SHELF SEA BIOGEOCHEMISTRY
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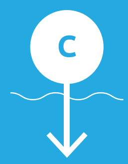
SHELF SEAS

THE ENGINE OF PRODUCTIVITY

UNDERPINNING SCIENCE FOR POLICY AND MANAGEMENT

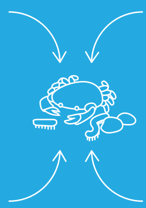
- ECOSYSTEM STATUS AND FUNCTIONING
- A VARIABLE SYSTEM
- EFFECTS OF HUMAN ACTIVITY
- EFFECTS OF CLIMATE CHANGE
- BLUE CARBON
- MONITORING, MODELLING & DATA FOR ASSESSMENT

MAIN HEADLINES



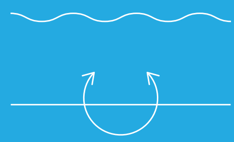
UK SHELF SEAS ARE A SIGNIFICANT CARBON SINK.

There is currently a large net annual uptake of carbon dioxide (CO_2) from the atmosphere to the water column in Northwest European shelf seas, including UK waters. However, there is regional and seasonal variability in that CO_2 uptake, and we are still unsure how much carbon is permanently removed from the climate system – since some may be returned to the atmosphere from elsewhere in the ocean on decadal to century timescales.



MANY INTERACTING FACTORS CONTROL BIOLOGICAL PRODUCTIVITY.

Nutrients for primary production are mostly supplied naturally from the Atlantic Ocean, but in coastal regions, land sources enhanced by human activities, are important. Unexpectedly, a lack of dissolved iron can potentially become growth limiting in the Celtic Sea. Low oxygen zones occur naturally in bottom waters during summer; whilst oxygen levels are currently above the critical thresholds for sealife, their further depletion would give cause for concern.

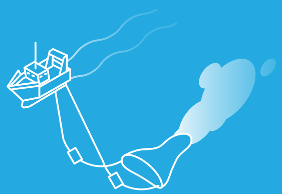


DYNAMIC PROCESSES CONNECT THE WATER COLUMN AND THE SEABED.

The rich biodiversity living in and close to the seafloor is crucially dependent on the biological, chemical and physical processes occurring in the overlying water column, as well as material re-cycling within sediments. Marine environmental status monitoring and assessments need to take account of these dynamic linkages, with greater recognition of the many important ecosystem services provided by the seabed, including carbon removal and storage.

SEASONAL CHANGES AND GEOGRAPHICAL VARIABILITY ARE FUNDAMENTAL TO SHELF SEA FUNCTION.

The natural variability found across UK shelf seas influences how their ecosystems respond to climate change and human pressures. Our emerging understanding of this variability will greatly improve the detection, projection and assessment of impacts of future change.

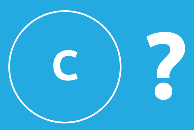


HUMAN ACTIVITIES IMPACT SHELF SEA FUNCTION.

UK shelf seas provide many economic benefits, whilst human impacts on them also result in environmental risks and costs. The most widespread direct impacts come from bottom trawling, with the first trawl pass resulting in significant seabed ecosystem changes. Marine protected areas provide opportunities to distinguish large-scale climate-related impacts from more local, human-induced changes in seafloor communities.

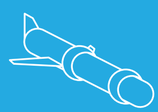
CLIMATE CHANGE IS ALREADY AFFECTING UK SHELF SEAS, AND IMPACTS WILL INTENSIFY.

Model simulations are now able to connect chemical and biological processes in the water column with those at the seafloor, showing likely future changes at the regional level for specific CO_2 emission scenarios. These changes potentially impact all levels of the marine food chain, including fisheries. The model projections can inform status and trend-tracking in monitoring programmes, identifying areas where change signals may be detected first.



BLUE CARBON IS UNDOUBTEDLY A VALUABLE SHELF SEA ECOSYSTEM SERVICE, BUT MANY KNOWLEDGE GAPS REMAIN.

Shelf and coastal habitats contain very large stores of organic carbon, mostly in sediments. These stocks are vulnerable to habitat loss, seabed disturbance and climate effects. However, the dynamics of these processes and their future behaviour are poorly quantified. Better evaluation of this service, and its potential for management, is needed for natural capital assessments and international applications.



NEW TOOLS PROVIDE NEW INSIGHTS - AND OPPORTUNITIES.

Research ships are still needed for shelf sea science, yet marine data-gathering now increasingly depends on sophisticated sensors, autonomous vehicles and satellite surveys to extend the temporal and spatial range of measurements. The NERC-Defra Shelf Sea Biogeochemistry programme helped pioneer the use of these techniques, combining them with modelling tools to provide a greater understanding of 'the engine of productivity' for shelf seas.

RECOGNISING THE VALUE OF SHELF SEAS

THE SHELF SEA BIOGEOCHEMISTRY PROGRAMME

This report summarises key policy-relevant results arising from the NERC-Defra Shelf Sea Biogeochemistry Programme (SSB), 2013-2018. It focuses on current scientific understanding of the shelf seas around Britain: the key processes that maintain their status, variability and response to impacts (climate and human); their potential to remove and store carbon ('blue carbon'); and the lessons for policy in monitoring, managing and valuing these precious habitats. These findings provide evidence for Defra, the devolved administrations and other stakeholders to help ensure the sustainable use of the UK marine environment

GLOBAL SHELF SEAS

25 million km²
7% of the total area of the global ocean

NORTHWEST EUROPEAN SHELF SEA

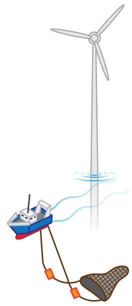
3.2 million km²
(OSPAR Regions II and III, Area to the 200 m depth contour)

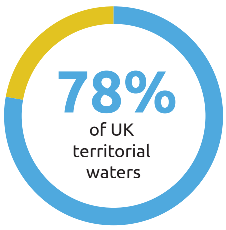
UK SHELF SEA

1.6 million km²

average depth **80m**

6 times the land area of the UK





The UK shelf sea is worth

£47 billion

(foresight Future of the Sea report 2018)

Nearly the **whole area** of the UK shelf seas

is directly impacted by human activities

Shelf seas are regions of shallow water (less than 200m depth) between land and the open ocean. They comprise only around 7% of the global ocean, yet are arguably the most important part - providing human society with a wide range of extremely valuable ecosystem services.

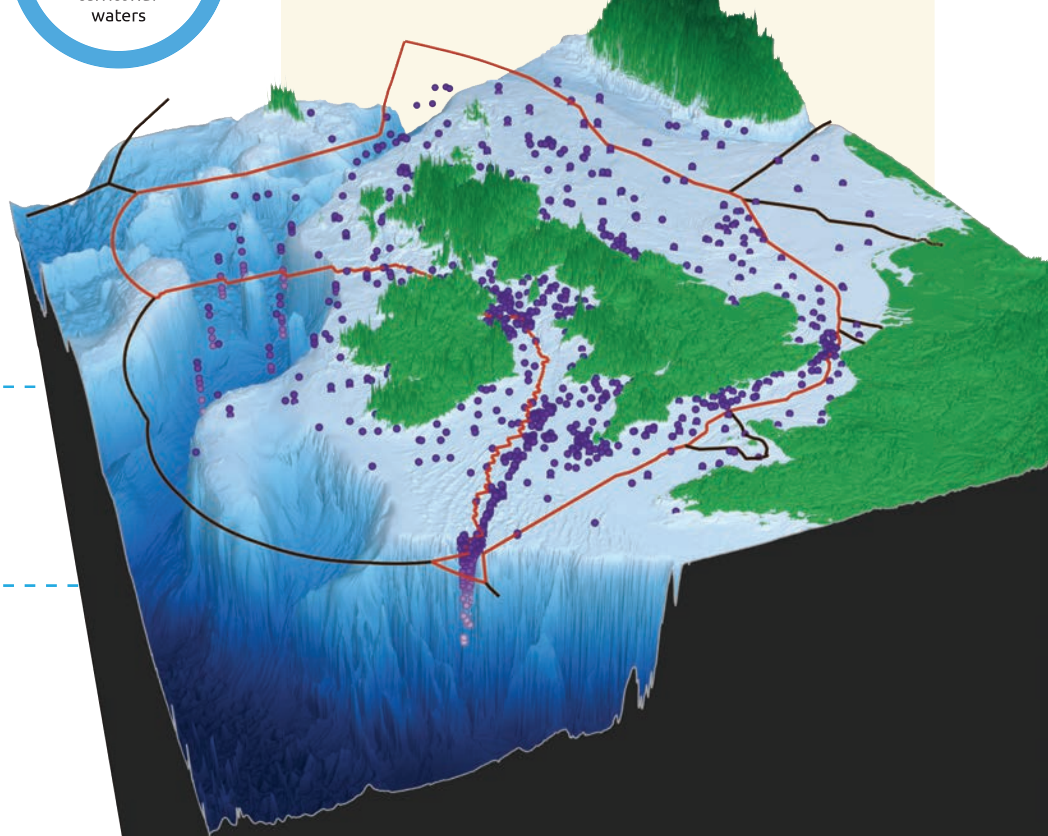
The shelf seas are highly productive compared to the open ocean, supporting more than 90% of global fisheries. Their importance to society also includes biodiversity, carbon cycling and storage, waste disposal, nutrient cycling, recreation and renewable energy resources. Consequently, the shelf seas have been estimated to be the most valuable biome on Earth. However, they are under considerable stress from human activities such as high nutrient inputs, overfishing, and habitat disturbance, as well as climate change and ocean acidification.

Around 78% of UK waters (Exclusive Economic Zone) are shelf sea. While responsibility for the Northwest European shelf sea (in OSPAR regions II 'Greater North Sea' and III 'Celtic Seas') is shared with nine other nations, the UK waters account for over 50% of the total area.

MAP OF UK SHELF SEAS

This map shows bathymetry (with vertical scale exaggerated), boundaries of national Exclusive Economic Zones (EEZs), and the sites of SSB sampling for the shelf-wide survey.

Image by Matthew Humphreys



POLICY LINKS

Understanding how the shelf system works and how it will respond to future pressures is highly relevant to Defra's marine evidence plan and complements the high-level policy themes and evidence requirements or science priorities in the UK Marine Science Strategy: in particular, understanding how the marine ecosystem functions; responding to human activities, climate change and its interaction with the marine environment; and sustaining and increasing ecosystem benefits.

Our findings will help implement the UK marine policy vision for 'clean, healthy, safe, productive and biologically diverse oceans and seas'. They also have important implications for national marine monitoring, management of marine protected areas, the UK carbon budget, climate change risk assessments, and marine natural capital. Our better knowledge of the studied processes is expected to improve the quality and cost-effectiveness of management decisions by marine policy-makers, at the local, national and international levels, under conditions of climate change and increasing human pressures.

Photo: Tom Hull

THE SSB PROGRAMME

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The aim of the UK Shelf Sea Biogeochemistry (SSB) research programme was to increase our fundamental understanding of how physical, chemical and biological processes interact on UK and European shelf seas.

The SSB programme was co-funded by the Natural Environment Research Council (NERC) and the Department for Environment, Food & Rural Affairs (Defra), bringing together more than 100 researchers from 15 universities and research centres.

The programme focused on the role of UK and European shelf seas in carbon storage, in the global cycles of key nutrients (nitrogen, phosphorus, silicate and iron) and oxygen, and in determining phytoplankton, zooplankton and benthos states and functioning, thereby underpinning the future delivery of many ecosystem services. Investigations were undertaken through fieldwork, experiments and modelling.

The SSB programme has greatly increased the information available on shelf seas and improved our understanding of how they function, achieved through advances in quantitative marine biogeochemical and ecosystem modelling, over a range of scales.

The programme outputs are therefore expected to support policy actions relating to the sustainable management of UK shelf seas.

The programme primarily addressed the following Defra marine strategy research questions, in the context of shelf seas:

1. What are the components of the marine system and how do they function?
2. What are the pressures and impacts of human activities (namely trawling and nutrient inputs) on the marine environment?

The work also provides relevant information regarding impacts of climate change and multiple stressors; differentiation between climate and trawling signatures; marine protected areas; monitoring; marine carbon management; and ecosystem modelling.

This report is divided into six sections that focus on differing aspects of the shelf seas in relation to policy research questions and theme evidence requirements.

1. ECOSYSTEM STATUS AND FUNCTIONING

2. A VARIABLE SYSTEM

3. EFFECTS OF HUMAN ACTIVITY

4. EFFECTS OF CLIMATE CHANGE

5. BLUE CARBON

6. MONITORING, MODELLING & DATA FOR ASSESSMENT

Each section provides an introduction to the topic, key science findings (with a **CONFIDENCE** assessment) and resulting *policy implications*.

Photo: Malcolm Woodward

Deployment of sediment multicorer on SSB research cruise. Photo: Torben Stichel

DEFRA EVIDENCE REQUIREMENTS

The table below maps the main Defra evidence requirements on to the six topics covered in sections of the report card.

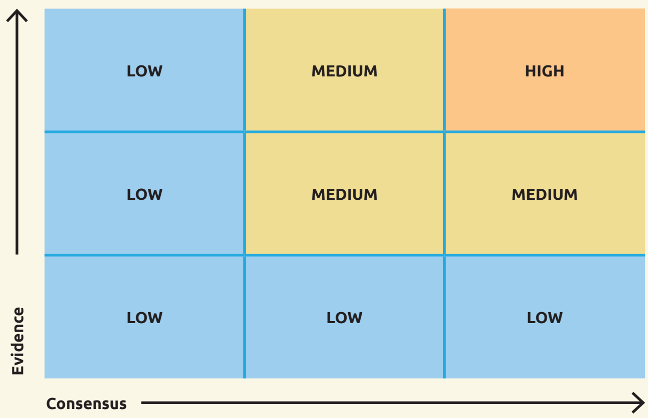
Defra Evidence requirements	1. Ecosystem Status and Functioning	2. A Variable System	3. Effects of Human Activity	4. Effects of Climate Change	5. Blue Carbon	6. Monitoring, Modelling & Data for Assessment
Ecosystem functioning	✓	✓	✓	✓	✓	
State and trends		✓	✓	✓	✓	
Response to environmental change			✓	✓	✓	✓
Marine carbon management	✓	✓	✓	✓	✓	✓
Pressures and impacts of human activity			✓		✓	
Monitoring	✓	✓	✓	✓	✓	✓

CONFIDENCE MEASURE

Throughout this report we have assigned a confidence measure against each of our science statements, categorised as **LOW**, **MEDIUM** or **HIGH**. We have employed the same method as the Marine Climate Change Impact Partnership to assess confidence, the details of which can be found at:

www.mccip.org.uk/impacts-report-cards/full-report-cards/2013/confidence-assessments/

The confidence ratings of low, medium or high are based upon the amount of evidence available and the level of scientific consensus. So a high rating indicates a large evidence base from differing sources (literature, studies, modelling and experiments), with a high level of consensus.



