weak, especially at night.

As for the radiation components at 1.5 m, DSR of the PV plant is higher than the reference site during the daytime, possibly because of the refracted solar shortwave radiation by PV panels, while USR in the PV plant is 0.95 MJ/m^2 lower than that of the reference site. The ULR emitted by the ground surface and DLR is decreased by 0.04 and 0.03 MJ/m^2 respectively in the PV plant mainly because of higher air temperature in the PV plant than that of the reference site caused by radiative and convective heat exchange. At night the difference between the PV site and the reference site is minimal. Consequently, for the radiation balance at the height of 1.5 m, the change of radiation component in the PV plant mainly comes from the increased net short-wave radiation, and the feedback of long-wave radiation caused by the change of surface temperature is almost negligible.

3.4. Surface energy partitioning

The water and heat balance of the surface is mainly composed of NR, H, LE and GS, among which H and LE come from the upwind location of flux sources. Since the reference site is located in the northeast of the PV plant, we infer that the reference site is located in the downwind area and the turbulence fields at the reference site may be affected by the PV array when the wind direction ranges

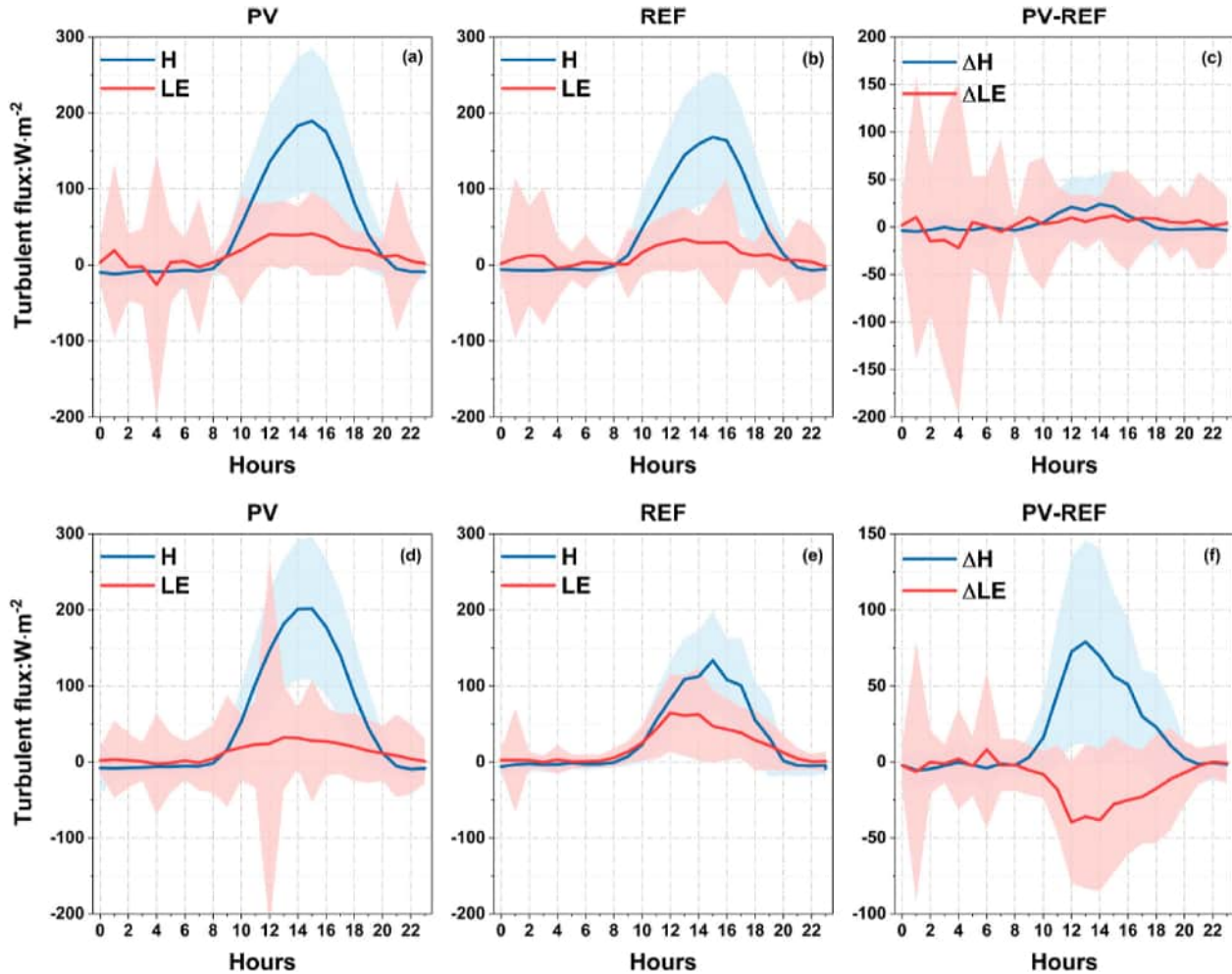


Fig. 10. Diurnally averaged turbulent fluxes of sensible heat H (blue line) and latent heat LE (red line) in the PV plant and the reference site for Jun 24, 2020–29 Nov 2020. (a)–(c) wind directions range from 200° to 310° (the turbulent field at reference site is affected by the upwind PV array); (d)–(f) other wind directions (the turbulent field at reference site is not affected by the upwind PV array). Shaded areas indicate plus and minus standard deviation about the mean of the corresponding curve.

from 200° to 310° . In this case, the average differences in turbulent fluxes between the two sites are given in Fig. 10 a~c, indicating that H and LE were higher at the PV plant than the reference, with the maximum δH (PV-REF) of 24 W/m^2 at 14:00 and average δH of 3.5 W/m^2 , and the maximum δLE (PV-REF) of 11.8 W/m^2 at 15:00 and average δLE of 2.7 W/m^2 . Fig. 10 d ~ f shows the turbulent fluxes under the situation that the turbulent field at the reference site is not affected by PV array. As indicated by Fig. 10(f), the higher maximum δH of 79 W/m^2 and average δH of 18 W/m^2 , while the negative maximum δLE of -39.7 W/m^2 and average δLE of -11.1 W/m^2 . The difference in δH and δLE imply that increased transport of heat from the PV plant to the reference site and decreased evaporation in the downwind of the PV plant during the daytime, and this reduction is derived from the lower wind speed in the downwind area of PV plant.

We further explore the partitioning of energy fluxes to comprehend the mechanism of asymmetric effects of PV panels. According to the energy balance equation (formula 3), GS is calculated with the assumption that the energy closure is 1 and the energy balance for the PV plant and the reference site is showed in Fig. 11. During the daytime, the proportion of the NR converted into PE is 9.2% (0.79 MJ/m^2), which is not enough to compensate the increase in NR (1.14 MJ/m^2). In the process of the remaining energy partitioning related to the increased roughness and Bowen ratio

compared with the reference site, the increased of the cumulative H reaches 0.94 MJ/m^2 which is equivalent of the increased NR, indicating that the most available energy is released into the ambient air in the form of H through convection. The PV plant, due to the larger surface area and lower heat capacity, also being aerodynamically rougher, is more efficient than the reference site in dissipating heat into near-surface air via turbulent diffusion, and as a result heating the ambient air faster than the reference site. Whereas the cumulative LE and GS reduced by 0.5 and 0.1 MJ/m^2 respectively in the PV plant, suggesting that evapotranspiration is weakened and less solar heat energy is stored in the soil, which may be caused by the shield and wind resistance of the PV modules. Further to quantify the impact of PV panels on energy partitioning, we explore the proportion of the H , LE and GS to the NR in the PV plant and the reference site respectively and found that the proportion of H to NR is increased by 6% , while the reductions of the proportion of LE and GS to NR are 8% and 7% respectively compared to the reference site. Additional intuitive evidence for the changes of PV panels in energy redistribution is H increased by 30.6% , and LE and GS decreased by 49% and 3% respectively related to the reference site in the daytime.

The radiative forcing vanishes at night, negative NR and H indicate that the surface releases heat to the atmosphere and turbulent energy is transported downward in the stably stratified

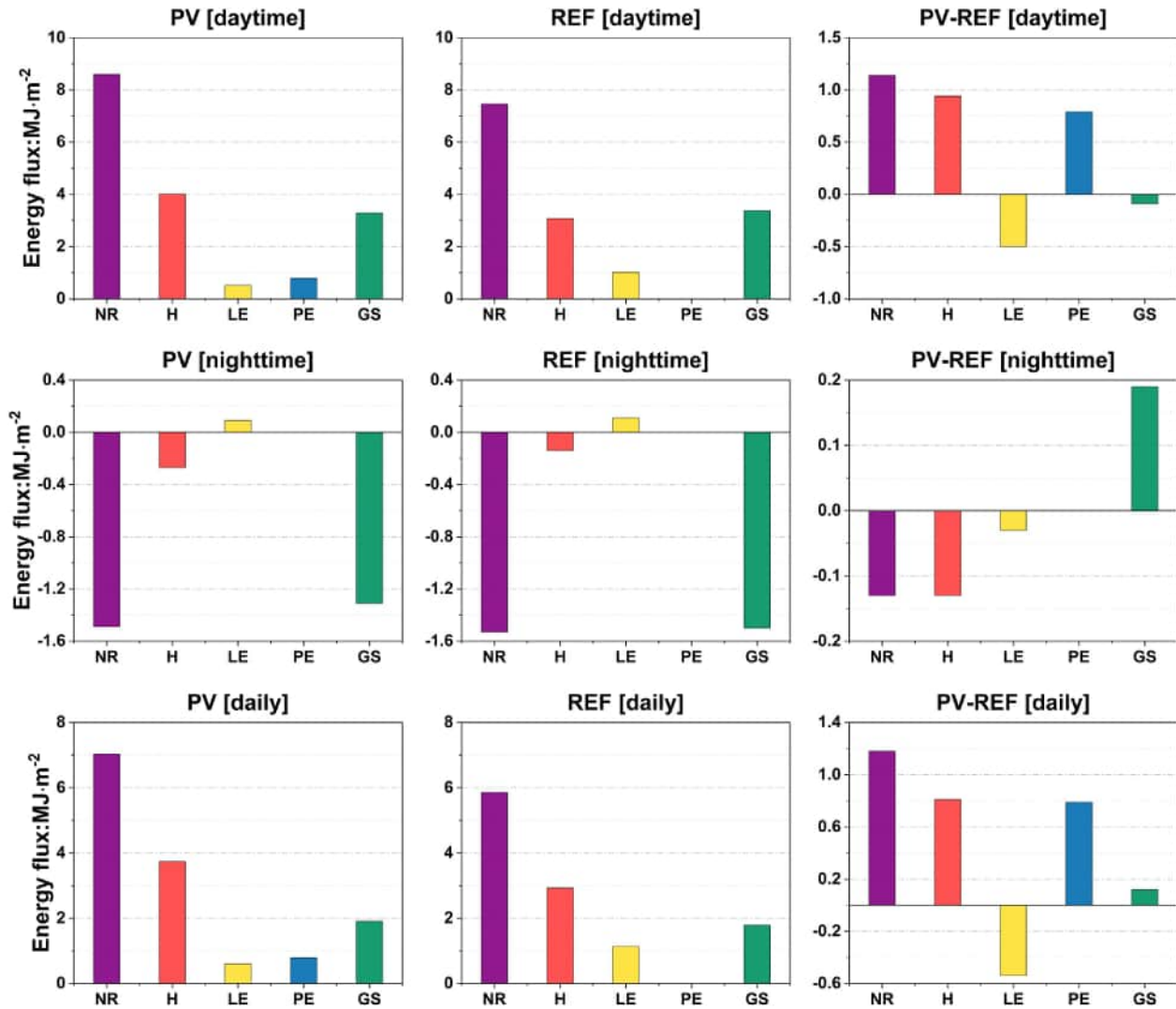


Fig. 11. Diurnal averaged total energy fluxes during the daytime, nighttime and the whole day in the PV plant and the reference site.

conditions, while LE still remain positive, indicating that evaporation exists at night of the barren area. However, the energy balance components respond differently at night from that in the daytime to PV panels. In the plant, the presence of PV panels causes enhanced vertical turbulent mixing which brings more heat from aloft atmosphere to the surface and prevents evaporation from the areas under the footprint of the panels, as a result increase the negative downward H (-0.13 MJ/m^2) and decrease positive upward LE (-0.03 MJ/m^2) slightly. While negative upward GS is reduced by 0.19 MJ/m^2 compared with the reference site, indicating that less heat flux is released to the atmosphere from soil in the PV plant than in the reference site, may resulted from the impeding effect of PV modules on surface radiative cooling.

In the course of daily cycle, the H in the PV plant increases by 0.81 MJ/m^2 , while the LE decreases by 0.54 MJ/m^2 compared to the reference site, which is consistent with the previous study [45]. Moreover, because the operation of PV modules occurs in the daytime, the impact of PV panels on the energy partitioning is not symmetrical through the course of the day. Further, in the PV plant, H increased by 27.6%, and LE decreased by 47.4% related to the reference site in the whole day, and these effects mainly come from the daytime. As regard to GS, due to the magnitude of reduced nocturnal storage heat release by the ground remain higher than

reduced heat storage in the soil, the PV plant had more negative GS of 6.7% compared to the reference site in the whole day.

4. Conclusion

In this study, the measurements of radiation and energy balance below and above the PV panels were designed for understanding the radiative forcing concerns with net short-wave radiation, and consequent surface longwave radiation, and energy redistribution of the PV plant. We found that the physical effect of PV panels presents distinct diurnal asymmetry through the course of the day.

During the daytime, because the albedo of the PV underlying surface is lower, the net shortwave radiative forcing in the PV plant at 10 m increase 8% related to the reference site, which lead to a slightly warming effect on the integrated underlying surface (0.1 K) and the outgoing long wave radiation ULR at 10 m increased accordingly as an internal feedback mechanism. Whereas a cooling effect ($\sim 2.6 \text{ K}$) on the ground surface in the PV plant is observed because of the physical shading effect of PV panels, and the corresponding ULR at 1.5 m decreased by 0.04 MJ/m^2 compare with the reference site. Part of the NR (9.2%) in the PV plant is converted into PE, because of the larger surface area and lower heat capacity, also being aerodynamically rougher in the PV plant than the

reference site, H increased by 30.6% whose contribute to the heating effect on the near-surface air temperature. The air temperature at the height of 2 m and 10 m in the PV plant is 0.64 K and 0.32 K higher than the reference site, respectively. LE and GS decreased by 49% and 3% respectively related to the reference site because less water is vaped and less solar energy is stored in the soil which attributed to the shield and wind resistance of the PV modules.

For nocturnal hours, the solar radiative forcing induced by PV panels vanishes, and PV panels has a cooling effect (~ 0.2 K) on the ground surface and a cooling effect on the integrated underlying surface (~ 2.3 K) resulted from the prevention of PV panels on the long wave radiative cooling of surface and the cooler PV panels compared with the reference site. Consequent changes in surface long wave radiation above and below the PV panels is slightly. The increased of the downward H is caused by the enhanced vertical mixing, and less GS is released to the atmosphere from soil in the PV plant at night which contribute to the cooling effects of 0.24 K and 0.08 K on the air temperature at the height of 2 m and 10 m respectively related to the reference site.

In the whole day, in the PV plant H increased by 27.6%, LE and GS decreased by 47.4% and 6.7% respectively, air temperature increased by 0.16 K and 0.1 K at 2 m and 10 m respectively.

The downstream turbulent field is impacted by PV array and the reference site received more heat from the upwind direction from PV plant than other wind directions. The detailed downstream effects of PV arrays on air temperature and turbulent fluxes should be explored further with additional observations.

The impacts of PV arrays on near-surface air temperature and energy fluxes have been studied and quantified in barren areas, results indicate that in the study region PV array could bring out possible local surface climate impacts. However, more observation in different seasons with distinct flow regimes are needed if accurate assessment for local climate effect of utility-scale PV arrays. We are currently still performing this observation in Wujiaqu. Additionally, the observed effect would be coupled into the regional climate numerical models to evaluate the impacts of PV array with different climates and scales and downstream effect of PV array.

The present study primarily assessed the local climate of a power plant with monofacial, fixed-mounted panels. In recent years, some other PV technologies such as one-axis tracking system and bifacial PV have received considerable attention due to the potential higher power energy yield compared to monofacial, fixed-mounted PV modules [56]. The radiation forcing and energy partitioning processes associated with PV surface energy balance induced by these PV technologies would likely to be different from conclusions of this study, future work is needed to evaluate how large scale of these PV applications affect local climates.

CRedit authorship contribution statement

Junxia Jiang: Conceptualization, Methodology, Software, Writing – original draft. **Xiaoqing Gao:** Data curation, Resources, Supervision, Project administration, Funding acquisition. **Qingquan Lv:** Visualization, Investigation, Formal analysis, Writing – review & editing. **Zhenchao Li:** Resources, Project administration, Funding acquisition. **Peidu Li:** Software, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- [1] N.L. Panwar, S.C. Kaushik, S. Kothari, Role of renewable energy sources in environmental protection: a review, *Renew. Sustain. Energy Rev.* 15 (3) (2011) 1513–1524.
- [2] S. Saud, S.S. Chen, A. Haseeb, Sumayya, the role of financial development and globalization in the environment: accounting ecological footprint indicators for selected one-belt-one-road initiative countries, *J. Clean. Prod.* 250 (2020) 15.
- [3] M.Z. Jacobson, Review of solutions to global warming, air pollution and energy security, *Geochim. Cosmochim. Acta* 73 (13) (2009) A581. A581.
- [4] N.M. Haegel, H. Atwater, T. Barnes, C. Breyer, A. Burrell, Y.M. Chiang, S. De Wolf, B. Dimmler, D. Feldman, S. Glunz, J.C. Goldschmidt, D. Hochschild, R. Inzunza, I. Kaizuka, B. Kroposki, S. Kurtz, S. Leu, R. Margolis, K. Matsubara, A. Metz, W.K. Metzger, M. Morjaria, S. Niki, S. Nowak, I.M. Peters, S. Philipps, T. Reindl, A. Richter, D. Rose, K. Sakurai, R. Schlatmann, M. Shikano, W. Sinke, R. Sinton, B.J. Stanbery, M. Topic, W. Tumas, Y. Ueda, J.V. de Lagemaat, P. Verlinden, M. Vetter, E. Warren, M. Werner, M. Yamaguchi, A.W. Bett, Terawatt-scale photovoltaics: transform global energy, *Science* 364 (6443) (2019) 836–4.
- [5] G.M. Wilson, M. Al-Jassim, W.K. Metzger, S.W. Glunz, P. Verlinden, G. Xiong, L.M. Mansfield, B.J. Stanbery, K. Zhu, Y. Yan, J.J. Berry, A.J. Ptak, F. Dimroth, B.M. Kayes, A.C. Tamboli, R. Peibst, K. Catchpole, M.O. Reese, C.S. Klinga, P. Denholm, M. Morjaria, M.G. Deceglie, J.M. Freeman, M.A. Mikofski, D.C. Jordan, G. Tamizhmani, D.B. Sulas-Kern, The 2020 photovoltaic technologies roadmap, *J. Phys. D Appl. Phys.* 53 (49) (2020).
- [6] N.M. Haegel, R. Margolis, T. Buonassisi, D. Feldman, A. Froitzheim, R. Garabedian, M. Green, S. Glunz, H.M. Henning, B. Holder, I. Kaizuka, B. Kroposki, K. Matsubara, S. Niki, K. Sakurai, R.A. Schindler, W. Tumas, E.R. Weber, G. Wilson, M. Woodhouse, S. Kurtz, Terawatt-scale photovoltaics: trajectories and challenges, *Science* 356 (6334) (2017) 141–143.
- [7] C. Breyer, D. Bogdanov, A. Gulagi, A. Aghahosseini, L. Barbosa, O. Koskinen, M. Barasa, U. Caldera, S. Afanasyeva, M. Child, J. Farfan, P. Vainikka, On the role of solar photovoltaics in global energy transition scenarios, *Prog. Photovolt.* 25 (8) (2017) 727–745.
- [8] IEA, Solar energy: mapping the road ahead. <https://www.iea.org/reports/solar-energy-mapping-the-road-ahead>, 2019.
- [9] IRENA, Future of Solar Photovoltaic: Deployment, Investment, Technology, Grid Integration and Socio-Economic Aspects (A Global Energy Transformation: Paper), 2019.
- [10] J.J. Burkhardt III, G. Heath, E. Cohen, Life cycle greenhouse gas emissions of trough and tower concentrating solar power electricity generation, *J. Ind. Ecol.* 16 (2012) S93–S109.
- [11] S. Ravi, D.B. Lobell, C.B. Field, Tradeoffs and synergies between biofuel production and large solar infrastructure in deserts, *Environ. Sci. Technol.* 48 (5) (2014) 3021–3030.
- [12] A. Louwen, W. van Sark, A.P.C. Faaij, R.E.I. Schropp, Re-assessment of net energy production and greenhouse gas emissions avoidance after 40 years of photovoltaics development, *Nat. Commun.* 7 (2016) 9.
- [13] S.A. Abbasi, N. Abbasi, The likely adverse environmental impacts of renewable energy sources, *Appl. Energy* 65 (1–4) (2000) 121–144.
- [14] K.A. Moore-O’Leary, R.R. Hernandez, D.S. Johnston, S.R. Abella, K.E. Tanner, A.C. Swanson, J. Kreidler, J.E. Lovich, Sustainability of utility-scale solar energy – critical ecological concepts, *Front. Ecol. Environ.* 15 (7) (2017) 385–394.
- [15] P. Cook, Infrastructure, rural electrification and development, *Energy Sustain. Dev.* 15 (3) (2011) 304–313.
- [16] H. Obane, Y. Nagai, K. Asano, Assessing land use and potential conflict in solar and onshore wind energy in Japan, *Renew. Energy* 160 (2020) 842–851.
- [17] G.F. Nemet, Net radiative forcing from widespread deployment of photovoltaics, *Environ. Sci. Technol.* 43 (6) (2009) 2173–2178.
- [18] B.R. Burg, P. Ruch, S. Paredes, B. Michel, Placement and efficiency effects on radiative forcing of solar installations, in: G. Siefer, M. Baudrit, I. Anton (Eds.), 11th International Conference on Concentrator Photovoltaic Systems 2015.
- [19] A. Sellers, A.J. Meadows, LONG-TERM variations IN albedo and surface-temperature OF earth, *Nature* 254 (5495) (1975) 44, 44.
- [20] R.A. Betts, Biogeophysical impacts of land use on present-day climate: near-surface temperature change and radiative forcing, *Atmos. Sci. Lett.* 2 (1–4) (2001) 39–51.

- [21] J.J. Feddema, K.W. Oleson, G.B. Bonan, L.O. Mearns, L.E. Buja, G.A. Meehl, W.M. Washington, The importance of land-cover change in simulating future climates, *Science* 310 (5754) (2005) 1674–1678.
- [22] R.A. Pielke, Land use and climate change, *Science* 310 (5754) (2005) 1625–1626.
- [23] D. Li, P. Tian, H. Luo, T. Hu, B. Dong, Y. Cui, S. Khan, Y. Luo, Impacts of land use and land cover changes on regional climate in the Lhasa River basin, Tibetan Plateau, *Sci. Total Environ.* 742 (2020).
- [24] R.R. Hernandez, S.B. Easter, M.L. Murphy-Mariscal, F.T. Maestre, M. Tavassoli, E.B. Allen, C.W. Barrows, J. Belnap, R. Ochoa-Hueso, S. Ravi, M.F. Allen, Environmental impacts of utility-scale solar energy, *Renew. Sustain. Energy Rev.* 29 (2014) 766–779.
- [25] E. Rotenberg, D. Yakir, Contribution of semi-arid forests to the climate system, *Science* 327 (5964) (2010) 451–454.
- [26] X. Lee, M.L. Goulden, D.Y. Hollinger, A. Barr, T.A. Black, G. Bohrer, R. Bracho, B. Drake, A. Goldstein, L.H. Gu, G. Katul, T. Kolb, B.E. Law, H. Margolis, T. Meyers, R. Monson, W. Munger, R. Oren, T.P.U. Kyaw, A.D. Richardson, H.P. Schmid, R. Staebler, S. Wofsy, L. Zhao, Observed increase in local cooling effect of deforestation at higher latitudes, *Nature* 479 (7373) (2011) 384–387.
- [27] H. Taha, The potential for air-temperature impact from large-scale deployment of solar photovoltaic arrays in urban areas, *Sol. Energy* 91 (2013) 358–367.
- [28] F. Salamanca, M. Georgescu, A. Mahalov, M. Moustauoui, A. Martilli, Citywide impacts of cool roof and rooftop solar photovoltaic deployment on near-surface air temperature and cooling energy demand, *Boundary-Layer Meteorol.* 161 (1) (2016) 203–221.
- [29] A. Cortes, Y. Murashita, T. Matsuo, A. Kondo, H. Shimadera, Y. Inoue, Numerical evaluation of the effect of photovoltaic cell installation on urban thermal environment, *Sustain. Cities Soc.* 19 (2015) 250–258.
- [30] V.r. Masson, M. Bonhomme, J.-L. Salagnac, X. Briottet, A. Lemonsu, Solar panels reduce both global warming and urban heat island, *Front. Environ. Sci.* 2 (2014).
- [31] A. Scherba, D.J. Sailor, T.N. Rosenstiel, C.C. Wamser, Modeling impacts of roof reflectivity, integrated photovoltaic panels and green roof systems on sensible heat flux into the urban environment, *Build. Environ.* 46 (12) (2011) 2542–2551.
- [32] J.S. Golden, J. Carlson, K.E. Kaloush, P. Phelan, A comparative study of the thermal and radiative impacts of photovoltaic canopies on pavement surface temperatures, *Sol. Energy* 81 (7) (2007) 872–883.
- [33] C. Efthymiou, M. Santamouris, D. Kolokotsa, A. Koras, Development and testing of photovoltaic pavement for heat island mitigation, *Sol. Energy* 130 (2016) 148–160.
- [34] B.R. Burg, A. Selviaridis, S. Paredes, B. Michel, in: G.S. Kinsey, D. Riley, S. Kurtz, K. Araki, M. Baudrit (Eds.), *Ecological and Economical Advantages of Efficient Solar Systems*, 10th International Conference on Concentrator Photovoltaic Systems, 2014, pp. 317–320.
- [35] D. Millstein, S. Menon, Regional climate consequences of large-scale cool roof and photovoltaic array deployment, *Environ. Res. Lett.* 49123 (2011) 98–204.
- [36] V. Fthenakis, Y.H. Yu, Ieee, analysis of the potential for a heat island effect in large solar farms, in: 2013 Ieee 39th Photovoltaic Specialists Conference, Ieee, New York, 2013, pp. 3362–3366.
- [37] G.A. Barron-Gafford, R.L. Minor, N.A. Allen, A.D. Cronin, A.E. Brooks, M.A. Pavao-Zuckerman, The Photovoltaic Heat Island Effect: larger solar power plants increase local temperatures, *Sci. Rep.* 6 (1) (2016) 35070.
- [38] R. Chang, Y. Shen, Y. Luo, B. Wang, Z. Yang, P. Guo, Observed surface radiation and temperature impacts from the large-scale deployment of photovoltaics in the barren area of Gonghe, China, *Renew. Energy* 118 (2018) 131–137.
- [39] L. Yang, X. Gao, F. Lv, X. Hui, L. Ma, X. Hou, Study on the local climatic effects of large photovoltaic solar farms in desert areas, *Sol. Energy* 144 (2017) 244–253.
- [40] X. Zhang, M. Xu, Assessing the effects of photovoltaic powerplants on surface temperature using remote sensing techniques, *Rem. Sens.* 12 (2020).
- [41] R. Chang, Y. Luo, R. Zhu, Simulated local climatic impacts of large-scale photovoltaics over the barren area of Qinghai, China, *Renew. Energy* 145 (2020) 478–489.
- [42] A.M. Broadbent, E.S. Krayenhoff, M. Georgescu, D.J. Sailor, The observed effects of utility-scale photovoltaics on near-surface air temperature and energy balance, *J. Appl. Meteorol. Climatol.* 58 (5) (2019) 989–1006.
- [43] A.X. Hu, S. Levis, G.A. Meehl, W.Q. Han, W.M. Washington, K.W. Oleson, B.J. van Ruijven, M.Q. He, W.G. Strand, Impact of solar panels on global climate, *Nat. Clim. Change* 6 (3) (2016) 290–294.
- [44] Y. Li, E. Kalnay, S. Motesharrei, J. Rivas, F. Kucharski, D. Kirk-Davidoff, E. Bach, N. Zeng, Climate model shows large-scale wind and solar farms in the Sahara increase rain and vegetation, *Science* 361 (6406) (2018) 1019–1022.
- [45] H. Marrou, L. Dufour, J. Wery, How does a shelter of solar panels influence water flows in a soil-crop system? *Eur. J. Agron.* 50 (2013) 38–51.
- [46] E.H. Adeg, J.S. Selker, C.W. Higgins, Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency, *PLoS One* 13 (11) (2018) 15.
- [47] G.A. Barron-Gafford, M.A. Pavao-Zuckerman, R.L. Minor, L.F. Sutter, I. Barnett-Moreno, D.T. Blackett, M. Thompson, K. Dimond, A.K. Geriak, G.P. Nabhan, J.E. Macknick, Agrivoltaics provide mutual benefits across the food-energy-water nexus in drylands, *Nat. Sustain.* 2 (9) (2019) 848–855.
- [48] K. Wilson, A. Goldstein, E. Falge, M. Aubinet, D. Baldocchi, P. Berbigier, C. Bernhofer, R. Ceulemans, H. Dolman, C. Field, A. Grelle, A. Ibrom, B.E. Law, A. Kowalski, T. Meyers, J. Moncrieff, R. Monson, W. Oechel, J. Tenhunen, R. Valentini, S. Verma, Energy balance closure at FLUXNET sites, *Agric. For. Meteorol.* 113 (1–4) (2002) 223–243.
- [49] W.J. Massman, A simple method for estimating frequency response corrections for eddy covariance systems, *Agric. For. Meteorol.* 104 (3) (2000) 185–198.
- [50] P. Schotanus, F.T.M. Nieuwstadt, H.A.R. Debruin, TEMPERATURE-MEASUREMENT with a SONIC anemometer and its application to heat and moisture fluxes, *Boundary-Layer Meteorol.* 26 (1) (1983) 81–93.
- [51] E.K. Webb, G.I. Pearman, R. Leuning, Correction OF flux measurements for density effects due to heat and water-vapor transfer, *Q. J. R. Meteorol. Soc.* 106 (447) (1980) 85–100.
- [52] T.W. Horst, J.C. Weil, Footprint estimation for scalar flux measurements IN the atmospheric surface-layer, *Boundary-Layer Meteorol.* 59 (3) (1992) 279–296.
- [53] N. Kljun, P. Calanca, M.W. Rotach, H.P. Schmid, A simple parameterisation for flux footprint predictions, *Boundary-Layer Meteorol.* 112 (3) (2004) 503–523.
- [54] R. Kormann, F.X. Meixner, An analytical footprint model for non-neutral stratification, *Boundary-Layer Meteorol.* 99 (2) (2001) 207–224.
- [55] T.S. Liang, M. Praveetoni, C. Deline, J.S. Stein, R. Kopecek, J.P. Singh, W. Luo, Y. Wang, A.G. Aberle, Y.S. Khoo, A review of crystalline silicon bifacial photovoltaic performance characterisation and simulation, *Energy Environ. Sci.* 12 (1) (2019) 116–148.



Projected PV plants in China's Gobi Deserts would result in lower evaporation and wind

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ABSTRACT

In this study, a promising photovoltaic (PV) deployment scenario is firstly designed to represent China's solar energy development in the context of its dual carbon target. Then, the potential climate effects of the designed PV plants under different emission scenarios are simulated using a newly developed weather research and forecasting (WRF)-PV regional climate model, which is initiated by the latest Coupled Model Intercomparison Project Phase 6 (CMIP6) projections. The modeling results indicate that the projected PV plants in China's Gobi Deserts could impact the local climate, causing positive change of $3.71 \pm 0.03\%$ in the surface relative humidity, and negative changes of $1.60 \pm 1.36 \text{ W/m}^2$ in the latent heat flux and $0.39 \pm 0.00 \text{ m/s}$ in the 10-m wind speed in July by about 2060 under the intermediate emission scenario, and these PV-induced climate effects are approximately equivalent to or even greater than the projected climate variability, but almost confined to the local area. These findings suggest that the projected PV deployment in China will lead to low carbon emissions while causing favorable climate effects, such as lower evaporation and wind speed in Gobi Deserts, which will bring environmental and ecological benefits to the PV industry.

1. Introduction

The massive cost reductions in solar technology and the accelerating progress toward climate neutrality have triggered a rapid development of solar energy worldwide. By 2022, China's cumulative installed solar photovoltaic (PV) capacity reached 393 GW- (IRENA, 2023). Recently, China announced that it will strive to reach peak carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060. Given such ambitions, the installed PV capacity will amount to 1,025 GW by 2030, and 3,600 GW by 2060 (GEIDCO, 2021). Although the expectations of the installed PV capacity projected by GEIDCO are conservative given the current rate of annual PV deployment in China, the capacity of utility-scale PV power will become especially large. Many of the regions in China that have the highest potential for utility-scale PV power also tend to be in parts of the Gobi Deserts with the driest climate. Therefore, carefully quantifying the climate effects of these projected PV power is essential for energy policy making in China.

The potential climate effects associated with solar power have been identified mainly based on historical data, ignoring future climate projections. Based on field observations, studies have demonstrated that PV panels exert a heating effect during the daytime and a shielding effect on

the land surface (Chang et al., 2018; Broadbent et al., 2019; Yue et al., 2021). Estimates obtained using remote sensing techniques have also indicated that the physical shading by the PV panels lowers the land surface temperature (Zhang and Xu, 2020) and increases the green area (Xia et al., 2022) over the PV regions. Further analyses based on numerical modeling, regardless of the inconsistency within the simulated results, were all conducted using historical reanalysis datasets (Taha 2013; Fthenakis and Yu, 2013; Masson et al., 2014; Salamanca et al., 2016; Chang et al., 2020; Heusinger et al., 2020). Since the climate response to the PV powering can vary among emission scenarios, it is fruitful to consider the implications of the projected PV deployment on the climate under future climate projections.

Numerical simulation is considered the most effective method for predicting the climate effects of PV plants under future scenarios. However, despite the influence of PV powering on the surface energy balance, its role is often not properly captured by the land process models. Many early models use the effective albedo (surface albedo plus conversion efficiency) to explain the air-land interaction inside the PV plants (Taha 2013; Fthenakis and Yu, 2013; Salamanca et al., 2016). This method underestimates the PV panels' heating effects, and treats the "effective albedo" as empirical values (Heusinger et al., 2020).

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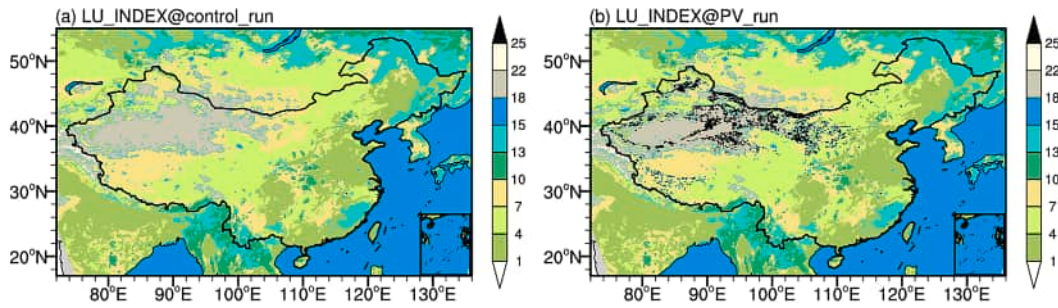


Fig. 1. Land-use index in the study domain (a) without PV plants and (b) with PV plants. The black dots in (b) represent the projected PV plant regions.

Table 1
Summary of model settings.

Model Setup:				
WRF (ARW) Version 4.2.1 with a PV plant parameterization (Chang et al., 2022)				
Model domain (542 × 659) with a 10 km grid on a Lambert projection (Fig. 1)				
Physical Parameterization:				
Planetary boundary layer (PBL) and land surface: MYNN scheme; Noah land surface model.				
Radiation: RRTM scheme for longwave radiation; Dudhia scheme for shortwave radiation.				
Simulation Setup:				
Scenarios	Historical	Future projection (SSP245 and SSP585)		
Start year	2008	2028	2048	2058
End year	2012	2032	2052	2062
Month	July / January			
Run	10 days × 3 per month			
Spin-up	24 h per run			

Therefore, studies based on this method may lead to high uncertainty (Taha, 2013; Masson et al., 2014; Salamanca et al., 2016). To overcome the drawbacks of this simple approach, recent progress has been made in developing more detailed PV energy balance models, such as the standalone microscale PV model (Heusinger et al., 2020) and the newly developed PV parameterization (Chang et al., 2022) embedded in the weather research and forecasting (WRF) model (Skamarock et al., 2021). Predicted near-surface climate features from this coupled WRF-PV model were verified by field observations, and the consistency of the model performance confirmed this model is a suitable tool for PV plants climate simulation (Chang et al., 2022).

To detect and quantify the potential climate effects of the utility-scale PV powering under different scenarios, the coupled WRF-PV model was initiated by the latest Coupled Model Intercomparison Project Phase 6 (CMIP6) projections in this study. The differences between the WRF simulations with the PV parameterization turned on and turned off were used to identify the climate responses under different emission scenarios. This study advances work on this research area by (1) assessing the PV-induced climate effects under a planned PV deployment scenario and projected emission scenarios, (2) making the first quantitative comparison between PV-induced climate effects and the projected climate variability, and (3) filling the current gap between the historical and future scenarios for PV-induced climate effects studies. The remainder of this paper is organized as follows. Section 2 introduces the data and methods, including the refined PV plant parameterization. The simulation settings are specified in Section 3, and the detailed modeling results are presented in Section 4. Finally, the discussion and conclusions are interpreted.

2. Data and methods

2.1. Initial and boundary conditions for the regional model

A bias-corrected global dataset based on the latest CMIP6 models is introduced as the initial and boundary conditions of the regional climate

model. The 18 CMIP6 models used in this bias-corrected dataset include the European Community Earth Model 3 (EC-Earth3), the Geophysical Fluid Dynamics Laboratory Earth System Model 4 (GFDL-ESM4), the Community Earth System Model 2 (CESM2), the Max Planck Institute Earth System Model 1.2 with high resolution (MPI-ESM1-2-HR), the Meteorological Research Institute Earth System Model 2.0 (MRI-ESM2-0), the Flexible Global Ocean-Atmosphere-Land System 3 (FGOALS-g3), and the Beijing Climate Center Climate System Model 2 with medium resolution (BCC-CSM2-MR), among others (Xu et al., 2021). The new scenarios used in the latest CMIP6 are the shared socioeconomic pathways (SSPs), and SSP245/SSP585 represent future scenarios of intermediate/high emission, respectively.

This bias-corrected global dataset spans the historical time period of 1979–2014 and future scenarios (SSP245 and SSP585) for 2015–2100 with a horizontal grid spacing of $1.25^\circ \times 1.25^\circ$ at six-hourly intervals (Xu et al., 2021). Compared with other types of CMIP6 data, this bias-corrected dataset is of better quality (Xu et al., 2021), making it a good candidate for our regional numerical experiments.

2.2. Data for model evaluation

The European Center for Medium-Range Forecasting reanalysis dataset 5 (ERA5 dataset) (Hersbach et al., 2021), which includes the daily surface downward short-wave radiation (SW), 2-m air temperature (T2), 2-m relative humidity (RH2), and surface pressure (PSFC) with a horizontal grid spacing of $0.25^\circ \times 0.25^\circ$, was used to evaluate the simulation performance of the model on regional scale. Under this scale, the five January and five July months during 2008–2012 were selected as two typical evaluation periods. January is typically the coldest month, and is characterized by extremely low temperatures. July typically is the hottest month. These periods were selected to compare different seasonal conditions.

Meanwhile, in situ meteorological observations from two PV power plants, located in Xinjiang and Qinghai, China, were also included to validate this model. Under this scenario, observed SW, T2, and wind speed in Qinghai during July 2015, October 2015, January 2016, April 2016 as well as observed SW, T2, wind speed, and sensible/latent heat flux in Xinjiang during July 2020 and October 2020 were compared with the model outputs. For a more detailed explanation and further information about these observations, refer to Jiang et al. (2021) and Chang et al. (2022).

2.3. PV plant parameterization

Here, a refined PV plant parameterization developed by Chang et al. (2022) was introduced to describe the climatic features of the PV plants regions. This novel and analytical expressed PV plant parameterization was established according to the surface energy balance principle. In this parameterization, each utility-scale PV plant is treated as a shortwave radiation sink and a sensible heat flux source, and the latent heat flux directly relates to evaporation through the latent heat of vaporization. When this refined PV plant parameterization was embedded into the

Table 2
Main land use types in the study domain.

Value in Fig. 1	Land-use type	Value in Fig. 1	Land-use type
19	Barren or sparsely vegetated	2	Dry-land cropland and pasture
8	Shrub land	5	Cropland/Grassland mosaic
7	Grassland		

WRF model, a coupled WRF-PV regional climate model was then developed.

3. Simulation settings

3.1. Modeling framework

To assess the likely PV-induced climate effects, we used the WRF-PV regional model with a 10 km grid on a Lambert projection over the continental China (Fig. 1a). The whole domain comprised 542×659 grid cells. The vertical dimension of the model was divided into 32 telescoped layers. These substantially higher horizontal and vertical resolutions can better represent the interactions of the PV panels within the boundary layer. As listed in Table 1, the WRF model used the Noah land-surface model (Chen and Dudhia, 2001). Longwave and shortwave radiations were simulated using the rapid radiative transfer model (RRTM) (Mlawer et al., 1997) and Dudhia scheme (Dudhia, 1989), respectively. The planetary boundary layer was simulated using the Mellor-Yamada-Nakanishi-Niino (MYNN scheme) (Nakanishi and Niino, 2006).

Solar energy is highly dependent on climate; thus, PV-induced climate effects exhibit substantial year-to-year variability. To reduce the influence of interannual variability, all simulations experiments in this study were performed for July and January during a historical period (2008–2012) and three future periods (2028–2032, 2048–2052, and 2058–2062) under both the SSP245 and SSP585 scenarios (Table 1). These 20 (four 5-year periods) July and January periods were selected to represent the typical summer/winter climatology, as determined from the bias-corrected CMIP6 dataset in Section 2.1. The models were reinitialized at 0000 UTC every 9 days and were run for 10 days. Discarding a 24 h spin-up time, the simulated outputs from the remaining 9-day periods were analyzed. Notably, because the 20-month simulation periods were completed in 10-day blocks, so we did not simulate the response of long-term climate dynamics influenced by PV plants. While

these simulation periods did not cover all climate scenarios that could impact the interactions between PV plants and land-surface processes, these 20 July and January periods did enable us to identify typical situations that may occur directly during summer/winter periods.

3.2. PV deployment scenario

Since information regarding the layouts of utility-scale PV plants was not yet available, a GIS weighted overlay analysis of criterion layers was performed to identify the optimal locations of PV plants (Wang et al., 2022). Considering the solar resource and the economic benefit, the annual utilization hours of solar energy should be greater than 1,000 h in China (Wang et al., 2022). In this study, 3% is treated as the maximum slope for PV plant, and the nature reserves were excluded. Finally, each grid was assigned a maximum utilization coefficient for PV deployment, ranging from 0.0 to 1.0 (Wang et al., 2022; Liu et al., 2022). Regions with a maximum utilization coefficient greater than 0.9 were reprojected onto our simulated domain (Fig. 1a). Then, the regions suitable for utility-scale PV plants were identified (black dots in Fig. 1b), and the underlying surfaces were mainly Gobi Desert areas with spare shrubs (Fig. 1a and Table 2). As shown in Fig. 1b, approximately 4,100 grid cells were suitable for PV siting, encompassing 1.2% of the whole domain.

Under the assumption that a 30 MW of PV plant will require an area of approximately 1 km^2 based on information from Wang et al. (2022), which took into account the influence of the coarse spatial resolution on the land utilization, the designed capacity of PV plants in Fig. 1b is about 12,000 GW, which is approximately three times the projected installed capacity by 2060 (3,600 GW from GEIDCO 2021). We regard this 12,000 GW benchmark scenario as a relatively promising scale of PV deployment scenario if PV power plays a major role in China's energy system in the latter half of this century.

As a step toward an improved policy-relevant understanding, we explored the climate effects of this promising scale of PV deployment over the continental China. This scale fills a gap between the smaller

Table 3
Spatial correlation coefficients/root-mean-square errors (W/m^2 , $^\circ\text{C}$, %, and hPa) of the modeled SW, T2, RH2, and PSFC against the ERA5 reanalysis during the historical period (2008–2012).

Month	SW	T2	RH2	PSFC
July	0.82/23.7	0.98/2.7	0.77/22.6	1.00/10.0
January	0.73/35.8	0.96/3.2	0.65/11.8	1.00/10.9

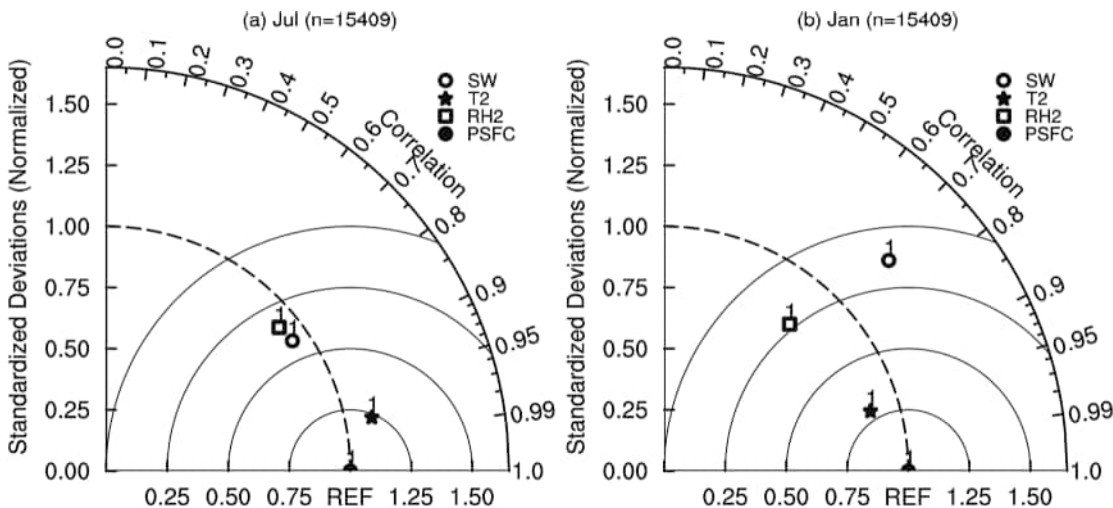


Fig. 2. Normalized Taylor diagrams comparing the modeled results with the ERA5 reanalysis for the daily SW, T2, RH2, and PSFC in (a) July and (b) January during the historical period (2008–2012). The diagrams show the correlations and ratios of the standard deviation.

