Marine Ecosystem Connections: essential indicators of healthy, productive and biologically diverse seas

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Welcome to this Special Issue of Biogeochemistry, which highlights the key research findings from a five-year study entitled “Marine Ecosystem Connections: essential indicators of healthy, productive and biologically diverse seas”. The overall aims of the programme were to improve our scientific understanding of the functioning of shelf seas, develop tools for predicting the impact of human activity on ecosystem structure and function, and contribute to the development of indicators for assessments of ecosystem health and environmental status. Key to these studies was the focus on linkages between benthic and pelagic food webs, in response to environmental drivers (Fig. 1), and an underpinning requirement to link the research on biogeochemical cycling to the development of tools and approaches for improved management of marine resources.

Around the world, in countries such as Australia, Canada, China, North America and South Africa, recent policy and legislative drivers require integrated, ecosystem-based assessments of the impacts of human activities (see Borja et al. 2008; Elliott 2011). In Europe, for example, the Marine Strategy Framework Directive (MSFD, CEC 2008) aims to achieve Good Environmental Status (GES) in all water bodies by

2020, and requires that “*the structure, functions and processes of the constituent marine ecosystems*” allow them “*to function fully and to maintain their resilience to human-induced environmental change*”, taking account of “*associated physiographic, geographic, geological and climatic factors*”. A number of coastal and marine regions, including the North Sea, have therefore become the focus of ongoing research on ecosystem structure and function, and the development of indicators for assessing environmental status (see COM 2010).

Studies carried out during ‘Marine Ecosystem Connections’ (MEC) are part of this effort. A combined fieldwork and modelling approach was used to quantify carbon and nitrogen fluxes through pelagic and benthic food webs in the temperate North Sea, to predict the impacts of climate change and demersal trawling on these fluxes (van der Molen et al. 2012), and to select and evaluate indicators of ecosystem functioning in terms of their suitability for assessing and managing the impacts of climate change and demersal trawling (Painting et al. 2012). For the pelagic food web, only lower trophic levels (up to zooplankton) were considered, as they have fast turnover rates and are useful as early warning indicators of environmental change. For the benthic food web, the main functional groups of the faunal communities were considered. Coupled physical-biogeochemical models (GOTM-ERSEM-BFM) were developed to improve their suitability for temperate shelf seas (see van der Molen et al. 2012), e.g. through parameterisation to allow growth of diatoms

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Fig. 1 Key linkages driving ecosystem dynamics and biogeochemical cycles (previously published in Salihoglu et al. 2013): with climate forcing, hydrography, benthic food webs, pelagic food webs and higher trophic levels all inter-linked. Climate is influenced by factors such as the North Atlantic Oscillation (NAO), the Gulf Stream Index (GSI), and atmospheric temperatures

during the spring phytoplankton bloom, enhanced diatom excretion of transparent exopolymer particles (TEP) under nutrient stress, the formation of TEP-diatom macro-aggregates to enhance rates of sinking to the seabed and associated fauna, and to improve simulation of the underwater light climate.

Fieldwork was carried out largely at three study sites (Fig. 2) representing different hydrodynamic-seabed types (also referred to as ecohydrodynamic types) likely to affect the biogeochemical cycling of carbon and nutrients in each region (see Tett et al. 2007). In situ semi-autonomous instruments were deployed at each site to obtain continuous high-frequency measurements of key biogeochemical parameters such as temperature, chlorophyll fluorescence, optical backscatter, photosynthetically active radiation, inorganic and organic dissolved nutrients, and dissolved oxygen over annual cycles (see Greenwood et al. 2010; Capuzzo et al. 2012; Johnson et al. 2012). Seasonal cruises allowed more in-depth studies of these key parameters, as well as of sediment re-suspension (Couceiro et al. 2012), hypoxia and nutrient cycling (Neubacher et al. 2011, 2012), structure and functioning of seabed communities (Birchenough 2012a, b), and the trophic dynamics of zooplankton (Kürten et al. 2011) and benthic and pelagic functional feeding groups (Kürten et al. 2012). Broader sampling contributed further understanding

of particulate nutrient sources in coastal waters (Bristow et al. 2012), temporal and/or spatial variability in primary production (Fernand et al. (2013); van Leeuwen et al. 2012), pelagic microbial communities (Brandsma et al. 2012) and oxygen depletion in bottom waters (Queste et al. 2012).

Features of the main study sites

The three sites selected for detailed study in the North Sea (2007 and 2008, Fig. 2; see papers in this Issue, and references therein, e.g. Bristow et al. 2012; Capuzzo et al. 2012; Kürten et al. 2011) were representative of larger regions with similar water column and seabed characteristics (see Fig. 3). The distribution of these regions was derived using k-means clustering based on water depth, percentage of silt and clay in the seabed sediment and degree of water column stratification (van der Molen et al. 2012). The site in the southern Bight (SB) is characterised by a shallow (ca 30 m), well-mixed water column and relatively coarse sediments with a deep oxic layer (>10 cm). The site is located in the East Anglian Turbidity Plume, which moves eastwards across the southern Bight towards the German Bight, and is subjected to strong tides and waves, which advect and re-suspend sediments. Physical processes

