From:	Together Against Sizewell C
To:	SizewellC
Subject:	FAO The Secretary of State BEIS re SZC DCO
Date:	18 March 2022 15:33:51
Attachments:	mapjaogbifaiidap.png TASC post D10 response FAO Sec of State BEIS Final.pdf

TOGETHER AGAINST SIZEWELL C

[redacted]

Dear Secretary of State,

Sizewell C DCO Application-PINS ref: EN010012

TASC note that you require further information from the Environment agency in relation to the Water Discharges Permit. TASC have prepared a post examination response in respect of documents relating to impacts on the marine environment lodged by the Applicant in the late stages of the examination, for your consideration. As you will see, a substantial part of this report has implications for discharges from the proposed cooling water system and highlights the Applicant's underestimate of marine biota fatalities resulting from the cooling water system. TASC trust you will take TASC's comments regarding the devastation Sizewell C will have on the marine environment and designated wildlife sites/species into account when making your decision. If you require any further information, please do not hesitate to contact us.

Please acknowledge receipt.

Yours sincerely

Chris Wilson for TASC: IP ref: 20026424

Together Against Sizewell C

Table of Contents

Post D10 comments on Sizewell C DCO submissions in relation to adverse impacts on the marine environment

FAO: Secretary of State, BEIS

During the latter part of the Sizewell C (SZC) DCO examination vast quantities of documents were submitted into the DCO examination by the Applicant (172 at deadline 10, 26 at deadline 9 and 135 at deadline 8), also many from interested parties (IPs). The statutory bodies and larger NGOs have voiced concerns about the overwhelming volume of information and the difficulties in coping with this and the 22 changes made by the Applicant, so how the smaller NGOS like TASC with no staff and other IPs were expected to cope is difficult to comprehend. The blame for the disproportionate amount of information being presented at the end of the examination falls fairly and squarely on the Applicant due to their failure to frontload the process and for submitting a DCO application which quite frankly was not fit for purpose with much information missing. TASC are still looking at those documents but remain concerned that many other IPs may not be aware they are able to comment on these thereby providing the Applicant with an unfair influence over the examination where the Applicant's submissions have gone unchallenged. TASC would like you to be made aware of the following matters:-

Adverse impact on the marine environment

Introduction

TASC are concerned that the extent of the adverse impact on the marine environment has been under-assessed by the Applicant throughout the examination. This has led to a knock-on adverse effect on the species, some of which are priority species, that depend on that environment and the designated sites inhabited by those species. The Applicant submitted various documents at deadline 10 attempting to address shortcomings of their assessment of the impact on the marine environment, but TASC consider the Applicant has failed in this attempt. Before addressing the reasons for this failure, TASC would advise the Secretary of State (SofS) that we have been assisted in this DCO application by marine ecologist, Dr Peter Henderson. His CV is at the front of the TASC submission at Annex A to this report but the important point to make here is that Dr Henderson (DrH) has a great deal of experience working on the cooling water systems (CWS) of thermal power plants and, perhaps most importantly, has worked on the Sizewell B (SZB) CWS. It is data from SZB that has been used by the Applicant when considering the impacts of SZC's CWS.

Background

TASC's initial submission on this subject was our Written Representation (WR), REP2-481h in which DrH set out, amongst other things, the reasons why the Applicant's assessment of fish mortality in their DCO application, was grossly underestimated. An example taken from REP2-481h [para 23, page 13] is that the number of sand goby entrapped (impinged plus entrained) each year, are calculated by the Applicant at 153 million whereas DrH recalculated the figure to be in excess of 800 million. The reasons were expressed by way of a summary when DrH spoke at ISH 7 and included in our submission REP5-298. Part of his statement is replicated here: *"At the broadest level, TASC's concerns are that the number of organisms, fish in particular, which will actually be killed by the intake are being grossly underestimated to date. This is because fundamentally, we sample the number of organisms sucked into Sizewell B's cooling water system by two methods. Method 1 counts the number which are impinged on the 10 millimetre travelling screens and that gives us our impingement number. Method 2 counts the number of organisms in a sample of water extracted from the cooling water intake system - normally in front of the travelling screens (as used in the case of Sizewell B) called a pump sampler. The problem is that the pump sampler will only sample larvae and eggs of fish and very small crustaceans. However, because you've got a 10 millimetre mesh, a lot of juvenile fish will pass through that mesh, but they won't be sampled by the pump sampler. The result is that at present, EDF and Cefas have grossly underestimated the number of small fish that will be caught by the power station and killed. This is because of this mismatch between the two systems under use.*

Now, to give some concrete examples: in the case of sprat, a sprat of less than 70 millimetres standard length can penetrate a 10 millimetre screen, as will an awful lot of the sprat of less than that length. In the case of gobies these small little fish which are so abundant in that part of the world, almost all of them will penetrate a 10 millimetre mesh, so a fish 50 millimetres long (40 millimetres long, which is an adult) go through the mesh and get entrained. But it's not counted in the entrainment or impingement calculations because they're not sampled by a pump sampler, because they can avoid the pump. Now, this becomes particularly serious when we deal with endangered species. Lamprey, for example, can penetrate a 10 millimetre mesh even when they're approximately 200 millimetres long. Now, in the environmental statement, it is asserted that you cannot entrain migratory fish like lamprey because the entrainable life stages occur in freshwater. But what they've forgotten is that you can entrain quite a large fish because it will go through the 10 millimetre mesh and hence pass through the condenser circuit. So, for that reason, on a very large scale, the numbers of animals which will actually be killed on Sizewell B power station and the proposed Sizewell C have been greatly underestimated to date."

At ISH 7, the Applicant (represented, as a paid consultant, by CEFAS) could not demonstrate how they would be able to assess the mortality of those fish that, as DrH had referred to above, are entrained in the cooling water system and pass through the 3 kilometres of tunnels, unrecorded, to an early death.

At deadline 10, the Applicant (but prepared by Cefas) submitted document 9.67 Quantifying uncertainty in Entrapment Predictions for Sizewell C [REP10-135] which acknowledged the DCO application had underestimated the entrapment of fish but provided only limited calculations for three species rather than the 80 species due to be affected by the SZC CWS. DrH has prepared a report [copied at Annex A at the end of this report] on TASC's behalf addressing issues covered by REP10-135 and this sets out reasons why the Applicant's document still underestimates the number of fish that will be entrapped by SZC's CWS and that it is ineffective in addressing the estimated mortality of fish because it does not cover all the fish likely to be adversely impacted.

One of these reasons why the Applicant continues to underestimate the number of fish that would be entrapped by SZC is due to the fact that the SZC estimates are based on figures from SZB and DrH is aware from his work at SZB there is a material lack of recording species entrained (as set out in REP2-481h) at SZB. This brings TASC to then consider another D10 submission from the Applicant, namely REP10-156: '9.120 Revision: 1.0 Comments on Earlier Deadlines, Subsequent Written Submissions to ISH11-14 and Comments on Responses to Change Request 19' which has four appendices, including REP10-157 and REP10-158 which are parts 1 and 2 of the appendices, respectively.

REP10-157, appendix A, sets out the Applicant's response to matters raised by the Environment Agency (EA) in respect of the impingement and entrainment monitoring plan. TASC are extremely disappointed to note that the Applicant still has not addressed the matter of monitoring the small and juvenile fish as well as the long slender fish that pass though the mesh screens and are too strong to be picked up by the pump sampler that monitors entrainment. This highlights the inadequacies of the proposed monitoring scheme which seems to be designed to hide the mortality of hundreds of millions of fish and other marine biota that will be entrained by the SZC CWS. TASC have covered this issue in our previous DCO submissions REP2-481h, REP5-298[marine ecology section], REP7-247[paras 6-18], REP8-284[2nd section re document 9.67] as well as in the TASC response to REP10-135 included at Annex A at the end of this report.

REP10-158, appendix L, sets out the Applicant's response to issues raised by TASC at the Issue Specific Hearings (ISHs). DrH has countered a lot of the matters set out in the document, in our Annex A report attached, but TASC wish to highlight some of the statements made by the Applicant (the numbers referenced being the paragraph numbers in appendix L to REP10-158):-

Para 1.2.1 includes: *"TASC contended that a number of species were at risk of being underestimated due to the 'entrainment gap',* ***primarily citing juvenile sprat and gobies*** [emphasis added]*. Concerns have also been raised for other species with slender morphologies including glass eel, river lamprey and sandeel."* The term 'primarily citing' conveys the impression that these are the species of main concern to TASC, so we just wish to advise that sprat and gobies are just examples of the many species that will suffer the same fate.

Para 1.2.24 includes: *"The minimum yellow eel size recorded at Sizewell was 22.5cm TL, which at a fineness ratio of 16 (Turnpenny, 1981) corresponds to a body height of 14mm. This exceeds the 10mm screen mesh size and therefore there is no significant 'entrainment gap' for this life stage."* This is an example of the point made by DrH in Annex A, where the Applicant/CEFAS makes an incorrect assessment- yellow eels with a body height of 14mm will pass through a 10mm square mesh on the diagonal.

Para 1.2.28 includes: *"Sandeels are an important part of diet of little terns in other regions of the North Sea, but off East Anglia they represent only a small proportion (<8%) of the diet of these birds (Green, 2017)."* TASC believe that the Applicant needs to consider that sandeels may only form a smaller part of the East Anglia little terns' diet due to the numbers killed by the SZB CWS, so their availability is not as great.

Para 1.2.29 states*: "TASC in its Deadline 7 Submission [REP7-247] questioned the absence of estimates for pipefish losses. Estimates of impingement of pipefish species at Sizewell B and predicted impingement rates at Sizewell C are presented in ES Addendum Appendix 2.17.A Marine Ecology [AS-238]."* This does not deal with the pipefish that are **entrained**.

Para 1.3.43 states: *"An additional point pertaining to the stock size raised by TASC is the incorrect assumption that Sizewell C impacts have been considered in isolation. TASC consider "in-combination mortality impact with all the other EDF and other power company cooling water intakes killing fish along the English, Northern French, Belgium and Dutch coasts" should be assessed with Sizewell C. However, for the species with quantifiable population estimates, particularly those ICES assessed species, the effects of existing anthropogenic impacts form part of the baseline population estimate against which effects have been compared. Furthermore, the cumulative effects of Sizewell C and Hinkley Point C operating on the same sea bass population has been assessed in Sizewell C European Sea Bass Stock Assessment ([REP8-131])."* TASC believe that the applicant has missed the point here. CEFAS have clearly recognised that cumulative impacts need to be considered by looking at the combination of the adverse impacts from HPC and SZC. However, if assessment is against ICES data covering a large area, then the cumulative impact of all the thermal power stations affecting that area need to be considered- SZC (and HPC) could be the final straw. TASC are aware that EDF have studied the impact on sea bass stocks of its thermal power stations with once-through CWS positioned on the French coast in the English Channel/North Sea region, so the Applicant (via EDF) already have information available to estimate the cumulative impact. Further there are also other thermal power stations in Belgium, Netherlands etc which also kill bass.

Sea Bass Assessment REP8-131: '9.110 Revision: 1.0 Sizewell C European Sea Bass Stock Assessment'

TASC consider it important to address the role of CEFAS as the Applicant's paid consultants in dealing with marine matters and the apparent conflict between CEFAS's statutory role to protect marine stocks and their role here where they are protecting a developer that will damage the marine environment. In preparing REP8-131, CEFAS are putting a veneer of careful scientific arguments that hide sweeping assumptions which cannot be justified. By far the most important one, in TASC's opinion, is the in-combination impact when CEFAS combine Hinkley Point C (HPC) and SZC. However, EDF operate a large number of once-through cooled power stations along the Northern coast of France that also kill large numbers of bass. So, any true in-combination calculation would include impingement/entrainment mortality from Graveline, Flamanville etc. As mentioned above, there are also stations in Belgium, Netherlands etc which also kill bass.

So, TASC are pleased that CEFAS have acknowledged the relevance of the in-combination impacts with HPC and SZC but they need to build on this and add the other locations to estimate the likely impact on the relevant ICES area.

TASC consider there is a worrying mismatch between the bass catch regulations administered by CEFAS and what they are claiming for SZC (see bass fishing guidelines: https://www.gov.uk/government/publications/bass-industry-guidance-2022/bass-fishing-guidance-2021). Recreational fishermen can only land 2 bass in a day to preserve stocks while Sizewell will kill thousands per day. Commercial fishing for sea bass is banned in some areas and in February and March to conserve stocks, yet SZC will continue to kill thousands of sea bass when fishing is banned/restricted. Annex B is a schedule prepared by TASC from the Applicant's record of fish impinged at SZB, from which you will see the estimated number of sea bass expected to be impinged by SZC is in excess of 2.1 million each year.

CEFAS has, over the years, highlighted the parlous state of the bass population and the need for fishing controls. These have included protected nursery waters to allow young bass to recruit. Now they argue that the single largest killer of bass ever proposed will not have a significant effect! They are now conflicting with their own regulations and efforts to conserve the stock, by promoting such killing.

