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An integrated approach for assessing the relative significance of human pressures and environmental forcing on the status of Large Marine Ecosystems

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ABSTRACT

An ecosystem approach to the management of the marine environment has received considerable attention over recent years. However, there are few examples which demonstrate its practical implementation. Much of this relates to the history of existing marine monitoring and assessment programmes which (for many countries) are sectoral, making it difficult to integrate monitoring data and knowledge across programmes at the operational level.

To address this, a scientific expert group, under the auspices of the International Council for the Exploration of the Sea (ICES), prepared a plan for how ICES could contribute to the development of an Integrated Ecosystem Assessment (IEA) for the North Sea by undertaking a pilot study utilising marine monitoring data. This paper presents the main findings arising from the expert group and in particular it sets out one possible integrated approach for assessing the relative significance of environmental forcing and fishing pressure on the ecological status of the North Sea, it then compares the findings with assessments made of other Large Marine Ecosystems (LMEs).

We define the North Sea ecosystem on the basis of 114 state and pressure variables resolved as annual averages between 1983 and 2003 and at the spatial scale of ICES rectangles. The paper presents results of integrated time-series and spatial analysis which identifies and explains significant spatial and temporal gradients in the data. For example, a significant shift in the status of the North Sea ecosystem (based upon 114 state-pressure variables) is identified to have occurred around 1993. This corresponds to previously documented shifts in the environmental conditions (particularly sea surface temperature) and changes in the distribution of key species of plankton (*Calanus* sp.), both reported to have occurred in 1989. The difference in specific timing between reported regime shifts for the North Sea may be explained, in part, by time-lag dependencies in the trophic structure of the ecosystem with shifts in higher trophic levels occurring later than 1989.

By examining the connection (or relatedness) between ecosystem components (e.g. environment, plankton, fish, fishery and seabirds) for the identified regime states (1983–1993; 1993–2003) we conclude that both the North Sea pelagic and benthic parts of the ecosystem were predominantly top-down (fishery) controlled between 1983 and 1993, whereas between 1993 and 2003 the pelagic stocks shifted to a state responding mainly to bottom-up (environment) influences. However, for the demersal fish stocks between 1993 and 2003 top-down (fishery) pressure dominated even though over this period significant reductions in fishing pressure occurred. The present analysis, therefore, provides further evidence in support of the need for precautionary management measures taken in relation to setting fishery quotas.

1. Introduction

In this paper we explain why integrated ecosystem assessments are needed and what defines them before we describe in detail one approach for conducting an integrated ecosystem assessment. That assessment utilises available monitoring data at the scale of a *Large Marine Ecosystem*; the North Sea.

1.1. Policy background

The management of marine ecosystems with the aim of achieving the sustainable use of their goods and services has in recent years moved up the political agenda, as witnessed by the growing

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number of global, regional and national policy initiatives demanding a more holistic and integrated approach to marine management (FAO, 2002, 2003; WSSD, 2002; Council of the EU, 2006). The origins of this political shift can be traced back to a United Nations Convention workshop on Biological Diversity held in Malawi in 1998 (UNEP/CBD decision COP V/6; UNEP, 1998) which set out the ideals of an ecosystem approach to the management of marine resources, namely: "*an approach based upon the application of appropriate scientific methodologies focused on levels of biological organisation which encompass the essential processes and interactions amongst organisms, including humans, and their environment*". To develop plans necessary for integrated management, as part of an ecosystem approach to management such as setting ecosystem objectives, identifying areas requiring enhanced protection and developing regulatory approaches to human activities, it is necessary to have an adequate understanding of the ecosystem in which the management is occurring. This must include identifying the features of the ecosystem which are structurally and functionally important, the nature and intensity of the human activities and how the ecosystem features (including human activities) interact on different time and spatial scales.

In practical terms the delivery of the Ecosystem Approach (EA) to management of marine resources can be translated into three types of activity, namely: (i) the need to have sound science supporting an adaptive management framework (assuming appropriate organisational frameworks are in place); (ii) the need to undertake integrated ecosystem assessments to inform management decisions and to regulate multiple human pressures; and (iii) the need to coordinate and integrate national and international monitoring programmes.

The global shift in policy towards EA is the inevitable response to the growing (and presently unsustainable) number of pressures exerted by humans on the resources of Large Marine Ecosystems (LME).[1] These are most notably observed in relation to the world's fish stocks of which about 70% are either fully or over exploited (FAO, 2002). In addition, there is growing pressure on coastal ecosystems exerted by the development of towns, cities and their associated industries, all in support of achieving economic growth. It has been estimated that about 60% (3.6 billion) of the world's population now lives within 60 km of the coast and this is predicted to rise to 75% (6.4 billion) within the next three decades (www.oceansatlas.org).

As a result, of the changes in policy and the demonstrable impacts now witnessed in the state of many LMEs, much stakeholder discussion has focused on turning the vision of marine EA into practical solutions which are integrated and cross-sectoral in their approach (Browman and Stergiou, 2004). Turning the discussion into practice inevitably takes time, simply because many national and regional monitoring and assessment programmes are designed around sectoral policy needs and interests such as ocean climate, mineral extraction (including oil and gas), hazardous wastes (including disposal and dredging operations), nutrients, biodiversity and fisheries to name a few. In most developed countries significant human resources and organisational infrastructures have evolved to support these sectoral interests and clearly a move to coordinate and integrate their activities to deliver a more adaptive management approach will take time (Mee, 2005; Walker et al., 2002; Rice, 2005), but progress is being made at national and regional levels to bring about these changes (Link et al., 2002; Rice, 2005; Mee, 2005; Backer and Leppänen, 2008). In this respect it is noteworthy that the assessment frameworks developed, for example, by the EU (Council of the EU, 2006) and the European Regional Sea Conventions (e.g. OSPAR, HELCOM, Barcelona and Bucharest Conventions – Fig. 1) make a distinction between assessments which are; (i) a process of actions which support 'adaptive management and the ecosystem approach' (ICES, 2003; Misund and Skjoldal, 2005), and; (ii) products describing the combined numerical assessment of data and information from various sources (including different human pressures and state changes – ICES, 2003). Assessment products are also divided into two types, namely; those which are *thematic* and those which are *generic*. Thematic assessments tend to deal with one aspect of the marine environment whereas generic assessments provide a holistic statement of the whole health of a defined maritime area and its coastal margins, including an evaluation of man's impact over space and time against the background of natural variability.

[1] A large area (typically 200,000 km^2 or larger) with distinct topography, hydrography and productivity, and trophically linked populations.

1.2. What is integrated ecosystem assessment?

The term *integrated ecosystem assessment* can be used in the context of both thematic and generic assessments. For example, a eutrophication assessment that considers various land uses, atmospheric and aquatic input of nutrients, environmental concentrations of nutrients and their biological effects is an integrated ecosystem assessment, since it integrates across nutrient *drivers* (land uses), nutrient *pressures* (inputs and pathways) and associated *state* changes (eutrophication effects), albeit specific to one issue. The advantage of this is that it enables thematic adaptive management strategies, which focus on single issue cause and effect chains, to be readily developed and implemented. Good examples of this are the thematic strategies developed by the OSPAR Joint Assessment and Monitoring Programme (www.ospar.org) and the associated discussion on setting objectives (Rogers et al., 2007). Thematic adaptive management strategies can also respond more rapidly to changes in state, typically on an annual cycle where appropriate monitoring programmes are in place, whereas *generic* Integrated Ecosystem Assessments (IEA) by virtue of their complexity and diversity of monitoring programmes are most likely to be undertaken on a less frequent basis, particular if they are applied at the scale of the LME where significant time-lags are to be expected between multiple pressure and state responses.

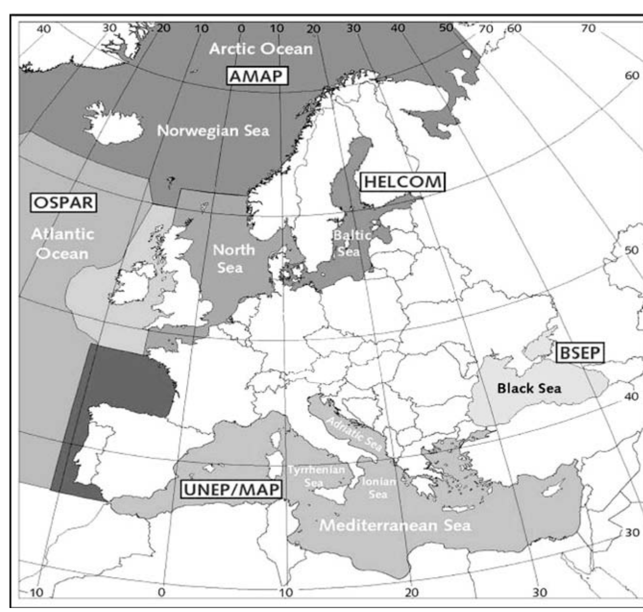

Fig. 1. Examples of European Large Marine Ecosystems recognised by the EU and Regional Sea Conventions denoted in boxes (HELCOM – Helsinki Convention, Baltic; AMAP – Arctic Monitoring & Assessment Programme, Arctic; OSPAR Commission, NE Atlantic; UNEP/MAP, Mediterranean and the BSEP – Black Sea Environment Programme, Black Sea).

Methods and approaches are, therefore, required to integrate and assess different sectoral monitoring data, which are often monitored at greatly different spatial and temporal scales, in order to evaluate the relative significance of human pressures and natural variation on the marine ecosystem (Mee and Bloxham, 2002; Kenny, 2006; Choi et al., 2005). Inevitably the development of such approaches has to be an iterative process in order to keep pace with the changing policy and management objectives, but their usefulness and up-take by environmental managers largely depends on good communication which is an essential requirement for effective adaptive management (Mee, 2005).

1.3. North Sea dynamics

The North Sea occupies part of the continental shelf of NW Europe and has been described as an epi-continental LME (Sherman et al., 2007). It is relatively shallow in the southern and central sectors (~30–40 m), deepening to >100 m in the northern sector, with greatest depths (~700 m) occurring in the Norwegian Trench adjacent to the Norwegian coast. It receives a significant freshwater input, including a large contribution from the Baltic Sea outflow. Some coastal regions are affected by increased land-based nutrient inputs but the greatest contribution arrives in Atlantic water.