1. ECOSYSTEM STATUS AND FUNCTIONING

How do shelf sea systems work and why are they important?

If one imagines the whole marine ecosystem as a machine, biogeochemical processes provide its engine and moving parts. These processes involve interactions between physics, chemistry and biology, and the cycling of carbon, oxygen, nutrients and trace elements such as iron.

Microscopic plants (phytoplankton) use sunlight and carbon dioxide (CO_2) to create organic molecules to fuel the engine – removing CO_2 from the atmosphere. The subsequent breakdown of the plant-derived organic material provides energy for all other marine life, from viruses to whales, whilst releasing CO_2. The rate at which CO_2 is taken up and released by the ocean (including shelf seas) has a significant influence on global climate.

Within the ocean, productivity and biological diversity are controlled by the carbon cycle, including the way carbon is partitioned into the different ecosystem compartments. All marine organisms require a carbon supply, and all are involved in its use and storage. But other elements such as nitrogen, phosphorus, silicon and iron are required too, and malfunction of the engine can result, if they are in excess or short supply.

MAIN BIOGEOCHEMICAL PROCESSES

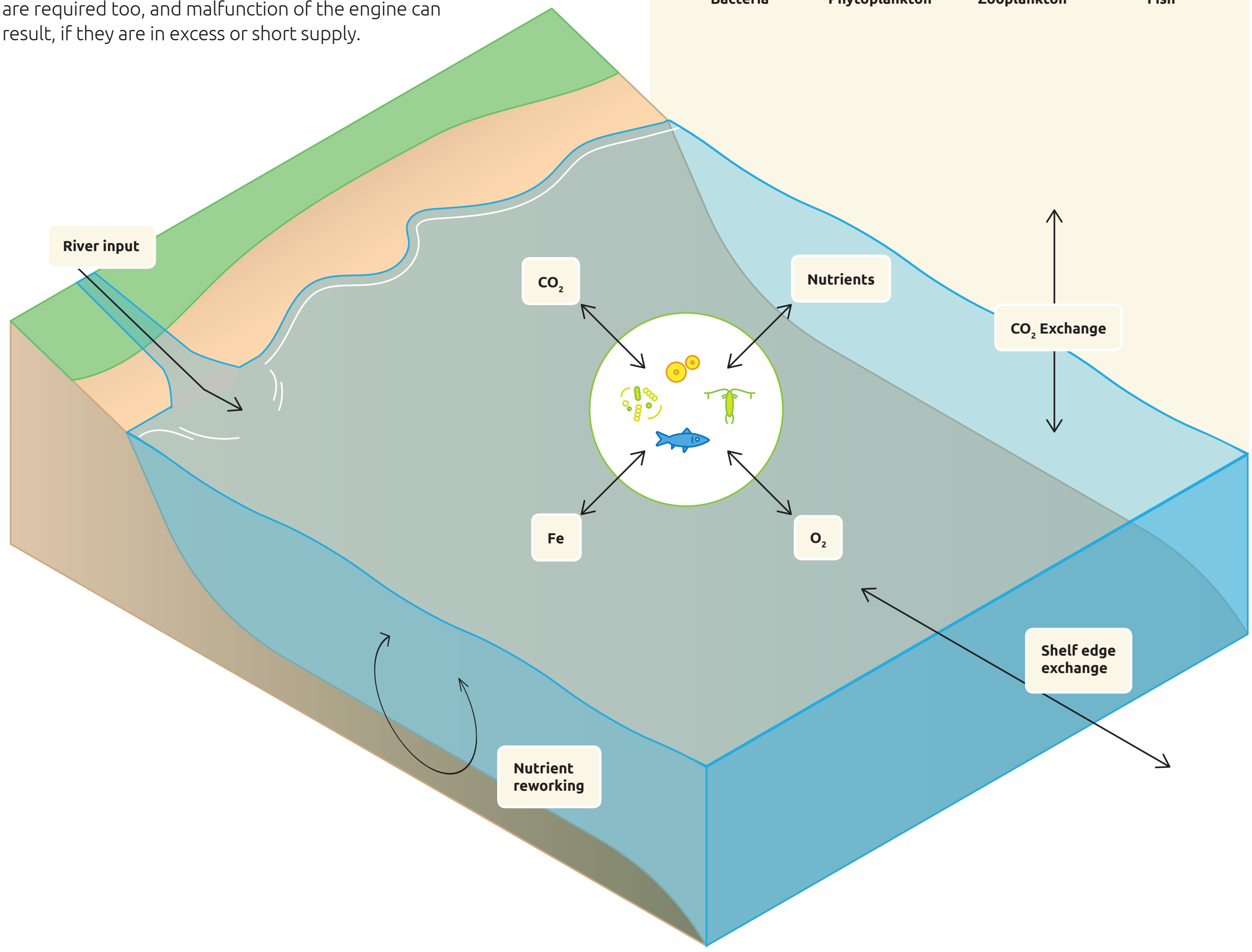
Nutrients and organic matter enter the marine system through riverine inputs, direct run-off from land and atmospheric deposition.

Photosynthesis by phytoplankton (primary production) combines CO_2 with inorganic nutrients (nitrate, phosphate, silicate, iron) to create organic compounds.

Coupling between the water column and seabed. Nutrients, carbon and contaminants are deposited from the overlying water column and either stored or recycled in marine sediments on the seafloor. The release of nutrients and iron from the seabed can stimulate water column productivity.

At the sea-surface, gases such as CO_2 and O_2 diffuse in and out, with exchanges controlled by concentration gradients, temperature and mixing processes.

Water exchanges between the shelf seas and the open ocean across the shelf-edge. Nutrients, iron and carbon compounds are also transferred, both dissolved in the water column and through suspended sediment, including off-shelf transport in particle-rich waters, called nepheloid layers.



WATER COLUMN

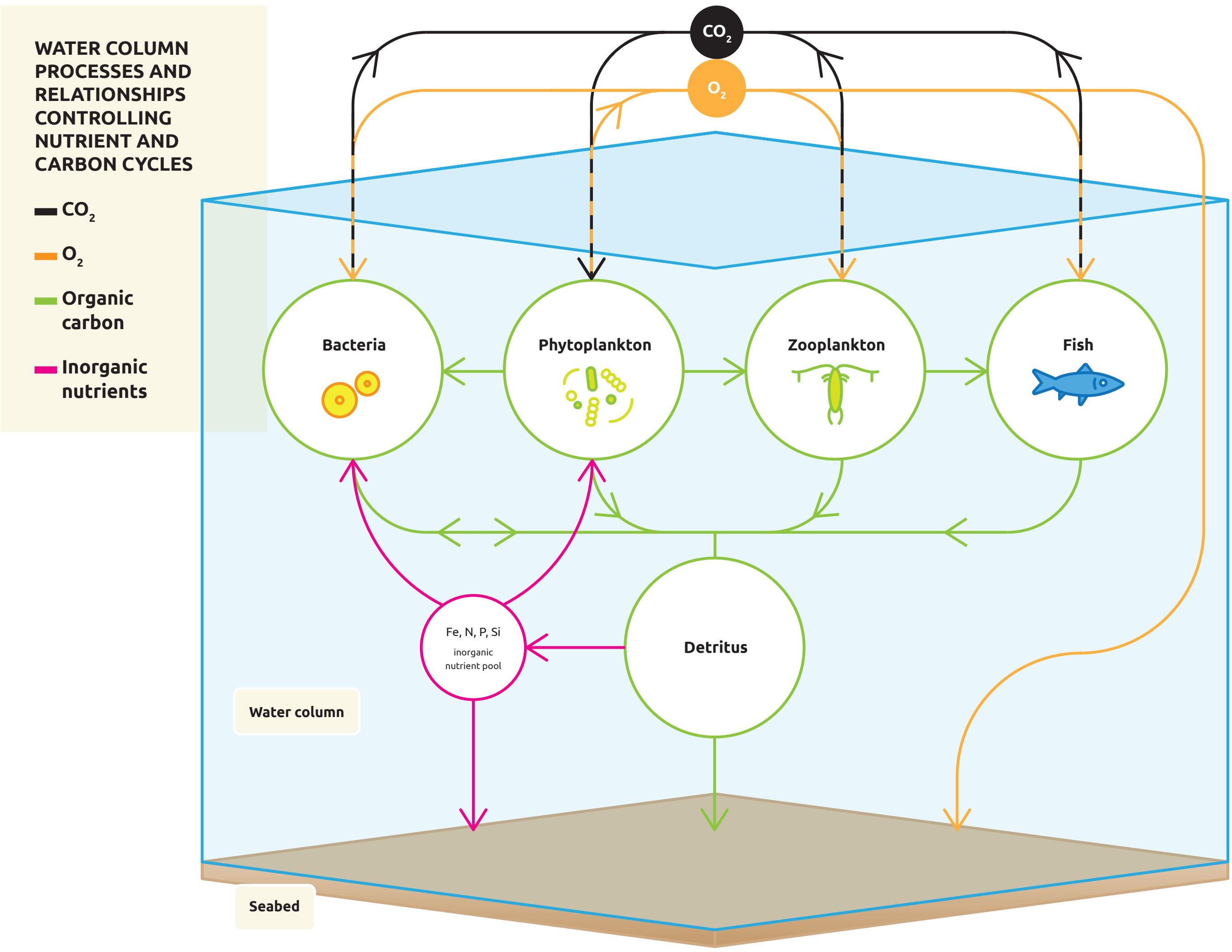
When CO_2 dissolves into the ocean, a proportion of it is taken up by phytoplankton (alongside nutrients such as nitrate, phosphate, silicate and iron) for photosynthesis and growth - a process known as primary production. Some of the carbon fixed in this way will stay as organic matter and travel up the food chain when larger organisms, such as zooplankton, consume the phytoplankton (secondary production). When organisms respire, carbon is released back into the water column as carbon dioxide, and oxygen is consumed. As organisms die, some will decay in the water column (with the aid of bacteria) releasing CO_2 and nutrients, whilst others will sink to the seafloor as detritus. The carbon involved in these processes may either stay in the shelf sea system, or return to the atmosphere, or be exported off the shelf into the deep ocean.

KEY SCIENTIFIC FINDINGS

- **HIGH CONFIDENCE:** On the basis of the most comprehensive survey conducted of shelf seas to date, the Northwest European shelf is a significant CO_2 sink. Biological productivity, regulated by temperature, light and nutrient availability is an important driver for this uptake.
This has implications for the UK response to the Climate Change Risk Assessment and requirements of the UK Climate Change Act (2008) in assessing the marine contribution to the UK carbon budget. Nutrient management measures and climate change (primarily through effects on plankton) can affect this balance and enhance or decrease net storage and export.
- **HIGH CONFIDENCE:** The nutrients that support biological production in UK shelf seas come from both the open ocean and rivers, with the former being by far the more important source. On the broad shelf seas around the UK it is likely that riverine nutrients (inorganic nitrogen and phosphate) contribute to about 10% of the total available nutrients in the sea. However, higher proportions occur in parts of the Irish Sea and southern North Sea, and more generally within 10- 20 km of the coast.
Circulation changes at the shelf edge (driven by climate change) may affect carbon uptake in complex, non-linear ways. Management of anthropogenic nutrient inputs will mostly affect coastal areas.
- **MEDIUM CONFIDENCE:** Iron, which is essential for the growth of phytoplankton, was found to reach vanishingly low levels in surface waters of the Celtic Sea during summer and so may be a growth limiting micro-nutrient at certain times of the year. Iron availability limits primary production in ~30% of open ocean waters, but was not previously considered to be in short supply in shelf seas.
This scientifically-novel finding is a priority area for further investigation if we are to understand the productivity of UK shelf waters and how best to manage them. Iron source is likely to be closely linked to other variables that should be included within seabed monitoring such as oxygen, sediment colour and faunal mixing.
- **HIGH CONFIDENCE:** Differences in sediment type (mud vs sand) and hydrographic conditions across the shelf influence the re-supply of iron into overlying shelf waters.

UNCERTAINTIES AND KNOWLEDGE GAPS

The largest knowledge gaps in assessing the riverine contribution to nutrient availability (and biological growth) in UK shelf seas relate to lack of data on how long water stays in specific areas, and how such residence times influence nutrient processing rates.



SEABED

The seabed in shelf seas is closely coupled with the water above it. Organic carbon (phytodetritus, faecal pellets, etc) falls through the water column and may be incorporated into the bed by faunal feeding or physical reworking. This carbon is gradually degraded through various elemental cycles, involving oxygen, nitrate, iron, manganese and sulphur. The relative strength of these different processes controls the fate of carbon: how much is buried and how much is degraded. Degradation releases CO_2 and associated nutrients from the organic matter, releasing them to the sediment and the water column. These cycles are controlled and sustained by the physical environment (sediment type, hydrography and resuspension) and biological (micro-, meio-, and macrofaunal) communities by their respiration and movement through the seabed (bioturbation and bioirrigation).