At Annex C, TASC have attached a recent bass paper published by CEFAS scientists and the following is a quotation from the introduction:-

*"Bass are currently managed in four discrete regions: (i) Iberian Coast; (ii) Bay of Biscay; (iii) west of Scotland and south and west of Ireland; and (iv) North Sea, English Channel, Celtic Sea, and Irish Sea (ICES, 2012). Scientific assessments of the northern stock have shown a rapid decline in the spawning stock biomass (SSB) since 2010 attributed to a succession of weak year classes from 2008 to 2012 and increased fishing mortality (ICES, 2015). The stock exhibits very large inter-annual variability in settlement, most probably driven by environmental factors. To conserve the stock, significant reductions in the harvest of sea bass have been implemented by the European Commission through seasonal and area closures, increasing the Minimum Conservation Reference Size to 42 cm, monthly boat limits or bycatch limits for commercial fishers, and bag limits for recreational anglers (Council Regulation (EU) 2107/127). Similar patterns were observed in the late 1980s that led to a number of conservation measures including the designation of bass nursery areas (BNAs) around England and Wales to protect aggregations of fish below the minimum landing size (**Pickett and Pawson, 1994**)."*

The two scientists who did the work on the need for conservation rules were Pickett and Pawson referenced above, both of whom worked for CEFAS, so CEFAS were instrumental in producing the fishing regulations.

TASC consider the Applicant/CEFAS's sea bass assessment, in only addressing impingement, under-assesses the impact on the sea bass population due to entrainment. Bass spawn offshore and the young fish move into estuaries to feed and grow. However, during the winter they move out of estuaries to warmer sea water and so quite small bass occur off Sizewell. It is highly likely that bass less than 14 mm deep in the body occur at Sizewell and these are capable of penetrating a 10 mm mesh. A 2018 CEFAS document (https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/996213/Presence_of_European_sea_bass__Dicentrarchus_labrax__and_other_species_in_proposed_bass_nursery_areas.pdf) reviewed Bass Nursery Areas (BNAs) and when considering Sizewell, its conclusion on page 65 states: *"There is good evidence that the area in the immediate vicinity of the power station has sufficient aggregation of juvenile sea bass to give a high probability of them being impinged by the cooling water intakes, although individuals of other species above MCRS are present (Table 5). Hence, there is evidence to support further consideration of the proposed Sizewell BNA (Table 5)."* TASC find it hard to understand how CEFAS can consider Sizewell as a BNA but then support the slaughter of bass through the SZC CWS. It is clear that the number of bass entrained has not been quantified by the Applicant/CEFAS.

Conclusion

(i) The Applicant/CEFAS have conceded that their estimates of the number of fish killed were too low because the 10 mm mesh does not retain small fish.

(ii) The Applicant/CEFAS have undertaken some revised calculations for a few species. They need to revise the estimates for all species so that a proper impact assessment can be made. Some small thin fish have been seriously under-sampled, and this must be addressed.

(iii) In particular, the Applicant/CEFAS need to produce revised estimates for long, thin species of conservation concern, eels and lamprey. This is an essential legal requirement.

(iv) The Applicant/CEFAS have tried to minimise the missing entrainment numbers caught, by assuming that the pump sampler efficiently catches small fish. This is incorrect, as the pump sampler is highly inefficient for this purpose. CEFAS know this to be the case, which is why they do not use pump samplers for their regular small fish surveys. This is a major defect, and the Applicant will need to undertake appropriate entrainment sampling to rectify the issue.

(v) The Applicant/CEFAS have also tried to question DrH's observations on mesh penetration through a 10 mm mesh by pointing out that sprat of a size DrH claims will go through the mesh have a head depth greater than 10 mm. As explained in Annex A , this is because it is the diagonal distance across the square mesh, which is the critical dimension for mesh penetration, a distance of just over 14 mm. TASC are surprised that the scientists at CEFAS would make such a schoolboy error.

(vi) As the sea bass assessment has not considered entrainment, it is incomplete.

(vii) As fish mortality is substantially underestimated, then the adverse impact of all the dead/dying biota that will be discharged at the outfall point will be underassessed. TASC note that the RSPB recognise this issue in para 1.1.10 of their D10 submission REP10-204.

(viii) The more biota in the outfall, the more birds and mammals attracted to the area where the chemical plume exists, therefore increasing the risks of contaminants poisoning birds, mammals, fish and other marine creatures. TASC say this as an area where the Habitat Regulation Assessment is inadequate in terms of the impacts on European sites, SPA species such as the little tern, as well as wildlife generally.

(ix) The greater the amount of biota in the outfall, the greater will be the attraction of unnatural numbers of predator and scavenger species upsetting the balance of nature in the vicinity of the outfall.

(x) As fish mortality is substantially underestimated, the impact on protected fish, those of conservation concern and the species that prey on them has been understated.

(xi) As fish mortality is substantially underassessed, then the benefits for the inclusion of mitigation in the form of acoustic fish deterrents will likely be incorrectly assessed (for further TASC comments regarding the acoustic fish deterrent see REP6-077), and

(xii) As fish mortality is substantially underassessed, then the consideration of, and comparison with, alternative cooling systems eg cooling towers, will be incomplete.

TASC, [redacted]

Annex A TASC report on document REP10-135:

Comments on REP10-135 9.67 Quantifying uncertainty in Entrapment Predictions for Sizewell C

Prepared by Dr Peter Henderson for TASC, January 2022

About the author; Dr P A Henderson

1 I am a marine biologist with an in-depth knowledge of the ecological issues linked to power generation having worked in the field for over 40 years. I also have extensive experience working on wedge wire screens for the protection of water intakes in both the USA and the UK. I lecture and hold the position of Senior Research Associate in the Department of Zoology, University of Oxford, UK. I am an ecological consultant and research scientist with 40 years' experience combining theoretical, applied, and field research, with extensive experience of the management of major ecological assessment projects including preparation and presentation of material for public enquires and liaising with conservation bodies and engineers. Projects undertaken include conservation planning for large tropical nature reserves, ecological effects studies of nuclear power station intakes (including the Sizewell B intakes), conservation studies of rare freshwater life and effects of climate change and drought. I have written 7 books including the standard textbook ‘Southwood’s Ecological Methods’.

2 The focus of these comments is the assessment of the level of under-estimation of the number of fish that will be sucked into the cooling water system at the proposed Sizewell C Nuclear Power Station. TASC, in their submission REP2-481h and supported by later submissions REP7-247 and REP8-284, pointed out that the total number of fish sucked into the cooling water system was seriously underestimated by the Applicant because small fish and long and thin eel-like species had not been sampled in the studies undertaken at Sizewell B cooling

water intakes. This was because small and thin fish would pass across the 10 mm filter screens and thus not be counted in the impingement samples. Further, they would not have been captured by the pump sampler used to sample the plankton because their swimming ability allows them to avoid capture. The water velocities close to the intake orifice of a pump sampler are too low to efficiently draw in fish once they perceive the sampler and take evasive swimming action. It is because of this low sampling efficiency that high speed nets rather than pump samplers are used by marine biologists including CEFAS to sample post-larval and juvenile fish at sea.

3 The calculations undertaken by CEFAS in 9.67 [REP10-135] show that they agree that under sampling did occur and that all the estimates previously produced for fish entrapment on the proposed Sizewell C cooling water intakes were underestimates. CEFAS have made estimates for sprat, herring and sand gobies in an attempt to assess the missing size fraction. They selected these species because they spawn nearby and are abundant in entrainment monitoring samples. However, approximately 80 species of fish are vulnerable to entrainment and impingement and, as many of these have been under-sampled, there needs to be a complete reanalysis of the estimated numbers of fish entrapped if a proper assessment of the impact of Sizewell C is to be produced. The choice of 3 taxa is arbitrary and dismisses the large impacts on many other species. The reasons given for the choice of species does not bear scientific scrutiny.

4 We have previously highlighted other fish species which will have been seriously underestimated in entrapment estimates. Examples include, sticklebacks (3 species), gobies such as transparent, crystal, painted, black and rock, butterfish and viviparous blenny. Another class of fish which has been greatly

underestimated are those with a long, thin body form that can penetrate the mesh as adults or late-stage juveniles. These include the abundant Nilsson's, greater and snake pipefishes. Nilsson's pipefish is particularly abundant at Sizewell and is regularly recorded in impingement samples. The vast majority of pipefish will penetrate the screens, so the number recorded in the impingement samples is probably a tiny fraction of the total that are killed. Another group of long, thin, fish which are common and have been grossly under-estimated are the sand eel, a number of species of which occur off Sizewell. CEFAS have taken the view that they need only reassess numbers for highly abundant species. However, for fish such as sand eel and transparent goby which have not been properly sampled there is not even the data to know how abundant they actually are. Another group which needs to be properly quantified are the flatfish. Juvenile flatfish such as sole are particularly adept at forcing themselves through a 10 mm mesh as their bodies are flexible and they are able to use the diagonal distance of 14 mm across the square mesh to pass across using a corkscrew action. Juvenile sole species, plaice and dab are highly abundant in the Sizewell region and are important commercial species which need to be correctly quantified. Finally, in addition, eel and river lamprey have certainly been underestimated as a wide size range occur in the sea and even quite long individuals can wriggle through a 10 mm mesh. The CEFAS calculations for the under-sampling of sprat and herring also apply to anchovy and pilchard. Why have calculations for these species not been included? The argument that none of the above species are commonly recorded by the pump sampler is irrelevant as they are all capable of swimming and avoiding capture by a pump sampler designed to sample eggs and larvae only.

5 Even for the 3 taxa for which they have attempted to assess the degree of under sampling, there are serious problems linked to the assumptions made.

6 In the case of sprat, it is claimed by CEFAS that TASC are wrong in claiming sprat need to be > 70 mm SL (‘Standard Length’)[1] before they are always retained by a 10 mm mesh (Section B.2.2). CEFAS reach this conclusion by showing that in a fish of 70 mm SL, the depth of the head is greater than 10 mm. **CEFAS have failed to understand that the critical dimension for mesh penetration is not the 10 mm length of each side of the mesh but the diagonal distance across the mesh**. For a 10 mm mesh this is the square root of 200 = 14.14 mm. Oddly and quite surprisingly, this lack of understanding by CEFAS that it is the diagonal dimension that is critical in defining the length of fish that will penetrate the mesh, is repeated elsewhere. For example, for smelt on p 71 the following is written “*Smelt ascent to upper estuaries and freshwaters in February to April to spawn. Most of the juvenile fish descend to the lower estuary by early autumn of their first year (Colclough and Coates, 2013) and by that time their lengths is ~ 6 cm TL* [Total length][2] *(Scholle et al., 2007). At this stage juvenile smelt have a body depth of approximately 10mm (Froese and Pauly, 2021), the size of the drum screen mesh.*” As in the case of sprat, they assert, incorrectly, that it is 10 mm body depth which is the maximum size for penetration when in actual fact it is closer to 14 mm.

7 A critical, incorrect assumption made by CEFAS, is that efficient entrainment sampling occurs up to a length of 35-39 mm TL. “*Therefore, this represents the starting point to back-calculate numbers of smaller fish between the maximum*

[1] Standard length (SL) is the length of a fish measured from the tip of the snout to the posterior end of the last vertebra or to the posterior end of the midlateral portion of the hypural plate. Simply put, this measurement excludes the length of the caudal (tail) fin.

[2] Total length (TL) is the length of a fish measured from the tip of the snout to the tip of the longer lobe of the caudal fin, usually measured with the lobes compressed along the midline. It is a straight-line measure, not measured over the curve of the body

size of efficient entrainment (35-39mm TL) and the minimum size of 100% impingement (85-89mm TL)." (p 73). There is no evidence presented that a pump sampler has a high efficiency of capture of sprat above 30 mm TL. The result is an underestimation of the number entrained.

8 Exactly the same errors occur with respect to herring. "We assume that entrainment sampling misses fish > 40mm TL (32mm SL) and the minimum size of fully impinged fish is the precautionarily assumed to be of the size class of 70 – 74mm SL, 85-89mm TL as suggested by TASC [REP2-481h]." (p76). There is no evidence presented that a pump sampler efficiently samples herring in the 30 – 40 mm size range.