The water circulation through the North Sea is generally counter-clockwise, with most of the water entering in north over the North Sea plateau and exiting through the Norwegian Trench along the coast of Norway. The inflow of Atlantic water shows large seasonal and interannual variability, driven by winds and pressure gradients along the continental slope (Pingree, 2005). It is suggested that this basin-wide influence is largely driven by the North Atlantic Oscillation (NAO) Winter Index, which is a measure of the air pressure gradient between the Azores high pressure and the Iceland low pressure (Pingree, 2005). The NAO has undergone both long-term and short-term fluctuations (Fig. 2) with high or positive NAO index conditions typically driving strong inflow and transport through the North Sea, while weaker flows are associated with negative NAO anomalies (Reid et al., 2003). The index decreased through the mid-part of the last century to a minimum in the 1960s which coincided with the "great salinity anomaly" of the North Atlantic. The great salinity anomaly was a signal of relatively low salinity and cold water that propagated around the sub-Arctic gyres of the northern North Atlantic (Dickson et al., 1988; Blindheim and Skjoldal, 1993) which arrived in the North Sea in the late 1970s. This event resulted in a pronounced minima in salinity and temperature in the North Sea, subsequently the NAO index shifted to high values from the late 1980s through the first part of the 1990s, followed by a marked drop to a strong negative anomaly in the Winter 1995/96. These were very marked climatic events

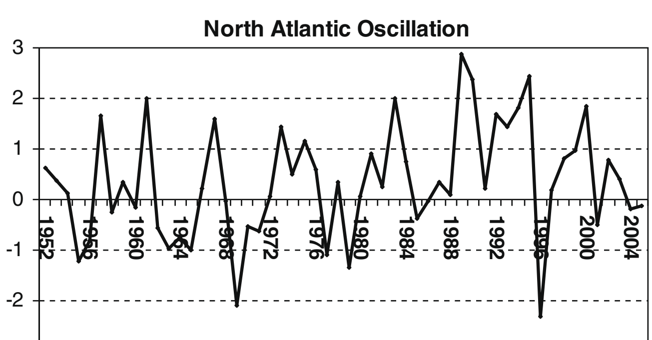

Fig. 2. The average Winter (Dec, Jan, Feb, Mar) North Atlantic Oscillation Index between 1952 and 2005, data obtained from the Climate Unit of the University of East Anglia, UK (Osborn, personal communication).

in the North Atlantic that have been associated with changes in plankton composition (Planque and Batten, 2000; Beaugrand et al., 2002; Beaugrand, 2003; Reid et al., 2003), fish populations and other biota in the North Sea (Reid and Edwards, 2001; Reid et al., 2001; Edwards et al., 2002; Reid and Beaugrand, 2002).

Modeled inflow of water (Skogen and Søiland, 1998) into the North Sea through the northern boundary between Orkneys, Shetland and the west coast of Norway during the 1st quarter of the year, was low in the late 1960s and late 1970s, while increasing substantially in the late 1980s and early 1990s (Fig. 3), corresponding to the low and high NAO index situations described above. These changes in flows have been related to changes in plankton abundance and composition in the North Sea and characterised as cold-biological and warm-biological events (Reid et al., 2003). They have also been related to the recruitment and distribution of 5 major North Sea fish populations with data for the time period 1971–1991 (Svendsen et al., 1995). Furthermore, climate forcing was thought to be the most likely explanation for the "gadoid outburst" in the 1960s, which was a period with favourable recruitment conditions for several of the gadoid groundfish species in the North Sea (Cushing, 1984).

Although it is evident that significant environmental events have had an impact on the status of the North Sea ecosystem, including its fishery, time series data on the spawning stock biomass (SSB) of six important demersal fish stocks (ICES, 2007) reveals considerable variation (Fig. 4), possibly reflecting the combined influences of environmental forcing and impacts from fishing. For example, North Sea haddock (*Melanogrammus aeglefinus*), cod (*Gadus morhua*) and saithe (*Pollachius virens*) were at high biomass levels in the late 1960 and early 1970s, reflecting the gadoid outburst, followed by subsequent declines to low levels in the first part of the 1990s. Haddock and saithe have since recovered whereas the decline of cod has continued. Fishing pressure (fishing mortality) in the 1990s was so high that the stock was predicted to collapse based upon theoretical considerations (Cook et al., 1997). However, the warm climate and low zooplankton abundance (particularly of *Calanus finmarchicus*) have also been suggested as contributing factors in the decline, and lack of recovery, of North Sea cod (Planque and Frédou, 1999; Beaugrand et al., 2003; Drinkwater, 2005; Rindorf and Lewy, 2006).

Pelagic, plankton-feeding fish are another important component of the North Sea ecosystem. North Sea herring (*Clupea harengus*) declined due to overfishing to a very low level in the 1970s (Fig. 5), but subsequent recovery efforts have aided in allowing the stock to increase to a level within safe biological limits (Nichols, 2001). North Sea mackerel (*Scomber scombrus*) stocks were also fished to unsafe levels in the 1970s and for the North Sea stock it has not recovered. For this reason no biomass data are available. However, mackerel from the western stock (in the NE Atlantic) are abundant and use the northern North Sea as part of its feeding area. Other important pelagic fish species in the North Sea ecosystem are sprat (*Sprattus sprattus*), sandeel (*Ammodytes marinus*), and blue whiting (*Micromesistius poutassou*).

Pelagic fish are likely to provide a pressure on the plankton which constitutes their food as seen by observations in the Barents Sea ecosystem (Skjoldal and Rey, 1989; Dalpadado and Skjoldal, 1996) and the North Sea (Reid et al., 2000). *Calanus finmarchicus* (a cold water arctic-boreal species of copepod) has fluctuated inversely with *Calanus helgolandicus* (a warm water temperate species of copepod), being abundant under negative NAO index conditions. A fairly strict correlation broke down after 1995, presumably reflecting less *Calanus finmarchicus* in the inflowing water originating in the Norwegian Sea (Planque and Reid, 1998; Reid et al., 2003), whilst at the same time, herring from the Norwegian spring spawning stock increased in abundance and resumed its migration to feed in the Norwegian Sea (Holst et al., 2004).

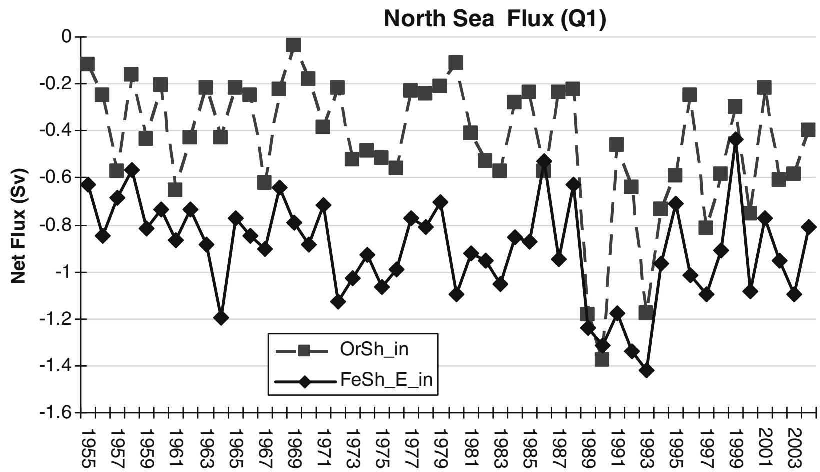

Fig. 3. The annual Q1 (Jan., Feb., Mar.) average net flux of seawater across two boundaries into the northern North Sea, namely; the Orkney/Shetland transect (OrSh-in) and the Faeroe/Shetland transect (FeSh_E_in). Both show a large negative flux (into the North Sea) in 1989 which is associated with a step increase in the North Sea temperature as the amount of cold deep water entering from the North East Atlantic was particular low at this time (Skogen and Søiland, 1998).

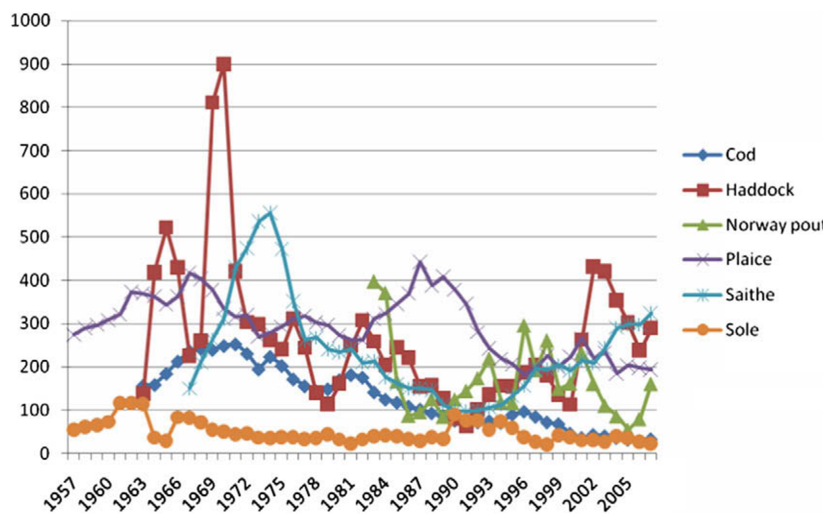

Fig. 4. Total North Sea Spawning Stock Biomass of the 6 most commercially important demersal species between 1957 and 2006. Values are 1000's of tons. (Data from ICES, 2007).

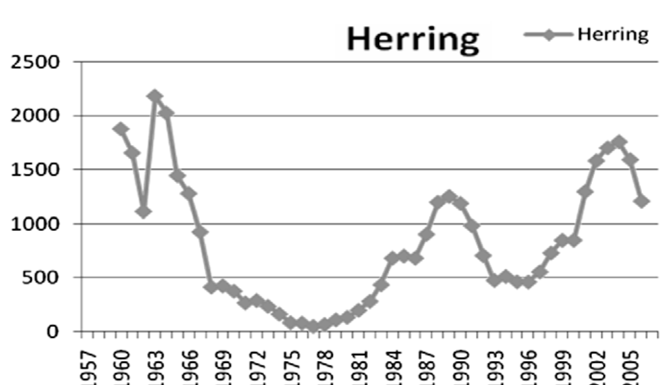

Fig. 5. Total North Sea Spawning Stock Biomass of herring between 1957 and 2006. Values are in 1000's tons.

In addition, recruitment conditions for blue whiting were exceptionally good for several years starting in 1995, leading to a marked increase in the stock of young fish feeding in the Norwegian Sea (Monstad, 2004; Skjoldal and Sætre, 2004). It has been suggested that predation by these two very large pelagic fish stocks, herring and blue whiting (each of them estimated to be of the order of 10 million tonnes as spawning stock biomass and supporting fish landings of 1–2 million tonnes each year) could have lowered the amount of *Calanus*, thereby indirectly influencing the adjacent North Sea ecosystem (Skjoldal and Sætre, 2004).

1.4. North Sea dynamics in comparison to other LMEs

The North Sea is part of the wider ocean circulation in the North Atlantic. This circulation is characterised by relatively warm Atlantic water (originating partly from the Gulf Stream) flowing north on the eastern (European) side, while cold water from the Arctic flows south on the western side. The water flows partly in closed loops in the sub-Arctic gyres in the Labrador Sea and the Nordic Seas, connected to the large scale circulation of the North Atlantic through the north-flowing Atlantic water and southward return flow of cold deepwater as part of the general thermohaline circulation (Hansen and Østerhus, 2000; Dickson et al., 2000; Dickson and Meincke, 2003; Hurrell and Dickson, 2004).