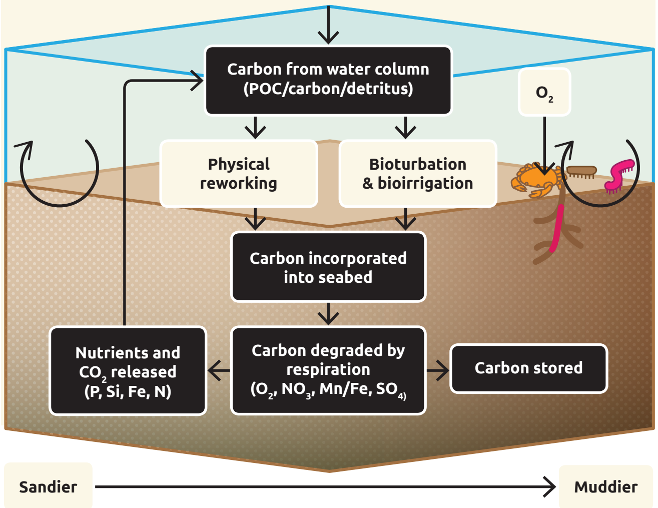
KEY SCIENTIFIC FINDINGS

- **HIGH CONFIDENCE:** The interplay between physical (sediment, temperature), chemical (carbon supply, oxygen) and biological (micro- to macrofauna) characteristics is key in how the bed processes carbon and nutrients and how it responds to forcing.
  Seabed monitoring of sediment type and faunal assemblage structure alone will not provide understanding of processes maintaining state or driving change nor inform management actions needed. Monitoring programmes should include combined seabed metrics to allow an integrated description of status, changes and functioning, which links more accurately to goods and services provision.
- **HIGH CONFIDENCE:** The biomass of benthic macrofauna (> 1 mm) may be small, but such organisms can have a large functional role in mediating carbon and nutrient cycling, both directly and via smaller organisms (meio- and microfauna). This is often not linked directly to macrofaunal biodiversity.
  It is important to differentiate between biodiversity and function when characterising a benthic assemblage.
- **MEDIUM CONFIDENCE:** In fine-grained, muddy sediments, macrofaunal characteristics (traits) are closely linked to carbon and nutrient cycles; however, in highly permeable sands, where physical processes dominate, their role is reduced.
  Different sediment types are controlled by different processes. Lack of inclusion of process-related metrics in seabed monitoring could result in state and function changes being missed, or differing states described inaccurately.

Common whelk taken with Sediment Profile Imagery (SPI) camera
Photo: Briony Silburn

SEABED PROCESSES CONTROLLING CARBON AND NUTRIENT CYCLES

Particulate carbon is incorporated into the seabed by faunal feeding (in muddier sediments) or by physical reworking (sandier sediments). Some carbon is degraded by various respiration processes and released as CO_2 and associated nutrients. The burial of residual carbon is more in muds and less in sands, controlled by mixing processes (biological and physical) and the oxygenation of the bed.



UNCERTAINTIES AND KNOWLEDGE GAPS:

Comprehensive understanding of faunal mediation of seabed chemical processes has not yet been achieved due to a lack of monitoring programmes collecting both faunal and biogeochemical observations. The SSB programme has shown the utility of co-collected data sets, and more frequent, well-integrated monitoring would greatly increase understanding of the role of biodiversity on ecosystem function, whilst also improving environmental impact assessments that involve seabed disturbance and faunal changes. Stronger links between biodiversity and ecosystem functioning in monitoring and modelling research would also lead to improved valuations of the goods and services provided by the seabed, and how they are likely to respond to climate change or direct human pressures.

POLICY IMPLICATIONS

- **Information on observed and potential future changes in marine carbon fixation and storage in UK waters needs to be included in Climate Change Risk Assessments.**
- **Carbon uptake on the shelf is affected by many factors, including circulation at the shelf edge and human nutrient inputs. Improved understanding of these processes, provided by the SSB programme, will allow us to distinguish between the different drivers of future change.**
- **Integrated seabed processes need to be considered in monitoring programmes to improve understanding of present day state, changes and their implications. Carbon and nutrient cycling of the seabed is a key ecosystem service, linked to marine policy priorities in terms of understanding biodiversity, ecology and functioning, controlling mechanisms and response to changes. Integrated physical, chemical and biological sampling will allow a more coherent assessment to be made of this service relevant to the valuation of marine natural capital.**

2. A VARIABLE SYSTEM

What is where, and when and how do changes occur?

The water-column and seabed of shelf seas are both physically-dynamic systems, resulting in high variability over a range of scales - both spatially (horizontal and vertical) and temporally (daily, seasonal and interannual).

The water column can be mixed or stratified, driven by tides, winds, and changes (seasonal and short-term) in temperature and freshwater inputs. These circulation processes in the water column interact with local geology and seafloor morphology to determine whether the seafloor is muddy, sandy or rocky, and whether sediments are eroding or accumulating, resulting in very different biological communities.

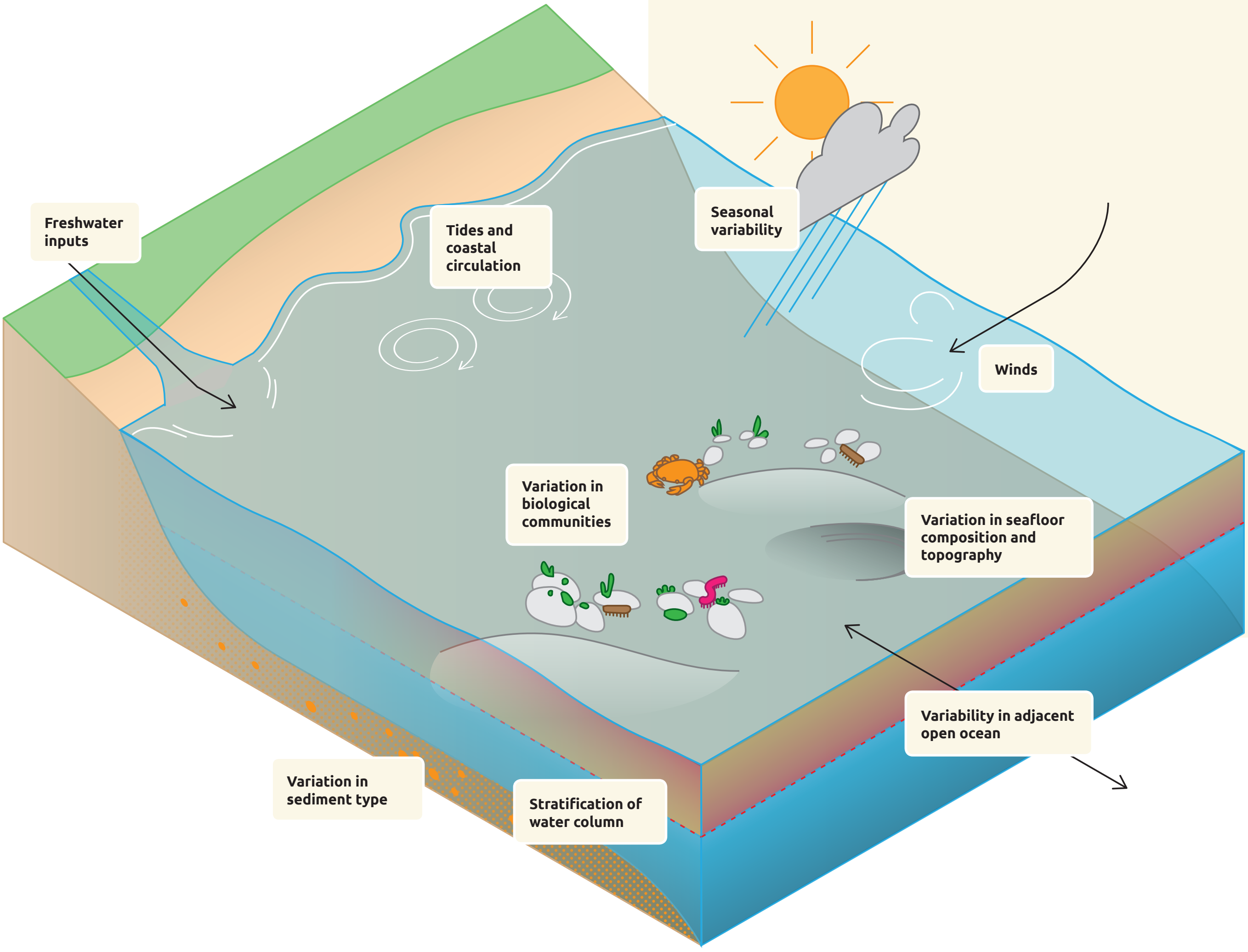
Biological assemblages and activity in both the water column and seabed are closely connected through exchanges of chemicals and movement of organisms. Characterisation of this complex variability is necessary to realistically assess baseline states, as the starting point to considering responses to environmental change.

Key issues include the spatial and temporal variation of oxygen and carbonate chemistry (including pH), the balance of sources of inorganic nutrients (riverine versus exchange across the shelf break), and the role of iron as an essential element for all marine biota.

SOURCES OF VARIABILITY

There are many sources of variability in the different components of the shelf seas. Seasonal cycles introduce patterns, modified by interannual differences. Winds and tides introduce mixing events.

The seafloor is a mosaic of different habitats, from fine muds to coarse sands or boulders and rocks, with associated diverse biological communities. Heterogeneity exists from a micro-to macro scale across time and space.



WATER COLUMN

In parts of the shelf seas, the water column stratifies seasonally. In spring, sunlight penetrates and warms surface waters, supporting primary production and resulting in a depletion of inorganic nutrients. Less light reaches the cooler bottom water, fewer nutrients are consumed and substance exchange with the bed results in resupply. Oxygen draw-down from the water column and bed can result in reduced oxygenation of bottom waters. Frequently, highly productive layers establish where these two water masses meet, causing thin layer blooms and a deep chlorophyll maximum. In summer, productivity is reduced due to nutrient limitation. However, stratification breaks down during autumn, as a result of reducing temperature gradients and increasing frequency of storms, mixing the entire water column. As a result, a secondary period of higher productivity, based on recycled nutrients, can occur. In winter, productivity is reduced due to temperature and light limitations, but in some regions on-going production has been observed.

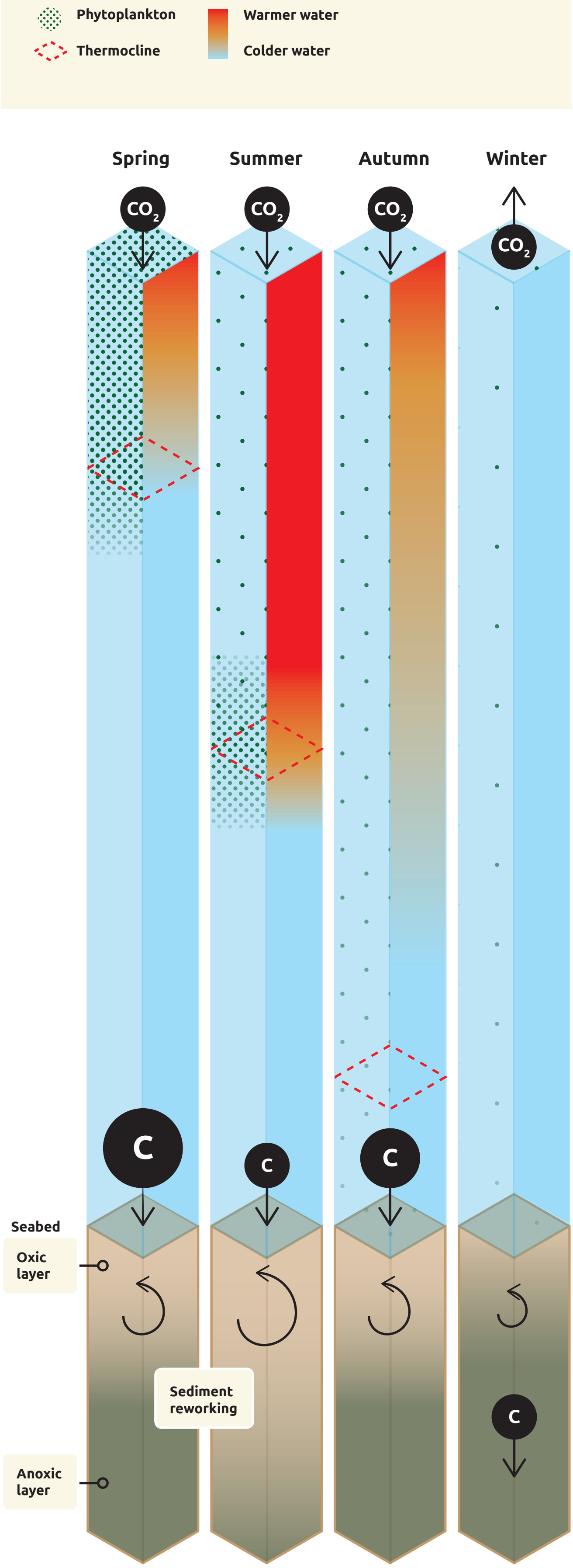
KEY SCIENTIFIC FINDINGS

- **HIGH CONFIDENCE:** Nutrient availability in shelf seas is regulated by interannual variability in riverine and open ocean supply, with the latter dominating except for areas closer than ~20 km from the coast.
  Riverine flows of nutrients are affected by climate, with higher values likely to lead to more carbon uptake.
- **MEDIUM CONFIDENCE:** Dynamic interactions between physical, chemical and biological processes drive net carbon uptake in the system. Observations over full annual cycles have revealed that short periods of calm can initiate phytoplankton blooms throughout the year; production in autumn can be more important than previously thought; and zooplankton grazing strongly influences phytoplankton abundance (and carbon cycling) throughout the year.
  Full annual cycles of carbon fixation must be observed to deduct correct carbon budgets.
- **HIGH CONFIDENCE:** Low oxygen levels occur near the seabed in many UK regions of the shelf. Such conditions arise naturally from stratification and seabed oxygen demand. Excess nutrients are generally not responsible.
  Present-day oxygen levels in UK shelf seas are not generally low enough to threaten marine life. Continued monitoring of this key variable and increasing application of modelling tools will identify any worsening in this situation.
- **HIGH CONFIDENCE:** Total oxygen content of shelf seas will decrease as sea temperature rises, due to solubility effects.
  This might lead to periods in summer where oxygen depletion in bottom waters could affect fish.
- **HIGH CONFIDENCE:** In shelf seas, the seasonal range in surface pH is larger than in the open ocean (~0.2 compared with ~0.1) and strong vertical gradients can occur in the water column, showing that shelf sea biota naturally experience high variability in pH.
  *Accounting for seasonal variability in ocean acidification conditions is essential when considering future scenarios. Experimental studies need to be based on **in situ** values experienced by organisms.*

Mixed phytoplankton and zooplankton from UK shelf seas

©Richard Kirby, www.planktonpundit.org

CHANGES IN SEASONALLY-STRATIFED WATER COLUMN AND SEABED SYSTEMS



SEABED

The amount and quality of organic matter supplied by the overlying water column to the bed varies seasonally, episodically and spatially. In stratified areas, the end of the spring and autumn phytoplankton blooms delivers an intense supply of fresh detritus. These events can trigger sediment re-working by biota and physical disturbance caused by their mobility (bioturbation) soon leads to incorporation of organic material into the bed. The rate of carbon breakdown through various oxidation pathways, regenerating CO_2 and inorganic nutrients, changes with time of year, closely coupled to bacterial community activity and other biota present. Carbon not respired at the end of the year may either be recycled the year after or stored on a long-term basis.