9 In the case of gobies there are a number of errors made in CEFAS's calculations. **First**, there is the error of not using the diagonal dimension of the mesh when considering mesh penetration. "*Sand gobies of 87mm SL (as suggested by TASC [REP2-481h]) would have a body depth of 15.3mm. This far exceeds the minimum size to be fully retained by 10 mm mesh. Therefore, we precautionarily assume the smallest size class subjected to 100% impingement by a 10mm mesh is 70-74mm TL (62-65mm SL) with a body depth of 10.9-11.4mm. This is based on the maximum body depth being 10% higher than 10mm mesh size.* " (p80) **Second**, they assume the pump sampler is 100 % effective up to a length of 35-39 mm TL. "*Therefore, we precautionarily defined the entrainment gap as occurring between the size classes of 35-39mm and 70-74mm TL.*" **This is untrue** as small gobies about 18 mm SL are fully formed fish and will avoid capture in a pump sampler. **Third** CEFAS assume the smallest juveniles are 20-24 mm TL. Gobies enter the water column at a length of about 9 mm and well-formed juveniles > 16 mm are observed in high numbers. No explanation of the 20-24 mm TL cut off length is

presented. The **fourth** erroneous assumption relates to the assumed age of maturity. "*The age of 50% maturity of P. minutus in the Northeast Atlantic is 1 year (Bouchereau and Guelorget, 1998). Impingement calculations precautionarily assumed all gobies (Pomatoschistus spp.) had an EAV on 1. To determine the EAV for the missing fraction we assume that the age of 100% maturity is 1.5 years as the maximum age is 2.7 years (Froese and Pauly, 2021) and that all gobies would be mature before the second year*." (p82). The maximum age of maturity of sand goby at Sizewell is not 2.7 years and is much closer to 1 year. They quote data for *P. minutus* and avoid data for *P. lozanoi* which is smaller and lives for only about 1 year. Further the maximum longevity of 2.7 years is not for southern North Sea British waters. **Finally**, CEFAS argue that the entrapment death rate is insufficient to affect the sand goby population. The problem here is that there is not a sand goby species, there are 3 species. CEFAS treats it as a single species which is incorrect. The *P. minutus* species complex in North Atlantic waters comprise 3 species *P. minutus*, *P. lozanoi* and *P. norvegicus*. *P. norvegicus* is an offshore species found at depths > 18 m. It would be unlikely to be caught by the Sizewell B intakes but may well be sucked into the offshore C station intakes. *P. minutus* and *P lozanoi* are closely related species: studies by Hamerlink in the 1980s demonstrated that these species had notably different ecological characteristics. *P. lozanoi* is smaller and predominately feeds on mysids. **CEFAS have not produced any evidence that the *P. lozanoi* or *P. minutus* populations are individually of a size that would not be impacted by the entrapment losses.**

CONCLUSION

10. In summary, while CEFAS have conceded that there is a serious under-estimation in entrapment losses of fish at the proposed Sizewell C cooling water system, the full extent of this under-estimation has not been assessed. Further, for the 3 taxa which have been assessed there are serious errors in the assumptions made which have resulted in a repeated under reporting of the likely losses. These errors, together with the absence of assessments for the entrapment for all 80 vulnerable species, lead to the inevitable conclusion that there is still a gross underestimate of the fish likely to be killed by the proposed Sizewell C cooling water system. As a result, TASC make the following observations:-

- as fish mortality is substantially underestimated, then the adverse impact of all the dead/dying biota that will be discharged at the outfall point will be underassessed, and

- as fish mortality is substantially underestimated, the impact on protected fish, those of conservation concern and the species that prey on them has been understated, and

- as fish mortality is substantially underassessed, then the benefits for the inclusion of mitigation in the form of acoustic fish deterrents will likely be underassessed (for further TASC comments regarding the acoustic fish deterrent see REP6-077), and

- as fish mortality is substantially underassessed, then the consideration of, and comparison with, alternative cooling systems eg cooling towers, will be incomplete.

TASC, [redacted]

Annex B

TASC calculation of fish impingement at Sizewell C

Sheet1

SIZEWELL NUCLEAR POWER STATIONS ANNUAL FISH IMPINGEMENT CALCULATIONS
BASED ON DATA TAKEN FROM SIZEWELL C DCO DOCUMENT 6.3 Vol 2 Chapter 22 Appendix 22D
(Appendix C : Predicted Sizewell B (SZB) Annual Impingement from 2009-2013 data)

Data from DCO document				TASC Calculations			
Common name	**Latin name**	**Protected Species**	**SZB Mean**	**% of total**	**cumulative %**	**Sizewell C (SZC) Estimate (*)**	**SZB +SZC 2035-2055**
Sprat	Sprattus sprattus		4,132,631	51.77%	51.77%	10,579,535	14,712,166
Herring	Clupea harengus	Blackwater Herring protected	968,431	12.13%	63.91%	2,479,183	3,447,614
Whiting	Merlangius merlangus		759,928	9.52%	73.43%	1,945,416	2,705,344
Bass	Dicentrarchus labrax	Protected	831,330	10.41%	83.84%	2,128,205	2,959,535
Goby, Sand	Pomatoschistus minutus		429,478	5.38%	89.22%	1,099,464	1,528,942
Sole, Dover	Solea solea		152,588	1.91%	91.13%	390,625	543,213
Dab	Limanda limanda		152,887	1.92%	93.05%	391,391	544,278
Anchovy	Engraulis encrasicolus		114,981	1.44%	94.49%	294,351	409,332
Mullet, Thin-lipped grey	Liza ramada		101,370	1.27%	95.76%	259,507	360,877
Pipefish, Nilsson's	Syngnathus rostellatus		47,202	0.59%	96.35%	120,837	168,039
Pout	Trisopterus luscus		61,610	0.77%	97.12%	157,722	219,332
Weever, lesser	Trachinus vipera		39,332	0.49%	97.61%	100,690	140,022
Rockling, 5-bearded	Ciliata mustela		16,766	0.21%	97.82%	42,921	59,687
Hooknose	Agonus cataphractus		16,881	0.21%	98.04%	43,215	60,096
Flounder	Platichthys flesus		14,451	0.18%	98.22%	36,995	51,446
Goby, Transparent	Aphia minuta		19,967	0.25%	98.47%	51,116	71,083
Plaice	Pleuronectes platessa		19,954	0.25%	98.72%	51,082	71,036
Cod	Gadus morhua		13,865	0.17%	98.89%	35,494	49,359
Smelt, Cucumber	Osmerus eperlanus		14,033	0.18%	99.07%	35,924	49,957
Sea snail, Common	Liparis liparis		4,843	0.06%	99.13%	12,398	17,241
Pilchard	Sardina pilchardus		7,925	0.10%	99.23%	20,288	28,213
Dragonet	Callionymus lyra		5,302	0.07%	99.29%	13,573	18,875
Dogfish, Lesser spotted	Scyliorhinus canicula		3,266	0.04%	99.33%	8,361	11,627
Gurnard, Tub	Trigla lucerna		3,382	0.04%	99.38%	8,658	12,040
Ray, Thornback	Raja clavata		3,154	0.04%	99.42%	8,074	11,228
Pipefish, Greater	Syngnathus acus		3,902	0.05%	99.46%	9,989	13,891
Stickleback, 3-spined	Gasterosteus aculeatus		4,448	0.06%	99.52%	11,387	15,835
Starry smooth-hound	Mustelus asterias		2,683	0.03%	99.55%	6,868	9,551
Witch	Glyptocephalus cynoglossus		4,287	0.05%	99.61%	10,975	15,262
Sandeel, Common	Ammodytes tobianus		3,714	0.05%	99.65%	9,508	13,222
Scaldfish	Arnoglossus laterna		1,740	0.02%	99.68%	4,454	6,194
Goby, Black	Gobius niger		2,184	0.03%	99.70%	5,591	7,775
Eel	Anguilla anguilla	Protected	1,469	0.02%	99.72%	3,761	5,230
Sandeel, Greater	Hyperoplus lanceolatus		1,256	0.02%	99.74%	3,215	4,471
Scad	Trachurus trachurus		3,013	0.04%	99.78%	7,713	10,726
Shad, Twaite	Alosa fallax	Protected	1,435	0.02%	99.79%	3,674	5,109
Lamprey, River	Lampetra fluviatalis	Protected	1,162	0.01%	99.81%	2,975	4,137
Pipefish, Snake	Entelurus aequoreus		2,618	0.03%	99.84%	6,702	9,320
Bullrout	Myoxocephalus scorpius		1,085	0.01%	99.85%	2,778	3,863
Brill	Scophthalmus rhombus		1,267	0.02%	99.87%	3,244	4,511
Goby, Rock	Gobius paganellus		2,019	0.03%	99.90%	5,169	7,188
Smelt, Sand	Atherina boyeri		705	0.01%	99.90%	1,805	2,510
Mackerel	Scomber scombrus		530	0.01%	99.91%	1,357	1,887
Solenette	Buglossidium luteum		600	0.01%	99.92%	1,536	2,136
Blenny, Tompot	Blennius gattorugine		1,012	0.01%	99.93%	2,591	3,603
Sole, Lemon	Microstomus kitt		576	0.01%	99.94%	1,475	2,051
Sea scorpion, long-spined	Taurulus bubalis		395	0.00%	99.94%	1,011	1,406
Goby, Painted	Pomatoschistus pictus		815	0.01%	99.95%	2,086	2,901
Butterfish	Pholis gunnellus		194	0.00%	99.96%	497	691
Mullet, Red	Mullus surmuletus		333	0.00%	99.96%	852	1,185
Viviparous blenny	Zoarces viviparus		397	0.00%	99.97%	1,016	1,413
Poor cod	Trisopterus minutus		342	0.00%	99.97%	876	1,218
Garfish	Belone belone		269	0.00%	99.97%	689	958
Gurnard, Grey	Eutrigla gurnardus		251	0.00%	99.98%	643	894
Wrasse, Corkwing	Crenilabrus melops		234	0.00%	99.98%	599	833
Sea snail, Montagu's	Liparis montagui		282	0.00%	99.98%	722	1,004
Rockling, Northern	Ciliata septentrionalis		156	0.00%	99.98%	399	555
Tadpolefish	Raniceps raninus		156	0.00%	99.99%	399	555
Saithe	Pollachius virens		156	0.00%	99.99%	399	555
John Dory	Zeus faber		78	0.00%	99.99%	200	278
Turbot	Psetta maxima		109	0.00%	99.99%	279	388
Wrasse, Ballan	Labrus bergylta		118	0.00%	99.99%	302	420
Lumpsucker	Cyclopterus lumpus		97	0.00%	99.99%	248	345
Mullet, Thick-lipped grey	Crenimugil labrosus		91	0.00%	99.99%	233	324
Sea bream, Black	Spondyliosoma cantharus		74	0.00%	100.00%	189	263
Norway bullhead	Micrenophrys lilljeborgii		53	0.00%	100.00%	136	189
Wrasse, Cuckoo	Labrus mixtus		67	0.00%	100.00%	172	239
Rockling, 4-bearded	Enchelyopus cimbrius		39	0.00%	100.00%	100	139
Pipefish, Deep-snouted	Syngnathus typhle		41	0.00%	100.00%	105	146
Rockling, Bigeye	Gaidropsarus macrophthalmus		23	0.00%	100.00%	59	82
Sea Trout	Salmo trutta		30	0.00%	100.00%	77	107
Rockling, Shore	Gaidropsarus mediterraneus		28	0.00%	100.00%	72	100
Pout, Norway	Trisopterus esmarkii		26	0.00%	100.00%	67	93
Goby, Crystal	Crystallogobius linearis		14	0.00%	100.00%	36	50
Sand sole	Pegusa lascaris		13	0.00%	100.00%	33	46
Pollack	Pollachius pollachius		13	0.00%	100.00%	33	46
Shad, Allis	Alosa alosa	Protected	11	0.00%	100.00%	28	39
Totals			7,982,167			20,434,349	28,416,516

(*) Based on a muliplier of 2.56 which has been calculated as follows:-
Sizewell B cooling water intake 51.5 cumecs
Sizewell C cooling water intake 131.86 cumecs
Sizewell C's intake is therefore 2.56 (131.86/51.5) times greater than Sizewell B

ALL FIGURES IN THIS TABLE REPRESENT ANNUAL IMPINGEMENT FIGURES. THE 28,416,516 TOTAL FOR COMBINED SZB AND SZC MUST THEREFORE BE MULTIPLED BY 20 TO ARRIVE AT THE ESTIMATED GROSS NUMBER OF FISH IMPINGEMENTS WHILE BOTH PLANTS ARE EXPECTED TO OPERATING AT THE SAME TIME (2035-2055) = 568,330,320

Annex C

‘The influence of oceanographic conditions and larval behaviour on settlement success—the European sea bass Dicentrarchus labrax (L.)’

Claire Beraud 1 *, Johan van der Molen 1,2 , Mike Armstrong 1 , Ewan Hunter 1 , Leila Fonseca 1,3 , and Kieran Hyder 1, The influence of oceanographic conditions and larval behaviour on settlement success—the European sea bass Dicentrarchus labrax (L.)

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Review Article

The influence of oceanographic conditions and larval behaviour on settlement success—the European sea bass *Dicentrarchus labrax* (L.)