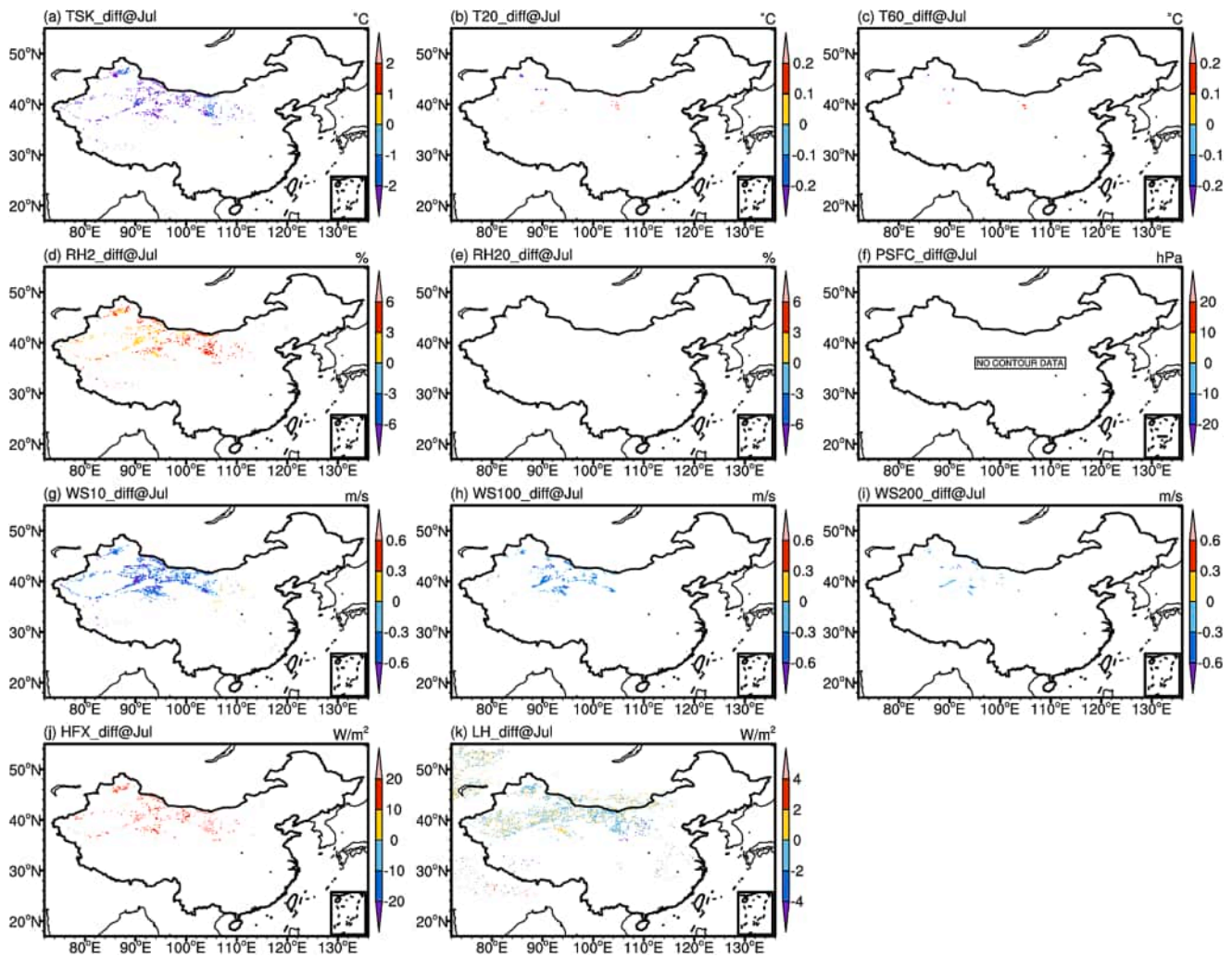


Fig. 3. Changes in (a) TSK, (b) T20, (c) T60, (d) RH2, (e) RH20, (f) PSFC, (g) WS10, (h) WS100, (i) WS200, (j) HFX, and (k) LH due to the benchmark PV deployment in July during the historical period (2008–2012). Only the regions with a 95% confidence level are displayed.

Table 4

Average changes with 95% confidence intervals (calculated based on $\bar{d}_{0.05}$ $t_{0.05} \times S_d / \sqrt{n}$) over PV plant regions.

	TSK (°C)	T20 (°C)	RH2 (%)
July	2.3 ± 0.02	0.02 ± 0.00	3.5 ± 0.03
January	0.50 ± 0.00	0.16 ± 0.00	3.6 ± 0.02
	WS10 (m/s)	HFX (W/m ²)	LH (W/m ²)
July	0.36 ± 0.00	18.9 ± 3.5	1.37 ± 0.65
January	0.39 ± 0.00	7.4 ± 0.94	0.11 ± 0.02

isolated PV plants and the global-scale climate model. Then, the PV-induced climate effects were detected by conducting two parallel numerical experiments: a control (CT) run without PV plants and a PV run under the 12,000 GW scenario of PV deployment.

4. Results

4.1. Model evaluation

(1) Evaluation on regional scale

Although the WRF model outputs, such as the surface downward short-wave radiation (SW), 2-m air temperature (T2), 2-m relative humidity (RH2), surface pressure (PSFC), and 10-m wind speed (WS10),

have been widely found to be highly consistent with observations and reanalysis in China (Yang, 2015; Sun et al., 2018; Chang et al., 2020), the model performance was further evaluated by ERA5 reanalysis to indicate its applicability for this study.

Based on the monthly mean values of SW, T2, RH2, and PSFC from 2008 to 2012, the spatial correlation coefficients (COR) and root-mean-square errors (RMSE) between the CT run and ERA5 reanalysis were calculated for July and January. The Student's *t* test was involved to calculate the statistical significance of the correlations. Then, these CORs and the standardized deviations were presented on the Taylor diagrams (Taylor, 2001) to indicate how closely the simulated patterns match the ERA5 reanalysis. Here, the standardized deviations were the ratios of the variances in the modeled values to those of the ERA5 values.

As shown in Fig. 2, the modeled SW, T2, RH2, and PSFC were consistent with those obtained from ERA5 reanalysis for different seasons. CORs were greater than 0.7 in most cases (Fig. 2 and Table 3), and the standardized deviations of SW, T2 and PSFC were very close to 1.0. Compared with reanalysis results, the spatial distribution of SW was well reproduced by the WRF model, which was characterized by the abundant solar resources in the northwestern region of China, mostly greater than 250.0 W/m², even greater than 300.0 W/m², and less solar radiation around Sichuan Basin, lower than 150.0 W/m² (Figure not shown for brevity). The CORs of the daily SW were 0.82 and 0.73 for July and January, respectively, with the RMSEs ranging from 23.7 to 35.8 W/m² (Table 3).

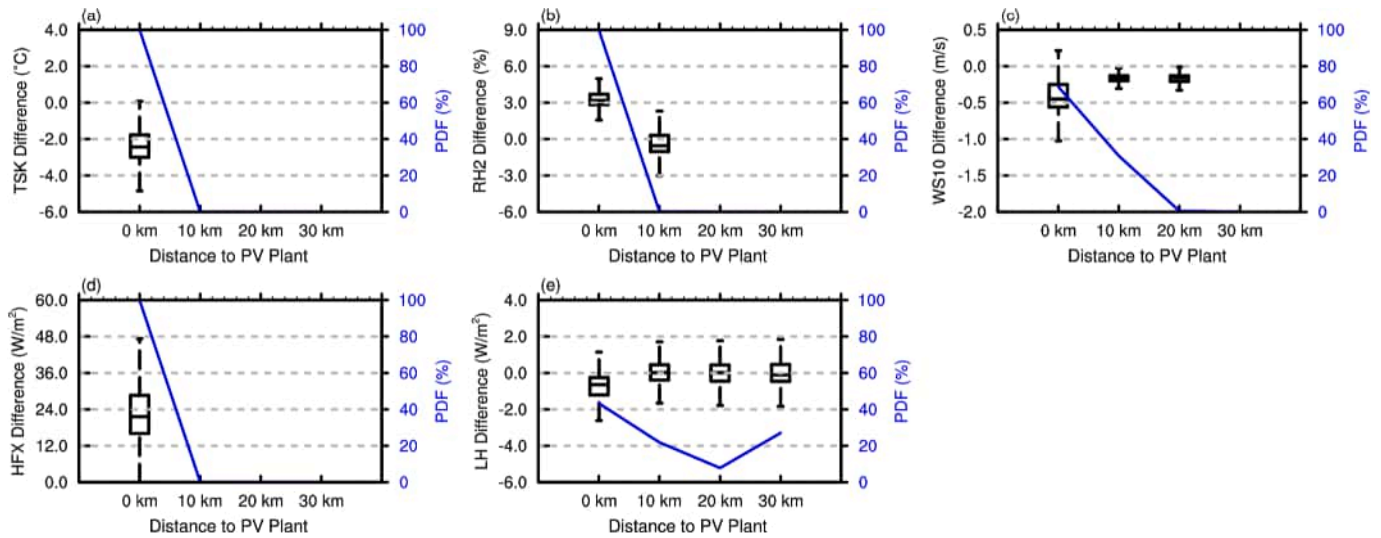


Fig. 4. Variations in the climate effects based on changes in the distance (black boxes) and probability density function (PDF) of the corresponding sample sizes (blue lines) in July. All values are averaged over the four subregions, which are classified based on the shaded grids in Fig. 3 by their distances to the PV plants. The vertical line extent shows the $1.5 \times$ interquartile range, and the box represents the 25th, 50th, and 75th percentiles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

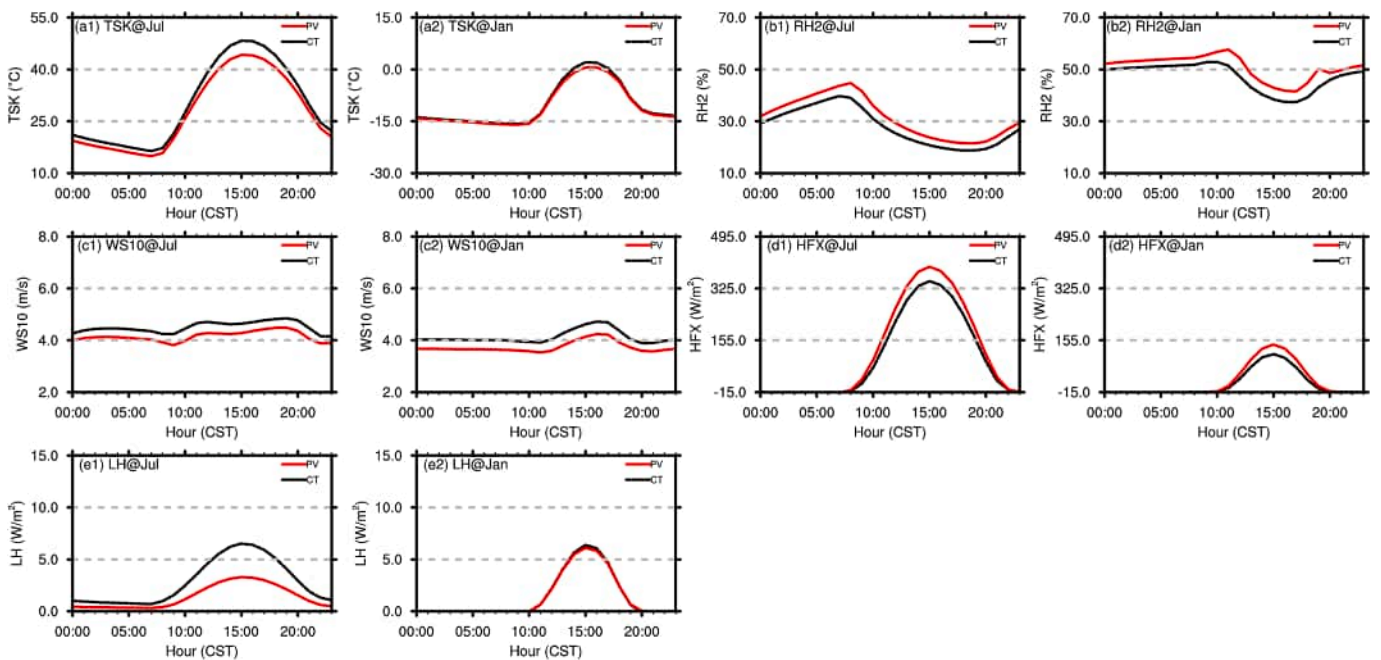


Fig. 5. Diurnal variations in (a) TSK, (b) RH2, (c) WS10, (d) HFX, and (e) LH over PV plant regions in (left) July and (right) January during the historical period (2008–2012). The X-axis represents one day in China Standard Time (CST).

The spatial pattern of the modeled T2 was also in good agreement with the ERA5 results, with CORs even ranging from 0.96 to 0.98 and RMSEs ranging from 2.7 to 3.2 °C during July and January (Table 3). Although the spatial correlation coefficients of RH2 were generally greater than 0.65 (Fig. 2), the RMSEs were still large (ranging from 11.8 to 22.6 %; Table 3), and the standardized deviation in January was lower than 0.8 (Fig. 2b). It is hypothesized that these biases were possibly related to the imperfect physical schemes of the WRF model and the uncertainty of the ERA5 reanalysis. However, the limited systematic bias was not a major problem for us, as the analysis method of the difference calculation could counteract this bias to some extent.

(2) Validation from two PV power plants

For the WRF model equipped with the PV plant parameterization, in situ observations from two PV plants during different seasons as described in Section 2.2, were used to validate this model's performance in capturing the variations of the near-surface meteorological variables. The statistical results indicated that this coupled WRF-PV model can reproduce the observed temporal patterns of the max daily temperature, land surface temperature, downward shortwave radiation, sensible heat flux, and latent heat flux over PV power plants, with correlation coefficients of 0.59–0.99 during different seasons and variables. This acceptable performance made this model a suitable tool for examining how PV plants alter climate (Chang et al., 2022). For a more detailed information about the validation and reliability of this model, refer to Chang et al. (2022).

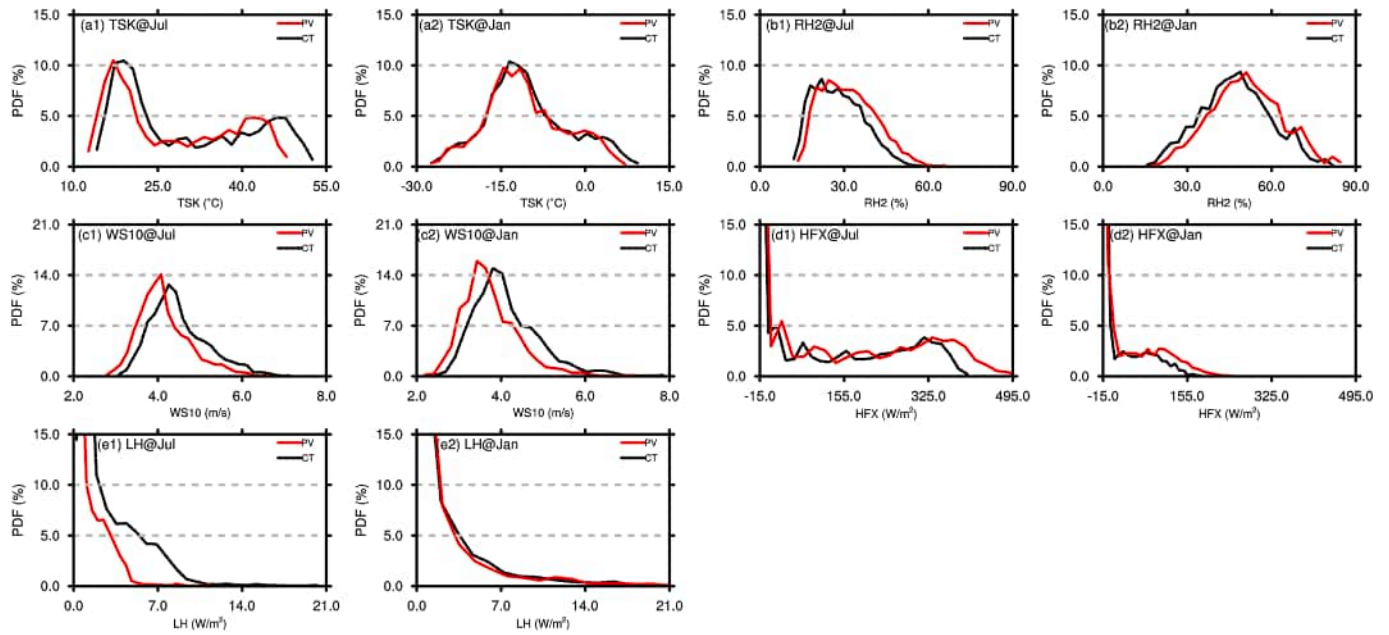


Fig. 6. Probability density functions of hourly (a) TSK, (b) RH2, (c) WS10, (d) HFX, and (e) LH over PV plant regions in July and January during the historical period (2008–2012).

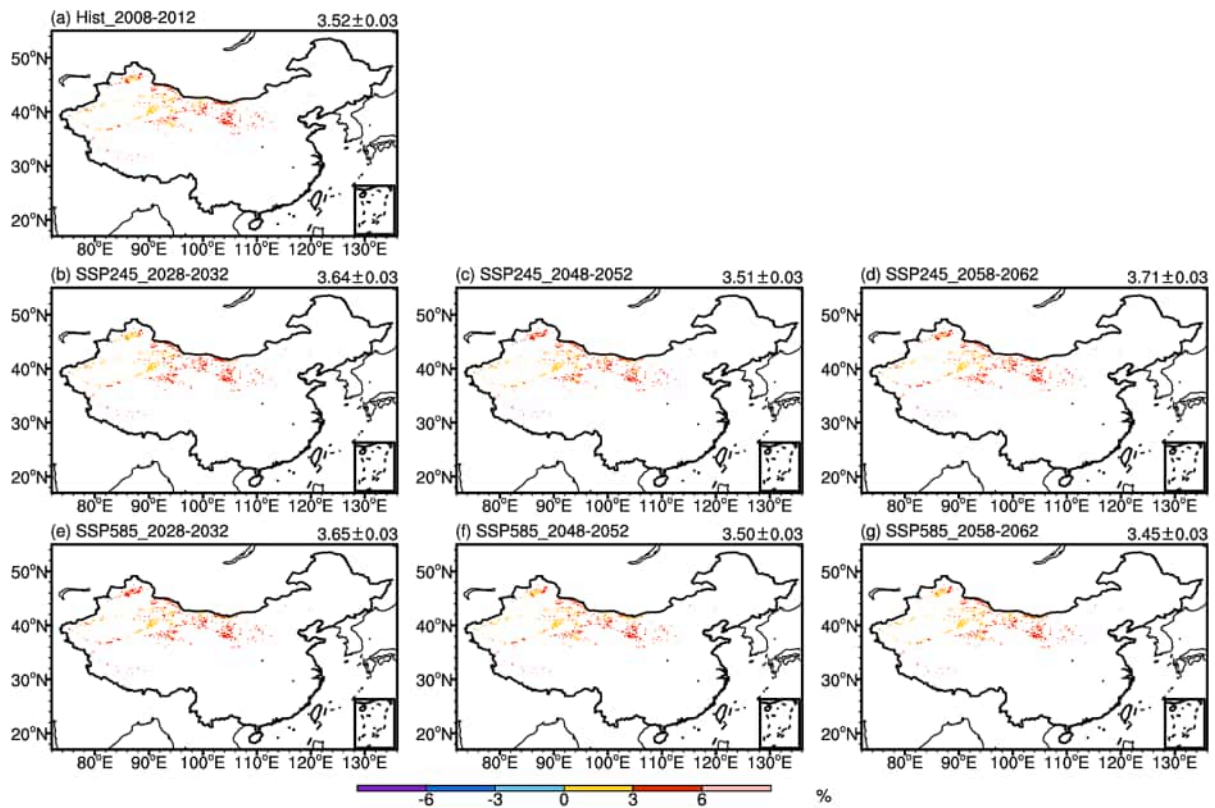


Fig. 7. (a) Historical and (b–g) projected changes in RH2 due to the benchmark PV deployment under the (b–d) SSP245 and (e–g) SSP585 scenarios for three future periods, (b, e) 2028–2032, (c, f) 2048–2052, and (d, g) 2058–2062. Regions with a 95% confidence level for the changes are displayed, and the changes averaged over PV plant regions with 95% confidence intervals (calculated based on $\bar{d}_{0.05} \pm t_{0.05} \times S_d / \sqrt{n}$) are labeled in the upper-right area of each plot.

4.2. Climate effects of PV plants

The potential climate effects of the PV plants under the benchmark deployment were computed for each grid cell as the difference between the WRF simulations with the PV parameterization turned on (PV run)

and turned off (CT run).

(1) Near-surface climate effects during the historical period

The PV-induced climate effects were limited to the near-surface

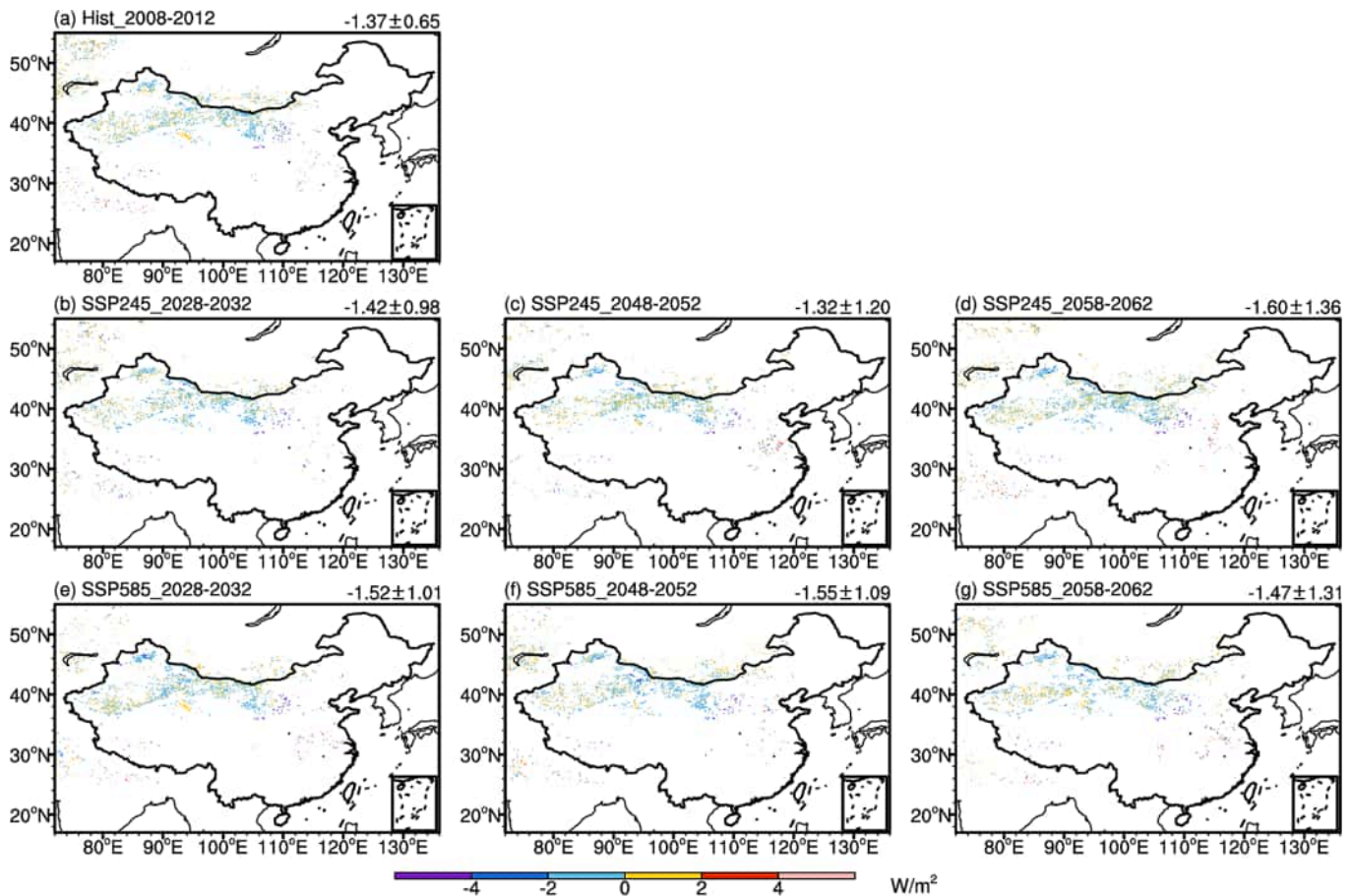


Fig. 8. Same as Fig. 7 but for the latent heat flux.

layer, and the intensity of these effects varied seasonally. In July, due to the physical shading of PV panels and the photovoltaic conversion, the skin temperature (TSK) over the PV plant regions decreased by an average of approximately 2.3°C (Fig. 3a and Table 4). Moreover, weak warming existed 20 m above the ground (Fig. 3b) and largely disappeared 60 m above the ground (Fig. 3c), which was closely related to the heating effect of the PV panels. Highly affected by the TSK reduction in Fig. 3a, RH2 increased by 3.5% (Fig. 3d and Table 4), and this anomalous humidity signal largely disappeared 20 m above the ground (Fig. 3e). Moreover, there were almost no anomalous surface pressure signals related to the deployment of the PV plants (Fig. 3f), indicating that their impact on the large-scale circulation system was limited. Subject to the dragging effect of PV panels, the wind speed consistently decreased, with an average decrease of 0.36 m/s at a height of 10 m (Fig. 3g and Table 4), and its horizontal range exceeded the PV plant local areas and reached 10–20 km along the downwind direction (see later analysis for details), while its vertical range reached 100 m (Fig. 3h) and even 200 m, but with significantly weakened intensity (Fig. 3i). Moreover, the sensible heating was stronger in the PV plant regions, with an average increase of approximately 18.9 W/m^2 (Fig. 3j and Table 4). However, the changes in the latent heat flux (LH) showed spatially scattered and varied horizontally, but the overall decrease was approximately 1.37 W/m^2 (Fig. 3k and Table 4).

In January, the response characteristics were essentially similar to those in July, and only the intensity was different (Table 4; figures not shown for brevity), mainly due to the different climates during winter and summer.

The near-surface climate effects of the PV plants were mostly confined to the local area. Based on their distances to the PV plant, the shaded grids in Fig. 3 were classified into four subregions, i.e., 0 km, 10

km, 20 km, and 30 km to the PV plant. The intensities of the effects in these four subregions were calculated for TSK, RH2, WS10, HFX, and LH (black box in Fig. 4), and their probability density functions (PDFs) of the sample sizes were also indicated by the blue curves in Fig. 4. In July, the climate effects, such as the decrease in TSK, the increase in RH2, and the increase in HFX, were essentially maintained within the PV plant regions, and the PDFs of the 0 km subregion all exceeded 99.5% (Fig. 4a, 4b, and 4d); WS10 consistently decreased in all subregions, and the decrease in the 0 km subregion was the largest with the highest PDF (68.7%); wind speed reductions also occurred in the 10 km and 20 km subregions, suggesting that the wind speed reduction could extend beyond the PV plant region and reach a horizontal range of 10–20 km downstream (Fig. 4c). In the four subregions, the median LHs were 0.64 W/m^2 , 0.02 W/m^2 , 0.02 W/m^2 , and 0.11 W/m^2 , and their PDFs were 43.3%, 21.9%, 7.8%, and 27.0%, respectively, indicating that the response of LH was spatially scattered and varied horizontally, and the areas with stronger responses were mainly located within the PV plant region (Fig. 4e). Indeed, the deployment of PV plants can impose various and even opposing effects on the “under-PV” environment. For example, PV panels lower the TSK (Fig. 3a) through their shading effects, and consequently reduce the rate of thermally induced water loss from the “under-PV” soil (Yue et al., 2021). Conversely, PV panels heat the surrounding air more rapidly (Fig. 3j), thereby increasing the evapotranspiration water loss. These complex interaction processes within PV plants are probably the main causes for the response features of the latent heat flux indicated in Fig. 3k and 4e.

The aforementioned near-surface climate effects of the PV plants were also characterized by diurnal variations. The average TSK decrease over the PV plant regions was significantly larger during the daytime than at night, and was larger in July than in January (Fig. 5a). In

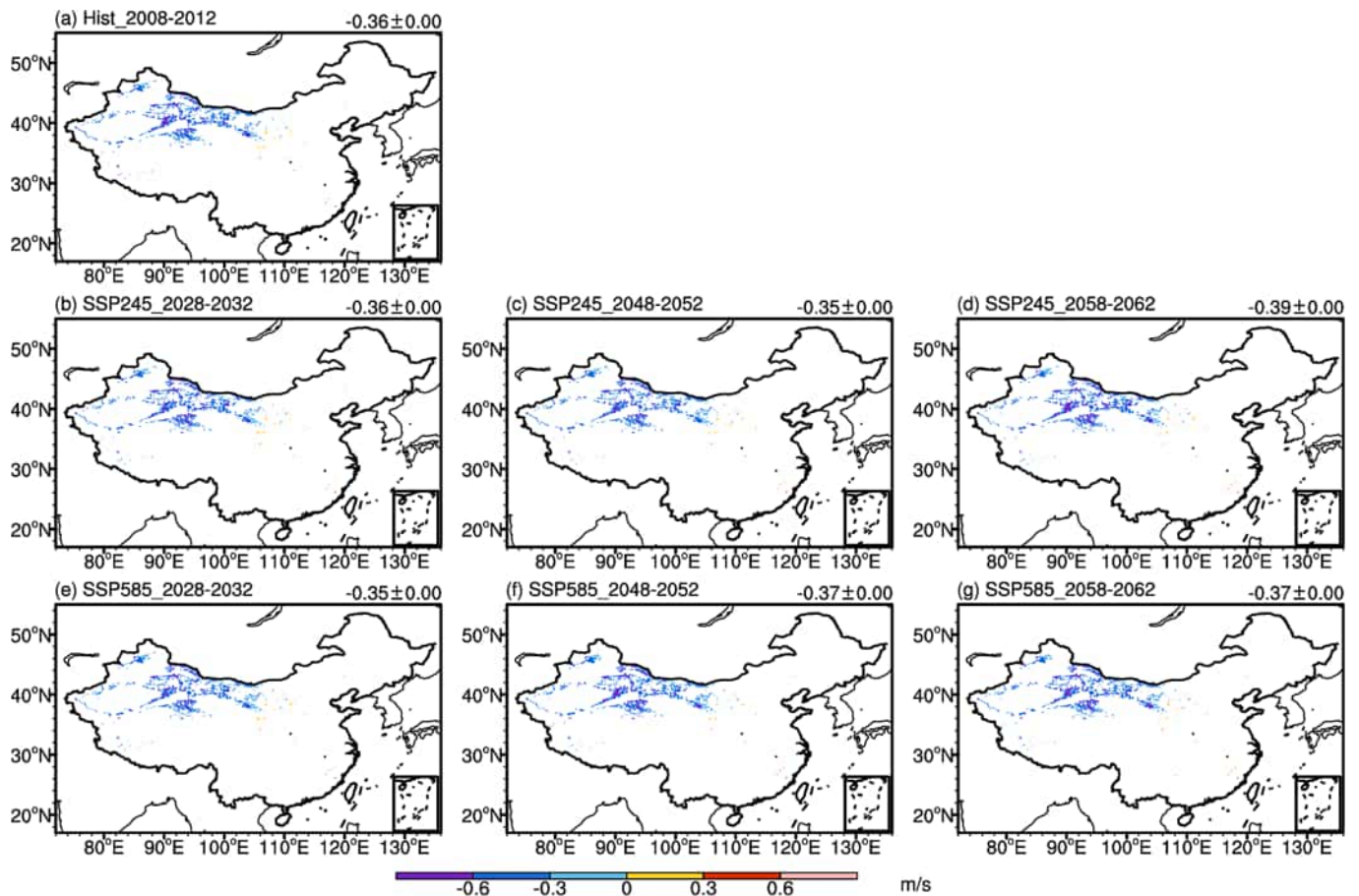


Fig. 9. Same as Fig. 7 but for the 10-m wind speed.

contrast, the increase in RH2 and the decrease in WS10 showed no obvious diurnal variations (Fig. 5b and 5c). The increase in HFX expressed obvious diurnal variations; it was significant during the daytime, whereas there was almost no signal at night (Fig. 5d). In July, the decrease in LH was significantly stronger during the daytime, and the response signal in January was weak, and decreased weakly only during the daytime (Fig. 5e).

Moreover, the deployment of the utility-scale PV plants also changed the probability density distributions of local meteorological elements. Compared with the CT run, the probability density curve of TSK from the PV run (red line) shifted to the left, showing cooling effects, and the higher the background temperature was, the more obvious the cooling effects (Fig. 6a). The probability density curve of RH2 shifted to the right, showing a consistent humidification effect (Fig. 6b). The probability density curve of WS10 shifted toward the low wind speed zone, which was less dependent on the climate background (Fig. 6c). However, the probability density change in HFX was closely related to the climate background; the greater the background HFX was, the stronger the heating effect (Fig. 6d). The probability density curve of LH shifted toward the low value zone, and the decrease in LH was more significant in July than in January (Fig. 6e).

(2) PV-induced climate effects under different scenarios

The PV-induced climate effects were largely similar among climate scenarios, and only the intensity differed. The modeling results indicated that the projected deployment of utility-scale PV plants could cause an increase in RH2 and a decrease in LH during both the historical and the projected future periods (Figs. 7 and 8). Compared with the historical period, the humidification effects during the three future periods under

the SSP245 scenario were enhanced with the strongest intensity during 2058–2062, followed by 2028–2032. The humidification effect under the SSP585 scenario was the weakest during 2058–2062, and it was of lower intensity than that during the historical period (Fig. 7). Similarly, the intensities of LH reduction under the SSP245 scenario were enhanced with the strongest intensity during 2058–2062. The LH reduction effect under the SSP585 scenario was weak but was generally stronger than that during the historical period (Fig. 8). Notably, under the SSP245 scenario, the PV-induced near-surface humidification effect and latent heat of evaporation reduction effect were more significant, which could be more conducive to the growth and restoration of local vegetation.

According to the results for both the historical and future periods, the deployment of utility-scale PV plants could cause lower wind speed in the near-surface layer (Fig. 9). Compared with the historical period, the wind resistance effects under the SSP245 and SSP585 scenarios were not very different, but they were slightly stronger than that in the historical period (Fig. 9), indicating an overall wind-proof and sand-fixing effect, which is conducive to desertification control in Gobi Desert area.

The climate effects caused by the deployment of PV plants are equivalent to or even greater than projected climate variability. Here, the projected climate variability under the SSP245 scenario was evaluated based on the anomaly computed with respect to the historical results following Yadidya and Rao (2022), with slight modifications. As shown in Fig. 10, in July, the intensity of PV-induced effects on RH2 (Fig. 10a1, blue column) was stronger than the projected RH2 variability under the SSP245 scenario (Fig. 10a1, red column); however, in January, the PV-induced effect was weaker than the projected RH2 variability under this SSP scenario (Fig. 10a2). Although the reduction in the latent heat of evaporation due to physical shading of the PV panels

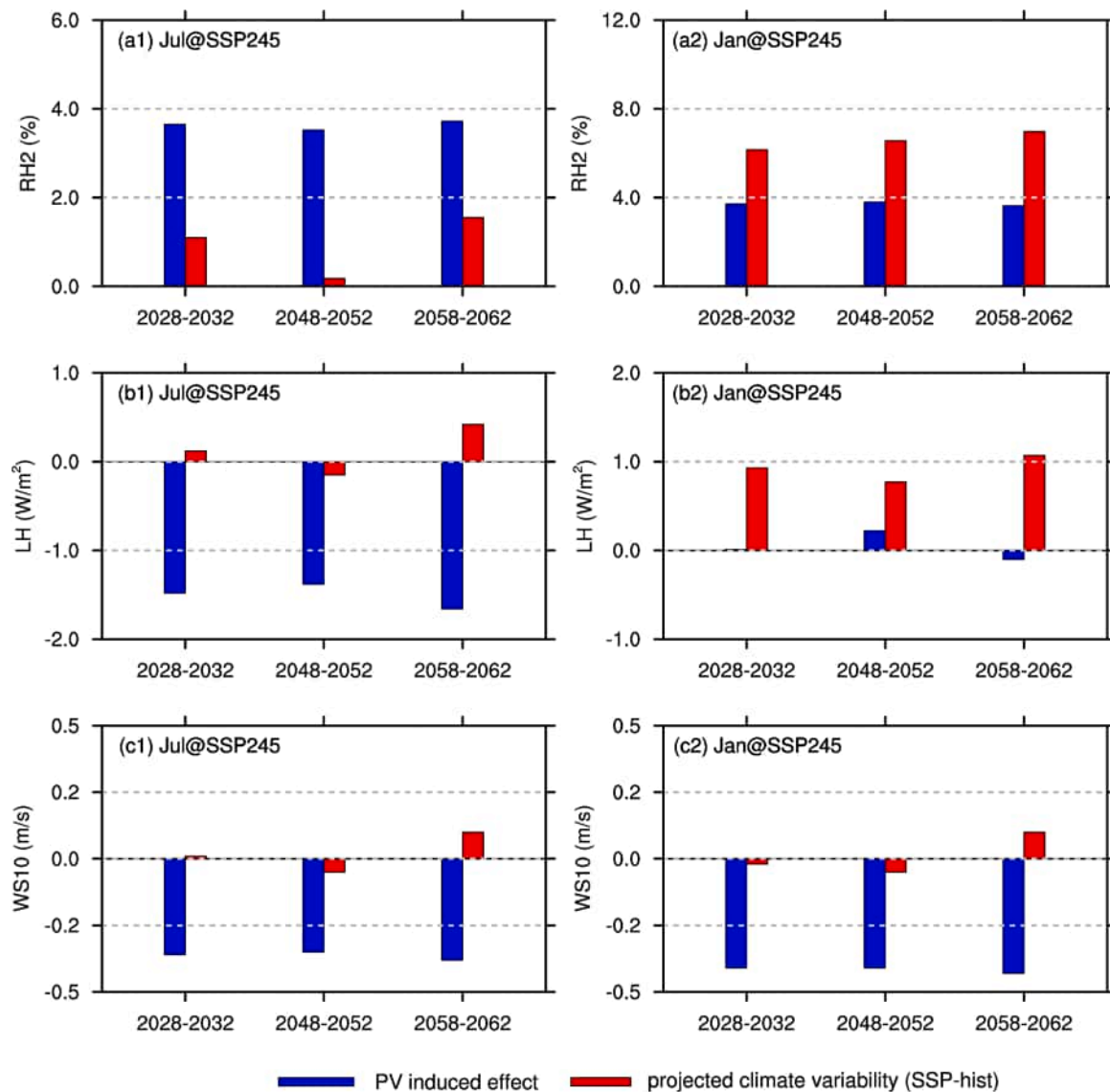


Fig. 10. Comparison of the PV-induced effects (blue bars) and the projected climate variability (red bars) averaged over PV plant regions under the SSP245 emission scenario. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

was negligible in January (Fig. 10b2), it was significantly stronger in July (the vegetation growth period) than the projected latent heat variability (Fig. 10b1). Moreover, the non-negligible wind resistance effect of the PV plants would alter the projected climate variability in WS10 under the future scenario (Fig. 10c), which can play a positive role in desertification control over the PV plant regions.

5. Discussions and future work

Based on a regional climate model, the potential climate effects of PV plants over the continental China were examined from both current and future perspectives. At this scale, several simplifying assumptions that contributed to uncertainty in the model predictions were included in this study, such as our insufficient consideration of the PV panels rain redistribution effects (Wu et al., 2022), and representation of different solar tracking systems (Heusinger et al., 2020). Specifically, individual PV panel and the corresponding microclimate processes could not be precisely resolved at the spatial resolution of our regional climate model, namely, approximately 10-km horizontal resolution and 32 telescoped layers. For example, the heating effects of the PV panels on the surrounding air (about 2 m above the ground) was reflected on a

higher vertical layer and the 2-m air temperature was highly affected by the skin temperature in our model. Therefore, the higher RH2 and T20 were detected over the PV plant regions in this study, which is consistent with the field studies in Qinghai barren area (Gao et al., 2016; Wu et al., 2020). Moreover, our PV deployment scenario was designed at the continental scale, whose capacity is relatively promising, and this scale fills the gap between the smaller isolated PV plants and global-scale climate models. Despite these limitations, our results indicate the favorable climate effects in the northwestern Gobi Deserts are still suitable and referenced under the scenario projected by GEIDCO (2021) based on two aspects. First, the statistically significant changes in many meteorological elements caused by PV plants were stable and mainly occurred in the local areas, indicating these PV-induced effects are direct and would occur if the PV panels were installed. Second, the model indicated that the impact of the installed capacity on the climate effects is more in terms of spatial coverage than intensity (Chang et al., 2020).

In addition, the climate effects revealed in this study are predominantly direct, as discussed in Section 3.1, which may fail to capture the long-term cumulative effects. Therefore, future work is needed to address this issue by conducting the long-term simulations under different scenarios, and the dependence of the PV-induced effects on

climate and soil conditions should be also considered. Meanwhile, when these near-surface meteorological changes caused by PV plants are absorbed into an ecological model, such as the carbon exchange between vegetation, soil and atmosphere model (Gu et al., 2017; Yu et al., 2020), it will be possible to predict the ecological effects of utility-scale PV plants quantitatively.

6. Conclusions

To characterize and quantify the PV-induced climate effects under different scenarios, a benchmark PV deployment was firstly designed to roughly represent China's solar energy development in the context of its dual carbon target. Each PV plant in this designed scenario was parameterized as a shortwave radiation sink and a sensible heat flux source in the WRF model. The modeling results indicated the following:

- (1) The projected utility-scale PV deployment in the northwestern region, which is covered by sand and includes the Gobi Deserts, would favor higher relative humidity, lower evaporation and wind speed under current and future climate scenarios.
- (2) These PV-induced climate effects are predominantly local to the PV plant regions, and shows seasonal and diurnal variations, namely, they are stronger in the summer and daytime, mainly affected by the photovoltaic conversion efficiency.
- (3) These local climate effects are approximately equivalent to or even stronger than the projected climate variability, especially over the PV plant regions.
- (4) The climate effects are largely similar among climate scenarios, and only the intensity differed with relatively stronger intensity in the SSP245 scenario.

These favorable changes in humidity, evaporation and wind speed, as predicted in this study, would contribute to improving ecological conditions, which are in line with the previous reports about the vigorously growth of vegetation in PV plants established in dry climates (Bousselot et al., 2017; Liu et al., 2020; Xia et al., 2022). Thus, the deployment of the PV plants not only reduce carbon emissions, but also create new environmental benefits through changes in the near-surface climate, especially in Gobi Deserts.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Bousselot, J., Slabe, T., Klett, J., Koski, R., 2017. Photovoltaic array influences the growth of green roof plants. *J. Living Archit.* 4 (3), 9–18. <https://doi.org/10.6084/m9.figshare.11977782>.

Broadbent, A.M., Krayenhoff, E.S., Georgescu, M., Sailor, D.J., 2019. The observed effects of utility-scale photovoltaics on near-surface air temperature and energy balance. *J. Appl. Meteorol. Climatol.* 58 (5), 989–1006.

Chang, R., Shen, Y., Luo, Y., Wang, B., Yang, Z., Guo, P., 2018. Observed surface radiation and temperature impacts from the large-scale deployment of photovoltaics in the barren area of Gonghe, China. *Renewable Energy*. 118, 131–137.

Chang, R., Luo, Y., Zhu, R., 2020. Simulated local climatic impacts of large-scale photovoltaics over the barren area of Qinghai, China. *Renewable Energy*. 145, 478–489.

Chang, R., Yan, Y., Luo, Y., Xiao, C., Wu, C., Jiang, J., Shi, W., 2022. A coupled WRF-PV mesoscale model simulating the near-surface climate of utility-scale photovoltaic plants. *Sol. Energy* 245, 278–289.

Chen, F., Dudhia, J., 2001. Coupling an advanced land surface–hydrology model with the Penn State–NCAR MM5 modeling system. Part I: Model implementation and sensitivity. *Mon. Wea. Rev.* 129, 569–585.

Dudhia, J., 1989. Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model. *J. Atmos. Sci.* 46, 3077–3107.

Fthenakis, V., Yu, Y., 2013. Analysis of the potential for a heat island effect in large solar farms. In: IEEE 39th Photovoltaic Specialists Conference, pp. 3362–3366.

Gao, X., Yang, L., Lv, F., Ma, L., Li, H., Hui, X., Hou, X., 2016. Observational study on the impact of the large solar farm on air temperature and humidity in desert areas of Golmud (in Chinese). *Acta Energetica Solaris Sinica*. 37 (11), 2909–2915.

GEIDCO, 2021. *China's 2030 energy and electric power planning and Outlook for 2060*. Global Energy Interconnection Development Cooperation Organization (GEIDCO). Retrieved from <http://www.chinasmartgrid.com.cn/news/20210319/638159.shtml>.

Gu, F., Zhang, Y., Huang, M., Tao, B., Liu, Z., Hao, M., Guo, R., 2017. Climate-driven uncertainties in modeling terrestrial ecosystem net primary productivity in China. *Agric. For. Meteorol.* 246, 123–132.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horanyi, A., Muñoz-Sabater, J., et al., 2020. The ERA5 global reanalysis. *Q. J. R. Meteorol. Soc.* 146 (730), 1999–2049.

Heusinger, J., Broadbent, A.M., Sailor, D.J., Georgescu, M., 2020. Introduction, evaluation and application of an energy balance model for photovoltaic modules. *Sol. Energy* 195, 382–395.

IRENA, 2023. *Renewable capacity statistics 2023*. International Renewable Energy Agency (IRENA). Retrieved from <https://www.irena.org/Publications/2023/Mar/Renewable-capacity-statistics-2023>.

Jiang, J., Gao, X., Lv, Q., Li, Z., Li, P., 2021. Observed impacts of utility-scale photovoltaics plant on local air temperature and energy partitioning in barren areas. *Renew. Energy* 174, 157–169.

Liu, L.B., Wang, Y., Wang, Z., Li, S., Li, J., He, G., Li, Y., et al., 2022. Potential contributions of wind and solar to China's carbon neutrality. *Resources. Conserv. Recycl.* 180, 106155.

Liu, Y., Zhang, R., Ma, X., Wu, G., 2020. Combined ecological and economic benefits of the solar photovoltaic industry in arid sandy ecosystems. *J. Clean. Prod.* 262, 121376.

Masson, V., Bonhomme, M., Salagnac, J.L., et al., 2014. Solar panels reduce both global warming and urban heat island. *Front. Environ. Sci.*, 2, Jun, 2014, Art no. 14, 10.3389/fenvs.2014.00014.

Mlawer, E.J., Taubman, S.J., Brown, P.D., Iacono, M.J., Clough, S.A., 1997. Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the long-wave. *J. Geophys. Res. Atmos.* 102, 16663–16682.

Nakanishi, M., Niino, H., 2006. An improved Mellor–Yamada level-3 model: Its numerical stability and application to a regional prediction of advection fog. *Bound.-Layer Meteorol.* 119, 397–407.

Salamanca, F., Georgescu, M., Mahalov, A., Moustau, M., Martilli, A., 2016. Citywide impacts of cool roof and rooftop solar photovoltaic deployment on near-surface air temperature and cooling energy demand. *Boundary-Layer Meteorol.* 161, 203–221.

Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D.O., Liu, Z., Berner, J., Wang, W., Powers, J.G., Duda, M.G., Barker, D., Huang, X., 2021. A Description of the Advanced Research WRF Model Version 4.3 (No. NCAR/TN-556+STR). doi: 10.5065/1dth-6p97.

