DATED 21 November 2012

ABLE HUMBER PORTS LIMITED

and

ELBA GROUP LIMITED

PLANNING OBLIGATION
BY UNDERTAKING

Relating to land at
Killingholme, North Lincolnshire
in favour of

NORTH LINCOLNSHIRE COUNCIL

Bircham Dyson Bell LLP
50 Broadway
London
SW1H 0BL

26 October 2012

THIS PLANNING OBLIGATION BY UNDERTAKING MADE ON 21 November **2012**

IS GIVEN BY

ABLE HUMBER PORTS LIMITED (company registration number 107029) whose registered office is at Ogier House, The Esplanade, St Helier, Jersey JE4 9WG (**AHPL**), and

ELBA GROUP LIMITED (company registration number 109540) whose registered office is at Ogier House, The Esplanade, St Helier, Jersey JE4 9WG (**EGL**)

IN FAVOUR OF:

NORTH LINCOLNSHIRE COUNCIL of Civic Centre, Ashby Road, Scunthorpe DN16 1AB (**NLC**).

BACKGROUND

A. NLC is the local planning authority for the purposes of the Town and Country Planning Act 1990 for the area within which the development is situated;

B. AHPL submitted the Application on 19 December 2011 to obtain authorisation for the Development in the form of the DCO and the Application was accepted by the IPC under section 55 of the 2008 Act on 12 January 2012

C. It is intended that AHPL will be the undertaker for the purposes of the DCO

D. AHPL intends to construct and operate the Development authorised by the DCO

1. DEFINITIONS

"**1990 Act**" means the Town and Country Planning Act 1990;

"**2008 Act**" means the Planning Act 2008;

"**The Application**" means the application for the DCO to authorise the Development on the Application Site made under section 37 of the 2008 Act by AHPL to the IPC on 19 December 2011;

"**The Application Site**" means land at Killingholme, North Lincolnshire which is subject to the DCO shown for the purposes of identification only edged red on Plan 1;

"**Development**" means redevelopment of the Application Site to provide a marine energy park consisting of a quay and associated onshore manufacturing, assembly and storage facilities, and environmental mitigation;

"**DCO**" means the order for development consent to be made under the 2008 Act pursuant to the Application;

"**Group Companies**" means Elba Group Limited and all of its subsidiary companies and "**Group Company**" means any of them;

"**Implement**" means the implementation on the Application Site of the works authorised by the DCO comprised in the Development in North Lincolnshire specified in Schedule 1 to the DCO by the carrying out of any material operation within the meaning of sections 56(2) and 56(4) of the 1990 Act provided that for the avoidance of doubt the carrying out of the demolition of existing buildings and structures, termination or diversion of existing services or temporary diversion of highways, temporary construction, site preparation, investigation works, archaeological investigations, environmental site investigations, decontamination works, or works and operations to enable any of the foregoing to take place, or the carrying out of any development pursuant to the DCO in the East Riding of Yorkshire shall not constitute a material operation and consequently shall not individually or together constitute a material operation and consequently shall not individually or together constitute implementation for the purposes of this definition or this deed and "**Implementation**" and cognate expressions shall be construed accordingly;

"**IPC**" means the Infrastructure Planning Commission;

2. INTERPRETATION

In this undertaking unless the context otherwise requires:

2.1 references to any party include the successors in title of that party and those deriving title through that party and, in the case of NLC, the successors to its function as local planning authority.

2.2 the words "including" and "include" and words of similar effect shall be deemed to limit the general effect of the words preceding them.

2.3 obligations undertaken by a party which comprises more than one person shall be deemed to be made by them jointly and severally;

2.4 words importing persons shall include firms, companies and bodies corporate and vice versa;

2.5 words importing the singular shall include the plural and vice versa;

2.6 words importing any one gender shall include either other gender;

2.7 construction of this agreement shall ignore the headings, contents list and front sheet (all of which are for reference only);

2.8 references to a numbered clause, schedule, paragraph or appendix are references to the clause, schedule, paragraph or appendix to or of this agreement so numbered;

2.9 any reference to any statutory provision shall be deemed to include any subsequent re-enactment or amending provision;

2.10 an obligation to do something includes an obligation to procure it being done;

2.11 an obligation not to do something includes an obligation not to allow it to be done; and

2.12 where any approval, consent or agreement is required from any party under this agreement, that approval, consent or agreement shall not be unreasonably withheld or delayed.

3. LEGAL EFFECT

3.1 This undertaking is a development consent obligation made pursuant to the provisions of section 106 of the 1990 Act and all other enabling powers with the intention of binding the Application Site.

3.2 With the exception of Clause 5, this undertaking will not take effect until the DCO has been made and comes into effect.

3.3 This undertaking is enforceable by NLC as local planning authority both under the provisions of section 106 of the 1990 Act and as an undertaking given under seal by EGL and AHPL.

3.4 No party shall be liable for a breach of this undertaking in respect of any period during which it no longer has an interest in the Land or the relevant part thereof but without prejudice to liability for any subsisting breach prior to parting with such interest.

3.5 Nothing in this undertaking prohibits or limits the right to develop any part of the Application Site in accordance with a planning permission (other than the DCO relating to the Development) granted (whether or not on appeal) after the date hereof.

4. PARENT COMPANY GUARANTEE

AHPL covenants with NLC:

4.1 not to implement the Development nor to exercise any powers of compulsory acquisition authorised by the DCO unless and until:

4.2 a parent company guarantee has been provided substantially in the form annexed ad Appendix 1 (or in such other form as may be approved by NLC acting reasonably) by a Group Company previously approved in writing for this purpose by NLC; or

4.3 alternative security in a form approved in writing for that purpose by NLC acting reasonably have been provided including but not limited to a bond, bank guarantee or policy of insurance;and

4.4 AHPL covenants not to take any steps to place AHPL into administration or liquidation (subject to any overriding statutory duty of AHPL).

5. ABLE HUMBER PORTS LTD

5.1 EGL covenants with NLC not to pass any resolution to put APHL into any form of insolvency or otherwise to procure its insolvency for so long as APHL remains the undertaker for the purposes of the DCO (subject to any overriding statutory duty of the directors of EGL).

6. COMMENCEMENT AND TERMINATION

6.1 With the exception of Clause 5 this Deed shall not have effect until the DCO is made.

6.2 This Deed shall determine if the DCO is quashed, cancelled, revoked or expires prior to implementation.

7. RIGHTS OF THIRD PARTIES

7.1 A person who is not a party to this undertaking will have no rights under the Contracts (Rights of Third Parties) Act 1999 to enforce any of the terms of this undertaking. This clause does not affect any right or remedy of any person which exists or is available otherwise than pursuant to that Act.

8. VARIATIONS

8.1 No variation to this undertaking shall be effective unless made by deed or pursuant to the determination of an application made under section 106A of the 1990 Act.

9. GOVERNING LAW AND JURISDICTION

9.1 This undertaking is governed by and is to be construed according to English law and the English courts will have jurisdiction with regard to all matters arising from it.

10. SEVERANCE

10.1 If any court or competent authority finds that any provision of this undertaking (or any part of any provision) is invalid, illegal or unenforceable, that provision or part-provision shall, to the extent required, be deemed to be deleted, and the validity and enforceability of the other provisions of this undertaking shall not be affected.

11. COUNTERPARTS

11.1 This undertaking may be executed in original and any number of counterparts.

IN WITNESS whereof the parties executing this undertaking as a deed the day and year first before written.

EXECUTED (but not delivered until the date)
hereof) as a deed by **ELBA GROUP**)
LIMITED acting by one director and its)
secretary or by two directors)

Director [redacted]

Director/Secretary [redacted]

Stephen Osmont
Alternate Director

EXECUTED (but not delivered until the date hereof) as a deed by **ABLE HUMBER PORTS LIMITED** acting by one director and its secretary or by two directors)

Director

Director/Secretary

[redacted]

Stephen Osmont
Alternate Directc.

APPENDIX 1: FORM OF PARENT COMPANY GUARANTEE

DATED **2012**

PARENT COMPANY GUARANTEE

relating to

Able Marine Energy Park at
Killingholme, North Lincolnshire

THIS GUARANTEE is made on 2012

AND IS GIVEN BY:

(1) (Group Company approved by NLC) ("Guarantor")

IN FAVOUR OF:

(2) **NORTH LINCOLNSHIRE COUNCIL** of Civic Centre, Ashby Road, Scunthorpe DN16 1AB (NLC).

BACKGROUND

A. NLC is a local planning authority for the purposes of the 1990 Act for the area within which the Development is situated.

B. A DCO was granted on 2013 authorising the Development.

C. AHPL will be the undertaker for the purposes of the DCO.

D. The Guarantor has agreed to guarantee the performance by AHPL, of certain obligations in the DCO.

IT IS AGREED:

1. DEFINITIONS AND INTERPRETATION

1.1 For the purposes of this deed the following expressions shall have the following meaning:

"**1990 Act**" means the Town and Country Planning Act 1990;

"**2008 Act**" means the Planning Act 2008;

"**AHPL**" means Able Humber Ports Limited (company registration number 107029) whose registered office is at Ogier House, The Esplanade, St Helier, Jersey JE4 9WG;

"**the Application**" means the application for the DCO to authorise the Development on the Application Site made under section 37 of the 2008 Act by AHPL to the IPC on 19 December 2011;

"**the Application Site**" means the land subject to the DCO;

"**Compensation**" means any compensation properly payable as a result of the exercise of the powers of compulsory acquisition by AHPL authorised by the DCO [xxx];

"**Development**" means redevelopment of the Application Site to provide a marine energy park consisting of a quay and associated onshore manufacturing, assembly and storage facilities, and environmental mitigation;

"**DCO**" means the order for development consent made under the 2008 Act pursuant to the Application;

"**Implement**" means the implementation on the Application Site of the works authorised by the DCO comprised in the Development in North Lincolnshire specified in Schedule 1 to the DCO by the carrying out of any material operation within the meaning of sections 56(2) and 56(4) of the 1990 Act provided that for the avoidance of doubt the carrying out of the demolition of existing buildings and structures, termination or diversion of existing services or temporary diversion of highways, temporary construction, site preparation, investigation works, archaeological investigations, environmental site investigations, decontamination works, or works and operations to enable any of the foregoing to take place, or the carrying out of any development pursuant to the DCO in the East Riding of Yorkshire shall not constitute a material operation and consequently shall not individually or together constitute a material operation and consequently shall not individually or together constitute implementation for the purposes of this definition or this deed and "**Implementation**" and cognate expressions shall be construed accordingly;

"**IPC**" means the Infrastructure Planning Commission;

"**Successful Claimant**" means any person claiming Compensation whose claim is admitted or compromised by AHPL or whose claim is finally determined (which shall include the disposal of all appeals and challenges in respect of any such determination) such that Compensation is payable by AHPL;

1.2 reference to any gender includes all genders, reference to the singular includes the plural (and vice versa) and reference to persons includes bodies corporate, unincorporated associations and partnerships (whether or not any of them have a separate legal personality);

1.3 reference to any legislative provisions will be deemed to include any subsequent re-enactment, amending or replacement provision;

1.4 reference to any agreement or document is to that agreement or document as amended or varied from time to time in accordance with the terms of such agreement or document; and

1.5 the list of contents and clause headings are included for convenience only and do not affect its interpretation.

2. GUARANTEE, ETC.

2.1 The Guarantor irrevocably and unconditionally:

2.1.1 guarantees to NLC and the Successful Claimants, as a continuing guarantee, the payment by AHPL of all Compensation properly payable by AHPL to any parties ("Obligations"); and

2.1.2 undertakes with NLC and the Successful Claimants that, whenever AHPL fails to perform or pay any of the Obligations, the Guarantor will immediately fully and properly perform (or cause to be fully and properly performed) each Obligation in respect of which AHPL has defaulted, make good (or cause to be made good) any breach by AHPL of an Obligation, and pay any amount due from AHPL to the person to whom such liability is owed.

2.2 The Guarantor covenants not to take any steps to place AHPL into administration or liquidation (subject to any overriding statutory duty of the directors of the Guarantor)

3. THE GUARANTOR'S WARRANTIES

The Guarantor warranties and represents that:

3.1 it has the full capacity and authority to enter into this deed;

3.2 the entry into and performance by the Guarantor of this deed and the transactions contemplated by it do not and will not:

3.2.1 conflict with (1) any law or regulation applicable to it or (2) the constitutional documents of the Guarantor;

3.2.2 conflict with or result in a breach or default under any agreement or other obligation binding on the Guarantor or any of its assets.

4. WAIVER OF DEFENCES

The obligations of the Guarantor under this deed will not be reduced, discharged, impaired or otherwise affected by any act, omission, matter or thing which, but for this clause 4, would reduce, release or prejudice any of its obligations under this deed (without limitation and whether or not known to it) including:

4.1 any time, waiver, consent, concession, compromise, forbearance or indulgence granted to, or composition with, AHPL or any other person;

4.2 any legal limitation, incapacity or lack of power, authority or legal personality of or any dissolution, merger, amalgamation, reconstitution, reorganisation or change in the members, name, status or constitution of AHPL;

4.3 any amendment, addition, omission or extension (however fundamental) to the DCO or any variation in the obligations undertaken under or pursuant to the DCO;

4.4 any amendment, addition, omission or extension to or variation of any security or guarantee or indemnity;

4.5 any unenforceability, illegality or invalidity of any obligation of any person under the DCO;

4.6 any insolvency, winding up, administration or similar proceedings or compromise or arrangement with creditors of AHPL or any other person; and

4.7 the making of (or any delay in making or failure to make) any demand on AHPL.

5. CONTINUING SECURITY

5.1 This deed is a continuing security which shall remain in full force and effect regardless of any intermediate discharge, performance or payment of any of the Obligations (in whole or in part) until the complete performance, observance and compliance by AHPL of all the Obligations subject to clause 5.2.

5.2 This deed shall determine if:

5.2.1 the DCO is quashed, cancelled, revoked or expires prior to implementation;

5.2.2 if the period of limitation for any claim in respect of the Obligations expires without any such claim being made; or

5.2.3 if claims validly made are settled and determined.

6. NOTICES

6.1 Any notice to be given under this deed is to be delivered personally (which includes delivery by courier) or sent by pre-paid recorded or special delivery post to the party concerned at its address set out in this deed or to such other address as may be notified by that party for the purposes of this clause.

6.2 Any notice given pursuant to this deed will be deemed to have been served as follows:

6.2.1 if delivered personally, at the time of delivery, and

6.2.2 if sent by recorded or special delivery post, 48 hours after being delivered into the custody of the postal authorities but excluding Saturdays, Sundays and public and bank holidays in England and Wales.

7. RIGHTS OF THIRD PARTIES

7.1 Save in respect of Successful Claimants, a person who is not a party to this deed will have no right under the Contracts (Rights of Third Parties) Act 1999 to enforce any of the terms of this deed. This clause does not affect any right or remedy of any person which exists or is available otherwise than pursuant to that Act.

8. GOVERNING LAW AND JURISDICTION

8.1 This deed is governed by and is to be construed according to English law and the English courts will have jurisdiction with regard to all matters arising from it.

IN WITNESS whereof the parties executing this undertaking as a deed the day and year first before written.

EXECUTED (but not delivered until the date)
hereof) as a deed by)
(Guarantor) acting by one director and its)
secretary or by two directors)

[redacted]

Director [redacted]

Director/Secretary [redacted] Stephen Osmont
Alternate Director

EXECUTED (but not delivered until the date)
hereof) as a deed by **ABLE HUMBER**)
PORTS LIMITED acting by one director)
and its secretary or by two directors) [redacted]

Director [redacted]

Director/Secretary [redacted]

KEY

Able Marine Energy Park Land Boundary

[redacted]

Rev	Date	Comments	Drw	Chk	App
A	16/11/12	Preliminary Issue	JH	PMS	PMS

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Project: ABLE Marine Energy Park

Client: North Lincolnshire Council

Title: Planning Obligation Guarantee Plan

PRELIMINARY

Scale:	Drawn	Checked	Approved
1:12,500@A3	J Harris	PMS	PMS
Date	16/11/2012	16/11/2012	16/11/2012

DATED 21 November 2012

(1) ABLE HUMBER PORTS LIMITED

and

(2) NORTH EAST LINCOLNSHIRE COUNCIL

UNILATERAL UNDERTAKING

Under Section 106 of the Town and Country Planning Act 1990
(relating to land at North and South Killingholme, North Lincolnshire)

BIRCHAM DYSON BELL

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THIS UNILATERAL UNDERTAKING is made the 21st day of November 2012

BY

(1) ABLE HUMBER PORTS LIMITED (Company number: 107029) registered at Ogier House, The Esplanade, St Helier, JE4 9WG **(the Developer)**;

TO

(2) NORTH EAST LINCOLNSHIRE COUNCIL of the Municipal Offices Town Hall Square, Grimsby, North East Lincolnshire DN31 1HU **(the Council)**

WHEREAS

(A) The Developer is the owner in fee simple in possession of the Site free from incumbrances;

(B) By a written application dated the nineteenth day of December 2011 to the Infrastructure Planning Commission (now the National Infrastructure Directorate (**"NID"**) of the Planning Inspectorate) and bearing the application reference number TR030001, the Developer applied for development consent for the Development (**"the Application"**);

(C) The Development is located within the local authority area of North Lincolnshire but may give rise to increased traffic movements on highways within the neighbouring local authority area of North East Lincolnshire;

(D) The Council is the Local Planning Authority for the purposes of the Town and Country Planning Act 1990 and the Highways Authority for the purposes of the Highways Act 1980 for the North East Lincolnshire authority area with which this Unilateral Undertaking is concerned;

(E) The Developer has agreed to enter into this Unilateral Undertaking to give the following obligations in the manner hereinafter appearing.