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The European Seabass (*Dicentrarchus labrax*) is a slow-growing late maturing fish. The northern stock has been declining since 2010 and is thought to be caused by a combination of fishing and weak year classes. Large inter-annual variation in settlement has been observed, so a better understanding of the mechanisms driving settlement success will aid interpretation of the variation between years, and help to improve the stock assessment models and management strategies. In this study, an individual-based model (IBM) was developed to investigate the factors affecting sea bass settlement on nursery grounds of the northern sea bass stock. The IBM was coupled with hydrodynamics to track particles, whereas egg and larval development, and vertical migration behaviour are fully incorporated. The IBM successfully predicted inter-annual differences in settlement regardless of larval behaviour. The highest settlement success was predicted with neutrally buoyant eggs, hatchlings, and larval stages, in combination with tidal migration at the final larval stage. Dispersal was driven mainly by the influence of wind on residual currents and water temperature, with warmer temperatures reducing the duration of the pelagic phase and stronger current increasing the potential to drift further. Eggs spawned in the central western English Channel settled in both England and France, with movement from the central to the eastern English Channel occurring only in warm years. Larval duration was driven by water temperature and showed an increase in duration from the southwest to northeast areas of the northern stock. The results are discussed in the context of sea bass management and conservation strategies.

Keywords: European sea bass, individual-based particle tracking model, larval migration behaviour, oceanographic conditions, pelagic stage modelling.

Introduction

Understanding the relationship between the adult stock and number of young fish recruiting to that stock (the stock–recruitment relationship) has been studied for many years (e.g. Beverton and Holt, 1954). Predicting this relationship remains one of the foremost challenges in fisheries science (Houde, 2008; Subbey *et al.*, 2014) as it underpins reference points for sustainable fishing, but is often obscured by large inter-annual variability and autocorrelation between the environmental factors that drive recruitment. The pelagic egg and larval phases (hereafter termed pelagic phase) has been well studied in many marine systems including coral reefs (Munday *et al.*, 2009), intertidal rocky shores (e.g. Gaines and Roughgarden, 1985; Caley *et al.*, 1996), and fully marine environments (Bolle *et al.*, 2009). Marine systems described as "open" (Roughgarden *et al.*, 1985; Hyder *et al.*, 2001) often have the potential for protracted larval dispersal (Gaines et al., 2007; van der Molen et al., 2007). Consequently, the pelagic phase is important in determining the variability in year class strength of many fish (van der Veer et al., 2000), but the underlying influencing factors are poorly understood (Houde, 2008; Subbey et al., 2014).

To improve understanding of the pelagic larval phase of marine fish, mathematical models have been developed including simple statistical approaches (Subbey et al., 2014), non-spatial structured population models (Hyder and Nash, 1998), and spatially explicit particle tracking approaches combining both hydrodynamics and individual dynamics (van der Veer et al., 1998; van der Molen et al. 2007; Savina et al., 2010; Rochette et al., 2012; Lacroix et al., 2013; Tiessen et al. 2014). Individual-based models (IBMs) are popular tools to aid interpretation of ecological and evolutionary processes (DeAngelis and Grimm, 2014). IBMs have been used to model fish populations (DeAngelis and Mooij, 2005), and incorporate behaviours including shoaling (Jeon et al., 2013; Accolla et al., 2015) and migration (Okunishi et al., 2009). For example, the movement towards nursery areas has been modelled using IBMs that include vertical migration for European anchovy (Ospina-Alvarez et al., 2012) and sole (Savina et al., 2010; Lacroix et al., 2013), and consistent directional movement along a river towards nursery grounds (Baetens et al., 2013). IBMs coupled with hydrodynamic models have been used to assess the temporal distribution of larvae (van der Molen et al., 2007), the importance of passive drift for variation in year class strength (van der Veer et al., 1998; Tiessen et al., 2014), the supply of larvae to coastal nursery grounds (Rochette et al., 2012), and link larval supply and habitat models (Rochette et al., 2013).

The European sea bass, *Dicentrarchus labrax*, is distributed across the North-East Atlantic from northwest Africa to southern Scandinavia, with individuals present in the Mediterranean and Black Seas (Pickett and Pawson, 1994). Sea bass in the northern stock are relatively slow growing fish that can reach up to 30 years of age and take between 4 and 7 years to reach maturity (Pawson and Pickett, 1996). Mature sea bass aggregate to spawn between February and April from the Celtic Sea to the southern North Sea (Dando and Demir, 1985; Sabriye et al., 1988; Jennings, 1990). The geographic extent of spawning is thought to be bounded by the 9°C isotherm and can expand both as the season progresses and in warmer years (Pickett and Pawson, 1994).

Spawning involves the release of ripe ova in two to three batches over a two- to three-week period (Mayer et al., 1990). The pelagic phase of sea bass lasts between 50 and 70 days (Jennings and Ellis, 2015) and dispersal brings a proportion of the larvae to the vicinity of nursery grounds in estuaries, salt marshes, and other sheltered coastal sites. From around 4 years of age, the juveniles become widely distributed in coastal waters before joining the adult population once mature (Pawson et al., 2007). Settlement in the northern stock is highly correlated with temperature with poor settlement in cold years (ICES, 2012). Temperature may act as a direct stressor affecting survival of juveniles in nursery areas and could also be correlated with meteorological processes driving egg and larval drift patterns. Genetic studies show limited distinction between stocks (Fritsch et al., 2007), and tagging studies have shown large migrations of bass (Pawson et al., 2007; Quayle et al., 2009) with some evidence of philopatry, where adults return to the same coastal site after spawning each year (Pawson et al., 2008).

Sea bass is a high value fish that is exploited by commercial fisheries (ICES, 2012) and is an important species for recreational anglers with removals constituting around 25% of the total harvest in 2012 for the northern stock (Armstrong et al., 2013). Bass are currently managed in four discrete regions: (i) Iberian Coast; (ii) Bay of Biscay; (iii) west of Scotland and south and west of Ireland; and (iv) North Sea, English Channel, Celtic Sea, and Irish Sea (ICES, 2012). Scientific assessments of the northern stock have shown a rapid decline in the spawning stock biomass (SSB) since 2010 attributed to a succession of weak year classes from 2008 to 2012 and increased fishing mortality (ICES, 2015). The stock exhibits very large inter-annual variability in settlement, most probably driven by environmental factors. To conserve the stock, significant reductions in the harvest of sea bass have been implemented by the European Commission through seasonal and area closures, increasing the Minimum Conservation Reference Size to 42 cm, monthly boat limits or bycatch limits for commercial fishers, and bag limits for recreational anglers (Council Regulation (EU) 2107/127). Similar patterns were observed in the late 1980s that led to a number of conservation measures including the designation of bass nursery areas (BNAs) around England and Wales to protect aggregations of fish below the minimum landing size (Pickett and Pawson, 1994).

In this study, factors affecting settlement of juvenile sea bass were investigated on nursery grounds in the North Sea, English Channel, Celtic Sea, and Irish Sea (the "northern stock"—ICES Areas IVb&c, VIIa, d–h). An IBM was developed that coupled hydrodynamics and particle tracking with a pelagic phase model that included egg and larval development and vertical migration behaviour. Potential effects of spawning stock and the spatial and temporal distributions of spawning were excluded to assess the effect of the physical environment on settlement levels, through adoption of a standardized method of particle release. Model predictions were assessed in terms of settlement density, spatial patterns, pelagic phase duration, and inter-annual variation, and were used to select the larval behaviour that maximized settlement in known nursery areas. The sensitivity of the settlement patterns to variation in the physical environment and the connectivity between spawning and nursery grounds were assessed. The implications of these findings are discussed in the context of management of sea bass.

Material and methods

The particle tracking model combines active and passive transport of a time-evolving "particle." The aim was to simulate pelagic migration from spawning ground to nursery area, by defining growth and behaviour that was dependent on the physical environment. The selection of the most appropriate behavioural scenario was based on field observation in river estuaries and other coastal sites defined as BNAs [Bass (Specified Sea Areas) (Prohibition of Fishing) Order 1990: SI1990 No. 1156] that are now sampled in support of the Water Framework Directive (Coates et al., 2007).

The hydrodynamic and particle tracking models

A three-dimensional implementation of the Eulerian General Estuarine Transport Model (GETM—www.getm.eu, Burchard & Bolding, 2002) was used to derive current vectors and water temperatures for the particle tracking model [General Individuals Transport Model (GITM)] (Wolk, 2003; Tiessen et al., 2014; van der Molen et al., 2015). Here, a version of GITM was developed that simulated sea bass development depending on environmental parameters (e.g. temperature) and drift using current fields mediated by position in the water column.

The north-west European shelf setup GETM was run using a time step of 10 s at a spatial resolution of 0.08 × 0.05°, with 25 vertical sigma layers. The model was forced at open-boundaries by tidal elevations from Topex-Poseidon satellite altimetry (Le Provost *et al.*, 1998) and by winds, temperature, and humidity derived from the European Centre for Medium-Ranged Weather Forecast reanalyses (ECMWF, 2006a, b). The relative contributions of warm water pockets were not included (e.g. outflow pipes from industrial developments such as power stations). A full description of the model setup and forcing can be found in van der Molen *et al.* (2015).

The GITM model allows the pelagic phase to be split into different stages that are representative of a type of development and/or behaviour. For larval stages, a variety of vertical behaviours have been implemented including diurnal and tidal migration. Movement of particles related to buoyancy can also be incorporated, and settlement was simulated by freezing particle motion on reaching a certain size and/or appropriate physical conditions (e.g. water depth, temperature, salinity, and sea-bed composition) (see Tiessen *et al.*, 2014; van der Molen *et al.*, 2015 for a full description).

This study focused on the northern sea bass stock in the North Sea, English Channel, Celtic Sea, and Irish Sea (ICES Fishing Areas IVb-c and VIIa, d–h) (ICES, 2012). The domain of the particle tracking model was defined as the area from 48°N to 54.5°N and 8°W to 8.5°E (Figure 1). The domain was based on sea bass data from 28 sampled estuaries (Kelley, 1988) and 37 BNAs in England and Wales [The Bass (Specified Sea Areas) (Prohibition of Fishing) Order 1990: SI1990 No. 1156; The Bass (Specified Areas) (Prohibition of Fishing) (Variation) Order 1999: SI 1999 No. 75]. The model domain covers most sea BNAs as sampling of 64 UK waterbodies had not provided evidence of populations of juvenile sea bass above 54°N (see Coates *et al.*, 2007 for a description of sampling).

Spawning

A total of 46548 individual sea bass eggs (particles) were released at the surface over the whole model domain (Figure 2); with this number of particle dictated by available computational resource. One particle was released in every three longitudinal grid cells and every second latitudinal grid cell. A total of 1724 particles were released every 3 days between February and April, with the 3-day interval giving a reasonable representation of simulated environmental conditions. This release pattern covered the known offshore spawning grounds and time period of interest (Pickett and Pawson, 1994), and allowed for uncertainty in observed spawning areas and water temperature preferences. In addition, it provided a good balance between computation effort and numbers of particles. Although such a release scheme did not replicate the real spawning distribution, it allowed assessment of the effects of environmental conditions on connectivity between spawning locations and coastal nursery grounds. More realistic spatial egg production scenarios could be developed, but this was not done as it would make it difficult to assess the effects of environmental conditions on settlement, and there would be large uncertainties surrounding the spatial and temporal variation in spawning. To test the impact of different spawning parameters, post-processing scripts were used to select particles spawned within certain environmental conditions at particular locations. The 9 °C isotherm has been postulated as the threshold above which bass spawning occurs (Pickett and Pawson, 1994), and was used to define spawning areas in the model.

Nursery areas

In the United Kingdom, all non-polluted estuaries from the Ribble Estuary in the North–West to the Blackwater in the South–East England are likely to be nursery habitats (Kelley, 1988). In England and Wales, 37 rivers, estuaries, and other coastal sites have been defined as BNAs for juvenile bass, where additional restrictions on commercial and recreational fishing are imposed for all or part of the year [Bass (Specified Sea Areas) (Prohibition of Fishing) Order 1990: SI1990 No. 1156] (Figure 1). It is very likely that nursery areas occur in other countries within the northern stock area, with some identified (e.g. Wadden Sea—Cardoso *et al.*, 2015) and studies underway in some countries to map these areas (e.g. France).

Sea bass development and vertical behaviour

The pelagic phase of sea bass was split into egg and larval stages (see Jennings, 1990). One egg and three larval stages (hatchling, larva, and fry) were defined with distinct sizes, rates of development, and behavioural characteristics (Table 1). Sea bass eggs have been found at or near to the surface (Pickett and Pawson, 1994; van Damme *et al.*, 2011a, b), so were assumed positively buoyant in the model with an upward velocity of 0.002 m s^{-1} (Edwards *et al.*, 2008). The resulting vertical positions were driven by this buoyancy and physical mixing. The development of eggs was dependent on temperature using an existing relationship (Jennings and Pawson, 1991):

$$\ln(age) = a + bT, \qquad (1)$$

where T was the temperature and a and b were defined for each of the 13 egg sub-stages (Jennings and Pawson, 1991). Jennings and Pawson (1991) also estimated the average hatching age, where half of the eggs have spawned, as 6.47 and –0.129 for a and b coefficient, respectively. Assuming a suitable temperatures range from 8 to 20 °C, the average duration of the egg phase ranged from 3 to 7.5days, which was consistent with reported duration in other studies (Olivier *et al.*, 2013). Once hatched, the hatchling carries a buoyant yolk sac and has limited swimming ability, so it was assumed that hatchlings were positively buoyant with an upward velocity of 0.003 m s^{-1} (Edwards *et al.*, 2008). Hatchlings were initially 1.5 mm in length and the duration of this stage (D) depended on temperature, using the following equation:

$$D = 10^{a}/10^{(bT)} \qquad (2)$$

with $a = 1.89$ and $b = 0.077$ (Jennings, 1990). The duration of the first larval stage was between 1 and 7 days and transition to the second larval stage occurred at a length of 5.5 mm that corresponded to absorption of the yolk sac (Jennings, 1990).