Sun, H., Luo, Y., Zhao, Z., Chang, R., 2018. The impacts of Chinese farms on climate. *J. Geophys. Res. Atmosphere*. 123, 5177–5187.

Taha, H., 2013. The potential for air-temperature impact from large-scale deployment for solar photovoltaics arrays in urban areas. *Sol. Energy* 91, 358–367.

Taylor, K., 2001. Summarizing multiple aspects of model performance in a single diagram. *J. Geophys. Res.* 106 (D7), 7183–7192.

Wang, Y., Chao, Q., Zhao, L., Chang, R., 2022. Assessment of wind and photovoltaic power potential in China. *Carb Neutrality* 1, 1–15. <https://doi.org/10.1007/s43979-022-00020-w>.

Wu, C., Liu, H., Yu, Y., Zhao, W., Liu, J., Yu, H., Yetemen, O., 2022. Ecohydrological effects of photovoltaic solar farms on soil microclimates and moisture regimes in arid Northwest China: A modelling study. *Sci. Total Environ.* 802, 149946.

Wu, W., Yue, S., Zhou, X., Guo, M., Wang, J., Ren, L., Yuan, B., 2020. Observational study on the impact of large-scale photovoltaic development in deserts on local air temperature and humidity. *Sustainability*. 12 (8), 3403.

Xia, Z., Li, Y., Zhang, W., Chen, R., Guo, S., Zhang, P., Du, P., 2022. Solar photovoltaic program helps turn deserts green in China: Evidence from satellite monitoring. *J. Environ. Manage.* 324, 116338.

Xu, Z. F., Han, Y., Tam, C.-Y., Yang, Z.-L., Fu, C.B., 2021. Bias-corrected CMIP6 global dataset for dynamical downscaling of the Earth's historical and future climate (1979–2100) (V4). *Science Data Bank*. 2021-01-04.

Yadidya, B., Rao, A.D., 2022. Projected climate variability of internal waves in the Andaman Sea. *Commun Earth Environ* 3, 252. <https://doi.org/10.1038/s43247-022-00574-8>.

Yang, L., 2015. Study on local Climate effect of the large solar farm in desert areas of Golmud, Cold and Arid Regions Environment and Engineering Research Institute, Chinese Academy of Science, *Master's Degree Thesis*, 2015 (in Chinese).

Yu, L., Gu, F., Huang, M., Tao, B., Hao, M., Wang, Z., 2020. Impacts of 1.5°C and 2°C global warming on net primary productivity and carbon balance in China's Terrestrial Ecosystems. *Sustainability* 12, 2849.

Yue, S., Guo, M., Zou, P., Wu, W., Zhou, X., 2021. Effects of photovoltaic panels on soil temperature and moisture in desert areas. *Environ. Sci. Pollut. Res.* 28 (12), 1–13.
Zhang, X., Xu, M., 2020. Assessing the effects of photovoltaic power plants on surface temperature using remote sensing techniques. *Remote Sens. (Basel)* 12, 19.

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This chapter deals with the calculation of crop evapotranspiration (ET_c) under standard conditions. No limitations are placed on crop growth or evapotranspiration from soil water and salinity stress, crop density, pests and diseases, weed infestation or low fertility. ET_c is determined by the crop coefficient approach whereby the effect of the various weather conditions are incorporated into ET_o and the crop characteristics into the K_c coefficient:

$$ET_c = K_c ET_o \quad (58)$$

The effect of both crop transpiration and soil evaporation are integrated into a single crop coefficient. The K_c coefficient incorporates crop characteristics and averaged effects of evaporation from the soil. For normal irrigation planning and

management purposes, for the development of basic irrigation schedules, and for most hydrologic water balance studies, average crop coefficients are relevant and more convenient than the K_c computed on a daily time step using a separate crop and soil coefficient (Chapter 7). Only when values for K_c are needed on a daily basis for specific fields of crops and for specific years, must a separate transpiration and evaporation coefficient ($K_{cb} + K_e$) be considered. The calculation procedure for crop evapotranspiration, ET_c , consists of:

1. identifying the crop growth stages, determining their lengths, and selecting the corresponding K_c coefficients;
2. adjusting the selected K_c coefficients for frequency of wetting or climatic conditions during the stage;
3. constructing the crop coefficient curve (allowing one to determine K_c values for any period during the growing period); and
4. calculating ET_c as the product of ET_o and K_c .

Length of growth stages

FAO Irrigation and Drainage Paper No. 24 provides general lengths for the four distinct growth stages and the total growing period for various types of climates and locations. This information has been supplemented from other sources and is summarized in Table 11.

In some situations, the time of emergence of vegetation and the time of effective full cover can be predicted using cumulative degree-based regression equations or by more sophisticated plant growth models. These types of models should be verified or validated for the local area or for a specific crop variety using local observations.

TABLE 11. Lengths of crop development stages* for various planting periods and climatic regions (days)

Crop	Init. (L_{ini})	Dev. (L_{dev})	Mid (L_{mid})	Late (L_{late})	Total	Plant Date	Region
a. Small Vegetables							
Broccoli	35	45	40	15	135	Sept	Calif. Desert, USA
Cabbage	40	60	50	15	165	Sept	Calif. Desert, USA
Carrots	20	30	50/30	20	100	Oct/Jan	Arid climate
	30	40	60	20	150	Feb/Mar	Mediterranean
	30	50	90	30	200	Oct	Calif. Desert, USA
Cauliflower	35	50	40	15	140	Sept	Calif. Desert, USA
Celery	25	40	95	20	180	Oct	(Semi) Arid
	25	40	45	15	125	April	Mediterranean

	30	55	105	20	210	Jan	(Semi) Arid
Crucifers ¹	20	30	20	10	80	April	Mediterranean
	25	35	25	10	95	February	Mediterranean
	30	35	90	40	195	Oct/Nov	Mediterranean
Lettuce	20	30	15	10	75	April	Mediterranean
	30	40	25	10	105	Nov/Jan	Mediterranean
	25	35	30	10	100	Oct/Nov	Arid Region
	35	50	45	10	140	Feb	Mediterranean
Onion (dry)	15	25	70	40	150	April	Mediterranean
	20	35	110	45	210	Oct; Jan.	Arid Region; Calif.
Onion (green)	25	30	10	5	70	April/May	Mediterranean
	20	45	20	10	95	October	Arid Region
	30	55	55	40	180	March	Calif., USA
Onion (seed)	20	45	165	45	275	Sept	Calif. Desert, USA
Spinach	20	20	15/25	5	60/70	Apr; Sep/Oct	Mediterranean
	20	30	40	10	100	November	Arid Region
Radish	5	10	15	5	35	Mar/Apr	Medit.; Europe
	10	10	15	5	40	Winter	Arid Region
b. Vegetables - Solanum Family (Solanaceae)							
Egg plant	30	40	40	20	130\1	October	Arid Region
	30	45	40	25	40	May/June	Mediterranean
Sweet peppers (bell)	25/30	35	40	20	125	April/June	Europe and Medit.
	30	40	110	30	210	October	Arid Region
Tomato	30	40	40	25	135	January	Arid Region
	35	40	50	30	155	Apr/May	Calif., USA
	25	40	60	30	155	Jan	Calif. Desert, USA
	35	45	70	30	180	Oct/Nov	Arid Region
	30	40	45	30	145	April/May	Mediterranean
c. Vegetables - Cucumber Family (Cucurbitaceae)							
Cantaloupe	30	45	35	10	120	Jan	Calif., USA
	10	60	25	25	120	Aug	Calif., USA
Cucumber	20	30	40	15	105	June/Aug	Arid Region
	25	35	50	20	130	Nov; Feb	Arid Region
Pumpkin, Winter squash	20	30	30	20	100	Mar, Aug	Mediterranean
	25	35	35	25	120	June	Europe
Squash, Zucchini	25	35	25	15	100	Apr; Dec.	Medit.; Arid Reg.
	20	30	25	15	90	May/June	Medit.; Europe
Sweet melons	25	35	40	20	120	May	Mediterranean
	30	30	50	30	140	March	Calif., USA
	15	40	65	15	135	Aug	Calif. Desert, USA
	30	45	65	20	160	Dec/Jan	Arid Region
Water melons	20	30	30	30	110	April	Italy

	10	20	20	30	80	Mat/Aug	Near East (desert)
d. Roots and Tubers							
Beets, table	15	25	20	10	70	Apr/May	Mediterranean
	25	30	25	10	90	Feb/Mar	Mediterranean & Arid
Cassava: year 1	20	40	90	60	210	Rainy	Tropical regions
year 2	150	40	110	60	360	season	
Potato	25	30	30/45	30	115/130	Jan/Nov	(Semi) Arid Climate
	25	30	45	30	130	May	Continental Climate
	30	35	50	30	145	April	Europe
	45	30	70	20	165	Apr/May	Idaho, USA
	30	35	50	25	140	Dec	Calif. Desert, USA
Sweet potato	20	30	60	40	150	April	Mediterranean
	15	30	50	30	125	Rainy seas.	Tropical regions
Sugarbeet	30	45	90	15	180	March	Calif., USA
	25	30	90	10	155	June	Calif., USA
	25	65	100	65	255	Sept	Calif. Desert, USA
	50	40	50	40	180	April	Idaho, USA
	25	35	50	50	160	May	Mediterranean
	45	75	80	30	230	November	Mediterranean
	35	60	70	40	205	November	Arid Regions
e. Legumes (<i>Leguminosae</i>)							
Beans (green)	20	30	30	10	90	Feb/Mar	Calif., Mediterranean
	15	25	25	10	75	Aug/Sep	Calif., Egypt, Lebanon
Beans (dry)	20	30	40	20	110	May/June	Continental Climates
	15	25	35	20	95	June	Pakistan, Calif.
	25	25	30	20	100	June	Idaho, USA
Faba bean, broad bean	15	25	35	15	90	May	Europe
	20	30	35	15	100	Mar/Apr	Mediterranean
- dry	90	45	40	60	235	Nov	Europe
- green	90	45	40	0	175	Nov	Europe
Green gram, cowpeas	20	30	30	20	110	March	Mediterranean
Groundnut	25	35	45	25	130	Dry	West Africa
	35	35	35	35	140	season	High Latitudes
	35	45	35	25	140	May May/June	Mediterranean
Lentil	20	30	60	40	150	April	Europe
	25	35	70	40	170	Oct/Nov	Arid Region
Peas	15	25	35	15	90	May	Europe

	20	30	35	15	100	Mar/Apr	Mediterranean
	35	25	30	20	110	April	Idaho, USA
Soybeans	15	15	40	15	85	Dec	Tropics
	20	30/35	60	25	140	May	Central USA
	20	25	75	30	150	June	Japan
f. Perennial Vegetables (with winter dormancy and initially bare or mulched soil)							
Artichoke	40	40	250	30	360	Apr (1 st yr)	California
	20	25	250	30	325	May (2 nd yr)	(cut in May)
Asparagus	50	30	100	50	230	Feb	Warm Winter
	90	30	200	45	365	Feb	Mediterranean
g. Fibre Crops							
Cotton	30	50	60	55	195	Mar-May	Egypt; Pakistan; Calif.
	45	90	45	45	225	Mar	Calif. Desert, USA
	30	50	60	55	195	Sept	Yemen
	30	50	55	45	180	April	Texas
Flax	25	35	50	40	150	April	Europe
	30	40	100	50	220	October	Arizona
h. Oil Crops							
Castor beans	25	40	65	50	180	March	(Semi) Arid Climates
	20	40	50	25	135	Nov.	Indonesia
Safflower	20	35	45	25	125	April	California, USA
	25	35	55	30	145	Mar	High Latitudes
	35	55	60	40	190	Oct/Nov	Arid Region
Sesame	20	30	40	20	100	June	China
Sunflower	25	35	45	25	130	April/May	Medit.; California
i. Cereals							
Barley/Oats/Wheat	15	25	50	30	120	November	Central India
	20	25	60	30	135	March/Apr	35-45 °L
	15	30	65	40	150	July	East Africa
	40	30	40	20	130	Apr	
	40	60	60	40	200	Nov	
	20	50	60	30	160	Dec	Calif. Desert, USA
Winter Wheat	20 ²	60 ²	70	30	180	December	Calif., USA
	30	140	40	30	240	November	Mediterranean
	160	75	75	25	335	October	Idaho, USA
Grains (small)	20	30	60	40	150	April	Mediterranean
	25	35	65	40	165	Oct/Nov	Pakistan; Arid Reg.
Maize (grain)	30	50	60	40	180	April	East Africa (alt.)
	25	40	45	30	140	Dec/Jan	Arid Climate
	20	35	40	30	125	June	Nigeria (humid)

	20	35	40	30	125	October	India (dry, cool)
	30	40	50	30	150	April	Spain (spr, sum.); Calif.
	30	40	50	50	170	April	Idaho, USA
Maize (sweet)	20	20	30	10	80	March	Philippines
	20	25	25	10	80	May/June	Mediterranean
	20	30	50/30	10	90	Oct/Dec	Arid Climate
	30	30	30	103	110	April	Idaho, USA
	20	40	70	10	140	Jan	Calif. Desert, USA
Millet	15	25	40	25	105	June	Pakistan
	20	30	55	35	140	April	Central USA
Sorghum	20	35	40	30	130	May/June	USA, Pakis., Med.
	20	35	45	30	140	Mar/April	Arid Region
Rice	30	30	60	30	150	Dec; May	Tropics; Mediterranean
	30	30.	80	40	180	May	Tropics
j. Forages							
Alfalfa, total season ⁴	10	30	var.	var.	var.		last -4°C in spring until first -4°C in fall
Alfalfa ⁴ 1 st cutting cycle	10	20	20	10	60	Jan Apr (last - 4°C)	Calif., USA.
	10	30	25	10	75		Idaho, USA.
Alfalfa ⁴ , other cutting cycles	5	10	10	5	30	Mar	Calif., USA.
	5	20	10	10	45	Jun	Idaho, USA.
Bermuda for seed	10	25	35	35	105	March	Calif. Desert, USA
Bermuda for hay (several cuttings)	10	15	75	35	135	---	Calif. Desert, USA
Grass Pasture ⁴	10	20	--	--	--		7 days before last -4°C in spring until 7 days after first -4°C in fall
Sudan, 1 st cutting cycle	25	25	15	10	75	Apr	Calif. Desert, USA
Sudan, other cutting cycles	3	15	12	7	37	June	Calif. Desert, USA
k. Sugar Cane							
Sugarcane, virgin	35	60	190	120	405		Low Latitudes
	50	70	220	140	480		Tropics
	75	105	330	210	720		Hawaii, USA
Sugarcane, ratoon	25	70	135	50	280		Low Latitudes
	30	50	180	60	320		Tropics
	35	105	210	70	420		Hawaii, USA
l. Tropical Fruits and Trees							
Banana, 1 st yr	120	90	120	60	390	Mar	Mediterranean
Banana, 2 nd yr	120	60	180	5	365	Feb	Mediterranean

Pineapple	60	120	600	10	790		Hawaii, USA
m. Grapes and Berries							
Grapes	20	40	120	60	240	April	Low Latitudes
	20	50	75	60	205	Mar	Calif., USA
	20	50	90	20	180	May	High Latitudes
	30	60	40	80	210	April	Mid Latitudes (wine)
Hops	25	40	80	10	155	April	Idaho, USA
n. Fruit Trees							
Citrus	60	90	120	95	365	Jan	Mediterranean
Deciduous Orchard	20	70	90	30	210	March	High Latitudes
	20	70	120	60	270	March	Low Latitudes
	30	50	130	30	240	March	Calif., USA
Olives	30	90	60	90	2705	March	Mediterranean
Pistachios	20	60	30	40	150	Feb	Mediterranean
Walnuts	20	10	130	30	190	April	Utah, USA
o. Wetlands - Temperate Climate							
Wetlands (Cattails, Bulrush)	10	30	80	20	140	May	Utah, USA; killing frost
	180	60	90	35	365	November	Florida, USA
Wetlands (short veg.)	180	60	90	35	365	November	frost-free climate

* Lengths of crop development stages provided in this table are indicative of general conditions, but may vary substantially from region to region, with climate and cropping conditions, and with crop variety. The user is strongly encouraged to obtain appropriate local information.

¹ Crucifers include cabbage, cauliflower, broccoli, and Brussel sprouts. The wide range in lengths of seasons is due to varietal and species differences.

² These periods for winter wheat will lengthen in frozen climates according to days having zero growth potential and wheat dormancy. Under general conditions and in the absence of local data, fall planting of winter wheat can be presumed to occur in northern temperate climates when the 10-day running average of mean daily air temperature decreases to 17° C or December 1, whichever comes first. Planting of spring wheat can be presumed to occur when the 10-day running average of mean daily air temperature increases to 5° C. Spring planting of maize-grain can be presumed to

occur when the 10-day running average of mean daily air temperature increases to 13° C.

³ The late season for sweet maize will be about 35 days if the grain is allowed to mature and dry.

⁴ In climates having killing frosts, growing seasons can be estimated for alfalfa and grass as:

alfalfa: last -4° C in spring until first -4° C in fall (Everson, D. O., M. Faubion and D. E. Amos 1978. "Freezing temperatures and growing seasons in Idaho." Univ. Idaho Agric. Exp. station bulletin 494. 18 p.)

grass: 7 days before last -4° C in spring and 7 days after last -4° C in fall (Kruse E. G. and Haise, H. R. 1974. "Water use by native grasses in high altitude Colorado meadows." USDA Agric. Res. Service, Western Region report ARS-W-6-1974. 60 pages)

⁵ Olive trees gain new leaves in March. See footnote 24 of Table 12 for additional information, where the K_c continues outside of the "growing period".

Primary source: FAO Irrigation and Drainage Paper 24 (Doorenbos and Pruitt, 1977), Table 22.

The lengths of the initial and development periods may be relatively short for deciduous trees and shrubs that can develop new leaves in the spring at relatively fast rates (Figure 23).

The rate at which vegetation cover develops and the time at which it attains effective full cover are affected by weather conditions in general and by mean daily air temperature in particular. Therefore, the length of time between planting and effective full cover will vary with climate, latitude, elevation and planting date. It will also vary with cultivar (crop variety). Generally, once the effective full cover for a plant canopy has been reached, the rate of further phenological development (flowering, seed development, ripening, and senescence) is more dependent on plant genotype and less dependent on weather. As an example, Figure 28 presents the variation in

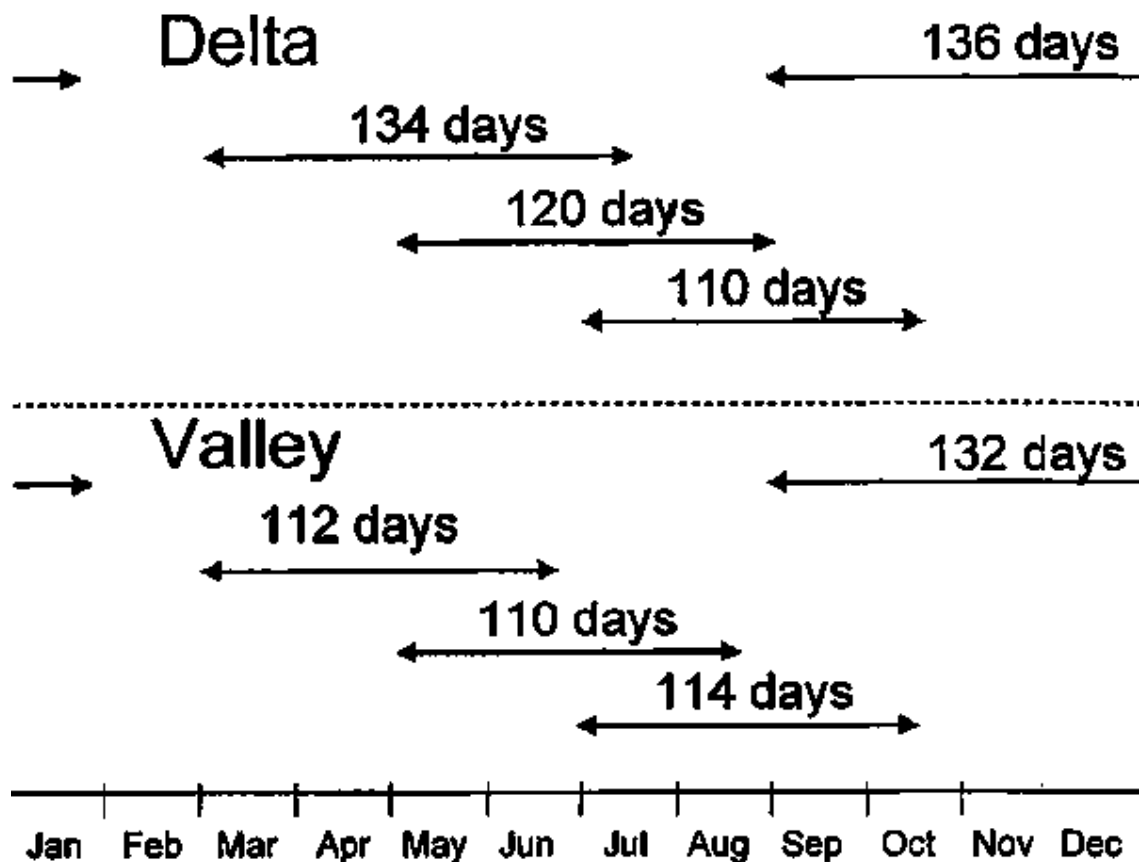
length of the growing period for one cultivar of rice for one region and for various planting dates.

The end of the mid-season and beginning of the late season is usually marked by senescence of leaves, often beginning with the lower leaves of plants. The length of the late season period may be relatively short (less than 10 days) for vegetation killed by frost (for example, maize at high elevations in latitudes $> 40^{\circ}\text{N}$) or for agricultural crops that are harvested fresh (for example, table beets and small vegetables).

High temperatures may accelerate the ripening and senescence of crops. Long duration of high air temperature ($> 35^{\circ}\text{C}$) can cause some crops such as turf grass to go into dormancy. If severely high air temperatures are coupled with moisture stress, the dormancy of grass can be permanent for the remainder of the growing season. Moisture stress or other environmental stresses will usually accelerate the rate of crop maturation and can shorten the mid and late season growing periods.

The values in Table 11 are useful only as a general guide and for comparison purposes. The listed lengths of growth stages are average lengths for the regions and periods specified and are intended to serve only as examples. Local observations of the specific plant stage development should be used, wherever possible, to incorporate effects of plant variety, climate and cultural practices. Local information can be obtained by interviewing farmers, ranchers, agricultural extension agents and local researchers, by conducting local surveys, or by remote sensing. When determining stage dates from local observations, the guidelines and visual descriptions may be helpful.

FIGURE 28. Variation in the length of the growing period of rice (cultivar: Jaya) sown during various months of the year at different locations along the Senegal River (Africa)



Crop coefficients

[Tabulated \$K_c\$ values](#)

[Crop coefficient for the initial stage \(\$K_{c\text{ ini}}\$ \)](#)

[Crop coefficient for the mid-season stage \(\$K_{c\text{ mid}}\$ \)](#)

[Crop coefficient for the end of the late season stage \(\$K_{c\text{ end}}\$ \)](#)

Changes in vegetation and ground cover mean that the crop coefficient K_c varies during the growing period. The trends in K_c during the growing period are represented in the crop coefficient curve. Only three values for K_c are required to describe and construct the crop coefficient curve: those during the initial stage ($K_{c\text{ ini}}$), the mid-season stage ($K_{c\text{ mid}}$) and at the end of the late season stage ($K_{c\text{ end}}$).

Tabulated K_c values

Table 12 lists typical values for $K_{c\text{ ini}}$, $K_{c\text{ mid}}$ and $K_{c\text{ end}}$ for various agricultural crops. The coefficients presented are organized by group type (i.e., small vegetables, legumes, cereals, etc.) to assist in locating the crop in the table and to

aid in comparing crops within the same group. There is usually close similarity in the coefficients among the members of the same crop group, as the plant height, leaf area, ground coverage and water management are normally similar. The coefficients in Table 12 integrate the effects of both transpiration and evaporation over time. The effects of the integration over time represent an average wetting frequency for a 'standard' crop under typical growing conditions in an irrigated setting. The values for K_c during the initial and crop development stages are subject to the effects of large variations in wetting frequencies and therefore refinements to the value used for $K_{c\text{ ini}}$ should always be made. For frequent wettings such as with high frequency sprinkler irrigation or rainfall, the values for $K_{c\text{ ini}}$ may increase substantially.

TABLE 12. Single (time-averaged) crop coefficients, K_c , and mean maximum plant heights for non stressed, well-managed crops in subhumid climates ($RH_{\text{min}} \approx 45\%$, $u_2 \approx 2$ m/s) for use with the FAO Penman-Monteith ET_o .

Crop	$K_{c\text{ ini}}^1$	$K_{c\text{ mid}}$	$K_{c\text{ end}}$	Maximum Crop Height (h) (m)
a. Small Vegetables	0.7	1.05	0.95	
Broccoli		1.05	0.95	0.3
Brussel Sprouts		1.05	0.95	0.4
Cabbage		1.05	0.95	0.4
Carrots		1.05	0.95	0.3
Cauliflower		1.05	0.95	0.4
Celery		1.05	1.00	0.6
Garlic		1.00	0.70	0.3
Lettuce		1.00	0.95	0.3
Onions				
- dry		1.05	0.75	0.4
- green		1.00	1.00	0.3
- seed		1.05	0.80	0.5
Spinach		1.00	0.95	0.3
Radish		0.90	0.85	0.3
b. Vegetables - Solanum Family (<i>Solanaceae</i>)	0.6	1.15	0.80	
Egg Plant		1.05	0.90	0.8
Sweet Peppers (bell)		1.05 ²	0.90	0.7
Tomato		1.15 ²	0.70-0.90	0.6
c. Vegetables - Cucumber Family (<i>Cucurbitaceae</i>)	0.5	1.00	0.80	
Cantaloupe	0.5	0.85	0.60	0.3
Cucumber				
- Fresh Market	0.6	1.00 ²	0.75	0.3
- Machine harvest	0.5	1.00	0.90	0.3
Pumpkin, Winter Squash		1.00	0.80	0.4

Squash, Zucchini		0.95	0.75	0.3
Sweet Melons		1.05	0.75	0.4
Watermelon	0.4	1.00	0.75	0.4
d. Roots and Tubers	0.5	1.10	0.95	
Beets, table		1.05	0.95	0.4
Cassava				
- year 1	0.3	0.80 ³	0.30	1.0
- year 2	0.3	1.10	0.50	1.5
Parsnip	0.5	1.05	0.95	0.4
Potato		1.15	0.75 ⁴	0.6
Sweet Potato		1.15	0.65	0.4
Turnip (and Rutabaga)		1.10	0.95	0.6
Sugar Beet	0.35	1.20	0.70 ⁵	0.5
e. Legumes (Leguminosae)	0.4	1.15	0.55	
Beans, green	0.5	1.05 ²	0.90	0.4
Beans, dry and Pulses	0.4	1.15 ²	0.35	0.4
Chick pea		1.00	0.35	0.4
Fababean (broad bean)				
- Fresh	0.5	1.15 ²	1.10	0.8
- Dry/Seed	0.5	1.15 ²	0.30	0.8
Grabanzo	0.4	1.15	0.35	0.8
Green Gram and Cowpeas		1.05	0.60-0.35 ⁶	0.4
Groundnut (Peanut)		1.15	0.60	0.4
Lentil		1.10	0.30	0.5
Peas				
- Fresh	0.5	1.15 ²	1.10	0.5
- Dry/Seed		1.15	0.30	0.5
Soybeans		1.15	0.50	0.5-1.0
f. Perennial Vegetables (with winter dormancy and initially bare or mulched soil)	0.5	1.00	0.80	
Artichokes	0.5	1.00	0.95	0.7
Asparagus	0.5	0.95 ⁷	0.30	0.2-0.8
Mint	0.60	1.15	1.10	0.6-0.8
Strawberries	0.40	0.85	0.75	0.2
g. Fibre Crops	0.35			
Cotton		1.15-1.20	0.70-0.50	1.2-1.5
Flax		1.10	0.25	1.2
Sisal ⁸		0.4-0.7	0.4-0.7	1.5
h. Oil Crops	0.35	1.15	0.35	
Castorbean (<i>Ricinus</i>)		1.15	0.55	0.3
Rapeseed, Canola		1.0-1.15 ⁹	0.35	0.6

Safflower		1.0-1.15 ⁹	0.25	0.8
Sesame		1.10	0.25	1.0
Sunflower		1.0-1.15 ⁹	0.35	2.0
i. Cereals	0.3	1.15	0.4	
Barley		1.15	0.25	1
Oats		1.15	0.25	1
Spring Wheat		1.15	0.25-0.4 ¹⁰	1
Winter Wheat				
- with frozen soils	0.4	1.15	0.25-0.4 ¹⁰	1
- with non-frozen soils	0.7	1.15	0.25-0.4 ¹⁰	
Maize, Field (grain) (<i>field corn</i>)		1.20	0.60-0.35 ¹¹	2
Maize, Sweet (<i>sweet corn</i>)		1.15	1.05 ¹²	1.5
Millet		1.00	0.30	1.5
Sorghum				
- grain		1.00-1.10	0.55	1-2
- sweet		1.20	1.05	2-4
Rice	1.05	1.20	0.90-0.60	1
j. Forages				
Alfalfa Hay				
- averaged cutting effects	0.40	0.95 ¹³	0.90	0.7
- individual cutting periods	0.40 ¹⁴	1.20 ¹⁴	1.15 ¹⁴	0.7
- for seed	0.40	0.50	0.50	0.7
Bermuda hay				
- averaged cutting effects	0.55	1.00 ¹³	0.85	0.35
- Spring crop for seed	0.35	0.90	0.65	0.4
Clover hay, Berseem				
- averaged cutting effects	0.40	0.90 ¹³	0.85	0.6
- individual cutting periods	0.40 ¹⁴	1.15 ¹⁴	1.10 ¹⁴	0.6
Rye Grass hay				
- averaged cutting effects	0.95	1.05	1.00	0.3
Sudan Grass hay (annual)				
- averaged cutting effects	0.50	0.90 ¹⁴	0.85	1.2
- individual cutting periods	0.50 ¹⁴	1.15 ¹⁴	1.10 ¹⁴	1.2
Grazing Pasture				
- Rotated Grazing	0.40	0.85-1.05	0.85	0.15-0.30
- Extensive Grazing	0.30	0.75	0.75	0.10
Turf grass				

- cool season ¹⁵	0.90	0.95	0.95	0.10
- warm season ¹⁵	0.80	0.85	0.85	0.10
k. Sugar Cane	0.40	1.25	0.75	3
I. Tropical Fruits and Trees				
Banana				
- 1 st year	0.50	1.10	1.00	3
- 2 nd year	1.00	1.20	1.10	4
Cacao	1.00	1.05	1.05	3
Coffee				
- bare ground cover	0.90	0.95	0.95	2-3
- with weeds	1.05	1.10	1.10	2-3
Date Palms	0.90	0.95	0.95	8
Palm Trees	0.95	1.00	1.00	8
Pineapple ¹⁶				
- bare soil	0.50	0.30	0.30	0.6-1.2
- with grass cover	0.50	0.50	0.50	0.6-1.2
Rubber Trees	0.95	1.00	1.00	10
Tea				
- non-shaded	0.95	1.00	1.00	1.5
- shaded ¹⁷	1.10	1.15	1.15	2
m. Grapes and Berries				
Berries (bushes)	0.30	1.05	0.50	1.5
Grapes				
- Table or Raisin	0.30	0.85	0.45	2
- Wine	0.30	0.70	0.45	1.5-2
Hops	0.3	1.05	0.85	5
n. Fruit Trees				
Almonds, no ground cover	0.40	0.90	0.65 ¹⁸	5
Apples, Cherries, Pears ¹⁹				
- no ground cover, killing frost	0.45	0.95	0.70 ¹⁸	4
- no ground cover, no frosts	0.60	0.95	0.75 ¹⁸	4
- active ground cover, killing frost	0.50	1.20	0.95 ¹⁸	4
- active ground cover, no frosts	0.80	1.20	0.85 ¹⁸	4
Apricots, Peaches, Stone Fruit ^{19, 20}				
- no ground cover, killing frost	0.45	0.90	0.65 ¹⁸	3
- no ground cover, no frosts	0.55	0.90	0.65 ¹⁸	3
- active ground cover, killing frost	0.50	1.15	0.90 ¹⁸	3
- active ground cover, no frosts	0.80	1.15	0.85 ¹⁸	3
Avocado, no ground cover	0.60	0.85	0.75	3
Citrus, no ground cover ²¹				
- 70% canopy	0.70	0.65	0.70	4
- 50% canopy	0.65	0.60	0.65	3
- 20% canopy	0.50	0.45	0.55	2

Citrus, with active ground cover or weeds ²²				
- 70% canopy	0.75	0.70	0.75	4
- 50% canopy	0.80	0.80	0.80	3
- 20% canopy	0.85	0.85	0.85	2
Conifer Trees ²³	1.00	1.00	1.00	10
Kiwi	0.40	1.05	1.05	3
Olives (40 to 60% ground coverage by canopy) ²⁴	0.65	0.70	0.70	3-5
Pistachios, no ground cover	0.40	1.10	0.45	3-5
Walnut Orchard ¹⁹	0.50	1.10	0.6518	4-5
o. Wetlands - temperate climate				
Cattails, Bulrushes, killing frost	0.30	1.20	0.30	2
Cattails, Bulrushes, no frost	0.60	1.20	0.60	2
Short Veg., no frost	1.05	1.10	1.10	0.3
Reed Swamp, standing water	1.00	1.20	1.00	1-3
Reed Swamp, moist soil	0.90	1.20	0.70	1-3
p. Special				
Open Water, < 2 m depth or in subhumid climates or tropics		1.05	1.05	
Open Water, > 5 m depth, clear of turbidity, temperate climate		0.6525	1.2525	

¹ These are general values for $K_{c\text{ ini}}$ under typical irrigation management and soil wetting. For frequent wettings such as with high frequency sprinkle irrigation or daily rainfall, these values may increase substantially and may approach 1.0 to 1.2. $K_{c\text{ ini}}$ is a function of wetting interval and potential evaporation rate during the initial and development periods and is more accurately estimated using Figures 29 and 30, or Equation 7-3 in Annex 7, or using the dual $K_{cb\text{ ini}} + K_e$.

² Beans, Peas, Legumes, Tomatoes, Peppers and Cucumbers are sometimes grown on stalks reaching 1.5 to 2 meters in height. In such cases, increased K_c values need to be taken. For green beans, peppers and cucumbers, 1.15 can be taken, and for tomatoes, dry beans and peas, 1.20. Under these conditions h should be increased also.

³ The midseason values for cassava assume non-stressed conditions during or following the rainy season. The $K_{c\text{ end}}$ values account for dormancy during the dry season.

⁴ The $K_{c\text{ end}}$ value for potatoes is about 0.40 for long season potatoes with vine kill.

⁵ This $K_{c\text{ end}}$ value is for no irrigation during the last month of the growing season. The $K_{c\text{ end}}$ value for sugar beets is higher, up to 1.0, when irrigation or significant rain occurs during the last month.

⁶ The first $K_{c\text{ end}}$ is for harvested fresh. The second value is for harvested dry.

⁷ The K_c for asparagus usually remains at $K_{c\text{ ini}}$ during harvest of the spears, due to sparse ground cover. The $K_{c\text{ mid}}$ value is for following regrowth of plant vegetation following termination of harvest of spears.

⁸ K_c for sisal depends on the planting density and water management (e.g., intentional moisture stress).

⁹ The lower values are for rainfed crops having less dense plant populations.

¹⁰ The higher value is for hand-harvested crops.

¹¹ The first $K_{c\text{ end}}$ value is for harvest at high grain moisture. The second $K_{c\text{ end}}$ value is for harvest after complete field drying of the grain (to about 18% moisture, wet mass basis).

¹² If harvested fresh for human consumption. Use $K_{c\text{ end}}$ for field maize if the sweet maize is allowed to mature and dry in the field.

¹³ This $K_{c\text{ mid}}$ coefficient for hay crops is an overall average $K_{c\text{ mid}}$ coefficient that averages K_c for both before and following cuttings. It is applied to the period following the first development period until the beginning of the last late season period of the growing season.

¹⁴ These K_c coefficients for hay crops represent immediately following cutting; at full cover; and immediately before cutting, respectively. The growing season is described as a series of individual cutting periods (Figure 35).

¹⁵ Cool season grass varieties include dense stands of bluegrass, ryegrass, and fescue. Warm season varieties include bermuda grass and St. Augustine grass. The 0.95 values for cool season grass represent a 0.06 to 0.08 m mowing height under general turf conditions. Where careful water management is practiced

and rapid growth is not required, K_c 's for turf can be reduced by 0.10.

¹⁶ The pineapple plant has very low transpiration because it closes its stomates during the day and opens them during the night. Therefore, the majority of ET_c from pineapple is evaporation from the soil. The $K_{c\ mid} < K_{c\ ini}$ since $K_{c\ mid}$ occurs during full ground cover so that soil evaporation is less. Values given assume that 50% of the ground surface is covered by black plastic mulch and that irrigation is by sprinkler. For drip irrigation beneath the plastic mulch, K_c 's given can be reduced by 0.10.

¹⁷ Includes the water requirements of the shade trees.

¹⁸ These $K_{c\ end}$ values represent K_c prior to leaf drop. After leaf drop, $K_{c\ end} \approx 0.20$ for bare, dry soil or dead ground cover and $K_{c\ end} \approx 0.50$ to 0.80 for actively growing ground cover (consult Chapter 11).

¹⁹ Refer to Eq. 94, 97 or 98 and footnotes 21 and 22 for estimating K_c for immature stands.

²⁰ Stone fruit category applies to peaches, apricots, pears, plums and pecans.

²¹ These K_c values can be calculated from Eq. 98 for $K_{c\ min} = 0.15$ and $K_{c\ full} = 0.75$, 0.70 and 0.75 for the initial, mid season and end of season periods, and $f_{c\ eff} = f_c$ where f_c = fraction of ground covered by tree canopy (e.g., the sun is presumed to be directly overhead). The values listed correspond with those in Doorenbos and Pruitt (1977) and with more recent measurements. The midseason value is lower than initial and ending values due to the effects of stomatal closure during periods of peak ET. For humid and subhumid climates where there is less stomatal control by citrus, values for $K_{c\ ini}$, $K_{c\ mid}$, and $K_{c\ end}$ can be increased by 0.1 - 0.2, following Rogers et al. (1983).

²² These K_c values can be calculated as $K_c = f_c K_{c\ ngc} + (1 - f_c) K_{c\ cover}$ where $K_{c\ ngc}$ is the K_c of citrus with no active ground cover (calculated as in footnote 21), $K_{c\ cover}$ is the K_c for the active ground cover (0.95), and f_c is defined in footnote 21. The values listed correspond with

those in Doorenbos and Pruitt (1977) and with more recent measurements. Alternatively, K_c for citrus with active ground cover can be estimated directly from Eq. 98 by setting $K_{c\ min} = K_{c\ cover}$. For humid and subhumid climates where there is less stomatal control by citrus, values for $K_{c\ ini}$, $K_{c\ mid}$, and $K_{c\ end}$ can be increased by 0.1 - 0.2, following Rogers et al. (1983).

For non-active or only moderately active ground cover (active indicates green and growing ground cover with LAI > about 2 to 3), K_c should be weighted between K_c for no ground cover and K_c for active ground cover, with the weighting based on the "greenness" and approximate leaf area of the ground cover.

²³ Conifers exhibit substantial stomatal control due to reduced aerodynamic resistance. The K_c can easily reduce below the values presented, which represent well-watered conditions for large forests.

²⁴ These coefficients represent about 40 to 60% ground cover. Refer to Eq. 98 and footnotes 21 and 22 for estimating K_c for immature stands. In Spain, Pastor and Orgaz (1994) have found the following monthly K_c 's for olive orchards having 60% ground cover: 0.50, 0.50, 0.65, 0.60, 0.55, 0.50, 0.45, 0.45, 0.55, 0.60, 0.65, 0.50 for months January through December. These coefficients can be invoked by using $K_{c\ ini} = 0.65$, $K_{c\ mid} = 0.45$, and $K_{c\ end} = 0.65$, with stage lengths = 30, 90, 60 and 90 days, respectively for initial, development, midseason and late season periods, and using K_c during the winter ("off season") in December to February = 0.50.

²⁵ These K_c 's are for deep water in temperate latitudes where large temperature changes in the water body occur during the year, and initial and peak period evaporation is low as radiation energy is absorbed into the deep water body. During fall and winter periods ($K_{c\ end}$), heat is released from the water body that increases the evaporation above that for grass. Therefore, $K_{c\ mid}$ corresponds to the period when the water body is gaining thermal energy and $K_{c\ end}$ when releasing thermal energy. These K_c 's should be used with caution.

Primary sources:

$K_{c\text{ ini}}$: Doorenbos and Kassam (1979)

$K_{c\text{ mid}}$ and $K_{c\text{ end}}$: Doorenbos and Pruitt (1977); Pruitt (1986); Wright (1981, 1982). Snyder et al., (1989)

The values for $K_{c\text{ mid}}$ and $K_{c\text{ end}}$ in Table 12 represent those for a sub-humid climate with an average daytime minimum relative humidity (RH_{min}) of about 45% and with calm to moderate wind speeds averaging 2 m/s. For more humid or arid conditions, or for more or less windy conditions, the K_c coefficients for the mid-season and end of late season stage should be modified as described in this chapter.

The values for K_c in Table 12 are values for non-stressed crops cultivated under excellent agronomic and water management conditions and achieving maximum crop yield (standard conditions). Where stand density, height or leaf area are less than that attained under such conditions, the value for $K_{c\text{ mid}}$ and, for most crops, for $K_{c\text{ end}}$ will need to be modified (Part C, Chapters 8, 9 and 10).

Crop coefficient for the initial stage ($K_{c\text{ ini}}$)

Calculation procedure

The values for $K_{c\text{ ini}}$ in Table 12 are only approximations and should only be used for estimating ET_c during preliminary or planning studies. For several group types only one value for $K_{c\text{ ini}}$ is listed and it is considered to be representative of the whole group for a typical irrigation water management. More accurate estimates of $K_{c\text{ ini}}$ can be obtained by considering:

Time interval between wetting events

Evapotranspiration during the initial stage for annual crops is predominately in the form of evaporation. Therefore, accurate estimates for $K_{c\text{ ini}}$ should consider the frequency with which the soil surface is wetted during the initial period. Where the soil is frequently wet from irrigation or rain, the evaporation from the soil surface can be considerable and $K_{c\text{ ini}}$ will be large. On the other hand, where the soil surface is dry, evaporation is restricted and the $K_{c\text{ ini}}$ will be small (Table 9).

Evaporation power of the atmosphere

The value of $K_{c\text{ ini}}$ is affected by the evaporating power of the atmosphere, i.e., ET_o . The higher the evaporation power of the atmosphere, the quicker the soil will dry between water applications and the smaller the time-averaged K_c will be for any particular period.

Magnitude of the wetting event

As the amount of water available in the topsoil for evaporation and hence the time for the soil surface to dry is a function of the magnitude of the wetting event, $K_{c\text{ ini}}$ will be smaller for light wetting events than for large wettings.

Depending on the time interval between wetting events, the magnitude of the wetting event, and the evaporation power of the atmosphere, $K_{c\text{ ini}}$ can vary between 0.1 and 1.15. A numerical procedure to compute $K_{c\text{ ini}}$ is provided in Annex 7.

Time interval between wetting events

In general, the mean time interval between wetting events is estimated by counting all rainfall and irrigation events occurring during the initial period that are greater than a few millimetres. Wetting events occurring on adjacent days can be counted as one event. The mean wetting interval is estimated by dividing the length of the initial period by the number of events.

Where only monthly rainfall values are available without any information on the number of rainy days, the number of events within the month can be estimated by dividing the monthly rainfall depth by the depth of a typical rain event. The typical depth, if it exists, can vary widely from climate to climate, region to region and from season to season. Table 13 presents some information on the range of rainfall depths. After deciding what rainfall is typical for the region and time of the year, the number of rainy days and the mean wetting interval can be estimated.

TABLE 13. Classification of rainfall depths

rain event	depth
Very light (drizzle)	$\leq 3\text{ mm}$
Light (light showers)	5 mm
Medium (showers)	$\geq 10\text{ mm}$
Heavy (rainstorms)	$\geq 40\text{ mm}$

Where rainfall is insufficient, irrigation is needed to keep the crop well watered. Even where irrigation is not yet developed, the mean interval between the future irrigations should be estimated to obtain the required frequency of wetting

necessary to keep the crop stress free. The interval might be as small as a few days for small vegetables, but up to a week or longer for cereals depending on the climatic conditions. Where no estimate of the interval can be made, the user may refer to the values for $K_{c\text{ ini}}$ of Table 12.

EXAMPLE 23. Estimation of interval between wetting events

Estimate, from mean monthly rainfall data, the interval between rains during the rainy season for a station in a temperate climate (Paris, France: 50 mm/month), dry climate (Gafsa, Tunisia: 20 mm/month) and tropical climate (Calcutta, India: 300 mm/month).				
Station	monthly rain (mm/month)	typical rainfall (mm)	number of rainy days	interval between rains
Paris	50	3	17	~ 2 days
Gafsa	20	5	4	weekly
Calcutta	300	20	15	~ 2 days

Determination of $K_{c\text{ ini}}$

The crop coefficient for the initial growth stage can be derived from Figures 29 and 30 which provide estimates for $K_{c\text{ ini}}$ as a function of the average interval between wetting events, the evaporation power ET_o , and the importance of the wetting event.

Light wetting events (infiltration depths of 10 mm or less): rainfall and high frequency irrigation systems

Figure 29 is used for all soil types when wetting events are light. When wetting during the initial period is only by precipitation, one will usually use Figure 29 to determine $K_{c\text{ ini}}$. The graph can also be used when irrigation is by high frequency systems such as microirrigation and centre pivot and light applications of about 10 mm or less per wetting event are applied.

EXAMPLE 24. Graphical determination of $K_{c\text{ ini}}$

A silt loam soil receives irrigation every two days during the initial growth stage via a centre pivot irrigation system. The average depth applied by the centre pivot system is about 12 mm per event and the average ET_o during the initial stage is 4 mm/day. Estimate the crop evapotranspiration during that stage.			
From Fig. 29 using the 2-day interval curve:	$K_{c\text{ ini}} =$	0.85	-
	$ET_c = K_c ET_o = 0.85 (4.0)$ =	3.4	mm/day
The average crop evapotranspiration during the initial growth stage is 3.4 mm/day			

Heavy wetting events (infiltration depths of 40 mm or more): surface and sprinkler irrigation

Figure 30 is used for heavy wetting events when infiltration depths are greater than 40 mm, such as for when wetting is primarily by periodic irrigation such as by sprinkler or surface irrigation. Following a wetting event, the amount of water available in the topsoil for evaporation is considerable, and the time for the soil surface to dry might be significantly increased. Consequently, the average K_c factor is larger than for light wetting events. As the time for the soil surface to dry is, apart from the evaporation power and the frequency of wetting, also determined by the water storage capacity of the topsoil, a distinction is made between soil types.