Ocean climate anomalies on both sides of the Northern Atlantic are related but with opposite signs, so that positive anomalies (high temperature and/or salinity) on the European side correspond to negative anomalies on the western side (Sundby and Drinkwater, 2007). The rate of propagation also varies, with positive anomalies on the eastern side and negative anomalies on the western side moving faster than anomalies with opposite sign (i.e. negative on the eastern side and positive on the western side; Sundby and Drinkwater, 2007). This suggests that the overall circulation of the sub-Arctic gyres oscillates between intensified and relaxed modes at multi-annual time scales. The oscillations may occur with different frequencies, including multi-decadal time scales that may be related to celestial forcing at the global scale (Dickson et al., 1996, 2000; Dickson and Meincke, 2003; Hurrell and Dickson 2004). These longer term oscillations are in addition to the seasonal cycle of intensified wind forcing of the ocean circulation in winter and relaxation of the wind forcing in summer (Jakobsen et al., 2004).

Commercial fish stocks partly depend on these broad ocean circulation patterns to regulate the drift of their larvae from spawning to nursery areas, the seasonal feeding migrations of juveniles and adults, and the spawning migration of adults back to the spawning areas. It is, therefore, likely that qualitative and quantitative changes in ocean circulation drive large changes in recruitment, year-class strength, and size of commercial fish populations (Skjoldal, 2004). The continuous nature and coherence of ocean circulation may therefore provide a simple explanation of the high degree of co-variation in recruitment of different fish stocks in different areas (Koslow, 1984; Ottersen and Loeng, 2000), responding simultaneously to changes in circulation and associated changes in distribution and properties of water masses, although perhaps in different ways and involving many different mechanisms in each specific case (Ottersen et al., 2004).

In common with fisheries in other regions of the world, the North Sea fish stocks have been subject to widespread over-exploitation, as illustrated by the substantial decline in overall biomass of predatory fishes over the last 100 years (Christensen et al., 2003). However, it is widely recognised that the link between fishing effort and fish abundance is complicated by the presence of internal trophic (predator/prey) interactions and external environmental factors (e.g. Reid et al., 2000; Curry et al., 2005), as has been demonstrated in the North Sea (Ducrotoy and Elliot, 2008) and in upwelling systems such as those off South Africa (Curry and Shannon, 2004; Shannon et al., 2008).

In considering climate forcing alone, such complexity imposes a limitation on directly correlating a single ecosystem component (e.g. a fish stock) with a single large scale environmental indicator, such as the North Atlantic Oscillation (NAO). This is particularly the case when considering ecosystems on a smaller spatial scale such as the Bay of Biscay (Hemery et al., 2008) and North Sea (Kenny, 2006) where other more localised environmental pressures may be exerting a greater influence on the animal populations. In an attempt to better explain the trends in fish stocks and other animal components in the southern Bay of Biscay, Hemery et al. (2008) developed a sub-regional multivariate oceanic climate index from an integrated analysis of 44 readily available oceanic variables (including the NAO) using Principal Component Analysis. The integrated ocean climate metric (known as the South Biscay Climate Index), whilst remaining highly correlated to the NAO, was able to account for trends in animal numbers not previously explained by variations in the NAO alone. In this case, the integrated approach reaffirms the dominance of bottom-up ocean climate forcing as the principal factor regulating ecosystem dynamics in this region. By contrast, other studies demonstrate a more direct link between large scale environmental indicators (like the NAO) and variability in the status of LMEs, such as the influence of the Pacific Decadal Oscillation (PDO) on fish stocks in the Aleutian Islands and Southeast Alaska ecosystems (Hare and Mantua, 2000; Heymans et al., 2007), the influence of the NAO on sprat (*Sprattus sprattus*) recruitment in the Baltic Sea (Mackenzie et al., 2008), copepods in the Northeast Atlantic (e.g. Beaugrand et al., 2002) and Northwest Mediterranean (Molinero et al., 2008).

In respect of human-induced pressures the North Sea has been shown to be relatively resilient, despite the combination of substantial fishing effort, the localised impacts of excessive nutrient inputs, the presence of contaminants and the introduction of non-native species. This is in marked contrast to the Black Sea and Canadian Scotian Shelf LMEs, where a combination of pressures has resulted in significant regime shifts effecting higher trophic levels (Frank et al., 2005; Daskalov et al., 2007; Oguz and Gilbert, 2007) and to a lesser extent the Baltic Sea (Ducrotoy and Elliot, 2008).

2. Integrated analysis – approach taken

2.1. Sources of data

Most of the data used to conduct this assessment were selected and collated by an expert study group of the International Council for the Exploration of the Sea (ICES). The Regional Ecosystem Study Group for the North Sea (REGNS), established in 2003, was part of the ICES response to the Ministerial Declaration from the Fifth International Conference on the Protection of the North Sea (Bergen, Norway, 2002). REGNS was asked to prepare a plan for how ICES could contribute to the development of an Integrated Ecosystem Assessment (IEA) for the North Sea, utilising the ICES expert group network and databases (ICES, 2004).

The compilation and synthesis of information and data revealed a considerable amount of spatial and temporal variation. In general, it was observed that certain types of data, notably variables related to fisheries, physical oceanography, plankton and nutrients, were measured throughout the North Sea, with many programmes covering several decades of observation. However, other sources of data, notably variables relating to biological effects (ecotoxicology), sediment chemistry (contaminants), species introductions, hazardous algal blooms in coastal waters and surveys of the macrobenthic fauna were more restricted. For example, these data tended to be concentrated in coastal waters, or covered a limited or fragmented period of time, e.g. sporadic years rather than continuous annual time-series. This was to be expected since most established monitoring programmes have been designed in response to specific human activities, or more localised phenomena, which often are managed by specific licensing and regulatory regimes. Other programmes measure processes and state changes driven by natural forces on a wider scale. The exceptions to this are the assessment programmes of fish stocks subject to regulation and management, but which also have wide spatial coverage. Clearly, an integrated assessment approach has to accommodate these fundamental differences in the types of monitoring data collected.

In earlier discussions (ICES, 2003, 2004, 2005a), a tabulation of metadata was undertaken, reflecting the data-sets required to carry out a comprehensive IEA, and indicating the existence and availability of these data over a range of space and time-scales. Metadata were ordered into three categories: abiotic, biotic and human activities. Individual data types were then assigned to one of two priorities. Priority 1 data were considered to be of relevance to a more immediate *generic* integrated ecosystem assessment of the status of the whole North Sea, whilst priority 2 data were regarded as being more suitable for either more localised or more *theme* specific IEAs.

The present analysis identified 114 (1st priority) variables with long (unbroken) time-series and broad spatial coverage thus making them suitable for an assessment of the North Sea as a whole.

Table 1
Parameters used for the North Sea integrated ecosystem assessment 1983–2003. Landings data includes both Scottish and English data, squid landings are Scottish.

Environment[1]	Plankton species	Fish stock[2]	Fishing pressure[3]	Seabirds
Ammonia (b, s)	*Bacillaria paxillifera*	Demersal Fish Length	Angler Fish (landings)	Auks
Dissolved-oxygen (b, s)	*Calanus finmarchicus*	Pelagic Fish Length	Cod (landings)	Black-headed-Gull
H_2S (b, s)	*Calanus helgolandicus*	Demersal Fish (CPUE)	Haddock (landings)	Black-legged-Kittiwake
Nitrate (b, s)	*Calanus* total traverse	Pelagic Fish (CPUE)	Herring (landings)	Common gull
Nitrite (b, s)	Candacia armata	Warm Water Fish Species (CPUE)	Mackerel (landings)	Divers
Phosphate (b, s)	*Ceratium furca*	Cod (SSB)	Nephrops (landings)	European-Shag
Salinity (b, s)	*Ceratium fusus*	Sole (SSB)	Skate (landings)	Great-cormorant
Silicate (b, s)	*Ceratium longipes*	Saithe (SSB)	Whiting (landings)	Grebes
Temperature (b, s)	*Ceratium macroceros*	Plaice (SSB)	Squid (landings)	Large Gulls
Sea level pressure	Phytoplankton Colour	Haddock (SSB)	Pair trawl (effort)	Little Gull
Wind direction (0-360)	*Cylindrotheca closterium*	Whiting (SSB)	Mid water trawl (effort)	Northern-Fulmar
Wind speed (Knots)	Decapoda total	Herring (SSB)	Beam trawl (effort)	Northern-Gannet
NAO	*Dinophysis* spp.	Sandeel (SSB)	Demersal seine (effort)	Seaduck
Sea water flux (Or_Sh)	Echinoderm larvae	Norway Pout (SSB)	Otter trawl (effort)	Shearwaters
	Euphausiacea total		Herring (TAC)	Skuas
	Chaetoceros spp.		Norway pout (TAC)	Storm-petrels
	Metridia lucens		Sprat (TAC)	Terns
	Pseudo-nitzschia delicatissima		Cod (TAC)	
	Pseudo-nitzschia seriata		Haddock (TAC)	
	Odontella regia		Plaice (TAC)	
	Chaetoceros spp.		Saithe (TAC)	
	Para-Pseudocalanus spp.		Sole (TAC)	
	Prorocentrum spp.		Whiting (TAC)	
	Skeletonema costatum			
	Temora longicornis			
	Thalassiosira spp.			
	Thalassiothrix longissima			
	Thalassionema nitzschioides			
	Total Copepods			
	Total Diatoms			
	Total Dinoflagellates			
	Total Copepods			
	Chlorophyll (b, s)			

[1] *b*, bottom; *s*, surface.
[2] CPUE, catch per unit effort; SSB, spawning stock biomass.
[3] TAC, total allowable catch.

These were grouped according to recognised ecosystem components, namely: 19 *environmental* variables, 34 *plankton* species, 14 *fish* stock assessment metrics, 31 *fishing pressure* metrics and 17 *seabird* species (Table 1). The longest time period common to all 114 variables was from 1983 to 2003, although for some variables annual records date back to the 1940s. Most of the variables were spatially resolved at the scale of ICES statistical rectangles (1° longitude by 0.5° latitude, or approximately 30 by 30 nautical miles at the latitude of the North Sea; see Fig. 6). The plankton data set was kindly provided by SAHFOS (Sir Alister Hardy Foundation for Ocean Science; www.sahfos.ac.uk) from the Continuous Plankton Recorder (CPR) surveys in the North Sea, and consisted of time-averaged data for 167 ICES rectangles comprising a total of 35 key plankton species. These species were selected in consultation with SAHFOS as being the most ecologically relevant from a list of over 100 recorded taxa. Fish landings data for Scotland and England were provided by DEFRA (Department for Environment, Food & Rural Affairs, UK) and SEERAD (Scottish Executive Environment and Rural Affairs Department) and consisted of 9 species of pelagic and demersal fish covering 210 statistical rectangles. Seabird data were provided by members of the European Seabirds at Sea Database Coordinating Group (ESAS) and consisted of 17 species covering 204 statistical rectangles. Fish stock assessment metrics such as spawning stock biomass were obtained from ICES but these were only resolved at the scale of the North Sea region IV so they were not included in the spatial analysis.