KEY SCIENTIFIC FINDINGS

- **HIGH CONFIDENCE:** Shelf sea sediments vary greatly with physical conditions, such as tidal currents and bed shear stress. Muddy and sandy sediments support different faunal communities and differ in their biogeochemical processes, controls and rates. *Different regions have differing ambient states, controlling processes and variability in time. Both monitoring and modelling need to take account of these factors, using data from a range of sediment types, and water column characteristics, to track shelf status and project future changes.*
- **HIGH CONFIDENCE:** In muddy sediments, key process rates are usually mediated by fauna and/or dominated by diffusion and are generally slower; in sandy sediments, physical drivers dominate, and carbon turnover is more rapid. These differences are reflected in oxygen penetration, nutrient cycling, and the rates and pathways of carbon storage and nutrient cycling. The boundary between these two kinds of substrates is a silt content of ~8%. *Measurement of silt content would enable the two types of seabed functioning to be distinguished.*
- **HIGH CONFIDENCE:** There is high variability in pH between sediment types and seasons, with strong decreases from water column into surface sediment layers. At 1 cm depth, pH values are frequently <7.3, with dissolution of unprotected calcium carbonate structures. *Natural variability in sediment pH values should be considered when evaluating impacts of ocean acidification on benthic organisms. For ocean acidification monitoring, a range of variables need to be considered.*
- **HIGH CONFIDENCE:** Hard seabed strata and environmental heterogeneity substantially increase both diversity and biomass, but high biodiversity is not linearly related to high ecosystem function. Species composition and functional type are important determinants. *Monitoring of faunal structure and function is essential to link status to ecosystem services and valuation.*
- **MEDIUM CONFIDENCE:** Sediment resuspension is strongly affected by water movements and wave conditions, with year-round resuspension occurring in the physically-dynamic Celtic Sea. In the more sheltered southern North Sea, resuspension is limited to winter peaks. The duration and intensity of resuspension affects the recycling of silicate, iron and other nutrients. *Apparently similar substrates may behave differently under different hydrographic settings.*

UNCERTAINTIES AND KNOWLEDGE GAPS

Improved understanding of the magnitude, causes and consequences of the year-to-year variability in ocean circulation and cross-shelf water exchange is needed for future climate change scenarios.

Further research on the role of fauna and sediment properties in controlling carbon and nutrient cycling within the seabed is needed. In particular, coarse substrates (sands, gravels, cobbles) are poorly characterised, though spatially significant on the shelf scale. The link between faunal assemblage, functional biodiversity, carbon incorporation and respiration in differing regions is poorly understood. Seabed processes are presently poorly represented in ecosystem models. Using the new measurements for model development would improve our projections of the future status and variability of shelf seas.

POLICY IMPLICATIONS

- **Awareness of temporal and spatial variability and its causes is essential when evaluating shelf sea processes such as biological productivity, eutrophication or ocean acidification.**
- **Nutrient levels away from the coast are driven by exchanges between open ocean and shelf water, which in turn are influenced by climatic conditions.**
- **Low oxygen events in bottom waters develop during stratification and climate change will enhance this phenomenon.**
- **Monitoring and management efforts have to be set in regional contexts with due consideration of benthic-pelagic coupling and seasonal effects. It is essential to appreciate the inherent variability of shelf systems and to understand that links between water column and the benthic system drive status and variability. A clear example is the timing of the carbon input from the spring bloom and its impact on benthic activity and storage.**
- **A more integrated view of the system in different regions is required in monitoring programmes and for model development. Physical processes, sediment type, biodiversity, biological functioning and chemistry all interact to create variability in space and time.**

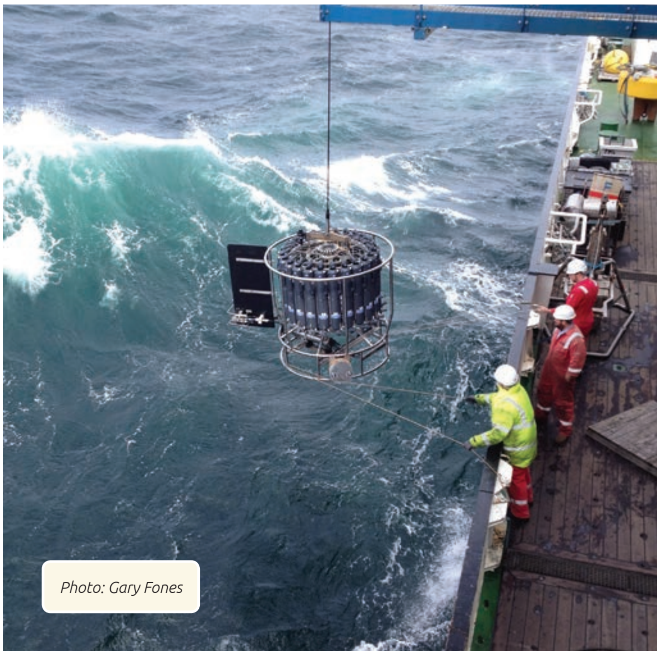


Photo: Gary Fones

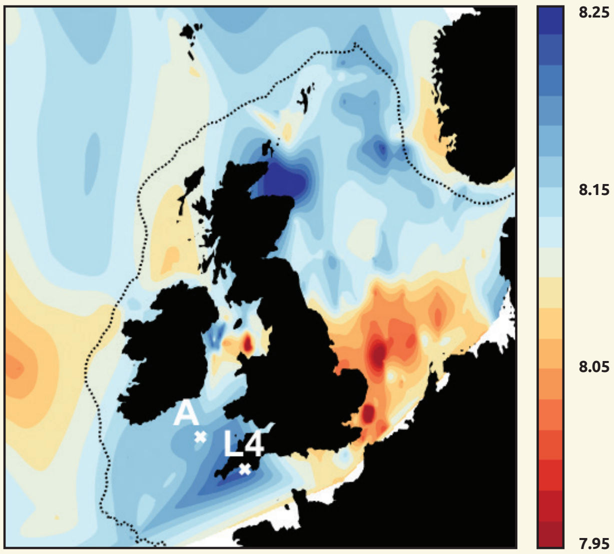
VARIATION OF pH VALUES IN SPACE AND TIME

The figure illustrates the observed variability in seawater pH (a measure of ocean acidification, inversely related to hydrogen ion concentration on a logarithmic scale) over a range of spatial and temporal scales. Spatial variability in pH can occur across distances of 10-100 km on the horizontal scale at the sea surface, and 10-100 m on the vertical scale in the water column. However, the greatest change can be over ~1cm in the top layer of sediment, reflecting changes in other conditions (e.g. oxygen). Temporal variability in the pH of surface seawater can occur from day to day, month to month, and year to year. These newly-observed patterns of variability are of crucial importance in understanding the responses of marine organisms and ecosystems to future ocean acidification.

Figure by Matthew Humphreys.

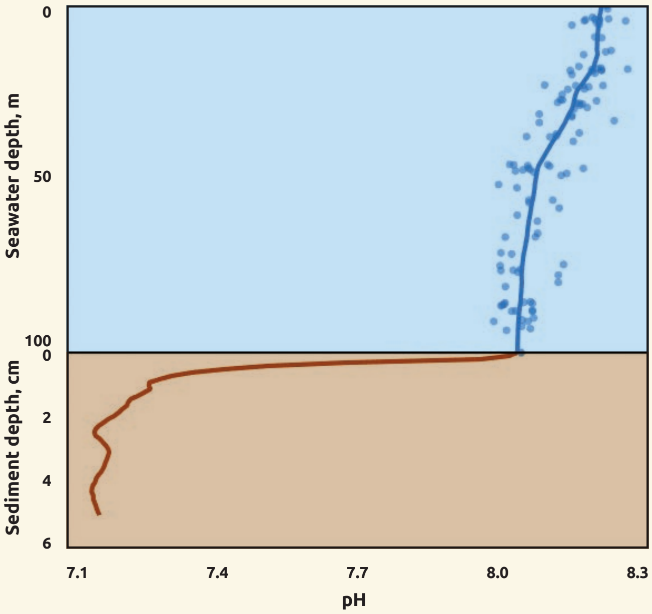
A: HORIZONTAL

Observed pH values in near-surface seawater over the Northwest European shelf in summer (July-August).



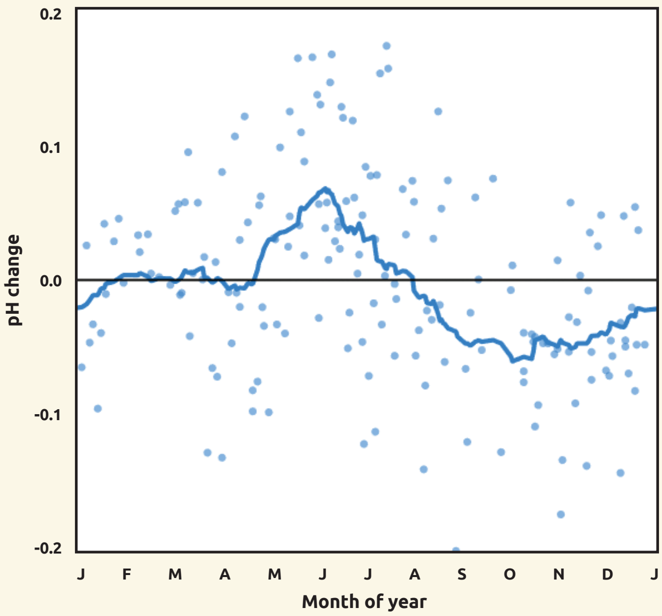
B: VERTICAL

Measured pH in water column (vertical scale in m) and sediment (scale in cm) in the central Celtic Sea in summer (Site A on map at left).



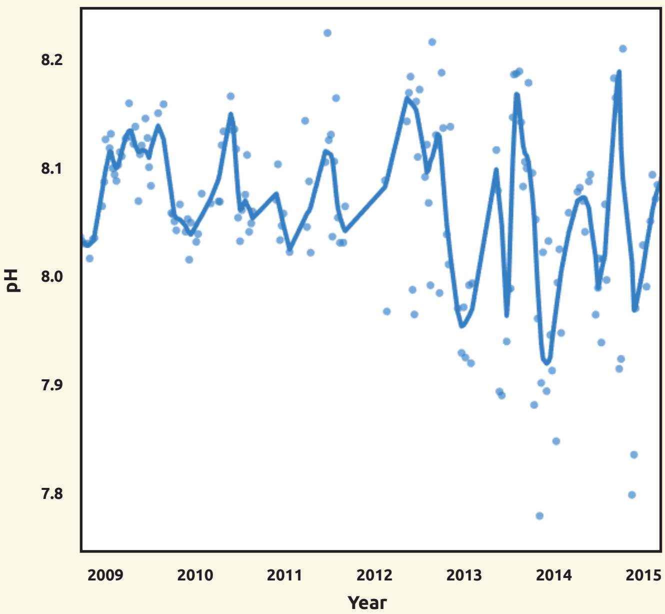
C: SEASONAL

Measured near-surface pH at Station L4, ~10 km south of Plymouth, combined values 2009-15 to show seasonal variation (individual values and weekly smoothed) relative to each year's annual mean pH.



D: INTERANNUAL

Data from (C), showing pH variation (individual values and monthly-smoothed) for the period 2009 to 2015.



3. EFFECTS OF HUMAN ACTIVITY

How do human activities affect the state and variability of shelf sea systems?

Human activities affect UK shelf seas in a range of ways at different scales and levels of severity.

The biogeochemistry of UK shelf seas will inevitably change in future as a result of direct human impacts (that might be considered positive or negative). Such changes to the 'engine of productivity' will translate into changes in the provision of ecosystem services and natural capital, such as the amount of carbon stored, food extracted and oxygen supplied to the atmosphere.

The SSB programme did not study all of the human impacts shown below. Instead its emphasis was on natural processes, with consideration of interactions with trawling and anthropogenic nutrient inputs - processes affecting relatively large areas of the shelf. Nutrient dynamics and the impacts arising from human nutrient inputs have been covered in previous sections ("Ecosystem status and functioning" and "A variable system"), thus trawling is the focus of this section.

IMPACTS OF HUMAN ACTIVITIES ON THE SHELF SEAS

Trawling causes many complex effects, discussed in more detail overleaf.

Nutrient loading and land runoff raise nutrients in the water column, increasing near-coastal primary production whilst decreasing oxygen near the sea floor.

Aquaculture, such as fish or mussel farms, can increase the flux of carbon to the seabed, potentially increasing local carbon storage but depleting dissolved oxygen.

Use of seawater for cooling power plants can result in local reductions in dissolved oxygen and biodiversity loss.

Increased ship traffic can have systemic, multi-stressor effects on marine biogeochemistry – through noise, organism transfer through ballast waters, and toxic chemicals.

Aggregate extraction causes acute disturbance to benthic fauna, and may lead to long-term destabilisation of the seafloor habitat.

Dredging and its disposal directly removes benthic communities and disrupts the biogeochemical cycling they mediate.