Fig. 2 Location of primary study sites (white circles) in each of three eco-hydrodynamic regions in the southern and central North Sea (see van der Molen et al. 2012). *Blue* the region represented by a site north of the Dogger Bank (North Dogger, ND). *Brown* the region represented by a site in the Oyster Grounds (OG). *Green* the region represented by a site in the southern Bight (SB)

control oxygenation of the seabed, and nutrient regeneration occurs largely in pore waters. The site north of the Dogger Bank (ND) is in deeper water (ca 80 m), where the upper 30–40 m of the water column is seasonally stratified, and is characterised by a deep chlorophyll maximum in summer and muddy-sand sediment. This site is largely influenced by inflow waters from the North Atlantic, which are the main source of nutrients. The site in the Oyster Grounds (OG) is a shallow depositional site (ca 45 m), with seasonal thermal stratification of the upper 15–20 m of the water column and muddy-sand sediments. Its southern edge delimits a transitional area, the Frisian Front, between the well-mixed southern Bight and the deeper summer stratified regions of the central North Sea. At both the ND and OG sites, muddy-sands have a shallow (<10 cm) oxic layer, and nutrient regeneration is likely to occur close to the sediment–water interface, rather than in pore-waters. Benthic fauna are abundant at the OG, and play an important role in controlling oxygenation of the seabed through bioturbation. Benthic fauna are sparse at the ND, resulting in a shallower oxic layer, and potential for storage of carbon and nutrients in the sediment. More detailed information about the benthic assemblages, sea-bed characteristics and carbon/nutrient cycling processes at the two stratified sites is given in Birchenough

(2012a, b). Details of the under-water light regime at the three sites are given by Capuzzo et al. (2012), and seasonal changes in trophodynamics of zooplankton and benthic and pelagic functional groups are described by Kürten et al. (2011, 2012).

Key strengths

The overall aims of the MEC study and the range of studies undertaken were very broad. Nonetheless, the focus on ecohydrodynamic types, a combined fieldwork and modelling approach, and linkages between benthic and pelagic food webs, and between research and the development of management tools, were key strengths of the programme. As were the combined use of in situ instruments and seasonal cruises, and traditional and novel methods, during the field campaign.

Certainly, the combined fieldwork-modelling approach adopted during MEC was invaluable for describing ecosystem structure and quantifying carbon and nutrient fluxes and budgets at the main study sites, predicting likely impacts of climate change and demersal trawling (van der Molen et al. 2012), and contributing to the development of indicators of ecosystem functioning (Painting et al. 2012).

Model confirmation and validation (van der Molen et al. 2012; van Leeuwen et al. 2012) indicated that the

Fig. 3 Conceptual model of the main carbon (C) and nitrogen (N) flows between pelagic and benthic food webs (from Painting et al. 2012). Main trophic pathways are from phytoplankton to heterotrophs to higher trophic levels, and from benthic fauna to fish. Nutrients are available from dissolved and detrital pools, and atmospheric inputs. Sediment communities are influenced by sediment types (coarse through muddy) and the depth of the oxic layer. The lower half of the diagram represents a gradient in sediment types across the study sites. *SB* site in the southern Bight, *OG* Oyster Grounds, *ND* site north of the Dogger Bank

coupled physical-biological models used during MEC provided realistic simulation of many parameters in the models, and the coupling between processes in the water column and the seabed. Model confirmation also indicated where improvements are needed in both the observations and the models to improve our confidence in the model results and the evaluation of indicators (van der Molen et al. 2012; Painting et al. 2012).

Key challenges

Studies carried out during MEC were based largely on a conceptual model of the main carbon and nitrogen flows through coupled benthic and pelagic food webs (Fig. 3), and key functional groups in both domains. A number of challenges were encountered during the project, including: the implementation of simultaneous intensive multi-disciplinary research during the primary field campaign; the availability of sufficient data for the analysis and interpretation of key carbon and nitrogen flows, and for validation and confirmation of numerical models capturing these flows; integration of biogeochemical fluxes through the dissolved carbon and nutrient pools (e.g. Johnson et al. 2012) with more traditional and/or innovative food web studies (e.g. Bolam et al. 2010; Kürten et al. 2011, 2012); and model developments required to improve simulations of trophic dynamics and benthic-pelagic coupling in the temperate North Sea. Many of these challenges are not unique to MEC and are discussed in greater detail by Salihoglu et al. (2013, see Fig. 4), who support this approach on local and regional scales for improved understanding of biogeochemical cycling and management of the marine environment. Certainly, the key challenge for science is to provide an adequate understanding of the structure and functioning of the marine environment so that future pressures such as anthropogenic climate change and changes in human activities can be put into context. This requires the development of methods to describe the structure and functioning of ecosystems and mechanisms to predict and minimise the impacts of human activities to avoid undesirable disturbances (Tett et al. 2007). Approaches to all future ecosystem studies will need to focus on key linkages between ecosystem compartments (Fig. 1), and to include field measurements and ecosystem models, such as those described in Salihoglu et al. (2013). These authors also recommend comparative studies in order to identify similarities and differences across ecosystems. For all approaches, key issues include establishing general requirements of the study, particularly in terms of field measurements and the level of detail required. The benefits of complex versus simple approaches (such as that used here) are a source of debate. While simple approaches with clear assumptions may be more powerful, species-based approaches are also needed (see Salihoglu et al. 2013 and references therein).

Fig. 4 Conceptual diagram of integrated studies on biogeochemical cycling and ecosystem structure and functioning (from Salihoglu et al. 2013). Flow charts indicate key interactions; bottom panels indicate approaches to enhance understanding and usefulness of integrated studies to resource managers

In conclusion, this Special Issue has brought together work by collaborators from across the UK, the Netherlands, Germany, Spain and the USA. These researchers have a wide range of expertise, and a common interest in the health, productivity and diversity of our seas. The broad selection of papers in this Special Issue is a valuable contribution to our knowledge and understanding of biogeochemical cycling and ecosystem structure and functioning in European shelf seas, and the development of tools for assessing environmental status. Furthermore, the approaches and findings are highly relevant to ongoing studies in the region, and in other oceans and seas.

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