2.2. Types of data analysis and pre-treatment

Two types of data matrices were generated to enable spatial and temporal analysis to be undertaken separately. For the spatial analysis the whole time-series for each variable was averaged within each ICES rectangle resulting in a matrix of averages for each variable by rectangle. For the time-series analysis each variable was averaged over the entire North Sea for each year resulting in a matrix of averages for each variable by year.

For both sets of spatial and time-series matrices the data were pre-treated (transformed and normalised[2]) and then analysed using multivariate statistical procedures in PRIMER v6 software (Clarke and Gorley, 2006). In addition, significant shifts in the time-series data were identified using a sequential algorithm procedure described by Rodionov (2004). Different methods were applied to the different types of data, notably; Principal Components Analysis (PCA) was applied to all the environmental, fish stock, fishing pressure and the combined matrix of all ecosystem components. The choice of PCA was influenced by the need to rank objectively the variables that best explain the overall variation in the data according to their eigenvalues and to enable trends in the sample component scores to be objectively compared with trends in selected pressure and state variables. Also for these matrices the data consist of variables measured in different units and therefore, it was necessary to convert them to a standard unit of measurement using a normalisation procedure.

The transformed time series data for the 4 main ecosystem components, environmental (abiotic) variables, plankton, fish stocks and fisheries, for the period 1983–2003 were integrated into one matrix comprising 114 variables then normalised before

[2] Literature terminology is inconsistent since this procedure is sometimes called standardisation. What we mean by normalisation is; that from each entry of a single variable one subtracts the mean and divides by the standard deviation for that variable following appropriate transformation.

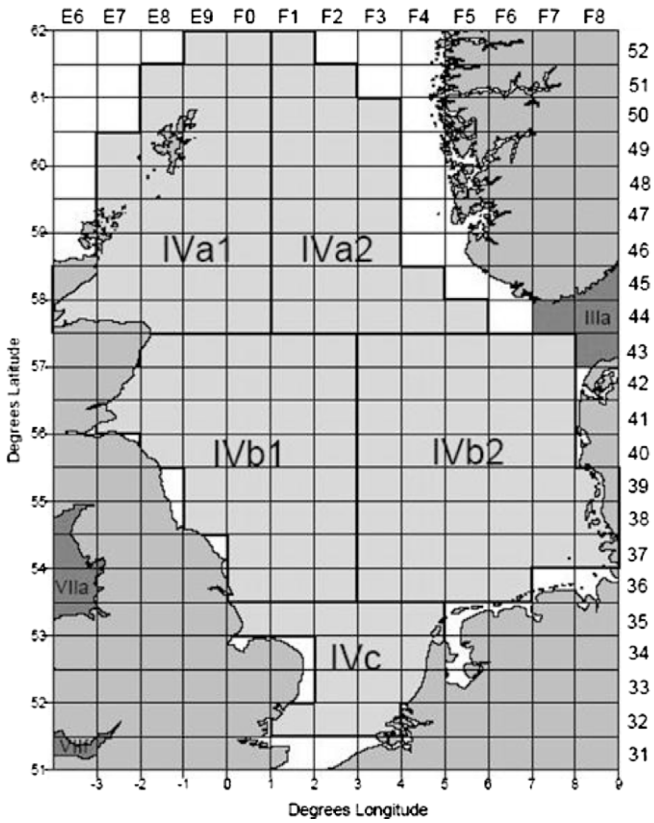

Fig. 6. The spatial units used in the assessment. The smallest cells are known as ICES statistical rectangles and are also commonly used for fisheries assessment purposes. These cells are aggregated into larger spatial units known as ICES sub-regions (IVa1, IVa2, IVb1, IVb2 and IVc) and these when combined constitute the greater North Sea Region (sub-area) IV.

undertaking PCA. Changes in the North Sea ecosystem can also be visualised by taking the variable eigenvalues which make up PC1 (the 1st component axis or eigenvector) and using their rank order to sort the normalised variables (anomalies) in the original integrated data matrix. The ordered 114 variable anomalies were then categorised into one of 20 groups and each assigned a colour ranging from blue to green representing *negative* and *positive* anomalies, respectively. In this way all the values in the original data file were categorised and ordered to construct a (1st principal component axis) 'shade plot'. The advantage of this type of plot is that one can readily (albeit subjectively) see changes in groups of variables over time and identify clusters of similar valued variables. This is particularly useful when considering ecosystem shifts, as the complexity of the system often results in time lags between dependent (or correlated) variables.

In addition, hierarchical cluster analysis was applied to the pretreated environmental data in order to identify significant clusters of samples using the SIMPROF test of significance at $p = 0.01$. SIMPROF is a 'similarity profile' permutation test and it is a method used in PRIMER to look for statistically significant evidence of genuine clusters of samples (Clarke and Gorley, 2006).

For the remaining data matrices (plankton and seabird densities) triangular matrices of similarity were created using the Bray–Curtis similarity index and the inter-sample similarities were assessed as an ordination diagram using a non Metric Multidimensional Scaling (MDS) procedure (Clarke and Gorley, 2006).

Based upon the results of the integrated analysis presented in Section 3.2.1 we split the time-series data into two matrices of equal duration (11 years), namely, (i) 1983–1993 and (ii) 1993–2003 with the year 1993 shared by each time series as it represents the mid point in the whole series. An ordination was performed, and a (dis)similarity matrix generated, for each box relating to an ecosystem component and consisting of a set of related variables (see Table 1) using either the Euclidean distance or Bray–Curtis similarity index following appropriate transformation and normalisation procedures described previously. In order to examine the degree of connection or relatedness between ecosystem components (e.g. matrices of related variables representing environment, plankton, fish stock, fishing pressure and seabirds) we used the RELATE routine (Clarke and Gorley, 2006). The starting point for this procedure are the (dis)similarity matrices described above, the method takes any two independently derived (dis)similarity matrices and compares the relationships among the same set of sample labels. The measure of agreement or relatedness is the rank correlation coefficient ρ (rho) between the corresponding elements of the two matrices. This is then compared to the ρ calculated by randomly assigning labels to samples of one of the matrices, this is then repeated many times (999 times) so as to construct a histogram of ρ values representing the null hypothesis case (e.g. when $\rho = 0$; there is no agreement between the sample matrices). This is then compared to the "real" value of ρ to test for the rejection of the null hypothesis, that is a significant correlation (or relatedness) exists between sample matrices. The BEST procedure finds the 'best' match between the biotic sample pattern and the sample pattern associated with selected environmental variables. A rank correlation between the two (dis)similarity matrices (Bray–Curtis for biota and Euclidean distance for environmental variables) provides an indication of match between the two datasets and by selecting different sets of environmental variables the 'best' match can be discovered. This method was used to identify the most important environmental variables explaining the spatial variation in the plankton, fisheries and seabirds matrices. A full explanation of the theory behind the procedures used is given in Clarke and Warwick (2001).

3. Results and discussion

3.1. Spatial analysis

The results of the spatial analysis are shown in Fig. 7, where each symbol represents the ordination of each individual ICES rectangle along the 2 principal component axes. Combined, these two axes capture a major portion of the overall variation in the abiotic state of the North Sea (37% and 20%, respectively, for PC1 and PC2). The PCA ordination highlights salinity and dissolved inorganic nitrogen (DIN) as the most important variables along PC1, and dissolved inorganic phosphate (DIP) and nearbed wave stress as the most important variables along PC2.

Seven clusters of rectangles were then categorised using the SIMPROF test of significance at $p = 0.01$ on a matrix of Euclidean dis-similarities. The geographic positions of these clusters are shown in Fig. 8, and the averages for each of the abiotic variables in each cluster are given in Table 2. The contiguous nature of the rectangles forming the spatial clusters (Fig. 8) should be noted, reflecting clear spatial gradients in salinity, wave stress and DIN across the North Sea. Clusters 5 and 2 are areas of the southern North Sea with tidally mixed, shallow waters. Cluster 3 includes the shallow waters of the Dogger Bank region which also is mostly tidally mixed. Clusters 1a, 1b and 1c are located along a deepening gradient on the North Sea plateau and have seasonally stratified waters, while cluster 4 is the deeper Norwegian Trench. Wave stress appears to be particularly important in the southern North Sea (Cluster 5), but it decreases significantly towards the northern North Sea where there is a significant increase in water depth. Clusters 5 and 2 are dominated by relatively high concentrations

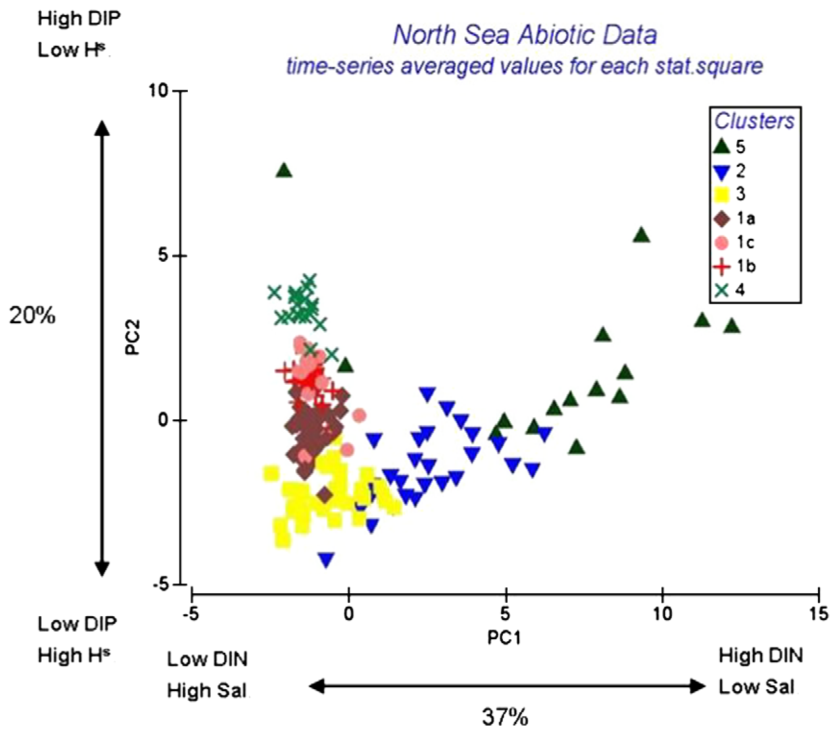

Fig. 7. Principal Component Analysis of the abiotic environmental data presented in Table 1. Each symbol represents the status of an individual ICES rectangle based upon its environmental characteristics and these have been coloured according to significantly distinctive clusters following methods described in the text. DIN and DIP refer to total Dissolved Inorganic Nitrogen and Phosphorous, respectively, Sal. refers to salinity and H^s is the seabed stress due to wave action. The spatial distribution of these clusters is shown in Fig. 8.