NOW THIS DEED WITNESSETH as follows

1 Interpretation

1.1 In this Unilateral Undertaking the following expressions shall unless the context otherwise requires have the following meanings:

"Commencement of the Development" means the date upon which the Development is begun by the carrying out of a material operation (as defined by Section 56 of the Town and Country Planning Act 1990) pursuant to the implementation of the Development with the exception of any works carried out in connection with any archaeological investigation of the Site or trial holes or other operations to establish ground conditions of the Site or any other preliminary investigations;

"Cycle Provision Scheme" means a scheme for the provision of new infrastructure for use by cyclists accessing the Site;

"Development" means the development of the Site as applied for in the development consent application to the IPC and detailed in the Schedule to this Undertaking;

"Draft Development Consent Order" means the latest draft of the Able Marine Energy Park Development Consent Order which accompanied the Application, a copy of which is appended to this Undertaking;

"Development Consent Order" means the Able Marine Energy Park Development Consent Order as finally made by the Secretary of State for Transport;

"Draft Requirement 25(2)" means paragraph 25(2) of Schedule 11 to the Draft Development Consent Order;

"Highways Contribution" means the maximum sum of £50,000 being the indicative cost to the Council of implementing the Pelham Road mini-roundabout Improvements;

"Occupation" means occupation of the Development for the purposes permitted by the Permission but shall not include occupation for the purposes of construction or occupation in relation to security;

"Peak Hours" means the hours between 07.00 and 09.30 and between 15.00 and 18.00 on any day other than a Saturday, Sunday, Bank or local school holiday;

"Pelham Road mini-roundabout" means the existing mini-roundabout located at the junction between Pelham Road and the A1173;

"Pelham Road mini-roundabout Improvements" means improvements to the existing layout of the mini-roundabout by relocating it approximately 2 metres northeast from its existing location, widening all arms to allow two lanes on each approach and to increase the flare on the Pelham Road approach arm as detailed in Drawing number NEA1114/PO/01 Rev B;

"Requirements" means the requirements within the Development Consent Order;

"Site" means the area of land at North and South Killingholme, North Lincolnshire, shown outlined in red on drawing number AME-02000 and AME-02001 annexed hereto;

"Travel Plan" means the Travel Plan to be prepared and submitted for approval pursuant to Draft Requirement 25(2) of the Draft Order; and

"Travel Plan Steering Group" means a steering group to be established by the Developer and to comprise representatives of:

(a) the Council;

(b) North Lincolnshire Council;

(c) the Highways Agency;

(d) the Developer; and

(e) other occupiers of the Site, from time to time as appropriate.

1.2 Words of the masculine gender shall incorporate the feminine and neuter genders and words denoting natural persons include companies corporations and firms and all such words shall be construed interchangeably in that manner.

1.3 References in this Deed to Draft Requirements are to be interpreted as being adjusted to the extent necessary to accord with the provisions of the Requirements.

2 Planning Obligation

2.1 This Unilateral Undertaking is made pursuant to Section 106 of the Act and is a Planning Obligation for the purposes of that section.

2.2 The Council is the Local Planning Authority by whom the provisions of this Planning Obligation are intended to be enforceable.

3 Highways Improvements

3.1 The Developer hereby undertakes:

3.1.1 to monitor and record traffic movements at Pelham Road mini-roundabout during Peak Hours:

(a) immediately prior to the Commencement of the Development (hereinafter referred to as "**the Baseline Results**"); and

(b) on the first working day falling three years after the date of first Occupation of the Development and at three yearly intervals thereafter for a total period of 9 years from the aforementioned date of first Occupation

and on each occasion to provide the monitoring results to the Council as soon as possible thereafter;

3.1.2 to undertake a second round of traffic monitoring at Pelham Road mini-roundabout during Peak Hours and provide the results to the Council as soon as possible thereafter but only if, on any occasion:

(a) the initial monitoring results referred to in clause 3.1.1(b) are deemed by the Council, acting reasonably, to demonstrate, when compared to the Baseline Results, that traffic movements generated by the Development are causing a significant increase in the overall number of traffic movements at Pelham Road mini-roundabout, and

(b) the Council provides written notice of this to Developer together with a request that further monitoring be undertaken;

3.1.3 to pay to the Council the Highways Contribution but only if subsequent monitoring results provided pursuant to clause 3.1.2 also demonstrate that traffic movements generated by the Development are causing a significant increase in the overall number of traffic movements at Pelham Road mini-roundabout and further that such an increase is causing a detrimental impact on the operation of the Pelham Road mini-roundabout.

4 Cycle Provision

4.1 The Developer hereby undertakes, within six months of the date of approval of the Travel Plan pursuant to Draft Requirement 25(2), to establish the Travel Plan Steering Group.

4.2 The Developer shall request the Travel Plan Steering Group to undertake an annual review of the Travel Plan and this shall include consideration of the adequacy of cycle access to the Site.

4.3 In the event that the Travel Plan Steering Group, in considering the adequacy of cycle access to the Site:

(a) identifies a need for improved cycle access to the Site;

(b) approves, by majority vote, a Cycle Provision Scheme for this purpose; and

(c) appoints a contractor to construct the Cycle Provision Scheme the Developer hereby undertakes to make an Appropriate financial contribution towards the costs of implementing the approved Cycle Provision Scheme.

4.4 For the purpose of this clause 4, an Appropriate financial contribution means such sum as may reasonably be proposed by the Steering Group and agreed by the Developer, having regard to:

(a) the total cost of the approved Cycle Provision Scheme,

(b) the overall purpose of the Cycle Provision Scheme and the properties which might be served or otherwise benefit from it;

(c) the contributions being made by other occupiers of the Site, and

(d) contributions being made by other employers and developers whose property might be served or otherwise benefit from the Cycle Provision Scheme

PROVIDED ALWAYS that in any case, the Appropriate financial contribution will not exceed the sum of £150,000.

5 Third Parties

It is agreed that nothing in this Unilateral Undertaking shall be construed as expressly providing a right for any third party within the meaning of the Contract (Rights of Third Parties) Act 1999 and nothing in this Unilateral Undertaking is intended to confer on any third party (whether referred to herein by name class description or otherwise) any benefit or any right to enforce any provision of this Unilateral Undertaking.

SCHEDULE: DEVELOPMENT AS APPLIED FOR IN THE DEVELOPMENT CONSENT

1. The construction and operation of a 1,320 metre quay and associated dredging and land reclamation;
2. the provision of onshore facilities for the manufacture, assembly and storage of marine energy infrastructure and related items;
3. the diversion of footpaths that run along the north and south shore of the Humber
4. any necessary upgrade works to surrounding roads (Rosper Road, Eastfield Road, the A160 and the A180);
5. the conversion of the railway into a private siding;
6. the extension or diversion of a sludge main and a drainage ditch;
7. the re-siting of apparatus;
8. the interference with rights of navigation;
9. the creation of a harbour authority;
10. a deemed licence under Part 4 of the Marine and Coastal Access Act 2009;
11. the modification of public and local legislation;
12. the creation of a compensatory environmental habitat on the north bank of the Humber; and
13. the compulsory acquisition of land and rights in land and powers of temporary occupation of the land to allow Able to carry out and operate the above development.

Signed as a Deed for and on behalf of)
ABLE HUMBER PORTS LIMITED)

[redacted]
Director

[redacted] Stephen Osmont
Alternate Director
Director or Secretary

Planning Act 2008
Infrastructure Planning (Applications: Prescribed Forms and Procedure) Regulations 2009
Regulation 5(2) [a]
Document reference: TR030001/APP/

Applicant's Response to Issues Raised by Natural England re Benthic Invertebrates in its Summary of Case for the Compensation Hearing

November 2012
Revision: 0
GOBE

Executive Summary

This report has been prepared to advise the Planning Inspectorate of the Applicant's response to questions raised by Natural England (NE) concerning the marine benthic invertebrate baseline at North Killingholme Marshes (NKM) foreshore. The report has been prepared by Gobe Consulting Ltd, with assistance from the Institute of Estuarine and coastal Studies at the University of Hull (IECS).

The report provides clarification on the Allen report dated 2006 which is referred to in the Environmental Statement for AMEP, making reference to the extensive clarification that IECS have previously provided to NE. It makes clear that the Applicant has used raw data from this report for setting biomass targets, rather than making use of the report's analysis.

The report further demonstrates that the Applicant's data are fit for the purpose of characterisation and are representative of a dynamic estuarine system. Through cross referencing with a number of other studies, the report demonstrates that the abundance is within the boundaries of "normal"; i.e abundance at NKM is not sparse, but other areas contain/have contained higher abundances; and in terms of numbers of *Macoma* in particular, NKM foreshore has a level of abundance which is demonstrably average for the estuary.

The report reiterates the need for a pre-construction benthic invertebrate biomass survey to support and further define the baseline purposes for the EMMP's, as previously agreed with Natural England and confirmed at the Hearings.

1. NE statement:

1.0.1. Monitoring targets are required for SPA birds invertebrate prey that colonise the intertidal compensation potentially to be created adjacent to Cherry Cobb Sands. These targets will rely upon baseline data for the Humber (Allen 2006) and baseline Killingholme Marshes Foreshore (IECS, 2010). Although thesetwo references provide very contrasting results, data from both studies are described as typical. With such a wide range in the figures it would be difficult to define a meaningful target unless the following points can be clarified:

1. Can the differences in the abundance of invertebrates between Killingholme (IECS 2010) and abundance at other sites in the Humber (Allen 2006), be solely the result of natural variation alone?
2. Can it be confirmed that the abundance figures in Allen are indeed individuals per $0.01m^2$? Is it possible these figures are based on individuals per 1 m^2, or alternatively a cumulative total of individuals per station (with up to five samples taken at each station across a transect from high to low shore)?
3. Why would sub-tidal invertebrate abundance in Allen (2006) be cumulative at each site (i.e. 3 x 0.1 = $0.3m^2$), whereas inter-tidal abundance is not, despite up to 5 x $0.01m^2$ samples being available.
4. Could the apparent discrepancy be the result of using different mesh diameters within the sieves used for the two surveys? Possibly it would account for differences particularly in the small fauna.
5. Could the apparent discrepancy be the result of using different sampling depths between the two surveys, so that whilst surface area remained constant, volume did not (15cm constant depth at Killingholme 2010 but unspecified in Allen)?
6. If there is not an issue with the data, is it possible for the mean abundance figures from a group of stations presented within the multivariate analysis (Allen 2006) to be lower than the minimum figures from any of the respective stations presented within the univariate analysis? For example:

   i. Multivariate groups 5 & 6 = samples from sites/stations 9 & 10.
   ii. Minimum individual sample at site 9 = 23 site & site 10 = 39 (i.e. all other individual samples must exceed these values).
   iii. Group 5.1 mean abundance = 12.45 (comprising a collection of unnamed individual samples from sites 9 & 10, the minimum value of which must exceed 23).
   iv. Group 5.2 mean abundance = 22.38 (comprising a collection of unnamed individual samples / sites, the minimum value of which must exceed 23).
   v. Group 5.3 mean abundance = 13.81 (comprising a collection of unnamed individual samples / sites, the minimum value of which must exceed 23).

vi. Group 6 = 45.3 (comprising a collection of unnamed individual samples / sites, the minimum value of any one sample must exceed 23).

7. Are *Hediste* and *Macoma* biomass data (and not just abundance) available within the EA datasets analysed within Allen 2006? If so, can these be presented in order to provide a like for like comparison for Killingholme?
8. How were sampling stations / sites selected for the 2010 Killingholme study, as the most relevant area we are concerned about (i.e. the mudflat that supports the high densities of black-tailed godwits), has the lowest density of samples (3 from a total of 36 with just one on the low-shore)? Sample selection was effectively 'random' but within a series of prescribed transects and elevations.
9. Key prey species for black-tailed godwit at Killingholme are likely to be *Hediste* and *Macoma*. What is the effect of sampling in May on both of these species, in terms of biomass and abundance? For example, what might be the effects of both prey depletion by waterbirds over the winter period, and also die-off of adult *Hediste* post-reproduction?
10. Invertebrate data were in fact collected at Killingholme as part of the early Allen study. This was not clear in the report however, as the south bank stations were numbered rather than named and site 6 (Killingholme) was omitted from the map showing sampling stations. What could account for the discrepancy between the Killingholme figures from Allen (2006) and IECS (2010)? For example:

	Killingholme[1] (Allen 2006)	**Killingholme (IECS 2010)**
Mean abundance	684	TBC
Minimum abundance	7	5
Peak abundance	2386	197

Given the various issues with the EA data, not the least its age (c. 15 years), I think this is too difficult to answer with any certainty.

I would add that there will be a detailed baseline benthic survey undertaken pre construction which will provide a more comprehensive dataset for any future target setting etc.

[1] South Killingholme 518585 417640

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2. Sean Leake response

2.0.1. The initial statement requires addressing prior to a response to the individual points. This is as a result of a number of assertions which are misplaced. The first point "These targets will rely upon baseline data for the Humber (Allen 2006) and baseline Killingholme Marshes Foreshore (IECS, 2010)" does not reflect the applicant's case on provision of a **baseline**. The data for NKM foreshore provide a characterisation of the area in order to inform the EIA and to allow for the design of subsequent baseline surveys as agreed by the applicant and Natural England. The targets provided are therefore indicative based on a wide range of data sources – not a ***reliance*** on characterisation surveys and 10 year old Environment Agency data. However to not discuss the available data and temporal patterns for the mid Humber estuary would be remiss.

2.0.2. A secondary assertion made within the initial statement is that "Although thesetwo[*sic*] references provide very contrasting results, data from both studies are described as typical." This position is certainly not atypical of intertidal mudflats within dynamic estuarine systems. The typical mid-estuary benthic intertidal community within the Humber has been described within a wide range of studies and has been both iterated in the supplementary environmental information and the Environmental Statement. Intertidal flats within an estuary exhibit significant spatial and temporal variability in benthic macrofaunal species composition, density and biomass, and there is a long history of investigations in which this variability has been related to such environmental variables as salinity, sediment types and tidal depth. IECS has further iterated this in previous answers provided below:

2.0.3. We have checked the raw data used in the Allen report, and it would seem to be broadly comparable to that identified from the 2010 Killingholme survey in terms of community composition and abundance. A quick look at the figures for the south bank area from the EA data (Allen report) would suggest an abundance of Hediste in the region of 32 individuals per core which gives an abundance of c 4,050 / m^2. This is compared to a max of 30 (c. 3,800 / m^2) and a mean of c. 10 individuals (upper shore) giving an m^2 abundance of c. 1,200 from the 2010 survey along the NK frontage. A quick look at Hediste abundance from the north bank (e.g. PHS and adjacent Cherry Cobb frontage) gives max densities of between c. 1,000 and 2,700 / m^2, as well as areas of absence or near absence as seen from the EA data and the NK work. As such, I would think that the NK Hediste abundance is reasonable and characteristic for the area, but would also add that their distribution can be patchy and so there is often a high degree of variability between stations (and even sometimes between replicate cores within a station) that needs to be considered.

2.0.4. As regards the individual points raised by Natural England, many of these have been answered directly by IECS already although it would appear prudent to provide some additional reference material. The individual points are addressed, in turn, below.

2.0.5.	**NE Point 1**: Can the differences in the abundance of invertebrates between Killingholme (IECS 2010) and abundance at other sites in the Humber (Allen 2006), be solely the result of natural variation alone?

2.0.6. **Response**: as highlighted in the original IECS response there does not appear to be a significant divergence beyond that which may be attributable to natural variation within a dynamic environment. This is very much demonstrated by the benthic communities found in the Humber in other studies. An example of this is the study by Fujii (2007) (annexed to this report) who found notable variation between stations on a single mudflat near Grimsby and between transects and individual stations across the Humber more widely. Of note in the following figures are the variation at Grimsby and also at transect N3 and transect S4 which correspond most closely to CCS and NKM respectively, during September of 2003 and 2004.

2.0.7. Of note is that N3 which corresponds with CCS (and for the purposes of the Fujii paper is the lower estuary) is considered to have significantly higher average biomass and abundance than the middle estuary (which corresponds with S4).

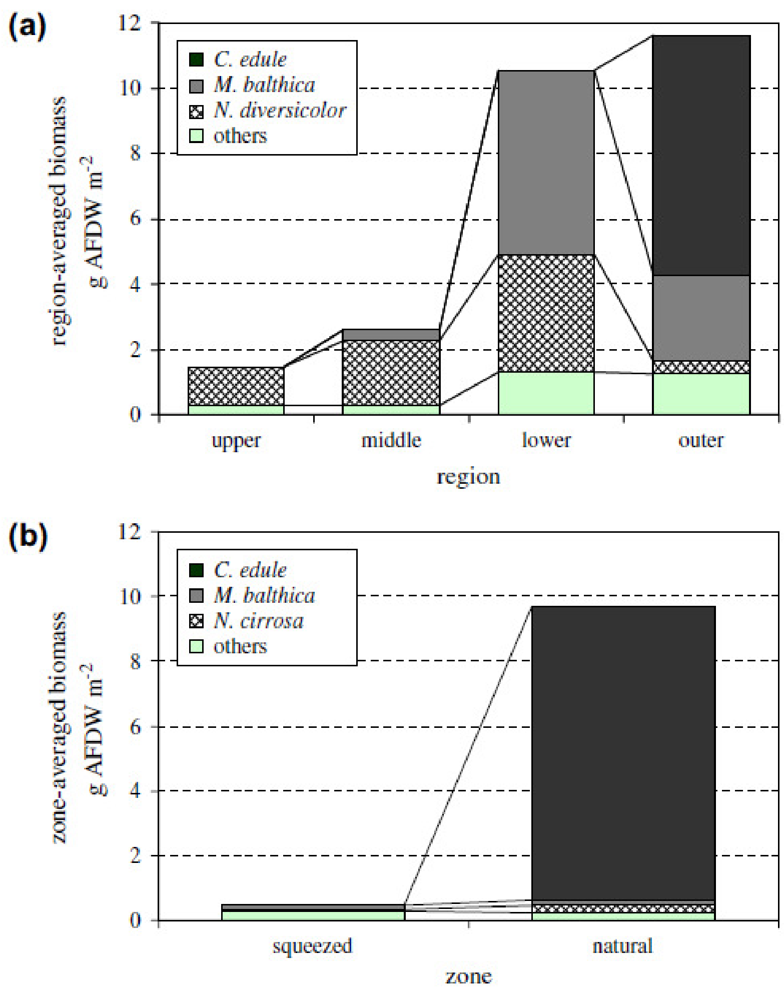

Fig. 3. Average biomasses of the three most characteristic and other remaining macrobenthic species across: (a) regions along the longitudinal gradient in the Humber and (b) zones along the beach width gradient at Grimsby.