Renewable energy, such as windfarms, mitigate climate change by producing clean energy. They also enhance local biodiversity, providing nursery grounds for fish. However, they can be noisy, and may cause seabird mortalities.

Undersea electrical cables emit heat and their strong electromagnetic fields could impact the migratory movement or prey detection of marine organisms.

Construction of oil rigs ***in situ*** can have strong local impacts on benthic fauna, as can their operation and subsequent decommissioning. Leaving structures *in situ* after their operational phase may have environmental benefits.

Increases in coastal erosion from land use strategies (and sea level rise) will increase water column turbidity, affecting seafloor filter feeders and the light available for primary production.

Human litter reaching the marine environment can impact biota in many ways, including entanglement, and 'false feeding'. The longevity and ubiquity of plastic waste gives particular cause for concern.

Atmospheric deposition of nutrients and harmful chemicals. Chemicals, such as flame retardants and lead from fuel, can accumulate in the food chain. However dissolved lead levels are now decreasing.

Marine protected areas greatly reduce direct human impacts and promote ecosystem health, with many research opportunities.

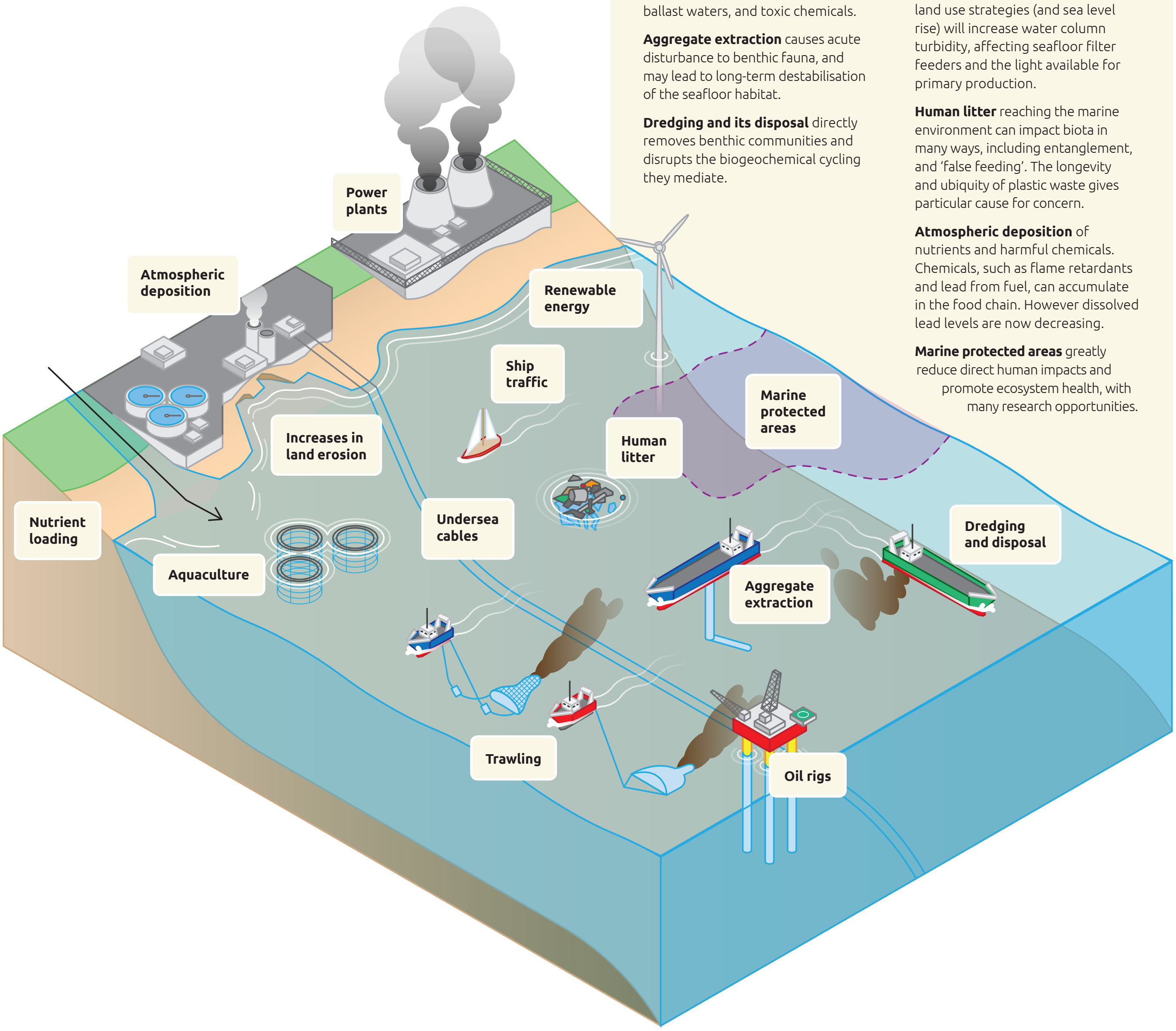


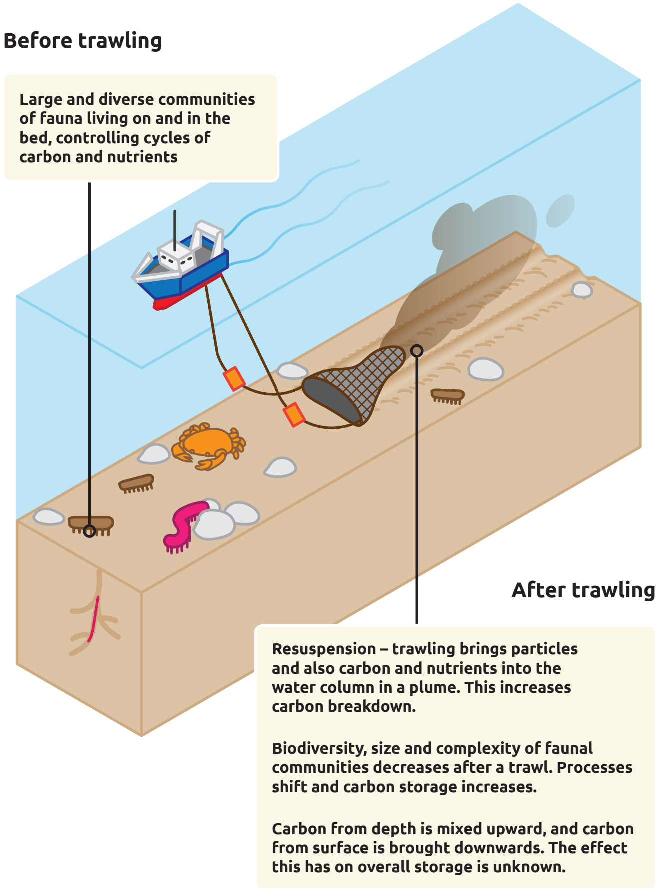

Photo: Simon Armstrong

TRAWLING

Demersal trawling is the most widely-spread human activity in European shelf seas. Trawling can affect the seabed state and processes through faunal mortality, sediment resuspension and associated carbon and nutrient release, and mechanical penetration and mixing.

KEY SCIENTIFIC FINDINGS

- **HIGH CONFIDENCE:** Trawling is a ubiquitous pressure across the shelf seas (see map showing trawling intensity). Because of this, there are few areas that can be classified as "un-trawled" to act as a control sites for baseline measurements.
  There is a need for "no-fishing"baselines for contrasting shelf regions. Marine protected areas that exclude trawling provide a unique opportunity to observe system recovery post trawling into the future, allowing separation of the impacts of climate change and fishing. An integrated characterisation of their current state and functioning is required to act as a baseline against future change.
- **HIGH CONFIDENCE:** Trawling has three main effects on the sediments of shelf seas: (1) changes to the faunal community, (2) resuspension of nutrients and carbon into the water column, (3) disturbance induced mixing. These effects act in different ways and timescales, and their interaction and control on seabed response will vary according to gear type, sediment type (mud vs sand), geographical location and hydrographic conditions.
- **MEDIUM CONFIDENCE:** Trawling will indirectly affect the seabed relationships between fauna and biogeochemical processes (via the microbial community), especially in muddy seabeds.
- **MEDIUM CONFIDENCE:** The physical resuspension of sediments and pore-waters can significantly change the timing and scale of carbon and nutrients exchanges between the seabed and water column.
- **HIGH CONFIDENCE:** The net effect of trawling on carbon storage in shelf sea sediments is not clear due to opposing mechanisms of impact.
  At present, only physical and biological (mainly structural) effects are usually considered in impact assessments; alteration of many key seabed functions are not described. The need is to move towards an integrated assessment of seabed functioning. Without treating the seabed as a coherent system, changes in services will be missed or undervalued in terms of trade-offs in effort management or predictions of change.
- **MEDIUM CONFIDENCE:** The impact of trawling on faunal communities (and associated biogeochemistry) is highly non-linear with trawling effort.

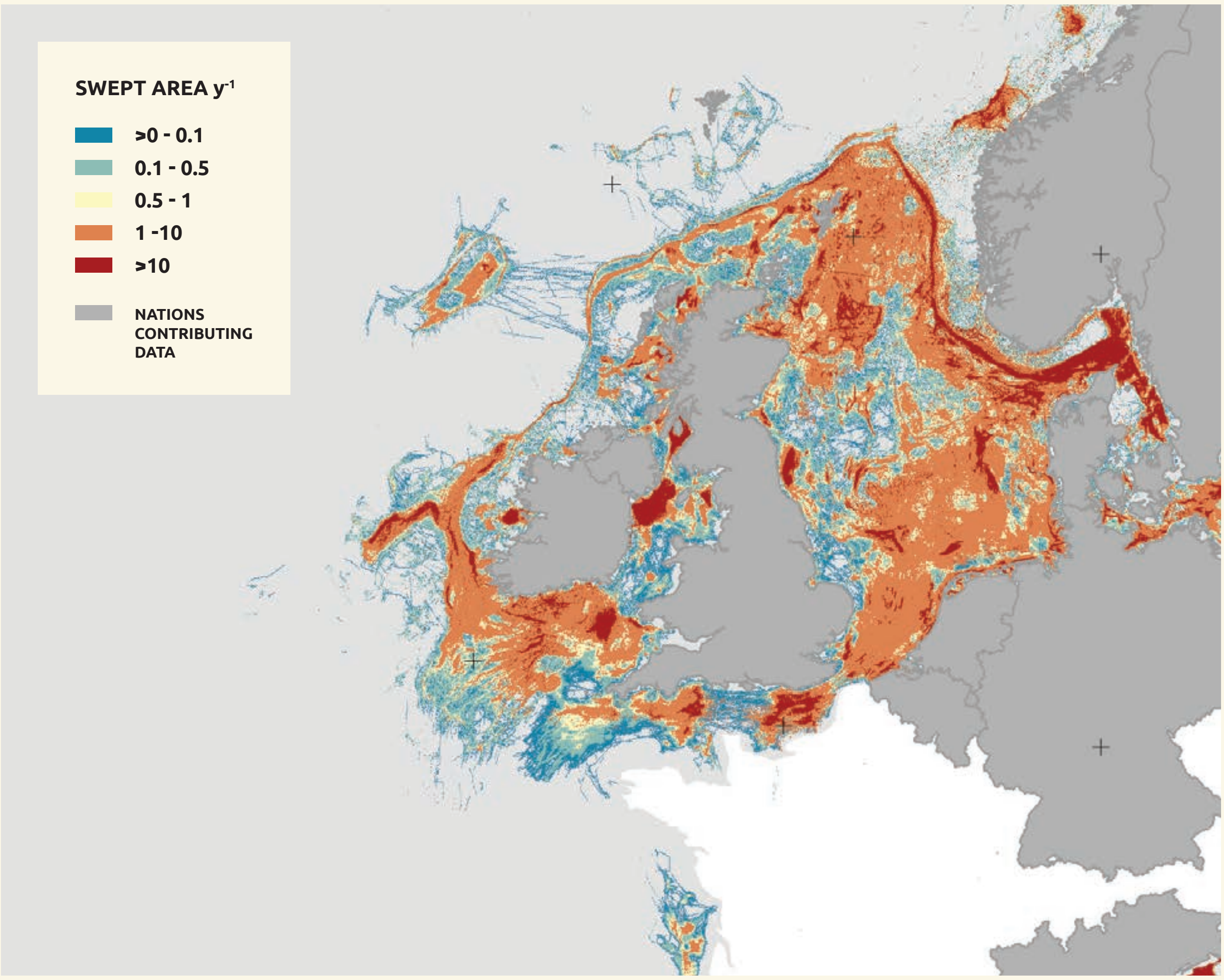


- **MEDIUM CONFIDENCE:** An initial trawl pass results in significant step changes in seabed communities and many associated aspects of biogeochemistry; subsequent passes appear to have less dramatic effects. Such changes can have long-term implications for the capacity for biologically-mediated (micro to macrofaunal) processes in shelf-sea sediments, especially as many areas are already heavily modified by long-term impacts of fleets.
  The severity of change arising from the first trawl pass means that full exclusion (no-take MPAs) is likely to have greater benefit for seabed fauna and function than allowing gradients of impacts or low levels of fishing.
- **LOW CONFIDENCE:** Initial modelling work indicates a recovery time of 2-10 years in marine protected areas, depending on taxonomic groups and community composition.
  Additional observations of site and function specific recovery times are needed, to improve models and management practices relating to trade-offs in seabed functions and value.

DISTRIBUTION OF TRAWLING INTENSITY

Map of Northwest Atlantic showing the estimated number of times per year that the seabed is fished by all mobile bottom-contacting gears. Data for 2010-2012, from vessel monitoring systems and logbooks.

From: O. Eigaard et al. (2017) ICES J Marine Sciences.



UNCERTAINTIES AND KNOWLEDGE GAPS

Assessments of chronic trawling effects are subject to large uncertainties related to assigning trawling impact from vessel monitoring system information (sampling location/impact resolution mismatch, time windows and fleet data availability).

New models are required which can integrate the coupled mechanisms (faunal mortality, resuspension and mixing) of gear effects (acute to chronic) on seabed functioning. Application and development of these models, supported by experimental and observational studies, will allow improved understanding of impact and recovery trajectories over space and time, and associated resilience of shelf regions.