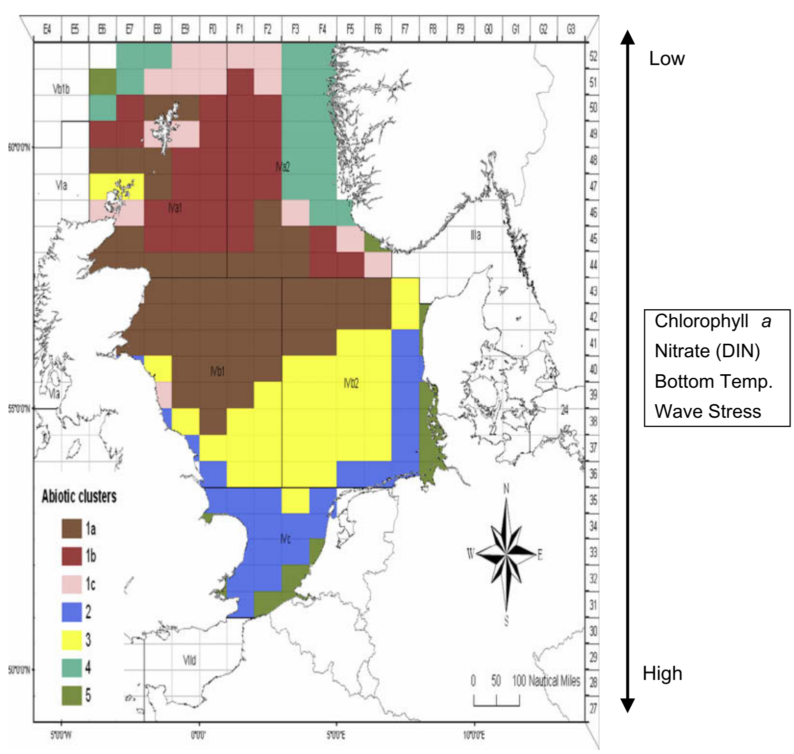

Fig. 8. Spatial clusters of the principal environmental characteristics of the North Sea based upon analysis presented in Fig. 7.

of surface chlorophyll and DIN, and have relatively high annual mean surface water temperatures compared to Clusters 4, 1a and 1b (Table 2). Also of significance is the relatively shallow depth in this region as indicated by the low bathymetry values and the associated high tidal and wave bed-stress values for Clusters 5 and 2 (Table 2). The relatively high level of nitrate is perhaps to

Table 2
Average values for each environmental variable within each significant cluster following SIMPROF® test of significance at $p = 0.01$. s = surface, b = bottom.

Parameter	Clusters (average values)						
	5	2	3	1a	1b	1c	4
Oxygen (b) (μ.mol/l)	298.63	281.19	276.89	277.73	279.03	271.94	277.89
Nitrate (b) (mg/l)	24.41	10.07	3.36	5.94	9.65	9.72	11.46
Nitrite (b) (mg/l)	0.71	0.47	0.3	0.16	0.11	0.11	0.08
Phosphate (b) (mg/l)	1.2	0.6	0.42	0.58	0.71	0.72	0.8
Salinity (b)	32.18	33.89	34.6	34.91	35.21	35.14	35.11
Silicate (b) (mg/l)	11.23	4.68	3.07	3.45	4.36	4.52	6.21
Temperature (b) (°C)	8.85	9.87	8.94	7.74	7.69	8.23	6.85
Chlorophyll (s) (mg/l)	5.34	3.15	1.7	0.75	0.67	0.87	0.75
Oxygen (s) (μ.mol/l)	103.22	83.64	85.35	57.16	53.89	71.58	76.81
Nitrate (s) (mg/l)	34.86	12.18	3.19	4.51	6.26	6.66	5.65
Nitrite (s) (mg/l)	1	0.59	0.27	0.1	0.09	0.11	0.12
Phosphate (s) (mg/l)	1.91	0.62	0.36	0.43	0.49	0.53	0.45
Salinity (s)	30.12	33.4	34.46	34.74	34.86	34.49	33.58
Temperature (s) (°C)	10.15	10.35	10.24	9.96	9.93	9.87	9.41
Bathymetry (metres)	12.81	30.63	45.22	65.89	109.69	179.93	413.78
Wave Stress (N.m^2.s)	0.09	0.05	0.03	0.01	0	0.01	0.01
Tidal Stress (N.m^2.s)	0.54	0.77	0.19	0.14	0.06	0.18	0.02
Mud/Silt (<63 μm)	7.41	5.67	6.85	5.59	19.13	10.49	45.61

be expected as the major riverine inputs into the North Sea (which are a significant source of nutrients) discharge to this region and are therefore, most likely to influence phytoplankton production as evidenced by the relatively high mean values of chlorophyll for coastal regions. It is noteworthy that an independent, more theoretical analysis to assess the flushing times of different parts of the North Sea by an ICES expert group in 1983 produced a very similar map of North Sea sub-divisions (Fig. 9; ICES, 1983).

Clearly, in terms of establishing water quality and marine environmental objectives, these clusters of rectangles based on a wide variety of abiotic variables would seem to be the most appropriate units to assess, particularly when investigating the relative and cumulative impacts of human activities and pressures in the North Sea.

Given such clear and consistent gradients in the environmental data it is not surprising that strong gradients in the biotic data

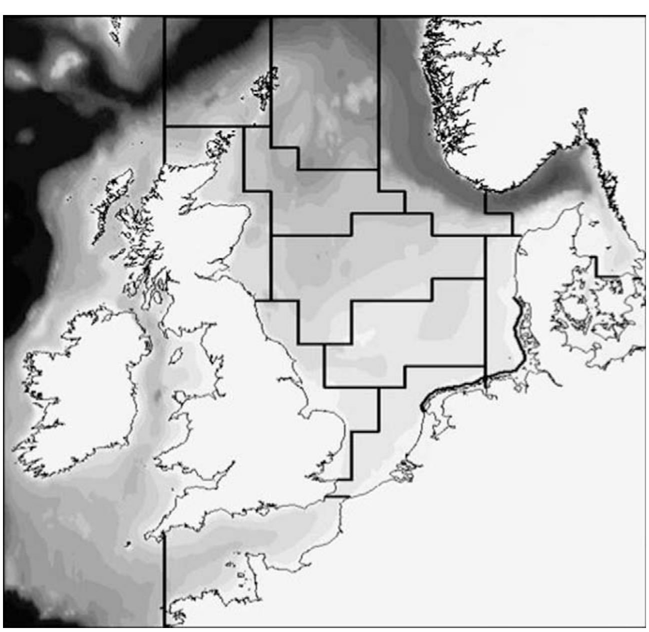

Fig. 9. Sub-regions of the North based upon hydrographical data and estimated (modelled) seawater residence times. The regions define areas of equal residence time (ICES, 1983) and the shading indicates relative changes in bathymetry – dark areas are deeper water regions.

were also observed. Indeed, performing the BEST procedure between pairs of similarity matrices for each of the ecosystem components (e.g. abiotic, plankton, fisheries and seabird matrices) revealed highly significant correlations between them. For example, the spatial variations in the plankton community data are most closely related to bottom phosphate, bottom salinity and wave stress ($\rho = 0.57$; $p = 0.01$); fish landings to bottom phosphate, bottom salinity, surface nitrate, wave stress and sediment grain size <63 μm ($\rho = 0.5$; $p = 0.01$); and seabirds to variations in bottom salinity alone ($\rho = 0.5$; $p = 0.01$). These highly significant correlations (e.g. $p = 0$ .01) should not be taken to imply causal relationships (for example, there is no simple relationship to explain high bottom water phosphate values correlating with variations in the near-surface plankton distribution) but they may be used as indicative of the influence of environmental variability on biological components, in this example the implied influence of Atlantic bottom water inflow on plankton distribution.

The shallow parts of the southern North Sea are clearly correlated with areas of higher seabed wave stress, which is possibly one of the more important factors determining ecosystem state in this part of the North Sea. Significant changes to the wave climate as a result of climate change are likely to have an impact on the state of the ecosystem, particularly in those regions subject to tide and wave induced bottom stress. However, the significance of the impact on the North Sea as an LME, at the spatial resolution we have adopted, is much less clear, although at more local scales the possible impact of changes in wave energy is likely to be much more significant, particularly in terms of habitat loss and coastal erosion. From a spatial planning perspective this is reassuring since the position of the spatial boundaries for the sub-regions of the North Sea LME are likely to remain relatively stable over time scales commensurate with planning policies (measured in decades rather than centuries). This does not mean that the attributes associated with each of the sub-regions (spatial clusters) will be the same, it is simply that the boundaries appear to be relatively stable when viewed at the North Sea scale. By contrast, changes in ecosystem state over time for the North Sea LME are more likely to be evident given known temporal trends in both natural and human pressures. Therefore, the benefits of assessing and predicting the relative temporal significance of natural *versus* human pressures on the state of LMEs are likely to be of greater significance in the shorter term (decades) compared to assessments of spatial gradients within LMEs.

3.2. Time series analysis

3.2.1. Integrated ecosystem assessment

The results of performing a PCA on the all the data combined, for the period 1983–2003, is presented in Fig. 10 which reveals cod landings, *C. finmarchicus* and Northern fulmar to be dominant components of PC1 which were abundant in 1983–1987, but then steadily declined with negative anomalies occurring from about 1996 onwards. The scores of the 1st component axis (PC1) and anomalies in North Sea cod landings are shown in Fig. 11 which clearly shows the steady decline from *positive* scores pre-1990 to *negative* scores post-1994. Step changes (regime shifts) in the time-series were identified in 1990 and 1997. What is particularly striking is the degree of similarity between the trends in PC1 scores and the cod landings. The 2nd component axis (PC2) in Fig. 10 accounts for 17% of the total variation and is dominated by beam trawling effort, with a negative sign; i.e. a decrease in PC2 implies an increase in beam trawling effort. PC2 showed a marked increase from 1983 to the early 1990s, but rapidly decreased from about 1995.

Trends in the data are further revealed in Fig. 12 which clearly demonstrates a transition in the state of the North Sea ecosystem between 1983 and 2003. Certainly for some variables (notably *C. finmarchicus* and sea surface temperature) there was an abrupt change in status around 1989 (Fig. 13, also Brander et al. (2003)), but based upon multiple sets of data shown in Fig. 12 it can be seen that the ecosystem as a whole did not change abruptly and that a gradual process of change has occurred. We, therefore, see two dominant regimes when ordering the variables on the 1st component PCA axis: one pre-1993 composed of positive PCA sample scores and characterised by a relatively productive cold water demersal fin fishery and an increasingly productive pelagic fishery, to one post-1993 composed of negative PCA sample scores characterised by increased seawater temperature, a decline in the demersal fin fishery, but the pelagic fishery (as indicated by total landings) remaining relatively high, stable and productive.