During the second larval stage, the "larva," sea bass have a swim bladder, develop fins, and range from 5.5 to 10.5 mm in length (http://www.fao.org/docrep/field/003/ac230e/AC230E02.htm#ch2.11). Sea bass larvae have some swimming ability, but with few data on the swimming velocity or direction, the vertical swimming velocity measured for black sea bass of 0.01 m s^{-1} was used (Edwards *et al.*, 2008). No information about the impact of

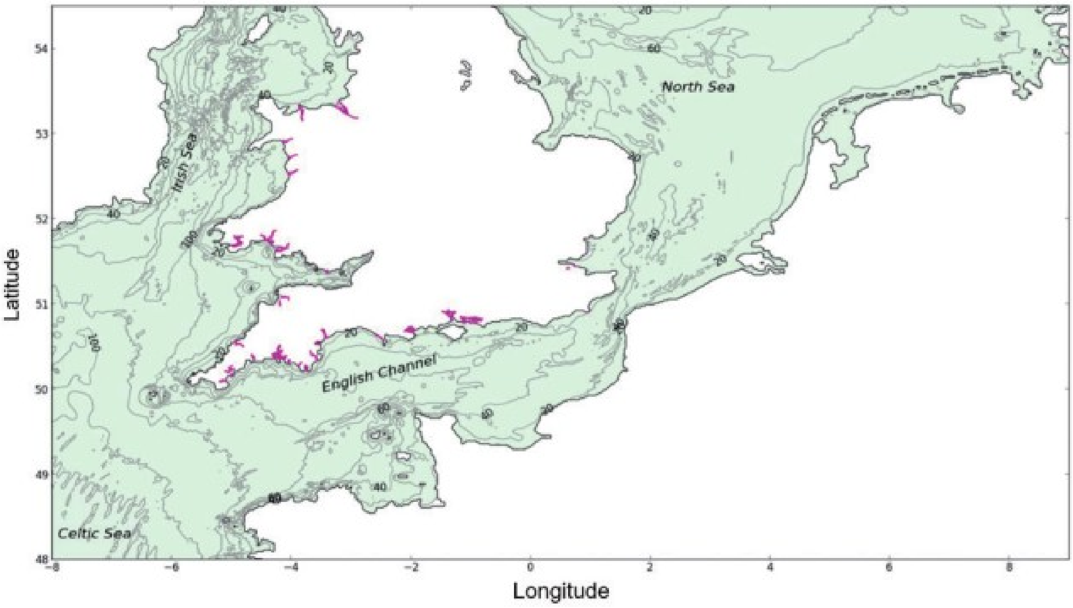

Figure 1. Known sea BNAs (purple/grey) in England and Wales (The Bass (Specified Areas) (Prohibition of Fishing) (Variation) Order 1999, SI 1999, No. 75). Contour lines indicate bathymetry (see online version for colours).

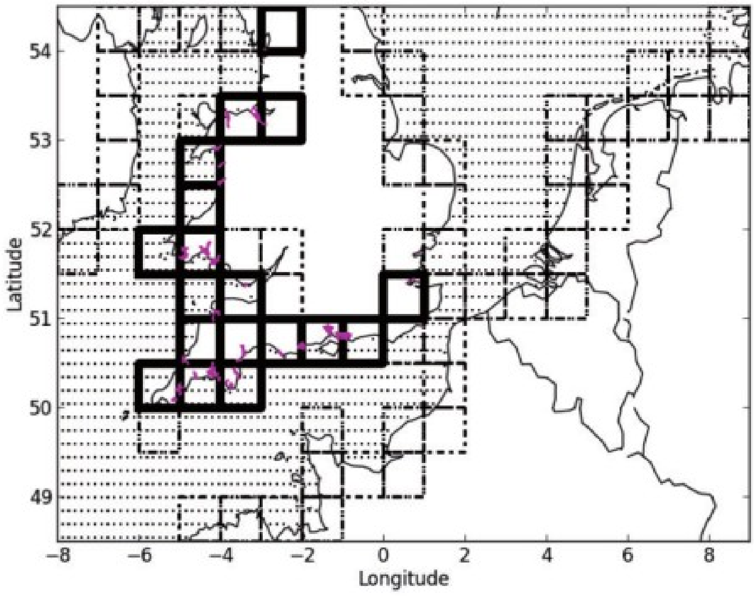

Figure 2. Coastal ICES rectangles (1 × 0.5° subdivisions of ICES Area) (dashed line) containing known BNAs (bold solid line) for the model domain. Dots indicate potential spawning locations where eggs were released.

temperature on growth at this stage was available, so a constant larval growth rate of 0.2 mm day^{-1} was assumed (Jennings and Pawson, 1992). This gave a stage duration of 25 days that was consistent with other studies (http://www.fao.org/docrep/field/003/ac230e/AC230E02.htm#ch2.10).

The final larval stage, the "fry," has good swimming ability and is ready to settle on a nursery ground, and was assumed to occur between lengths of 10.5 and 15 mm. A vertical swimming velocity based on black sea bass of 0.02 m s^{-1} was used (Edwards *et al.*, 2008). A constant growth rate of 0.2 mm day^{-1} (Jennings and Pawson,

Table 1. Predicted duration and size of sea bass at different pelagic developmental stages, parameters used to model growth, and behaviours.

Phase	Egg	Larvae		
Stage	Egg	Hatchling	Larva	Fry
Development	Egg	Yolk sac	Swim bladder and development of fins	Swim bladder and active swimming
Duration (days)	3–7.5	1–7	25	22.5
Size (mm)	1.3	1.5–5.5	5.5–10.5	10.5–18
Growth	Temperature dependent Exponential (base e) increase with temperature (Jennings and Pawson, 1991)	Temperature dependent Exponential (base 10) increase with temperature (Jennings, 1990b)	0.2 mm day^{-1} (Jennings and Pawson, 1992)	0.2 mm day^{-1} (Jennings and Pawson, 1992)
Behaviour	Drift + float (0.002 m s^{-1})	Drift + float (0.003 m s^{-1})	Vertical migration (0.01 m s^{-1})	Vertical migration at 0.02 m s^{-1} Settles in shallow coastal water (<20 m) if large enough (15–20 mm)
Behavioural regime				
• Scenario 1	Float	Float	Diurnal	Float when ready to settle
• Scenario 2	Float	Float	Diurnal	Tidal when ready to settle
• Scenario 3	Float	Float	Float	Float when ready to settle
• Scenario 4	Float	Float	Float	Tidal when ready to settle

1992) gave a duration of 22.5 days that was consistent with other studies (http://www.fao.org/docrep/field/003/ac230e/AC230E02.htm#ch2.10). When larvae are smaller than 15 mm, they are not able to swim sufficiently fast for long enough to influence dispersal (Leis *et al.*, 2012), so swimming was assumed not to influence settlement location significantly. Settlement was considered to have been successful when a fry of length of 15 mm or above (Jennings and Ellis, 2015) arrived in a coastal area at a depth of <20 m. The total pelagic phase duration based on this parameterization ranged between 49.5 and 61.5 days, and was consistent with the observed field settlement time of 50–70 days (Jennings and Ellis, 2015).

Mortality

Mortality studies generally focus on adult farmed fish (El-Shebly, 2009), but studies have provided constant daily instantaneous mortality rates for the larvae of some fish (Houde, 1989) or derived instantaneous mortality rates from other life history characteristics (McGurk, 1986). Daily instantaneous mortality has been implemented in some IBMs for egg and larval stages, but were generally not related to temperature or food availability (Rochette *et al.*, 2012). A variety of approaches have been used to model mortality including temperature-dependent mortality for egg and first larval stages (Lacroix *et al.*, 2013), paritioning instanteous mortality into baseline and predation effects (Hyder and Nash, 1998), and exclusion of mortality (van der Molen *et al.*, 2007). However, as no mortality rates have been reported for sea bass eggs or larvae in field conditions (El-Shebly, 2009), the stage duration was used as a proxy for instantaneous mortality in the model, and was equivalent as assuming a constant daily instantaneous mortality rate. Considering the lack of information on sea bass mortality, this assumption was appropriate because only constant mortality rates could be applied, and was the most flexible approach to maximize the potential for use of post-processing.

Model behaviour selection

Behaviour was selected from simulated scenarios. First, the spatial distribution of larvae settling into coastal areas was compared with known nursery areas. Hence, when larvae did not reach a coastline encompassing reported nursery areas, larval behaviour was not considered relevant. Second, relevant behaviour was selected when inter-annual differences in settlement rate between good and poor settlement years were properly reproduced, with the same method used to setup model forcing for the relevant period. Successful settlement was defined as larvae reaching coastal areas containing known nursery grounds (Figure 1).

Simulating the pelagic phase

Evaluating the effects of inter-annual variation and larval behaviour on settlement

Sea bass settlement has high inter-annual variation that is strongly associated with temperature (ICES, 2012). Hydrodynamics were simulated using a hindcast GETM model over the period 1995–2009, and predictions of monthly averaged salinity and temperature were assessed. In addition, a visual comparison between model outputs and yearly averaged SSB measurements from ICES was done over the same period. Environmental conditions were general similar between years, except for the two successive years, 1996 and 1997, which represented the minimum and maximum reported settlement for the modelled time period. Computational limitations meant that the number of years modelled was highly constrained, so two contrasting years were chosen based on a settlement index for year class strength derived from juvenile sea bass surveys conducted in the Solent since 1977 (Brown, 2013). These were 1996, a poor settlement year (hereafter PSY), and 1997, a good settlement year (hereafter GSY). The effects of the physical environment, life history characteristics, and vertical migration behaviours on settlement of sea bass were assessed for both years.

Eulerian GETM runs were used to force GITM simulations covering the pelagic phase period from February to September. Environmental parameters and current velocities were extracted hourly for both years and were used to drive the particle tracking model GITM. Hydrodynamics and temperature drove the particle passive motion, development, and growth over the pelagic phase. The number of particles released depended on the local temperature distribution. The number of particles settling in known nursery areas and the percentage of successful settlement were assessed and compared for both years.

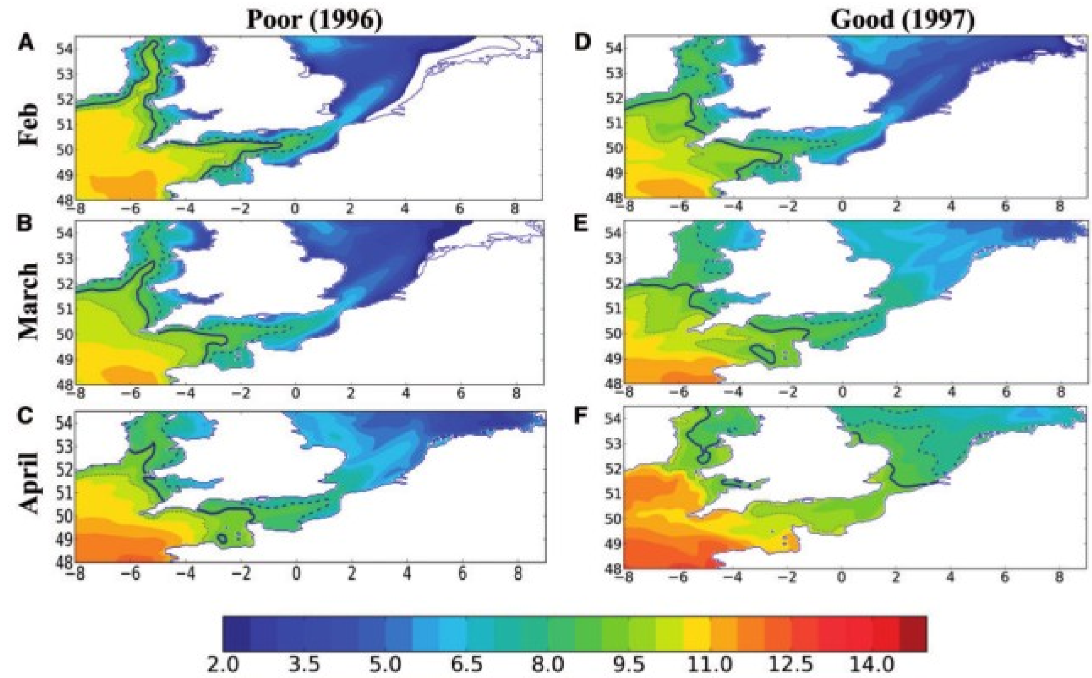

Figure 3. Monthly averaged temperature for February (a, d), March (b, e), and April (c, f) for poor (1996, a–c) and good (1997, d–f) settlement years. Contour lines represent the 8°C (dashed), 9°C (solid), and 10°C (dotted) isotherms. Axes are longitude and latitude.