FIGURE 29. Average $K_{c\ ini}$ as related to the level of ET_o and the interval between irrigations and/or significant rain during the initial growth stage for all soil types when wetting events are light to medium (3-10 mm per event)

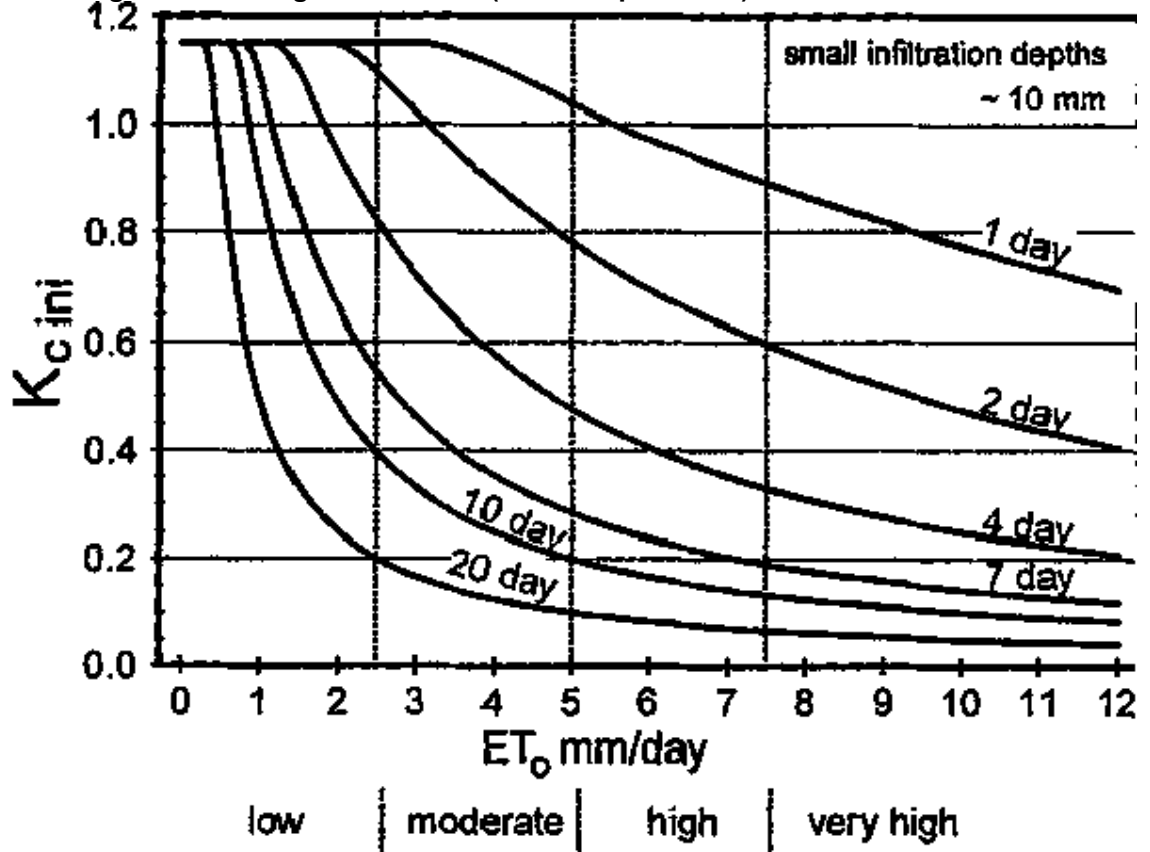


Figure 30a is used for coarse textured soils and Figure 30b is used for fine and medium textured soils. Coarse textured soils include sands and loamy sand textured soils. Medium textured soils include sandy loam, loam, silt loam and silt textured soils. Fine textured soils include silty clay loam, silty clay and clay textured soils.

Average wetting events (infiltration depths between 10 and 40 mm):

Where average infiltration depths are between 10 and 40 mm, the value for $K_{c\ ini}$ can be estimated from Figures 29 and 30:

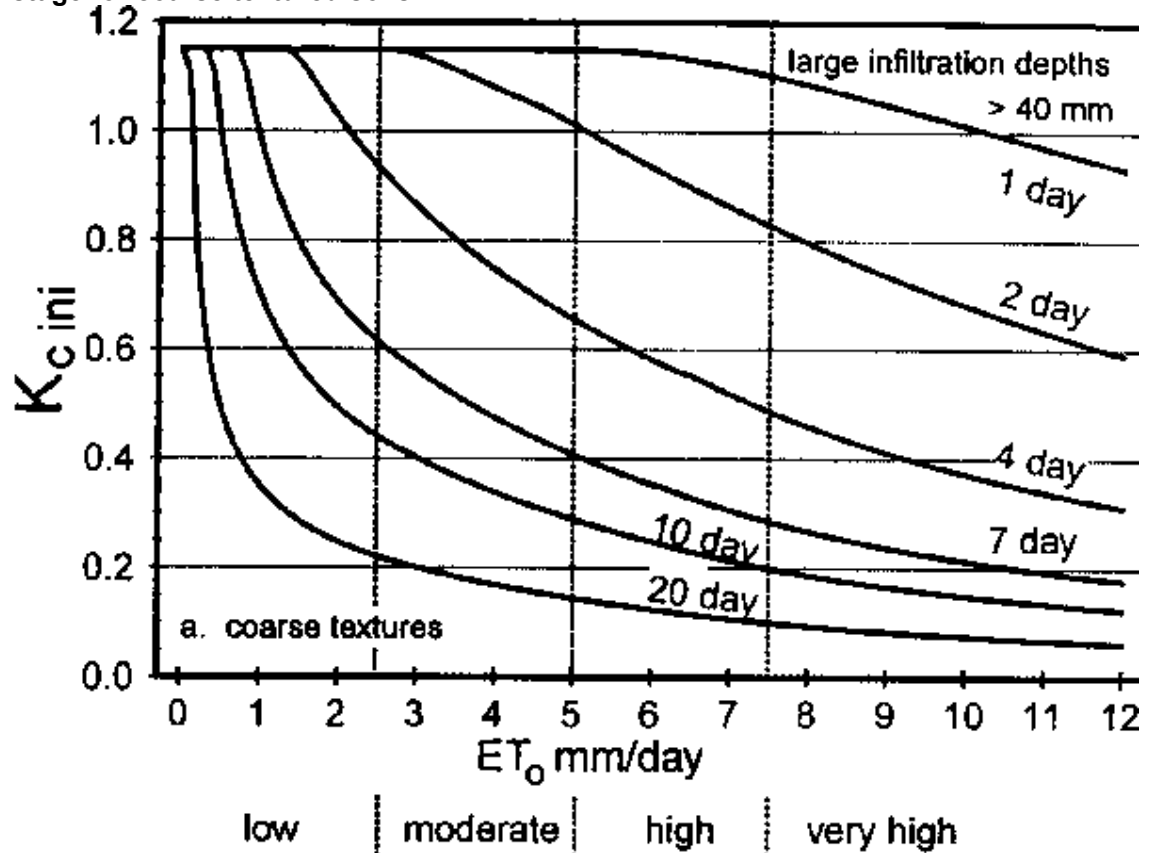
$$K_{c\ ini} = K_{c\ ini}(\text{Fig.29}) + \frac{(I - 10)}{(40 - 10)} [K_{c\ ini}(\text{Fig.30}) - K_{c\ ini}(\text{Fig.29})] \quad (59)$$

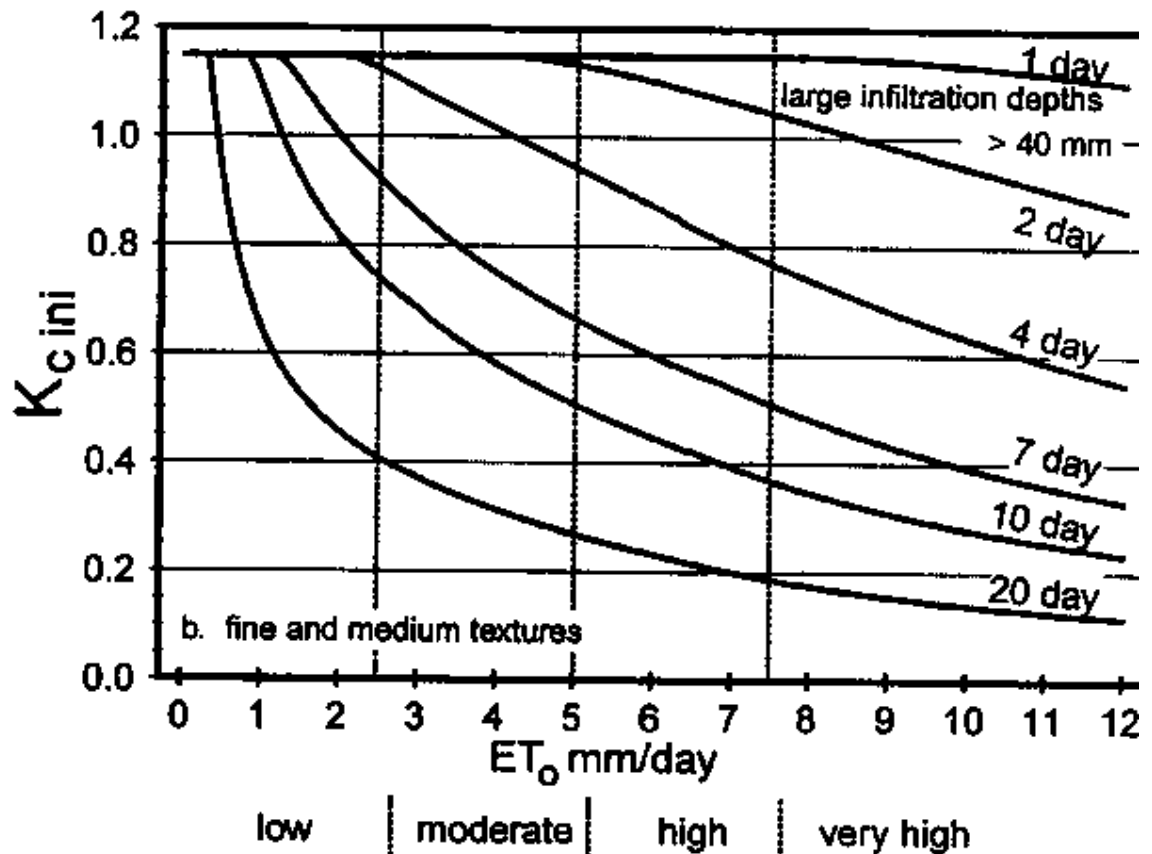
where

$K_{c\ ini}$ (Fig.29) value for $K_{c\ ini}$ from Figure 29,
 $K_{c\ ini}$ (Fig.30) value for $K_{c\ ini}$ from Figure 30,
 I average infiltration depth [mm].

The values 10 and 40 in Equation 59 are the average depths of infiltration (millimetres) upon which Figures 29 and 30 are based.

FIGURE 30. Average $K_{c\text{ ini}}$ as related to the level of ET_o and the interval between irrigations greater than or equal to 40 mm per wetting event, during the initial growth stage for coarse textured soils





EXAMPLE 25. Interpolation between light and heavy wetting events

Small vegetables cultivated in a dry area on a coarse textured soil receive 20 mm of water twice a week by means of a sprinkler irrigation system. The average ET_0 during the initial stage is 5 mm/day. Estimate the crop evapotranspiration during that stage.

For:	$7/2 =$	3.5	day interval
	$ET_0 =$ and a coarse textured soil	5	mm/day
From Fig. 29:	$K_{c\ ini}$ (Fig. 29) $\approx$	0.55	-
From Fig. 30. a:	$K_{c\ ini}$ (Fig. 30a) $\approx$	0.7	-
For:	$I =$	20	mm
From Eq. 59:	$K_{c\ ini} = 0.55 + [(20 - 10)/(40 - 10)] (0.7 - 0.55) = 0.55 + 0.33(0.15) =$	0.60	
From Eq. 58:	$ET_c = 0.60 (5) =$	3.0	mm/day

The average crop evapotranspiration during the initial growth stage for the small vegetables is 3.0 mm/day.

Adjustment for partial wetting by irrigation

Many types of irrigation systems wet only a fraction of the soil surface. For example, for a trickle irrigation system, the fraction of the surface wetted, f_w , may be only 0.4. For furrow irrigation systems, the fraction of the surface wetted may range from 0.3 to 0.8. Common values for the fraction of the soil surface wetted by irrigation or precipitation are given in Table 20. When only a fraction of the soil surface is wetted, the value for $K_{c\ ini}$ obtained from Table 12 or from Figures 29

or 30 should be multiplied by the fraction of the surface wetted to adjust for the partial wetting:

$$K_{c \text{ ini}} = f_w K_{c \text{ ini (Tab, Fig)}} \quad (60)$$

where

f_w the fraction of surfaced wetted by irrigation or rain [0 - 1],
 $K_{c \text{ ini (Tab Fig)}}$ the value for $K_{c \text{ ini}}$ from Table 12 or Figure 29 or 30.

In addition, in selecting which figure to use (i.e., Figure 29 or 30), the average infiltrated depth, expressed in millimetres over the entire field surface, should be divided by f_w to represent the true infiltrated depth of water for the part of the surface that is wetted (Figure 31):

$$I_w = \frac{I}{f_w} \quad (61)$$

where

I_w irrigation depth for the part of the surface that is wetted [mm],
 f_w fraction of surface wetted by irrigation,
 I the irrigation depth for the field [mm].

When irrigation of part of the soil surface and precipitation over the entire soil surface both occur during the initial period, f_w should represent the average of f_w for each type of wetting, weighted according to the total infiltration depth received by each type.

FIGURE 31. Partial wetting by irrigation

EXAMPLE 26. Determination of $K_{c \text{ ini}}$ for partial wetting of the soil surface

Determine the evapotranspiration of the crop in Example 24 if it had been irrigated using a trickle system every two days (with 12 mm each application expressed as an equivalent depth over the field area), and where the average fraction of surface wet was 0.4, and where little or no precipitation occurred during the initial period.

The average depth of infiltration per event in the wetted fraction of the surface:

From Eq. 61;	$I_w = I/f_w = 12 \text{ mm}/0.4 =$	30 mm
--------------	-------------------------------------	-------

Therefore, one can interpolate between Fig. 29 representing light wetting events (~10 mm per event) and Fig. 30.b representing medium textured soil and large wetting events (~40 mm per event).

For:	$ET_o = 4 \text{ mm/day}$	4 mm/day
and:	a 2 day wetting interval:	- -
Fig. 29 produces:	$K_{c \text{ ini}} = 0.85$	0.85 -
Fig. 30.b produces	$K_{c \text{ ini}} = 1.15$	1.15 -
From Eq. 59:	$K_{c \text{ ini}} = 0.85 + [(30-10)/(40-10)] (1.15 - 0.85) =$	1.05 -

Because the fraction of soil surface wetted by the trickle system is 0.4, the actual $K_{c \text{ ini}}$ for

the trickle irrigation is calculated as:			
From Eq. 60:	$K_{c\ ini} = f_w K_{c\ ini\ Fig} = 0.4 (1.05) =$	0.42	-
	This value (0.42) represents the $K_{c\ ini}$ as applied over the entire field area.		
-	$ET_c = K_{c\ ini} ET_o = 0.42(4) =$	1.7	mm/day
The average crop evapotranspiration during the initial growth stage for this trickle irrigated crop is 1.7 mm/day.			

$K_{c\ ini}$ for trees and shrubs

$K_{c\ ini}$ for trees and shrubs should reflect the ground condition prior to leaf emergence or initiation in case of deciduous trees or shrubs, and the ground condition during the dormancy or low active period for evergreen trees and shrubs. The $K_{c\ ini}$ depends upon the amount of grass or weed cover, frequency of soil wetting, tree density and mulch density. For a deciduous orchard in frost-free climates, the $K_{c\ ini}$ can be as high as 0.8 or 0.9, where grass ground cover exists, and as low as 0.3 or 0.4 when the soil surface is kept bare and wetting is infrequent. The $K_{c\ ini}$ for an evergreen orchard (having no concerted leaf drop) with a dormant period has less variation from $K_{c\ mid}$, as exemplified for citrus in Table 12, footnotes 21 and 22. For 50% canopy or less, the $K_{c\ ini}$ also reflects ground cover conditions (bare soil, mulch or active grass or weed cover).

$K_{c\ ini}$ for paddy rice

For rice growing in paddy fields with a water depth of 0.10-0.20 m, the ET_c during the initial stage mainly consists of evaporation from the standing water. The $K_{c\ ini}$ in Table 12 is 1.05 for a sub-humid climate with calm to moderate wind speeds. The $K_{c\ ini}$ should be adjusted for the local climate as indicated in Table 14.

TABLE 14. $K_{c\ ini}$ for rice for various climatic conditions

Humidity	Wind speed		
	light	moderate	strong
arid - semi-arid	1.10	1.15	1.20
sub-humid - humid	1.05	1.10	1.15
very humid	1.00	1.05	1.10

Crop coefficient for the mid-season stage ($K_{c\ mid}$)

Illustration of the climatic effect

Typical values for the crop coefficient for the mid-season growth stage, $K_{c\ mid}$, are listed in Table 12 for various agricultural crops.

As discussed in Chapter 5, the effect of the difference in aerodynamic properties between the grass reference surface and agricultural crops is not only crop specific but also varies with the climatic conditions and crop height (Figure 21). More arid climates and conditions of greater wind speed will have higher values for $K_{c\ mid}$. More humid climates and conditions of lower wind speed will have lower values for $K_{c\ mid}$.

The relative impact of climate on $K_{c\ mid}$ is illustrated in Figure 32 where the adjustments to the values from Table 12 are

shown for various types of climates, mean daily wind speeds and various crop heights. As an example, expected variations for $K_{c\text{ mid}}$ for tomatoes in response to regional climatic conditions are presented in Box 14.

Determination of $K_{c\text{ mid}}$

For specific adjustment in climates where RH_{min} differs from 45% or where u_2 is larger or smaller than 2.0 m/s, the $K_{c\text{ mid}}$ values from Table 12 are adjusted as:

$$K_{c\text{ mid}} = K_{c\text{ mid(Tab)}} + [0.04(u_2 - 2) - 0.004(RH_{\text{min}} - 45)] \left(\frac{h}{3}\right)^{0.3} \quad (62)$$

where

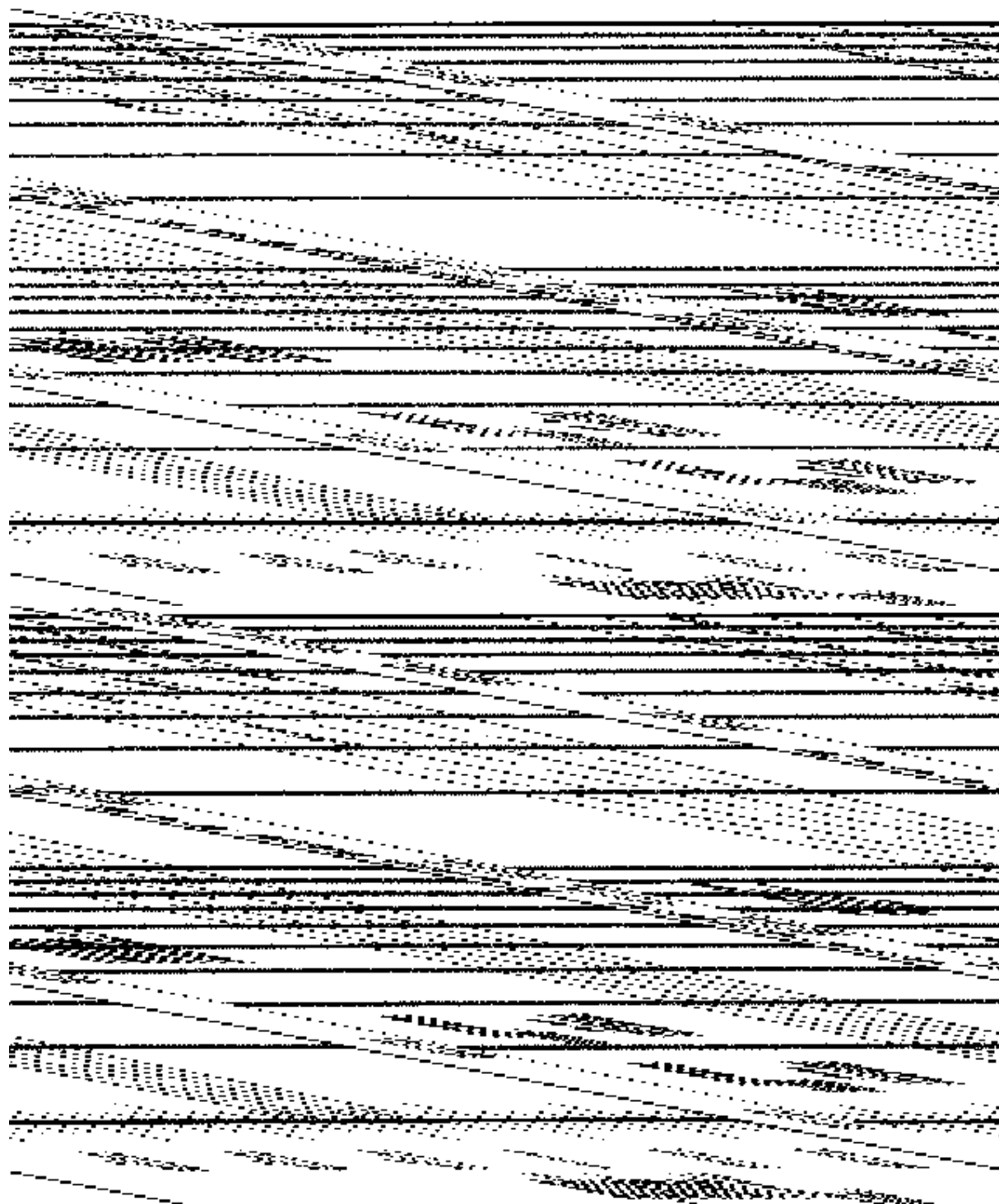
$K_{c\text{ mid(Tab)}}$ value for $K_{c\text{ mid}}$ taken from Table 12,

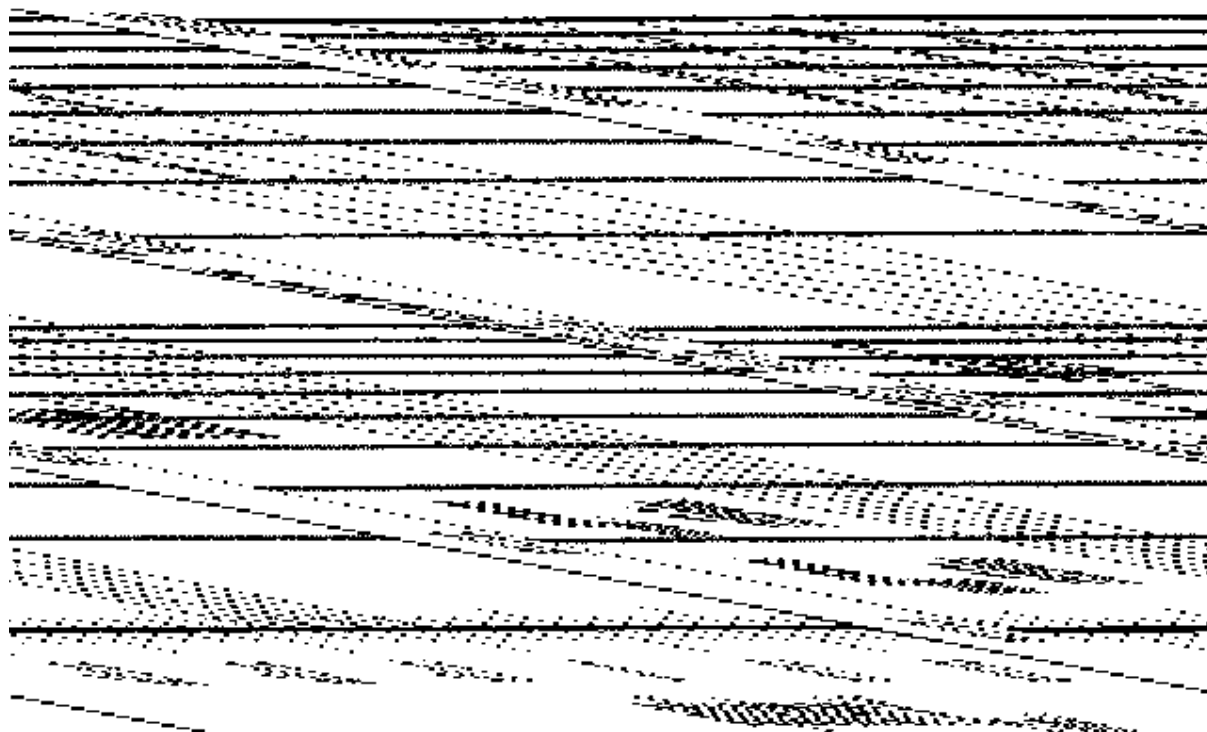
u_2 mean value for daily wind speed at 2 m height over grass during the mid-season growth stage [m s^{-1}], for $1 \text{ m s}^{-1} \leq u_2 \leq 6 \text{ m s}^{-1}$,

RH_{min} mean value for daily minimum relative humidity during the mid-season growth stage [%], for $20\% \leq RH_{\text{min}} \leq 80\%$,

h mean plant height during the mid-season stage [m] for $0.1 \text{ m} < h < 10 \text{ m}$.

FIGURE 32. Adjustment (additive) to the $K_{c\text{ mid}}$ values from Table 12 for different crop heights and mean daily wind speeds (u_2) for different humidity conditions





The $K_{c\text{ mid}}$ values determined with equations 62 and 65 are average adjustments for the midseason and late season periods. The values for parameters u_2 and $RH_{\min}$ should be accordingly taken as averages for these periods (see example, Annex 8). The limits expressed for parameters u_2 , $RH_{\min}$ and h should be observed.

BOX 14. Demonstration of effect of climate on $K_{c\text{ mid}}$ for wheat crop grown under field conditions

From Table 12 for wheat: $K_{c\text{ mid}} = 1.15$ and $h = 1.0$ m

For semi-arid to arid conditions

- for strong wind (4 m/s)	$K_{c\text{ mid}} = 1.15 + 0.10 = 1.25$
- for moderate wind (2 m/s)	$K_{c\text{ mid}} = 1.15 + 0.05 = 1.20$
- for calm wind (1 m/s)	$K_{c\text{ mid}} = 1.15 + 0.00 = 1.17$

For sub-humid conditions

- for strong wind (4 m/s)	$K_{c\text{ mid}} = 1.15 + 0.05 = 1.20$
- for moderate wind (2 m/s)	$K_{c\text{ mid}} = 1.15 + 0.00 = 1.15$
- for calm wind (1 m/s)	$K_{c\text{ mid}} = 1.15 - 0.05 = 1.12$

For humid and very humid conditions

- for strong wind (4 m/s)	$K_{c\text{ mid}} = 1.15 - 0.05 = 1.10$
- for moderate wind (2 m/s)	$K_{c\text{ mid}} = 1.15 - 0.10 = 1.05$
- for calm wind (1 m/s)	$K_{c\text{ mid}} = 1.15 - 0.15 = 1.02$

Depending on the aridity of the climate and the wind conditions, the crop coefficient for wheat during the mid-season stage ranges from 1.02 (humid and calm wind) to 1.25 (arid and strong wind).

Where the user does not have access to a calculator with an exponential function, the solution of the $(h/3)^{0.3}$ expression can be approximated as $[(h/3)^{0.5}]^{0.5}$ where the square root key is used.

RH_{min} is used rather than RH_{mean} because it is easier to approximate RH_{min} from T_{max} where relative humidity data are unavailable. Moreover, under the common condition where T_{min} approaches T_{dew} (i.e., $RH_{max} \approx 100\%$), the vapour pressure deficit ($e_s - e_a$), with e_s from Equation 12 and e_a from Equation 17, becomes $[(100 - RH_{min})/200] e^\circ(T_{max})$, where $e^\circ(T_{max})$ is saturation vapour pressure at maximum daily air temperature. This indicates that RH_{min} better reflects the impact of vapour pressure deficit on K_c than does RH_{mean} . RH_{min} is calculated on a daily or average monthly basis as:

$$RH_{min} = \frac{e^\circ(T_{dew})}{e^\circ(T_{max})} 100 \quad (63)$$

where T_{dew} is mean dewpoint temperature and T_{max} is mean daily maximum air temperature during the mid-season growth stage. Where dewpoint temperature or other hygrometrie data are not available or are of questionable quality, RH_{min} can be estimated by substituting mean daily minimum air temperature, T_{min} , for T_{dew} ¹. Then:

$$RH_{min} = \frac{e^\circ(T_{min})}{e^\circ(T_{max})} 100 \quad (64)$$

¹ In the case of arid and semi-arid climates, T_{min} in equation (64) should be adjusted as indicated in Annex 6 (equation 6-6) by subtracting 2°C from the average value of T_{min} to better approximate T_{dew} .

The values for u_2 and RH_{min} need only be approximate for the mid-season growth stage. This is because Equation 62 is not strongly sensitive to these values, changing 0.04 per 1 m/s change in u_2 and per 10% change in RH_{min} for a 3 m tall crop. Measurements, calculation, and estimation of missing wind and humidity data are provided in Chapter 3. Wind speed measured at other than 2 m height should be adjusted to reflect values for wind speed at 2 m over grass using Equation 47. Where no data on u_2 or RH_{min} are available, the general classification for wind speed and humidity data given in Tables 15 and 16 can be used.

TABLE 15. Empirical estimates of monthly wind speed data

description	mean monthly wind speed at 2 m
light wind	... ≤ 1.0 m/s
light to moderate wind	2.0 m/s
moderate to strong wind	4.0 m/s
strong wind	... ≥ 5.0 m/s
general global conditions	2 m/s

TABLE 16. Typical values for RH_{min} compared with RH_{mean} for general climatic classifications

Climatic classification	RH _{min} (%)	RH _{mean} (%)
Arid	20	45
Semi-arid	30	55
Sub-humid	45	70
Humid	70	85
Very humid	80	90

Equation 62 is valid for mean plant heights up to 10 m. For plant heights smaller than 0.1 m, vegetation will behave aerodynamically similar to grass reference and eq. 62 should not be applied. Example values for h are listed in Table 12 for various crops. However, the mean plant height will greatly vary with crop variety and with cultural practices. Therefore, wherever possible, h should be obtained from general field observations. However, the presence of the 0.3 exponent in Equation 62 makes these equations relatively insensitive to small errors in the value used for h . Generally, a single value for h is used to represent the mid-season period.

Adjustment for frequency of wetting

$K_{c\text{ mid}}$ is less affected by wetting frequency than is $K_{c\text{ ini}}$, as vegetation during this stage is generally near full ground cover so that the effects of surface evaporation on K_c are smaller. For frequent irrigation of crops (more frequently than every 3 days) and where the $K_{c\text{ mid}}$ of Table 12 is less than 1.0, the value can be replaced by approximately 1.1-1.3 to account for the combined effects of continuously wet soil, evaporation due to interception (sprinkler irrigation) and roughness of the vegetation, especially where the irrigation system moistens an important fraction of the soil surface ($f_w > 0.3$).

EXAMPLE 27. Determination of $K_{c\text{ mid}}$

Calculate $K_{c\text{ mid}}$ for maize crops near Taipei, Taiwan and near Mocha, Yemen. The average mean daily wind speed (u_2) during the mid-season stage at Taipei is about 1.3 m/s and the minimum relative humidity (RH_{min}) during this stage averages 75%. The average u_2 during the mid-season near Mocha is 4.6 m/s and the RH_{min} during this stage averages 44%.

From Table 12, the value for $K_{c\text{ mid}}$ is 1.20 for maize. The value for h from Table 12 is 2 m. Using Eq. 62

For Taipei (humid climate):

$$K_{c\text{ mid}} = 1.20 + [0.04(1.3 - 2) - 0.004(75 - 45)] \left(\frac{2}{3} \right)^{0.3} = 1.07$$

For Mocha (arid climate):

$$K_{c\text{ mid}} = 1.20 + [0.04(4.6 - 2) - 0.004(44 - 45)] \left(\frac{2}{3} \right)^{0.3} = 1.30$$

The average crop coefficient predicted during the mid-season stage is 1.07 for Taipei and 1.30 for Mocha.

Crop coefficient for the end of the late season stage ($K_{c\text{ end}}$)

Typical values for the crop coefficient at the end of the late season growth stage, $K_{c\text{ end}}$, and listed in Table 12 for various agricultural crops. The values given for $K_{c\text{ end}}$ reflect crop and water management practices particular to those crops. If the crop is irrigated frequently until harvested fresh, the topsoil remains wet and the $K_{c\text{ end}}$ value will be relatively high. On the other hand, crops that are allowed to senesce and dry out in the field before harvest receive less frequent irrigation or no irrigation at all during the late season stage. Consequently, both the soil surface and vegetation are dry and the value for $K_{c\text{ end}}$ will be relatively small (Figure 33).

Where the local water management and harvest timing practices are known to deviate from the typical values presented in Table 12, then the user should make some adjustments to the values for $K_{c\text{ end}}$. Some guidance on adjustment of K_c values for wetting frequency is provided in Chapter 7. For premature harvest, the user can construct a K_c curve using the $K_{c\text{ end}}$ value provided in Table 12 and a late season length typical of a normal harvest date; but can then terminate the application of the constructed curve early, corresponding to the time of the early harvest.

The $K_{c\text{ end}}$ values in Table 12 are typical values expected for average $K_{c\text{ end}}$ under the standard climatic conditions. More arid climates and conditions of greater wind speed will have higher values for $K_{c\text{ end}}$. More humid climates and conditions of lower wind speed will have lower values for $K_{c\text{ end}}$. For specific adjustment in climates where RH_{min} differs from 45% or where u_2 is larger or smaller than 2.0 m/s, Equation 65 can be used:

$$K_{c\text{ end}} = K_{c\text{ end(Tab)}} + [0.04(u_2 - 2) - 0.004(RH_{\text{min}} - 45)] \left(\frac{h}{3}\right)^{0.3} \quad (65)$$

where

$K_{c\text{ end(Tab)}}$ value for $K_{c\text{ end}}$ taken from Table 12,

u_2 mean value for daily wind speed at 2 m height over grass during the late season growth stage [m s^{-1}], for $1 \text{ m s}^{-1} \leq u_2 \leq 6 \text{ m s}^{-1}$,

RH_{min} mean value for daily minimum relative humidity during the late season stage [%], for $20\% \leq RH_{\text{min}} \leq 80\%$,

h mean plant height during the late season stage [m], for $0.1 \text{ m} \leq h \leq 10 \text{ m}$.

FIGURE 33. Ranges expected for $K_{c\text{ end}}$

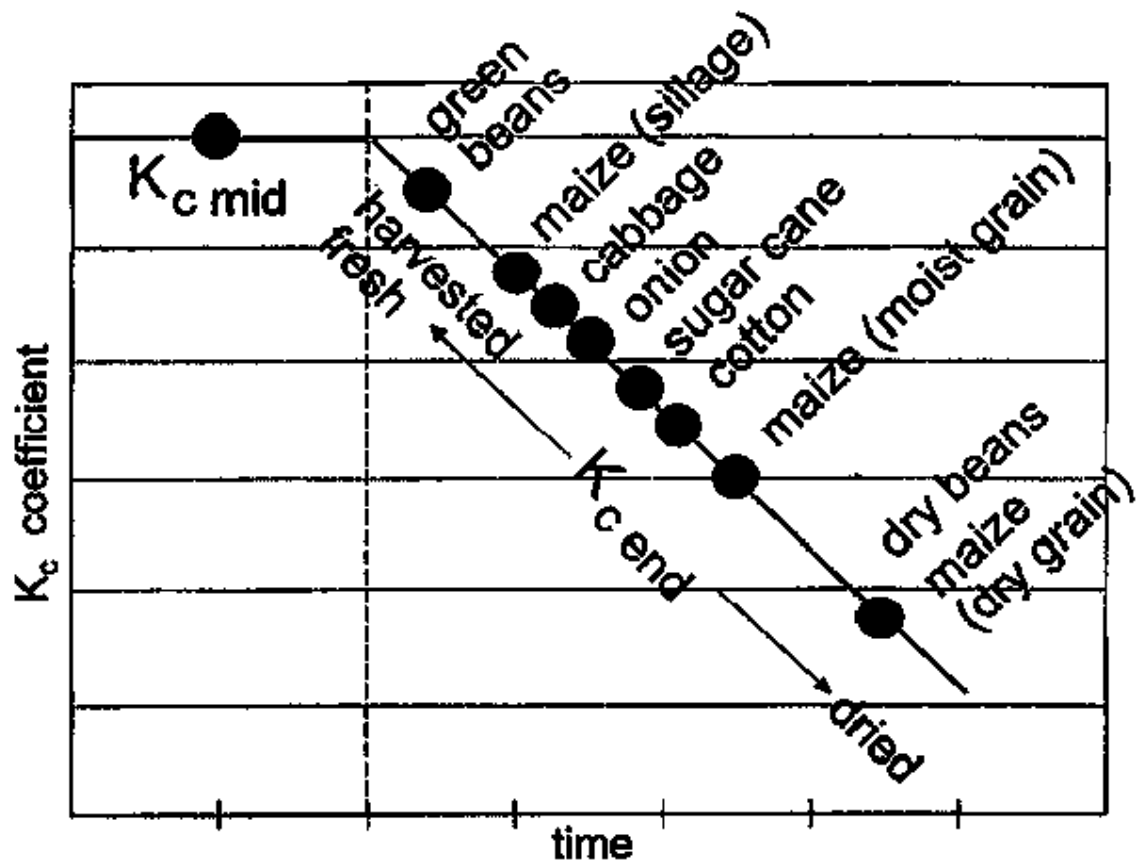
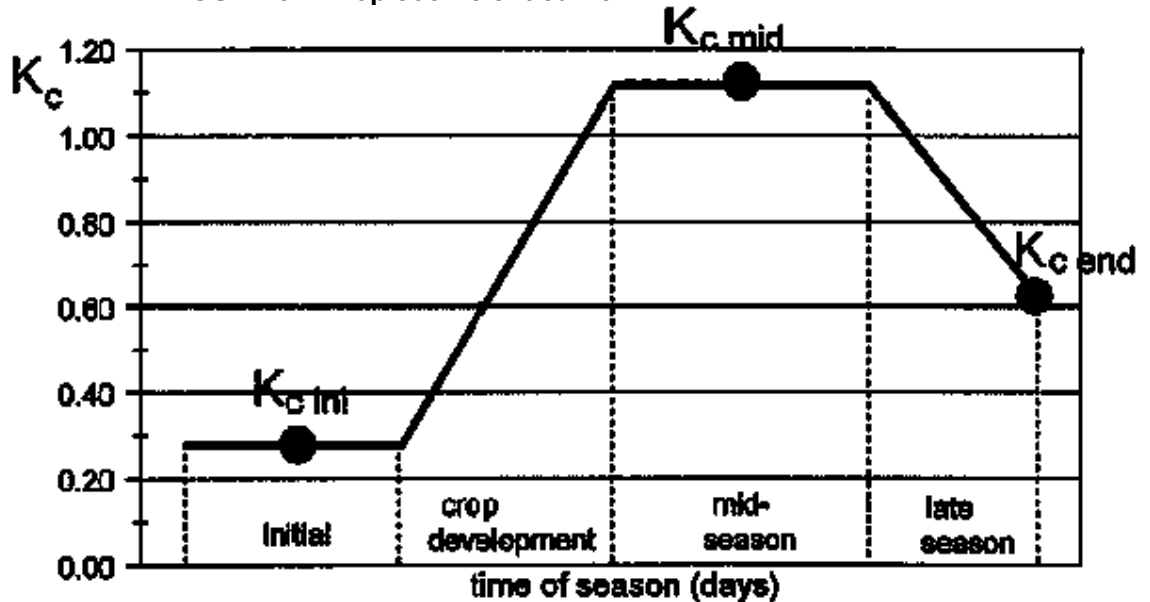


FIGURE 34. Crop coefficient curve



Equation 65 is only applied when the tabulated values for $K_{c \text{ end}}$ exceed 0.45. The equation reduces the $K_{c \text{ end}}$ with increasing RH_{min} . This reduction in $K_{c \text{ end}}$ is characteristic of crops that are harvested 'green' or before becoming completely dead and dry (i.e., $K_{c \text{ end}} \geq 0.45$). No adjustment is made when $K_{c \text{ end (Table)}} < 0.45$ (i.e., $K_{c \text{ end}} = K_{c \text{ end (Tab)}}$). When crops are allowed to senesce and dry in the field (as evidenced by $K_{c \text{ end}} < 0.45$), u_2 and RH_{min} have less

effect on $K_{c\text{ end}}$ and no adjustment is necessary. In fact, $K_{c\text{ end}}$ may decrease with decreasing RH_{min} for crops that are ripe and dry at the time of harvest, as lower relative humidity accelerates the drying process.

Construction of the K_c curve

[Annual crops](#)
[K_c curves for forage crops](#)
[Fruit trees](#)

Annual crops

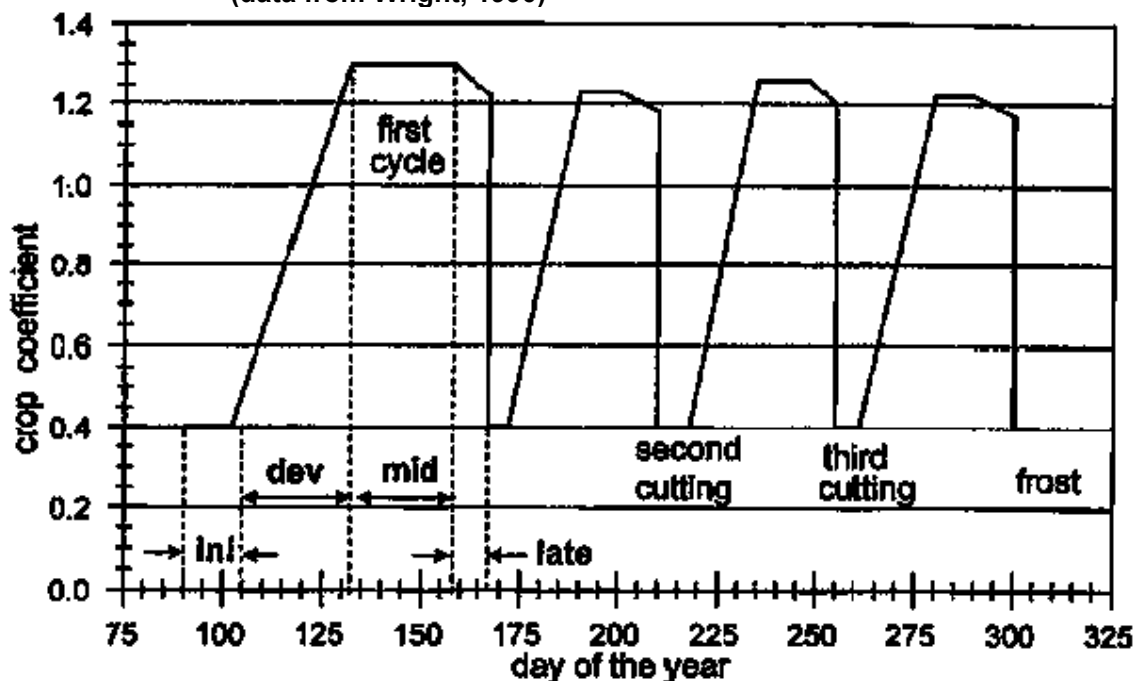
Only three point values for K_c are required to describe and to construct the K_c curve. The curve such as that shown in Figure 34 is constructed using the following three steps:

1. Divide the growing period into four general growth stages that describe crop phenology or development (initial, crop development, mid-season, and late season stage), determine the lengths of the growth stages, and identify the three K_c values that correspond to $K_{c\text{ ini}}$, $K_{c\text{ mid}}$ and $K_{c\text{ end}}$ from Table 12.
2. Adjust the K_c values to the frequency of wetting and/or climatic conditions of the growth stages as outlined in the previous section.
3. Construct a curve by connecting straight line segments through each of the four growth stages. Horizontal lines are drawn through $K_{c\text{ ini}}$ in the initial stage and through $K_{c\text{ mid}}$ in the mid-season stage. Diagonal lines are drawn from $K_{c\text{ ini}}$ to $K_{c\text{ mid}}$ within the course of the crop development stage and from $K_{c\text{ mid}}$ to $K_{c\text{ end}}$ within the course of the late season stage.

K_c curves for forage crops

Many crops grown for forage or hay are harvested several times during the growing season. Each harvest essentially terminates a 'sub' growing season and associated K_c curve and initiates a new 'sub' growing season and associated K_c curve. The resulting K_c curve for the entire growing season is the aggregation of a series of K_c curves associated with each sub-cycle. Figure 35 presents a K_c curve for the entire growing season constructed for alfalfa grown for hay in southern Idaho.

FIGURE 35. Constructed curve for K_c for alfalfa hay in southern Idaho, the United States using values from Tables 11 and 12 and adjusted using Equations 62 and 65 (data from Wright, 1990)



In the southern Idaho climate, greenup (leaf initiation) begins in the spring on about day 90 of the year. The crop is usually harvested (cut) for hay three or four times during the growing season. Therefore, Figure 35 shows four K_c sub-cycles or cutting cycles: sub-cycle 1 follows greenup in the spring and the three additional K_c sub-cycles follow cuttings. Cuttings create a ground surface with less than 10% vegetation cover. Cutting cycle 1 is longer in duration than cycles 2, 3 and 4 due to lower air and soil temperatures during this period that reduce crop growth rates. The lengths for cutting cycle 1 were taken from the first entry for alfalfa ("1st cutting cycle") in Table 11 for Idaho, the United States (10/30/25/10). The lengths for cutting cycles 2, 3 and 4 were taken from the entry for alfalfa in Table 11 for "individual cutting periods" for Idaho, the United States (5/20/10/10). These lengths were based on observations. In the southern Idaho climate, frosts terminate the growing season sometime in the fall, usually around day 280-290 of the year (early to mid-October).

The magnitudes of the K_c values during the mid-season periods of each cutting cycle shown in Figure 35 vary from cycle to cycle due to the effects of adjusting the values for $K_{c\text{mid}}$ and $K_{c\text{end}}$ for each cutting cycle period using Equations 62 and 65. In applying these two adjustment equations, the u_2 and RH_{min} values were averages for the mid-season and late season stages within each cutting cycle. Basal K_{cb} curves similar to Figure 35 can be constructed for forage or hay crops, following procedures presented in Chapter 7.

$K_{c\text{mid}}$ when effects of individual cutting periods are averaged

Under some conditions, the user may wish to average the effects of cuttings for a forage crop over the course of the growing season. When cutting effects are averaged, then only a single value for $K_{c\ mid}$ and a only single K_c curve need to be employed for the whole growing season. When this is the case, a "normal" K_c curve is constructed as in Figure 25, where only one midseason period is shown for the forage crop. The $K_{c\ mid}$ for this total midseason period must average the effects of occasional cuttings or harvesting. The value that is used for $K_{c\ mid}$ is therefore an average of the K_c curve for the time period starting at the first attainment of full cover and ending at the beginning of the final late season period near dormancy or frost. The value used for $K_{c\ mid}$ under these averaged conditions may be only about 80% of the K_c value that represents full ground cover. These averaged, full-season $K_{c\ mid}$ values are listed in Table 12. For example, for alfalfa hay, the averaged, full-season $K_{c\ mid}$ is 1.05, whereas, the $K_{c\ mid}$ for an individual cutting period is 1.20.