POLICY IMPLICATIONS

- **UK shelf seas are subject to many direct human impacts. The significance of some of these, e.g. pollution by microplastics, has only recently been recognised. Although impacts are usually investigated separately, important interactions can occur. A combination of modelling, observations and experiments provides the best approach to consider holistic effects on biogeochemistry, ecosystem services and more widely.**
- **The management of trawling effort (spatial extent and frequency) should include the aim to maintain seabed function whilst recognising the need for trade-offs. Tools need to be developed that take better account of carbon and nutrient cycling under conditions of physical disturbance, in the context of the non-linearities of complex systems, the range of scales involved, other impacts, and the sustainability of harvested resources.**

4. EFFECTS OF CLIMATE CHANGE

How will climate change drive changes in shelf sea state and functioning?

Climate change, caused by increasing greenhouse gases in the atmosphere, is one of the biggest future threats to the marine environment.

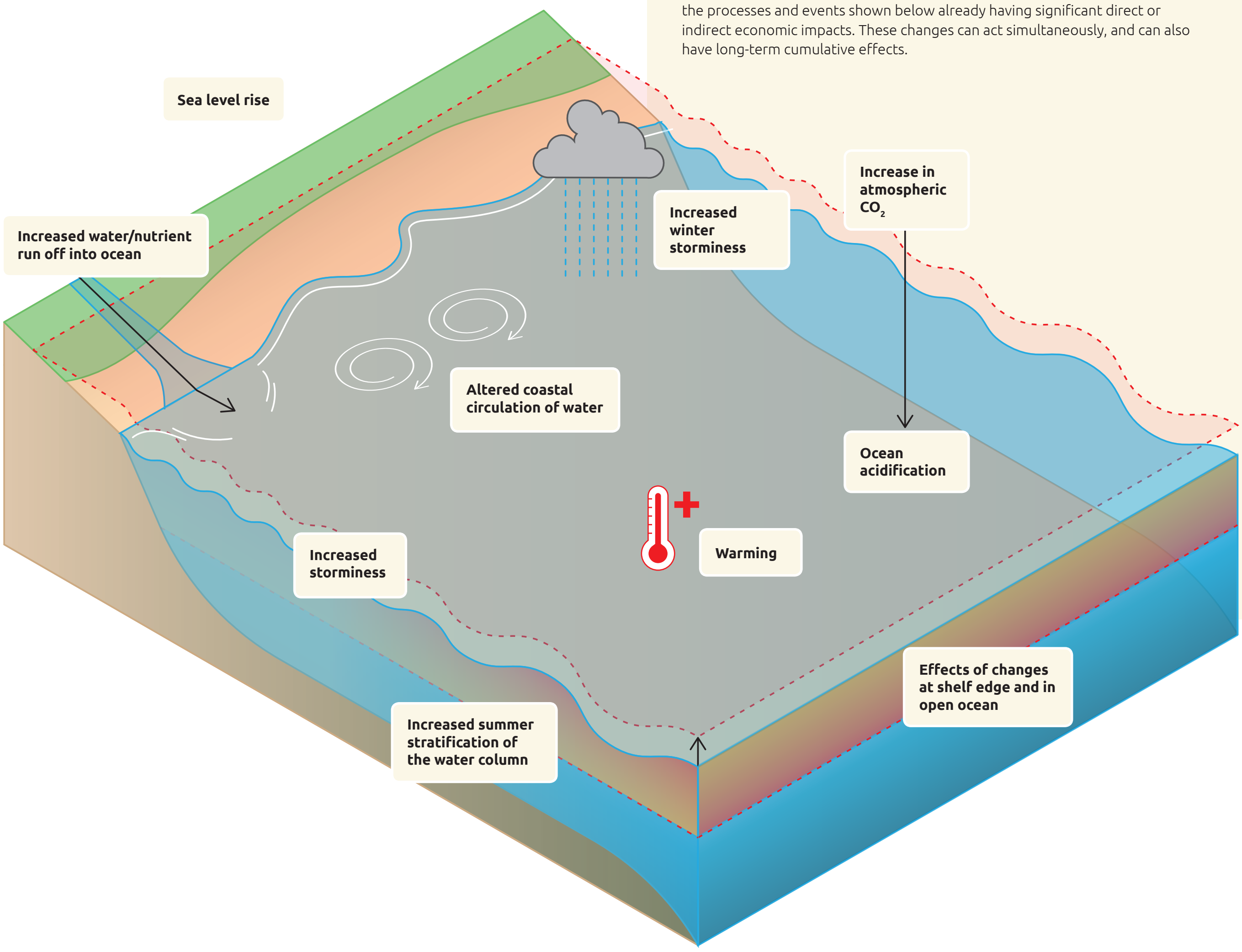
The global ocean represents the largest active carbon sink, and has removed between 25-30% of all carbon dioxide (CO_2) produced by human activities. The vast quantities of CO_2 absorbed by the ocean are causing fundamental changes to its chemistry, resulting in ocean acidification - with many impacts on marine life and human society. Increased atmospheric CO_2 (together with other greenhouse gases) is also causing ocean warming and sea level rise, with associated changes in the intensity and duration of stratification, dissolved oxygen, primary production, recycling within the water column and the supply of carbon to the sea-bed. Changes in weather patterns and storms can alter river run-off and affect the timing and magnitude of input of freshwater and nutrients, whilst also altering coastal circulation. All these climate change impacts have differing modes of action and pressure points on the shelf seas around the UK.

Well-structured ecosystem models combine our knowledge of different processes to provide best-estimate projections of future conditions under different climate policy scenarios, linking the effects of changes in temperature, CO_2 and other parameters.

Researchers in the Shelf Sea Biogeochemistry programme used the latest version of the European Regional Seas Ecosystem Model (ERSEM) to explore the likely consequences of future climate change, initially focusing on the impacts of 'worst case' (high emission, RCP 8.5) scenarios up to 2050. Although these are the conditions we wish to avoid, on that timescale they are similar to the climate changes we are already committed to - unless global emissions of greenhouse gases are very rapidly reduced.

CLIMATE CHANGE PRESSURES ON THE SHELF SEA

UK shelf seas are affected by climate change in many ways, with most of the processes and events shown below already having significant direct or indirect economic impacts. These changes can act simultaneously, and can also have long-term cumulative effects.

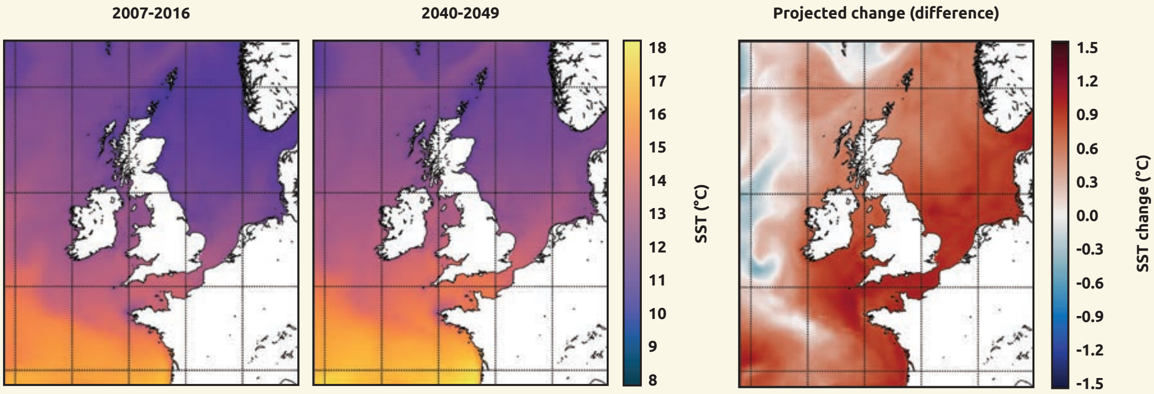


HOW CLIMATE CHANGE MAY ALTER SHELF SEA SYSTEMS

Model-based recent conditions (2007-2016), near-future projections (2040-2049) and their differences for decadal mean values under continued high emissions of greenhouse gases.

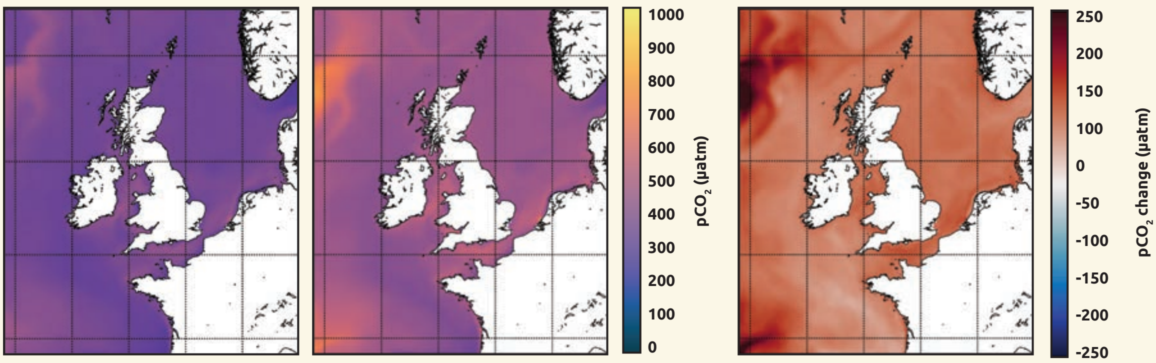
SEA SURFACE TEMPERATURE

The expected increase in atmospheric temperature will result in increased seawater temperatures, initially at the surface then propagating down. Shallow areas will be affected more strongly, with increases across the area of around 0.5-1 ºC.



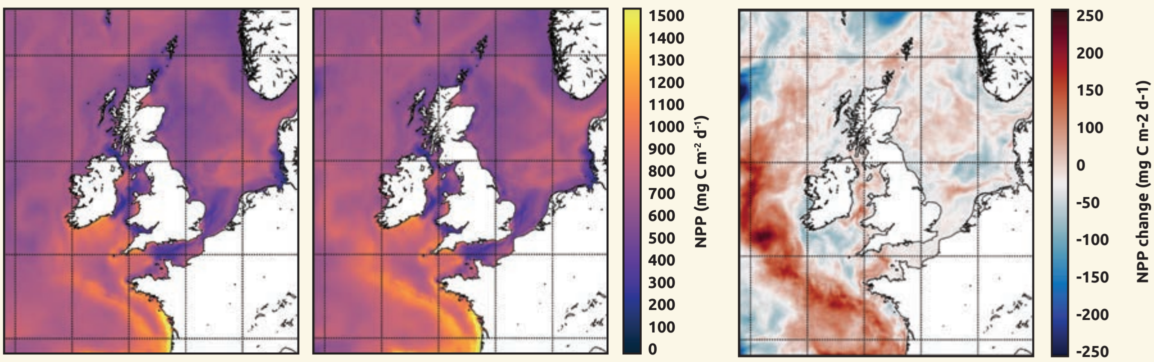
CO_2

Atmospheric increases in CO_2 will result in more dissolved CO_2 in the water column (75-125 µatm), further increasing ocean acidification.



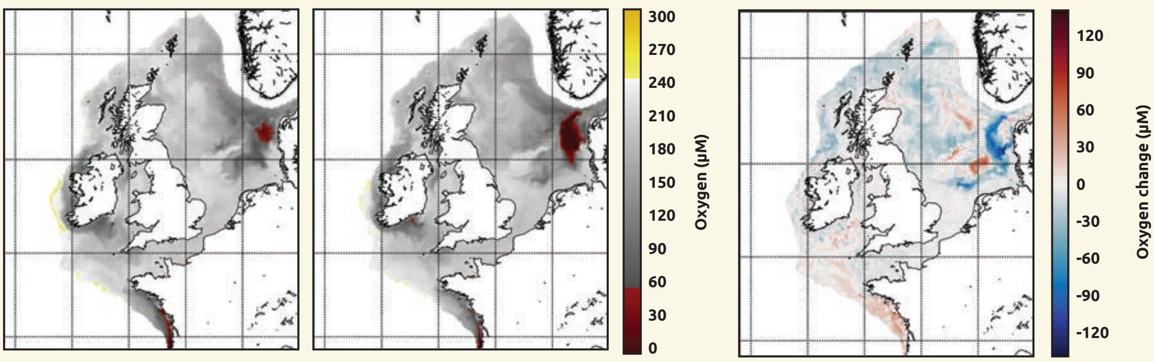
NET PRIMARY PRODUCTION

Increased CO_2 availability and higher temperatures are expected to increase primary production in most areas. This will not necessarily increase carbon supply to the seafloor, as recycling in the water column is also expected to increase.



BOTTOM WATER OXYGEN

In seasonally stratified areas, bottom water oxygen concentrations are expected to decrease significantly, potentially impacting seabed processes and resulting in areas of concern.



KEY SCIENTIFIC FINDINGS

- **HIGH CONFIDENCE:** The modelling studies show that future climate will not only affect chemical and biological processes in the water column but also recycling at the seafloor, with potential impacts at all levels of the marine food chain.
- **MEDIUM CONFIDENCE:** For high emission scenarios, by ~2050, sea surface temperature and dissolved CO_2 are projected to increase across large parts of the UK shelf, by 0.5 - 1.0 ºC and 75 - 125 µatm respectively. The changes are relatively uniform and closely linked to atmospheric changes.
- **LOW CONFIDENCE:** The net amount of carbon taken up by marine plants (phytoplankton) is projected to increase across large areas of the UK shelf seas by 2050 under high emission scenarios. However, there is a large decadal variability, and it is uncertain whether this trend will continue into the second half of the century.
- **MEDIUM** to **HIGH CONFIDENCE:** Oxygen: Near seafloor minimum oxygen levels (July to October) are projected to decrease as a result of changes in temperature, biological production and stratification patterns. Knock-on effects for ecosystem function and services are possible.
- **MEDIUM CONFIDENCE:** Carbon cycling: Despite the likely increase in net primary production (above), less carbon is expected to reach the seafloor, affecting long-term carbon removal and storage - with potential implications for fishery yields.
- **HIGH CONFIDENCE:** Ocean acidification: Relatively large changes in pH and carbonate saturation state are projected for the seafloor. **MEDIUM CONFIDENCE:** Biological impacts are still uncertain: whilst cold-water corals seem vulnerable.
- **MEDIUM CONFIDENCE:** Seabed fauna: Experiments showed that projected temperature increases (together with other changes) seem likely to reduce species richness and abundance at the seafloor. Changes in species burrowing and ventilation behaviour would affect sediment biogeochemical processes, particularly the nitrogen cycle.