Sea bass eggs have been reported as buoyant, but little is known about larval behaviour. To establish vertical behaviour(s) leading to successful settlement, several biologically plausible combinations of vertical migration behaviours (floating, diurnal, and tidal vertical migration) were implemented for each larval stage (Table 1). Float was defined as a positively buoyant passive particle with a constant upward vertical velocity. Diel migration was defined as a vertical movement up to the surface during daylight hours and descent to depth at night, and is a commonly observed behaviour of planktonic organisms (Enright and Hamner, 1967). Tidal migration is a tactic used by many organisms to selectively achieve directional movement, where individuals move up into mid-water during transporting tides (Gibson, 2003). For both vertical diurnal and tidal migrations, movements occur at the vertical swimming velocity of the larvae and horizontal movement is passive (advection by ambient currents). Particles were assigned one of four possible behavioural regimes composed of combinations of behaviours at different larval stages, and successful settlement was assessed for each behavioural regime (Table 1), through the number of settlers reaching nursery areas, the associated number particles settling, and replicating the difference between the PSY and GSY. The behavioural regime that replicated these criteria most accurately was selected and used to assess the importance of physical parameters in successful settlement and connectivity between spawning and nursery areas.

Assessing the environmental drivers for success of settlement and pelagic duration

The main environmental drivers in the model are current velocities, air temperature and wind direction and strength, with air temperature affecting water temperature and varying with wind. The differences in residual current velocities between years are also driven mainly by wind and will dominate the inter-annual variability in passive dispersal of particles. Wind velocity variability among the PSY and GSY was assessed by averaging the wind strength and direction over the pelagic phase. The differences between years were used to assess the importance of wind in driving settlement and pelagic phase duration (proxy for instantaneous constant mortality) in PSY (1996) and GSY (1997).

Water temperature defines the spawning area and affects growth, so will influence the location of release, settlement, and duration of the pelagic phase. Sea bass eggs are sensitive to water temperature and have been shown to develop at temperatures between 8.7 and 18.6°C (Jennings and Pawson, 1991). As a result, the 9°C isotherm has been postulated as the threshold at which bass spawning occurs (Pickett and Pawson, 1994). Post-processing scripts were used to assess the sensitivity of settlement to the spawning temperature threshold using the 8, 9, and 10°C isotherms, with larger spawning areas at a lower than a higher temperature threshold. The impact on number of particles released, numbers settling, and percentage and duration of successful settlement was assessed for the PSY and GSY. As the spawning extent varies with temperature, only the ratio of the number settling to number released was compared for both years.

Connectivity between spawning areas and nursery ground

The connectivity between spawning and nursery areas was assessed using model outputs of the locations of spawned particles that settled successfully across the whole model domain. A more

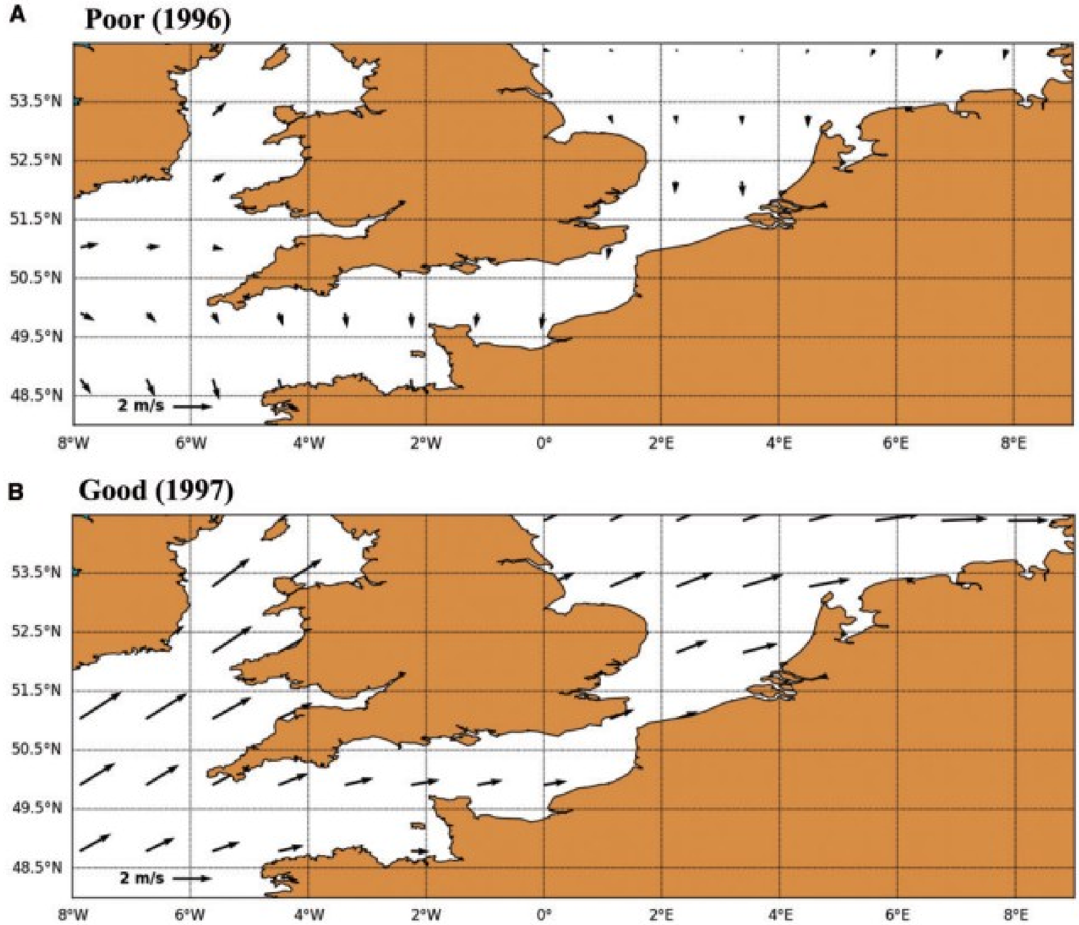

Figure 4. Wind velocity averaged over the sea bass pelagic phase duration (from February to September) for poor (1996—a) and good (1997—b) settlement years.

detailed spatial analysis was carried out for three regions representing differing environmental conditions: North Sea, English Channel, Celtic Sea and Bristol Channel, and Irish Sea. Analysis was performed to link the settlement of particles to spawning at an ICES area scale that included both transport (released in offshore water and settlement in coastal water) and self-seeding (particles released in a particular coastal area that settle in the same area) processes. The first of these processes linked different ICES areas and the second process implied local spawning population that supply nursery areas in the same ICES area.

Results

Environmental characteristics over 1996 and 1997

During the spawning period, the area delimited by 9°C isotherm in the GSY (1997) gradually expanded with time, whereas in the PSY (1996), this area contracted slightly over the first two months and then expanded in April (Figure 3). Temperature gradients shown by distances among isotherms were much larger in the GSY (1997) than the PSY (1996) (Figure 3). The averaged wind field over the period simulated was markedly different in the PSY (1996) and GSY (1997) (Figure 4). In the GSY (1997) winds were relatively strong and homogeneous westerlies, but in the PSY (1996) average winds were more variable with no particularly clear directionality or strength (Figure 4).

The effects of inter-annual variation

More eggs were spawned in the GSY (Table 2) as warmer sea temperatures increased the area available for spawning (Figure 5). Settlement in the known BNAs (indicated in Figures 1 and 2) was predicted to be higher in GSY than in PSY, the only exception was areas with very low settlement in North Wales (Rivers Conwy and Dee) and the Teifi Estuary (Table 3). However, the difference in predicted settlement between the two years was much smaller than estimated in the stock assessment (ICES 2016) (Table 2). Overall, more larvae and higher levels of settlement were observed in GSY than PSY irrespective of behaviour.

The effect of larval behaviour on settlement

Settlement in the Wadden Sea and Morecambe Bay only occurred in the model when tidal migration occurred (Scenarios 2 and 4),

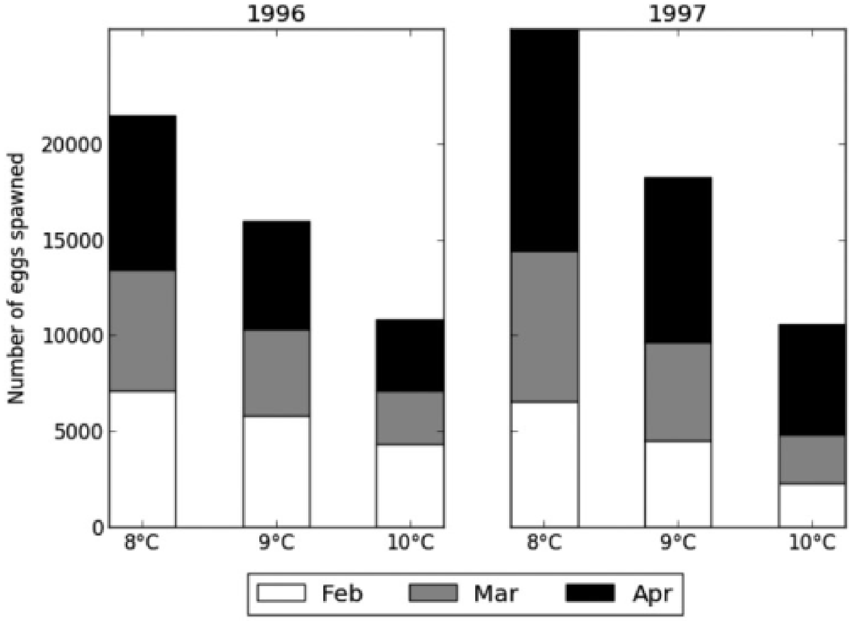

Figure 5. Number of eggs spawned between February and April for different temperature thresholds (8, 9, and 10 °C) in poor (1996—a) and good (1997—b) settlement years.

Table 2. ICES stock assessments estimated in 1997 and 1996 (ICES, 2016), number of particles released in poor (1996) and good (1997) settlement year, and the predicted numbers and percentage of released particles settling (reaching coastal areas) for spawning at water temperatures of above 9 °C and behavioural scenarios 1–4 (see Table 1).

Year	ICES stock assessments	Released particles	Number settling				Percentage settling			
			Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4
1996	1 024	15 957	1 919	3 105	2 112	3 882	12.0	19.5	13.2	24.3
1997	23 272	18 241	4 011	5 717	4 282	6 591	22.0	31.3	23.5	36.1
Ratio	22.7	1.14	2.09	1.84	2.03	1.70	1.83	1.61	1.77	1.49

Ratio represents the ratio between good (1997) and poor (1996) settlement years. Mortality is not included in those simulations and is investigated later as a post-process.

so Scenarios 1 and 3 were excluded from further analysis. Diurnal migration in the larva stage (Table 1) did not affect the number settling or nursery areas reached, but stronger larval dispersal was found with floating behaviour. Similar trends in connectivity were found for the scenarios including diurnal migration in Stage 3 (Figure 6). In this case, connectivity in the English Channel was split between the east and west, and was northward in the Irish Sea and the North Sea. However, connectivity depended on the behavioural scenario, with the maximum settlement obtained in Scenario 4 (float, float, float, and tidal) (Table 2). As a result, Scenario 4 was considered to be the most appropriate, as it produced the highest settlement and reproduced the PSY and GSY, so it was used for all subsequent model simulations. The spatial distribution of settlers in Scenario 4 showed that settlement occurred in most known bass nursery grounds and the highest levels were found in the southwest United Kingdom (Figure 7a and b). There was also settlement predicted in the more northerly regions of the Irish Sea and more broadly across the North Sea (Figure 7a and b).

Assessing the environmental drivers for success of settlement and pelagic duration

Lowering the spawning temperature threshold led to more eggs spawned, with larger numbers of settlers in the GSY than PSY (Figures 3 and 5). More particles were release in PSY than in GSY at a threshold of 10°C, but the opposite was observed at 8 and 9°C (Table 4). However, number settling was always larger in GSY than PSY, regardless of the spawning temperature threshold (Table 4). Settlement was lower and dispersal was over a smaller area in the PSY than GSY, because of weaker average wind speed in northerly or westerly directions (Figure 4a). However, in the warm year (1997), settlement was higher and extended further north in the Irish and North Seas, with prevailing westerly winds of on average of 2 m s^{-1} influenced dispersal (Figure 4b).