There are well documented time lag dependencies between trophic levels in ecosystems and the North Sea is no exception (Beaugrand et al., 2003). In addition, the presence of feedback mechanisms, such as the rapid coupled benthic-pelagic recycling of nutrients and carbon following disturbance, will contribute to the capacity of ecosystems to withstand shifts in regime (Viitasalo, 2007). The relative importance of both processes (trophic lags and feedback loops) may be partly responsible for determining the time-period for transition from one state to another, although we are not able to quantify these effects at present. In simple terms we may expect the more complex the ecosystem (e.g. the greater number of trophic levels) the longer the transition time from one state to another. In addition, the complexity of an ecosystem may be dependent on its spatial extent (Connell and Sousa,

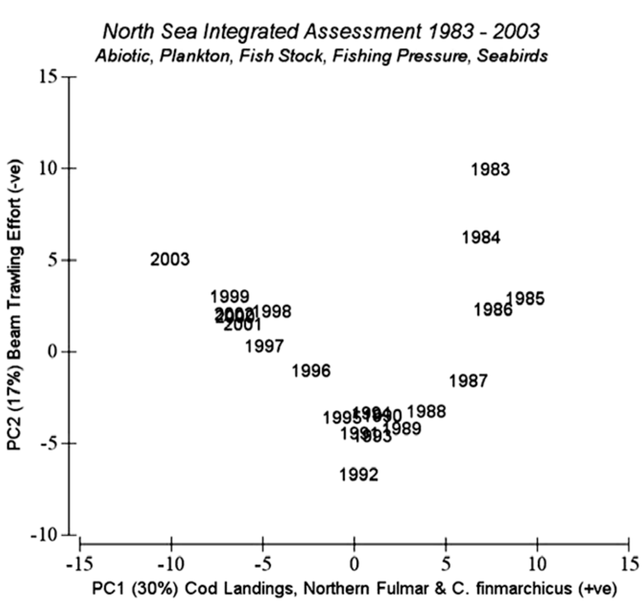

Fig. 10. Principal components analysis on all 114 ecosystem variables. The variables highlighted on each PC axis are those which have the highest eigenvalues making up each axis. Note the negative sign for sample scores on PC2 - a decrease in PC2 implies an increase in beam trawling effort and vice versa.

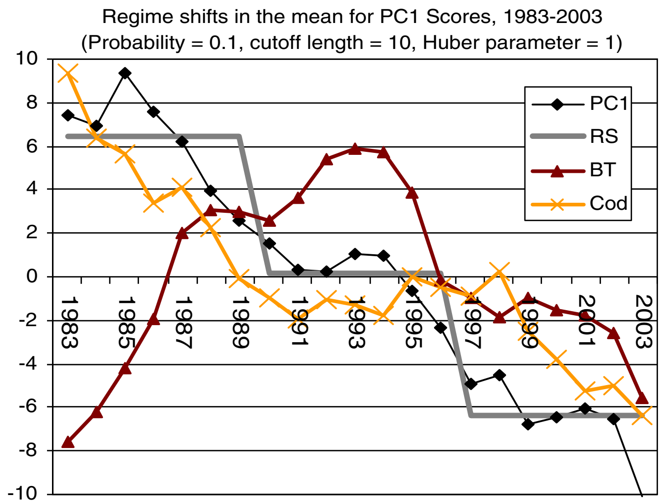

Fig. 11. Plots of total North Sea cod landings (as anomalies – orange line (Cod)), beam trawling effort (as anomalies – brown line (BT)) and PC1 scores (black line (PC1)). The solid grey line is the result of applying an algorithm to detect significant shifts in the time-series of the PC1 scores (RS) (Rodionov, 2004).

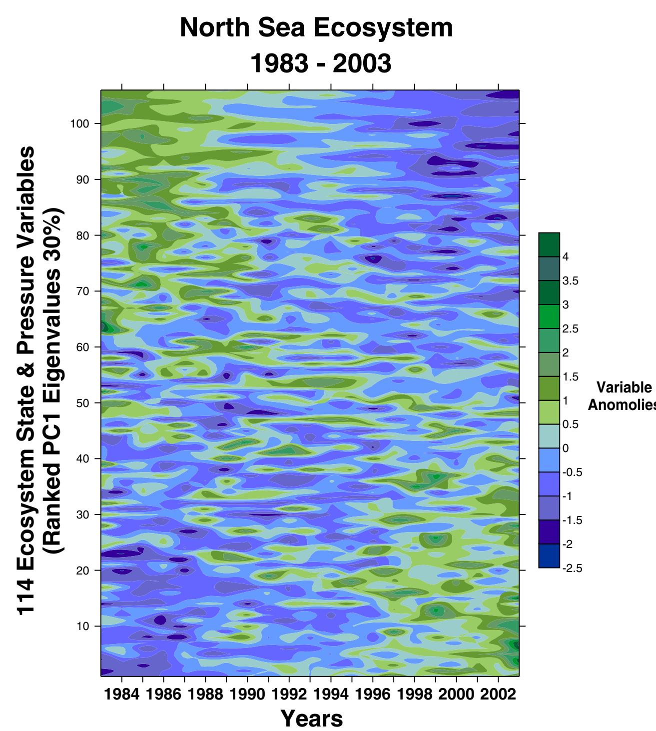

Fig. 12. A shade plot showing the variation (as anomalies) of all 114 categorised ecosystem variables in rank order according to their PC1 eigenvalues for the years 1983 to 2003 (see Table 1 for a list of the variables).

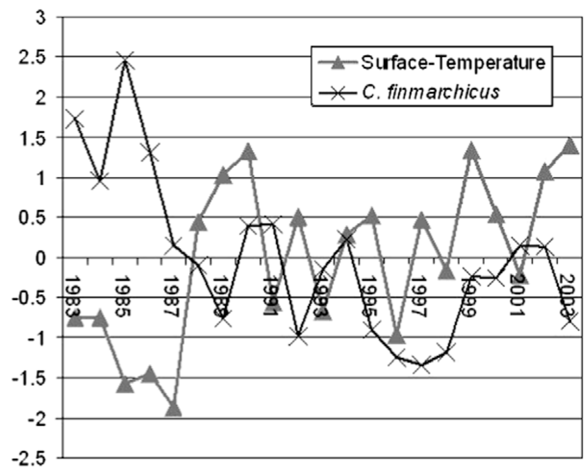

Fig. 13. Anomalies of North Sea sea surface temperature and *Calanus finmarchicus* densities between 1983 and 2003.

1983). In the present study for the North Sea the change in ecosystem state (based upon the rank order of PC1 eigenvalues accounting for 30% of the variation) would appear to be about 10 years.

The North Sea regime shifts described by Reid et al. (2003) and Weijerman et al. (2005) appear, in part, to be variations in timing between these two principal states. For example, Reid et al. (2003) described the impacts of cold water and low salinity events on the North Sea plankton community between 1978 and 1983. Our analysis supports this interpretation of a transition from a relatively 'cold', to a relatively 'warm', ocean state. However, we interpret the change as happening over a longer time frame than previously reported. By the end of 1983, however, there is evidence (in the present assessment) that a decline in the cold water regime had already started such that by 1988 there was a significant change in the ecosystem state which was reinforced by a sharp increase in surface seawater temperature by about 1.5 °C in 1989.

Clearly this result has implications for assessing (and therefore managing) the state of the North Sea ecosystem. Table 3 highlights the most dominant and recessive variables associated with the change in North Sea regime during this period. These then represent the most likely 'stable' state descriptors for each regime, but these are not necessarily the best descriptors to detect early signs of a likely regime shift. The present assessment highlights several variables which are either positive or negative (they switch on or off) from one year to the next, including the net flux of seawater between the North Sea and the NE Atlantic, which taken on their own do not provide a reliable means of detecting early change, but taking several sensitive parameters together may provide the weight of evidence required to increase the certainty of detecting early regime change. Such an approach may therefore allow precautionary management measures to be put in place before a regime shift occurs. Clearly this assertion would require further testing to validate its utility.

Although this analysis clearly demonstrates a change in ecosystem state and possibly provides some scope for detecting the onset of ecosystem shifts at the scale of the whole North Sea there is a need to more closely examine the relationship between sets of similar variables, namely; abiotic, plankton, fish stock, fishery and seabird variables. Examining the degree of relatedness or connection between these ecosystem components for different time periods may help to identify if the system is responding predominantly to top-down pressure caused by fishing, or bottom-up pressure driven by natural ocean climate processes and forcing.

3.2.2. Links between North Sea plankton, fish stocks, fisheries and seabirds

The approach we use builds upon the existing knowledge on the structure and function of the North Sea marine ecosystem (Jones, 1982; Heath, 2005; Mackinson and Daskalov, 2007). The ecosystems energy, in the form of carbon and nutrients, flows between the trophic levels as a result of predator–prey interactions. These interactions to a large extent are size based such that numerous small animals tend to be eaten by rather fewer larger animals creating complex foodwebs (Jones, 1982; Heath, 2005; Blanchard et al., 2005; Steele et al., 2007; Moll and Radach, 2001). Also the recycling of carbon and nutrients by micro-organisms ensures energy passes back down the foodweb as a series of microbial feedback loops and that coupling between the pelagic and benthic parts of the ecosystem is maintained. The links between the pelagic and benthic ecosystem components (or groups of variables) represented by the present North Sea data set can be summarised in the form of a simplified diagram (Fig. 14).

The boxes represent ecosystem components composed of data obtained from established monitoring programmes which have both the broad spatial and temporal coverage in the North Sea. The benthos box has been shaded out as no long time series data are available except from a limited number of sites in the North Sea (<10 sites) and further tests would be required to examine how representative the sites are of the North Sea as a whole before including the data in the present analysis.

Clearly if the main driving force or pressure for the ecosystem was bottom-up then the degree of relatedness between components might be expected to be higher at the bottom end of the foodweb compared to the relatedness between components higher up the foodweb (e.g. at higher trophic levels) since these are further removed (trophically) from the driving pressure. By contrast, if the pressure were top-down then the gradient of relatedness may be reversed with higher relatedness values occurring at the top of the foodweb closer to the pressure whilst lower relatedness values would occur towards the bottom (reflecting comparatively weaker links between abiotic variables and the lower trophic levels such as the plankton). This approach then depends on comparing ratios of ecosystem component relatedness and assessing if the

Table 3
The dominant variables associated with each of the principal North Sea states between 1983 and 2003 defined by the analysis presented in Fig. 12.