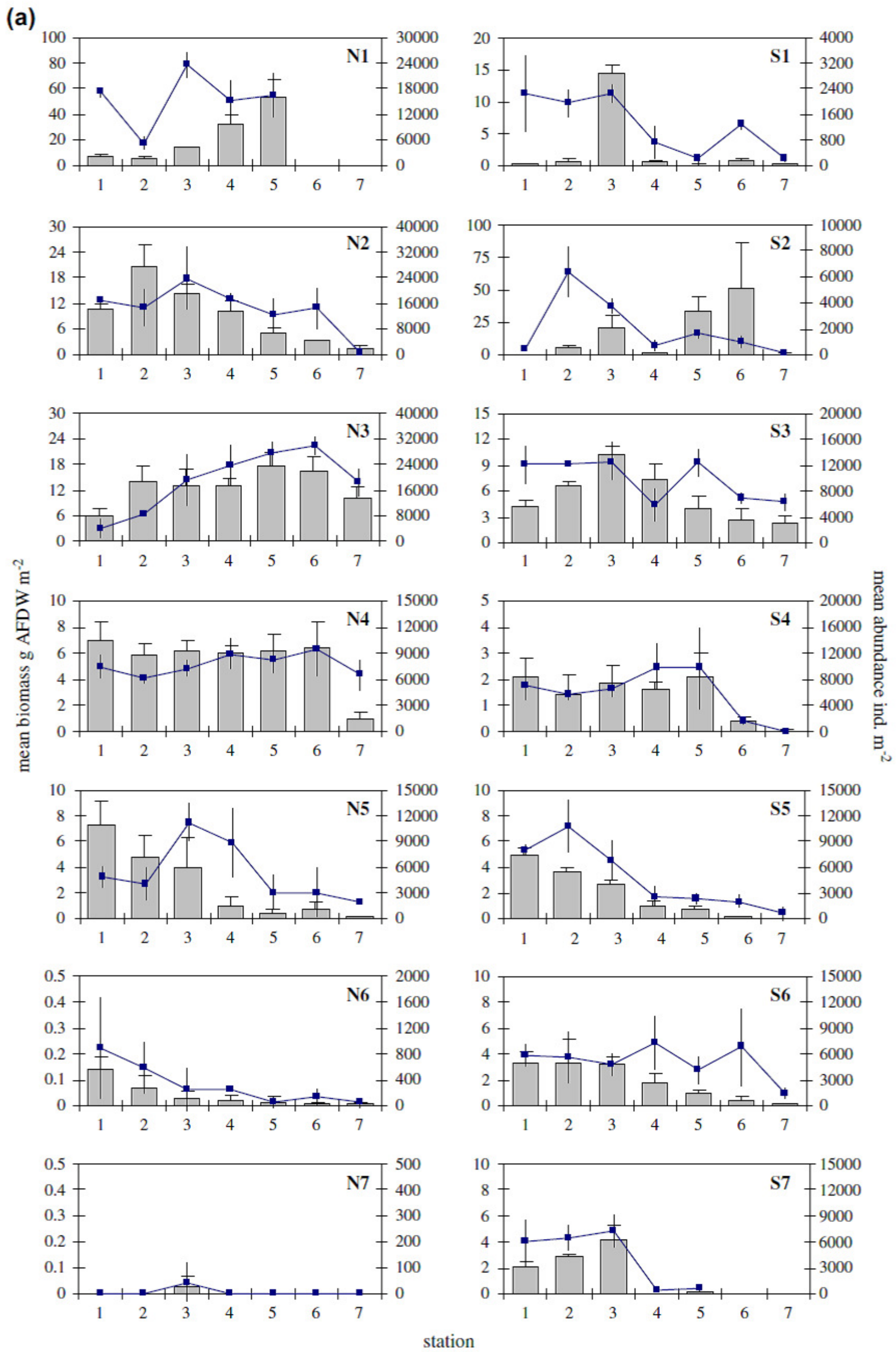

Fig. 7. Mean total macrobenthic biomass (bar graph) and abundance (markers with line) across stations: (a) for the 14 transects along the longitudinal gradient in the Humber estuary and (b) for the 9 transects along the beach width gradient at Grimsby. Vertical T bars show ±SD for biomass, and normal vertical bars show ±SD for abundance.

(a)

(b)

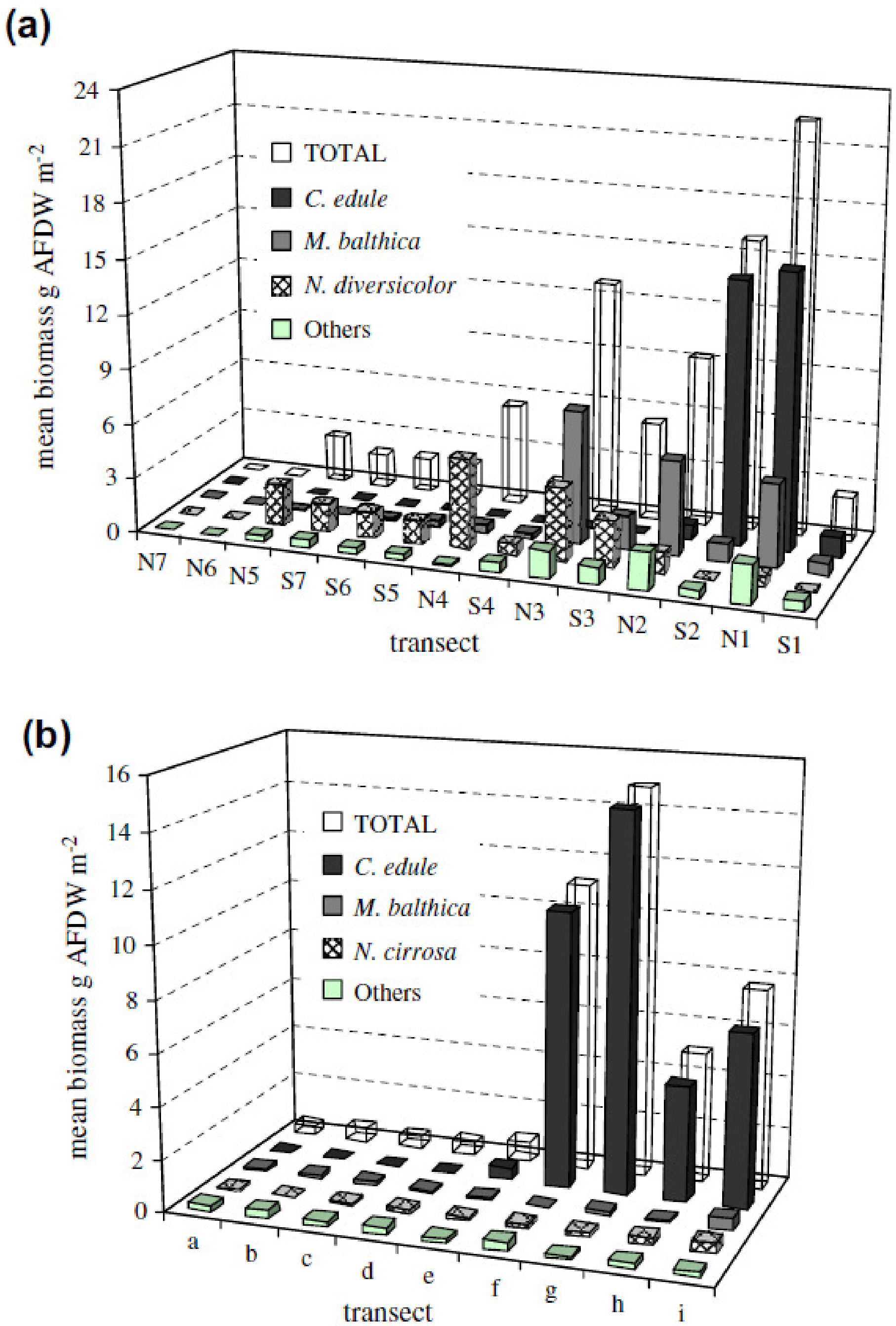

Fig. 5. Mean biomasses of the three most characteristic and other remaining macrobenthic species with total values across transects along: (a) the longitudinal gradient in the Humber and (b) the beach width gradient at Grimsby. In (a), transects are arranged along the *x*-axis in order from upper to outer estuary.

2.0.8. **NE Point 2**: Can it be confirmed that the abundance figures in Allen are indeed individuals per $0.01m^2$? Is it possible these figures are based on individuals per 1 m^2, or alternatively a cumulative total of individuals per station (with up to five samples taken at each station across a transect from high to low shore)?

2.0.9. **NE Point 3**: Why would sub-tidal invertebrate abundance in Allen (2006) be cumulative at each site (i.e. 3 x 0.1 = $0.3m^2$), whereas inter-tidal abundance is not, despite up to 5 x $0.01m^2$ samples being available.

2.0.10. **NE Point 4**: Could the apparent discrepancy be the result of using different mesh diameters within the sieves used for the two surveys? Possibly it would account for differences particularly in the small fauna.

2.0.11. **Responses 2 + 3 + 4: T**his has been answered by IECS previously; the reliance has been placed on the analysis and interpretation of the raw data rather than previous reports. As regards the presentation of the data (treatment of individual samples) it is our understanding that this is how the data were provided by the EA. It is considered unlikely that the Environment Agency would use a sieve size different to the norm for estuaries (500 µm).

2.0.12. **NE Point 5:** Could the apparent discrepancy be the result of using different sampling depths between the two surveys, so that whilst surface area remained constant, volume did not (15cm constant depth at Killingholme 2010 but unspecified in Allen)?

2.0.13. **Response 5:** Whilst it is likely that the core used would be 15 cm depth the efficacy depends greatly on the species in question, and the size range of the species in question. For example in a study of the Humber Mortimer et al (1999) found that *Macoma balthica* bivalves lie buried in the sediment at depths ranging from a few millimetres to as much as 8 cm depending on their size, whereas the same author found that *Hediste* (Nereis) *diversicolor* can be (in large specimens) up to 20 cm within the sediment. Notably *Hediste diversicolor* burial depth is related to body size and temperature (Scaps, 2002) and *Hediste diversicolor* are generally considered to be smaller in the mid estuary such as at NKM than at the outer estuary in the Humber. Thus in terms of comparing between sites for *Macoma and Hediste* it is unlikely that a different methodology would account for any suggested discrepancy as both species would be present within the upper section of the mud.

2.0.14. **NE Point 6**: relating to the multivariate analysis conducted by Allen (2006).

2.0.15. **Response 6**: The author of the multivariate analysis would be required to answer questions specifically regarding the analysis and any possible discrepancies. Needless to say it is necessary to bear in mind that reliance has been placed on the station specific data in order to characterise the area and not provide a contemporaneous baseline. This is agreed as common ground as being a requirement.

2.0.16. NE Point 7: Are *Hediste* and *Macoma* biomass data (and not just abundance) available within the EA datasets analysed within Allen 2006? If so, can these be presented in order to provide a like for like comparison for Killingholme?

2.0.17. Response 7: This has been answered previously by IECS; biomass data were not available for the EA dataset reported by Alan (2006) (a situation that is consistent across the Environment Agency's Humber status reports in the 1990s). However other data sets within a more recent period (2003/2004) for the North side of the Humber as presented above (e.g. Transect N3 of the Fujii (2007) paper) indicate a biomass which varies according to the height on the shore but the peak point on the shore is around 18 g AFDW/m^2 **.** Abundance at this station is 24 000 individuals/m^2.

2.0.18. **NE Point 8**: How were sampling sations[sic] / sites selected for the 2010 Killingholme study, as the most relevant area we are concerned about (i.e. the mudflat that supports the high densities of black-tailed godwits), has the lowest density of samples (3 from a total of 36 with just one on the low-shore)? Sample selection was effectively 'random' but within a series of prescribed transects and elevations.

2.0.19. **Response 8:** IECS have answered this question previously but it is worth noting that the survey characterised the shore sufficiently to detect two patches of high numbers of *Hediste* (Transect 3 and Transect 12) and varying numbers of *Macoma balthica*. It also characterised the community and sediment as a whole to a sufficient level to provide a fit for purpose characterisation of the benthic community of the study area.

2.0.20. **NE Point 9:** Key prey species for black-tailed godwit at Killingholme are likely to be *Hediste* and *Macoma*. What is the effect of sampling in May on both of these species, in terms of biomass and abundance? For example, what might be the effects of both prey depletion by waterbirds over the winter period, and also die-off of adult *Hediste* post-reproduction?

2.0.21. **Response 9:** The in-year seasonal variation in abundance (but not biomass) has been studied on the Humber and has been found to vary according to the site and obviously species (Mortimer, 1999). Areas on the North shore at Paull were found in the period 1995-1996 to vary very little in their numbers (abundance) between April and August of the same year. Between February of 1995 and October 1995 there was a 3 fold decrease in numbers of *Hediste* (Nereis). *Macoma balthica* at the same site displayed a 4 fold increase in abundance between February 1995 and October 1995.

2.0.22. The pattern at Pyewipe during the same period saw a significant increase in Hediste between April 1996 and August 1996, and a similar increase in abundance (a 3-fold to 4-fold increase over the same period) was seen for *Macoma balthica*.

2.0.23. As can be seen in the following tables the numbers of Hediste during this period at Paull are higher in April and February than the numbers witnessed at NKM in May (2010). The numbers of *Macoma* are different with both Paull and Pyewipe for this period of time being lower than those of NKM 2010.

2.0.24. Referring back to the more recent study by Fujii the mean abundance of *Macoma balthica* in the Humber was found to be 1358 individuals m^{-2} suggesting that a seasonal 3.5-fold increase in the abundance at NKM (mean 398 individuals m^{-2}) as seen at Pyewipe (combined 1995 and 1996) would result in a mean abundance of 1393 individuals m^{-2}. Whilst drawing definitive conclusions based on patterns in 1995 and 1996 and now are of limited validity this provides an indicative 3.5-fold increase in abundance over a year and indicates that the mean abundance of *Macoma balthica* at NKM in May 2010 was slightly higher than the mean abundance present in September 2003.

2.0.25. For *Hediste diversicolor* the variation in abundance appears to have a less obvious pattern with an increase at Paull being 20% and increases at Pyewipe being a ~48x increase and abundance at Skeffling seeing a ~100x increase. In other areas of the East coast of England (Essex) the increase is seen to be 4-fold between May and September (with the lowest levels being in March) (Aberson et al 2011). The validity of drawing conclusions regarding the amount by which abundance may increase at NKM is therefore too tenuous to present. The requirement for a seasonally adjusted baseline survey is therefore reiterated.

2.0.26. It should also be noted that there are numerous records of seasonal predator-prey relationships between *Macoma* and its predators and the pressures are not simply limited to birds. They are preyed on by a suite of epibenthic species, including other *Macoma* and *Hediste*, which may peak in the summer months; therefore a reliance on the winter reduction according to bird predation requires caution.

2.0.27. **NE Point 10**: Invertebrate data were in fact collected at Killingholme as part of the early Allen study. This was not clear in the report however, as the south bank stations were numbered rather than named and site 6 (Killingholme) was omitted from the map showing sampling stations. What could account for the discrepancy between the Killingholme figures from Allen (2006) and IECS (2010)?

2.0.28. **Response 10:** Answered by IECS. Given the various issues with the EA data, not the least its age (c. 15 years), I think this is too difficult to answer with any certainty. IECS reiterate that there will be a detailed baseline benthic survey undertaken pre construction which will provide a more comprehensive dataset for any future target setting etc.

References

Aberson, M.J.R., Bolam, S.G., Hughes, R. G. 2011. The dispersal and colonisation behaviour of the marine polychaete Nereis diversicolor in South East England. Hydrobiologia. 672. 3-14

R.J.G. Mortimer, J.T. Davey, M.D. Krom, P.G. Watson, P.E. Frickers, R.J. Clifton, The Effect of Macrofauna on Porewater Profiles and Nutrient Fluxes in the Intertidal Zone of the Humber Estuary, Estuarine, Coastal and Shelf Science, Volume 48, Issue 6, June 1999, Pages 683-699,

Scaps, P. *2002.* A review of the biology, ecology and potential use of the common ragworm Hediste diversicolor (O.F. Müller) (Annelida: Polychaeta). Hydrobiologia*.*

T. Fujii, Spatial patterns of benthic macrofauna in relation to environmental variables in an intertidal habitat in the Humber estuary, UK: Developing a tool for estuarine shoreline management, Estuarine, Coastal and Shelf Science, Volume 75, Issues 1–2, October 2007, Pages 101-119

Annex

T. Fujii, Spatial patterns of benthic macrofauna in relation to environmental variables in an intertidal habitat in the Humber estuary, UK: Developing a tool for estuarine shoreline management, Estuarine, Coastal and Shelf Science, Volume 75, Issues 1–2, October 2007, Pages 101-119

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Spatial patterns of benthic macrofauna in relation to environmental variables in an intertidal habitat in the Humber estuary, UK: Developing a tool for estuarine shoreline management

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Abstract

Spatial variations in benthic macrofaunal species composition, abundance and biomass in estuarine intertidal habitats have been often related to such environmental variables as salinity, sediment types and tidal depth. However, there have been few attempts to investigate the relations between such macrobenthic parameters and intertidal beach width gradient in order to predict their likely responses to coastal squeeze induced by accelerating sea-level rise in an estuarine environment. This article investigates the linkages between environmental variables and patterns in the distribution, abundance and biomass of estuarine intertidal macrobenthos in order to provide a basis for describing the effect of future sea-level rise in the Humber estuary, UK. Field surveys were conducted in September 2003 and 2004 over a variety of spatial scales based on a hierarchically scaled field study (system: 10^5 m; region: 10^5–10^4 m; local 10^4–10^3 m; transect: 10^3–10^2 m; station; 10^2–10^1 m) along two focal environmental gradients: (1) the longitudinal gradient (length of the estuary) over an entire estuarine system and (2) the beach width gradient (varying beach width altered by historic land-claim) over a sub-area of the estuary. Statistical analysis was carried out in order to identify key environmental variables and the most relevant spatial scales that best explain the observed spatial variability in macrobenthic biomasses. At the system scale, the dominant species were two bivalves *Cerastoderma edule* and *Macoma balthica* and a polychaete *Nereis diversicolor*, which accounted for 51.7%, 25.0% and 12.1%, respectively, of the total biomass. At the regional scale, univariate analysis showed clear trends in species richness, abundance and biomass along the longitudinal and beach width gradient. At the transect scale, multiple regression analysis revealed that the variances in biomass of *M. balthica*, *C. edule* and other remaining species as well as total macrobenthic biomass were largely explained (54–98%) by the key environmental variables, such as salinity, organic matter content, beach width and beach slope. At the station scale, the degree of variability explained by the environmental variables was markedly lower along beach width gradient (8–32%) than along longitudinal gradient (34–77%), but the analysis revealed a significant role of tidal depth along both gradients at this spatial scale. Overall, intertidal habitats with higher macrobenthic biomass were significantly positively related to higher salinity, muddier sediments, wider beach and shallower beach slope. This article indicates that such areas are currently situated around the lower and outer regions of the estuary where extensive shallow muddy intertidal areas can be found, but they will also be most susceptible to the impacts of sea-level rise due to their outer location and the shallowness of the beach in the Humber estuary.