The average pelagic phase duration for successful settlement was only very slightly longer in the PSY (1996 ~ 75 ± 5.5 days) than in the GSY (1997 ~ 73 ± 5.5 days), but the spatial

Table 3. Locations of known BNAs by ICES rectangle, latitude and longitude, and percentage of released particles settling (reaching coastal areas) for spawning at water temperatures of above 9 °C and behavioural Scenario 4 (see Table 1).

BNAs	ICES rectangle	Latitude	Longitude	1996	1997	Ratio
Fal Estuary, Percuil River, Helford River	VIIf10	50 to 50.5°	−6 to −5°	2.71	3.76	1.39
Milford Haven	VIIg05	51.5 to 52°	−6 to −5°	1.12	3.49	3.13
River Yealm, Plymouth Rivers—Plym, Tamar, Tavyand Lynher, River Fowey	VIIe03	50 to 50.5°	−5 to −4°	2.30	3.08	1.34
River Camel	VIIf08	50.5 to 51°	−5 to −4°	0.76	1.14	1.50
River Torridge, River Taw	VIIf04	51 to 51.5°	−5 to −4°	0.71	1.32	1.84
Burry Inlet, The Three Rivers—Taf, Tywi and Gwendraeth	VIIf01	51.5 to 52°	−5 to −4°	1.47	2.04	1.39
Teifi estuary	VIIa22	52 to 52.5°	−5 to −4°	0.04	0.07	1.62
River Dyfi, River Mawddach, Dwyryd and Glaslyn Estuary	VIIa19	52.5 to 53°	−5 to −4°	0.32	0.29	0.89
River Dart, Salcombe Harbour, River Avon	VIIe04	50 to 50.5°	−4 to −3°	0.66	1.53	2.30
River Exe, River Teign	VIIe01	50.5 to 51°	−4 to −3°	0.11	0.30	2.67
Aberthaw Power Station Outfall	VIIf05	51 to 51.5°	−4 to −3°	0.28	0.35	1.25
River Conwy, River Dee	VIIa16	53 to 53.5°	−4 to −3°	0.16	0.01	0.07
The Fleet	VIIe02	50.5 to 51°	−3 to −2°	0.13	0.40	3.19
Langstone Harbour, Portsmouth Harbour, Southampton water, Fawley Power Station Outfall—Stanwood Bay, Poole Harbour	VIId01	50.5 to 51°	−2 to −1°	0.06	0.21	3.79
Chichester Harbour	VIId02	50.5 to 51°	−1 to 0°	0.00	0.07	–
Dungeness Power Station	VIId03	50.5 to 51°	0 to 1°	0.19	0.52	2.65
Grain Power Station Outfall, Kingsnorth Power Station Outfall	IVc25	51 to 51.5°	0 to 1°	0.00	0.01	–
Bradwell power station	IVc21	51.5 to 52°	0 to 1°	0.01	0.05	7.87

Ratio represents the ratio between good (1997) and poor (1996) settlement years. Map of ICES rectangle delimiting BNA is presented in Figure 1.

distribution varied between the years (Figure 8a and b). The longest pelagic stage durations in GSY were located at the extremities of the model domain (northern Celtic and North Seas), with shorter durations in southwest England (Figure 8b). In the PSY, longer pelagic duration was seen in coastal areas, notably on southern and western coasts in the PSY compared with GSY (Figure 8a and b). Limited larval dispersal in the PSY meant that only the southern North Sea was reached in the PSY, but settlement occurred in the northern North Sea nursery areas in GSY, even with moderate pelagic phase duration.

Connectivity between spawning areas and nursery grounds

The spawning location of particles that settled successfully showed a broader distribution in GSY than in PSY (Figure 9). Large numbers of particles were spawned in deep areas settled successful, especially in the southern Irish Sea in the GSY and on the Cornwall promontory in both years (Figure 9). A detailed analysis of the mean connectivity patterns between spawning and nursery grounds was performed separately for the Irish Sea, North Sea, and English Channel. Self-seeding was more common in GSY than in PSY (Figure 6), with higher levels of self-seeding in the Irish Sea in GSY driven by sufficiently high sea temperatures for spawning close to nursery grounds (Figure 6e). Less self-seeding occurred in the central Irish sea in PSY (Figure 6b), yet successful migration towards the northern Irish Sea was driven by prevailing south-westerly winds (Figure 6a). The model also showed strong connections between north Cornwall, Devon, and Bristol Channel with the Irish nursery areas in both years, with spawning grounds extending westward in GSY (Figure 6b and e). Eggs spawned in the central western English Channel could settle both in England and France, with movement from the central to the eastern English Channel only found in GSY (Figure 6a and d).

Discussion

Model performance

Model performance in relation to the larval behaviour scenario had no effect on inter-annual settlement variability. The vertical behaviour strategy was selected to make larger numbers of particles reach nursery areas, and a combination of floating behaviour for the egg and early-larval stages in which no active vertical migration occurs, resulted in particles dispersion driven by wind. Coastward migration was only achieved in the model by implementing tidally synchronized vertical migration, with strong tidal currents occurring throughout the domain. The importance of active migration in the final larval stage has been reported for plaice (Fox *et al.*, 2006) and supports the patterns observed from our model.

The predicted areas of highest successful settlement showed good agreement with the main known spawning grounds located in the English Channel, Celtic Sea, Bristol Channel, and North Sea (Thompson and Harrop, 1987; Jennings and Pawson, 1992; Pickett and Pawson, 1994; Fritsch *et al.*, 2007); the annual variability between the GSY and the PSY was also reproduced. The model also predicted successful migration to known nursery grounds in the Wadden Sea (Cardoso *et al.*, 2015) and the Western Scheldt estuary although at lower abundance in other estuaries and lagoons surveyed (ICES, 2014). Sea BNAs occur in estuaries in France and southern Ireland, although at relatively low density in most years compared with similar habitats in England (Fahy *et al.*, 2000). No information on BNAs was available for the Belgian coast, although the short coastline has few potential habitats for young sea bass.

The observed differences in settlement between the GSY and the PSY could be driven by a combination of many factors including: spawning stock, spawning distribution and success, predation, food availability, disease, environmental conditions, and the larval dispersal patterns that we focus on here. The model

A Poor (1996)

Spawning \ Settling	IVb	IVc	VIIa	VIId	VIIe	VIIf	VIIg	VIIh
IVb	1	0	0	0	0	0	0	0
IVc	0	12	0	0	0	0	0	0
VIIa	0	0	489	0	0	0	8	0
VIId	0	27	0	202	17	0	0	0
VIIe	0	0	1	145	1346	536	35	0
VIIf	0	0	15	0	3	180	35	0
VIIg	0	0	241	0	0	81	98	0
VIIh	0	0	41	0	12	149	25	0

B Good (1997)

Spawning \ Settling	IVb	IVc	VIIa	VIId	VIIe	VIIf	VIIg	VIIh
IVb	3	0	0	0	0	0	0	0
IVc	0	115	9	0	0	0	0	0
VIIa	0	50	449	12	0	0	2	0
VIId	0	176	0	674	26	6	0	0
VIIe	0	0	82	215	1104	632	339	0
VIIf	0	0	200	0	20	320	128	0
VIIg	0	0	534	1	0	200	85	0
VIIh	0	0	7	0	32	148	201	0

Figure 6. Connectivity matrices between spawning and settlement by ICES areas for the whole model domain including Bristol Channel and Celtic Sea (VIIf, g&h), English Channel (VIId&e), Irish Sea (VIIa), and North Sea (IVb&c) for poor (1996—a) and good (1997—b) settlement years. Connectivity (number of particles) is coloured according to its strength, with white for no connectivity (0 particle), green for weak connectivity (1 to 100 particles), orange for medium connectivity (100 to 500 particles), and red for strong connectivity (more than 500 particles). ICES areas with self-seeding (the number of particles that are released in a particular coastal area that settle in the same area) have bold borders.

Table 4. Number of particles released, numbers and percentage of released particles settling (reaching coastal areas) for different spawning temperatures thresholds and behavioural Scenario 4 (see Table 1).

Year	Number released			Number settling			Percentage settling		
	8 °C	9 °C	10 °C	8 °C	9 °C	10 °C	8 °C	9 °C	10 °C
1996	21 458	15 957	10 810	6 282	3 105	1 069	29.3	19.5	9.9
1997	25 941	18 241	10 611	10 068	5 717	2 127	38.8	31.3	20.1
Ratio	1.21	1.14	0.98	1.60	1.84	1.99	1.33	1.61	2.03

Ratio represents the ratio between good (1997) and poor (1996) settlement years. Mortality is not included in those simulations and is investigated later as a post-process.

experiments were set up to focus on the effects of larval dispersal patterns in response to inter-annual differences in environmental forcing, so only included a subset of these factors and was likely to be the reason for differences in the magnitude of the ratio between PSY and GSY. The correspondence between model predictions and observations of higher settlement in the GSY was a strong indication that hydrodynamic conditions are an important factor in settlement success of sea bass.

Adult spawning in coastal waters led to higher settlement in the GSY than in the PSY, highlighting importance of appropriate spawning conditions in the coastal water for settlement success. The spatial density of spawning was the same for both the PSY and the GSY, and only occurred where water temperature was above a threshold, leading to more particles being spawned in the GSY or warm year (1997) than for the PSY or cold year (1996). In reality, the spawning output of the stock will vary between years and also be a highest at the centre of spawning aggregations (Fahy et al., 2000), with this centre changing throughout the spawning season moving eastward in the English Channel as sea temperatures increase.

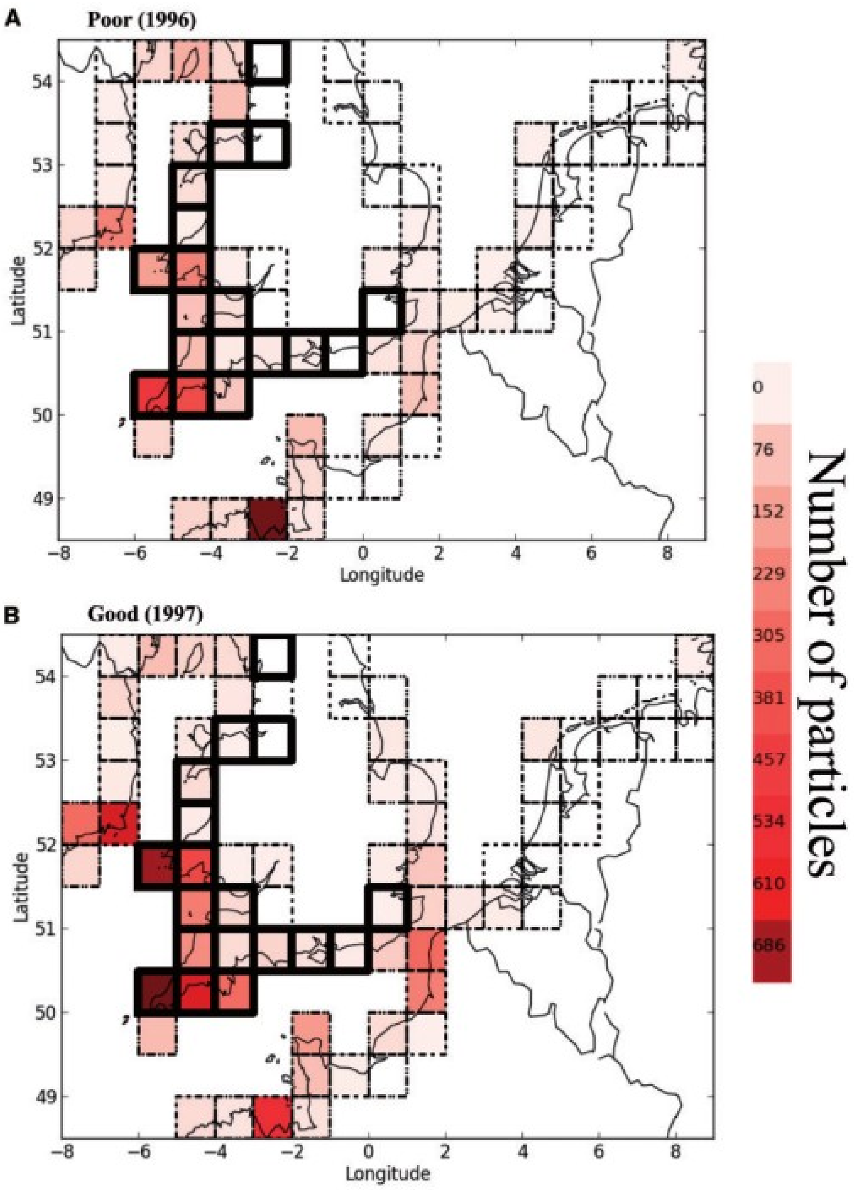

Figure 7. Number of particles settling in coastal areas in Scenario 4 for poor (1996—a) and good (1997—b) settlement years. Coastal ICES rectangles (dashed line) that contain known BNAs (bold solid line).