(a) High pre-1993, low post-1993		(b) Low pre-1993, high post-1993	
Variable	PC1	Variable	PC1
Plaice (TAC)	0.153	Echinoderm larvae	0.139
Whiting Spawning Stock Biomass	0.154	Bottom-silicate-conc	0.132
Pair Trawl fishing effort	0.156	Northern-Gannet	0.123
Cod Landings	0.157	*Calanus helgolandicus*	0.122
Whiting landings	0.162	Surface-Temperature	0.177
Demersal seine fishing effort	0.164	Terns	0.117
Otter Trawl fishing effort	0.166	Surface-Oxygen	0.111
Whiting (TAC)	0.166	Sprat	0.108

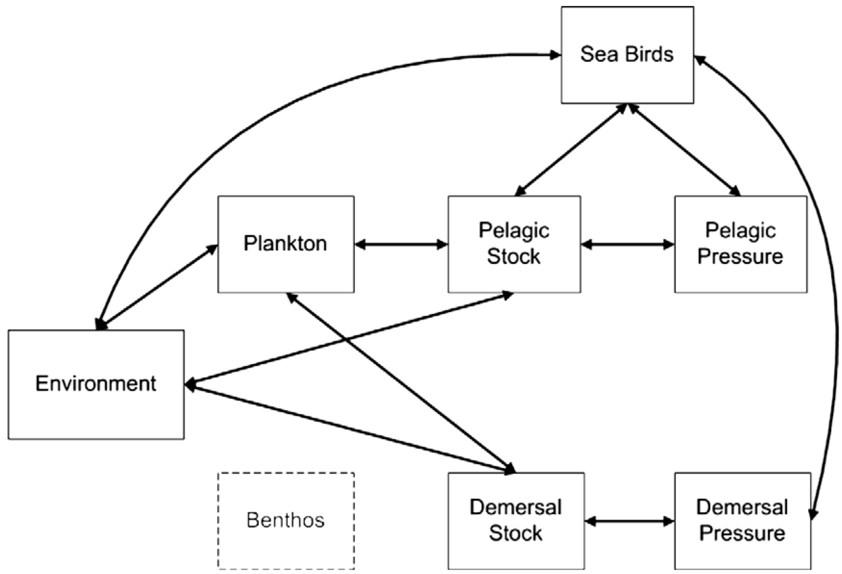

Fig. 14. Ecosystem components used to create data matrices of associated variables taken from established sectoral North Sea monitoring programmes. Links between boxes are those where some direct connection is expected based upon existing knowledge of ecosystem dynamics.

gradient of ratios are either top-down or bottom-up in nature for either the pelagic or demersal parts of the ecosystem.

The advantage which this approach has over more mechanistic mass balance techniques (Heath, 2005; Hunt and Mckinnell, 2006; Steele et al., 2007) is it makes no assumption about the causal links between sets of variables, it simply allows the relative degree of possible connection between multiple ecosystem components to be assessed and, therefore, the overall significance of any one pressure can be judged simultaneously against all others in any combination of spatial and temporal scales. Clearly for the result to make sense the assignment of variables to ecosystem components and their links should be based upon a sound understanding of ecosystem function and dynamics and this should be as realistic as possible. Also the number and type of data sets available will be a limiting factor in the suitability of applying this method in all LMEs. For example, the incorporation of diet-related variables (such as fish stomach contents, e.g. www.cefas.co.uk/dapstom; Frid and Hall, 1999) would further strengthen the analysis. However, this was somewhat beyond the scope of the present paper, given the significant effort undertaken to include a wide range of abiotic variables and biological data across different trophic levels.

For the earlier period (1983–1993), the results of this analysis are shown in Fig. 15 which suggests a more significant top-down fishing pressure is acting on the ecosystem during this period with climate forcing being comparatively weak, as indicated by generally higher relatedness values between ecosystem components at the top-end of the food web compared to those at lower levels. Significant top-down fishing pressure was indicated by the highest relatedness values occurring between the demersal fishery (demersal pressure) and demersal stock ($\rho = 0.8$), and the pelagic fishery (pelagic pressure) and pelagic stock ($\rho = 0.5$). For both the demersal and pelagic parts of the ecosystem it appears from this analysis that the predominant pressure acting on the North Sea ecosystem (as represented by the ecosystem components described for the period 1983–1993) was from fishing pressure and not natural environmental forcing.

Indeed, during the 1980s a doubling of the annual sandeel landings was witnessed from 0.5 million tonnes in 1983 to 1.1 million tonnes in 1989 (Pedersen et al., 1999); landings of demersal fish such as cod were in steady decline which is usually attributed to both climate and (mainly) otter trawl fishing (Hislop, 1996; Horwood et al., 2006; Brander, 2007). Beam trawling effort also increased significantly over this period putting further pressure on the system (Jennings et al., 1999 – see Fig. 11). In addition, there is a significant and high degree of relatedness between seabirds and both pelagic and demersal fisheries and fish stocks. In this respect it is noteworthy that the highest value is between the demersal fishery and seabirds ($\rho = 0.7$) possibly reflecting the increase in discards (upon which certain seabirds feed) associated with the demersal fishery compared to the pelagic fishery (Furness, 2003).

By contrast for the period 1993–2003 (Fig. 16) there is an observed increase in the relatedness values at the bottom of the pelagic foodweb such that the highest value is now between the abiotic and plankton components ($\rho = 0.6$) and that these values decrease moving further up the food chain. This would suggest that the pelagic part of the ecosystem (as represented by the ecosystem components analysed) is now responding more to factors at the base of the food chain, i.e. more environment driven than fishing pressure driven. It might be considered that bottom-up control was more favourable for the maintenance of ecosystem integrity and fisheries, but changes in environmental forcing, which are beyond management control, may add to the pressure of a system already under stress particularly if such forcing is extreme. For example, it has been suggested that the removal of top predators, having a stabilising role, by fishing makes the system more susceptible to environmental controls, introducing increased variability and making the system more difficult to manage (Shannon and Waremeyer, personal communication). However, the relatedness between the demersal fishery and demersal fish stock components in the North Sea remains significantly high, although it has decreased compared to the period pre-1993, suggesting top-down fishery pressure remains significant. The inclusion of macrobenthic invertebrate data would help test this assertion and this is something we wish to address in the future as fishing pressure has been cited as bringing about significant changes in the benthic community, with an increased prevalence of scavengers and decreased prevalence of sedentary polychaetes being described in the stomach contents of dab (*Limanda limanda*) in the North Sea (Frid and Hall, 1999). In addition, it is noteworthy that the degree of relatedness between the seabirds and both fisheries and fish stock components has decreased over this period compared to the period 1983–1993, which is perhaps to be expected given the overall decline in

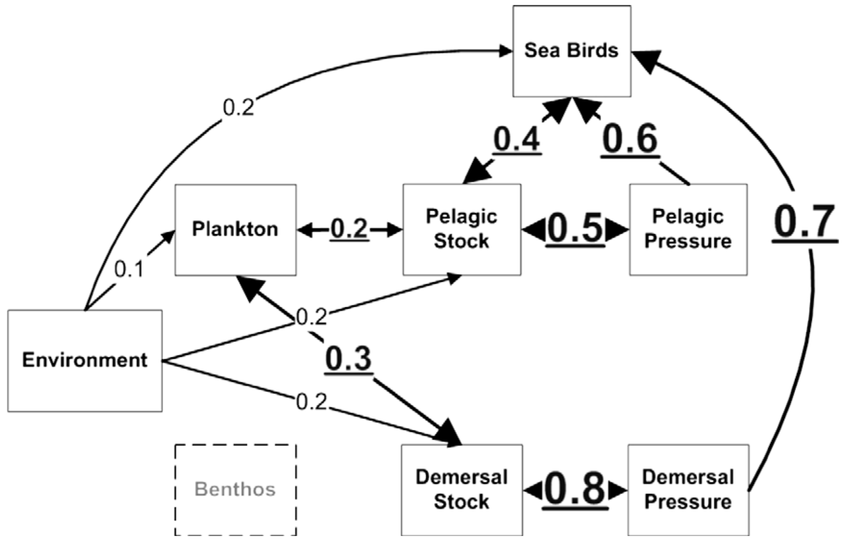

Fig. 15. The relatedness (or degree of connection) between ecosystem components of the North Sea for the period 1983–1993, highlighting a significant possible top-down pressure as a result of fishing. Numbers underlined indicate a significant correlation.

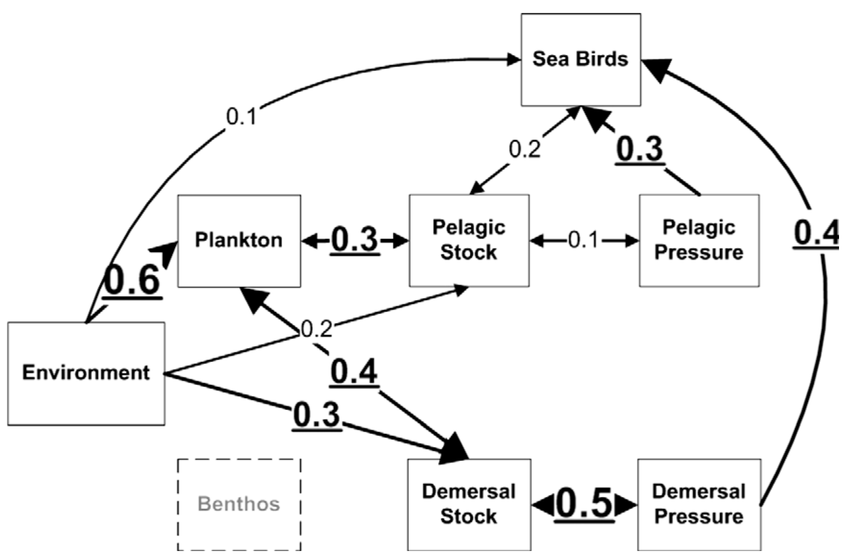

Fig. 16. The relatedness (or degree of connection) between ecosystem components of the North Sea for the period 1993–2003, highlighting a significant bottom-up pressure for the pelagic part of the ecosystem and top-down pressure for the benthic part of the ecosystem. Numbers underlined indicate a significant correlation.

fish discards (as inferred from the overall decline in demersal fish landings) over the assessment period. Interestingly a decline has been described in the seabird populations in the North Sea, particularly for the northern fulmar and black-legged kittiwake (Parsons, personal communication).

4. Perspectives and conclusions

4.1. LME regime shifts

The changes in the North Sea ecosystem during the recent decades, as revealed in this integrated ecosystem assessment, show many parallel features to those shown in other ecosystems of the North Atlantic, demonstrating a level interdependence between adjacent systems. For example, in the adjacent Norwegian Sea, the inflowing Atlantic water has shown a warming trend and an increase in salinity from the late 1970s to the early 2000s. However, these trends are influenced by pronounced fluctuations related to variations in the NAO index in a complex (non steady) way (Mork and Blindheim, 2000; Blindheim, 2004; Polyakova et al., 2006). The late 1980s and mid-1990s were periods of rapid warming of the inflowing Atlantic water in the southeastern Norwegian Sea, corresponding in time to the stepwise changes in the North Sea ecosystem (see Fig. 11). Blue whiting had good recruitment in 1982 and 1989, and then produced an unprecedented (in the relatively short time series) sequence of strong year-classes starting in 1995 that led to a marked increase in population of blue whiting, including increased numbers of juveniles, which probably had a direct influence on the densities of North Sea *Calanus* at the time (Heath, 2005).