Keywords: estuarine ecosystems; intertidal habitats; benthic macrofauna; sea-level rise; coastal squeeze; Humber estuary; England; UK

1. Introduction

Estuarine intertidal habitats are dynamic features which are structured primarily by the interactions of physical elements such as prevailing wind direction, wave action, tidal and current movements, sediment transportation and

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chemical conditions (Carter, 1988). Geographically they are situated within a transitional zone between freshwater and the sea, but they often show much higher primary productivity and secondary productivity than either habitat (McLusky, 1989; Heip et al., 1995; Kennish, 2002). Despite their steep environmental gradients, estuarine intertidal areas harbour a very high abundance and biomass of macrobenthic invertebrates, attributable to a high concentration of organic matter and nutrients retained in the system. The high stocks of macrobenthos in turn provide an essential food sources for higher trophic levels of epibenthic crustaceans, fishes and shorebirds (Wolff, 1987; McLusky, 1989), and this is one of the reasons why estuarine intertidal flats are of high conservation value.

Intertidal flats within an estuary, however, exhibit significant variability in benthic macrofaunal species composition, density and biomass, and there is a long history of investigations in which this variability has been related to such environmental variables as salinity, sediment types and tidal depth (McIntyre, 1970; Boesch, 1977; Dankers et al., 1981; Key, 1983; Elliott and Kingston, 1987; Jones, 1988; McLusky, 1989; Meire et al., 1991; Dauer, 1993; Elliott et al., 1998; Beukema, 2002; Ysebaert and Herman, 2002; Ysebaert et al., 2003). However, there have been few attempts to investigate the relations between benthic invertebrate abundance and biomass, and intertidal beach width gradient in order to predict their likely responses to accelerated sea-level rise as a result of global warming in an estuarine environment. In many European estuaries, extensive areas of intertidal habitats could be lost in the future through a process of coastal squeeze in which rising sea levels squeeze beaches and tidal flats against both established and newly constructed sea defences. In the case of the Humber estuary in the UK, the rate of sea-level rise relative to land has been between 2 and 2.5 mm per year over the last 100 years (Winn et al., 2003). However, the Ministry of Agriculture, Fisheries and Food (MAFF, 1999) has recommended that for planning purposes an average rate of 6 mm per year should be assumed for the next 50 years, implying that sea levels may rise by a total of 0.3 m over that period, causing a reduction in intertidal beach width particularly in the shallow intertidal mud and sand flats. In addition, an increase in sea levels will cause a widening and deepening in estuarine water volume, leading to a greater saline intrusion further upstream (Jones, 1994; Scavia et al., 2002). For estuarine intertidal geomorphology, Taylor et al. (2004) have investigated changes in 1084 coastal profiles throughout England and Wales, and found that 61% of the coastlines studied had experienced steepening since in the middle of 19th century, primarily due to foreshore erosion and the use of sea walls and embankments. Further, there are predicted increases in the frequency of surges and greater wave action in response to rising sea levels (Hulme et al., 2002), and enhanced wave and tidal energy may cause a change in sediment regime (Goss-Custard et al., 1990; Raffaelli and Hawkins, 1996). These predicted physical changes could have significant implications for the future distribution of intertidal macrobenthos, and thus their predators.

In the face of such potential environmental changes, there is increasing interest from conservation and management agencies for reliable predictive tools for planning the sustainable use of estuarine and coastal systems. One approach is to create a model which can make quantitative predictions of how intertidal habitats and their macrobenthic biomass may change in response to changes in key environmental variables induced by sea-level rise. Such a model can be used, for example, to decide how much land needs to be set aside for recreation of intertidal habitats to compensate for the future loss and where such schemes would be most effective in the context of ecological restoration in estuarine shoreline management. Investigation of the spatial distribution patterns of macrobenthos along both the entire length of the estuary and a sub-area of the estuary where beach width has been progressively altered by historic land-claim will help to identify the relations between macrobenthic distributions and estuarine physical processes, and hence to provide a basis for predicting how macrobenthos will respond to the coastal squeeze resulting from sea-level rise.

The long-term objective of this study is to develop a method for predicting the potential impacts of sea-level rise on estuarine ecosystem with particular emphasis on the abundance and biomass of macrobenthos, and hence the consumers they support, in order to identify appropriate coastal and estuarine management approaches that can sustain both nature conservation interests and socio-economic needs. Specifically, the aim of this article is to identify the linkages between the abundance and biomass of macrobenthos, and key environmental variables such as salinity, sediment characteristics and beach morphological elements over the two focal environmental gradients in estuarine intertidal habitats: (1) the longitudinal gradient over an entire estuarine system and (2) the beach width gradient over a local site. Patterns in the distribution, abundance and biomass of benthic macrofauna in the Humber estuary are thus analysed over a variety of spatial scales based on a hierarchically scaled field study along the two environmental gradients. The results are then used to investigate the role of environmental variables in explaining the observed variability within the system and the local site using multiple regression analyses. The rules which best link values of key environmental variables with macrobenthic biomass at the most relevant spatial scales were then identified to describe how the biomass of macrobenthos in the system would respond to environmental variables and gradients in the Humber estuary.

2. Material and methods

2.1. Study site

The sites sampled were estuarine intertidal flats situated along the Humber on the east coast of England which forms the boundary between Yorkshire and Lincolnshire and flows into the North Sea (Fig. 1a). The mean tidal range is approximately 5 m and maximum spring tide range can attain over 7 m, being one of the largest macro-tidal estuaries in the UK. The Humber is also the largest estuarine system in

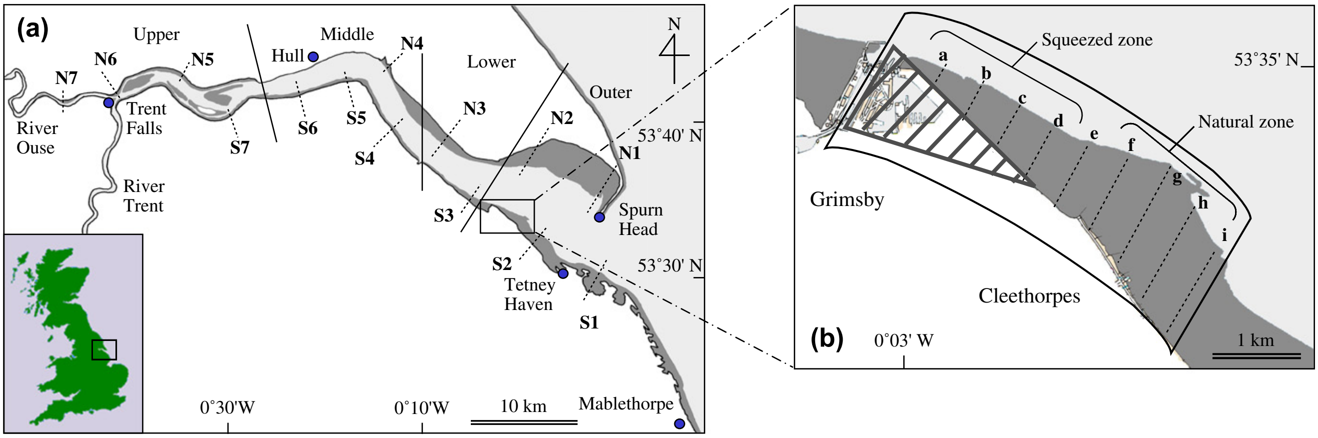

Fig. 1. (a) The Humber estuary and location of transects (N1–N7 and S1–S7 with dotted line) along the longitudinal gradient at low tide. Dark shaded area represents intertidal area and long solid line represents a boundary between regions. (b) Location of the study site at Grimsby and Cleethorpes (within the slightly distorted rectangle), showing 9 transects from *a* to *i* (the dotted lines) and two arbitrary zones with respect to beach width gradient: squeezed and natural (unsqueezed). Each zone contains 4 transects. The triangular hatched area is the reclaimed site that used to be a part of intertidal flat before the middle of the 19th century.

England in terms of mean flow (250 $m^3 s^{-1}$) (Jickells et al., 2000), and it is characterised as a well-mixed estuary with only a small vertical salinity gradient in contrast to a pronounced longitudinal gradient (Barr et al., 1990). Its flushing time varies from 20 days in winter time to 160 days in the summer depending on flowing conditions (Gameson, 1982). The estuary mouth at Spurn Head is approximately 8 km wide, while the head of the estuary is less than 0.5 km at both the river Trent and river Ouse. The Humber has a catchment area of 24,472 km^2, a fifth of the area of England, and the tidal waters have a length of 317 km (Winn et al., 2003), the Humber itself stretching approximately 60 km from the confluence of the Trent and the Ouse (Trent falls) to the mouth at Spurn. In this study, the mouth of the Humber is defined as a midpoint between Spurn Head on the north bank and Tetney Haven on the south (OS grid ref. 538000, 408000). The system supports a large area of intertidal habitat particularly towards its mouth, estimated at 120 km^2, 90% of which comprises mudflat and sandflat (Winn et al., 2003). However, in areas with extensive sea defence walls and commercial development such as around Hull and Grimsby, tidal flats are narrow or absent because of truncation by sea defence walls. To assess the spatial distribution patterns of macrobenthos in relation to environmental variables, field surveys were conducted along the longitudinal gradient (length of the estuary) and beach width gradient (width of the beach) in September 2003 and 2004, respectively.

2.1.1. Longitudinal gradient

The Humber estuary can be divided into 4 large sections (upper, middle, lower and outer region) defined by Barr et al. (1990) (solid lines in Fig. 1a), and sediment types vary considerably from relatively sandy particles with some fringing fine mud in the upper region, through fine mud in the middle and lower regions, to coarse sand towards the outer region. Sampling sites were thus carefully chosen to cover the range of sediment types. 7 transects were selected on the north (N1–N7) and 7 transects on the south bank (S1–S7) of the Humber, so that they were evenly distributed over the four regions of the estuary (Fig. 1a). Each transect was established so that it ran from MHWL (mean high water level) to MLWL (mean low water level) aligned along the direction of tidal ebb. Both MHWL and MLWL were determined by consulting Ordnance Survey 1:25,000 scale map revised in 2000, and 7 sampling stations were selected along the transect at equal intervals over the intertidal profile. Thus, total of 98 stations (14 transects × 7 stations) were chosen throughout the estuarine longitudinal gradient and sampling was replicated 3 times at each station. This sampling design was hierarchically scaled, covering 5 different spatial scales: system (10^5 m), region (10^5–10^4 m), transect (10^3–10^2 m), station (10^2–10^1 m), and replicate (10^1–10^0 m). All the field sampling and survey were carried out from 8 to 27 September, 2003, except for one transect at Patrington (Transect N2 in Fig. 1a) where the field work was conducted on 25 October, 2003. Only 5 out of 7 stations were sampled along two of the transects due to difficulty in working on extremely deep mud in the lower part of Kilnsea (Transect N1 in Fig. 1a), and due to much shorter length of transect than expected from a consulted map at South Ferriby (Transect S7 in Fig. 1a).

2.1.2. Beach width gradient

An another study site was identified at an estuarine sandy intertidal flat situated around outer region of the Humber located along approximately 4 km of the coast between Grimsby and Cleethorpes (from 53°33′ to 53°35′ N, and from 0°00′ to 0°03′ W) (Fig. 1b). This intertidal flat was selected because of the marked change in beach width from the south-eastern end to the north-western end, due to the extensive land-reclamation that took place in front of Grimsby in the middle of the 19th century (Murby, 2001). The study site was progressively squeezed towards the western end, showing distinctive zones of intertidal habitats between "squeezed" to the northwest and "natural" (unsqueezed) to the southeast in terms of beach width gradient (Fig. 1b). Investigation of such environmental gradients and how macrobenthos have adapted to historical land-claim that are located within a relatively restricted local site (10^4–10^3 m) may provide a basis for predicting how macrobenthos will respond to coastal squeeze resulting from sea-level rise. 9 transects were established to cover the whole range of beach width gradients, which run from mean high water (MHWL) to mean low water (MLWL), aligned along the direction of tidal flow (Fig. 1b). Along each transect, 9 equally spaced shore levels were chosen to establish sampling stations. Data from 81 sampling stations (9 transects $\times$ 9 stations) were thus obtained with 3 replications, and all the field sampling was carried out from 14 to 28 September, 2004 at this site. As shown in Fig. 1b, the transects were grouped into two zones (squeezed zone and natural zone) (Fig. 1b), with transects *a* to *d* in the "squeezed zone", transects *f* to *i* in the "natural zone" (4 transects per zone) and transect *e* treated as an intermediate. For this sampling design, similar hierarchical scaling was thus employed: local site (10^4–10^3 m), zone (2×10^3 m), transect (10^3–10^2 m), station (10^2–10^1 m), and replicate (10^1–10^0 m), which allowed simultaneous analyses of macrobenthos along the two focal environmental gradients (longitudinal and beach width) over a range of spatial scales.

2.2. Biological measurements and sampling

At each sampling station, a cylindrical corer (10 cm in diameter) was pushed into the sediment to the depth of 15 cm on a randomly chosen surface to sample the benthic macrofauna. This material was sieved on a 0.86 mm mesh with filtered sea water (with a 0.063 mm mesh) on site. This procedure was replicated three times and, on return to laboratory, the organisms collected were preserved in 70% ethanol for subsequent sorting, species identification, counting and biomass measurements. Identification was done either by eye or by a binocular microscope and compound microscope where necessary. For each core sample, the number of species present and the abundance of each species were recorded. Subsequently, the biomass of each species was measured and expressed in g Ash Free Dry Weight (g AFDW) by carrying out a procedure after Hartley et al. (1987).

2.3. Physical measurements and sampling

2.3.1. Longitudinal elements

Monthly measurements over at 40 monitoring locations along the Humber estuary were used for estimates of salinity value at each transect. The data were derived from the coastal (C) component of the Rivers-Atmosphere-Coast Study, RACS(C), of NERC's Land-Ocean Interaction Study (LOIS) programme, and, in the programme, the locations of the monitoring stations were chosen to cover the salinity range from fresh to coastal and to take into account any possible lateral heterogeneity in the entire Humber system (Uncles et al., 1998). Salinity was measured at a depth of 1 m at each of the monitoring stations, and surveys were undertaken during spring tides, except for May and December 1994 and March 1995 when surveys were conducted during neap tides (Uncles et al., 1998). Salinity values used in subsequent analysis were the mean salinity of the period of 12 months between March 1994 and March 1995 at monitoring stations located over each of the transects established in this study. This was the most recent detailed salinity data set available for the Humber estuary, and thus differences in monthly average salinity between the above period and year 2003 and 2004 (survey year in this study) could not be examined. Wave exposure for each transect was defined as a simple open angle of the shore (midpoint of each transect) to, or subtended by, the open sea horizon, expressed in radians (after Baker and Crothers, 1987).

2.3.2. Sedimentary elements

Three replicate core samples (30 mm in diameter) were taken from the top 5 cm of the sediment at each sampling station for sediment analysis at the same time as the biological samples were collected. Organic matter content of these samples was measured as loss on ignition over 16 h at 375 °C, after drying the samples at 90 °C until constant weight (after Sutherland, 1996). For particle size composition, both wet sieving (for particle sizes smaller than 0.063 mm) and dry sieving (for particle sizes larger than 0.063 mm) were used to measure cumulative percentage weights of gravel (>2 mm), very coarse sand (2–1 mm), coarse sand (1–0.5 mm), medium sand (0.5–0.25 mm), fine sand (0.25–0.125 mm), very fine sand (0.125–0.063 mm) and silt (<0.0063 mm) sediment fractions. The median particle size expressed in the Wentworth scale (phi) was determined graphically from the cumulative curve as defined in Holme and McIntyre (1971). However, the fraction of particle sizes <0.031 mm (>5 phi) could not be examined in this study and therefore median particle sizes which fell <0.063 mm (>4 phi) may be subject to slight change depending on the percentage fraction of particles <0.031 mm (the more fraction of particles <0.031 mm, the smaller median particle sizes (phi), when they are >4 phi).

2.3.3. Morphological elements

The tidal depth (elevation) of each sampling station in relation to mean high water level (MHWL) was measured by a theodolite and a staff. The length of the staff was 4 m and the MHWL at each site was determined by the height of the point where a marked line of algal growth or entangling dried organic matter (drift line) was uniformly found on sea defence walls, beaches, or fringing saltmarshes. Because tidal range varies along the longitudinal gradient, tidal depth for each station was standardised by taking a percentage of the depth measurement in relation to the local mean tidal range observed at each transect. The local mean tidal range was calculated as:

$$\text{Mean tidal range} = (\text{mean spring tidal amplitude} + \text{mean neap tidal amplitude})/2$$

and tidal depth thus can be expressed 0% and 100% if the station is located at MHWL and at MLWL, respectively. In addition, the median depth of each transect was determined from the intertidal profile by reading the tidal depth which corresponds to the point where the horizontal distance from the MHWL reaches 50% of the total width of the beach. The median depth indicates that if the value is larger than 50%, the beach profile is concave, but if the value is smaller than 50%, then the shape of the beach is convex. Beach width was measured as the distance between mean high water level (MHWL) and mean low water level (MLWL) aligned along the direction of tidal ebb taken from the Ordnance Survey 1:25,000 scale map revised in 2000. Because MLWL does not emerge during neap tides, field sampling was carried out only around the period of spring tides when the pre-established transects were fully exposed at ebb tide. In this study, measures of beach steepness were obtained at transect scale (transect slope) and at station scale (station slope). Transect slope was measured differently depending on where MHWL was located in relation to the highest level of beach:

$$\text{Transect slope} = -\text{Log}_{10}(\text{mean tidal range}/\text{beach width})$$

where MHWL is located on the beach (sedimentary part), or

$$\text{Transect slope} = -\text{Log}_{10}(\text{height between top of the shore and MLWL}/\text{beach width})$$

where MHWL or the drift line is found up on the sea defence wall, so that steepness of transect only reflect the sedimentary part of the beach. Secondly, the slope at each station was calculated as follows:

$$\text{Station slope}_i = -\text{Log}_{10}(\text{relative vertical height } (S_{i-1} - S_{i+1})/\text{relative width}(S_{i+1} - S_{i-1}))$$

where S denotes station and i represents an arbitrary station number. The slope values calculated in this study typically fall in a range between 1 and 5, higher values indicating shallower slopes.

2.4. Statistical analysis

Macrobenthic abundance and biomass data were expressed in numbers per square metre (ind. m^{-2}) and g Ash Free Dry Weight (g AFDW m^{-2}), respectively. The general trends in physical characteristics and species richness, abundance and biomass of macrobenthos were examined mainly in relation to the longitudinal and beach width gradients of the Humber estuary using univariate analyses over 4 spatial scales (system (local site), region (zone), transect and station).