The present model can be used to predict the settlement pattern for larvae at nursery habitats [Kelley, 1988; Bass (Specified Sea Areas) (Prohibition of Fishing) Order 1999: SI1999 No. 75], based on any plausible time-dependent density distribution of eggs should such data be available for a given year. Currently, spawning distribution data for sea bass in the northern stock are limited to egg distribution maps from the early 1980s and one area in 1990 (Pickett and Pawson 1994). The IBM results presented here were based on uniform egg distribution, therefore provided a biased prediction of the numbers of sea bass larvae reaching nursery habitats relative to numbers of eggs spawned. However, the model predicted the dispersal patterns from individual spawning locations, so indicates physically plausible connectivity between spawning locations and nursery areas and how this varied between years. Moreover, using the same spawning pattern for both years allows for closer identification of the contribution of environmental factors influencing larval dispersal on settlement (see later). For the years examined, the results showed that there was a greater incidence of shorter distance linkages between spawning location and nursery areas in the PSY than in the

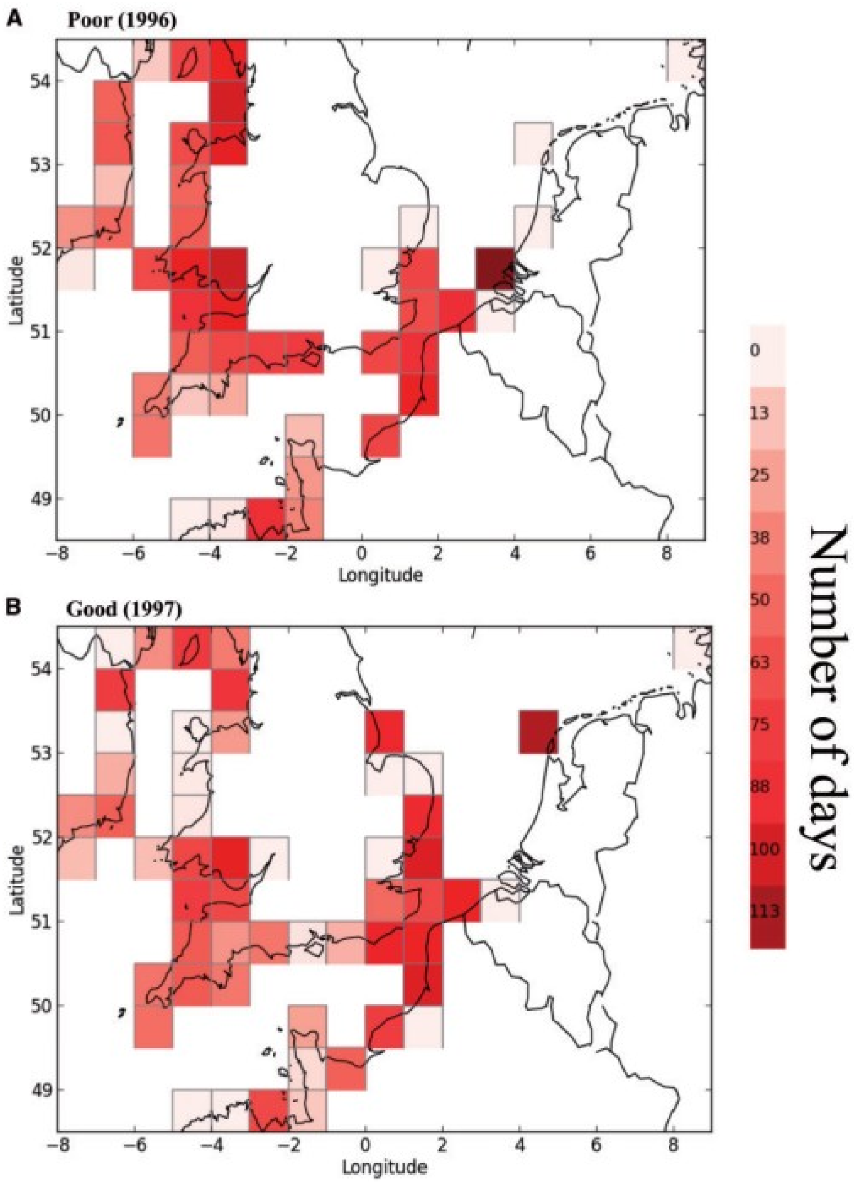

Figure 8. Average duration of pelagic phase for bass settling in different ICES rectangles for poor (1996—a) and good (1997—b) settlement years.

GSY. As similar trends in main connectivity directions and settlement success based on spawning locations were found for different migration strategies, a similar connectivity pattern would be found with a different spawning distributions despite differences in numbers of settlers.

Role of hydrodynamics in determining year class strength

The two environmental factors represented in the model forcing with potential to cause a difference in the results for the two years were air temperature and wind stress, leading to differences in water temperature and residual circulation between the years. In this area, wind and temperature tend to be related. Westerly winds associated with Atlantic depressions bring temperate air from the Atlantic Ocean while enhancing the southwest to northeast residual circulation. In contrast, northerly and easterly winds, associated with high-pressure systems over the continent, bring arctic and/or continental air and stall the residual circulation (Furnes, 1980; Pingree and Griffiths, 1980). The differences in (surface) water temperature between the years affected the size of the spawning area through shifts in the position of the spawning

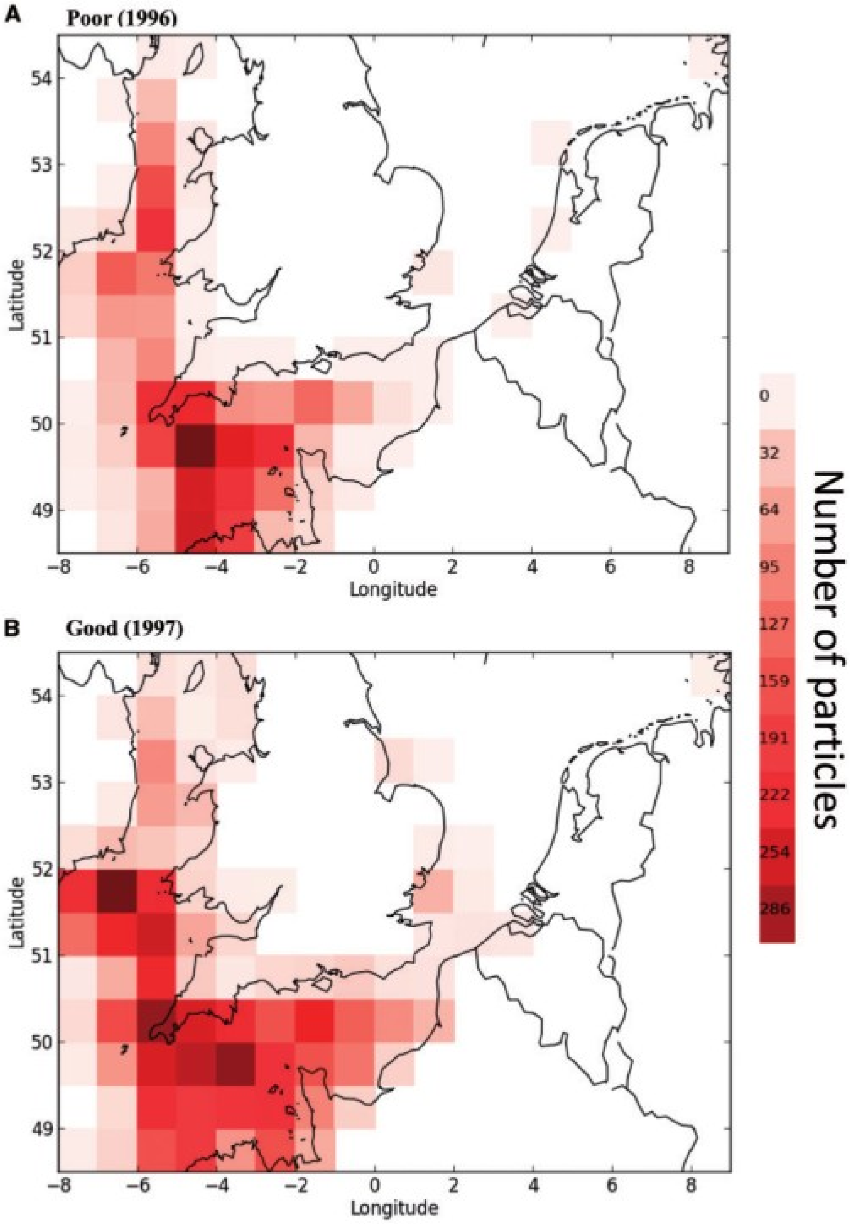

Figure 9. Number of particles originating from an ICES rectangle (spawning location) that settle in a nursery area for poor (1996—a) and good (1997—b) settlement years.

temperature threshold, and affected both development and growth rates. Hence, environmental changes related to increasing sea temperature could lead to earlier spawning and broader spawning area (Politikos *et al.*, 2015), but may also be mediated by latitudinal variations in day length (Vinagre *et al.*, 2009).

Hydrodynamics drive the variation of water temperature, so the spatial extent of an area with a temperature above a threshold varied. For example, in the GSY (1997), the 10°C isotherm encompassed a smaller spawning area than in the PSY (1996). With fewer eggs released at higher spawning temperatures threshold, lower settlement was observed, although the success rate was quite high in PSY compared with GSY. The effect of temperature on egg and larval stage duration, through growth and development rates, was probably under-estimated in the model. This was due to the assumption of constant growth rates for the last two larval stages, but a lack of information on temperature-dependant growth led to this approach. Nevertheless, slightly longer larval durations were simulated in the cold year (1996), resulting in a longer time to reach the settlement size. Mortality was not included explicitly because of lack of data, with stage duration used instead as a proxy for mortality (equivalent to assuming a constant daily mortality). Hence, longer stage durations would also result in higher cumulative mortality. It is not possible to infer which of these effects would dominate, but it is likely that the effect was overshadowed in the model by the difference in wind-driven circulation. The effects of temperature and wind could be separated further with additional model runs using winds from one year and air temperatures from another, but was beyond the scope of the present study.

The difference in wind stress between the two years led to a reduction in north-eastward transport in the English Channel in the PSY (1996) that decreased the number transported successfully to UK nursery grounds. In the GSY (1997), westerly winds predominated, advecting warm oceanic water further eastwards into the English Channel. This caused more short-distance connections between spawning sites and nursery areas, and led to a higher proportion reaching nursery areas. At the local level of individual nursery areas, there were variations on this general theme, most likely related to the complex topography of the area, which could not be investigated within this study. The difference of settlement in the Morecambe Bay for both years was probably driven by the north-easterly wind, with a stronger wind for the GSY, even in the case where spawning in offshore waters was higher in the PSY because of local water temperature. Pelagic duration was negatively correlated with temperature and wind, and was proportional to the migration distance from the spawning ground to coastal areas. As a result, it may be possible to use averaged wind direction, influencing residual current and water temperature, as a proxy for successful settlement. This was not possible within the scope of the current study, but further investigation of the links between annual settlement variability and key drivers (i.e. wind and temperature) would enable a more thorough quantification of their effect, and help to develop a tool for forecasting sea bass settlement.

Implications of connectivity on sea bass management

The definition of biological stocks of sea bass in the NE Atlantic has proved elusive (ICES, 2012). Adult sea bass show strong site fidelity in the non-spawning period (Pawson *et al.*, 2008) and then undertake annual migrations of widely differing distances depending on their location to reach water of appropriate temperature for spawning. The IBM scenarios explored in this paper show that known nursery areas around southwest England, southwest Wales and coastal sites in northwest Brittany and southeast Ireland, are likely to have high settlement rates with relatively short larval transport connections with the main spawning sites in the western English Channel and Celtic Sea. As the spawning season progresses, and particularly in years with stronger westerly winds and warmer conditions, spawning is likely to penetrate farther east in the Channel and into the North Sea. The model shows that in years with stronger penetration of warmer water into the southern North Sea, spawning there can lead to advection of larvae into nursery areas such as in the Wadden Sea and estuaries in the Netherlands, or in the Thames.

From a fisheries management perspective, the results of this study suggest that there is considerable potential for genetic mixing because of larval dispersal leading to weak stock differentiation. Despite the wide and variable dispersal of larvae from spawning sites indicated by the model, spatial management measures to reduce targeting of spawning aggregations in only some areas could have a disproportionate benefit on settlement of young sea bass in nursery areas, with the strongest transport connectivity with the spawning sites being protected. For example, protection of spawning aggregations in the northeast Celtic Sea and off the Bristol Channel might have greatest benefit for settlement to sea BNAs in the Bristol Channel, southwest Wales, parts of southeast Ireland, and in the Irish Sea. Conversely, protection of aggregations only in the Western Channel would mainly benefit nursery areas in both sides of the English Channel depending on the wind conditions and residual current patterns driving the larval transport. Finally, protection of spawning aggregations farther east in the English Channel and in the southern North Sea would have greatest benefits for nursery areas in the eastern Channel and North Sea. Ultimately, consideration of spatial management measures will need an understanding of where the fish spawning at any location have migrated from.

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