Fruit trees

Values for the crop coefficient during the mid-season and end of late season stages are given in Table 12. As mentioned before, the K_c values listed are typical values for standard climatic conditions and need to be adjusted by using Equations 62 and 65 where RH_{min} or u_2 differ. As the mid and late season stages of deciduous trees are quite long, the specific adjustment of K_c to RH_{min} and u_2 should take into account the varying climatic conditions throughout the season. Therefore, several adjustments of K_c are often required if the mid and late seasons cover several climatic seasons, e.g., spring, summer and autumn or wet and dry seasons. The $K_{c\ ini}$ and $K_{c\ end}$ for evergreen non dormant trees and shrubs are often not different, where climatic conditions do not vary much, as happens in tropical climates. Under these conditions, seasonal adjustments for climate may therefore not be required since variations in ET_c depend mostly on variations in ET_o .

Calculating ET_c

[Graphical determination of \$K_c\$](#)
[Numerical determination of \$K_c\$](#)

From the crop coefficient curve the K_c value for any period during the growing period can be graphically or numerically determined. Once the K_c values have been derived, the crop evapotranspiration, ET_c , can be calculated by multiplying the K_c values by the corresponding ET_o values.

Graphical determination of K_c

Weekly, ten-day or monthly values for K_c are necessary when ET_c calculations are made on weekly, ten-day or monthly time steps. A general procedure is to construct the K_c curve, overlay the curve with the lengths of the weeks, decade or months, and to derive graphically from the curve the K_c value for the period under consideration (Figure 36). Assuming that all decades have a duration of 10 days facilitates the derivation of K_c and introduces little error into the calculation of ET_c .

The constructed K_c curve in Box 15 was used to construct the curve in Figure 36. This curve has been overlaid with the lengths of the decades. K_c values of 0.15, 1.19 and 0.35 and the actual lengths for growth stages equal to 25, 25, 30 and 20 days were used. The crop was planted at the beginning of the last decade of May and was harvested 100 days later at the end of August.

For all decades the K_c values can be derived directly from the curve. The value at the middle of the decade is considered to be the average K_c of that 10 day period. Only the second decade of June, where the K_c value changes abruptly, requires some calculation.

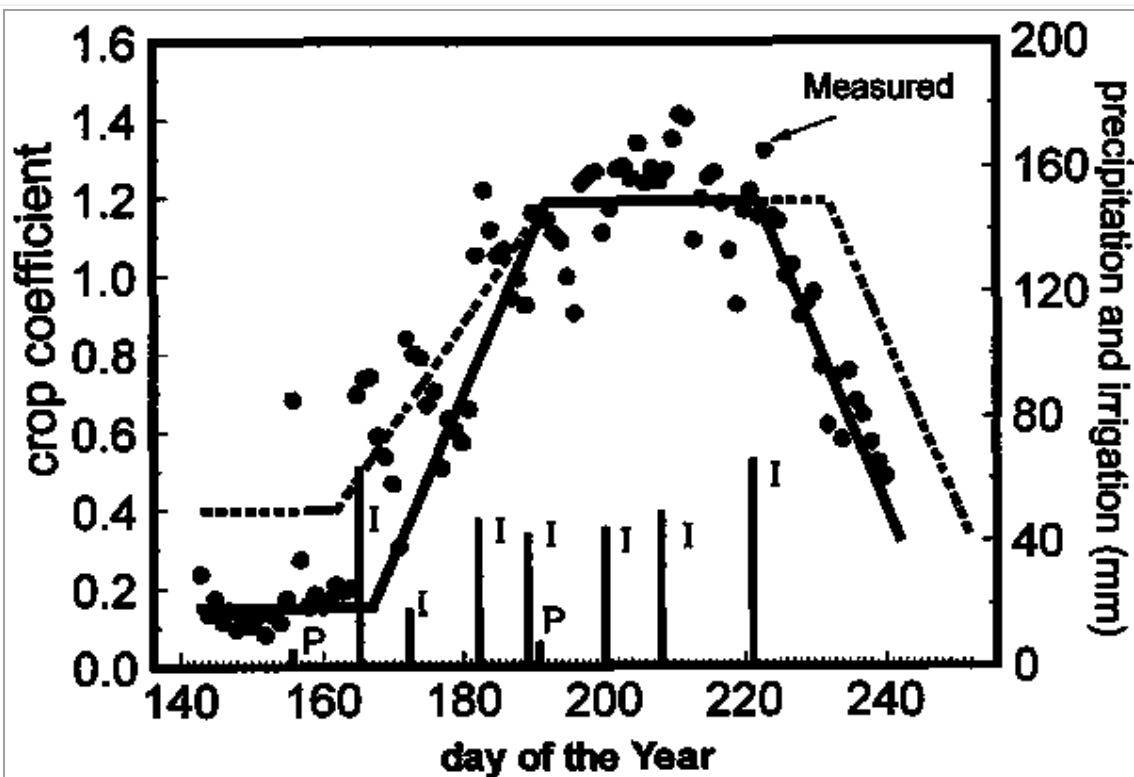
BOX 15. Case study of a dry bean crop at Kimberly, Idaho, the United States (single crop coefficient)

An example application for using the K_c procedure under average soil wetness conditions is presented for a dry bean crop planted on 23 May 1974 at Kimberly, Idaho, the United States (latitude = 42.4°N). The initial, development, mid-season and late season stage lengths are taken from Table 11 for a continental climate as 20, 30, 40 and 20 days (the stage lengths listed for southern Idaho were not used in this example in order to demonstrate the only approximate accuracy of values provided in Table 11 when values for the specific location are not available). Initial values for $K_{c\text{ ini}}$, $K_{c\text{ mid}}$ and $K_{c\text{ end}}$ are selected from Table 12 as 0.4, 1.15, and 0.35.

The mean RH_{min} and u_2 during both the mid-season and late season growth stages were 30% and 2.2 m/s. The maximum height suggested in Table 12 for dry beans is 0.4 m. Therefore, $K_{c\text{ mid}}$ is adjusted using Eq. 62 as:

$$K_{c\text{ mid}} = 1.15 + [0.04(2.2 - 2) - 0.004(30 - 45)] \left(\frac{0.4}{3} \right)^{0.3} = 1.19$$

As $K_{c\text{ end}} = 0.35$ is less than 0.45, no adjustment is made to $K_{c\text{ end}}$. The value for $K_{c\text{ mid}}$ is not significantly different from that in Table 12 as $u_2 \approx 2$ m/s, RH_{min} is just 15% lower than the 45% represented in Table 12, and the height of the beans is relatively short. The initial K_c curve for dry beans in Idaho can be drawn, for initial, planning purposes, as shown in the graph (dotted line), where $K_{c\text{ ini}}$, $K_{c\text{ mid}}$ and $K_{c\text{ end}}$ are 0.4, 1.19 and 0.35 and the four lengths of growth stages are 20, 30, 40 and 20 days. Note that the $K_{c\text{ ini}} = 0.4$ taken from Table 12 serves only as an initial, approximate estimate for $K_{c\text{ ini}}$.



Constructed K_c curves using values from Tables 11 and 12 directly (dotted line) and modified using $K_{c\text{ ini}}$ from Fig. 29 and $L_{\text{ini}} = 25$, $L_{\text{dev}} = 25$, $L_{\text{mid}} = 30$, and $L_{\text{late}} = 20$ days (heavy line) for dry beans at Kimberly, Idaho. Also shown are daily measured K_c (lysimeter data from Wright, 1990).

$K_{c\text{ ini}}$ can be more accurately estimated using the approach described in this chapter. ET_o during the initial period at Kimberly (late May - early June, 1974) averaged 5.3 mm/day, and the wetting interval during this period was approximately 14 days (2 rainfall events occurred averaging 5 mm per event). Therefore, as the wetting events were light (< 10 mm each), Fig. 29 is used. The soil texture at Kimberly, Idaho is silt loam. From Fig. 29, $K_{c\text{ ini}}$ for the 14 day wetting interval and $ET_o = 5.3$ mm/day is about 0.15. This value is substantially less than the general 0.4 value suggested by Table 12, and emphasizes the need to utilize local, actual precipitation and irrigation data when determining $K_{c\text{ ini}}$.

Comparison of constructed curves with measurements

Because the ET_o data for the dry bean crop at Kimberly, Idaho were measured using a precision lysimeter system during 1974 by Wright (1990), the actual K_c measurements can be compared with the constructed K_c curves, where actual K_c was calculated by dividing lysimeter measurements of ET_o by daily ET_o estimated using the FAO Penman-Monteith equation.

As illustrated in the graph, the mid-season length as taken from Table 11 for the general, continental climate overestimated the true mid-season length for dry beans in southern Idaho, which averaged only about 30 days rather than 40 days as suggested by Table 11. This illustrates the importance of using the local observation of 30 days for mid-season period length rather than the general value from Table 11.

The final, best estimate for the K_c curve for the dry bean crop in southern Idaho is plotted (lower curve in graph) using K_c values of 0.15, 1.19, and 0.35 and the actual observed lengths of growth stages equal to 25, 25, 30 and 20 days. Note the impact that the error in estimating mid-season length has on the area under the K_c curve. This supports the need to obtain local observations of

growth stage dates and lengths.

The value calculated for $K_{c\text{ mid}}$ (1.19) appears to have underestimated the measured value for K_c during portions of the mid-season period at Kimberly. Some of this effect was due to effects of increased soil water evaporation following four irrigations during the 1974 mid-season which increased the effective K_c . This is illustrated in Box 16, where the basal $K_{cb} + K_e$ approach is introduced and demonstrated for this same example.

The 0.15 value calculated for $K_{c\text{ ini}}$ using Fig. 29 agrees closely with measured K_c during the initial period. Measured K_c during the development period exceeded the final K_c curve during days on or following wetting events. The day to day variation in the lysimeter measured K_c is normal and is caused by day to day variations in weather, in wind direction, by errors in prediction of R_n and ET_o , and by some random errors in the lysimeter measurements and weather measurements.

FIGURE 36. K_c curve and ten-day values for K_c and ET_c derived from the graph for the dry bean crop example (Box 15)

first five days of that decade, $K_c = 0.15$, while during the second part of the decade K_c varies from 0.15 to 0.36 at the end of day 10. The K_c for that decade is consequently: $5/10(0.15) + 5/10(0.15+0.36)/2 = 0.20$.

Numerical determination of K_c

The K_c coefficient for any period of the growing season can be derived by considering that during the initial and mid-season stages K_c is constant and equal to the K_c value of the growth stage under consideration. During the crop development and late season stage, K_c varies linearly between the K_c at the end of the previous stage ($K_{c\text{ prev}}$) and the K_c at the beginning of the next stage ($K_{c\text{ next}}$), which is $K_{c\text{ end}}$ in the case of the late season stage:

$$K_{ci} = K_{c\text{ prev}} + \left[\frac{i - \sum(L_{\text{prev}})}{L_{\text{stage}}} \right] (K_{c\text{ next}} - K_{c\text{ prev}}) \quad (66)$$

where

i day number within the growing season [1.. length of the growing season],
 K_{ci} crop coefficient on day i ,
 L_{stage} length of the stage under consideration [days],
 $\sum(L_{\text{prev}})$ sum of the lengths of all previous stages [days].

Equation 66 applies to all four stages.

EXAMPLE 28. Numerical determination of K_c

Determine K_c at day 20, 40, 70 and 95 for the dry bean crop (Figure 36).

Crop growth stage	Length (days)	K_c
initial	25	$K_{c\text{ ini}} = 0.15$
crop development	25	0.15... 1.19
mid-season	30	$K_{c\text{ mid}} = 1.19$

late season	20	1.19 .. $K_{c\text{ end}} = 0.35$	
At i = 20:	initial stage, $K_c = K_{c\text{ ini}} =$	0.15	-
At i = 40	Crop development stage,		
For:	$\Sigma (L_{\text{prev}}) = L_{\text{ini}} =$	25	days
and:	$L_{\text{stage}} = L_{\text{dev}} =$	25	days
From Eq. 66:	$K_c = 0.15 + [(40 - 25)/25](1.19 - 0.15) =$	0.77	-
At i = 70:	mid-season stage, $K_c = K_{c\text{ mid}} =$	1.19	-
At i = 95	late season stage,		
For:	$\Sigma (L_{\text{prev}}) = L_{\text{ini}} + L_{\text{dev}} + L_{\text{mid}} = (25 + 25 + 30) =$	80	days
and:	$L_{\text{stage}} = L_{\text{late}} =$	20	days
From Eq. 66:	$K_c = 1.19 + [(95-80)/20](0.35-1.19) =$	0.56	-
The crop coefficients at day 20, 40, 70 and 95 for the dry bean crop are 0.15, 0.77, 1.19 and 0.56 respectively.			

Alfalfa-based crop coefficients

As two reference crop definitions (grass and alfalfa) are in use in various parts of the world, two families of K_c curves for agricultural crops have been developed. These are the alfalfa-based K_c curves by Wright (1981; 1982) and grass-based curves by Pruitt (Doorenbos and Pruitt 1977; Jensen *et al.* 1990) and those reported in this paper. The user must exercise caution to avoid mixing grass-based K_c values with alfalfa reference ET and vice versa. Usually, a K_c based on the alfalfa reference can be 'converted' for use with a grass reference by multiplying by a factor ranging from about 1.0 to 1.3, depending on the climate (1.05 for humid, calm conditions, and 1.2 for semi-arid, moderately windy conditions, and 1.35 for arid, windy conditions):

$$K_{c\text{ (grass)}} = K_{\text{ratio}} K_{c\text{ (alfalfa)}} \quad (67)$$

where

$K_{c\text{ (grass)}}$ grass-based K_c (this handbook),
 $K_{c\text{ (alfalfa)}}$ alfalfa-based K_c ,
 K_{ratio} conversion factor (1.0... 1.3).

A reference conversion ratio can be established for any climate by using the $K_{c\text{ mid}} = 1.20$ listed for alfalfa in Table 12 and then adjusting this $K_{c\text{ mid}}$ for the climate using Equation 62. For example, at Kimberly, Idaho, the United States, where $RH_{\text{min}} = 30\%$ and $u_2 = 2.2$ m/s are average values during the summer months, a reference conversion ratio between alfalfa and grass references using Equation 62 is approximately:

$$K_{\text{ratio}} = 1.2 + [0.04(2.2 - 2) - 0.004(30 - 45)] \left(\frac{0.5}{3} \right)^{0.3} = 1.24 \quad (68)$$

where

$h = 0.5$ m is the standard height for the alfalfa reference.

Transferability of previous K_c values

The values for $K_{c\text{ mid}}$ and $K_{c\text{ end}}$ listed in Table 12 are for a large part based on the original values presented in FAO Irrigation and Drainage Papers No. 24 and 33 (FAO-24 and FAO-33), with some adjustment and revisions to reflect recent findings. Similarly adjustments in $K_{c\text{ mid}}$ to compensate for differences in aerodynamic roughness and leaf area, as introduced in Equation 62 are derived from the K_c values given for different wind and RH_{min} conditions in the concerned K_c table in FAO-24, with some upward adjustment to better reflect increased ET_{crop} values under high wind and low RH_{min} when applied with the FAO Penman-Monteith equation. The K_c 's from FAO-24 were based primarily on a living grass reference crop. The FAO Penman-Monteith equation presented in this publication similarly represents the same standardized grass reference. For that reason K_c values are in general not very different between these publications except under high wind and low RH_{min} .

The No. 24 modified Penman was found frequently to overestimate ET_o even up to 25 % under high wind and low evaporative conditions and required often substantial local calibration (see chapter 2). K_c values derived from crop water use studies which used the FAO-24 Penman equation to compute grass reference crop evapotranspiration, can therefore not be used and need to be adjusted using ET_o values estimated from the FAO Penman-Monteith equation. Similarly crop water requirement estimates based on the FAO-24 Modified Penman equation will need to be reassessed in view of the found differences between the FAO-24 Penman and the FAO Penman-Monteith reference equations.

A hydrological perspective on evaporation: historical trends and future projections in Britain

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ABSTRACT

Evaporation is an important component of the hydrological cycle. Potential evaporation (PE) from a vegetated surface is the amount of water that would be lost to the atmosphere were the supply unlimited; actual evaporation (AE) is a fraction of PE dependent on soil wetness. Many formulae exist for estimating PE from meteorological data. PE is usually a required input, with rainfall, for hydrological modelling, but PE accuracy is generally considered less important than rainfall accuracy for model performance. Few studies investigate historical evaporation trends in Britain, but generally indicate increases. Most studies presenting future PE projections for Britain indicate increased annual PE, but some suggest small decreases in some months. Limited consensus on the best formulae to derive PE projections from climate model data is further complicated by possible changes in plant behaviour (transpiration and growth) under higher carbon dioxide concentrations. Appropriate PE estimation could be particularly important in regions where precipitation and PE are in close balance, but PE uncertainty could be less important than climate model uncertainty for hydrological impacts. Further research is needed into which PE formulae are likely to be most reliable when applied with climate model data, and into climate change and plant feedbacks.

Key words | actual evaporation, climate change impacts, evapotranspiration, hydrology, potential evaporation

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INTRODUCTION

Evaporation transfers water from the land-surface to the atmosphere, so is an important part of the hydrological cycle. While there is ongoing debate on terminology (Lhomme 1997; Cain *et al.* 1998), here the terms evaporation and evapotranspiration each encompass transfer via both evaporation (loss of water lying on a surface, e.g., lake, soil, leaf) and transpiration (loss via plant stomata). Potential evaporation (PE or PET) is generally considered as the amount of water that would be lost to the atmosphere if there were no limits to soil-moisture supply (Federer *et al.* 1996). So actual evaporation (AE or AET) can be estimated as a fraction of PE dependent on soil wetness; it can be less than PE if soils are dry, but generally cannot be greater than PE. PE is difficult to measure directly, although several techniques attempt to measure AE. Some of the complexities of

measuring and modelling evaporation are described by Shuttleworth (2007).

Four meteorological variables influence PE: radiation (or sunshine), temperature, humidity (or vapour pressure) and wind speed. Further variables influence the transpiration component: plant height, rooting depth, leaf area and vegetation roughness. Thus PE varies for different plant types. To simplify matters, the 'reference crop' concept was introduced, with average crop parameters provided for estimation of reference PE. The reference crop is often short grass (Pereira *et al.* 1999). Many formulae have been developed for estimating PE, some for particular reference crops and some where crop parameters can be specified. The simplest, empirical formulae involve a single meteorological variable (e.g., the temperature-based formulations of

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Thornthwaite (1948), Hamon (1961) and Oudin *et al.* (2005a)), while the most complex and physically based formulae involve all four meteorological variables (e.g., Penman–Monteith; Monteith 1965), with a range in between (e.g., Blaney–Criddle, involving temperature and sunshine (Blaney & Criddle 1950), and Priestley–Taylor, involving temperature and radiation (Priestley & Taylor 1972)). Oudin *et al.* (2005a) provide a useful summary of 17 variations found in the literature. Penman–Monteith is recommended by the United Nations Food and Agricultural Organisation (FAO) for deriving grass reference PE (Pereira *et al.* 1999), and is used by the UK Climate Projections 09 (UKCP09) weather generator (Jones *et al.* 2009). The UK Met Office Rainfall and Evaporation Calculation System (MORECS; Thompson *et al.* 1981; Hough *et al.* 1996) and the Met Office Surface Exchange Scheme (MOSES; Cox *et al.* 1998) use modified versions of Penman–Monteith.

PE estimates are a required input for hydrological modelling, alongside rainfall. PE changes, on their own or in combination with rainfall changes, can contribute to changes in hydrological indices like mean monthly river flows. This paper provides some background on AE and PE in Britain, influence of PE in hydrological modelling, and the ways in which environmental change can affect PE. A review of historical evaporation trends in Britain is presented, with a global context. Future PE projections in Britain are reviewed, with estimation difficulties and effects of PE uncertainty on hydrological climate change impacts discussed. Finally, a discussion and conclusions are presented. Although the focus here is the hydrological perspective, evaporation is of interest in other areas (e.g., agriculture and ecology; Fisher *et al.* 2011), and many of the same issues will apply.

BACKGROUND

Penman–Monteith PE, MORECS and MOSES

Penman–Monteith PE for short grass (m/s) is given by:

$$PE_{PM} = \frac{1}{\lambda \rho_w} \frac{\Delta(R_n - G) + \rho_a c_p (e_a - e_d)/r_a}{\Delta + \gamma(1 + r_c/r_a)}$$

with λ latent heat flux (J/kg), ρ_w water density (kg/m³), ρ_a air density (kg/m³), c_p specific heat of air (J/kg/°C), γ the psychrometric constant (kPa/°C), $e_a = e(T_a) = 0.611 \exp(17.27T_a/(T_a + 237.3))$ saturation vapour pressure (kPa) with T_a air temperature (°C), $e_d = e(T_d)$ actual vapour pressure (kPa) with T_d dew-point temperature (°C), $\Delta = de_a/dT_a = 17.27 \times 237.3 e_a / (T_a + 237.3)^2$ the slope of the vapour pressure curve (kPa/°C), R_n net solar radiation (J/m²/s), G soil heat flux (J/m²/s), $r_a = 208/W_2$ aerodynamic resistance (s/m) with W_2 wind speed (m/s) at a 2 m height, and r_c canopy surface resistance of short grass (s/m). The FAO recommend $r_c = 70$ s/m for short grass (height 0.12 m) (Allen *et al.* 1994). The equation was developed for daily weather data but its applicability has been demonstrated for monthly mean data (Allen *et al.* 1998; Oudin *et al.* 2010). Penman PE (Penman 1948) has $r_c = 0$ and $G = 0$, essentially representing loss from open water.

Penman–Monteith forms part of MORECS, which converts daily synoptic weather station data into estimates of weekly and monthly PE, AE and soil moisture deficit (SMD) for short grass (and several other land covers) on a 40 × 40 km grid over Britain, for a range of soils defined by their available water capacity (AWC; Hough & Jones 1997). It implements a slightly modified version of Penman–Monteith to that recommended by the FAO. In particular, MORECS includes a correction for the assumption that surface temperature equals the measured (air) temperature, and uses monthly-varying r_c for short grass (height 0.15 m), ranging from 44.5 s/m (late spring) to 88.7 s/m (winter) (average ~73 s/m).

MOSES calculates water and energy fluxes between the land-surface and atmosphere alongside estimates of carbon dioxide (CO₂) fluxes and their effects on vegetation physiology (Cox *et al.* 1999). It can run operationally at a 2 km resolution and hourly time-step (Smith *et al.* 2006), providing outputs including soil moisture, AE and PE for a range of vegetated and non-vegetated surface types, with land-cover maps used to determine the proportion of each type within each grid-box. Like MORECS, MOSES calculates PE using Penman–Monteith but with variable r_c assumed to depend on photosynthesis, which depends on air temperature, radiation, humidity and vegetation type. MOSES also includes processes such as canopy evaporation and sublimation from snow. MOSES now forms the basis of the

Joint UK Land Environment Simulator (JULES; [Best *et al.* 2011](#)), which is a land-surface model used for research into the carbon cycle and climate change at local and global scales. JULES has been benchmarked against eddy-covariance AE data from around the world ([Blyth *et al.* 2010](#)). MOSES and JULES PE can be expected to change in line with contemporary understanding of earth-system processes, while MORECS PE reflects a standardised, but arguably older, physical understanding.

PE, AE and hydrological modelling

PE estimates (or the variables to make them) are required inputs for most hydrological models. This includes models that provide continuous simulation of river flow at a catchment outlet, like CATCHMOD (the Thames Catchment Model; [Wilby *et al.* 1994](#)) or CLASSIC (Climate and LAnd use Scenario Simulation In Catchments; [Crooks & Naden 2007](#)), and fully distributed area-wide models, like G2G (Grid-to-Grid; [Bell *et al.* 2009](#)) or WASIM (Water flow and balance SIMulation; [Kleinn *et al.* 2005](#)). It also applies to models such as the Palmer Drought Severity Index ([Sheffield *et al.* 2012](#)). Typically, hydrological models estimate AE as a fraction of PE dependent upon soil moisture, modelled continuously using a water-accounting scheme.

PE is much less spatially and temporally variable than rainfall, and highly seasonally predictable ([Calder *et al.* 1983](#)), so relatively simple data are considered sufficient to obtain a closed water balance in hydrological modelling. Thus rainfall accuracy is generally more important than PE accuracy for hydrological model performance ([Paturel *et al.* 1995](#); [Nandakumar & Mein 1997](#); [Boughton 2006](#); [Manning *et al.* 2009](#)). However, [Parmele \(1972\)](#) shows varying sensitivity to PE biases of +10% and -20% in nine US catchments, indicating that relative importance is likely to vary by location, as well as how performance is assessed (e.g., focussing on high or low flows). Also, some of the perceived insensitivity of models to PE accuracy could be due to recalibration, which can allow model parameters to compensate for differing PE ([Andréassian *et al.* 2004](#)).

[Oudin *et al.* \(2005a\)](#) tested 27 PE formulations with four rainfall-runoff models for 308 catchments in France, Australia and the USA. They found that PE based on temperature or radiation often provided more accurate streamflow

simulations than more complex formulae, but PE from all formulae was scaled by mean annual Penman PE, so only the effects of variability were tested, and the models were recalibrated for each set of inputs. [Vorosmarty *et al.* \(1998\)](#) compare 11 PE formulae over the USA and state ‘there is negative feedback, in that the drier the climate, and the larger the PE, the less important the PE estimate becomes in determining AE and thus runoff’. [Manning *et al.* \(2009\)](#) suggest, for their modelling of Thames water resources, ‘possible underestimation of PE in very hot summers is offset in the subsequent hydrological modelling because AE is limited by moisture supply rather than determined by PE’.

The lower year-to-year variation in PE than rainfall even means that climatological PE (i.e., a seasonal pattern duplicated each year) can be used, rather than PE time-series. [Calder *et al.* \(1983\)](#) showed that using PE time-series led to no clear improvement in SMD estimation compared with climatological PE, for six grassland sites in Britain. Further, [Fowler \(2002\)](#) showed that using climatological monthly mean PE distributed equally over each day of the month led to no significant degradation in SMD estimation when compared with either more complex climatological means or PE time-series, for a site in Auckland, New Zealand. This was the case even for years that were much wetter or dryer than average. Similarly, [Oudin *et al.* \(2005a, b\)](#) found no significant improvements in river flow simulation when using PE time-series, rather than climatological PE, as input to their four rainfall-runoff models for 308 catchments, although they noted that arid and/or small catchments ($PE \geq \text{rainfall}$; area $< 150 \text{ km}^2$) generally gained more benefit from time-series than wet and/or large catchments.

PE, AE and hydrology in Britain

Monthly MORECS short grass PE is often used to provide hydrological model inputs in Britain. [Figure 1](#) shows maps of MORECS annual mean rainfall, PE and AE (for short grass and median AWC soils), and the ratios PE/rainfall and AE/PE, for 1961–1990. There is a south/east to north/west rainfall gradient, with an approximately reverse PE gradient. However, the latter does not carry through to AE, which decreases again in the south/east. The ratio PE/rainfall shows the dryness of eastern Britain and wetness ($PE/\text{rainfall} < 1$) of north/west Britain. The ratio AE/PE

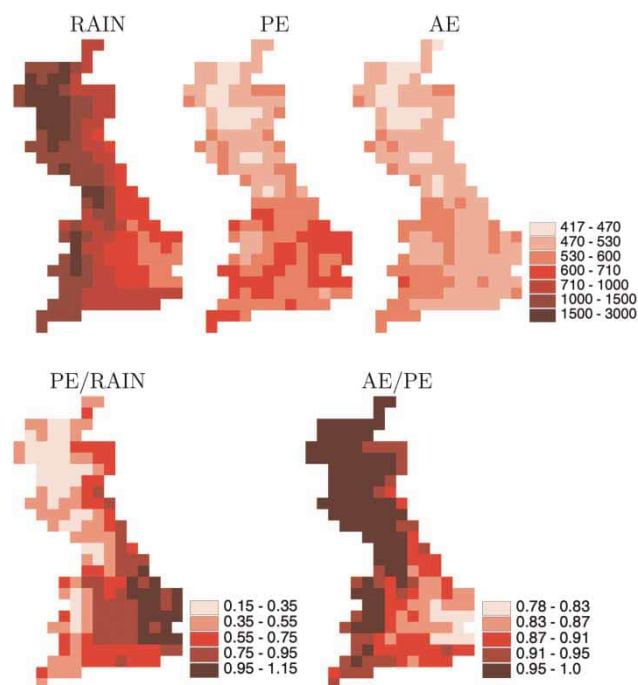


Figure 1 | Maps of MORECS annual mean rainfall, PE and AE (mm) for 1961–1990 (for short grass and median AWC soils), and the ratios PE/rainfall and AE/PE.

shows that AE in the north/west is generally energy-limited ($AE \sim PE$), with AE in the east generally water-limited ($AE < PE$). The dry/wet 'boundary' (where PE approaches rainfall) and water-limited/energy-limited 'boundary' (where

AE approaches PE) are related (e.g., [Arora 2002](#)), creating a transition region where the supply of water and energy to the land surface are in closer balance (hereby termed energy-water balanced).

The maps in [Figure 1](#), using annual mean data, are only indicative; PE/rainfall and AE/PE patterns will vary month-to-month and year-to-year (e.g., AE in the north-west could also be water-limited in a hot, dry summer like that of 1976; see [Rodda & Marsh \(2011\)](#)). To illustrate the effect of seasonal variation of PE and rainfall on AE and runoff, [Figure 2\(a\)](#) shows 1961–1990 monthly means of these variables for three contrasting catchments (modelled with CLASSIC): wet/energy-limited, energy-water balanced and dry/water-limited. In summer, the wet/energy-limited catchment shows $PE < rainfall$ with near-constant AE close to PE, while the energy-water balanced catchment has PE close to rainfall and a slightly larger difference between PE and AE. In the dry/water-limited catchment $PE > rainfall$ for the middle part of the year, leading to higher SMDs and $AE < PE$, with reduced AE as summer progresses (peak AE precedes peak PE). A given PE change for a wet/energy-limited catchment is likely to result in a similar AE change, whereas the same PE change for a dry/water-limited catchment is likely to result in little AE change (assuming little/no rainfall change). Thus

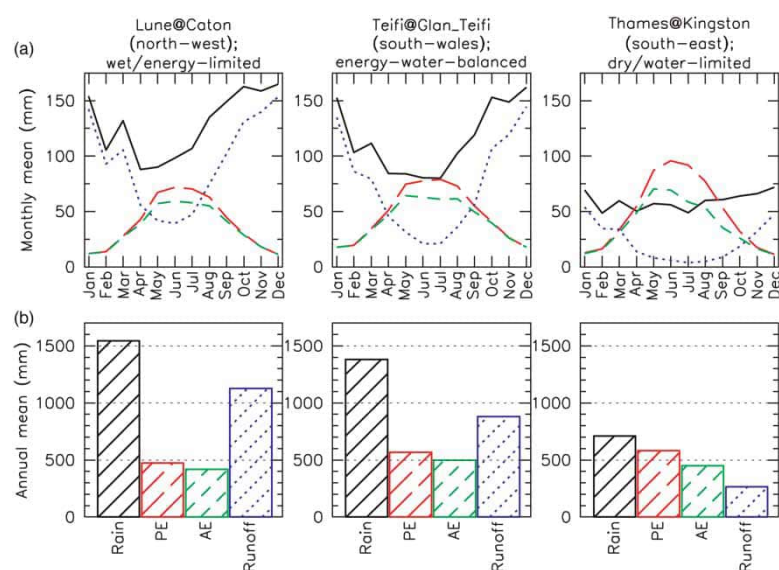


Figure 2 | Rainfall (solid line, black), PE (long-dashed line, red), AE (short-dashed line, green) and runoff (dotted line, blue), plotted as (a) monthly means; and (b) mean annual totals for 1961–1990 (mm), for three contrasting catchments modelled with CLASSIC. For references to colour see the online version of the paper: <http://www.iwaponline.com/jwcc/toc.htm>.

dry/water-limited catchments in the south/east are likely to be less sensitive to PE accuracy. But wet/energy-limited catchments in the north/west are also likely to be less sensitive to PE accuracy, since they get more rainfall and lose a much smaller proportion of rainfall to evaporation than catchments in the south/east. Catchments most sensitive to PE accuracy are those in the more energy-water balanced transition region, since PE forms a larger proportion of their rainfall and PE changes can more easily push them into a different regime, via their affect on soil moisture storage. Histograms of mean annual rainfall, PE, AE and runoff for the three example catchments (Figure 2(b)) show that the energy-water balanced catchment has the highest AE; summer rainfall in this catchment is able to sustain a higher AE rate than in the water-limited catchment. Similar conclusions on the sensitivity of energy-water balanced catchments to PE changes are reached by Wang & Alimohammadi (2012) from annual water balance analyses in 277 US catchments.

PE and environmental change

The situation becomes more complicated under climate change, as amounts and seasonal distribution of rainfall, as well as atmospheric demand for water (PE), are likely to change. PE changes can occur through changes in the meteorological controls, but also through changes in the transpiration controls. The relationship between climate change, meteorology and plant physiology is highly complex (Wullschleger *et al.* 2002). For example, higher concentrations of CO₂ in the atmosphere can lead to plant stomata opening less widely, giving greater surface resistance and less transpiration, but higher CO₂ concentrations can also enhance plant growth, leading to greater leaf area and more stomata, possibly counter-acting the effect of stomatal closure (Betts *et al.* 2007). Lower light levels, due to sunshine reductions or greater canopy shading, can also lead to stomatal closure (Wullschleger *et al.* 2002). Climate change impact studies generally consider only meteorological controls on PE, with transpiration controls kept constant. Gedney *et al.* (2006) showed that increasing trends in continental runoff through the twentieth century were most consistent with the reduction in transpiration due to CO₂-induced stomatal closure, suggesting the

importance of this mechanism of PE change for hydrological modelling under climate change.

A further complication is land-use change. Different land-covers have different PE rates, so large-scale changes in land-cover can influence AE, affecting runoff and river flows. Some hydrological models, e.g., CLASSIC, allow for different land-covers. Crooks & Davies (2001) used CLASSIC to investigate the sensitivity of flooding in the Thames to land-use change, showing that covering the catchment with 100% grass resulted in lower flood frequency than for 1990 land-use, with 100% trees resulting in even lower frequency. Similarly, Dunn & Mackay (1995) investigated the sensitivity of two sub-catchments of the River Tyne (north-east England) to land-use change, using a distributed hydrological model. Their results showed that the same land-use change had a negligible effect on hydrology in the highland catchment, but much more effect in the lowland catchment because its evaporation is a greater proportion of total rainfall.

Ideally, climate and land-use change would be considered together, as there are possible two-way feedbacks between them (e.g., Dirmeyer *et al.* 2010). At the local scale, eco-hydrological indicators, such as those of Hill *et al.* (2000), can be used to assess which species could appear/disappear following environmental change at a site. Feedbacks on evaporation, humidity, etc. could follow (e.g., Teuling *et al.* (2010) show how forests and grasslands differentially affect overlying air-temperature during droughts).

HISTORICAL TRENDS

PE and AE trends in Britain

There are few published analyses of historical evaporation trends in Britain, and most look at specific sites; none has national coverage. The longest used daily temperature and rainfall observations from Oxford for 1815–1996 (Burt & Shahgedanova 1998). Thornthwaite monthly PE was first estimated from temperature data, then seasonal regression equations were applied to correct this towards Penman PE. Monthly AE was then estimated, via SMDs. The results suggest PE increases and AE decreases, but with considerable annual and decadal variation (no trend quantification was provided). Crane & Hudson (1997) used daily data

from a site in Wales to calculate Penman PE for 1969–1995. They found no clear PE trend, although there were trends in some components, and concluded that local factors (e.g., tree-felling) have had a greater impact on climate variables and PE at this site than any larger-scale climatic changes.

Plots of trends in MORECS data include those of Rodda & Marsh (2011), who show water-year total PE and AE for 1961–2009 averaged over England and Wales, and Price & McKenna (2003), who show annual total PE for 1961–1993 averaged over Scotland. Each shows apparent increases, but with no quantification. Similarly, Yang *et al.* (2005) plot MORECS PE for 1961–1993, separately for each month, for a single MORECS grid-box in Surrey; increasing trends are apparent in most months (with no quantification). Figure 3 shows MORECS PE and AE for 1961–2012 (for short grass and median AWC soils) averaged over grid-boxes covering England and Wales, and Scotland, again showing increasing trends in each case. Fitted linear trend lines indicate very similar trends in PE and AE over Scotland (~0.6 mm/year), whereas over England and Wales trends in AE are slightly higher (~0.7 mm/year) and those in PE are higher still (~1.0 mm/year); all trends are significant at the 1% level ($p < 0.01$), based on permutation tests. An analysis of UK AE modelled by JULES also shows a slow upward trend over 1971–2007 (Blyth pers. comm.). Much more analysis is required, however, to investigate spatial and seasonal variation and consistency between modelling systems.

Unfortunately, neither PE nor AE is included in the UK climate trend report of Jenkins *et al.* (2007), based on 5 ×

5 km grids of numerous climate variables. Although there are several methods for measuring AE, including eddy-covariance, lysimeters and large aperture scintillometers (e.g., Shuttleworth 2007), there are no long-term AE observations in Britain. Any apparent trends in relatively short records should be treated with caution, as they may be due to natural climatic variations rather than climate change (Robson 2002); a problem potentially exacerbated by particularly wet/dry periods towards the start/end of the record (Hannaford & Buys 2012).

Global context

The shortage of information on evaporation trends is not limited to Britain; the Intergovernmental Panel on Climate Change concludes ‘there is little literature on observed trends in evapotranspiration, whether actual or potential’ (Bates *et al.* 2008). There is evidence that pan evaporation (a proxy for PE) has been decreasing in several regions of the globe over the last five decades (Fu *et al.* 2009); known as the ‘pan evaporation paradox’ since it has occurred despite temperature increases (Shuttleworth *et al.* 2009). The global review of McVicar *et al.* (2012) suggests that declining evaporation is primarily due to declining wind speeds, implying the importance of including wind when estimating PE.

A global study finds large basins with positive (e.g., Niger), negative (e.g., Amazon) and non-significant (e.g., Congo) PE trends over 1958–2001 (Weedon *et al.* 2011), and both increases and decreases have been found in

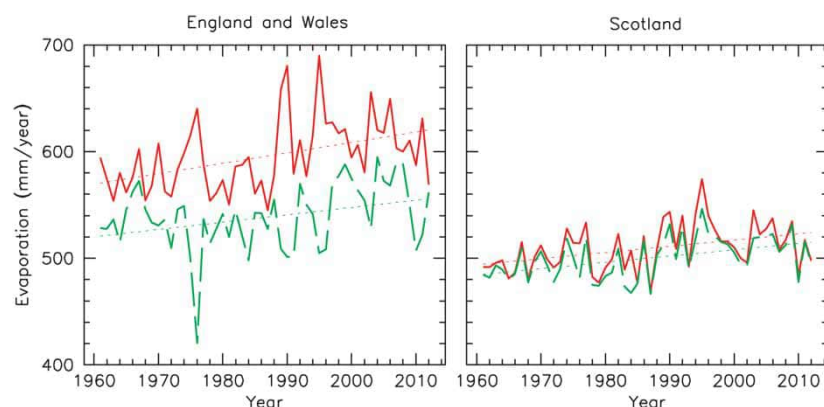


Figure 3 | MORECS PE (solid line, red) and AE (dashed line, green) for 1961–2012 (for short grass and median AWC soils), averaged over England and Wales (left) and Scotland (right). In each case a fitted linear trend line is shown (dotted). For references to colour see the online version of the paper: <http://www.iwaponline.com/jwc/toc.htm>.

China (Thomas 2000). Analysis of open-water PE for the Canadian Prairies suggests that decreasing wind speeds are the main factor decreasing PE in the south, while vapour pressure deficits are the main factor increasing PE in the north (Burn & Hesch 2007). Irmak *et al.* (2012) show a significant decrease in grass reference PE in the Platte basin, USA, but with no significant change in wind speeds, and suggest that increasing rainfall and related decreasing short-wave radiation are instead responsible.

Jung *et al.* (2010) examine data-driven estimates of global land AE, which show a (highly significant) increase for 1982–1997 but a (less significant) decrease for 1998–2008. Their correlation analyses suggest the recent decline is due to increasing soil moisture limitation, but the time periods studied are too short to imply trends; differences could be due to decadal variability.

FUTURE PROJECTIONS

Issues with PE estimation under climate change

Projections of PE from vegetated surfaces are generally not produced directly by Global or Regional Climate Models (GCMs or RCMs), so have to be made offline. But which PE formulae are likely to perform best when using climate model data, as opposed to observed weather data? One consideration is whether the climate model PE estimates will be used directly, so the absolute values need to be reasonable, or whether they are simply used to estimate PE changes applied to baseline observed PE using the change factor method (Kay & Jones 2012). Note that an alternative way of estimating future PE is via statistical downscaling; fitting a regression relationship between large-scale weather data and catchment PE data, then applying it using GCM data to estimate future catchment PE (e.g., Wilby & Harris 2006). Similarly, Chun *et al.* (2012) develop a generalised linear model (GLM) for PE. These methods are likely to have many of the same issues as estimating PE using climate model variables in more standard PE formulae.

The use of more complex formulae with climate model data is not necessarily straightforward, since some variables may be less reliable (Vorosmarty *et al.* 1998; Kingston *et al.* 2009), or simply not available from all climate models. For

example, the probabilistic UKCP09 projections (Murphy *et al.* 2009) did not initially include wind speed, as wind data were not available from all the GCMs used in the statistical methodology (Sexton & Murphy 2010). Fisher *et al.* (2011) discuss issues with input data uncertainty and sensitivity in PE formulae. A related issue is that climate model data may have different inter-variable correlations than observed data (Chun *et al.* 2012).

As simpler, empirical formulae rely on fixed relationships between atmospheric variables and PE, these may not hold under extrapolation to very different future climates (Shaw & Riha 2011), although some level of extrapolation may be acceptable where formulae perform well for a wide range of locations and climatic conditions (Sperna Weiland *et al.* 2012). Irmak *et al.* (2012) suggest that, as many climate variables affecting PE have been changing and are expected to change in future, single-variable PE formulae should be avoided when estimating PE (historical or future) trends ‘due to the inherent nature of the trend passed to PE from the variable’. A view echoed by Donohue *et al.* (2010) as ‘the greater the number of the four key variables ... in a formulation, the more realistic the trends from that formulation become’, although this clearly depends on the sensitivity of a formula to each variable and the relative strengths and directions of any trends in those variables (likely to have some level of inter-dependency; Fisher *et al.* 2011).

The sensitivity of PE formulae cannot necessarily be predicted directly from the meteorological variables included; Bormann (2011) compared PE changes given by 18 formulae, for six locations in Germany, and found as much variability for formulae of the same type as for different types. However, Shaw & Riha (2011) show that the temperature-only Hamon and Thornthwaite formulae are much more temperature-sensitive than the more complex Penman–Monteith and Priestley–Taylor formulae. This should be interpreted carefully, since changes in other variables were neglected but are likely to co-vary with temperature (Fisher *et al.* 2011; Chun *et al.* 2012), and their inclusion could increase the response of more complex formulae. Interestingly, Shaw & Riha (2011) show that the temperature-sensitivity of the Oudin formula is mid-way between that of the other two pairs of formulae. Oudin PE is temperature-based but also includes extraterrestrial radiation (dependent only on Julian

day and latitude), so has some dependence on radiation even though its only true variable is temperature.

Shaw & Riha (2011) also show that radiation, rather than temperature, is the main driver of PE in broadleaf forests in the USA. They suggest that the strong relationship between radiation and temperature for longer averaging-periods (weekly and above) allows temperature-only formulae to work well in the current climate, but that this relationship will alter under climate change, leading to temperature-only formulae perhaps overestimating PE changes. They thus recommend the Priestley–Taylor formula, if Penman–Monteith is not used, but suggest that other formulae including radiation could also work; even those that only include extraterrestrial radiation (e.g., Oudin or Hargreaves), as long as they are applied over longer averaging-periods. Hargreaves PE (Hargreaves & Samani 1985) is an empirical formula using temperature, extraterrestrial radiation and diurnal temperature range (a humidity proxy).

Spurna Weiland *et al.* (2012) compared Penman–Monteith, Priestley–Taylor, Hargreaves and Blaney–Criddle formulae for estimating global reference PE using daily re-analysis data. Blaney–Criddle provided the best match to monthly observation-based Penman–Monteith PE, but they concluded that its need for cell-specific calibration, with large spatial variation in calibrated coefficients, meant it was unsuitable for climate change applications. They also concluded that Penman–Monteith was not ideal, since it did not outperform other methods, has a high data demand and is sensitive to data accuracy. Their preferred formula was a globally recalibrated version of Hargreaves PE, which performs well across a range of climate zones so is likely to do the same under climate change.

Kay & Davies (2008) calculated Penman–Monteith and Oudin PE over Britain, using monthly data from 13 climate models for 1961–1990, and compared them with MORECS PE. Perhaps surprisingly, Oudin PE matched better than Penman–Monteith PE; the latter was lower than MORECS for most months and most climate models, leading to clear underestimation of mean annual PE. The authors postulated that this was due to lower reliability of some of the extra variables required for Penman–Monteith. Ekstrom *et al.* (2007) similarly found that Penman–Monteith PE derived from climate model variables for a baseline period was lower, in every month, than PE derived from weather observations.

Sometimes, bias-correction is applied to allow for perceived biases in climate model data (Piani *et al.* 2010). However, it should be remembered that climate model variables are expected to be internally consistent; applying bias-correction separately to each variable, or only to some variables, could introduce inconsistency (e.g., Fischer & Knutti 2013) and potentially cause incorrect PE. A possible alternative is direct bias-correction of PE. This was attempted by Ekstrom *et al.* (2007), but the resulting PE time-series was still considered unrealistic in terms of the range of daily values. Furthermore, bias-correction assumes that any differences between observations and climate model estimates are due solely to climate model bias, rather than multi-decadal natural variability for example (e.g., Deser *et al.* 2012), and that the same bias applies for future periods.

PE projections for Britain

Table 1 summarises the PE changes for Britain presented in several references, described in more detail below.

Arnell (2011) uses data from 21 GCMs, for six catchments in Britain, for a scenario representing a 2 °C rise in global mean temperature. Annual PE (calculated using Penman–Monteith but with fixed wind speeds) increases for all but one climate model, with significant variation between climate models and catchments (range –4–40%). Annual PE changes are shown to be broadly related to annual temperature changes, although changes to relative humidity and (to a lesser extent) radiation also have an effect.