To avoid the confusion, ‘‘mean’’ value and ‘‘average’’ value were differentiated in this study: the mean value is calculated simply by adding all the measurements in a group and dividing the total by the number of measurements, whereas averaged value is derived by taking spatial areas represented by each measurement into account. For example, 120 km^2 of intertidal habitats within the Humber estuary is divided by 14 transects established in Section 2.1.1 (Fig. 1a) with different area represented by different transect (see Table 1 for details). System averaged abundance (ind. m^{-2}) and biomass (g AFDW m^{-2}) for dominant macrobenthic species were then calculated as follows:

$$\text{System averaged abundance} = \sum(D(T_n) * \text{Area}(T_n))/(\text{total area}) \quad (n = 1, 2, \ldots, 14)$$

$$\text{System averaged biomass} = \sum(B(T_n) * \text{Area}(T_n))/(\text{total area}) \quad (n = 1, 2, \ldots, 14)$$

where $D(T_n)$, $B(T_n)$ and Area(T_n) denote mean density, mean biomass for transect T_n and spatial area (km^2) represented by transect T_n, respectively. Similarly, site-, region- and zone-averaged values were all calculated by taking spatial areas into account.

Analysis of variance (ANOVA) was performed to test differences in mean macrobenthic biomasses between regions (zones) and between transects with post hoc (Tukey) test along the longitudinal and beach width gradients.

To assess the relation between tidal depth and macrobenthic biomass distribution, special attention was paid to identify the depth of tidal level at which peak biomass could be found over the intertidal profile. Subsequently, a new variable, ‘‘depth index’’, was established to express how the value of tidal depth at any station deviates from the maximum biomass level (see Section 3.3.1 for details).

Multiple regressions were then used to identify the role of the measured environmental variables in explaining the observed spatial variability in macrobenthic biomass at the station and transect scales. For these statistical processes, the biomass data were $\log(1000x + 1)$ transformed prior to analysis due to their non-normality and heterogeneity of variance in most cases. The $1000x$ scalar was used because this generated the best normal distribution of the data. Data for salinity were normalised by natural log transformation. The environmental variables were divided into three physical components: longitudinal (salinity and exposure), sedimentary (median particle size, silt content and organic matter content) and morphological (beach width, station slope, transect slope, tidal depth, median tidal depth and depth index). A forward step procedure was used to determine the subset of environmental variables that best explained the observed variation in macrobenthic biomass. All statistical analyses were performed with SPSS for Windows.

Table 1
Physical characteristics of 14 transects along system longitudinal gradients on the Humber and 9 transects along beach width gradients at Grimsby. Environmental variables: Distance, distance from mouth (km); T-range, mean tidal range (m); Area, area represented by transect (km^2); SAL, salinity; EXP, exposure (radian); MD, median particle size (phi); ORG, organic matter content (%); SIL, silt content (%); WID, beach width (m); T-SLO, transect slope; S-SLO, station slope; DEP, tidal depth (%); M-DEP, median tidal depth (%); DEP-I, depth index (see Section 3.3.1), for each transect. Mean values are expressed with ±SD

Transect	Distance	T-Range	Area	LONGITUDINAL		SEDIMENTARY			MORPHOLOGICAL				
				SAL	EXP	MD	ORG	SIL	WID	T-SLO	S-SLO	M-DEP	DEP-I
Along system longitudinal gradient													
N1	1.3	4.29	19.6	28.0	0.00	4.48 ± 0.69	3.20 ± 1.38	72.7 ± 21.6	2525	2.77	3.62 ± 0.79	14.0	0.38 ± 0.14
N2	7.9	4.45	13.4	23.1	0.14	4.47 ± 0.63	2.56 ± 0.69	73.6 ± 15.1	2300	2.77	3.14 ± 0.29	25.0	0.72 ± 0.20
N3	18.3	4.63	7.6	19.5	0.30	4.89 ± 0.04	3.62 ± 0.31	90.2 ± 3.5	925	2.35	2.44 ± 0.60	66.4	0.66 ± 0.25
N4	29.3	4.93	3.7	14.8	0.00	4.80 ± 0.04	3.91 ± 0.86	83.3 ± 3.0	375	1.92	1.98 ± 0.09	47.7	0.72 ± 0.25
N5	52.5	4.85	4.8	5.6	0.00	4.74 ± 0.07	4.22 ± 0.74	79.3 ± 4.0	70	1.16	2.54 ± 1.80	9.2	0.48 ± 0.32
N6	59.6	4.55	5.3	3.8	0.00	4.40 ± 0.44	2.78 ± 1.00	55.9 ± 31.3	68	1.17	1.45 ± 0.44	85.7	0.47 ± 0.35
N7	68.1	4.25	0.8	2.6	0.00	3.89 ± 0.53	1.84 ± 1.36	33.4 ± 27.2	90	1.33	1.50 ± 0.32	73.3	0.68 ± 0.23
S1	−3.0	4.17	26.5	30.0	2.04	2.52 ± 0.11	0.55 ± 0.24	4.7 ± 3.7	2350	2.75	2.89 ± 0.69	12.2	0.42 ± 0.23
S2	4.1	4.24	13.6	25.9	1.01	2.67 ± 0.35	0.66 ± 0.19	5.5 ± 5.7	1050	2.39	2.53 ± 0.32	27.5	0.70 ± 0.23
S3	12.1	4.43	3.5	23.0	0.00	4.85 ± 0.05	4.02 ± 0.73	87.2 ± 3.9	750	2.32	2.35 ± 0.12	50.0	0.81 ± 0.19
S4	23.8	4.80	1.8	17.5	0.24	4.82 ± 0.03	3.39 ± 0.56	85.1 ± 2.3	150	1.53	1.44 ± 0.24	50.0	0.58 ± 0.31
S5	32.9	5.00	6.7	12.4	0.00	4.80 ± 0.06	3.45 ± 0.36	83.6 ± 4.4	300	1.84	1.83 ± 0.41	88.6	0.50 ± 0.36
S6	39.2	5.10	5.2	9.6	0.00	4.77 ± 0.10	3.79 ± 0.43	81.8 ± 6.1	275	1.78	1.76 ± 0.16	65.6	0.52 ± 0.32
S7	47.1	5.05	7.3	9.3	0.00	4.82 ± 0.04	3.97 ± 0.65	85.1 ± 3.1	120	1.38	1.66 ± 0.88	23.8	0.47 ± 0.23
Along local beach width gradient													
a	8.6	4.55	0.3	23.9	0.68	3.75 ± 0.90	2.51 ± 0.69	49.6 ± 23.2	204	1.76	1.81 ± 0.25	64.8	0.64 ± 0.29
b	8.1	4.55	0.6	24.1	0.72	2.71 ± 0.70	1.74 ± 0.98	22.9 ± 19.2	390	1.93	1.97 ± 0.32	62.6	0.63 ± 0.32
c	7.7	4.55	0.8	24.4	0.75	2.56 ± 0.21	1.33 ± 0.91	12.1 ± 12.2	535	2.18	2.27 ± 0.32	67.7	0.66 ± 0.23
d	7.2	4.55	0.9	24.6	0.79	2.74 ± 0.18	1.69 ± 0.60	21.0 ± 14.3	644	2.27	2.35 ± 0.31	75.4	0.53 ± 0.25
e	6.7	4.55	1.2	24.8	0.83	2.58 ± 0.13	1.06 ± 0.25	8.5 ± 6.4	833	2.32	2.41 ± 0.30	67.0	0.65 ± 0.26
f	6.3	4.55	1.4	25.1	0.86	2.87 ± 0.83	2.59 ± 3.51	17.6 ± 24.9	957	2.32	2.63 ± 0.89	49.7	0.80 ± 0.35
g	5.8	4.55	1.7	25.3	0.90	2.74 ± 0.31	0.94 ± 0.75	7.3 ± 8.1	1230	2.43	2.58 ± 0.51	89.0	0.47 ± 0.23
h	5.4	4.55	1.7	25.5	0.94	2.59 ± 0.08	0.66 ± 0.19	3.3 ± 1.1	1188	2.58	2.58 ± 0.46	53.2	0.66 ± 0.33
i	4.9	4.55	1.6	25.8	0.98	2.56 ± 0.15	0.68 ± 0.19	3.3 ± 1.2	1099	2.38	2.47 ± 0.35	21.1	0.57 ± 0.23

3. Results

3.1. Physical characteristics of the Humber estuary

The physical characteristics of 14 transects (N1-S7) established along the estuarine longitudinal gradients and 9 transects (*a*−*i*) along the beach width gradients are summarised in Table 1.

3.1.1. Salinity and tidal range

Along the estuarine longitudinal gradient, salinity decreased steadily from 30 at the mouth to 2.6 in the upper most region, whereas the transects along the beach width gradient were located within a relatively small part of the Humber estuary, and mean annual salinity varied little between 23.9 at transect *a* and 25.8 at transect *i*. The apparent low salinity around the mouth (30 at Transect S1) may be a reflection of winter months when the Humber has significantly higher freshwater inflow (Uncles et al., 1998). Mean tidal range (defined in Section 2.3.3) was 4.2 m at transect S1 located at the mouth rising to a maximum of 5.1 m at transect S6 around the middle region of the Humber, then decreasing again to 4.25 m at the upper most transect N7. Along the beach width gradient, exposure increased from 0.68 at transect *a* to 0.98 at transect *i*, indicating transects in the natural zone were more exposed to the open coastal environment than those in the squeezed zone, although this factor is likely to be more related to geographical location than the squeezed nature of the beach.

3.1.2. Sedimentary elements

Median particle size (mean) for transects along the longitudinal gradient was 2.5 phi at the outer most transect S1, characterised by fine sand, with the highest value of 4.9 phi at transect S3 situated near the boundary between lower and outer regions, characterised by highly muddy sediment (Table 1). Uniform muddy sediments occur over the 40 km along the middle and lower regions along the longitudinal gradient, but there is an abrupt change from fine to coarse sediment at the outer region towards the mouth, and more gradual change in the upper region. Similar trends were also observed for silt content and organic matter content. Sediment characteristics observed around upper region could be attributable to the high average freshwater inflow and therefore stronger scouring (Jickells et al., 2000). All the transects situated in middle and lower regions of the estuary had >80% sediment silt content and a high organic matter content of around 3−4%, values decreasing towards both outer marine and upper freshwater sections.

Sediment along beach width gradient also consisted of the range of sizes between fine sand and silt, and median grain size per transect varied from 2.56 (fine sand) to 3.75 (silt) (Table 1). There was no obvious trend in median particle sizes across the study site, except for transect *a* where sediments were much finer than any other transect. In contrast, silt content and organic matter content showed clearer decreasing trends from the natural zone to the squeezed zone. Silt content varied from 3.3% at transect *i* to 49.6% at transect *a*, whereas organic matter content varied from 0.7% at transect *h* to 2.5% at transect *a*. The high organic matter content observed at transect *f* was attributable to the presence of a patchy sediment area with a large amount of plant debris at higher shore levels, which increased average value of organic matter content for the transect. Sediment generally become muddier with more organic matter and a high silt content from the most natural beach through to most squeezed beach (Table 1).

3.1.3. Morphological elements

The transect profiles are shown in Fig. 2. For each transect, tidal depth (%) of each station in relation to mean tidal range is plotted against distance from MHWL.

Along the longitudinal gradient, transect slope varied between 1.16 at transect N5, and 2.77 at transect N1 (Table 1). Low median depth values (%) were found at transect N5 (9.2%) and transect S1 (12.2%), indicating that their slopes are shallow over the upper and middle shore, but steeply shelving at lower shore showing concave shape over the intertidal profile (Fig. 2a). In contrast, transect N6 and transect S5 had a high percentage median depth of 85.7% and 88.6%, respectively, indicating that they shelve steeply at high and middle shore levels, but becoming shallower towards the lower shore level showing concave beach face morphology (Fig. 2a). The width of the transects tended to become exponentially longer and the steepness of the profiles became shallower towards the mouth along the estuarine longitudinal gradient.

Along the beach width gradient, the width of beach varied from 195 m to 1230 m (Table 1). Transects *a*, *b*, *c* and *d* are situated in front of the land-claimed area in Grimsby (squeezed), and transects beyond *e* towards the outer coastal region are natural beaches. The squeezed beaches (*a*−*d*) are characterised by a short, steep beach width (<800 m), and the beach face profiles became homogenously lower from mean high water to mean low water level (Fig. 2b). Natural beaches (*f*−*i*) were longer (>800 m) and showed more varied morphology, with some flatter and deepened areas within each transect. Transect slope and mean station slope values decreased from the natural zone of transect *i* to the squeezed beach of transect *a* (Table 1), showing that beaches became progressively steeper when squeezed. Median beach depth varied from 21.1% at transect *i* to 89.0% at transect *g*, with lower values in transects in the natural zone (Table 1), showing that longer and natural beaches tended to have concave profiles. Median depth did not vary between transects *a* and *e* despite the observed change in beach width, indicating that coastal squeeze does not affect the value of median depth of this beach (Table 1).

3.2. Macrobenthos

3.2.1. Macrobenthos at the system and local site scales

Along the longitudinal gradients in the Humber, a total of 42 macrobenthic species were recorded from the 14 transects: 9 oligochaetes, 17 polychaetes, 8 crustaceans, 6 molluscs and 2 others (dipteran larvae). *Pygospio elegans* (polychaeta) attained the highest system averaged density accounting for

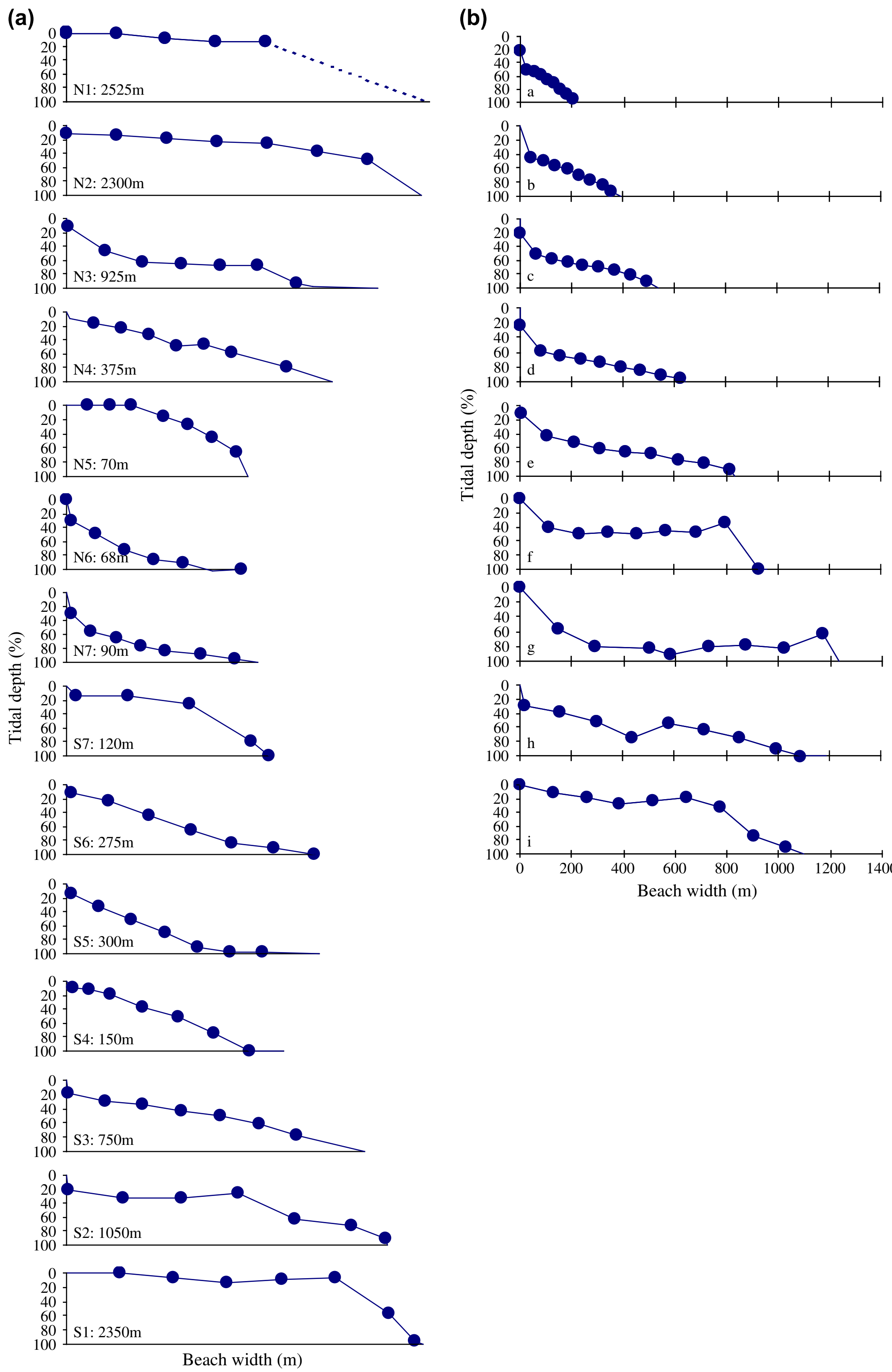

Fig. 2. Intertidal face profiles at the transects sampled in this study showing percentage tidal depth (%) for each sampling station plotted against beach width (m). (a) Along the longitudinal gradient: the beach width axis is log-scaled to make the varying sizes of transects comparable. Transect numbers and their actual lengths (m) are also indicated in each diagram. (b) Along the beach width gradient: the beach width axis is expressed in (m).

Table 2
(a) System-averaged abundance of macrobenthic species in the Humber and (b) site-averaged abundance of macrobenthic species at Grimsby. The species are listed in a decreasing rank order of average density m^{-2}

Species	Average density (ind. m^{-2})	Percentage (%)	Cumulative percentage (%)
(a)			
Pygospio elegans	1956.8	26.4	26.4
Tubificoides benedeni	1684.9	22.7	49.1
Macoma balthica	1358.0	18.3	67.3
Nereis diversicolor	559.4	7.5	74.9
Corophium volutator	470.8	6.3	81.2
Paranais litoralis	333.0	4.5	85.7
Tharyx spp.	225.9	3.0	88.7
Cerastoderma edule	219.4	3.0	91.7
Nephtys hombergii	141.5	1.9	93.6
Eteone longa	76.6	1.0	94.6
Hydrobia ulvae	71.1	1.0	95.6
Others	326.6	4.4	100.0
TOTAL	7424.0	100.0	
(b)			
Cerastoderma edule	1082.3	69.2	69.2
Nephtys cirrosa	140.6	9.0	78.2
Macoma balthica	79.4	5.1	83.3
Bathyporeia spp.	63.3	4.0	87.4
Spiophanes bombyx	46.9	3.0	90.4
Urothoe spp.	35.1	2.2	92.6
Pygospio elegans	29.4	1.9	94.5
Tharyx spp.	22.3	1.4	95.9
Others	63.6	4.1	100.0
TOTAL	1562.9	100.0	

26.4% of the total abundance, followed by *Tubificoides benedeni* (oligochaeta, 22.7%) and *Macoma balthica* (bivalve, 18.3%) (Table 2a). An averaged >7400 macrobenthic individuals m^{-2} were found in the intertidal area along the Humber longitudinal gradient, and 11 species accounted for over 95% of the total mean abundance. System averaged biomass was dominated by three species: *Cerastoderma edule* (bivalve), *M. balthica* and *Nereis diversicolor* (polychaeta) which accounted for 51.7%, 25.0% and 12.1% of the total biomass in the study site, respectively (Table 3a). The system-averaged total biomass was 8.65 g AFDW m^{-2} and 15 species were found to account for over 99% of total biomass.