UNCERTAINTIES AND KNOWLEDGE GAPS

Global climate models have been successful to date in identifying the large-scale patterns of climate change, with continual updating and improvement from worldwide data streams. Regional marine ecosystem models such as ERSEM are now providing equivalent insights into the likely future evolution of the highly complex climate impacts and interactions in shelf seas with associated single, combined and cumulative pressures on natural capital and environmental services. But there is still scope for improvement, requiring linked observations, experiments and modelling to iteratively inform and develop a system-based approach.

In particular, the models continue to need data from well-coordinated monitoring, and further improvements in our understanding of the processes involved, for a wide range of variables and timescales.

Seafloor life from the central Celtic Sea
Photo: Finn Ni Fhaolain

POLICY IMPLICATIONS

- **Future conditions in UK shelf seas will inevitably be different, in a non-uniform way: the model results provide insights into the likely scale of changes to different components and their spatial variation. This information is directly relevant to identifying trends and the survey design of marine monitoring programmes, to detect early change signals. For example, monitoring of regions with low present-day variability would make it easier to detect emerging differences from current baselines.**
- **Marine protected areas (with much reduced human activities) are likely to provide clearer signals of climate change for contrasting sea regions, for comparison against model projections.**
- **The effects of climate and trawling on the seafloor differ in their nature, and also in their importance in different regions. When combined with modelling, targeted monitoring can improve understanding of the processes involved, and thereby help protect ecosystem services.**
- **Greater integration of monitoring, modelling and experiments would provide added-value information of societally-important changes within shelf regions, linking climate change to cumulative effects of other stressors and the signals associated with differing drivers.**
- **The projected changes in shelf sea carbon budgets are directly relevant to Blue Carbon (see next section). They are also of interest to the government's Climate Change Risk Assessment (CCRA) under the Climate Change Act and associated carbon management policies.**

5. BLUE CARBON

How do shelf seas help mitigate climate change? And how can their carbon removal and storage services be valued and managed?

Blue carbon is the carbon stored and exchanged within the marine environment, with focus on biologically-derived carbon in coastal vegetated habitats such as salt marshes and seagrass beds but also in seabed sediments in intertidal and shelf environments.

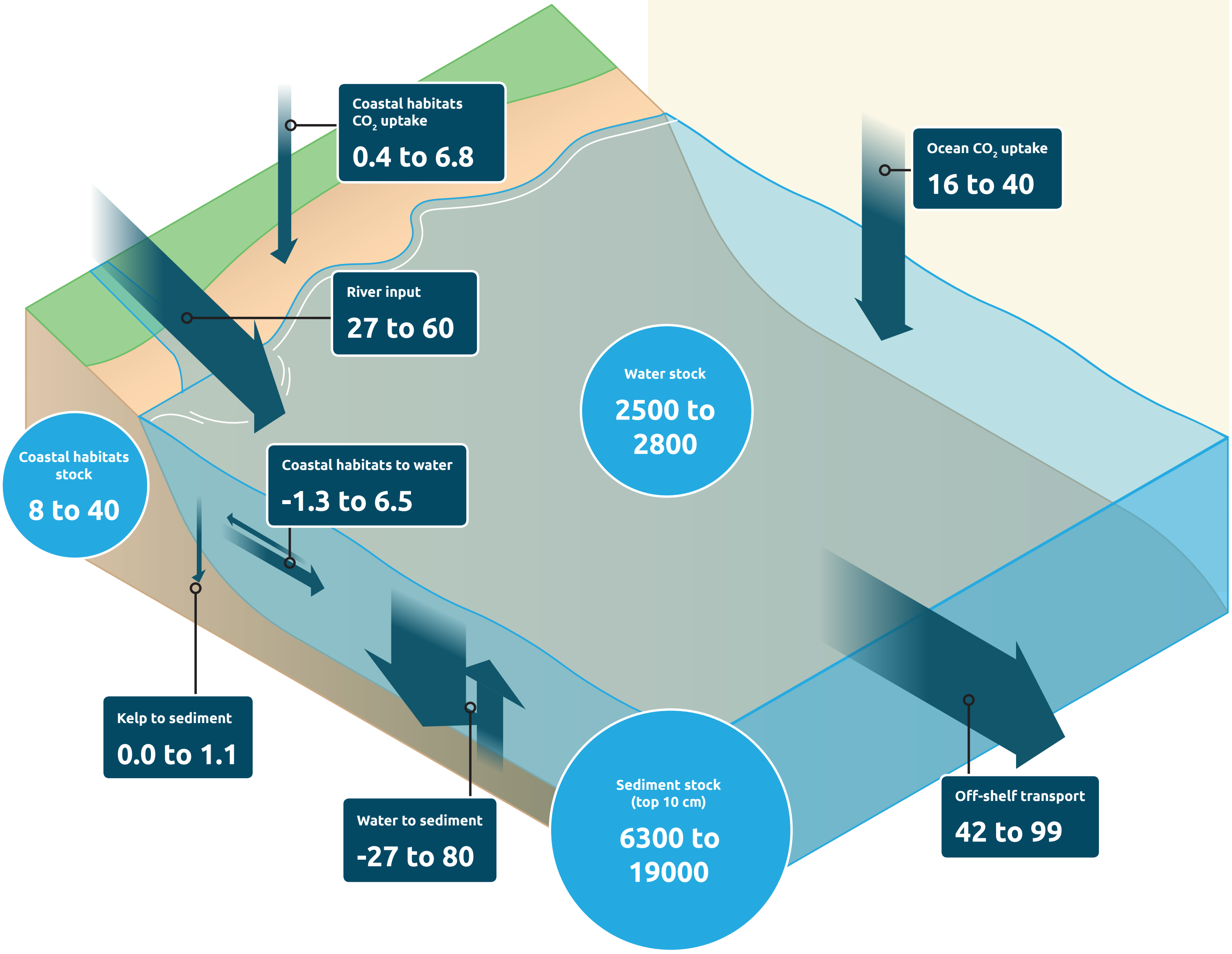
KEY SCIENTIFIC FINDINGS

- **HIGH CONFIDENCE:** The net uptake of CO_2 from the atmosphere by the global ocean has a significant role in mitigating climate change. The Northwest European shelf seas are part of that carbon sink, absorbing 15-40 million tonnes of carbon per year from the atmosphere – equivalent to 10-25% of UK emissions. Some, but not all, of this uptake is stored for decades to centuries or millennia in sediments and in deep ocean water.
- **HIGH CONFIDENCE:** Carbon stocks in coastal habitats and shelf seas are important in terms of their amount and potential economic value. Integrated estimates for carbon exchanges and storage in the Northwest European shelf are shown below, combining organic and inorganic forms. Total storage was calculated to be in the range 8-22 billion tonnes, of which 0.1-0.2% is in the coastal system, 12-30% in the water column and 70-88% in the top 10 cm layer of shelf sediments. Most of the carbon in shelf sediments is inorganic. *More accurate quantification of sediment carbon stocks and water column to sediment carbon fluxes is a key research priority.*

CARBON BUDGET OF THE NORTHWEST EUROPEAN SHELF

A first carbon budget has been attempted for the different compartments of the Northwest European shelf.

Dark blue boxes are **FLOWS** in million tonnes per year and lighter blue circles are **STOCKS** in million tonnes. Values found in the scientific literature are given for each component of the budget; their wide ranges show that large uncertainties remain.



- **MEDIUM CONFIDENCE:** The potential release of CO_2 from Northwest European shelf seas (organic carbon in coastal sinks and near-surface sediments) over the next 25 years could result in around £9 billion of damage costs, based on upper-end carbon values for CO_2 emissions. Such release might result from both direct human disturbance and climate change, such as warming and storms.
- **HIGH CONFIDENCE:** The protection of coastal habitats will preserve uptake of carbon from the atmosphere, increase long-term storage and increase carbon stocks. Conversely, the degradation of coastal habitats or conversion to other land uses exposes organic carbon to oxygen, allowing microbial activity to release carbon.
  The protection of coastal habitats has numerous co-benefits such as natural sea defence leading to reduced flood risk, recreation benefits, maintenance of habitats which are important for many coastal species, and the uptake of nutrients.
- **MEDIUM CONFIDENCE:** The reduction in benthic disturbance in marine protected areas (MPAs) is likely to increase benthic carbon stock.
  MPAs also protect biodiversity. Recovery time of different organisms varies between groups.
- Climate change is expected to affect marine carbon storage in a number of ways:
  - **HIGH CONFIDENCE:** Sea level rise threatens the integrity of coastal habitats such as salt marshes and their carbon storage.
  - **MEDIUM** TO **HIGH CONFIDENCE:** Increased storminess would result in increased erosion and destruction of coastal habitat, leading to a decrease in coastal carbon stocks.
  - **HIGH CONFIDENCE:** Temperature increase impacts on pelagic carbon stocks are complex and hard to predict. Warmer water dissolves less CO_2, reducing the uptake of atmospheric CO_2.
  - **MEDIUM CONFIDENCE:** Higher temperatures will increase water column stratification, increasing recycling of carbon and thus reducing the supply of particulate organic carbon to the benthos, resulting in a decrease in sediment carbon stock. However, oxygen decrease could counteract that effect, with slower recycling at the seabed increasing benthic carbon.

Photo: Julian Andrews

EXPECTED IMPACT OF THE EIGHT MOST SIGNIFICANT CLIMATE INFLUENCES ON SHELF SEA CARBON STOCKS

Colour represents the confidence we have in the expected changes (**LOW**, **MEDIUM** or **HIGH**), with upward arrows indicating increases in carbon stock, downward arrows decreases, and question marks indicating that the direction of change is unknown.

	Coastal	Pelagic	Benthic
CO_2 increase	↑	↑	?
Warming	↓	↓	↓
Increased storminess	↓	?	
Sea level rise	↓		
Decreasing oxygen			↑
Increased nutrient input	↑	↑	↑
Conservation/MPAs	↑		↑
Trawling			?

UNCERTAINTIES AND KNOWLEDGE GAPS

Although knowledge of coastal and shelf sea carbon cycling has much improved, there are still many uncertainties. New approaches are needed for more reliable quantification of carbon sources, transport from land and to the deep ocean, rates of accumulation in sediment, and storage vulnerability under future climate change. Such improved knowledge would improve ecosystem service valuation, and marine management for climate mitigation.

POLICY IMPLICATIONS

- **Shelf seas have a role in climate regulation through long-term uptake, storage or export of carbon. Human activities influence the location and extent of carbon storage, so management of those activities can potentially increase the total carbon stored in shelf seas.**
- **Inclusion of blue carbon in monitoring and habitat mapping programmes would allow more accurate quantification and valuation of marine and coastal carbon storage.**
- **Wider recognition of the role that blue carbon plays in climate regulation will provide a more holistic view of the UK carbon budget, although reliable quantification of changes in removal and storage will not be straightforward.**

6. MONITORING, MODELLING AND DATA FOR ASSESSMENT

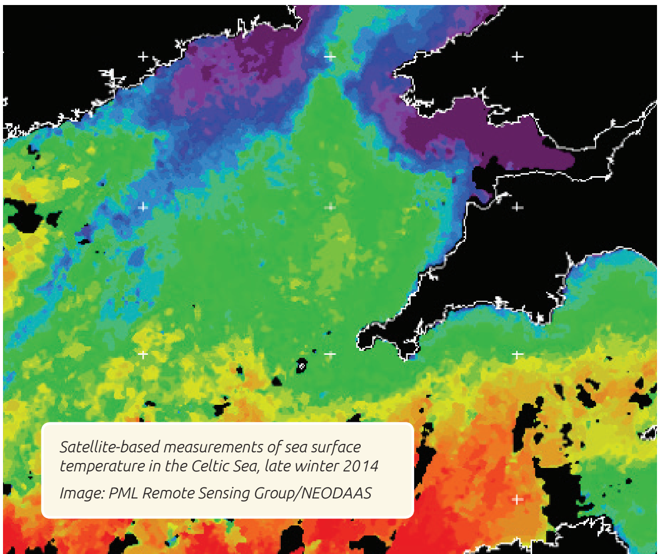
How can our new knowledge improve operational marine monitoring and status assessments?

The comprehensive observational, experimental and modelling work of the SSB programme has improved understanding of shelf sea state and functioning, carbon cycling and storage, nutrient and iron exchange, ocean acidification, and responses to environmental change.

MONITORING

- Observations of seabed biogeochemistry are not yet routinely included in marine monitoring programmes. As a result, we still have gaps in our understanding of: linkages between water column and seafloor processes; the responses of benthic fauna to their changing environment; the role of the seafloor in sustaining the overall health of UK shelf seas; and the climatic and human factors affecting their delivery of ecosystem goods and services.
  Integrated measurements of water column and seabed parameters (physical, chemical and biological) within existing monitoring programmes would provide substantive added value. Additional information on carbon cycling and storage, ocean acidification, and faunal characterisation would be particularly valuable.
- The strong variability (both in time and space) of shelf seas needs to be taken into account when planning and implementing monitoring programmes. Areas with high variability require more monitoring effort than those with low variability, where long-term trends may be easier to detect.
  A prioritisation of metrics to describe status and detect change, and flexible measurement strategies, will improve the cost-effectiveness of status assessment.
- Recently-established marine protected areas (MPAs) provide unique opportunities to separate the effects of different stressors; for example, distinguishing the impacts of climate change and fishing impacts.
  Thorough characterisation of the current status and future changes of selected MPAs in terms of their biogeochemical processes and faunal communities (structure and function) would be scientifically productive and should help answer key policy questions.