Fowler *et al.* (2008) use data from 13 RCMs, for the 2080s time-horizon with A2 emissions, with a weather generator for the River Eden (Cumbria). They show increases in mean Penman–Monteith PE in all seasons, with the largest percentage increases in autumn (30–80%) and winter (30–60%) and smallest in spring (0–50%) and summer (20–40%). Similarly, Kay & Davies (2008) use data from 13 climate models (2080s A2) to calculate changes in Penman–Monteith and Oudin PE for Britain. They show that percentage changes in Oudin PE are positive throughout the year, and larger in winter than summer, whereas changes in Penman–Monteith PE can be negative for some months and some climate models, and show greater monthly variability. Increases in annual Oudin PE are

Table 1 | Summary of PE projections for Britain

Reference	Spatial coverage	Climate data; scenario (e.g., time-horizon; emissions)	PE formula(e)	Projected PE changes
Arnell (2011)	6 British catchments	21 GCMs; 2 °C global mean <i>T</i> rise	Penman–Monteith (wind speed fixed)	Annual increase for all but 1 climate model
Fowler <i>et al.</i> (2008)	River Eden (Cumbria)	13 RCMs; 2080s; A2	Penman–Monteith	Increase in all seasons
Kay & Davies (2008)	Great Britain: northern and southern averages	5 GCMs, 8 RCMs; 2080s; A2	Oudin; Penman–Monteith	Increase in all months; Increase in most months, but decrease in some months for some climate models
Ekstrom <i>et al.</i> (2007)	Europe	1 RCM; 2080s; A2	Penman–Monteith	Increase in all seasons
Cameron (2006)	River Lossie (Scotland)	1 RCM; 2080s; A1F1, A2, B2, B1	Thornthwaite	Increase in all months
Wilby & Harris (2006)	Thames (SE England)	4 GCMs; 2020s, 50s, 80s; A2, B2	Statistical downscaling	Increase in winter and summer
Wilby <i>et al.</i> (2006)	Kennet (SE England)	3 GCMs; 2020s, 50s, 80s; A2, B2	Statistical downscaling	Increase in winter and summer
Diaz-Nieto & Wilby (2005)	Thames (SE England)	1 GCM/RCM; 2020s, 50s, 80s; A2, B2	Statistical downscaling; Penman–Monteith	Increase in all months except Dec 2020s; Increase, often greater than above
Chun <i>et al.</i> (2012)	25 sites in Great Britain	1 GCM; 2080s; A2	GLM; Penman–Monteith	Annual increase almost everywhere; Annual increase almost everywhere, greater than above
Christierson <i>et al.</i> (2012)	UK (plus 2 example catchments)	UKCP09; 2020s; A1B	Oudin	Increase in ensemble median all months; for example catchments, decrease in some months for some ensemble members
Kay & Jones (2012)	9 British catchments	UKCP09; 2080s; A1B	Oudin	As above
Prudhomme & Williamson (2013)	Great Britain	1 RCM; 2050s; A1B	Blaney–Criddle, Hamon, Oudin, Thornthwaite, McGuinness–Bordne, Makkink, Jensen–Haise, 2 Priestley–Taylor, Turc, 2 Penman–Monteith	Increase in month representing each of 4 seasons, everywhere, for all formulae except Priestley–Taylor
Kingston <i>et al.</i> (2009)	Globe, latitudinally-averaged	5 GCMs; 2 °C global mean <i>T</i> rise	Blaney–Criddle, Hamon, Hargreaves, Jensen–Haise, Priestley–Taylor, Penman–Monteith	Annual increase in all cases

~12–34%, whereas those in Penman–Monteith PE are ~6–56%; increases are generally lower for Penman–Monteith than Oudin in the north, but generally higher in the south.

Ekstrom *et al.* (2007) use data from the HadRM3H RCM over Europe (2080s A2) and show seasonal absolute differences between future and baseline Penman–Monteith PE. Differences are largest in summer (4–8 mm/day over large

parts of Europe; less over Britain) and smallest in winter (<0.5 mm/day for most of Europe). However, for hydrological modelling of a catchment in north-west England they used Blaney–Criddle instead of Penman–Monteith PE, as the latter gave a spread of daily values too large compared with observations, and percentage increases that were too high (up to 80%) in summer (Blaney–Criddle gave a

summer increase <20%). Based on this, [Cameron \(2006\)](#) decided to apply Thornthwaite, rather than Penman–Monteith, to estimate PE changes in the Lossie catchment (Scotland), obtaining changes ranging from 6.2% (June) to 20.8% (January) for the 2080s with A2 emissions.

[Wilby & Harris \(2006\)](#) use data from four GCMs (2080s A2 and B2) with statistical downscaling for the Thames. They obtain PE increases of 5–43% in winter and 11–22% in summer, but for two GCMs, the summer changes are larger than winter, with the opposite for the other two GCMs. [Wilby *et al.* \(2006\)](#) use a similar method for the Kennet, using three of the same GCMs, but find much smaller PE increases (winter 3–9%; summer 5–16%) presumably due to a different regression model. [Diaz-Nieto & Wilby \(2005\)](#) showed that projected PE increases for the Thames derived via statistical downscaling (using temperature and specific and relative humidity) were roughly half those derived using Penman–Monteith. [Chun *et al.* \(2012\)](#) use data from the HadCM3 GCM (1950–2099 A2) to estimate PE at 25 sites across Britain using Penman–Monteith and a GLM with four variables (radiation, temperature, wind and humidity). They show annual percentage increases almost everywhere by the 2080s, with greater increases in the south/east than north/west, but smaller increases using the GLM than Penman–Monteith. However, the site-specific parameter calibration required by the GLM may make its use under climate change questionable, as for Blaney–Criddle ([Sperna Weiland *et al.* 2012](#)).

[Christierson *et al.* \(2012\)](#) use UKCP09 probabilistic temperature data (2020s A1B) to calculate Oudin PE percentage changes for each river-basin region in the UK. They present maps of the central estimate of PE changes, which show an increase across the country, with the largest changes in winter. The range of monthly PE changes, for two example catchments, almost always show increases, usually 0–30%, with a greater variation in winter than summer (but only a 20-member subset of the full 10,000 UKCP09 set is shown, selected via latin-hypercube sampling). These PE changes are shown to be generally consistent with an older set of scenarios, and with those calculated using temperature data from the 11-member UKCP09 RCM ensemble in the Oudin formula. Similarly, [Kay & Jones \(2012\)](#) use UKCP09 probabilistic temperature data (2080s A1B) to calculate Oudin PE changes for nine catchments in Britain. Again,

the PE changes are almost always positive, and generally larger (with greater variation) in winter than summer, but the range of 5–60% is larger than that of [Christierson *et al.* \(2012\)](#), because of the later time-horizon. [Prudhomme & Williamson \(2013\)](#) use data from one member of UKCP09 RCM ensemble (2050s A1B) and compare PE changes across Britain for 12 formulae for a month representative of each of the four seasons. PE almost always shows an increase, although the magnitude varies by season, location and formula.

[Kingston *et al.* \(2009\)](#) use data from five GCMs, for a scenario representing a 2 °C rise in global mean temperature, and compare latitudinally averaged annual PE changes (for 60°S to 60°N) for six formulae. PE increases were found for all latitudes, GCMs and formulae, and broadly followed corresponding temperature changes. However, significant differences were found between formulae; Hamon and Jensen–Haise ([Jenson & Haise 1963](#)) gave the largest PE changes at most latitudes, then Hargreaves, Penman–Monteith and Priestly–Taylor, although the differences are less at Britain's latitude than at lower latitudes. Blaney–Criddle gave PE changes that varied much less with latitude than other formulae.

PE projections with changes in transpiration controls

[Bell *et al.* \(2011\)](#) developed a method to estimate Penman–Monteith PE using surface resistance (r_c) values produced by an RCM with an embedded land-surface scheme, so allowing r_c to vary with the level of CO₂ in the atmosphere. Comparisons over Britain, using data from the HadRM3 RCM for 1961–1990, showed that using RCM r_c gave PE comparable with MORECS, but generally lower than when using MORECS' 12 fixed monthly r_c values, particularly in spring. Similarly, for 2070–2099, using RCM r_c gave lower PE than when using fixed r_c . Looking at percentage PE changes between the two periods, using fixed r_c gave increases of 15–34%, whereas using RCM r_c gave significantly lower increases (3–7%). Thus r_c changes could be an important mechanism for limiting PE change. However, not all possible feedbacks are included in this RCM run (e.g., changes to leaf area or land cover); PE changes may be somewhere in between if other mechanisms are included.

[Kay & Jones \(2012\)](#) used the method above with data from the UKCP09 11-member RCM ensemble (with

corresponding r_c time-series) and showed that the corresponding percentage PE changes were more variable than those derived using UKCP09 probabilistic temperature data to calculate Oudin PE changes. The biggest difference occurred in winter and in spring, where varying r_c PE changes were often lower than Oudin PE changes. However, even large percentage PE changes are not really significant in winter in Britain, since baseline PE is very small. Differences in spring could be more important.

Moratiel *et al.* (2011) investigate possible changes in grass reference PE in part of Spain, including the effect of r_c changes due to CO₂ concentrations rising from 372 to 550 ppm by 2050. They do this by quantifying trends in observed weather variables for 1980–2009, extending these over the next 50 years, and using them to calculate Penman–Monteith PE both with current r_c (70 s/m) and an approximate future r_c assuming stomatal closure (87 s/m). They find PE increases of about 10% with current r_c but only about 5% with future r_c . This is similar to Bell *et al.* (2011), although there the differences are larger, perhaps because of the later time-horizon. Islam *et al.* (2012) also find much smaller PE increases (or decreases) for the US Great Plains when the effect of elevated CO₂ on stomatal resistance is included.

Effect of PE uncertainty on hydrological projections

From a hydrological perspective, differences in PE projections are only crucial if they are likely to result in different hydrological projections. The apparently frequent insensitivity of hydrological modelling to PE accuracy suggests that accurate PE projections will not always be important. Sperna Weiland *et al.* (2012), using reanalysis data for 1979–2002, show a general reduction in variability of results between six different PE formulae when moving down their global hydrological modelling chain, from PE to AE to runoff to river flows. They thus suggest ‘the selection of a PET method may be of minor influence on the resulting river flow modelled with a hydrological model’, except for relatively limited regions where the variability remains high (not Britain).

Kay & Davies (2008) look at the extra uncertainty introduced into hydrological impacts for three catchments in Britain, using PE changes derived from Penman–Monteith

and Oudin formulae with data from 13 climate models. The results suggest that the extra uncertainty is greatest for changes in low to median flows, although possibly still important for high flows in some catchments, but that climate model uncertainty dominates. Arnell (1999) tested the effect of using Priestly–Taylor in place of Penman–Monteith PE, when modelling changes in European runoff under four scenarios for the 2050s. As Priestly–Taylor PE increases were generally smaller than those for Penman–Monteith, the pattern of runoff changes followed that of rainfall changes more closely. However, PE uncertainty was generally less than scenario uncertainty.

Kingston *et al.* (2009) assessed the effect of six PE formulae on the global extent of arid (rainfall/PE < 1) and humid (rainfall/PE ≥ 1) regions, with five GCMs for a 2 °C rise in global mean temperature. They showed that, although almost all GCMs and PE formulae agreed on an increased arid area (and corresponding decreased humid area), they disagreed on the amount of change; eastern England verges on aridity (Figure 1) so this uncertainty could apply. Furthermore, regional analysis of water surpluses (annual rainfall minus PE, for months where rainfall > PE) suggests that PE uncertainty is of comparable magnitude to GCM uncertainty, but the analysis only covers the Mediterranean, East Africa and Southeast Asia (not Britain). Sheffield *et al.* (2012) showed that the global drought severity trend is exaggerated when modelled using Thornthwaite PE rather than Penman–Monteith PE, while Milly & Dunne (2011) showed that using Jensen–Haise PE for 10 catchments in the USA gave smaller runoff changes than suggested by the driving climate models directly.

Betts *et al.* (2007) modelled change in continental runoff under a doubling of CO₂, and showed that including the effect of stomatal closure led to larger runoff increases (17 ± 5%) than including only radiative forcing (11 ± 6%). The difference was slightly less when changes in land cover and leaf area were also included. Similar effects were seen for percentage changes in flood peaks in the Thames, using data from the UKCP09 11-member RCM perturbed-physics ensemble to drive the G2G hydrological model (Bell *et al.* 2012); changes were higher when averaged over the six members which included stomatal closure, and lower when averaged over the five members which did not. However, simultaneous variation of other parameters in the

perturbed-physics ensemble means that this should be interpreted with caution.

DISCUSSION AND CONCLUSIONS

The aim of this paper was to present a review of historical trends and future projections for evaporation in Britain, from a hydrological perspective. Evaporation is generally estimated from meteorological data, using formulae of varying complexity. The UK Met Office's MORECS and MOSES systems apply the physically based Penman–Monteith formula to estimate PE from meteorological observations over Britain. These PE are often used, with rainfall, as inputs for hydrological modelling. While hydrological models may appear to be relatively insensitive to the absolute accuracy of PE data, inaccurate data can cause difficulties with calibration, such as failure to close the annual water balance or parameter instability. Although PE is less variable than rainfall, with a well defined seasonal pattern, AE accounts for loss of a significant proportion of rainfall across much of south/east Britain. These factors are important considerations when hydrological models are applied, especially when simulating impacts of environmental change.

There is relatively little information on historical evaporation trends in Britain, or indeed globally, whether actual or potential. The few British studies generally indicate PE increases, and some also show AE increases. Globally, both increases and decreases in PE have been detected in different areas, with different causes, although decreasing wind speeds tend to be implicated in PE decreases. A more recent global decline in data-driven AE estimates has been attributed to decreasing soil moisture. Direct AE measurement is progressing from localised observations to remotely sensed estimates from large areas. Combined analyses of measurements, satellite data, observed changes in meteorological variables affecting evaporation, and observed changes in river flows should, together with further modelling, enable a better understanding of the direction, magnitude and causes of AE or PE change (e.g., Donohue *et al.* 2010).

There is little consensus on the best approach for deriving future PE projections; some authors believe that formulae including all meteorological variables influencing PE must be applied, while others believe that sensitivity of such

formulae to data quality makes this inadvisable, or that the choice will make little difference in subsequent hydrological modelling. The dilemma is summarised by Kingston *et al.* (2009), who considers 'whether more reliable estimation of changes in PET can be obtained from physically based methods (e.g. Penman–Monteith) with uncertain data quality, or more empirical methods (e.g. Hargreaves) with more reliable input data'. Vorosmarty *et al.* (1998) argue that 'Although these [physically based PE] methods are attractive on theoretical grounds, the degree to which the necessary input data sets can be successfully assembled ... remains an open question. Use of more physically realistic evaporation functions must be weighed against potential inaccuracies in, and inconsistencies among, the several climatic forcing fields used by these methods'. The choice is further complicated when considering possible changes in plant behaviour under higher CO₂ concentrations (stomatal closure, increased plant growth, etc.).

Most studies presenting PE projections for Britain indicate increases in annual PE, although some studies suggest (usually small) PE decreases in some months (Table 1). However, there is considerable variation in the magnitude of projections, caused not just by the PE formula applied but by the climate model, emissions scenario and time-horizon, and by location. These factors make it difficult to compare PE projections between studies, as do the varied ways of describing changes (i.e., percentage or absolute; monthly, seasonal or annual).

It has been suggested that the choice of PE formula could be particularly important in regions where precipitation and PE are in close balance (e.g., Kingston *et al.* 2009). The maps in Figure 1, based on MORECS data, show that this is likely to include parts of Britain, although changes in rainfall as well as PE make it difficult to predict precisely which areas are likely to be most affected. Bormann (2011) suggests calculating the change in annual climatic water budget (annual precipitation minus annual PE) between baseline and future climates, to test the sensitivity of a given location to choice of PE formula; the choice is probably not crucial if changes are relatively consistent between formulae, but needs greater consideration if there is more variation. However, likely changes in the seasonality of rainfall under climate change (Murphy *et al.* 2009) mean that such annual water balance tests may

mask important seasonal changes. Plots of monthly mean rainfall and PE under climate change may be more informative. In some circumstances, it may be necessary to extend the sensitivity study to the hydrological modelling, as the importance of PE is likely to vary according to the hydrological aspect under investigation as well as catchment location (e.g., Kay & Davies 2008). Nevertheless, several studies have shown that uncertainty due to climate model structure is greater than that due to PE formulation, implying that, where there is limited capacity for hydrological model runs, the priority should be to cover climate model uncertainty more comprehensively.

The question remains: which PE formulae are likely to be more (or less) reliable when applied with climate model data? For each region of the globe, the answer requires investigation of: (1) which meteorological variables are most important for PE changes (i.e., the necessary level of complexity), and (2) the reliability of each of these meteorological variables when taken from different climate models. Together, these could enable the derivation of improved PE projections, and so improved hydrological projections. Further investigation is also needed into feedbacks between climate change and plant transpiration and growth. Clarification of the best ways to measure/model evaporation would also be useful for detection and attribution, as evaporation trends are easier to detect and attribute than precipitation or runoff trends (Ziegler *et al.* 2003; Douville *et al.* 2012).

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REFERENCES

- Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. 1998 Crop evapotranspiration (guidelines for computing crop water requirements). FAO Irrigation and Drainage Paper No. 56. Food and Agricultural Organization of the United Nations, Rome.
- Allen, R. G., Smith, M., Pereira, L. S. & Perrier, A. 1994 An update for the calculation of reference evapotranspiration. *ICID Bull.* **43**, 35–92.
- Andréassian, V., Perrin, C. & Michel, C. 2004 Impact of imperfect potential evapotranspiration knowledge in the efficiency and parameters of watershed models. *J. Hydrol.* **286**, 19–35.
- Arnell, N. W. 1999 The effect of climate change on hydrological regimes in Europe: a continental perspective. *Glob. Environ. Change* **9**, 5–23.
- Arnell, N. W. 2011 Uncertainty in the relationship between climate forcing and hydrological response in UK catchments. *Hydrol. Earth Syst. Sci.* **15**, 897–912.
- Arora, V. K. 2002 The use of the aridity index to assess climate change effect on annual runoff. *J. Hydrol.* **265**, 164–177.
- Bates, B. C., Kundzewicz, Z. W., Wu, S. & Palutikof, J. P. (eds) 2008 Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp.
- Bell, V. A., Gedney, N., Kay, A. L., Smith, R., Jones, R. G. & Moore, R. J. 2011 Estimating potential evaporation from vegetated surfaces for water management impact assessments using climate model output. *J. Hydrometeorol.* **12**, 1127–1136.
- Bell, V. A., Kay, A. L., Cole, S. J., Jones, R. G., Moore, R. J. & Reynard, N. S. 2012 How might climate change affect river flows across the Thames Basin? An area-wide analysis using the UKCP09 Regional Climate Model ensemble. *J. Hydrol.* **442–443**, 89–104.
- Bell, V. A., Kay, A. L., Jones, R. G., Moore, R. J. & Reynard, N. S. 2009 Use of soil data in a grid-based hydrological model to estimate spatial variation in changing flood risk across the UK. *J. Hydrol.* **377**, 335–350.
- Best, M. J., Pryor, M., Clark, D. B., Rooney, G. G., Essery, R. L. H., Ménard, C. B., Edwards, J. M., Hendry, M. A., Porson, A., Gedney, N., Mercado, L. M., Sitch, S., Blyth, E., Boucher, O., Cox, P. M., Grimmond, C. S. B. & Harding, R. J. 2011 The Joint UK Land Environment Simulator (JULES), model description – Part 1: Energy and water fluxes. *Geosci. Model Dev.* **4**, 677–699.
- Betts, R. A., Boucher, O., Collins, M., Cox, P. M., Falloon, P. D., Gedney, N., Hemming, D. L., Huntingford, C., Jones, C. D., Sexton, D. M. H. & Webb, M. J. 2007 Projected increase in continental runoff due to plant responses to increasing carbon dioxide. *Nature* **448**, 1037–1041.
- Blaney, H. F. & Criddle, W. D. 1950 Determining water requirements in irrigated areas from climatological and irrigation data. US Department of Agriculture (Soil Conservation Service) Technical Paper 96.
- Blyth, E. M., Gash, J. H. C., Lloyd, A., Pryor, M., Weeden, G. P. & Shuttleworth, W. J. 2010 Evaluating the JULES land surface model energy fluxes using FLUXNET data. *J. Hydrometeorol.* **11**, 509–519.

- Bormann, H. 2011 Sensitivity analysis of 18 different potential evapotranspiration models to observed climatic change at German climate stations. *Clim. Change* **104**, 729–753.
- Boughton, W. 2006 Calibrations of a daily rainfall-runoff model with poor quality data. *Environ. Modell. Softw.* **21**, 1114–1128.
- Burn, D. H. & Hesch, N. M. 2007 Trends in evaporation for the Canadian Prairies. *J. Hydrol.* **336**, 61–73.
- Burt, T. P. & Shahgedanova, M. 1998 An historical record of evaporation losses since 1815 calculated using long-term observations from the Radcliffe Meteorological Station, Oxford, England. *J. Hydrol.* **205**, 101–111.
- Cain, J. D., Batchelor, C. H., Gash, J. H. C. & Harding, R. J. 1998 Comment on the paper 'Towards a rational definition of potential evaporation' by J.P. Lhomme. *Hydrol. Earth Syst. Sci.* **2**, 257–264.
- Calder, I. R., Harding, R. J. & Rosier, P. T. W. 1983 An objective assessment of soil-moisture deficit models. *J. Hydrol.* **60**, 329–355.
- Cameron, D. 2006 An application of the UKCIP02 climate change scenarios to flood estimation by continuous simulation for a gauged catchment in the northeast of Scotland, UK (with uncertainty). *J. Hydrol.* **328**, 212–226.
- Christierson, B. V., Vidal, J. & Wade, S. D. 2012 Using UKCP09 probabilistic climate information for UK water resource planning. *J. Hydrol.* **424–425**, 48–67.
- Chun, K. P., Wheeler, H. S. & Onof, C. 2012 Projecting and hindcasting potential evaporation for the UK between 1950 and 2009. *Clim. Change* **113**, 639–661.
- Cox, P. M., Betts, R. A., Bunton, C. B., Essery, R. L. H., Rowntree, P. R. & Smith, J. 1999 The impact of new land surface physics on the GCM simulation of climate and climate sensitivity. *Clim. Dynam.* **15**, 183–203.
- Cox, P. M., Huntingford, C. & Harding, R. J. 1998 A canopy conductance and photosynthesis model for use in a GCM land surface scheme. *J. Hydrol.* **213**, 79–94.
- Crane, S. B. & Hudson, J. A. 1997 The impact of site factors and climate variability on the calculation of potential evaporation at Moel Cynnedd, Plynlimon. *Hydrol. Earth Syst. Sci.* **1**, 429–445.
- Crooks, S. & Davies, H. 2001 Assessment of land use change in the Thames catchment and its effect on the flood regime of the river. *Phys. Chem. Earth B* **26**, 583–591.
- Crooks, S. M. & Naden, P. S. 2007 CLASSIC: a semi-distributed modelling system. *Hydrol. Earth Syst. Sci.* **11**, 516–531.
- Deser, C., Knutti, R., Solomon, S. & Phillips, A. S. 2012 Communication of the role of natural variability in future North American climate. *Nat. Clim. Change* **2**, 775–779.
- Diaz-Nieto, J. & Wilby, R. L. 2005 A comparison of statistical downscaling and climate change factor methods: impacts on low flows in the River Thames, United Kingdom. *Clim. Change* **69**, 245–268.
- Dirmeyer, P. A., Niyogi, D., de Noblet-Ducoudre, N., Dickinson, R. E. & Snyder, P. K. 2010 Impacts of land use change on climate. *Int. J. Climatol.* **30**, 1905–1907.
- Donohue, R. J., McVicar, T. R. & Roderick, M. L. 2010 Assessing the ability of potential evaporation formulations to capture the dynamics in evaporative demand within a changing climate. *J. Hydrol.* **386**, 186–197.
- Douville, H., Ribes, A., Decharme, B., Alkama, R. & Sheffield, J. 2012 Anthropogenic influence on multidecadal changes in reconstructed global evapotranspiration. *Nat. Clim. Change* **3**, 59–62.
- Dunn, S. M. & Mackay, R. 1995 Spatial variation in evapotranspiration and the influence of land use on catchment hydrology. *J. Hydrol.* **171**, 49–73.
- Ekstrom, M., Jones, P. D., Fowler, H. J., Lenderink, G., Buishand, T. A. & Conway, D. 2007 Regional climate model data used within the SWURVE project 1: projected change in seasonal patterns and estimation of PET. *Hydrol. Earth Syst. Sci.* **11**, 1069–1083.
- Federer, C. A., Vorosmarty, C. & Fekete, B. 1996 Intercomparison of methods for calculating potential evaporation in regional and global water balance models. *Water Resour. Res.* **32**, 2315–2321.
- Fischer, E. M. & Knutti, R. 2013 Robust projections of combined humidity and temperature extremes. *Nat. Clim. Change* **3**, 126–130.
- Fisher, J. B., Whittaker, R. J. & Malhi, Y. 2011 ET come home: potential evapotranspiration in geographical ecology. *Glob. Ecol. Biogeogr.* **20**, 1–18.
- Fowler, A. 2002 Assessment of the validity of using mean potential evaporation in computations of the long-term soil water balance. *J. Hydrol.* **256**, 248–263.
- Fowler, H. J., Tebaldi, C. & Blenkinsop, S. 2008 Probabilistic estimates of climate change impacts on flows in the river Eden, Cumbria. *Proceedings of the British Hydrological Society 10th National Hydrology Symposium*, Exeter, 15–17th September 2008.
- Fu, G., Charles, S. P. & Yu, J. 2009 A critical overview of pan evaporation trends over the last 50 years. *Clim. Change* **97**, 193–214.
- Gedney, N., Cox, P. M., Betts, R. A., Boucher, O., Huntingford, C. & Stott, P. A. 2006 Detection of a direct carbon dioxide effect in continental river runoff records. *Nature* **439**, 835–838.
- Hamon, W. R. 1961 Estimating potential evaporation. *J. Hydraul. Div., Proc. Am. Soc. Civil Eng.* **87**, 107–120.
- Hannaford, J. & Buys, G. 2012 Trends in seasonal river flow regimes in the UK. *J. Hydrol.* **475**, 158–174.
- Hargreaves, G. H. & Samani, Z. A. 1985 Reference crop evapotranspiration from temperature. *Appl. Eng. Agric.* **1**, 95–99.
- Hill, M. O., Roy, D. B., Mountford, J. O. & Bunce, R. G. H. 2000 Extending Ellenberg's indicator values to a new area: an algorithmic approach. *J. Appl. Ecol.* **37**, 3–15.
- Hough, M. & Jones, R. J. A. 1997 The United Kingdom Meteorological Office rainfall and evaporation calculation system: MORECS version 2.0 – an overview. *Hydrol. Earth Syst. Sci.* **1**, 227–239.

- Hough, M., Palmer, S., Weir, A., Lee, M. & Barrie, I. 1996 *The Meteorological Office Rainfall and Evaporation Calculation System: MORECS version 2.0* (1995). An update to Hydrological Memorandum 45, The Met. Office, Bracknell, UK.
- Irmak, S., Kabenge, I., Skaggs, K. E. & Mutiibwa, D. 2012 *Trend and magnitude of changes in climate variables and reference evapotranspiration over 116-yr period in the Platte River Basin, central Nebraska, USA*. *J. Hydrol.* **420–421**, 228–244.
- Islam, A., Ahuja, L. R., Garcia, L. A., Saseendran, L. & Ma, A. S. 2012 Modeling the effect of elevated CO₂ and climate change on reference evapotranspiration in the semi-arid central Great Plains. *Trans. ASABE* **55** (6), 2135–2146.
- Jenkins, G. J., Perry, M. C. & Prior, M. J. O. 2007 The climate of the United Kingdom and recent trends. UKCP09 scientific report, Met Office Hadley Centre, Exeter, UK.
- Jenson, M. E. & Haise, H. R. 1963 Estimating evapotranspiration from solar radiation. *J. Irrig. Drain. E-ASCE* **89**, 15–41.
- Jones, P. D., Kilsby, C. G., Harpham, C., Glenis, V. & Burton, A. 2009 *UK Climate Projections Science Report: Projections of Future Daily Climate for the UK from the Weather Generator*. University of Newcastle, UK.
- Jung, M., Reichstein, M., Ciais, P., Seneviratne, S. I., Sheffield, J., Goulden, M. L., Bonan, G., Cescatti, A., Chen, J., de Jeu, R., Dolman, A. J., Eugster, W., Gerten, D., Gianelle, D., Gobron, N., Heinke, J., Kimball, J., Law, B. E., Montagnani, L., Mu, Q., Mueller, B., Oleson, K., Papale, D., Richardson, A. D., Rouspard, O., Running, S., Tomelleri, E., Viovy, N., Weber, U., Williams, C., Wood, E., Zaehle, S. & Zhang, K. 2010 *Recent decline in the global land evapotranspiration trend due to limited moisture supply*. *Nature* **467**, 951–954.
- Kay, A. L. & Davies, H. N. 2008 *Calculating potential evaporation from climate model data: a source of uncertainty for hydrological climate change impacts*. *J. Hydrol.* **358**, 221–239.
- Kay, A. L. & Jones, R. G. 2012 *Comparison of the use of alternative UKCP09 products for modelling the impacts of climate change on flood frequency*. *Clim. Change* **114**, 211–230.
- Kingston, D. G., Todd, M. C., Taylor, R. G., Thompson, J. R. & Arnell, N. W. 2009 *Uncertainty in the estimation of potential evaporation under climate change*. *Geophys. Res. Lett.* **36**, L20403.
- Kleinn, J., Frei, C., Gurtz, J., Luthi, D., Vidale, P. L. & Schar, C. 2005 *Hydrological simulations in the Rhine Basin driven by regional climate models*. *J. Geophys. Res.* **110**, D04102.
- Lhomme, J.-P. 1997 *Towards a rational definition of potential evaporation*. *Hydrol. Earth Syst. Sci.* **1**, 257–264.
- Manning, L. J., Hall, J. W., Fowler, H. J., Kilsby, C. G. & Tebaldi, C. 2009 *Using probabilistic climate change information from a multimodel ensemble for water resources assessment*. *Water Resour. Res.* **45**, W11411.
- McVicar, T. R., Roderick, M. L., Donohue, R. J., Tao Li, L., Van Niel, T. G., Thomas, A., Grieser, J., Jhajharia, D., Himri, Y., Mahowald, N. M., Mescherskaya, A. V., Kruger, A. C., Rehman, S. & Dinpashoh, Y. 2012 *Global review and synthesis of trends in observed terrestrial near-surface wind speeds: implications for evaporation*. *J. Hydrol.* **416–417**, 182–205.
- Milly, P. C. D. & Dunne, K. A. 2011 *On the hydrological adjustment of climate-model projections: the potential pitfall of potential evapotranspiration*. *Earth Interact.* **15**, 1–14.
- Monteith, J. L. 1965 *Evaporation and environment*. 19th Symposia of the Society for Experimental Biology, University Press Cambridge, pp. 205–234.
- Moratiel, R., Snyder, R. L., Duran, J. M. & Tarquis, A. M. 2011 *Trends in climatic variables and future reference evapotranspiration in Duero Valley (Spain)*. *Nat. Hazard. Earth Syst. Sci.* **11**, 1795–1805.
- Murphy, J. M., Sexton, D. M. H., Jenkins, G. J., Booth, B. B. B., Brown, C. C., Clark, R. T., Collins, M., Harris, G. R., Kendon, E. J., Betts, R. A., Brown, S. J., Humphrey, K. A., McCarthy, M. P., McDonald, R. E., Stephens, A., Wallace, C., Warren, R., Wilby, R. & Wood, R. A. 2009 *UK Climate Projections Science Report: Climate Change Projections*. Met Office Hadley Centre, Exeter, UK.
- Nandakumar, N. & Mein, R. G. 1997 *Uncertainty in rainfall-runoff model simulations and the implications for predicting the hydrologic effects of land-use change*. *J. Hydrol.* **192**, 211–232.
- Oudin, L., Hervieu, F., Michel, C., Perrin, C., Andreassian, V., Anctil, F. & Loumagne, C. 2005a *Which potential evapotranspiration input for a lumped rainfall-runoff model? Part 2 – Towards a simple and efficient potential evapotranspiration model for rainfall-runoff modelling*. *J. Hydrol.* **303**, 290–306.
- Oudin, L., Michel, C. & Anctil, F. 2005b *Which potential evapotranspiration input for a lumped rainfall-runoff model? Part 1 – Can rainfall-runoff models effectively handle detailed potential evapotranspiration inputs?* *J. Hydrol.* **303**, 275–289.
- Oudin, L., Moulin, L., Bendjoudi, H. & Ribstein, P. 2010 *Estimating potential evapotranspiration without continuous daily data: possible errors and impact on water balance equations*. *Hydrol. Sci. J.* **55**, 209–222.
- Parmele, L. H. 1972 *Errors in output of hydrologic models due to errors in input potential evapotranspiration*. *Water Resour. Res.* **8**, 348–359.
- Paturel, J. E., Servat, E. & Vassiliadis, A. 1995 *Sensitivity of conceptual rainfall-runoff algorithms to errors in input data – case of the GR2M model*. *J. Hydrol.* **168**, 111–125.
- Penman, H. L. 1948 *Natural evaporation from open water, bare soil and grass*. *Proc. Roy. Soc. Lond.* **193**, 120–145.
- Pereira, L. S., Perrier, A., Allen, R. G. & Alves, I. 1999 *Evapotranspiration: concepts and future trends*. *J. Irrig. Drain. Eng.* **125**, 45–51.
- Piani, C., Weedon, G. P., Best, M., Gomes, S. M., Viterbo, P., Hagemann, S. & Haerter, J. O. 2010 *Statistical bias correction of global simulated daily precipitation and temperature for the application of hydrological models*. *J. Hydrol.* **395**, 199–215.
- Price, D. J. & McKenna, J. E. 2003 *Climate change: review of levels of protection offered by flood prevention schemes: UKCIP02 update* (2003). Report to Scottish Executive, Babbie Group.

- Priestley, C. H. B. & Taylor, R. J. 1972 On the assessment of surface heat fluxes and evaporation using large-scale parameters. *Mon. Weather Rev.* **100**, 81–92.
- Prudhomme, C. & Williamson, J. 2013 Derivation of RCM-driven potential evapotranspiration for hydrological climate change impact analysis in Great Britain: a comparison of methods and associated uncertainty in future projections. *Hydrol. Earth Syst. Sci.* **10**, 597–624.
- Robson, A. J. 2002 Evidence for trends in UK flooding. *Phil. Trans. R. Soc. Lond. A* **360**, 1327–1343.
- Rodda, J. C. & Marsh, T. J. 2011 *The 1975–76 Drought – A Contemporary and Retrospective Review*. Centre for Ecology & Hydrology, Wallingford, UK, 58 pp.
- Sexton, D. M. H. & Murphy, J. 2010 *UKCP09: Probabilistic Projections of Wind Speed*. Met Office Hadley Centre, Exeter, UK.
- Shaw, S. B. & Riha, S. J. 2011 Assessing temperature-based PET equations under a changing climate in temperate, deciduous forests. *Hydrol. Process.* **25**, 1466–1478.
- Sheffield, J., Wood, E. F. & Roderick, M. L. 2012 Little change in global drought over the past 60 years. *Nature* **491**, 435–438.
- Shuttleworth, W. J. 2007 Putting the ‘vap’ into evaporation. *Hydrol. Earth Syst. Sci.* **11**, 210–244.
- Shuttleworth, W. J., Serrat-Capdevilla, A., Roderick, M. L. & Scott, R. L. 2009 On the theory relating changes in area-average and pan evaporation. *Q. J. Roy. Meteor. Soc.* **135** (642), 1230–1247.
- Smith, R. N. B., Blyth, E. M., Finch, J. W., Goodchild, S., Hall, R. L. & Madry, S. 2006 Soil state and surface hydrology diagnosis based on MOSES in the Met Office Nimrod nowcasting system. *Meteorol. Appl.* **13**, 89–109.
- Spina Weiland, F. C., Tisseuil, C., Durr, H. H., Vrac, M. & van Beek, L. P. H. 2012 Selecting the optimal method to calculate daily global reference potential evaporation from CFSR reanalysis data. *Hydrol. Earth Syst. Sci.* **16**, 983–1000.
- Teuling, A. J., Seneviratne, S. I., Stöckli, R., Reichstein, M., Moors, E., Ciais, P., Luyssaert, S., van den Hurk, B., Ammann, C., Bernhofer, C., Dellwik, E., Gianelle, D., Gielen, B., Grünwald, T., Klumpp, K., Montagnani, L., Moureaux, C., Sottocornola, M. & Wohlfahrt, G. 2010 Contrasting response of European forest and grassland energy exchange to heatwaves. *Nat. Geosci.* **3**, 722–727.
- Thomas, A. 2000 Spatial and temporal characteristics of potential evapotranspiration trends over China. *Int. J. Climatol.* **20**, 381–396.
- Thompson, N., Barrie, I. A. & Ayles, M. 1981 *The Meteorological Office Rainfall and Evaporation Calculation System: MORECS (July 1981)*. Hydrological Memorandum No. 45, Met Office, Bracknell, UK.
- Thorntwaite, C. W. 1948 An approach towards a rational classification of climate. *Geogr. Rev.* **38**, 55–94.
- Vorosmarty, C. J., Federer, C. A. & Schloss, A. L. 1998 Potential evaporation functions compared on US watersheds: possible implications for global-scale water balance and terrestrial ecosystem modeling. *J. Hydrol.* **207**, 147–169.
- Wang, D. & Alimohammadi, N. 2012 Responses of annual runoff, evaporation and storage change to climate variability at the watershed scale. *Water Resour. Res.* **48**, W05546.
- Weedon, G. P., Gomes, S., Viterbo, P., Shuttleworth, W. J., Blyth, E., Österle, H., Adam, J. C., Bellouin, N., Boucher, O. & Best, M. 2011 Creation of the WATCH Forcing Data and its use to assess global and regional reference crop evaporation over land during the twentieth century. *J. Hydrometeorol.* **12**, 823–848.
- Wilby, R. L. & Harris, I. 2006 A framework for assessing uncertainties in climate change impacts: low-flow scenarios for the River Thames, UK. *Water Resour. Res.* **42**, W02419.
- Wilby, R. L., Greenfield, B. & Glenney, C. 1994 A coupled synoptic-hydrological model for climate change impact assessment. *J. Hydrol.* **153**, 265–290.
- Wilby, R. L., Whitehead, P. G., Wade, A. J., Butterfield, D., Davis, R. J. & Watts, G. 2006 Integrated modelling of climate change impacts on water resources and quality in a lowland catchment: River Kennet, UK. *J. Hydrol.* **330**, 204–220.
- Wullschlegel, S. D., Gunderson, C. A., Hanson, P. J., Wilson, K. B. & Norby, R. J. 2002 Sensitivity of stomatal and canopy conductance to elevated CO₂ concentration – interacting variables and perspectives of scale. *New Phytol.* **153**, 485–496.
- Yang, C., Chandler, R. E., Isham, V. S., Annoni, C. & Wheeler, H. S. 2005 Simulation and downscaling models for potential evaporation. *J. Hydrol.* **302**, 239–254.
- Ziegler, A. D., Sheffield, J., Maurer, E. P., Nijssen, B., Wood, E. F. & Lettenmaier, D. P. 2003 Detection of intensification in global- and continental-scale hydrological cycles: temporal scale of evaluation. *J. Clim.* **16**, 535–547.

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CAMELS-GB: hydrometeorological time series and landscape attributes for 671 catchments in Great Britain

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Abstract. We present the first large-sample catchment hydrology dataset for Great Britain, CAMELS-GB (Catchment Attributes and MEteorology for Large-sample Studies). CAMELS-GB collates river flows, catchment attributes and catchment boundaries from the UK National River Flow Archive together with a suite of new meteorological time series and catchment attributes. These data are provided for 671 catchments that cover a wide range of climatic, hydrological, landscape, and human management characteristics across Great Britain. Daily time series covering 1970–2015 (a period including several hydrological extreme events) are provided for a range of hydro-meteorological variables including rainfall, potential evapotranspiration, temperature, radiation, humidity, and river flow. A comprehensive set of catchment attributes is quantified including topography, climate, hydrology, land cover, soils, and hydrogeology. Importantly, we also derive human management attributes (including attributes summarising abstractions, returns, and reservoir capacity in each catchment), as well as attributes describing the quality of the flow data including the first set of discharge uncertainty estimates (provided at multiple flow quantiles) for Great Britain. CAMELS-GB (Coxon et al., 2020; available at <https://doi.org/10.5285/8344e4f3-d2ea-44f5-8afa-86d2987543a9>) is intended for the community as a publicly available, easily accessible dataset to use in a wide range of environmental and modelling analyses.

1 Introduction

Data underpin our knowledge of the hydrological system. They advance our understanding of water dynamics over a wide range of spatial and temporal scales and are the foundation for water resource planning and regulation. With the emergence of new digital technologies and increased monitoring of the earth system via satellites and sensors, we now have greater access to data than ever before. This prolifera-

tion of data has been reflected in recent projects where there has been a focus on sharing data and collaborative research (SWITCH-ON; Ceola et al., 2015), collecting new datasets through the creation of terrestrial environmental observatories (TERENO; Zacharias et al., 2011) or the Critical Zone Observatories (CZOs; Brantley et al., 2017), and cloud-based resources for modelling and visualising large datasets such as

the Environmental Virtual Observatory (EVO; Emmett et al., 2014) and the CUAHSI HydroDesktop (Ames et al., 2012).

To synthesise hydrologically relevant data and learn from differences between catchments, several large-sample hydrological datasets have been produced over the last decades. These datasets rely on complementary data sources to provide the community with hydrometeorological time series and landscape attributes enabling the characterisation of dozens to thousands of catchments (see Addor et al., 2019, for a review). Many studies have demonstrated the importance of large-sample catchment datasets for understanding regional variability in model performance (Coxon et al., 2019; Kollat et al., 2012; Lane et al., 2019; Newman et al., 2015; Perrin et al., 2003), testing model behaviour and robustness under changing climate conditions (Coron et al., 2012; Fowler et al., 2016; Werkhoven et al., 2008), understanding variability in catchment behaviour including hydrologic signatures and classification (Sawicz et al., 2011; Yadav et al., 2007), assessing trends in hydro-climatic extremes (Berghuijs et al., 2017; Blöschl et al., 2017; Gudmundsson et al., 2019; Hannaford and Buys, 2012; Stahl et al., 2010), exploring model and data uncertainty (Coxon et al., 2014; Westerberg et al., 2016) and regionalising model structures and parameters (Lee et al., 2005; Merz and Blöschl, 2004; Mizukami et al., 2017; Parajka et al., 2005; Pool et al., 2019; Singh et al., 2014).

However, while the number of studies involving data from large samples of catchments is rapidly increasing, publicly available large-sample catchment datasets are still rare. Researchers spend considerable time and effort compiling large-sample catchment datasets, yet these datasets are rarely made available to the community due to data licensing restrictions, strict access policies, or the time required to make these datasets readily usable (Addor et al., 2019; Hannah et al., 2011; Hutton et al., 2016; Nelson, 2009; Viglione et al., 2010). Notable exceptions of open-source, large-sample catchment datasets include the MOPEX dataset that includes hydro-meteorological time series and catchment attributes for 438 US catchments (Duan et al., 2006), the CAMELS dataset that covers 671 US catchments (Catchment Attributes and MEteorology for Large-Sample studies; Addor et al., 2017; Newman et al., 2015), the CAMELS-CL dataset that contains data for 516 catchments across Chile (Alvarez-Garretón et al., 2018), and the Canadian model parameter experiment (CANOPEX) database (Arsenault et al., 2016). Daily streamflow records often are not allowed to be redistributed; thus researchers have computed streamflow indices (hydrological signatures) and made them publicly available together with catchment attributes. This is the approach taken for the Global Streamflow Indices and Metadata Archive (Do et al., 2018; Gudmundsson et al., 2018), which includes > 35 000 catchments globally, and the dataset produced by Kuentz et al. (2017) which includes data for > 30 000 catchments across Europe. Overall, datasets for large samples of catchments are vital to advance knowledge on hydrologi-

cal processes (Falkenmark and Chapman, 1989; Gupta et al., 2014; McDonnell et al., 2007; Wagener et al., 2010), to underpin common frameworks for model evaluation across complex domains (Ceola et al., 2015) and ensure hydrological research is reusable and reproducible through the use of common datasets and code (Buytaert et al., 2008; Hutton et al., 2016).

In Great Britain, there is a wide availability of gridded, open-source datasets and free access to quality-controlled river flow data via the UK National River Flow Archive (NRFA). While this is a large resource of open data by international standards, these datasets have not yet been combined and processed over a consistent set of catchments and made publicly available in a single location. Further these are dynamic datasets subject to change which cannot support consistent repeatable analysis. Finally, the range of variables and catchment attributes is more limited than other large-sample datasets such as CAMELS.

To address this data gap, we produced the CAMELS-GB dataset (Coxon et al., 2020). CAMELS-GB collates river flows, catchment attributes, and catchment boundaries from the NRFA together with a suite of new meteorological time series and catchment attributes for 671 catchments across Great Britain. In the following sections we describe the key objectives behind CAMELS-GB and how they have shaped the content of the dataset. We also provide a comprehensive description of all data contained within CAMELS-GB including (1) its source data, (2) how the time series and attributes were produced, and (3) a discussion of the associated limitations.

2 Objectives

CAMELS (Catchment Attributes and MEteorology for Large-sample Studies) began as an initiative to provide hydro-meteorological time series (Newman et al., 2015) and catchment attributes covering climatic indices, hydrologic signatures, land cover, soil, and geology (Addor et al., 2017) for the contiguous United States. Since then, the dataset has been used widely in other studies (e.g. Addor et al., 2018; Gnan et al., 2019; Pool et al., 2019; Tyrallis et al., 2019) and has provided the framework for the production of similar datasets. CAMELS for Chile (CAMELS-CL; Alvarez-Garretón et al., 2018) was released, and CAMELS datasets for other countries are in production (Brazil and Australia). While each CAMELS dataset has unique features (for example CAMELS-CL provides snow water equivalent estimates and CAMELS-GB characterises uncertainties in streamflow time series), all the CAMELS datasets consistently apply the same core objective: make hydrometeorological time series and landscape attributes for a large sample of catchments publicly available. They strive to use the same open-source code, variable names, and datasets in order to increase the comparability and reproducibility of hydrological studies. In

creating the CAMELS-GB dataset, we wanted to build on the successful CAMELS blueprint to provide a large-sample catchment dataset for Great Britain based on four core objectives.

Firstly, we wanted to build on the wealth of data already available for GB catchments but synthesise the diverse range of data into a single, consistent, up-to-date dataset. The UK has a rich history of leading research in catchment hydrology and integrating large samples of data for many catchments. For example, the Flood Studies Report (NERC, 1975) extracted high rainfall events, peak flows, and catchment characteristics for 138 catchments to support flood estimation using catchment characteristics. The UK NRFA contains a wealth of data (including flow time series, catchment attributes, catchment masks) for the UK gauging station network which contains approximately 1500 gauging stations as summarised in the UK Hydrometric Register (Marsh and Hannaford, 2008). Where possible, we have made use of the existing data available on the NRFA in CAMELS-GB to ensure consistency and to avoid duplicating efforts. We also build on these existing datasets by providing new catchment attributes and time series that are currently not available on the NRFA (e.g. potential evapotranspiration, temperature, soils, and human impacts).

Secondly, we wanted to provide a large-sample catchment dataset for Great Britain based on information that (i) is sufficiently detailed to enable the exploration of hydrological processes at the catchment scale, (ii) is well documented (ideally in open-access peer-reviewed journals), (iii) relies on state-of-the-art methods, and (iv) includes recent observations. Consequently, some catchment attributes currently available on the NRFA have been re-calculated for CAMELS-GB as better-quality or higher-spatial-resolution datasets are now available (e.g. to derive land cover and hydrogeological attributes). This also means that we have primarily used the best available national datasets for the derivation of the catchment time series and attributes. These time series and attributes can be compared at a later stage to estimates derived from global datasets.

Thirdly, we wanted to provide qualitative and quantitative estimates of the limitations/uncertainties of the data provided in CAMELS-GB. Characterising data uncertainties is crucial as different data collection techniques or quality standards can bias comparisons between catchments. By providing quantitative estimates of uncertainty (including the first set of national discharge uncertainty estimates), we hope to raise awareness and encourage users of the dataset to consider these uncertainties in their analyses.