Along the beach width gradient at the local site of Grimsby, a total of 24 macrobenthic species was recorded from the study site: 2 oligochaetes, 13 polychaetes, 4 molluscs, 3 crustaceans and 2 others (dipteran larvae). Tables 2b and 3b show the characteristic species listed in a decreasing order of site-averaged abundance and biomass at Grimsby, respectively. *C. edule* showed the highest mean density accounting for 69.2% of the total abundance at the study site, followed by *Nephtys cirrosa* (polychaeta, 9.0%) and *M. balthica* (5.1%) (Table 2b). Average total abundance was 1562.9 ind. m^{-2} within the study site and 8 macrobenthic species accounted for over 95% of the total abundance. Trends in mean biomass were also similar, dominated by the three species, *C. edule*, *N. cirrosa* and *M. balthica*, accounting for 91.2%, 3.1% and 2.4% of the total biomass, respectively (Table 3b). Site-averaged total biomass was 6.33 g AFDW m^{-2}, and 5 macrobenthic species accounted for over 99% of the total biomass within the site.

3.2.2. Macrobenthos at the region and zone scales

Fig. 3a shows average biomasses of the three most characteristic (*Cerastoderma edule*, *Macoma balthica* and *Nereis diversicolor*) and other remaining macrobenthic species across the four regions along the longitudinal gradient in the Humber. Average total biomasses were markedly higher in the lower and outer regions than in the upper and middle regions. Statistical test showed that the mean total biomasses per station across the 4 regions were significantly different (ANOVA, $F_{3,90} = 9.2$, $p < 0.0001$), with the outer region significantly different from the middle and upper regions ($p < 0.001$ for both cases) and the lower region different from the upper region ($p < 0.05$). Species composition was also markedly different across the four regions. Amongst the polychaetes worms, *N. diversicolor* was found throughout the system (Fig. 3a), and *Pygospio elegans* was the second most numerous polychaete in the estuary. Other characteristic polychaete species, such as *Nephtys hombergii* and *Eteone longa*, were common towards the outer region, and *Nephtys cirrosa* was only found on the very sandy flats in the outer region. The oligochaete *Paranais litoralis* was commonly found around upper region, but this was gradually replaced by *Tubificoides benedeni* when moving towards the lower and outer regions. The crustacean amphipod *Corophium volutator* was widely distributed, but abundance was markedly higher around the middle region. *M. balthica* was distributed mostly from the lower region and most of the molluscs, such as *Hydrobia ulvae* or *C. edule* became common towards the outer estuary (Fig. 3a). Both the number of macrobenthic species recorded in each region (species richness) and region-averaged macrobenthic abundance became higher towards the lower region, and the abundance was markedly higher in the lower region of the estuary (Fig. 4a).

Fig. 3b shows average biomasses of the three most characteristic (*Cerastoderma edule*, *Macoma balthica* and *Nephtys cirrosa*) and other remaining macrobenthic species across the two zones along the beach width gradient at Grimsby. The mean total biomass per station in the natural zone was significantly higher than that in the squeezed zone (ANOVA, $F_{1,70} = 7.7$, $p < 0.01$). However, it is clear that the site was dominated by *C. edule* and the mean biomasses for the rest of macrobenthic species were not significantly different between the two zones. Polychaetes such as *N. cirrosa*, *Spiophanes bombyx* and the bivalve, *M. balthica* were the other characteristic species across the site. There was no marked difference in species richness between the squeezed and natural zones, but the zone-averaged macrobenthic abundance was much higher in the natural zone (Fig. 4b).

3.2.3. Macrobenthos at the transect scale

Fig. 5a shows mean biomasses of the three most characteristic and other remaining macrobenthic species with total values across transects that are arranged in order from upper to outer estuary. The highest mean biomass was recorded on

Table 3
(a) System-averaged biomass of macrobenthic species in the Humber and (b) site-averaged biomass of macrobenthic species at Grimsby. The species are listed in a decreasing rank order of average biomass g AFDW m^{-2}

Species	Average biomass (g AFDW m^{-2})	Percentage (%)	Cumulative percentage (%)
(a)			
Cerastoderma edule	4.47	51.7	51.7
Macoma balthica	2.16	25.0	76.7
Nereis diversicolor	1.05	12.1	88.9
Nephtys hombergii	0.30	3.5	92.3
Pygospio elegans	0.16	1.8	94.2
Tubificoides benedeni	0.11	1.3	95.5
Scrobicularia plana	0.07	0.8	96.3
Ampharetidae	0.07	0.8	97.1
Corophium volutator	0.05	0.6	97.7
Nephtys cirrosa	0.03	0.3	98.0
Eteone longa	0.02	0.2	98.3
Hydrobia ulvae	0.02	0.2	98.5
Tharyx spp.	0.02	0.2	98.7
Paranais litoralis	0.02	0.2	98.9
Spiophanes bombyx	0.02	0.2	99.1
Others	0.08	0.9	100.0
TOTAL	8.65	100.0	
(b)			
Cerastoderma edule	5.77	91.2	91.2
Nephtys cirrosa	0.20	3.1	94.3
Macoma balthica	0.15	2.4	96.7
Spiophanes bombyx	0.13	2.0	98.6
Urothoe spp.	0.03	0.4	99.1
Others	0.06	0.9	100.0
TOTAL	6.33	100.0	

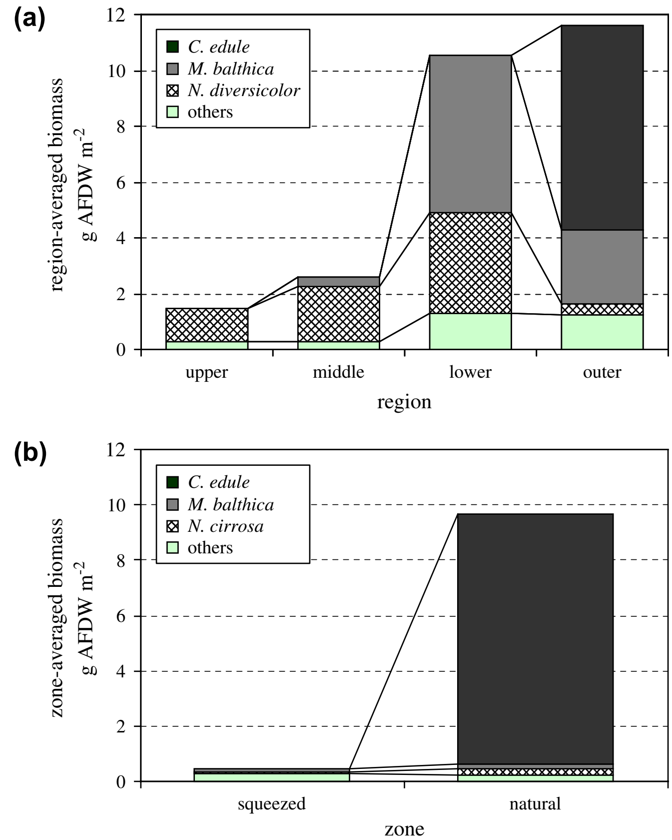

Fig. 3. Average biomasses of the three most characteristic and other remaining macrobenthic species across: (a) regions along the longitudinal gradient in the Humber and (b) zones along the beach width gradient at Grimsby.

transect N1 (mean value of 22.5 g AFDW m^{-2}) and the lowest on transect N7 (mean value of 0.00036 g AFDW m^{-2}). Generally, transects on the north bank had higher mean biomass than those on the south bank. However, the mean biomass on both banks showed a similar increase from the upper through the middle to the lower region of the estuary, although the biomass for the transect outside the mouth was lower on the south bank (S1 in Fig. 5a). Statistical test showed that the mean total biomasses per replicate across the 14 transects were significantly different (ANOVA, $F_{13,28} = 58.2$, $p < 0.0001$), and the results of post hoc (Tukey) test for the difference for all possible combination of transect pairs are shown in Table 4a. A similar overall trend can be seen for mean abundance at the transect scale, showing general increase on the north bank towards the mouth of estuary, but marked decline in the south (Fig. 6a). For species richness per transect, only 1 species was recorded at transect N7 at the upper most site, whilst the maximum number of 26 was found at transect S1 with gradual increase in between (Fig. 6a). However, mean species richness per station was lower on the outer open coast at S1.

Fig. 5b shows mean biomasses of the three most characteristic and other remaining macrobenthic species with total values across transects at Grimsby. Much smaller biomasses were found towards the squeezed zone between transect *a* and *d*, than transects (*f*–*i*) located in natural zone with the highest value of 14.9 g AFDW m^{-2} at transect *g* (Fig. 5b). Statistical test showed that the mean total biomasses per replicate across the 9 transects were also significantly different (ANOVA, $F_{8,18} = 50.4$, $p < 0.0001$), and the results of post hoc (Tukey) test for the difference for all possible combination of transect pairs are shown in Table 4b. The mean total abundance for each transect ranged from 354 to 2994 ind. m^{-2}, and transect *i*, *g* and *h* had the most individuals which were located at the natural zone of the study site (Fig. 6b). Total abundance was lower on the remaining transects, located towards the squeezed end, except for transect *a* that had a slightly higher value than any other transect in the squeezed zone (Fig. 6b). For trend in species richness, transect *f* showed the highest species richness of 14 and transect *h* showed the lowest of 8, whereas mean species richness was more uniform with the highest value of 4.8 at transect *a* (Fig. 6b). There were no clear trends in species richness in relation to the beach width gradient, from the natural beach to the squeezed beach, suggesting that coastal squeeze does not have an influence on species richness in estuarine intertidal area.

3.2.4. Macrobenthos at the station scale

Fig. 7a shows mean total macrobenthic biomass and abundance across stations for the 14 transects along the longitudinal gradient. The amplitude (scale) of the biomass and abundance varied across transects. Although the observed

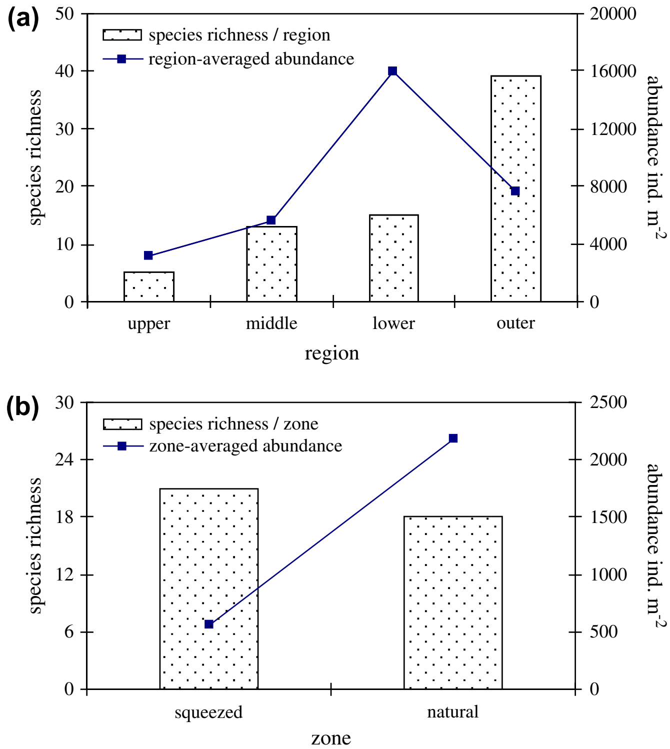

Fig. 4. Species richness (the number of macrobenthic species recorded), and average total macrobenthic abundance across: (a) regions along the longitudinal gradient in the Humber and (b) zones along the beach width gradient at Grimsby.

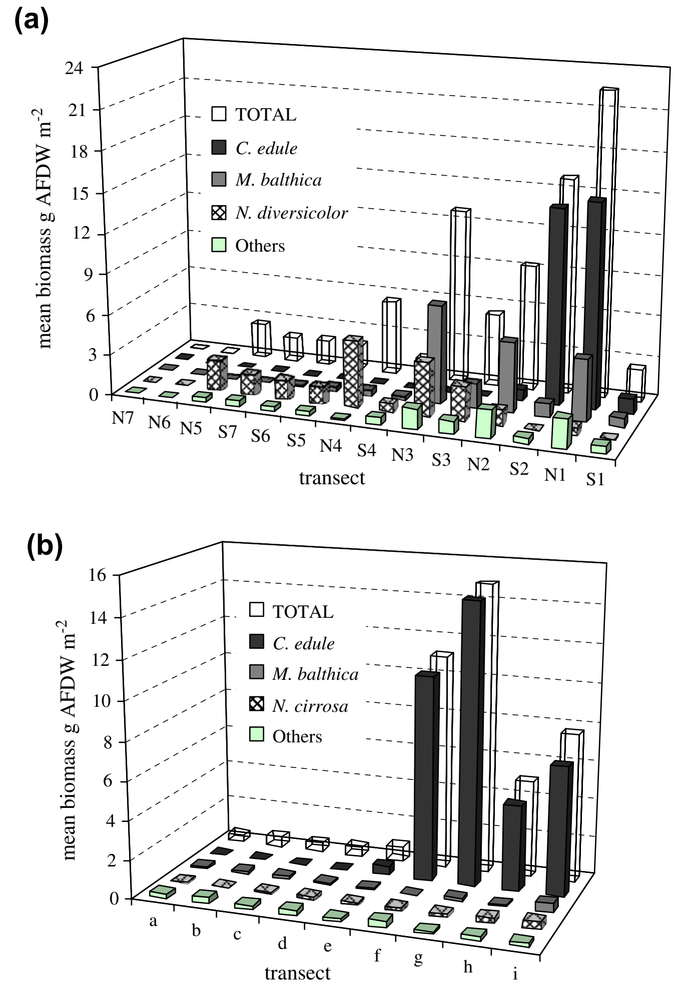

Fig. 5. Mean biomasses of the three most characteristic and other remaining macrobenthic species with total values across transects along: (a) the longitudinal gradient in the Humber and (b) the beach width gradient at Grimsby. In (a), transects are arranged along the *x*-axis in order from upper to outer estuary.

patterns of macrobenthic abundance were not straightforward, both biomass and abundance tended to become lower or close to 0 towards station 7 and thus towards mean low water level (Fig. 7a). Some transects showed the highest biomass around mid shore level (e.g. N2, N3, N7, S1, S3 and S7) and some showed around the highest shore level (station 1) (e.g. N5, N6, S5 and S6). However, intertidal flats were often truncated by sea defence walls in the Humber estuary and for many transects, sampling stations at highest elevation were located lower than mean high water level, indicating that station 1 could be situated around mid-shore level in terms of tidal depth gradient.

At Grimsby study site, the highest biomass and abundance occurred around mid shore level (stations 2–4) and the values decreased close to 0 towards both station 1 and station 9 on most of the transects (Fig. 7b).

3.3. Macrobenthic biomass and environmental variables

3.3.1. Depth index

Using the data set from 14 transects along the longitudinal gradient, the relationship between biomass and tidal depth (intertidal vertical gradient) across transects was explored. The biomass for each station was standardised as a percentage so that the sum of the new values within each transect was 100%. This was done in order to make biomass distributions comparable between transects and thus to avoid the influence of longitudinal gradients such as salinity. These data were further natural log-transformed to stabilise the variance and plotted against tidal depth (in relation to mean tidal range for each transect) as shown in Fig. 8. Sediment characteristics for stations could vary substantially depending on the transect (Table 1), and in order to avoid the influence of sediment variation on macrobenthic biomass, only biomass data taken from similar sediment types within each transect were used for the plot. There was a quadratic relationship between the two variables (Fig. 8), indicating that when longitudinal and sediment gradients are held constant, macrobenthic biomass tends to have a peak value at the point where the tidal depth was around 40% of mean tidal range lower from MHWL within each transect ($y' = 0$ when $x = 39.7$ in the quadratic equation in Fig. 8). The new environmental variable "depth index" was thus established for the subsequent analysis to express how the value of tidal depth for each station deviates from the value 39.7% as follows:

$$\text{depth index} = f(x)/f(39.7)$$

Table 4
Test results of the statistical significance for differences of the mean values in total macrobenthic biomass for all possible combinations of transect pairs along: (a) the longitudinal gradient on the Humber and (b) the beach width gradient at Grimsby, derived from the post hoc (Tukey) test (***$P < 0.001$; **$P < 0.01$; *$P < 0.05$; n.s., not significant)

Transect	N1	N2	N3	N4	N5	N6	N7	S7	S6	S5	S4	S3	S2
(a)													
N2	***												
N3	***	n.s.											
N4	***	n.s.	***										
N5	***	***	***	n.s.									
N6	***	***	***	**	n.s.								
N7	***	***	***	**	n.s.	n.s.							
S7	***	***	***	n.s.	n.s.	n.s.	n.s.						
S6	***	***	***	n.s.	n.s.	n.s.	n.s.	n.s.					
S5	***	***	***	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.				
S4	***	***	***	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.			
S3	***	n.s.	***	n.s.	n.s.	*	n.s.	n.s.	n.s.	n.s.	n.s.		
S2	**	***	n.s.	***	***	***	***	***	***	***	***	***	
S1	***	***	***	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	***
(b)													
	a	*b*	*c*	*d*	*e*	*f*	*g*	*h*					
b	n.s.												
c	n.s.	n.s.											
d	n.s.	n.s.	n.s.										
e	n.s.	n.s.	n.s.	n.s.									
f	***	***	***	***	***								
g	***	***	***	***	***	n.s.							
h	*	*	*	*	*	***	***						
i	***	***	***	***	***	n.s.	***	n.s.					

where x and $f(x)$ denote tidal depth (%) for each station and the quadratic equation y shown in Fig. 2.9, respectively. This indicates that if the tidal depth for a station deviates from 39.7%, depth index deviates from 1 and becomes <1.