Deploying the Cefas SmartBuoy
Photo: Dave Sivyer



Satellite-based measurements of sea surface temperature in the Celtic Sea, late winter 2014
Image: PML Remote Sensing Group/NEODAAS

Bottom lander ready for deployment
Photo: Dave Sivyer

EXAMPLES OF MODELLING APPROACHES

Two main types of modelling approaches have been used within the SSB programme to investigate present shelf sea state and processes and predict changes. These are mechanistic (where many detailed processes are reproduced and combined) and correlative (where statistical relationships between observations are explored and then used to examine potential changes between parameters). The figures illustrate these two approaches and their strengths and weaknesses are given below.

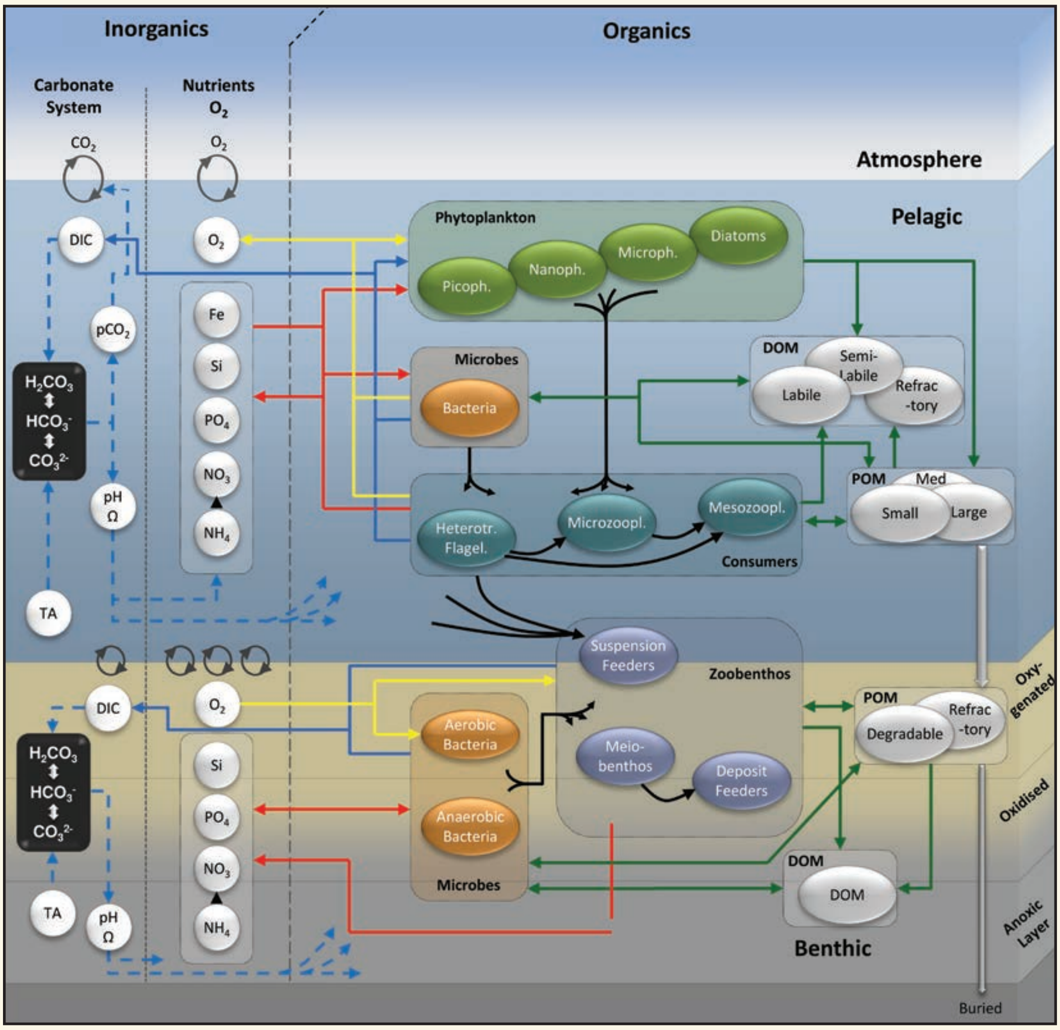
MECHANISTIC MODEL (ERSEM)

European Regional Seas Ecosystem Model, ERSEM

STRENGTHS: detailed processes described, states and rates emerge, temporal and spatial detail resolved and can be predicted, validated using data for comparison. Good in new areas with similar functions, good in tracking climate projections, especially for temperature and physics (when driven by NEMO).

WEAKNESSES: inclusion of new processes is possible, but in order to constrain the uncertainty specific *in situ* or lab data need to be collected. Predictions of bed status, particularly biological structure and functioning, are currently poor.

Figure from Butenschön et al. (2016) Geoscientific Model Development

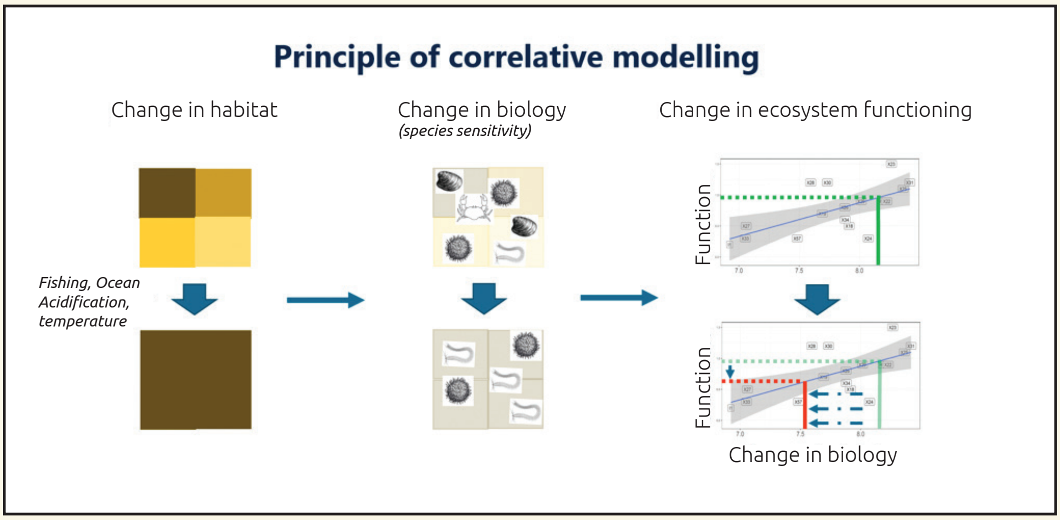


CORRELATIVE MODEL (STATISTICAL)

STRENGTHS: relationships derived using observations, simple, flexible, include detailed assemblage information.

WEAKNESSES: limited in space and time to observational data and relationships, need co-located datasets of biology and function.

Figure by Clement Garcia



MODELLING

- The Shelf Sea Biogeochemistry programme has developed, tested and applied a suite of ecosystem and statistical models. These models have provided insights and information relevant to policy assessments that cannot be determined directly from observational studies; for example, characterizing complex functions (recycling, storage) and simulating future status and functioning under climate change or human pressures.
- A coupled model system has been developed, based on the physical oceanographic model NEMO and the ecosystem model ERSEM (see Figure). This mechanistic-type model explicitly describes and connects physical, chemical and biological processes, providing a comprehensive description of the shelf sea state in space and time. ERSEM has been developed as a UK community tool, with open-access software and coding, to the benefit of the international scientific community.
- The new developments have expanded model capability in interpreting bloom dynamics, greenhouse gases exchanges and other aspects of shelf seas variability. Comparisons between model simulations and real-world data highlight model strengths (e.g. water column interactions between physics, nutrients and plankton) and areas needing further development (e.g. vertical mixing, resuspension, coarse sediments and faunal diversity).
- Statistical models have also been used to improve confidence in scenario projections, drawing on empirical data and spatial or temporal correlations between various variables.
- This synergy between models and data is of paramount importance. Models provide continuity in space and time that is otherwise unachievable; they can also assist the design of monitoring strategies, by assessing its efficacy and by identifying regions where monitoring effort should focus. Nevertheless, there remains need for *in situ* and remote observations to evaluate and constrain model uncertainty, and for additional experiments to test and improve model assumptions.

DATA FOR ASSESSMENT

The various work packages have generated large amounts of data (observed and modelled). Over 300 observational datasets have been deposited with the British Oceanographic Data Centre (BODC), and 45 DOI's have been produced, adding to the published outputs from the programme.

The ERSEM simulation results will be uploaded to the Climate Data Store by April 2019 and made fully accessible to both policy makers and the public. All of these data and model outputs will be valuable to future European and international assessments (e.g. OSPAR), as well as providing information relevant to marine protected areas and generally support the wider understanding of physical, chemical and biological processes.

SSB field data were collected through ship-based measurements during dedicated research cruises, and using moored platforms (surface buoys and bottom landers), autonomous vehicles such as gliders and Autosub as well as satellite observations. Parameters included:

Water column: Phytoplankton, zooplankton, oxygen, different forms of carbon, total alkalinity, pH, nutrients and trace metals, including iron and lead.

Seabed: Sediment types (particle size analysis), apparent redox layer discontinuity depth (aRPD), oxygen penetration depth (OPD), pH, carbons, nutrients, fauna assemblage information (micro to mega), bioturbation, traits, iron, isotopic composition of dissolved iron; physics, respiration rates and pathways.

Furthermore, experiments were conducted in laboratories to explore particular research questions, such as the response of communities to predicted future conditions.

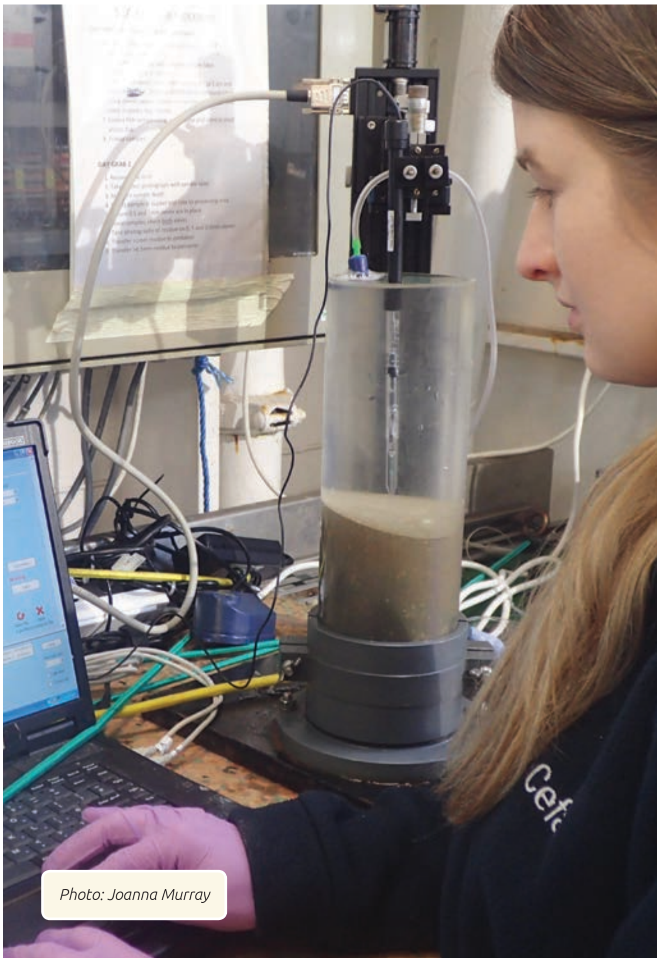


Photo: Joanna Murray

POLICY IMPLICATIONS

- **Observations of seabed biogeochemical parameters, including those relevant to blue carbon, need adding to monitoring programmes. They need to be coincident with water column and faunal parameters, to allow integrated assessments of shelf sea status and functioning.**
- **Modelling tools allow simulation of shelf status and variability at present day and for projections into the future. Modelling tools can also inform monitoring in terms of areas and parameters which are different, likely to change or remain consistent in future. They can provide signature profiles of parameters associated with differing impacts (climate or trawling).**
- **Closer linkage between these models and results from monitoring programmes will greatly improve future assessments.**
- **The synergy between models and data needs to be maintained and nourished across research, monitoring and operational programmes, in order to deliver societally-relevant marine information.**

ADDITIONAL INFORMATION

CONTRIBUTORS TO THIS REPORT

This report was prepared by the Centre for Environment, Fisheries and Aquaculture Science (Cefas) with extensive contributions by the NERC-Defra Shelf Sea Biogeochemistry community.

It was edited by Silke Kröger, Ruth Parker, Gemma Cripps and Phil Williamson, with additional inputs including those from Yuri Artioli, Icarus Allen, James Clark, Darren Clark (Plymouth Marine Laboratory); Martin Solan and Rachael James (University of Southampton/NOC); Jonathan Sharples (University of Liverpool); Martin Johnson, Tim Jickells, Ollie Legge and Matthew Humphreys (University of East Anglia), Angie Milne (University of Plymouth) and Paul Buckley (Cefas).

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WHERE TO GET MORE INFORMATION

For further information on the Shelf Sea Biogeochemistry programme, visit www.uk-ssb.org, or contact either silke.kroeger@cefas.co.uk or ruth.parker@cefas.co.uk. The SSB website includes the full references to more than 85 programme publications (51 peer reviewed, to September 2018) that provide the factual basis for this report.

Other recent and current relevant research programmes and projects:

- Marine Ecosystems Research Programme (MERP) marine-ecosystems.org.uk
- UK Ocean Acidification research programme (UKOA) oceanacidification.org.uk
- The Ocean Shelf-Edge Exchange programme nerc.ukri.org/research/funded/programmes/shelfedge
- Celtic Seas Partnership celticseaspartnership.eu
- Land Ocean Carbon Transfer (LOCATE) locate.ac.uk
- Benthic Ecosystem Fisheries Impact Study (BENTHIS) www.benthis.eu
- Combining Autonomous Observations and Models for Predicting and Understanding Shelf Seas (CAMPUS) gtr.ukri.org/projects?ref=NE%2FR006849%2F1
- An Alternative Framework to Assess Marine Ecosystem in Shelf Seas (AlterEco) altereco.ac.uk

CITATION

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PARTICIPATING INSTITUTIONS

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