Finally, where possible, we have ensured that the underlying datasets (such as gridded geophysical and meteorological data) are publicly available to allow reproducibility and reusability.

3 Catchments

The catchments included in the CAMELS-GB dataset were selected from the UK NRFA Service Level Agreement (SLA) network. Approximately half of the NRFA gauging stations are designated as SLA stations in collaboration with measuring authorities (as described in Dixon et al., 2013; Hannaford, 2004), embracing catchments which are considered to contribute most to the overall strategic utility of the gauging network. Selection criteria include hydrometric performance, representativeness of the catchment, length of record, and degree of artificial disturbance to the natural flow regime. The flow records for these SLA stations are subject to an additional level of validation on the NRFA and are also used to calculate performance metrics that quantify completeness and quality (see the methods and metrics outlined in Dixon et al., 2013, and Muchan and Dixon, 2014). This process focuses on the credibility of flows in the extreme ranges and the need to maintain sensibly complete time series, thus providing good-quality and long time series for CAMELS-GB. All gauges from the UK SLA network are included in CAMELS-GB except catchments from Northern Ireland (due to a lack of consistent meteorological datasets across the UK) and two gauges where no suitable surface area catchment could be derived (e.g. a groundwater spring for which surface catchment area is not hydrologically relevant). This results in a total of 671 catchments (includes nested catchments – see Fig. S1 in the Supplement) covering a wide range of climatic and hydrologic diversity across GB that is representative of the wider gauging network (see Figs. S2 and S3 for a comparison of key attributes for the CAMELS-GB catchments and all GB gauged catchments).

In keeping with the CAMELS-CL dataset (Alvarez-Garretón et al., 2018), we chose to include both non-impacted and human-impacted catchments in the dataset complemented with catchment attributes on the size and type of human impacts these catchments experience. Human-impacted catchments are provided to support the current IAHS Panta Rhei decade which is focused on how the water cycle is impacted by human activities (McMillan et al., 2016; Montanari et al., 2013) and also enable national-scale hydrological modelling and analyses across catchments that are impacted by reservoirs, abstractions, and land use change.

4 Catchment masks

Catchment masks are provided in the dataset to allow other users to create their own catchment hydro-meteorological time series and attributes from gridded datasets not used in this study. The catchment masks were derived from the UK Centre for Ecology & Hydrology (CEH) 50 m Integrated Hydrological Digital Terrain Model (IHDTM; Morris and Flavin, 1990) and a set of 50 m flow direction grids. The flow direction grids are based on a digital elevation model and contours from the UK Ordnance Survey Land-

Form Panorama dataset (now withdrawn and superseded by OS Terrain 50) and hydrologically corrected by “burning in” rivers using CEH’s 1 : 50 K digital river network (Moore et al., 2000). The catchment boundaries were created using bespoke code for identifying all IHDTM cells upstream of the most appropriate grid cell to represent the gauging station location and generate a meaningful “real-world” boundary around these cells. In a few cases, where the topographical data make automated definition difficult, catchment masks were manually derived. Catchment masks are provided as shapefiles in the OSGB 1936 co-ordinate system (British National Grid).

ASCII files were generated from the shapefiles by converting the shapefile onto a 50 m raster grid and then exporting the rasters to individual ASCII files. These files are used to calculate all catchment-averaged time series and attributes in CAMELS-GB. To calculate the catchment-average time series/attribute for each dataset, the 50 m grid cells in each catchment mask were assigned a value from the respective dataset grid cell (determined by which dataset grid cell the lower left-hand corner of the mask grid cell lay within), and an arithmetic mean of these values was calculated (unless specified otherwise). This ensures a weighted average is calculated that accounts for the differences in grid cell sizes between the catchment mask (on a 50 m grid) and any other datasets (often on a 1 km grid). This is particularly important for smaller catchments in areas of highly variable data.

It is important for users to note that as the topographical boundaries are used throughout the study to quantify the hydrometeorological time series and attributes, this could mean significant errors where the catchment area is poorly defined.

5 Time series data

Daily meteorological and hydrological time series data are provided for the 671 CAMELS-GB catchments including flow, rainfall, potential evapotranspiration, temperature, short-wave radiation, long-wave radiation, specific humidity, and wind speed (summarised in Table 1). These datasets were chosen for inclusion in CAMELS-GB to cover the common forcing and evaluation data needed for catchment hydrological modelling, to allow users to derive different estimates of potential evapotranspiration, and to provide the key hydrometeorological data for catchment characterisation.

Hydro-meteorological time series data for the 671 catchments were obtained from a number of datasets for a 45-year time period from 1 October 1970 to 30 September 2015. These long time series enable the dataset’s use in trend analysis, provide a valuable dataset for model forcing and evaluation, and ensure the robust calculation of hydro-climatic signatures. These long time series also cover a wide range of nationally important hydroclimatic events such as the 1976 drought and 2007 floods (see summaries of UK drought and flood episodes for a more extensive review including Fol-

land et al., 2015; Marsh et al., 2007; Stevens et al., 2016). From previous analyses, it is important to note that there are key known non-stationarities over this period in hydrometeorological data and human activity (see for example Hannaford and Marsh, 2006) for GB. For example, seasonal changes in precipitation have been well documented (Jenkins et al., 2009) and linked to changes in river flow (Hannaford and Buys, 2012; Harrigan et al., 2018).

5.1 Meteorological time series

Meteorological time series were derived from high-quality national gridded products chosen for their high spatial resolution (1 km²), long time series availability, and basis on UK observational networks. For each of the meteorological datasets, daily time series of catchment areal averages were calculated using the catchment masks and methods described in Sect. 4. These time series are available for all CAMELS-GB catchments with no missing data.

Daily rainfall time series were derived from the CEH Gridded Estimates of Areal Rainfall dataset (CEH-GEAR) (Keller et al., 2015; Tanguy et al., 2016). This dataset consists of 1 km² gridded estimates of daily rainfall for Great Britain and Northern Ireland from 1 January 1961 to 31 December 2015. The daily rainfall grids are derived using natural neighbour interpolation of a national database of quality-controlled, observed precipitations from the Met Office UK rain gauge network. It should be noted that the rainfall time series available in CAMELS-GB use the same underlying data but are not identical to catchment-average rainfall series available from the NRFA which are derived using only 1 km grid cells with > 50 % of their area within the catchment boundary.

Daily meteorological time series were derived from the Climate Hydrology and Ecology research Support System meteorology dataset (CHESS-met; Robinson et al., 2017a). The CHESS-met dataset consists of daily 1 km² gridded estimates for Great Britain from 1 January 1961 to 31 December 2015 and includes several meteorological variables derived from observational data (see Table 1). CHESS-met was derived from the observation-based MORECS, which is a 40 km resolution gridded dataset, derived by interpolating daily station data (Hough and Jones, 1997; Thompson et al., 1981). The CHESS-met variables are obtained by downscaling MORECS variables to 1 km resolution and adjusting for local topography using lapse rates, modelled wind speeds, and empirical relationships. CHESS-met air temperature and wind speed were directly downscaled from MORECS, specific humidity was calculated from MORECS vapour pressure, downward short-wave radiation was calculated from MORECS sunshine hours, and long-wave radiation was calculated from the downscaled temperature, vapour pressure, and sunshine hours (see Robinson et al., 2017b, for detail).

Daily potential evapotranspiration time series were derived from the Climate Hydrology and Ecology re-

Table 1. Summary table of catchment hydro-meteorological time series available in CAMELS-GB.

Time series class	Time series name	Description	Unit	Data source
Meteorological time series (available from 1 Oct 1970 to 30 Sep 2015)	precipitation	catchment daily averaged precipitation	mm d ⁻¹	CEH-GEAR (Keller et al., 2015; Tanguy et al., 2016)
	pet	catchment daily averaged potential evapotranspiration for a well-watered grass (Penman–Monteith equation)	mm d ⁻¹	CHESS-PE (Robinson et al., 2017a, b)
	peti	catchment daily averaged potential evapotranspiration for a well-watered grass (Penman–Monteith equation with a correction added for interception on days where rainfall has occurred)	mm d ⁻¹	
	temperature	catchment daily averaged temperature	°C	
	windspeed	catchment daily averaged wind speed	m s ⁻¹	CHESS-met (Robinson et al., 2017a)
	humidity	catchment daily averaged specific humidity	g kg ⁻¹	
	shortwave_rad	catchment daily averaged downward short-wave radiation	W m ⁻²	
Hydrological time series (available from 1 Oct 1970 to 30 Sep 2015)	longwave_rad	catchment daily averaged long-wave radiation	W m ⁻²	
	discharge_spec	catchment-specific discharge (converted to millimetres per day using catchment areas described in Sect. 6.1)	mm d ⁻¹	UK National River Flow Archive using the NRFA API*
	discharge_vol	catchment discharge	m ³ s ⁻¹	

* <https://nrfaapps.ceh.ac.uk/nrfa/nrfa-api.html> (last access: 11 December 2019).

search Support System Potential Evapotranspiration dataset (CHESS-PE; Robinson et al., 2016). The CHESS-PE dataset consists of daily 1 km² gridded estimates of potential evapotranspiration for Great Britain from 1 January 1961 to 31 December 2015. Potential evapotranspiration is calculated using the Penman–Monteith equation and CHESS-met datasets (see Robinson et al., 2017b). In recognition of the uncertainty in PET estimates, we provide two estimates of potential evapotranspiration available from CHESS-PE. The first estimate (PET) is calculated using the Penman–Monteith equation for FAO-defined well-watered grass (Allen et al., 1998) and is used to calculate all subsequent PET catchment attributes provided in CAMELS-GB. This estimate only accounts for transpiration and does not allow for canopy interception. The second estimate (PETI) uses the same meteorological data and the Penman–Monteith equation for well-watered grass, but a correction is added for interception on days where rainfall has occurred (Robinson et al., 2017b). The seasonal differences between these two data products can be seen in Fig. S12b. Generally, the PETI estimate with the interception correction is higher because interception is a more ef-

fective flux than transpiration under the same meteorological conditions. CHESS PETI can be between 5 % and 25 % higher than CHESS PET at the grid-box level, whereas at a regional level, CHESS PETI is 7 % higher than PET in England and 11 % higher than PET in Scotland overall (Robinson et al., 2017b). In comparison to other PET products commonly used in GB, the CHESS PETI estimate is similar to grass-only MORECS (the United Kingdom Meteorological Office rainfall and evaporation calculation system; Hough and Jones, 1997), which has its own interception correction. It is important to note that the effect of seasonal land cover is not accounted for in the CHESS-PE products; this means that for arable agriculture which may have bare soil for part of the year, or deciduous trees which lose leaves and thus reduce both transpiration and interception, the potential evapotranspiration could be lower during winter than is estimated here. This leads to a varying difference between the PET and PETI of grass and other land cover types throughout the year (Beven, 1979).

5.2 Hydrological time series

Daily streamflow data for the 671 gauges were obtained from the UK NRFA on the 27 March 2019 using the NRFA API (<https://nrfaapps.ceh.ac.uk/nrfa/nrfa-api.html>, last access: 11 December 2019). These data are collected by measuring authorities including the Environment Agency (EA), Natural Resources Wales (NRW), and Scottish Environmental Protection Agency (SEPA) and then quality controlled, on an ongoing annual cycle, before being uploaded to the NRFA site. It is important to note that, on occasion, these flow time series are reprocessed when a rating curve is revised (for example) and so there may be differences between the flow time series on the NRFA website and contained in CAMELS-GB. If users wish to extend the time series beyond that available in CAMELS-GB, we suggest downloading and using the extended flow time series available from the NRFA website and recalculating the hydrological signatures using the code we have archived (see Sect. 6.3). Data are provided in cubic metres per second and millimetre per day and calculated using catchment areas derived from the catchment boundaries described in Sect. 4.

Figure 1a shows the flow data availability for all gauges contained in the CAMELS-GB dataset covering different time periods. Over the 45-year time period (1970–2015), 60 % (401) of the gauges have 5 % missing flow data or less, and 81 % (542) of the gauges have 20 % missing flow data or less. Figure 1b shows the number of years of available flow data for each CAMELS-GB gauge across Great Britain. A total of 97 % (654) of the gauges have at least 20 years of data, and 70 % (468) of the gauges have at least 40 years of data. Overall, there is good spatial coverage of long flow time series across Great Britain, with slightly shorter time series concentrated in Scotland and in central GB.

6 Catchment attributes

6.1 Location, area, and topographic data

Catchment attributes describing the location and topography were extracted for each catchment from the NRFA (see Table 2). Catchment areas are calculated from the catchment masks described in Sect. 4. Catchment elevation is extracted from CEH's 50 m Integrated Hydrological Digital Terrain Model, and the minimum and maximum catchment elevations within the catchment mask are provided alongside different percentiles (10th, 50th, and 90th). On occasion, minimum elevation may differ slightly from the gauge elevation attributes. The latter are as reported to the NRFA by the measuring authorities and derived in a variety of ways with different levels of accuracy. Furthermore some may refer to the bank top, the gauge minimum, or a local datum. The minimum elevation attribute provides a more consistent metric (though itself limited in accuracy due to the 50 m grid representation). Mean elevation and mean drainage path slope

are also provided from pre-computed grids developed for the Flood Estimation Handbook (Bayliss, 1999). The mean drainage path slope provides an index of overall catchment steepness by calculating the mean of all inter-nodal slopes from the IHD TM for the catchment. For two catchments (18011 and 26006) where automatic derivation of the catchment boundary from the IHD TM for the gauge location was not possible and catchment masks were manually derived, no appropriate pre-computed values for the mean elevation or mean drainage path slope were available.

6.2 Climatic indices

Climatic indices were derived using the catchment daily rainfall, potential evapotranspiration, and temperature time series described in Sect. 5.1 (see Table 2). The Penman–Monteith formulation without correction for interception is used to calculate all PET catchment attributes provided in CAMELS-GB as it has more consistency with other global and national PET products. To provide consistency with previous CAMELS datasets, we compute the same climatic indices for all catchments in CAMELS-GB. However, it is important to note that in CAMELS-GB climatic indices are calculated for the full meteorological time series available in CAMELS-GB (water years from 1 October 1970 to 30 September 2015), whereas CAMELS and CAMELS-CL both use the water years from 1990 to 2009. The meteorological time series and code (<https://github.com/naddor/camels>, last access: 11 December 2019) are provided for users to calculate indices over different time periods if required.

6.3 Hydrologic signatures

Hydrologic signatures were derived using the catchment daily discharge and rainfall time series described in Sect. 5.1 and 5.2 (see Table 2). To provide consistency with the previous CAMELS datasets, we compute the same hydrologic signatures for all catchments in CAMELS-GB but add an additional formulation of base flow index developed by the UK Centre for Ecology & Hydrology and commonly used in Great Britain (Gustard et al., 1992; see Appendix A and Fig. S12a). Hydrologic signatures are calculated for the flow time series available during water years from 1 October 1970 to 30 September 2015 (previous CAMELS datasets calculated these metrics during water years from 1990 to 2009) using code available on GitHub (<https://github.com/naddor/camels>, last access: 11 December 2019). We advise users to take the length of the flow time series and percentage of missing data (available in the hydrometry catchment attributes – see Sect. 6.7) into account when comparing hydrologic signatures across catchments.

Table 2. Summary table of catchment attributes available in CAMELS-GB.

Attribute class	Attribute name	Description	Unit	Data source
Location and topography	gauge_id	catchment identifier (corresponds to the gauging station ID provided by the NRFA)	–	UK National River Flow Archive using the NRFA API
	gauge_name	gauge name (river name followed by gauging station name)	–	
	gauge_lat	gauge latitude	°	
	gauge_lon	gauge longitude	°	
	gauge_easting	gauge easting	m	
	gauge_northing	gauge northing	m	
	gauge_elev	gauge elevation	m a.s.l.	
	area	catchment area	km ²	CEH's Integrated Hydrological Digital Terrain Model (Morris and Flavin, 1990)
	dpsbar	catchment mean drainage path slope	m km ^{−1}	
	elev_mean	catchment mean elevation	m a.s.l.	
	elev_min	catchment minimum elevation	m a.s.l.	
	elev_10	catchment 10th percentile elevation	m a.s.l.	
	elev_50	catchment median elevation	m a.s.l.	
	elev_90	catchment 90th percentile elevation	m a.s.l.	
	elev_max	catchment maximum elevation	m a.s.l.	
Climatic indices (computed for 1 Oct 1970 to 30 Sep 2015)	p_mean	mean daily precipitation	mm d ^{−1}	Catchment time series of precipitation, potential evapotranspiration, and temperature described in Sect. 5.1 and Table 1
	pet_mean	mean daily PET (Penman–Monteith equation without interception correction)	mm d ^{−1}	
	aridity	aridity, calculated as the ratio of mean daily potential evapotranspiration to mean daily precipitation	–	
	p_seasonality	seasonality and timing of precipitation (estimated using sine curves to represent the annual temperature and precipitation cycles, positive (negative) values indicate that precipitation peaks in summer (winter), and values close to zero indicate uniform precipitation throughout the year). See Eq. (14) in Woods (2009)	–	
	frac_snow	fraction of precipitation falling as snow (for days colder than 0 °C)	–	
	high_prec_freq	frequency of high-precipitation days (≥ 5 times mean daily precipitation)	d yr ^{−1}	
	high_prec_dur	average duration of high-precipitation events (number of consecutive days ≥ 5 times mean daily precipitation)	d	
	high_prec_timing	season during which most high-precipitation days (≥ 5 times mean daily precipitation) occur. If two seasons register the same number of events, a value of NaN is given.	season	
	low_prec_freq	frequency of dry days (< 1 mm d ^{−1})	d yr ^{−1}	
	low_prec_dur	average duration of dry periods (number of consecutive days < 1 mm d ^{−1})	d	
	low_prec_timing	season during which most dry days (< 1 mm d ^{−1}) occur. If two seasons register the same number of events, a value of NaN is given.	season	

Table 2. Continued.

Attribute class	Attribute name	Description	Unit	Data source
Hydrologic signatures (computed for 1 Oct 1970 to 30 Sep 2015)	q_mean	mean daily discharge	mm d ⁻¹	Catchment time series of streamflow and precipitation described in Sect. 5.2 and 5.1 respectively and Table 1. Thresholds for high/low flow frequency and duration were obtained from Clausen and Biggs (2000) and Westerberg and McMillan (2015)
	runoff_ratio	runoff ratio, calculated as the ratio of mean daily discharge to mean daily precipitation	–	
	stream_elas	streamflow precipitation elasticity (sensitivity of streamflow to changes in precipitation at the annual timescale, using the mean daily discharge as reference). See Eq. (7) in Sankarasubramanian et al. (2001), with the last element being $\overline{P/Q}$ not $\overline{Q/P}$	–	
	slope_fdc	slope of the flow duration curve (between the log-transformed 33rd and 66th streamflow percentiles) (Yadav et al., 2007). There can be NAs in this metric when over a third of the flow time series are zeros (see zero_q_freq)	–	
	baseflow_index	base flow index (ratio of mean daily base flow to daily discharge, hydrograph separation performed using the Ladson et al., 2013, digital filter)	–	
	baseflow_index_ceh	base flow index (ratio of mean daily base flow to daily discharge, hydrograph separation performed using the Gustard et al. (1992) method described in Appendix A)	–	
	hfd_mean	mean half-flow date (date on which the cumulative discharge since 1 Oct reaches half of the annual discharge)	days since 1 Oct	
	Q5	5 % flow quantile (low flow)	mm d ⁻¹	
	Q95	95 % flow quantile (high flow)	mm d ⁻¹	
	high_q_freq	frequency of high-flow days (> 9 times the median daily flow)	d yr ⁻¹	
	high_q_dur	average duration of high-flow events (number of consecutive days > 9 times the median daily flow)	d	
	low_q_freq	frequency of low-flow days (< 0.2 times the mean daily flow)	d yr ⁻¹	
	low_q_dur	average duration of low-flow events (number of consecutive days < 0.2 times the mean daily flow)	d	
Land cover attributes	zero_q_freq	fraction of days with $Q = 0$	–	1 km percent-age target class, Land Cover Map 2015 (Rowland et al., 2017)
	dwood_perc	percentage cover of deciduous woodland	%	
	ewood_perc	percentage cover of evergreen woodland	%	
	grass_perc	percentage cover of grass and pasture	%	
	shrub_perc	percentage cover of medium-scale vegetation (shrubs)	%	
	crop_perc	percentage cover of crops	%	
	urban_perc	percentage cover of suburban and urban	%	
	inwater_perc	percentage cover of inland water	%	
	bares_perc	percentage cover of bare soil and rocks	%	
	dom_land_cover	dominant land cover (the land cover class that has the highest percentage cover in each catchment)	–	

Table 2. Continued.

Attribute class	Attribute name	Description	Unit	Data source
Soil attributes Each soil attribute (apart from percentage sand, silt, clay, and organic content) is accompanied by the 5th, 50th, and 95th percentiles of that attribute across the catchment and the percentage missing	sand_perc	percentage sand	%	European Soil Database Derived Data product (Hiederer, 2013a, b), and the modelled depth-to-bedrock global product (Pelletier et al., 2016b)
	silt_perc	percentage silt	%	
	clay_perc	percentage clay	%	
	organic_perc	percentage organic content	%	
	bulkdens	bulk density	g cm^{-3}	
	tawc	total available water content (calculated over the soil depth available for roots)	mm	
	porosity_cosby	volumetric porosity (saturated water content estimated using a pedo-transfer function based on sand and clay fractions)	–	
	porosity_hypres	volumetric porosity (saturated water content estimated using a pedo-transfer function based on silt, clay and organic fractions, bulk density, and topsoil)	–	
	conductivity_cosby	saturated hydraulic conductivity (estimated using a pedo-transfer function based on sand and clay fractions)	cm h^{-1}	
	conductivity_hypres	saturated hydraulic conductivity (estimated using a pedo-transfer function based on silt, clay and organic fractions, bulk density, and topsoil)	cm h^{-1}	
Hydrogeology attributes	root_depth	depth available for roots	m	British Geological Survey hydrogeology map (BGS, 2019) and superficial deposit map
	soil_depth_pelletier	depth to bedrock (maximum 50 m)	m	
	inter_high_perc	significant intergranular flow – high productivity	%	
	inter_mod_perc	significant intergranular flow – moderate productivity	%	
	inter_low_perc	significant intergranular flow – low productivity	%	
	frac_high_perc	flow through fractures – high productivity	%	
	frac_mod_perc	flow through fractures – moderate productivity	%	
	frac_low_perc	flow through fractures – low productivity	%	
	no_gw_perc	rocks with essentially no groundwater	%	
	low_nsig_perc	generally low productivity (intergranular flow) but some not significant aquifer	%	
	nsig_low_perc	generally not significant aquifer but some low productivity (intergranular flow)	%	

Table 2. Continued.

Attribute class	Attribute name	Description	Unit	Data source
Hydrometry	station_type	gauging station type denoted by the following abbreviations (B: broad-crested weir; C: crump profile single-crest weir; CB: compound broad-crested weir; CC: compound crump weir; EM: electromagnetic gauging station; EW: Essex weir; FL: flume; FV: flat V triangular profile weir; MIS: miscellaneous; TP: rectangular thin-plate weir; US: ultrasonic gauging station; VA: velocity–area gauging station; VN: triangular (V notch) thin-plate weir). Two abbreviations may be applied to each station relating to the measurement of low or high flows.	–	UK National River Flow Archive using the NRFA API
	flow_period_start	first date that daily flow time series provided in CAMELS-GB are available for this gauging station	–	Catchment time series of streamflow described in Sect. 5.2
	flow_period_end	end date that daily flow time series provided in CAMELS-GB are available for this gauging station	–	
	flow_perc_complete	percentage of days with flow time series available from 1 Oct 1970 to 31 Sep 2015	%	
	bankfull_flow	flow at which the river begins to overlap the banks at a gauging station (obtained from stage–discharge relationships so may be derived by extrapolation)	$\text{m}^3 \text{s}^{-1}$	UK National River Flow Archive using the NRFA API
	structurefull_flow	flow at which the river begins to the wingwalls of a structure at a gauging station (obtained from stage–discharge relationships so may be derived by extrapolation)	$\text{m}^3 \text{s}^{-1}$	
	qXX_uncert_upper	upper bound of the discharge uncertainty interval for the XX percentile flow given as a percentage of the XX percentile flow – estimates for XX values of 5, 25, 50, 75, 95, and 99 are provided	%	Derived from Coxon et al. (2015)
	qXX_uncert_lower	lower bound of the discharge uncertainty interval for the XX percentile flow given as a percentage of the XX percentile flow – estimates for XX values of 5, 25, 50, 75, 95, and 99 are provided	%	
	quncert_meta	metadata describing the reasons why discharge uncertainty estimates are (not) provided; calculated discharge uncertainties; no stage–discharge measurements available; fewer than 20 stage–discharge measurements available for most recent rating; discharge uncertainty estimates not provided as the estimated uncertainty bounds were deemed to not accurately reflect the discharge uncertainty or because there was no sensible relationship between stage and discharge.	–	

Table 2. Continued.

Attribute class	Attribute name	Description	Unit	Data source
Human influence attributes	benchmark_catch	benchmark catchment (Y indicates the catchment is part of the UK Benchmark Network, while N indicates that it is not)	Y/N	UK National River Flow Archive; Harrigan et al. (2018)
	surfacewater_abs	mean surface water abstraction	mm d ⁻¹	Abstractions and discharges sourced from the Environment Agency
	groundwater_abs	mean groundwater abstraction	mm d ⁻¹	
	discharges	mean discharges (daily discharges into water courses from water companies and other discharge permit holders reported to the Environment Agency)	mm d ⁻¹	
	abs_agriculture_perc	percentage of total (groundwater and surface water) abstractions in catchment for agriculture	%	
	abs_amenities_perc	percentage of total (groundwater and surface water) abstractions in catchment for amenities	%	
	abs_energy_perc	percentage of total (groundwater and surface water) abstractions in catchment for energy production	%	
	abs_environmental_perc	percentage of total (groundwater and surface water) abstractions in catchment for environmental purposes	%	
	abs_industry_perc	percentage of total (groundwater and surface water) abstractions in catchment for industrial, commercial and public services	%	
	abs_watersupply_perc	percentage of total (groundwater and surface water) abstractions in catchment for water supply	%	
	num_reservoir	number of reservoirs in the catchment	–	UK Reservoir Inventory (Durant and Counsell, 2018) and SEPA's publicly available controlled reservoirs register (http://map.sepa.org.uk/reservoirsfloodmap/Map.htm , last access: 11 December 2019)
	reservoir_cap	total storage capacity of reservoirs in the catchment in megalitres	ML	
	reservoir_he	percentage of total reservoir storage in catchment used for hydroelectricity	%	
	reservoir_nav	percentage of total reservoir storage in catchment used for navigation	%	
	reservoir_drain	percentage of total reservoir storage in catchment used for drainage	%	
	reservoir_wr	percentage of total reservoir storage in catchment used for water resources	%	
	reservoir_fs	percentage of total reservoir storage in catchment used for flood storage	%	
	reservoir_env	percentage of total reservoir storage in catchment used for environmental	%	
	reservoir_nousedata	percentage of total reservoir storage in catchment where no use data were available	%	
	reservoir_year_first	year the first reservoir in the catchment was built	–	
	reservoir_year_last	year the last reservoir in the catchment was built	–	

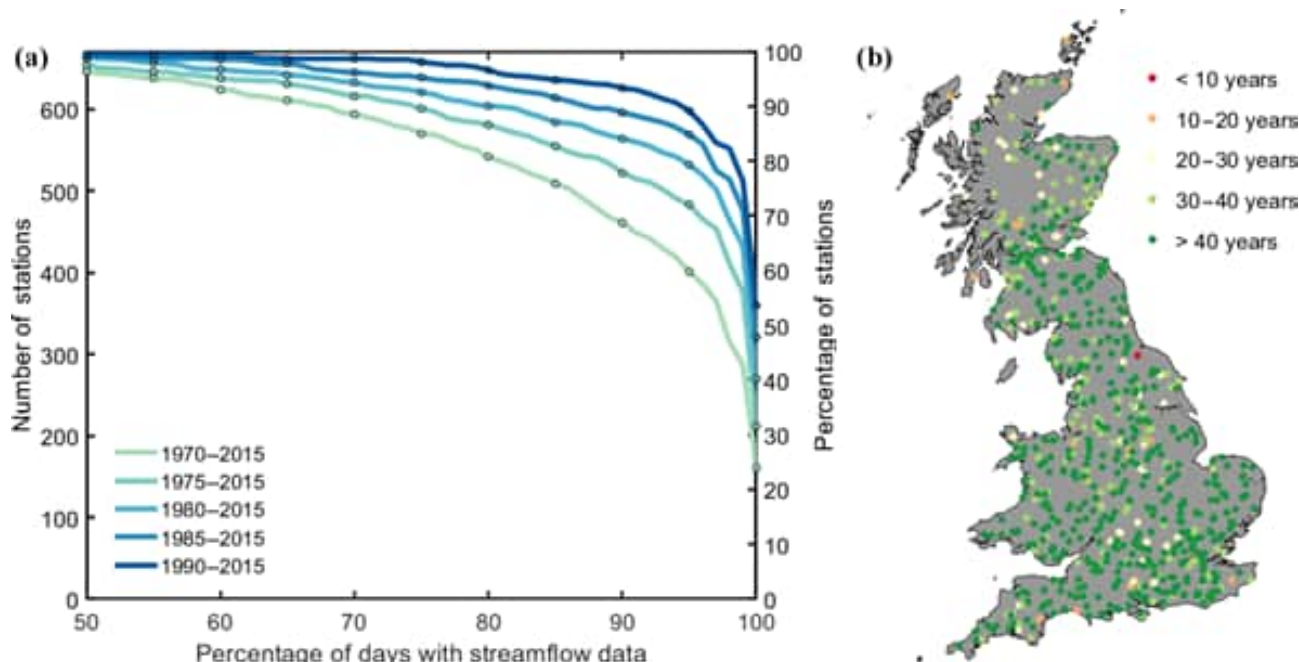


Figure 1. (a) Number of stations with percentage of available streamflow data for different periods. (b) Length of the flow time series for each gauge.

6.4 Land cover attributes

Land cover attributes for each catchment were derived from the UK Land Cover Map 2015 (LCM2015) produced by CEH (Rowland et al., 2017). While other land cover maps are available from CEH for 1990, 2000, and 2007, attributes are only provided for LCM2015 as different methods have been used to derive each of the land cover maps, preventing straightforward analysis of changes in land cover over time. LCM2015 was chosen as it contains the most up-to-date data and methodology used to derive the land cover. LCM2015 uses a random forest classification of Landsat-8 satellite images based on the Joint Nature Conservation Committee (JNCC) broad habitats, encompassing the range of UK habitats.

In this study, the 1 km percentage target class is used from the LCM2015 products, consisting of a 1 km raster with 21 bands relating to the percentage cover value of different target classes that represent broad habitats. This is a significant number of land cover classes, and so the 21 target classes were mapped to eight land cover classes: deciduous woodland, evergreen woodland, grass and pasture, shrubs, crops, suburban and urban, inland water, bare soil, and rocks (see Appendix B). These are the same as the eight land cover classes used when running the JULES model with the CHES meteorological driving data and so provide consistency with other national-scale efforts across Great Britain (Best et al., 2011; Blyth et al., 2019; Clark et al., 2011). For each catchment, the percentage of the catchment covered by each of the eight land cover types was calculated and is pro-

vided in CAMELS-GB, alongside the most dominant land cover type (see Table 2).

Key limitations of this dataset are that the land cover attributes reflect a snapshot of the land cover in time and are subject to uncertainties in the Landsat-8 satellite images and the random forest classification. It is important to note that the land cover attributes provided in CAMELS-GB are different to those provided on the NRFA website which use LCM2000 and different land use groupings.

6.5 Soil attributes

Soil attributes for each catchment were derived from the European Soil Database Derived Data product (Hiederer, 2013a, b), and the modelled depth-to-bedrock global product from Pelletier et al. (2016). The European Soil Database (ESDB; European Commission Joint Research Centre, 2003) is the most detailed and comprehensive soil dataset available for Europe. It was selected for CAMELS-GB as no national soil datasets exist for GB that are both freely available and cover the same comprehensive range of soil descriptors.

As this dataset only characterises the top soil layers (up to 1.3 m), we also used the Pelletier et al. (2016) modelled soil depth dataset to give an indication of the depth to unweathered bedrock extending up to 50 m depth. Soil attributes for depth available to roots, percentage sand, silt and clay content, organic carbon content, bulk density, and total available water content were calculated from the ESDB. We additionally estimated the saturated hydraulic conductivity and porosity (saturated volumetric water content) using

two pedo-transfer functions, with the aim of providing one estimate consistent with CAMELS and a best estimate for European soil types. These were (1) the widely applied regressions based on sand and clay fractions first proposed by Cosby et al. (1984) based on soil samples across the United States and (2) the HYPRES continuous pedo-transfer functions using silt and clay fractions, bulk density, and organic matter content developed using a large database of European soils (Wösten et al., 1999, 2001; Wösten, 2000) (see Appendix C for equations).

To estimate average values of all soil properties with depth, we calculated a weighted mean of the topsoil and subsoil data for each 1 km grid cell. Weights were assigned based on the topsoil–subsoil proportion of the overall soil depth for that cell. Catchment-average soil properties were calculated by taking the arithmetic mean (or harmonic mean for saturated hydraulic conductivity as advised in Samaniego et al., 2010) of all 1 km grid cells that fell within the catchment boundaries. To give an indication of the distribution of soil properties across the catchment, the 5th, 50th, and 95th percentile values of all grid cell values falling within the catchment boundaries were also calculated for all soil attributes apart from percentage sand, silt, and clay. There were some grid cells where no soil data were available. Rather than set default values for these grid cells, we chose to exclude them from the calculations of catchment-average properties and provide the percentage of no-data cells within a catchment as an indication of the data availability of the catchment-average properties.

There are some key limitations associated with these datasets. Firstly, the soil information given on a 1 km grid is only representative of the dominant soil typological class within that area. This means that much of the soil information is not represented in the soil maps, and the variation in soil properties within the 1 km grid is lost. The high spatial heterogeneity of soil data means that correlations between soil property values given in the soil product and ground soil measurements are likely to be low (Hiederer, 2013a, b). Secondly, as can be seen from Fig. S12c–d, there are large uncertainties relating to the choice of pedo-transfer function. Care should be taken when interpreting results for saturated hydraulic conductivity, as the HYPRES equation is relatively inaccurate with a low R^2 value of 0.19, and application of a single continuous pedo-transfer function may result in poor results for some soil types (Wösten et al., 2001). Finally, it is important to be aware that measured soil data were unavailable for some urban areas including London, and these areas had been gap-filled (Hiederer, 2013a, b).

6.6 Hydrogeological attributes

Hydrogeological attributes for each catchment were derived from the UK bedrock hydrogeological map (BGS, 2019) and a new superficial deposit productivity map, both developed by the British Geological Survey. The UK bedrock hydrogeological

map is an open-access dataset that provides detailed information (at 1 : 625 000 scale) on the aquifer potential based on an attribution of lithology with seven classes of primary and secondary permeability and productivity (see Appendix D). The superficial deposit productivity map is a new dataset of similarly attributed superficial deposit aquifer potential across Great Britain (at 1 : 625 000 scale). These two datasets were chosen as they are the only two spatially continuous, consistently attributed hydrogeological maps of the bedrock and superficial deposits at the national scale for GB.

These two datasets were combined by superimposing the superficial deposit layer on top of the bedrock layer to provide catchment attributes for CAMELS-GB that characterise the uppermost geological layer (i.e. superficial deposits where present and bedrock where superficial deposits are absent). Combining the two datasets gave a total of nine hydrogeological productivity classes (see Appendix D). For each catchment, the percentage of the nine hydrogeological classes was calculated and is provided in CAMELS-GB (see Table 2). These nine classes indicate the influence of hydrogeology on river flow behaviour and describe the proportion of the catchment covered by deposits of high, moderate, or low productivity and whether this is predominantly via fracture or intergranular flow (see Table 2). Such classifications have previously been used to enable correlations between catchment hydrogeology and measures of base flow (Bloomfield et al., 2009).

Users should be aware that the aquifer productivity dataset is heuristic, based on hydrogeological inference that is based on mapped lithologies rather than on statistical analysis of borehole yields. It can be used for comparison between catchments at the regional to national scales. It should not be used at the sub-catchment scale where more refined hydrogeological information would be required to understand groundwater–surface water interactions. The hydrogeological attributes provided in CAMELS-GB will differ to those available on the NRFA website as CAMELS-GB uses the latest geological data.

6.7 Hydrometry and discharge uncertainty

Several attributes are provided in CAMELS-GB describing the gauging station type (i.e. the type of weir, structure, or measurement device used to measure flows) as listed on the NRFA, period of flow data available, gauging station discharge uncertainty, and channel characteristics such as bankfull (see Table 2). The catchment attributes for discharge uncertainty are described in more detail below.

Discharge uncertainty estimates

Discharge uncertainty estimates for CAMELS-GB were calculated from a large dataset of rating curves and stage–discharge measurements using a generalised framework designed to estimate place-specific discharge uncertainties out-

lined in Coxon et al. (2015). This framework estimates discharge uncertainties using a nonparametric locally weighted regression (LOWESS). Subsets of the stage–discharge data contained within a moving window are used to calculate the mean and variance at every stage point, which then define the LOWESS-fitted rating curve and discharge uncertainty, respectively. Stage and discharge gauging uncertainties are incorporated into the framework by randomly sampling from estimated measurement error distributions to fit multiple LOWESS curves and then combining the multiple fitted LOWESS curves and variances in a Gaussian mixture model. Time-varying discharge uncertainties are accounted for by an automatic procedure where differences in historical rating curves are used to separate the stage–discharge rating data into subsets for which discharge uncertainty is estimated separately. The framework has been shown to provide robust discharge uncertainty estimates for 500 gauging stations across England and Wales (see Coxon et al., 2015, for more details).

For CAMELS-GB we extended the application of the framework to Scottish gauging stations to provide discharge uncertainty estimates across Great Britain. Discharge uncertainty estimates for CAMELS-GB catchments are provided for several flow percentiles (Q95, Q75, Q50, Q25, Q5, and Q1 derived from the flow time series provided in CAMELS-GB described in Sect. 5.2) for the most recent rating curve to allow users to evaluate discharge uncertainty across the flow range. The upper and lower bounds of the discharge uncertainty prediction interval are provided as a percentage of the flow percentile for each catchment and flow percentile where available. In total, discharge uncertainty estimates are available for 503 (75 %) CAMELS-GB gauges. As the method is data based, the rating curve and its uncertainty interval cannot be computed for gauging stations where there are fewer than 20 stage–discharge measurements or for flows above (below) the highest (lowest) stage–discharge measurement. This means that for some (or all) flow percentiles (particularly Q95 and Q1) there may be no discharge uncertainty estimate as indicated by “NaN”. There are 45 stations where stage–discharge data were available, but discharge uncertainty estimates are not provided as the resulting uncertainty bounds were deemed to not accurately reflect the discharge uncertainty at that gauging station or because there was no sensible relationship between stage and discharge.

Users are advised that the CAMELS-GB discharge uncertainty estimates (1) are dependent on the types of error included in and underlying assumptions of the discharge uncertainty estimation method (see Kiang et al., 2018, for a comparison of seven discharge uncertainty estimation methods) and (2) may not be applicable to the whole flow time series (as they cover the most recent rating curve) or for stations where flow is measured directly (i.e. at ultrasonic or electromagnetic stations).

6.8 Human influences

Providing information on the impact of humans in each catchment is a vital part of CAMELS-GB. To account for the degree of human intervention in each catchment, we compiled data on reservoirs, abstraction, and discharge returns provided by national agencies. We focused on providing quantitative data of human impacts in CAMELS-GB; however it is important to note that additional datasets are available that qualitatively characterise human impacts in GB including the Factors Affecting Runoff (FAR) codes available from the NRFA.

6.8.1 Benchmark catchments

Catchments are identified as being either part or not part of the UK Benchmark Network in CAMELS-GB. The UK Benchmark Network consists of 146 gauging stations that have been identified by the NRFA as suitable for the identification and interpretation of long-term hydrological variability and change against several criteria including length of record, quality of flow data, known impacts within the catchment, and expert consultation (for a full description see Harrigan et al., 2018). Consequently, these gauging stations can be treated as relatively “near-natural” and indicate that the influence of humans on the flow regimes of these catchments is modest. It is important to note that some impacts were tolerated where they were deemed to have a modest overall influence on flows and known to be stable over time. This was to ensure coverage in regions such as the heavily impacted south and east of GB.

6.8.2 Abstraction and discharges

The abstraction data consist of monthly abstraction data from January 1999 to December 2014 that are reported by abstraction licence holders to the Environment Agency. These data are the actual abstraction returns and represent the total volume of water removed by the licence holder for each month over the time period. A mean daily abstraction rate for all English catchments is provided in CAMELS-GB for groundwater and surface water sources. The monthly returns for each abstraction licence in the database were averaged to provide a mean monthly abstraction from 1999 to 2014. All abstraction licences that fell within each catchment boundary (using the catchment masks outlined in Sect. 4) were then summed for surface water and groundwater abstractions and converted into millimetres per day using catchment area. The mean daily abstraction rate is provided alongside attributes describing the use of the abstracted water (agriculture, amenities, environmental, industrial, energy, or water supply). The discharge data consist of daily discharges into water courses from water companies and other discharge permit holders reported to the Environment Agency from 1 January 2005 to 31 December 2015. To calculate a mean daily discharge rate for each catchment, the daily discharge data

for each discharge record were averaged, and then all discharge records that fell within the catchment boundary were summed and then converted into millimetres per day using catchment area.

There are several important caveats associated with these data. Firstly, these data are only available for England. Consequently, there are many catchments where no data are available (identified by “NaN”), and only a proportion of the abstractions may have been accounted for catchments which lie on the border of England–Wales or England–Scotland. Furthermore, not all licence types/holders are required to submit records to the Environment Agency; therefore this is not the full picture of human intervention within each catchment. Secondly, the abstraction and discharge data cover different time periods. Thirdly, the topographical catchment mask was used to define which abstraction returns were included in each catchment. Groundwater abstractions that lie within the topographical catchment may not have a direct impact on the catchment streamflow and instead may impact a neighbouring catchment that shares the same aquifer. Conversely, groundwater abstractions that lie outside the catchment could have an impact on the catchment streamflow. Fourthly, there is large inter-annual and intra-annual variation in the abstraction and discharge data, and its impacts will be different across the flow regime. Consequently, it is important that the mean abstraction totals are used as a guide to the degree of human intervention in each catchment rather than absolute totals of the abstraction for any given month. Finally, although “abstractions” represent removed water from surface water or groundwater sources, some of this water will be returned to catchment storages. The discharge data provided account just for treated water from sewage treatment works and do not provide information on other water returns that may be fed back into catchment storages. The mean totals for abstractions and discharges are a very broad guide that point to the possible influence of abstractions but do not quantify the net influence of these impacts on the actual flow regime. Other (less widely available) metrics have been applied in the UK which use modelling approaches to assess the net impact of abstractions/discharges across the whole flow regime (for example the LowFlows Enterprise methodology; see also Hannaford et al., 2013).

6.8.3 Reservoirs

Reservoir attributes are derived from an open-source UK reservoir inventory (Durant and Counsell, 2018) supplemented with information from SEPA’s publicly available controlled reservoirs register. The UK reservoir inventory includes reservoirs above 1600 megalitre (ML) capacity, covering approximately 90 % of the total reservoir storage in the UK. This dataset was collected from the Environment Agency through a freedom of information request, the UK Lakes Portal (CEH), and subsequent internet searches. It includes information on the location of the reservoir, its ca-

capacity, use, and the year the reservoir was built. To check the accuracy of this dataset, we cross-referenced the reservoirs in the UK reservoir inventory with reservoirs in the Global Reservoir and Dam (GRanD v1.3) database (Lehner et al., 2011). While many of the reservoirs and their capacity data were consistent for reservoirs for England and Wales, many Scottish reservoirs contained in the GRanD database were not present in the UK reservoir inventory or reported very different storage capacities. This is likely due to the estimation of storage capacities of Scottish reservoirs in the UK reservoir inventories (see Hughes et al., 2004) rather than actual storage capacities. Consequently, for reservoirs in Scotland, we used information from SEPA’s publicly available controlled reservoir register (<http://map.sepa.org.uk/reservoirsfloodmap/Map.htm>, last access: 11 December 2019) including the reservoir name, location, and storage capacity. Then we supplemented this information with the year the reservoir was built and reservoir use by cross-referencing data from the UK reservoir inventory (users should be aware that reservoir use and the year the reservoir was built were not available for every reservoir).

For CAMELS-GB several reservoir attributes are derived for each catchment by determining the reservoirs that lie within the catchment mask from the reservoir locations and then calculating (1) the number of reservoirs in each catchment; (2) their combined capacity, (3) the fraction of that capacity that is used for hydroelectricity, navigation, drainage, water supply, flood storage, and environmental purposes; and (4) the year when the first and last reservoirs in the catchment were built.

6.9 Regional variability in catchment characteristics

Figure 2 highlights some of the key catchment variables, and in this section we discuss their regional variability (according to the regions in Fig. 2a). Spatial maps of all catchment attributes can be found in Figs. S4–S11.