3.3.2. Multiple regression analysis

Multiple regression analysis (linear regression) was used to assess the explanatory role of the environmental variables for macrobenthic biomass over two different spatial scales (station and transect) along the two environmental gradients (longitudinal and beach width). Because the biomasses of the two bivalves *Macoma balthica* and *Cerastoderma edule* accounted for approximately 25% and 52% of the total biomass in the Humber, respectively (Table 3a), these species were analysed separately along with biomass for the remaining species and for total biomass. For the station scale, mean values of replicates for each sampling station were used, and for the transect scale, mean values of station data within each transect were used.

Table 5a shows the results of this analysis for macrobenthic biomasses along the longitudinal gradient. Models explained between 34% and 77% of the variance in biomass of *Macoma balthica*, *Cerastoderma edule*, other remaining species and total biomass at the station scale, and between 81% and 98% at the transect scale. At the station scale, biomass of *M. balthica* was negatively related to exposure, and positively related with finer particles, whereas *C. edule* was negatively related to the silt content. At the same spatial scale, the sum of the remaining species and total biomass showed positive relations with salinity and organic matter content, suggesting that overall macrobenthic biomass tends to be high where salinity and organic matter content are high. The remaining macrobenthos was also negatively related to tidal depth, while the total macrobenthic biomass was positively related to depth index, suggesting that overall biomass tends to be high where tidal depth is high or close to the mid-point of the local tidal range. At the transect scale, the degree of variability explained by environmental variables was higher than at the station scale (Table 5a). For total biomass and other macrobenthic biomass (excluding *C. edule* and *M. balthica*), only longitudinal components (salinity) and sedimentary components (organic matter content) explained >80% of the variation in biomass. However, for the biomass of the two bivalve species on transect scale, morphological components, such as beach width or median depth of the beach, significantly explained biomass together with salinity.

In comparison with the longitudinal gradient, models along the beach width gradient at Grimsby explained the variance in macrobenthic biomasses very poorly with a range between 8% and 32% at the station scale (Table 5b). For the biomass of *Cerastoderma edule*, the degree of variance explained was similar at the station scale along the both gradients, but those for others were markedly lower at Grimsby study site than along the entire length of the estuary, suggesting that the station scale may not be meaningful if there is little variation in salinity gradient across study site. However, the degree of variance explained by the key environmental variables was markedly higher when the transect scale was applied at Grimsby

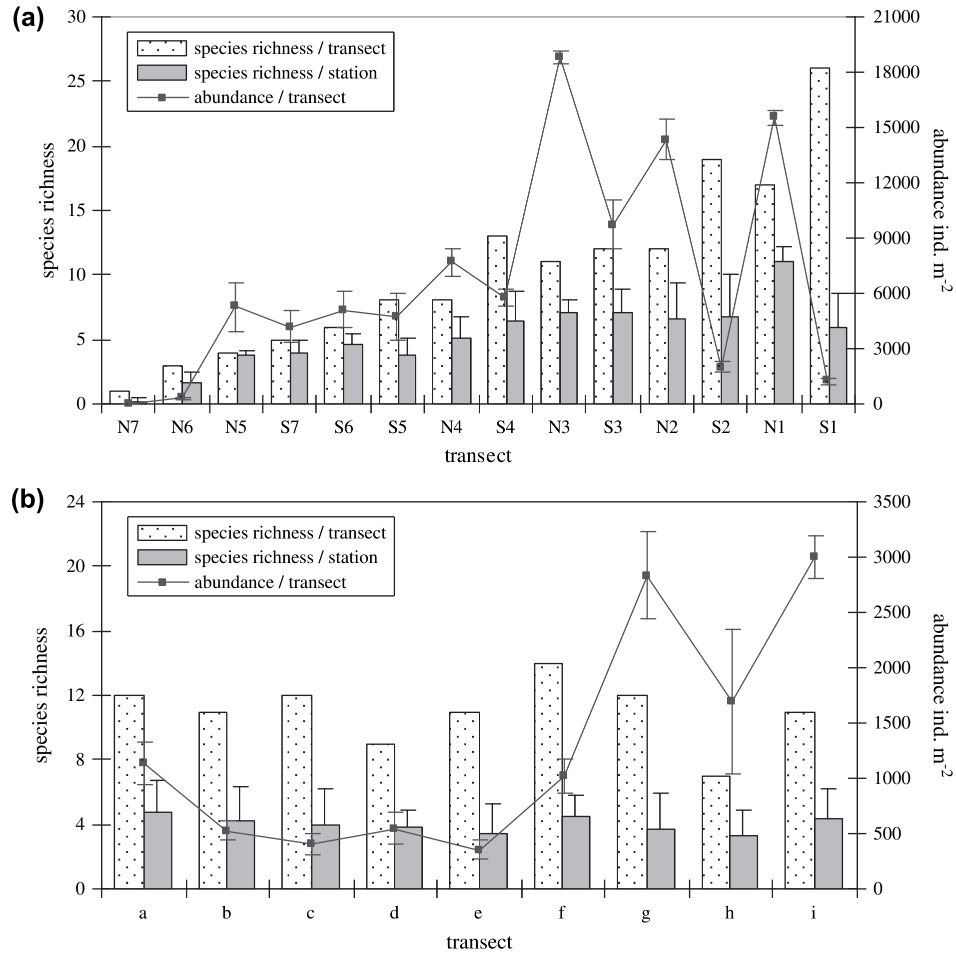

Fig. 6. Species richness per transect, mean species richness per station and mean total macrobenthic abundance across transects along: (a) the longitudinal gradient in the Humber and (b) the beach width gradient at Grimsby. In (a), transects are arranged along the x-axis in order from upper to outer estuary.

(Table 5b). In particular, the dominant species, *C. edule*, was significantly positively related to a single variable of beach width at the transect scale, indicating that the reduction of beach width caused by sea-level rise could have significant impacts on the total system biomass overall. The explanatory role of the environmental variables for *Macoma balthica* was not significant at the transect scale, and markedly lower along beach width gradient at Grimsby than along the longitudinal gradient of the entire estuary, which may be attributable to the little variation in salinity or exposure observed at Grimsby study site.

4. Discussion

This study has investigated the spatial patterns in intertidal macrobenthic biomass observed in the Humber estuary and confirmed that macrobenthic biomass is to be significantly related to key environmental variables from longitudinal, sedimentary and morphological components along the estuarine longitudinal as well as the local beach width gradients, depending on the spatial scales used. These important environmental variables identified in this study have also shown similar relationships with macrobenthos in other studies (e.g. McIntyre, 1970; Dankers et al., 1981; Elliott and Kingston, 1987; Dauer, 1993; Beukema, 2002; Ysebaert and Herman, 2002). In this respect, this study in the Humber could provide a useful test case in the context of identifying an ecologically sustainable estuarine management, which is of relevance to other estuaries in the UK, NW Europe as well as elsewhere trying to cope with sea-level rise.

At the estuarine system scale, the average macrobenthic biomass was 8.65 g AFDW m^{-2} and two bivalve species, *Cerastoderma edule* and *Macoma balthica* were found to account for over 75% of the total macrobenthic biomass in the Humber. The results at such spatial scale (ca 10^5 m) along with the local scale at Grimsby (10^4–10^3 m), can be useful if the trends are to be compared with other habitats across estuaries or sites over a wider geographical context. On the other hand, the spatial scales used for regions (10^5–10^4 m) and zones (2×10^3 m) can be more informative when the linkages between biological and physical processes at relatively large scales are to be investigated within a estuarine system. However, such spatial resolution may be too large to be incorporated into the context of shoreline management in order to cope with sea-level rise because the explanatory role of the environmental variables for macrobenthic biomass could be too obscured. At the station scale (10^2–10^1 m), between

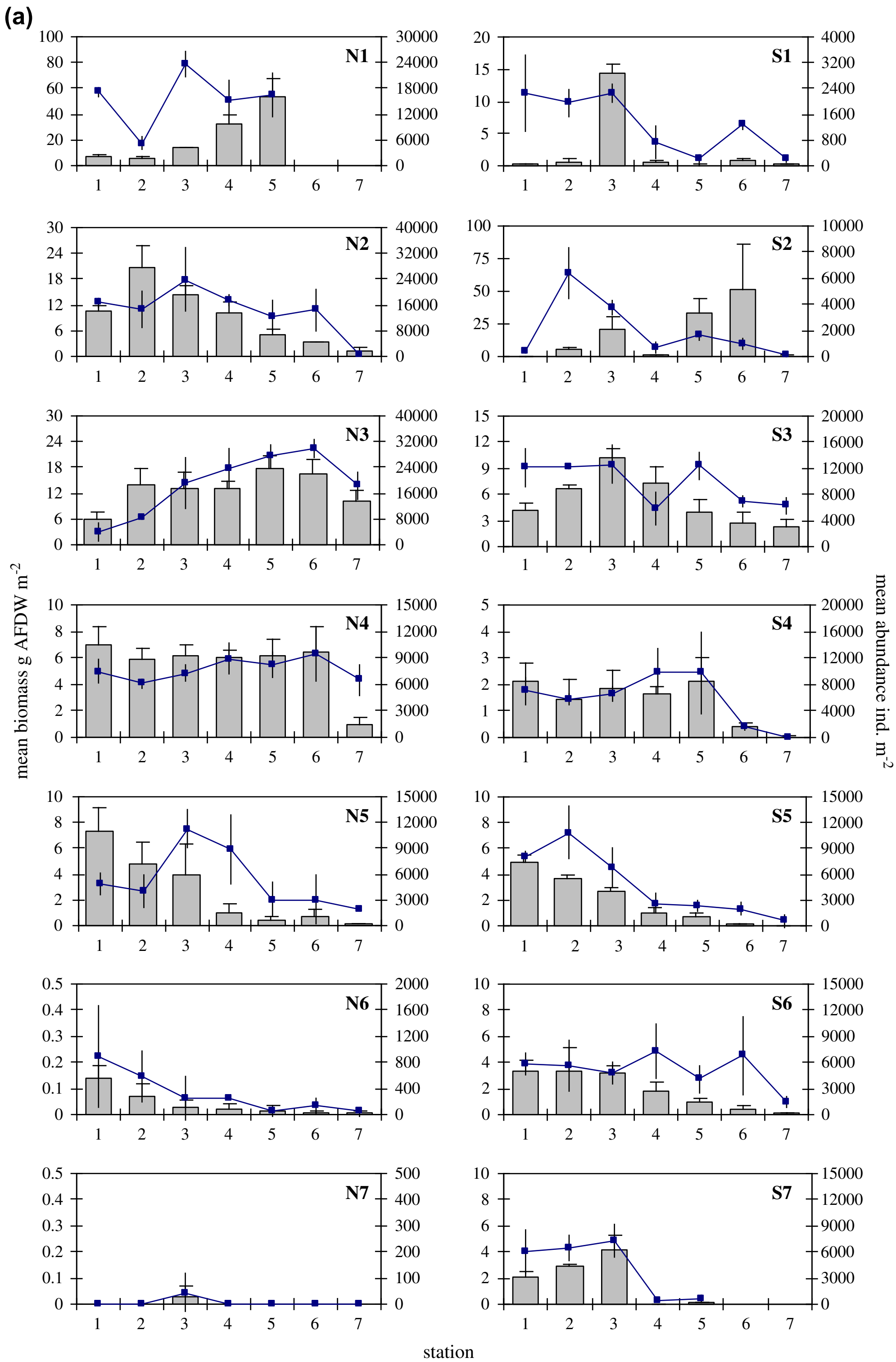

Fig. 7. Mean total macrobenthic biomass (bar graph) and abundance (markers with line) across stations: (a) for the 14 transects along the longitudinal gradient in the Humber estuary and (b) for the 9 transects along the beach width gradient at Grimsby. Vertical T bars show ±SD for biomass, and normal vertical bars show ±SD for abundance.

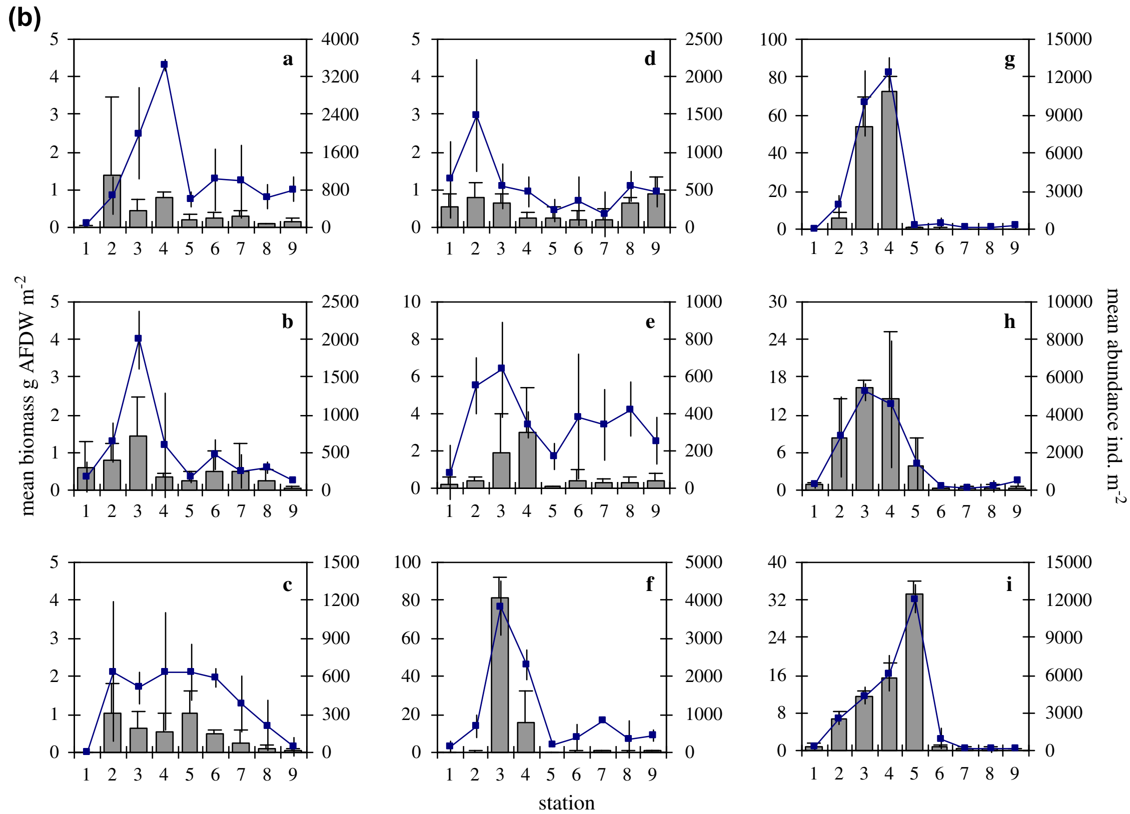

Fig. 7 (*continued*).

34% and 77% of the variance in their biomasses were explained by the key environmental variables when the data were taken along the estuarine longitudinal gradient, but these values were markedly lowered along the beach width gradient at Grimsby (Table 5). Due to the very high degree of variability explained by at the transect scale (10^3–10^2 m) along both longitudinal and beach width gradients, this spatial resolution would provide a useful basis for predicting the impacts of environmental changes on an estuarine ecosystem, which would also be a relevant spatial scale for estuarine shoreline management. For many macrobenthic biomasses examined at the transect scale, the variance was largely explained by the key environmental variables, such as salinity, organic matter content, beach width, beach slope (Table 5). Further, many macrobenthic biomasses (5 out of 8) were significantly positively related to depth index at the station scale (Table 5). This suggests that the quality of intertidal area, or availability of food items for higher trophic levels, is positively associated with higher salinity, muddier sediments, wider beach, shallower beach slope and tidal depths that are closer to mid-shore level.

In the context of estuarine shoreline management, the Humber flood defences protect nearly 90,000 ha of land (Winn et al., 2003), and there is little undefended land throughout the system. This indicates that unless the accretion of the intertidal areas keeps pace with the rate of sea-level rise or appropriate areas are made available for flooding, the intertidal habitats will be squeezed between the rising sea and the defence walls, which will inevitably change the benthic invertebrate assemblages through the loss of their habitats and changes in their physical environment. The results from this study indicate that the biomass of intertidal macrobenthos is likely to be affected by sea-level rise through its potential effects on the salinity distribution, the width and steepness of the flats and the particle size composition of sediments. This study also showed that areas with high macrobenthic biomass are currently situated around the outer region of the estuary (Fig. 5a) where extensive shallow muddy intertidal areas can be found (Table 1).

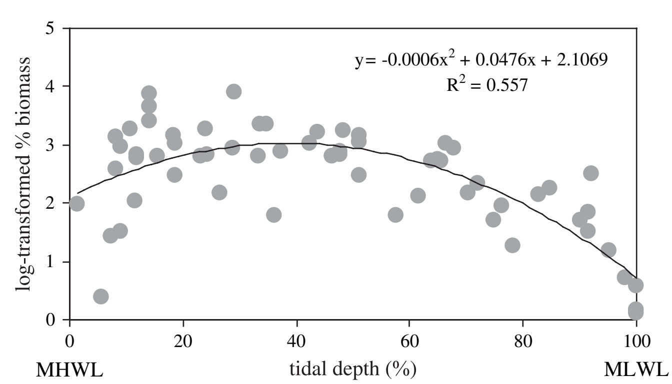

Fig. 8. Relations between percentage biomasses for stations and tidal depth across transects over the estuarine longitudinal gradient. The percentage biomass was natural log-transformed. The quadratic equation and R^2 value are shown in the plot and the biomass attains the highest when the tidal depth is 39.7% lower than mean high water level.