There are distinct regional differences in climate across GB (Fig. 2b). Precipitation is typically higher in the west and north of GB corresponding with the areas of high elevation and prevailing winds from the west that bring significant rainfall. The wettest areas of the UK are in mountainous regions with a maximum of 9.6 mm d^{-1} (annual average of 3500 mm yr^{-1}) in the north-west. Snow fractions are generally very low across Great Britain (median snow fraction of 0.01) except for catchments in the Cairngorm mountains in north-east Scotland where the fraction of precipitation falling as snow can reach 0.17 (see Fig. S5e). Precipitation is lowest in the south and east of GB with a minimum of 1.5 mm d^{-1} in the east. In contrast, potential evapotranspiration (PET) is much less variable across GB, with mean daily totals ranging from 1 to 1.5 mm d^{-1} . PET is highest in the south (where temperatures are highest) and lowest in the north. Mean flow varies from 10 to 0.09 mm d^{-1} and is typically higher in the north and west, reflecting the regional

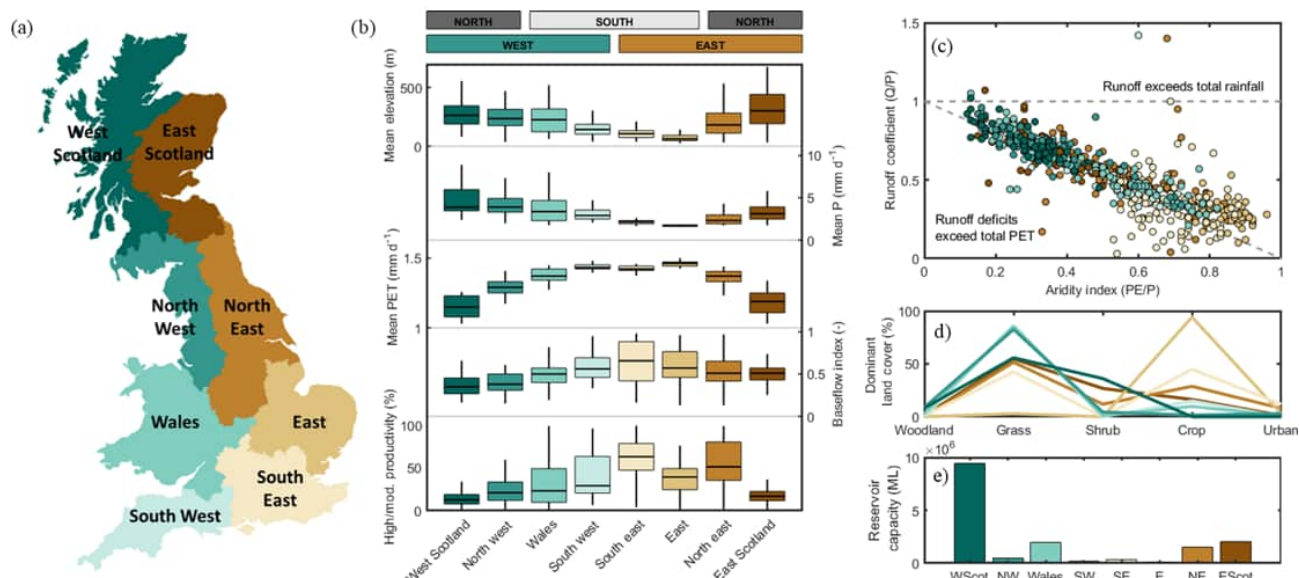


Figure 2. Key catchment variables. **(a)** Map of Great Britain river basin regions based on the UKCP09 river basins aggregated from 21 river basin districts to eight regions. **(b)** Box plots showing the range of key climatic, hydrology, and hydrogeologic (defined by the proportion of the catchment underlain by high or moderate productivity aquifers) catchment attributes for each region. **(c)** Budyko-type curve relating runoff coefficient to aridity index; points are coloured by region, and the y axis is limited to 1.5, which means two gauges (26006 and 27038) are not shown that have a runoff coefficient of 3. **(d)** The percentage of catchments in each region with a dominant land cover of either woodland (evergreen and deciduous), grass, shrub, crop, or urban. **(e)** The total reservoir capacity in the catchments in each region.

variability in precipitation and PET. This is also reflected in Fig. 2c, where catchments in the north and west of GB tend to be wetter with higher runoff coefficients, and catchments in the south and east are much drier with lower runoff coefficients. Figure 2c also shows that annual precipitation totals exceed annual PET totals; the aridity index is below 1 for all catchments, reflecting the temperate and humid climate of GB. It is important to note that these estimates are dependent on the underlying data. For example, there can be significant variability in the calculation of PET, depending on the methods and assumptions used (e.g. Tanguy et al., 2018), and here we have used a PET estimate where canopy interception is not accounted for. Interception is an important component of the water cycle in GB, which experiences a large amount of low to moderate rainfall intensities (Blyth et al., 2019). Thus using the CHES PETI estimate would instead increase the aridity index above 1 in some locations.

There is also regional variability in base flow index (the ratio of mean daily base flow to daily discharge), which is typically higher in the south and east of GB and lower in the north-west. Some of these differences can be attributed to regional aquifers that have high/moderate productivity which are more prevalent in the south-east, east, and north-east (see Fig. 2b).

From Fig. 2c, it is notable that runoff deficits significantly exceed total potential evapotranspiration for many of the CAMELS-GB catchments in the south-east – this could be due to water loss to regional aquifers, the issue of catch-

ment areas not mapping onto the contributing area, and/or the choice of PET used (see above). There are also seven catchments where the runoff exceeds total rainfall – this could be due to water gains from regional aquifers, catchment areas not mapping onto the contributing area, inter-basin transfers, and/or under-estimation of rainfall. Many of the widely used hydrological models and analysis techniques will not be able to reproduce catchment water balances which are outside the water and energy limitations shown in Fig. 2c, unless the models or analysis techniques are explicitly adapted to consider the sources of uncertainty, potential unmeasured groundwater flow pathways, and/or human influences that we have noted. We encourage users of the data to consider whether the assumptions of their methods are consistent with the uncertainties we have documented.

Land cover and human modifications can also impact river flows. Crops and grassland tend to be the dominant land cover for GB catchments, with crops typically being the dominant land cover for catchments in the east and grassland for catchments in the west (Fig. 2d). There is also a higher percentage of catchments in the east which are dominated by urban land cover. Large reservoir capacity is concentrated in the more mountainous northern and western regions of GB, particularly in western Scotland (Fig. 2e).

7 Data availability

The CAMELS-GB dataset (Coxon et al., 2020) detailed in this paper is freely available via the UK Centre for Ecology & Hydrology Environmental Information Data Centre (<https://doi.org/10.5285/8344e4f3-d2ea-44f5-8afa-86d2987543a9>). The data contain catchment masks, catchment time series, and catchment attributes as described above. A full description of the data format is provided in the supporting documentation available on the Environmental Information Data Centre.

8 Conclusions

This study introduces the first large-sample, open-source catchment dataset for Great Britain, CAMELS-GB (Catchment Attributes and MEteorology for Large-sample Studies), consisting of hydro-meteorological catchment time series, catchment attributes, and catchment boundaries for 671 catchments. A comprehensive set of catchment attributes is quantified describing a range of catchment characteristics including topography, climate, hydrology, land cover, soils, and hydrogeology. Importantly, we also derive attributes describing the level of human influence in each catchment and the first set of national discharge uncertainty estimates that quantify discharge uncertainty across the flow range.

The dataset provides new opportunities to explore how different catchment characteristics control river flow behaviour, develop common frameworks for model evaluation and benchmarking at regional–national scales, and analyse hydrologic variability across the UK. To ensure the reproducibility of the dataset, many of the codes and datasets are made available to users.

While a wealth of data are provided in CAMELS-GB, there are many opportunities to expand the dataset that were outside the scope of this study. Currently there are no plans to regularly update CAMELS-GB; however, future work will concentrate on (1) expanding the dataset to include higher-resolution data (such as hourly rainfall, e.g. Lewis et al., 2018, and flow time series) and datasets for the analysis of trends (such as changes in land cover over time), and (2) refining the characterisation of uncertainties in catchment attributes and forcing (particularly for rainfall data). We are also striving to increase the consistency among the CAMELS datasets (in terms of time series, catchment attributes, naming conventions, and data format; see Addor et al., 2019) and to create a dataset that is globally consistent. We anticipate that this will happen as part of a second phase, which will build upon the current first phase that is focussed on the release of national products, such as CAMELS-GB.

Appendix A: A base flow index

The base flow separation followed the Manual on Low-flow Estimation and Prediction of the World Meteorological Organization (2008). It relies on identifying local minima in daily streamflow series and producing a continuous base flow hydrograph by linear interpolation between the identified local streamflow minima. The base flow separation was performed using the R package *lfstat* (Koffler et al., 2016). The streamflow minima were identified using non-overlapping periods of $N = 5$ (block size) consecutive days and $f = 0.9$ as the turning point parameter value.

Appendix B: Land cover classes

We used the following classification to map the 21 land cover classes contained in the UK Land Cover Map 2015 to the eight land cover classes used in CAMELS-GB.

Table B1. Band ID and name from Land Cover Map (LCM) 2015 and corresponding land cover classes used in CAMELS-GB.

Band	LCM2015 band name	CAMELS-GB land cover classes
1	Broadleaved woodland	Deciduous woodland
2	Coniferous woodland	Evergreen woodland
3	Arable and horticulture	Crops
4	Improved grassland	Grass and pasture
5	Neutral grassland	Grass and pasture
6	Calcareous grassland	Grass and pasture
7	Acid grassland	Grass and pasture
8	Fen, marsh, and swamp	Grass and pasture
9	Heather	Medium-scale vegetation (shrubs)
10	Heather grassland	Medium-scale vegetation (shrubs)
11	Bog	Medium-scale vegetation (shrubs)
12	Inland Rock	Bare soil and rocks
13	Saltwater	Not classified
14	Freshwater	Inland water
15	Supralittoral rock	Bare soil and rocks
16	Supralittoral sediment	Bare soil and rocks
17	Littoral rock	Not classified
18	Littoral sediment	Not classified
19	Salt marsh	Inland water
20	Urban	Urban and suburban
21	Suburban	Urban and suburban

Appendix C: Soil pedo-transfer functions

We estimated the saturated hydraulic conductivity and porosity (also referred to as maximum water content, saturated water content, satiated water content) using two pedo-transfer functions.

The first was the widely applied regressions based on sand and clay fractions first proposed by Cosby et al. (1984):

$$K_s = 2.54 \times 10^{-0.6+0.012Sa-0.0064Cl}$$

$$\theta_s = 50.5 - 0.142Sa - 0.037Cl,$$

where K_s is saturated hydraulic conductivity in centimetres per hour and θ_s is porosity in percent ($\text{m}^3 \text{m}^{-3}$). Predictor variables are sand (Sa) and clay (Cl).

The second was the HYPRES continuous pedo-transfer functions using silt and clay fractions, bulk density, and organic matter content (Wösten et al., 1999; Wösten, 2000).

$$K_s = 0.04167 e^{(7.755+0.0352Si+0.93Tp-0.967Db^2-0.000484Cl^2-0.000322Si^2+0.001Si^{-1}-0.0748Om^{-1}-0.643\ln(Si)-0.01398DbCl-0.1673DbOm+0.02986TpCl-0.03305TpSi)}$$

$$\theta_s = 0.7919 + 0.001691Cl - 0.29619Db - 0.000001491Si^2 + 0.0000821Om^2 + 0.02427Cl^{-1} + 0.01113Si^{-1} + 0.01472\ln(Si) - 0.0000733OmCl - 0.000619DbCl - 0.001183DbOm - 0.0001664TpSi$$

Here K_s is saturated hydraulic conductivity in centimetre per hour and θ_s is porosity ($\text{m}^3 \text{m}^{-3}$). Predictor variables are sand (Sa) and clay (Cl). Predictor variables are percentage silt (Si), percentage clay (Cl), percentage organic matter (Om), bulk density (Db), and a binary variable for topsoil (Tp).

Appendix D: Hydrogeological classes

For CAMELS-GB, we combined the BGS hydrogeology map and superficial deposit layer. The table below provides a summary of the different classes in each dataset and how these were amalgamated to form the nine classes used in CAMELS-GB.

Table D1. Data source, class, and description of the hydrogeological datasets.

Data source	Original data		CAMELS-GB	
	Class ID	Description	Class ID	Description
British Geological Survey Hydrogeology Map (BGS, 2019)	1	Aquifers with significant intergranular flow – highly productive	1	Significant intergranular flow – high productivity
	2	Aquifers with significant intergranular flow – moderately productive	2	Significant intergranular flow – moderate productivity
	3	Aquifers with significant intergranular flow – low productivity	3	Significant intergranular flow – low productivity
	4	Aquifers in which flow is virtually all through fractures – highly productive	4	Flow through fractures – high productivity
	5	Aquifers in which flow is virtually all through fractures – moderately productive	5	Flow through fractures – moderate productivity
	6	Aquifers in which flow is virtually all through fractures – low productivity	6	Flow through fractures – low productivity
	7	Rocks with essentially no groundwater	7	Rocks with essentially no groundwater
British Geological Survey superficial deposit layer	8	Moderate productivity	2	Significant intergranular flow – moderate productivity
	9	Low productivity	3	Significant intergranular flow – low productivity
	10	Generally low productivity but some not a significant aquifer	8	Generally low productivity (intergranular flow) but some not a significant aquifer
	11	Generally not a significant aquifer but some low productivity	9	Generally not a significant aquifer but some low productivity (intergranular flow)
	12	Not a significant aquifer	7	Rocks with essentially no groundwater

Supplement. The supplement related to this article is available online at: <https://doi.org/10.5194/essd-12-2459-2020-supplement>.

Author contributions. GC initiated and led the project. GC produced the CAMELS-GB dataset with the following contributions. (1) NA derived the climatic indices and hydrologic signatures, (2) RL derived the soil attributes, (3) ML derived the superficial deposit geological layer and provided guidance with JPB on deriving the hydrogeological attributes, (4) ELR provided guidance on the meteorological datasets (CHESS-met and CHESS-PE) and mapping the land cover data, and (5) MF provided the streamflow data, catchment masks, and all catchment attributes sourced from the National River Flow Archive. All co-authors contributed to the design of the dataset. The manuscript was prepared by GC with contributions from all co-authors.

Competing interests. The authors declare that they have no conflict of interest.

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References

- Addor, N., Newman, A. J., Mizukami, N., and Clark, M. P.: The CAMELS data set: catchment attributes and meteorology for large-sample studies, *Hydrol. Earth Syst. Sci.*, 21, 5293–5313, <https://doi.org/10.5194/hess-21-5293-2017>, 2017.
- Addor, N., Nearing, G., Prieto, C., Newman, A. J., Le Vine, N., and Clark, M. P.: A Ranking of Hydrological Signatures Based on Their Predictability in Space, *Water Resour. Res.*, 54, 8792–8812, <https://doi.org/10.1029/2018WR022606>, 2018.
- Addor, N., Do, H. X., Alvarez-Garretón, C., Coxon, G., Fowler, K., and Mendoza, P. A.: Large-sample hydrology: recent progress, guidelines for new datasets and grand challenges, *Hydrol. Sci. J.*, 0, 1–14, <https://doi.org/10.1080/02626667.2019.1683182>, 2019.
- Allen, R. G., Pereira, L. S., Raes, D., and Smith, M.: Crop evapotranspiration – Guidelines for computing crop water requirements, Food and Agriculture Organization of the United Nations, Rome, available at: <http://www.fao.org/3/X0490E/X0490E00.htm> (last access: 7 October 2019), 1998.
- Alvarez-Garretón, C., Mendoza, P. A., Boisier, J. P., Addor, N., Galleguillos, M., Zambrano-Bigiarini, M., Lara, A., Puelma, C., Cortes, G., Garreaud, R., McPhee, J., and Ayala, A.: The CAMELS-CL dataset: catchment attributes and meteorology for large sample studies – Chile dataset, *Hydrol. Earth Syst. Sci.*, 22, 5817–5846, <https://doi.org/10.5194/hess-22-5817-2018>, 2018.
- Ames, D. P., Horsburgh, J. S., Cao, Y., Kadlec, J., Whiteaker, T., and Valentine, D.: HydroDesktop: Web services-based software for hydrologic data discovery, download, visualization, and analysis, *Environ. Model. Softw.*, 37, 146–156, <https://doi.org/10.1016/j.envsoft.2012.03.013>, 2012.
- Arsenault, R., Bazile, R., Dallaire, C. O., and Brissette, F.: CANOPEX: A Canadian hydrometeorological watershed database, *Hydrol. Process.*, 30, 2734–2736, <https://doi.org/10.1002/hyp.10880>, 2016.
- Bayliss, A.: Flood estimation handbook: Catchment descriptors, Institute of Hydrology, 1999.
- Berghuijs, W. R., Aalbers, E. E., Larsen, J. R., Trancoso, R., and Woods, R. A.: Recent changes in extreme floods across multiple continents, *Environ. Res. Lett.*, 12, 114035, <https://doi.org/10.1088/1748-9326/aa8847>, 2017.
- Best, M. J., Pryor, M., Clark, D. B., Rooney, G. G., Essery, R. L. H., Ménard, C. B., Edwards, J. M., Hendry, M. A., Porson, A., Gedney, N., Mercado, L. M., Sitch, S., Blyth, E., Boucher, O., Cox, P. M., Grimmond, C. S. B., and Harding, R. J.: The Joint UK Land Environment Simulator (JULES), model description – Part 1: Energy and water fluxes, *Geosci. Model Dev.*, 4, 677–699, <https://doi.org/10.5194/gmd-4-677-2011>, 2011.
- Beven, K.: A sensitivity analysis of the Penman-Monteith actual evapotranspiration estimates, *J. Hydrol.*, 44, 169–190, [https://doi.org/10.1016/0022-1694\(79\)90130-6](https://doi.org/10.1016/0022-1694(79)90130-6), 1979.

- BGS: BGS hydrogeology 625k, available at: <https://www.bgs.ac.uk/products/hydrogeology/maps.html>, last access: 8 October 2019.
- Bloomfield, J. P., Allen, D. J., and Griffiths, K. J.: Examining geological controls on baseflow index (BFI) using regression analysis: An illustration from the Thames Basin, UK, *J. Hydrol.*, 373, 164–176, <https://doi.org/10.1016/j.jhydrol.2009.04.025>, 2009.
- Blöschl, G., Hall, J., Parajka, J., Perdigão, R. A. P., Merz, B., Arheimer, B., Aronica, G. T., Bilbashi, A., Bonacci, O., Borga, M., Čanjevac, I., Castellarin, A., Chirico, G. B., Claps, P., Fiala, K., Frolova, N., Gorbachova, L., Gül, A., Hannaford, J., Harrigan, S., Kireeva, M., Kiss, A., Kjeldsen, T. R., Kohnová, S., Koskela, J. J., Ledvinka, O., Macdonald, N., Mavrova-Guirguinova, M., Mediero, L., Merz, R., Molnar, P., Montanari, A., Murphy, C., Osuch, M., Ovcharuk, V., Radevski, I., Rogger, M., Salinas, J. L., Sauquet, E., Šraj, M., Szolgay, J., Viglione, A., Volpi, E., Wilson, D., Zaimi, K., and Živković, N.: Changing climate shifts timing of European floods, *Science*, 357, 588–590, <https://doi.org/10.1126/science.aan2506>, 2017.
- Blyth, E. M., Martínez-de la Torre, A., and Robinson, E. L.: Trends in evapotranspiration and its drivers in Great Britain: 1961 to 2015, *Prog. Phys. Geogr. Earth Environ.*, 43, 666–693, <https://doi.org/10.1177/0309133319841891>, 2019.
- Brantley, S. L., McDowell, W. H., Dietrich, W. E., White, T. S., Kumar, P., Anderson, S. P., Chorover, J., Lohse, K. A., Bales, R. C., Richter, D. D., Grant, G., and Gaillardet, J.: Designing a network of critical zone observatories to explore the living skin of the terrestrial Earth, *Earth Surf. Dynam.*, 5, 841–860, <https://doi.org/10.5194/esurf-5-841-2017>, 2017.
- Buytaert, W., Reusser, D., Krause, S., and Renaud, J.-P.: Why can't we do better than Topmodel?, *Hydrol. Process.*, 22, 4175–4179, <https://doi.org/10.1002/hyp.7125>, 2008.
- Ceola, S., Arheimer, B., Baratti, E., Blöschl, G., Capell, R., Castellarin, A., Freer, J., Han, D., Hrachowitz, M., Hundecha, Y., Hutton, C., Lindström, G., Montanari, A., Nijzink, R., Parajka, J., Toth, E., Viglione, A., and Wagener, T.: Virtual laboratories: new opportunities for collaborative water science, *Hydrol. Earth Syst. Sci.*, 19, 2101–2117, <https://doi.org/10.5194/hess-19-2101-2015>, 2015.
- Clark, D. B., Mercado, L. M., Sitch, S., Jones, C. D., Gedney, N., Best, M. J., Pryor, M., Rooney, G. G., Essery, R. L. H., Blyth, E., Boucher, O., Harding, R. J., Huntingford, C., and Cox, P. M.: The Joint UK Land Environment Simulator (JULES), model description – Part 2: Carbon fluxes and vegetation dynamics, *Geosci. Model Dev.*, 4, 701–722, <https://doi.org/10.5194/gmd-4-701-2011>, 2011.
- Clausen, B. and Biggs, B. J. F.: Flow variables for ecological studies in temperate streams: groupings based on covariance, *J. Hydrol.*, 237, 184–197, [https://doi.org/10.1016/S0022-1694\(00\)00306-1](https://doi.org/10.1016/S0022-1694(00)00306-1), 2000.
- Coron, L., Andréassian, V., Perrin, C., Lerat, J., Vaze, J., Bourqui, M., and Hendrickx, F.: Crash testing hydrological models in contrasted climate conditions: An experiment on 216 Australian catchments, *Water Resour. Res.*, 48, W05552, <https://doi.org/10.1029/2011WR011721>, 2012.
- Cosby, B. J., Hornberger, G. M., Clapp, R. B., and Ginn, T. R.: A Statistical Exploration of the Relationships of Soil Moisture Characteristics to the Physical Properties of Soils, *Water Resour. Res.*, 20, 682–690, <https://doi.org/10.1029/WR020i006p00682>, 1984.
- Coxon, G., Freer, J., Wagener, T., Odoni, N. A., and Clark, M.: Diagnostic evaluation of multiple hypotheses of hydrological behaviour in a limits-of-acceptability framework for 24 UK catchments, *Hydrol. Process.*, 28, 6135–6150, <https://doi.org/10.1002/hyp.10096>, 2014.
- Coxon, G., Freer, J., Westerberg, I. K., Wagener, T., Woods, R., and Smith, P. J.: A novel framework for discharge uncertainty quantification applied to 500 UK gauging stations, *Water Resour. Res.*, 51, 5531–5546, <https://doi.org/10.1002/2014WR016532>, 2015.
- Coxon, G., Freer, J., Lane, R., Dunne, T., Knoben, W. J. M., Howden, N. J. K., Quinn, N., Wagener, T., and Woods, R.: DECIPHeR v1: Dynamic fluxES and Connectivity for Predictions of HydRology, *Geosci. Model Dev.*, 12, 2285–2306, <https://doi.org/10.5194/gmd-12-2285-2019>, 2019.
- Coxon, G., Addor, N., Bloomfield, J. P., Freer, J. E., Fry, M., Hannaford, J., Howden, N. J. K., Lane, R., Lewis, M., Robinson, E. L., Wagener, T., and Woods, R.: Catchment attributes and hydro-meteorological timeseries for 671 catchments across Great Britain (CAMELS-GB), NERC Environ. Inf. Data Cent., <https://doi.org/10.5285/8344e4f3-d2ea-44f5-8afa-86d2987543a9>, 2020.
- Dixon, H., Hannaford, J., and Fry, M. J.: The effective management of national hydrometric data: experiences from the United Kingdom, *Hydrol. Sci. J.*, 58, 1383–1399, <https://doi.org/10.1080/02626667.2013.787486>, 2013.
- Do, H. X., Gudmundsson, L., Leonard, M., and Westra, S.: The Global Streamflow Indices and Metadata Archive (GSIM) – Part 1: The production of a daily streamflow archive and metadata, *Earth Syst. Sci. Data*, 10, 765–785, <https://doi.org/10.5194/essd-10-765-2018>, 2018.
- Duan, Q., Schaake, J., Andréassian, V., Franks, S., Goteti, G., Gupta, H. V., Gusev, Y. M., Habets, F., Hall, A., Hay, L., Hogue, T., Huang, M., Leavesley, G., Liang, X., Nasonova, O. N., Noilhan, J., Oudin, L., Sorooshian, S., Wagener, T., and Wood, E. F.: Model Parameter Estimation Experiment (MOPEX): An overview of science strategy and major results from the second and third workshops, *J. Hydrol.*, 320, 3–17, <https://doi.org/10.1016/j.jhydrol.2005.07.031>, 2006.
- Durant, M. J. and Counsell, C. J.: Inventory of reservoirs amounting to 90 % of total UK storage, NERC Environ. Inf. Data Cent., <https://doi.org/10.5285/f5a7d56c-cea0-4f00-b159-c3788a3b2b38>, 2018.
- Emmett, B., Gurney, R. J., McDonald, A. T., Blair, G., Buytaert, W., Freer, J., Haygarth, P., Johnes, P. J., Rees, G. H., Tetzlaff, D., Afgan, E., Ball, L. A., Beven, K., Bick, M., Bloomfield, J., Brewer, P., Delle, J., El-khatib, Y., Field, D., Gemmell, A. L., Greene, S., Huntingford, C., Mackay, E., Macklin, M. V., MacLeod, K., Marshall, K. E., Odoni, N., Percy, B. J., Quinn, P. F., Reaney, S., Stutter, M., Surajbali, B., Thomas, N. R., Vitolo, C., Williams, B. L., Wilkinson, M., and Zelazowski, P.: Environmental Virtual Observatory: Final Report, available at: [https://research-information.bris.ac.uk/en/publications/environmental-virtual-observatory\(32e19260-0aae-44fb-a6be-7eecc497aaa\)/export.html](https://research-information.bris.ac.uk/en/publications/environmental-virtual-observatory(32e19260-0aae-44fb-a6be-7eecc497aaa)/export.html) (last access: 12 December 2019), 2014.
- Falkenmark, M. and Chapman, T. G.: Comparative Hydrology: An Ecological Approach to Land and Water Resources, Unesco, 1989.

- Folland, C. K., Hannaford, J., Bloomfield, J. P., Kendon, M., Svensson, C., Marchant, B. P., Prior, J., and Wallace, E.: Multi-annual droughts in the English Lowlands: a review of their characteristics and climate drivers in the winter half-year, *Hydrol. Earth Syst. Sci.*, 19, 2353–2375, <https://doi.org/10.5194/hess-19-2353-2015>, 2015.
- Fowler, K. J. A., Peel, M. C., Western, A. W., Zhang, L., and Peterson, T. J.: Simulating runoff under changing climatic conditions: Revisiting an apparent deficiency of conceptual rainfall-runoff models, *Water Resour. Res.*, 52, 1820–1846, <https://doi.org/10.1002/2015WR018068>, 2016.
- Gnann, S. J., Woods, R. A., and Howden, N. J. K.: Is There a Baseflow Budyko Curve?, *Water Resour. Res.*, 55, 2838–2855, <https://doi.org/10.1029/2018WR024464>, 2019.
- Gudmundsson, L., Do, H. X., Leonard, M., and Westra, S.: The Global Streamflow Indices and Metadata Archive (GSIM) – Part 2: Quality control, time-series indices and homogeneity assessment, *Earth Syst. Sci. Data*, 10, 787–804, <https://doi.org/10.5194/essd-10-787-2018>, 2018.
- Gudmundsson, L., Leonard, M., Do, H. X., Westra, S., and Seneviratne, S. I.: Observed Trends in Global Indicators of Mean and Extreme Streamflow, *Geophys. Res. Lett.*, 46, 756–766, <https://doi.org/10.1029/2018GL079725>, 2019.
- Gupta, H. V., Perrin, C., Blöschl, G., Montanari, A., Kumar, R., Clark, M., and Andréassian, V.: Large-sample hydrology: a need to balance depth with breadth, *Hydrol. Earth Syst. Sci.*, 18, 463–477, <https://doi.org/10.5194/hess-18-463-2014>, 2014.
- Gustard, A., Bullock, A., and Dixon, J. M.: Low flow estimation in the United Kingdom, available at: <http://nora.nerc.ac.uk/id/eprint/6050/> (last access: 12 December 2019), 1992.
- Hannaford, J.: Development of a strategic data management system for a national hydrological database, the uk national river flow archive, in *Hydroinformatics*, 637–644, World Scientific Publishing Company, 2004.
- Hannaford, J. and Buys, G.: Trends in seasonal river flow regimes in the UK, *J. Hydrol.*, 475, 158–174, <https://doi.org/10.1016/j.jhydrol.2012.09.044>, 2012.
- Hannaford, J. and Marsh, T.: An assessment of trends in UK runoff and low flows using a network of undisturbed catchments, *Int. J. Climatol.*, 26, 1237–1253, <https://doi.org/10.1002/joc.1303>, 2006.
- Hannaford, J., Holmes, M. G. R., Laizé, C. L. R., Marsh, T. J., and Young, A. R.: Evaluating hydrometric networks for prediction in ungauged basins: a new methodology and its application to England and Wales, *Hydrol. Res.*, 44, 401–418, doi:10.2166/nh.2012.115, 2013.
- Hannah, D. M., Demuth, S., Lanen, H. A. J. van, Looser, U., Prudhomme, C., Rees, G., Stahl, K., and Tallaksen, L. M.: Large-scale river flow archives: importance, current status and future needs, *Hydrol. Process.*, 25, 1191–1200, <https://doi.org/10.1002/hyp.7794>, 2011.
- Harrigan, S., Hannaford, J., Muchan, K., and Marsh, T. J.: Designation and trend analysis of the updated UK Benchmark Network of river flow stations: the UKBN2 dataset, *Hydrol. Res.*, 49, 552–567, <https://doi.org/10.2166/nh.2017.058>, 2018.
- Hiederer, R.: Mapping Soil Properties for Europe – Spatial Representation of Soil Database Attributes, Luxembourg, 2013a.
- Hiederer, R.: Mapping soil typologies: spatial decision support applied to the European Soil Database., Publications Office, Luxembourg, available at: <http://dx.publications.europa.eu/10.2788/87286> (last access: 20 June 2019), 2013b.
- Hough, M. N. and Jones, R. J. A.: The United Kingdom Meteorological Office rainfall and evaporation calculation system: MORECS version 2.0-an overview, *Hydrol. Earth Syst. Sci.*, 1, 227–239, <https://doi.org/10.5194/hess-1-227-1997>, 1997.
- Hughes, M., Hornby, D. D., Bennion, H., Kernan, M., Hilton, J., Phillips, G., and Thomas, R.: The Development of a GIS-based Inventory of Standing Waters in Great Britain together with a Risk-based Prioritisation Protocol, *Water Air Soil Pollut. Focus*, 4, 73–84, <https://doi.org/10.1023/B:WAF0.0000028346.27904.83>, 2004.
- Hutton, C., Wagener, T., Freer, J., Han, D., Duffy, C., and Arheimer, B.: Most computational hydrology is not reproducible, so is it really science?, *Water Resour. Res.*, 52, 7548–7555, <https://doi.org/10.1002/2016WR019285>, 2016.
- Jenkins, G. J., Perry, M., Prior, J., UKCIP09 and UK Climate Impacts Programme: The climate of the United Kingdom and recent trends, Met Office Hadley Centre, Exeter, available at: http://www.ukcip.org.uk/images/stories/08_pdfs/Trends.pdf (last access: 12 December 2019), 2009.
- Keller, V. D. J., Tanguy, M., Prosdociimi, I., Terry, J. A., Hitt, O., Cole, S. J., Fry, M., Morris, D. G., and Dixon, H.: CEH-GEAR: 1 km resolution daily and monthly areal rainfall estimates for the UK for hydrological and other applications, *Earth Syst. Sci. Data*, 7, 143–155, <https://doi.org/10.5194/essd-7-143-2015>, 2015.
- Kiang, J. E., Gazoorian, C., McMillan, H., Coxon, G., Le Coz, J., Westerberg, I. K., Belleville, A., Sevez, D., Sikorska, A. E., Petersen-Øverleir, A., Reitan, T., Freer, J., Renard, B., Mansanarez, V., and Mason, R.: A Comparison of Methods for Streamflow Uncertainty Estimation, *Water Resour. Res.*, 54, 7149–7176, <https://doi.org/10.1029/2018WR022708>, 2018.
- Koffler, D., Gauster, T., and Laaha, G.: Ifstat: Calculation of Low Flow Statistics for Daily Stream Flow Data version 0.9.8 from R-Forge, available at: <https://rdr.io/rforge/lfstat/> (last access: 7 October 2019), 2016.
- Kollat, J. B., Reed, P. M., and Wagener, T.: When are multiobjective calibration trade-offs in hydrologic models meaningful?, *Water Resour. Res.*, 48, W03520, <https://doi.org/10.1029/2011WR011534>, 2012.
- Kuentz, A., Arheimer, B., Hundecha, Y., and Wagener, T.: Understanding hydrologic variability across Europe through catchment classification, *Hydrol. Earth Syst. Sci.*, 21, 2863–2879, <https://doi.org/10.5194/hess-21-2863-2017>, 2017.
- Ladson, A. R., Brown, R., Neal, B., and Nathan, R.: A Standard Approach to Baseflow Separation Using The Lyne and Hollick Filter, *Australas. J. Water Resour.*, 17, 25–34, <https://doi.org/10.7158/13241583.2013.11465417>, 2013.
- Lane, R. A., Coxon, G., Freer, J. E., Wagener, T., Johnes, P. J., Bloomfield, J. P., Greene, S., Macleod, C. J. A., and Reaney, S. M.: Benchmarking the predictive capability of hydrological models for river flow and flood peak predictions across over 1000 catchments in Great Britain, *Hydrol. Earth Syst. Sci.*, 23, 4011–4032, <https://doi.org/10.5194/hess-23-4011-2019>, 2019.
- Lee, H., McIntyre, N., Wheeler, H., and Young, A.: Selection of conceptual models for regionalisation of the rainfall-runoff relationship, *J. Hydrol.*, 312, 125–147, <https://doi.org/10.1016/j.jhydrol.2005.02.016>, 2005.

- Lehner, B., Liermann, C. R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., Döll, P., Endejan, M., Frenken, K., Magome, J., Nilsson, C., Robertson, J. C., Rödel, R., Sindorf, N., and Wissler, D.: High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management, *Front. Ecol. Environ.*, 9, 494–502, <https://doi.org/10.1890/100125>, 2011.
- Lewis, E., Quinn, N., Blenkinsop, S., Fowler, H. J., Freer, J., Tanguy, M., Hitt, O., Coxon, G., Bates, P., and Woods, R.: A rule based quality control method for hourly rainfall data and a 1 km resolution gridded hourly rainfall dataset for Great Britain: CEH-GEAR1hr, *J. Hydrol.*, 564, 930–943, <https://doi.org/10.1016/j.jhydrol.2018.07.034>, 2018.
- Marsh, T. and Hannaford, J.: UK hydrometric register. A catalogue of river flow gauging stations and observation wells and boreholes in the United Kingdom together with summary hydrometric and spatial statistics, edited by T. Marsh and J. Hannaford, Centre for Ecology & Hydrology, Wallingford, available at: <http://nora.nerc.ac.uk/id/eprint/3093/> (last access: 16 July 2019), 2008.
- Marsh, T., Cole, G., and Wilby, R.: Major droughts in England and Wales, 1800–2006, *Weather*, 62, 87–93, <https://doi.org/10.1002/wea.67>, 2007.
- McDonnell, J. J., Sivapalan, M., Vaché, K., Dunn, S., Grant, G., Haggerty, R., Hinz, C., Hooper, R., Kirchner, J., Roderick, M. L., Selker, J., and Weiler, M.: Moving beyond heterogeneity and process complexity: A new vision for watershed hydrology, *Water Resour. Res.*, 43, W07301, <https://doi.org/10.1029/2006WR005467>, 2007.
- McMillan, H., Montanari, A., Cudennec, C., Savenije, H., Kreibich, H., Krueger, T., Liu, J., Mejia, A., Loon, A. V., Aksoy, H., Baldassarre, G. D., Huang, Y., Mazvimavi, D., Rogger, M., Sivakumar, B., Bibikova, T., Castellarin, A., Chen, Y., Finger, D., Gelfan, A., Hannah, D. M., Hoekstra, A. Y., Li, H., Maskey, S., Mathevet, T., Mijic, A., Acuña, A. P., Polo, M. J., Rosales, V., Smith, P., Viglione, A., Srinivasan, V., Toth, E., van Nooyen, R., and Xia, J.: Panta Rhei 2013–2015: global perspectives on hydrology, society and change, *Hydrol. Sci. J.*, 61, 1174–1191, <https://doi.org/10.1080/02626667.2016.1159308>, 2016.
- Merz, R. and Blöschl, G.: Regionalisation of catchment model parameters, *J. Hydrol.*, 287, 95–123, <https://doi.org/10.1016/j.jhydrol.2003.09.028>, 2004.
- Mizukami, N., Clark, M. P., Newman, A. J., Wood, A. W., Gutmann, E. D., Nijssen, B., Rakovec, O., and Samaniego, L.: Towards seamless large-domain parameter estimation for hydrologic models, *Water Resour. Res.*, 53, 8020–8040, <https://doi.org/10.1002/2017WR020401>, 2017.
- Montanari, A., Young, G., Savenije, H. H. G., Hughes, D., Wagener, T., Ren, L. L., Koutsoyiannis, D., Cudennec, C., Toth, E., Grimaldi, S., Blöschl, G., Sivapalan, M., Beven, K., Gupta, H., Hipsey, M., Schaeffli, B., Arheimer, B., Boegh, E., Schymanski, S. J., Baldassarre, G. D., Yu, B., Hubert, P., Huang, Y., Schumann, A., Post, D. A., Srinivasan, V., Harman, C., Thompson, S., Rogger, M., Viglione, A., McMillan, H., Characklis, G., Pang, Z., and Belyaev, V.: “Panta Rhei – Everything Flows”: Change in hydrology and society – The IAHS Scientific Decade 2013–2022, *Hydrol. Sci. J.*, 58, 1256–1275, <https://doi.org/10.1080/02626667.2013.809088>, 2013.
- Moore, R. V., Morris, D. G., and Flavin, R. W.: CEH digital river network of Great Britain (1:50,000), EIDC, available at: <https://catalogue.ceh.ac.uk/id/7d5e42b6-7729-46c8-99e9-f9e4efddde1d> (last access: 2 November 2019), 2000.
- Morris, D. G. and Flavin, R. W.: A digital terrain model for hydrology, in *Proc 4th International Symposium on Spatial Data Handling*, Vol. 1, 250–262, Zürich, 1990.
- Muchan, K. and Dixon, H.: Ensuring hydrometric data are fit-for-purpose through a national Service Level Agreement, in: *Hydrology in a changing world: environmental and human dimensions*, edited by: Daniell, T. M., pp. 323–329, International Association of Hydrological Sciences, Wallingford, UK, available at: <http://nora.nerc.ac.uk/id/eprint/502971/> (last access: 22 September 2020), 2014.
- Nelson, B.: Data sharing: Empty archives, *Nature*, 461, 160–163, <https://doi.org/10.1038/461160a>, 2009.
- NERC: Flood Studies Report, London, 1975.
- Newman, A. J., Clark, M. P., Sampson, K., Wood, A., Hay, L. E., Bock, A., Viger, R. J., Blodgett, D., Brekke, L., Arnold, J. R., Hopson, T., and Duan, Q.: Development of a large-sample watershed-scale hydrometeorological data set for the contiguous USA: data set characteristics and assessment of regional variability in hydrologic model performance, *Hydrol. Earth Syst. Sci.*, 19, 209–223, <https://doi.org/10.5194/hess-19-209-2015>, 2015.
- Parajka, J., Merz, R., and Blöschl, G.: A comparison of regionalisation methods for catchment model parameters, *Hydrol. Earth Syst. Sci.*, 9, 157–171, <https://doi.org/10.5194/hess-9-157-2005>, 2005.
- Pelletier, J. D., Broxton, P. D., Hazenberg, P., Zeng, X., Troch, P. A., Niu, G., Williams, Z., Brunke, M. A., and Gochis, D.: A gridded global data set of soil, intact regolith, and sedimentary deposit thicknesses for regional and global land surface modeling, *J. Adv. Model. Earth Syst.*, 8, 41–65, <https://doi.org/10.1002/2015MS000526>, 2016a.
- Pelletier, J. D., Broxton, P. D., Hazenberg, P., Zeng, X., Troch, P. A., Niu, G., Williams, Z. C., Brunke, M. A., and Gochis, D.: Global 1-km Gridded Thickness of Soil, Regolith, and Sedimentary Deposit Layers, ORNL DAAC, <https://doi.org/10.3334/ORNLDAAAC/1304>, 2016b.
- Perrin, C., Michel, C., and Andréassian, V.: Improvement of a parsimonious model for streamflow simulation, *J. Hydrol.*, 279, 275–289, [https://doi.org/10.1016/S0022-1694\(03\)00225-7](https://doi.org/10.1016/S0022-1694(03)00225-7), 2003.
- Pool, S., Viviroli, D., and Seibert, J.: Value of a Limited Number of Discharge Observations for Improving Regionalization: A Large-Sample Study Across the United States, *Water Resour. Res.*, 55, 363–377, <https://doi.org/10.1029/2018WR023855>, 2019.
- Robinson, E. L., Blyth, E., Clark, D. B., Comyn-Platt, E., Finch, J., and Rudd, A. C.: Climate hydrology and ecology research support system potential evapotranspiration dataset for Great Britain (1961–2015) [CHESS-PE], NERC Environ. Inf. Data Cent., <https://doi.org/10.5285/8baf805d-39ce-4dac-b224-c926ada353b7>, 2016.
- Robinson, E. L., Blyth, E., Clark, D. B., Comyn-Platt, E., Finch, J., and Rudd, A. C.: Climate hydrology and ecology research support system meteorology dataset for Great Britain (1961–2015) [CHESS-met] v1.2, NERC Environ. Inf. Data Cent., <https://doi.org/10.5285/b745e7b1-626c-4ccc-ac27-56582e77b900>, 2017a.

- Robinson, E. L., Blyth, E. M., Clark, D. B., Finch, J., and Rudd, A. C.: Trends in atmospheric evaporative demand in Great Britain using high-resolution meteorological data, *Hydrol. Earth Syst. Sci.*, 21, 1189–1224, <https://doi.org/10.5194/hess-21-1189-2017>, 2017b.
- Rowland, C. S., Morton, R. D., Carrasco, L., McShane, G., O’Neil, A. W., and Wood, C. M.: Land Cover Map 2015 (1km percentage target class, GB), NERC Environ. Inf. Data Cent., <https://doi.org/10.5285/505d1e0c-ab60-4a60-b448-68c5bbae403e>, 2017.
- Samaniego, L., Kumar, R., and Attinger, S.: Multiscale parameter regionalization of a grid-based hydrologic model at the mesoscale, *Water Resour. Res.*, 46, W05523, <https://doi.org/10.1029/2008WR007327>, 2010.
- Sankarasubramanian, A., Vogel, R. M., and Limbrunner, J. F.: Climate elasticity of streamflow in the United States, *Water Resour. Res.*, 37, 1771–1781, <https://doi.org/10.1029/2000WR900330>, 2001.
- Sawicz, K., Wagener, T., Sivapalan, M., Troch, P. A., and Carrillo, G.: Catchment classification: empirical analysis of hydrologic similarity based on catchment function in the eastern USA, *Hydrol. Earth Syst. Sci.*, 15, 2895–2911, <https://doi.org/10.5194/hess-15-2895-2011>, 2011.
- Singh, R., van Werkhoven, K., and Wagener, T.: Hydrological impacts of climate change in gauged and ungauged watersheds of the Olifants basin: a trading-space-for-time approach, *Hydrol. Sci. J.*, 59, 29–55, <https://doi.org/10.1080/02626667.2013.819431>, 2014.
- Stahl, K., Hisdal, H., Hannaford, J., Tallaksen, L. M., van Lanen, H. A. J., Sauquet, E., Demuth, S., Fendekova, M., and Jódar, J.: Streamflow trends in Europe: evidence from a dataset of near-natural catchments, *Hydrol. Earth Syst. Sci.*, 14, 2367–2382, <https://doi.org/10.5194/hess-14-2367-2010>, 2010.
- Stevens, A. J., Clarke, D., and Nicholls, R. J.: Trends in reported flooding in the UK: 1884–2013, *Hydrol. Sci. J.*, 61, 50–63, <https://doi.org/10.1080/02626667.2014.950581>, 2016.
- Tanguy, M., Dixon, H., Prosdociimi, I., Morris, D. G., and Keller, V. D. J.: Gridded estimates of daily and monthly areal rainfall for the United Kingdom (1890–2015) [CEH-GEAR], NERC Environ. Inf. Data Cent., <https://doi.org/10.5285/33604ea0-c238-4488-813d-0ad9ab7c51ca>, 2016.
- Tanguy, M., Prudhomme, C., Smith, K., and Hannaford, J.: Historical gridded reconstruction of potential evapotranspiration for the UK, *Earth Syst. Sci. Data*, 10, 951–968, <https://doi.org/10.5194/essd-10-951-2018>, 2018.
- Thompson, N., Barrie, I. A., and Ayles, M.: The Meteorological Office rainfall and evaporation calculation system: MORECS, *Meteorol. Off. Bracknell*, 1981.
- Tyralis, H., Papacharalampous, G., and Tantane, S.: How to explain and predict the shape parameter of the generalized extreme value distribution of streamflow extremes using a big dataset, *J. Hydrol.*, 574, 628–645, <https://doi.org/10.1016/j.jhydrol.2019.04.070>, 2019.
- Viglione, A., Borga, M., Balabanis, P., and Blöschl, G.: Barriers to the exchange of hydrometeorological data in Europe: Results from a survey and implications for data policy, *J. Hydrol.*, 394, 63–77, <https://doi.org/10.1016/j.jhydrol.2010.03.023>, 2010.
- Wagener, T., Sivapalan, M., Troch, P. A., McGlynn, B. L., Harman, C. J., Gupta, H. V., Kumar, P., Rao, P. S. C., Basu, N. B., and Wilson, J. S.: The future of hydrology: An evolving science for a changing world, *Water Resour. Res.*, 46, <https://doi.org/10.1029/2009WR008906>, 2010.
- Werkhoven, K., Wagener, T., Reed, P., and Tang, Y.: Characterization of watershed model behavior across a hydroclimatic gradient, *Water Resour. Res.*, 44, W01429, <https://doi.org/10.1029/2007WR006271>, 2008.
- Westerberg, I. K. and McMillan, H. K.: Uncertainty in hydrological signatures, *Hydrol. Earth Syst. Sci.*, 19, 3951–3968, <https://doi.org/10.5194/hess-19-3951-2015>, 2015.
- Westerberg, I. K., Wagener, T., Coxon, G., McMillan, H. K., Castellarin, A., Montanari, A., and Freer, J.: Uncertainty in hydrological signatures for gauged and ungauged catchments, *Water Resour. Res.*, 52, 1847–1865, <https://doi.org/10.1002/2015WR017635>, 2016.
- Woods, R. A.: Analytical model of seasonal climate impacts on snow hydrology: Continuous snowpacks, *Adv. Water Resour.*, 32, 1465–1481, <https://doi.org/10.1016/j.advwatres.2009.06.011>, 2009.
- World Meteorological Organization (Geneva): Manual on low-flow estimation and prediction, WMO, Geneva, 2008.
- Wösten, J. H. M., Lilly, A., Nemes, A., and Le Bas, C.: Development and use of a database of hydraulic properties of European soils, *Geoderma*, 90, 169–185, [https://doi.org/10.1016/S0016-7061\(98\)00132-3](https://doi.org/10.1016/S0016-7061(98)00132-3), 1999.
- Wösten, J. H. M., Pachepsky, Y. A., and Rawls, W. J.: Pedotransfer functions: bridging the gap between available basic soil data and missing soil hydraulic characteristics, *J. Hydrol.*, 251, 123–150, [https://doi.org/10.1016/S0022-1694\(01\)00464-4](https://doi.org/10.1016/S0022-1694(01)00464-4), 2001.
- Wösten, J. J. H.: The HYPRES database of hydraulic properties of European soils, in: Subsoil compaction; distribution, processes and consequences, edited by: R. Horn, J. J. H., van den Akker, and Arvidsson, J., 135–143, 2000.
- Yadav, M., Wagener, T., and Gupta, H.: Regionalization of constraints on expected watershed response behavior for improved predictions in ungauged basins, *Adv. Water Resour.*, 30, 1756–1774, <https://doi.org/10.1016/j.advwatres.2007.01.005>, 2007.
- Zacharias, S., Boga, H., Samaniego, L., Mauder, M., Fuß, R., Pütz, T., Frenzel, M., Schwank, M., Baessler, C., Butterbach-Bahl, K., Bens, O., Borg, E., Brauer, A., Dietrich, P., Hajsek, I., Helle, G., Kiese, R., Kunstmann, H., Klotz, S., Munch, J. C., Papen, H., Priesack, E., Schmid, H. P., Steinbrecher, R., Rosenbaum, U., Teutsch, G., and Vereecken, H.: A Network of Terrestrial Environmental Observatories in Germany, *Vadose Zone J.*, 10, 955, <https://doi.org/10.2136/vzj2010.0139>, 2011.

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