Table 5

Multiple regression analysis of the four macrobenthic biomass categories against physical variables from three environmental components along: (a) the longitudinal gradient on the Humber estuary and (b) the beach width gradient at Grimsby, over two different spatial scales. The data at the station scale consisted of the mean values of replicates, whereas the data at the transect scale consisted of the mean of stations. Overall model R^2 and significance P are presented, along with partial correlation coefficients in parentheses. ***$P < 0.001$; **$P < 0.01$; *$P < 0.05$; n.s., not significant. Environmental variables: SAL, salinity; EXP, exposure; MD, median particle size; ORG, organic matter content; SIL, silt content; WID, beach width; T-SLO, transect slope; S-SLO; station slope; DEP; percentage tidal depth; M-DEP, median tidal depth; DEP-I, depth index, for each sampling station. The subscript number indicates the rank order in which environmental variables were retained in the stepwise procedure

	R^2	P	LONGITUDINAL		SEDIMENTARY			MORPHOLOGICAL					
			SAL	EXP	MD	ORG	SIL	WID	T-SLO	S-SLO	DEP	M-DEP	DEP-I
(a)													
Station scale ($n = 94$)													
M. balthica	0.65	<0.0001		$(-0.21)_4$*	$(0.29)_2$**				$(0.76)_1$***				$(0.29)_3$**
C. edule	0.34	<0.0001					$(-0.23)_3$*	$(0.27)_1$**		$(0.24)_2$*			
Other macrobenthos	0.75	<0.0001	$(0.79)_1$***			$(0.71)_2$***					$(-0.38)_3$***		
Total biomass	0.77	<0.0001	$(076)_1$***			$(0.65)_2$***				$(0.47)_3$***			$(0.40)_4$***
Transect scale ($n = 14$)													
M. balthica	0.92	<0.0001	$(0.94)_1$***							$(0.72)_3$**		$(0.85)_2$***	
C. edule	0.98	<0.0001	$(0.93)_4$***	$(-0.96)_3$***	$(-0.97)_2$***			$(0.94)_1$***	$(-0.81)_5$**				
Other macrobenthos	0.86	<0.0001	$(0.91)_1$***			$(0.88)_2$***							
Total biomass	0.81	<0.0001	$(0.91)_1$***			$(0.61)_2$*							
(b)													
Station scale ($n = 81$)													
M. balthica	0.14	<0.001											$(0.39)_1$***
C. edule	0.32	<0.0001		$(0.55)_1$***			$(0.26)_3$*						$(0.31)_2$**
Other macrobenthos	0.08	<0.01								$(0.31)_1$**			
Total biomass	0.29	<0.0001		$(0.31)_3$**	$(0.25)_4$*					$(0.26)_1$*			$(030)_2$**
Transect scale ($n = 9$)													
M. balthica	−	n.s.											
C. edule	0.80	<0.001						$(0.91)_1$**					
Other macrobenthos	0.54	<0.05										$(-0.77)_1$*	
Total biomass	0.95	<0.001				$(0.80)_3$*		$(0.97)_1$***	$(-0.85)_2$*				

Such areas will also be the most subject to the impacts of sea-level rise due to their outer location and the shallowness of the beach, suggesting that effort needs to be made to identify suitable sites for habitat creation around the outer region of the estuary in order to effectively counteract the future loss of macrobenthic biomass.

For many estuaries, oceanographic and biochemical processes co-vary with other physical and sedimentary elements (Snelgrove and Butman, 1994; Thrush et al., 2003), and the resident organisms themselves further modify the sedimentary components, influencing local physical and chemical characteristics (Paterson and Black, 1999; Widdows and Brinsley, 2002; Wood and Widdows, 2002). Such relations can be further influenced by higher trophic levels such as migratory shorebirds that arrive in large numbers and affect the behaviour of prey organisms and thus erodibility of estuarine sedimentary shores (Daborn et al., 1993). Given the strong feedback effects between biological and environmental components, construction of deterministic models based on cause-and-effect relationships to precisely describe future changes in macrobenthic biomass may be difficult in a large-scale estuarine environment. The statistical (empirical) modelling approach used in this study could be a useful tool in the context of coastal and estuarine management, particularly when there is an urgent need to know how macrobenthic biomass is likely to change in response to long-term changes in their physical environment, including changes caused by global warming and sea-level rise. However, such modelling of species-habitat relationships requires large amounts of data from a number of locations over a wide range of habitats (Thrush et al., 2003). In terms of biomass response to the beach width gradient, this study looked at squeezed and natural beach only in one location and, in this respect, more data from other areas, such as the upper or middle regions of the estuary that has clear beach width gradient, should be obtained in order to make quantitative predictions with further confidence.

There are other uncertainties involved in present approach in using the models for predicting the future change in macrobenthic biomass because this does not incorporate the impacts of temporal factors, such as inter-annual variability in climatic conditions, increase in ambient temperature, increased occurrence of extreme climatic events (e.g. storms and surges) and changes in nutrient load or primary production. For example, annual variability in climatic conditions is known to strongly influence the ecology of estuarine benthic invertebrate assemblages through changes in fecundity and individual growth (Beukema et al., 1993, 1998; Widdows and Brinsley, 2002) or through changes in predation patterns (Jensen and Jensen, 1985). Further, enhanced primary productivity through increased nitrogen or nutrient run off, as well as increased temperatures may also increase benthic biomass, because there is increasing evidence that primary production is one of the key factors regulating benthic biomass and secondary production by affecting individual growth rate and fecundity (Olafsson et al., 1994; Heip et al., 1995; Herman et al., 1999). In view of the relationships between the above temporal factors which would influence the amplitude of macrobenthic biomass distribution over the entire estuarine scale, and the key environmental variables (spatial factors) which are associated with the local spatial variation within the estuarine system, the system total macrobenthic biomass in year t may be described as follows:

$$\text{System Total Biomass}(t) = Kcpn(t) \times \sum \left(\text{Biomass}\left(\mathrm{T}_{\mathrm{n}(t)}\right) \times \text{Area}\left(\mathrm{T}_{\mathrm{n}(t)}\right)\right)$$

$$\text{Biomass}\left(\mathrm{T}_{\mathrm{n}(t)}\right) = F\{\text{key environmental variables in year}(t)\}$$

where $Kcpn(t)$ denotes a term determined by factors such as climatic condition (inter-annual variability, ambient temperature or extreme climatic events) c, primary production p and nutrient load n in year t, Biomass($\mathrm{T}_{\mathrm{n}(t)}$) denotes mean macrobenthic biomass at transect $\mathrm{T_n}$ in year t expressed as a function of the key environmental variables in year t, and Area($\mathrm{T}_{\mathrm{n}(t)}$) indicates the area represented by transect $\mathrm{T_n}$ in year t. Here, $Kcpn(t)$ could be interpreted as a coefficient for the term $\sum$(Biomass($\mathrm{T}_{\mathrm{n}(t)}$) × Area($\mathrm{T}_{\mathrm{n}(t)}$)). These equations therefore indicate that the spatial patterns of observed macrobenthic biomass within a system can be significantly explained by the key environmental variable in any year t, yet the system total macrobenthic biomass (t) could still fluctuate depending on how the coefficient term $Kcpn(t)$ varies over time. This study fully explores the term $\sum$(Biomass($\mathrm{T}_{\mathrm{n}(t)}$) × Area($\mathrm{T}_{\mathrm{n}(t)}$)), assuming that the coefficient $Kcpn$ is held constant. However, factors relating to $Kcpn$ will strongly influence the ecology of estuarine benthic invertebrate assemblages over time, and long-term studies are essential to improve the understanding of such factors.

Notwithstanding the above, the construction of simple models for identifying the role of readily measurable environmental variables in explaining the spatial pattern of macrobenthic biomass is a significant advance for predicting the potential impacts of sea-level rise on the future estuarine environments.

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References

Baker, J.M., Crothers, J.H., 1987. Intertidal rock. In: Baker, J.M., Wolff, W.J. (Eds.), Biological Surveys of Estuaries and Coasts. Cambridge University Press, Cambridge, pp. 157–197.

Barr, R., Watson, P.G., Ashcroft, C.R., Barnett, B.E., Hilton, C., 1990. Humber estuary—a case study. Hydrobiologia 195, 127–143.

Beukema, J.J., 2002. Expected change in the benthic fauna of Wadden sea tidal flats as a result of sea-level rise or bottom subsidence. Journal of Sea Research 47, 25–39.

Beukema, J.J., Essink, K., Michaelis, H., Zwarts, L., 1993. Year-to-year variability in the biomass of macrobenthic animals on tidal flats of the Wadden Sea: How predictable is this food source for birds? Netherlands Journal of Sea Research 31, 319–330.

Beukema, J.J., Honkoop, P.J.C., Dekker, R., 1998. Recruitment in *Macoma balthica* after mild and cold winters and its control by egg production and shrimp predation. Hydrobiologia 375/376, 23–34.

Boesch, D.F., 1977. A new look at the zonation of the benthos along the estuarine gradient. In: Coull, B.C. (Ed.), Ecology of Marine Benthos. Belle W. Baruch Library in Marine Science. University of South Carolina Press, Columbia, pp. 245–266.

Carter, R.W.G., 1988. Coastal Environments: An Introduction to the Physical, Ecological and Cultural Systems of Coastlines. Academic Press, London.

Daborn, G.R., Amos, C.L., Brylinsky, M., Christian, H., Drapeau, G., Faas, R.W., Grant, J., Long, B., Paterson, D.M., Perillo, G.M.E., Piccolo, M.C., 1993. An ecological cascade effect: Migratory birds affect stability of intertidal sediments. Limnology and Oceanography 38, 225–231.

Dankers, N., Kühl, H., Wolff, W.J., 1981. Invertebrates of the Wadden Sea. A.A. Balkema, Rotterdam.

Dauer, D.M., 1993. Biological criteria, environmental health and estuarine macrobenthic community structure. Marine Pollution Bulletin 26, 249–257.

Elliott, M., Kingston, P.F., 1987. The sublittoral benthic fauna of the estuary and Firth of Forth, Scotland. Proceedings of the Royal Society of Edinburgh 93B, 449–465.

Elliott, M., Nedwell, S., Jones, N.V., Read, S.J., Cutts, N.D., Hemingway, K.L., 1998. Intertidal sand and mudflats and subtidal mobile sandbanks: an overview of dynamic and sensitivity characteristics for conservation management of marine SACs. Institute of Estuarine and Coastal Studies, University of Hull. WWW Page: http://www.english-nature.org.uk/uk-marine/reports/pdfs/sandmud.pdf.

Gameson, A.H.L., 1982. The Quality of the Humber Estuary 1961–1981. Yorkshire Water Authority, Leeds.

Goss-Custard, J.D., McGrorty, S., Kirby, R., 1990. Inshore birds of the soft coasts and sea-level rise. In: Beukema, J.J., Wolff, W.J., Brouns, J.J.W.M. (Eds.), Expected Effects of Climatic Change on Marine Coastal Ecosystems. Kluwer Academic Publishers, Netherlands, pp. 189–193.

Hartley, J.P., Dicks, B., Wolff, W.J., 1987. Processing sediment macrofauna samples. In: Baker, J.M., Wolff, W.J. (Eds.), Biological Surveys of Estuaries and Coasts. Cambridge University Press, Cambridge, pp. 131–139.

Heip, C.H.R., Goosen, N.K., Herman, P.M.J., Kromkamp, J., Middelberg, J.J., Soetaert, K., 1995. Production and consumption of biological particles in temperate tidal estuaries. Oceanography and Marine Biology: an Annual Review 33, 1–149.

Herman, P.M.J., Middelburg, J.J., Van De Koppel, J., Heip, C.H.R., 1999. Ecology of estuarine macrobenthos. Advances in Ecological Research 29, 195–240.

Holme, N.A., McIntyre, A.D., 1971. Methods for the Study of Marine Benthos. Blackwell Scientific Publications, Oxford and Edinburgh.

Hulme, M., Jenkins, G.J., Lu, X., Turnpenny, J.R., Mitchell, T.D., Jones, R.G., Lowe, J., Murphy, J.M., Hassell, D., Boorman, P., McDonald, R., Hill, S., 2002. Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report. Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK.

Jensen, K.T., Jensen, J.N., 1985. The importance of some epibenthic predators on the density of juvenile benthic macrofauna in the Danish Wadden Sea. Journal of Experimental Marine Biology and Ecology 89, 157–174.

Jickells, T., Andrews, J., Samways, G., Sanders, R., Malcolm, S., Sivyer, D., Parker, R., Nedwell, D., Trimmer, M., Ridgway, J., 2000. Nutrient fluxes through the Humber estuary—past, present and future. Ambio 29, 130–135.

Jones, G., 1994. Global warming, sea level change and the impact on estuaries. Marine Pollution Bulletin 28, 7–14.

Jones, N.V., 1988. Life in the Humber, invertebrate animals. In: Jones, N.V. (Ed.), A Dynamic Estuary: Man, Nature and the Humber. Hull University Press, pp. 58–70.

Kennish, M.J., 2002. Environmental threats and environmental future of estuaries. Environmental Conservation 29, 78–107.

Key, R.S., 1983. Ecology of the infauna of Spurn Bight mudflats: an area proposed for reclamation. Ph.D. Thesis, University of Hull.

MAFF, 1999. Ministry of Agriculture, Fisheries and Food. Flood defence and Coastal Defence Appraisal Guidance: Economic Appraisal. MAFF Publication PB 4650, London.

McIntyre, A.D., 1970. The range of biomass in intertidal sand, with special reference to the bivalve Tellina tenuis. Journal of Biological Association of the UK 50, 561–575.

McLusky, D.S., 1989. The Estuarine Ecosystem (Tertiary level biology series), second ed. Blackie and Son, Glasgow.

Meire, P.M., Seys, J.J., Ysebaert, T.J., Coosen, J., 1991. A comparison of the macrobenthic distribution and community structure between two estuaries in SW Netherlands. In: Elliott, M., Ducrotoy, J.P. (Eds.), Estuaries and Coasts: Spatial and Temporal Intercomparisons. Olsen and Olsen, Fredensborg, pp. 221–230.

Murby, P.J., 2001. The causes, extent and implications of intertidal change—a regional view from eastern England. MSc Dissertation. University of Hull.

Olafsson, E.B., Peterson, C.H., Ambrose, W.G., 1994. Does recruitment limitation structure populations and communities of macro-invertebrates in marine soft-sediments: the relative significance of pre- and post-settlement processes. Oceanography and Marine Biology: An Annual Review 32, 65–109.

Paterson, D.M., Black, K.S., 1999. Water flow, sediment dynamics and benthic ecology. Advances in Ecological Research 29, 155–193.

Raffaelli, D., Hawkins, S., 1996. Intertidal Ecology. Kluwer Academic Publishers, The Netherlands.

Scavia, D., Field, J.C., Boesch, D.F., Buddemeier, R.W., Burkett, V., Cayan, D.R., Fogarty, M., Harwell, M.A., Howarth, R.W., Mason, C., Reed, D.J., Royer, T.C., Sallenger, A.H., Titus, J.G., 2002. Climate change impacts on U.S. coastal and marine ecosystems. Estuaries 25, 149–164.

Snelgrove, P.V.R., Butman, C.A., 1994. Animal-sediment relationships revisited: cause versus effect. Oceanography and Marine Biology: An Annual Review 32, 111–177.

Sutherland, W.J., 1996. Ecological Census Techniques: A Hand Book. Cambridge University Press, Cambridge.

Taylor, J.A., Murdock, A.P., Pontee, N.I., 2004. A macroscale analysis of coastal steepening around the coast of England and Wales. The Geographical Journal 170, 179–188.

Thrush, S.F., Hewitt, J.E., Norkko, A., Nicholls, P.E., Funnell, G.A., Ellis, J.I., 2003. Habitat change in estuaries: predicting broad-scale responses of intertidal macrofauna to sediment mud content. Marine Ecology Progress Series 263, 101–112.

Uncles, R.J., Easton, A.E., Griffiths, M.L., Harris, C., Howland, R.J.M., King, R.S., Morris, A.W., Plummer, D.H., 1998. Seasonality of the turbidity maximum in the Humber-Ouse estuary, UK. Marine Pollution Bulletin 37, 206–215.

Widdows, J., Brinsley, M., 2002. Impact of biotic and abiotic processes on sediment dynamics and the consequence to the structure and functioning of the intertidal zone. Journal of Sea Research 48, 143–156.

Winn, P.J.S., Young, R.M., Edwards, A.M.C., 2003. Planning for the rising tides: the Humber Estuary Shoreline Management Plan. The Science of the Total Environment 314–316, 13–30.

Wolff, W.J., 1987. Flora and macrofauna of intertidal sediments. In: Baker, M.J., Wolff, W.J. (Eds.), Biological Surveys of Estuaries and Coasts. Cambridge University Press, Cambridge, pp. 81–105.

Wood, R., Widdows, J., 2002. A model of sediment transport over an intertidal transect, comparing the influences of biological and physical factors. Limnology and Oceanography 47, 848–855.

Ysebaert, T., Herman, P.M.J., 2002. Spatial and temporal variation in benthic macrofauna and relationship with environmental variables in an estuarine, intertidal soft-sediment environment. Marine Ecology Progress Series 244, 105–124.

Ysebaert, T., Herman, P.M.J., Meire, P., Craeymeersch, J., Verbeek, H., Heip, C.H.R., 2003. Large-scale spatial pattern in estuaries: estuarine macrobenthic communities in the Schelde estuary, NW Europe. Estuarine. Coastal and Shelf Science 57, 335–355.

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To Whom It May Concern

Dear Sirs

OUR CLIENT ABLE HUMBER PORTS LIMITED

As solicitors for Able Humber Ports Limited we write to confirm that our client has entered into a Tenancy Agreement in respect of 39 hectares of land at Sands Farm Cherry Cob Sands East Yorkshire. The tenancy is for an indefinite term until such time as our client gives notice to terminate if the grassland is no longer required to satisfy any condition in any planning consent but if our client has not given notice to terminate the tenancy will end on 1 October 2160.

Yours faithfully

Wilkin Chapman LLP
Philip D Day Partner

Angus,

The Crown Estate confirms that it has entered into an option agreement with ABLE Humber Ports Limited for the purchase of Cherry Cobb Sands Compensation site on the north Bank of the River Humber, this is conditional upon Able receiving a Development Consent Order (DCO) through the National Infrastructure Planning process.

I trust this is sufficient for your purposes.

Regards

Jane

Jane Dagnall
Solicitor

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Please think - do you need to print this email?

Angus,

I confirm the protective provisions set out below are acceptable to my client

Kind Regards

Martyn

Martyn Chilvers
Partner

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Main Tel: 01472 262626
Website: www.wilkinchapman.co.uk

From: WALKER Angus [mailto:AngusWALKER@bdb-law.co.uk]
Sent: 20 October 2012 22:11
To: Martyn Chilvers
Subject: AMEP: Bethany Jayne Ltd

Dear Martyn

For the purposes of being able to confirm this to the Panel, please could you reply to let me know whether this verson of the proposed protective provision is acceptable to your client:

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FOR THE PROTECTION OF BETHANY JAYNE LTD

89. Before interfering with or extinguishing any existing rights for Bethany Jayne Ltd to

(a) pass along parcel 03009 (Station Road), or

(b) use services and utilities in, on or over the Order land which serve land owned by Bethany Jayne Limited at the date of the coming into force of this Order,

the undertaker shall, with the agreement of Bethany Jayne Ltd, create substitute rights (including appropriate ancillary rights of entry for the purposes of connection, maintenance, repair and renewal) that are reasonably convenient for Bethany Jayne Ltd, such agreement not to be unreasonably withheld or delayed, and to be subject to arbitration under article 58.

Many thanks

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