The Barents Sea ecosystem lies further north but is connected to the Norwegian Sea as is the North Sea. The Barents Sea has seen a similar warming trend with fluctuations since the late 1970s as witnessed in the Norwegian and North Seas. The climatic variations have been associated with pronounced ecological changes involving the collapse and rise of the capelin stock and trophic interactions between plankton, fish and seabirds (Skjoldal and

Sætre, 2004; Blindheim and Skjoldal 1993; Dalpadado et al., 2002). The strong 1983 year-class of herring, which had its nursery area in the southern Barents Sea, contributed to recruitment failure and collapse of the capelin stock which had large repercussions in the ecosystem, affecting the Barents Sea cod stock, harp seals, and seabirds through food limitation, causing reduced growth and increased mortality (Blindheim and Skjoldal, 1993; Dalpadado et al., 2002). The capelin stock recovered in the late 1980s and has since fluctuated with lows in the mid-1990s and early 2000s.

Changes in the LMEs in the Northwest Atlantic; namely the Newfoundland-Labrador Shelf and Scotian Shelf, have been equally large but with broadly opposite patterns to those seen in the LMEs of the Northeastern Atlantic (Rice, 2002; Zwanenburg et al., 2002). The ocean climate in the Northwestern Atlantic showed a cooling trend from the 1960s to a minimum in the early 1990s (Drinkwater, 2002). During this period the Canadian cod stocks declined, with a major collapse of the northern cod stock of the Grand Banks in the late 1980s which was followed by a moratorium on fishing cod, imposed in 1992 (Rice, 2002). Overfishing was an important reason for the collapse of the cod stock, but ocean climate and ecological factors were also contributing as indicated by reduced individual growth and recruitment in the period prior to the collapse (Drinkwater, 2002). Several other changes in the Canadian ecosystems took place, affecting stocks of capelin, shrimp, crabs and others (Rice, 2002; Zwanenburg et al., 2002), and trophic cascades have been implied for the changes involved in the collapse and subsequent very slow recovery of the cod stocks despite closure of the fisheries (Carscadden et al., 2001; Frank et al., 2005).

Regime shifts are often described as the outcome of pronounced changes in marine ecosystems as seen for example on the Canadian shelf off Nova Scotia and the North Sea. However, it should be noted that such regime shifts may simply be part of a multi-annual or multi-decadal oscillation related to climatic shifts occurring at large (hemispherical or global) scales. The expression in any one geographical ecosystem of changes resulting from climatic forcing may take on different patterns reflecting the detailed mechanisms and local processes that are playing roles within the constraints of the larger scale forcing. However, it is evident from this review that although climate forcing appears to be a trigger for many regime shifts in LMEs, the scale of the ecological impact (and possibly also the social and economic consequences) appears, in part, to be related also to the level of fishing effort. A quantification of this relationship through a more systematic review of this phenomena could possibly provide a systems level indicator of "regime shift risk" to combined climate and fishing pressures.

4.2. Spatial analysis

Of significance, in terms of the North Sea findings, is the description of eco-hydrodynamic regions through integrated spatial analysis which supports more theoretical based work undertaken by ICES in the 1980s using hydrographical data and estimates of residence times of water (ICES, 1983). The identification of sub-regions of the North Sea should form the basis for establishing scientifically meaningful ecosystem management units, although we recognise that boundaries will always be influenced by geo-political considerations. Nevertheless to move too far from those described here may have significant implications for the effectiveness of any future management measures including the achievement of good environmental status under the EU Marine Strategy Directive (Council of the EU, 2006).

4.3. Time-series analysis

The integrated time-series analysis presents new evidence to support the conclusion that a regime shift occurred in the North Sea sometime between 1986 and 1996. The analysis presents further insight into how ecosystems change state at the scale of the North Sea, which appears to be a gradual process with only certain parameters showing abrupt changes in state around 1988 and 1989. Clearly it is the integration of a number of variables from numerous trophic levels and pressures which describe an ecosystem. Taking some of these (114 in all, representing 6 principal ecosystem components) into consideration we see that the North Sea ecosystem appears to have witnessed a gradient of gradual change punctuated by abrupt variations in only some state variables between 1983 and 2003. It is obvious that trying to assess and manage such a dynamic system with multiple trophic level dependencies presents a challenge, especially given the sectoral approach for regulating human activities which do not consider the consequences of multiple pressures impacting at the ecosystem level. Nevertheless, the present analysis by examining the degree of connection between principal ecosystem components and using all available monitoring data provides a means of objectively assessing the relative significance of multiple pressures acting on the North Sea ecosystem at any one time.

4.4. Ecosystem connections – a potential indicator of LME status and health

Heath (2005) looked at both the pelagic and demersal foodweb structure of the North Sea between 1973 and 2000 and concluded that the pelagic foodweb appears to be predominantly controlled by bottom-up production processes. In the present study we conducted an integrated ecosystem assessment (Section 3.2.1) to identify significant changes in the time-series which may correspond to changes in the factors forcing the system. In this respect we observe a significant bottom-up influence associated with the pelagic foodweb but only for the period 1993–2003. During the period from 1983 to 1993 both the pelagic and demersal foodwebs appear to be dominated by top-down fishing pressures. Clearly both environmental and fishery pressures are acting simultaneously on the North Sea ecosystem (along with many other pressures), therefore, an integrated ratio of ecosystem component relatedness may provide a means of indicating how appropriate the levels of resource exploitation are at any given time. An example of such an integrated ratio for the pelagic ecosystem is shown in Fig. 17 which highlights how the gradient of ratios is positive when the system is responding predominantly to top-down fishing pressure (between 1983 and 1993), and negative when the system is predominantly responding to environmental forcing (between 1993 and 2003). However, this analysis in itself does not tell one what the overall state is, it is simply a relative measure of which pressures dominate in a system for any given period of time. As previously described, a situation can arise where the ratio of relatedness indicates a system responding to bottom-up processes but the resultant state may be impoverished due to over-exploitation or a shift towards more extreme environmental forcing. Nevertheless, in this situation one may expect some recovery of the system to be initiated as long as the exploitation pressure continues to be below that of the bottom-up environmental forcing and that the climate forcing is not extreme. In this respect it is interesting to note the ratio for the demersal ecosystem components between 1983–1993 (Fig. 15) and 1993–2003 (Fig. 16) shows the environment forcing on the demersal stocks has increased over this period relative to the fishing pressure. Yet although the fishing pressure has been significantly reduced over the later period (see Fig. 11), the fishing pressure remains more dominant than the environmental forcing, suggesting the need for a continued precautionary approach to the setting of demersal fishing quotas.

There are other examples which describe bottom-up vs. top-down pressures on ecosystems using different methods, notably

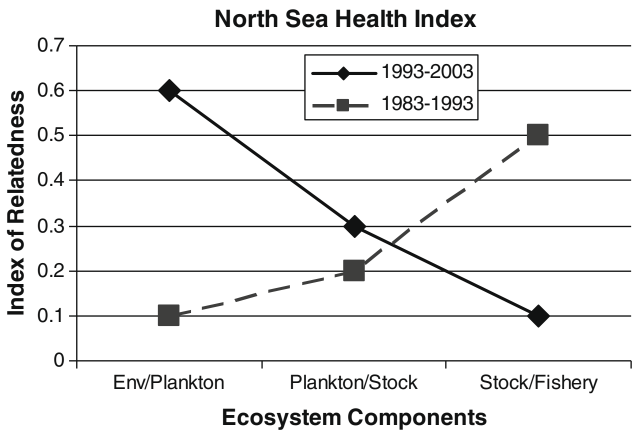

Fig. 17. A possible index of ecosystem health. The example presented here is based upon gradients of pelagic ecosystem component relatedness. The ratios between each pair of components changes for different time periods such that the gradient is positive for the period 1983–1993 (indicating a predominant top-down pressure on the ecosystem) to negative gradient between 1993–2003 (indicating a predominantly bottom-up driven system).

in relation to the Canadian Scotian Shelf, Black Sea and Baltic Sea ecosystems (Hunt and McKinnell, 2006; Choi et al., 2005; Frank et al, 2006; Daskalov et al., 2007; Flinkman et al., 1998). However, where this assessment differs is in simultaneously assessing the degree of relatedness or connection between multiple ecosystem components which has the advantage of identifying the most important pressures acting in combination on the system for the period under evaluation. By adding other components to the model and constraining the spatial extent this approach could be applied to assess multiple human pressures such as dredging, shipping or chemical contamination. However, it does have limitations, since it is dependent on having relatively long time-series data (probably in the order of 10 years or more) and therefore the approach described is not suitable for annual assessments of monitoring data. Rather it has utility for the periodic assessment of LMEs conducted at intervals of between 5 and 10 years, as an overall assessment of ecosystem health.

4.5. Adaptive management response

As previously stated the present assessment highlights several variables which 'switch on and off' from one year to the next which when taken together may provide the weight of evidence required to increase the certainty of detecting early regime change. Such an approach may, therefore, allow precautionary management measures to be put in place before a regime shift occurs. The dominant environmental (climate) signature on the state of the North Sea ecosystem, for certain periods, offers an opportunity to use ocean climate predictions and models to support a more effective approach to marine ecosystem management. If we accept that regime shifts will occur in the future triggered by large-scale climatic variations then the challenge we face is how to predict such changes with sufficient advance warning and certainty to enable the ecological and socio-economic impacts to be managed and minimised in an effective way. The management of regional marine ecosystems, therefore, needs to strike a balance between anticipating regime shifts and the regulation of localised human activities. At present most of the management effort is directed at regulating activities and not mitigating for, or adapting to, inevitable and largely unmanageable changes in state. It is clear that for the successful implementation of the ecosystem approach to management, assessment tools which can both predict and observe changes in pressure and state will be needed. Only then can targets (agreed by society and set out in legislation) for good environmental status be achieved with any degree of manageable certainty.

4.6. Improvements

As reported by ICES (2006a), there are still some additional considerations to take into account before these analyses can be used as a reliable contribution to integrated management in the North Sea. One of these relates to the range of datasets that have been made available. It is notable that a number of key ecosystem components are not represented at all in this assessment, including macrophytes, marine mammals and benthic macro-invertebrates. Others are only represented by very few data points that would preclude any useful assessment of status and trends at the North Sea scale (e.g. chemical sediment contaminants) whilst several are only available for a limited spatial extent (e.g. water column and bio-chemical habitat). Some of this is simply due to difficulties in obtaining the data, but in other instances the data do not exist. The potential for additional data collection on existing routine surveys should be investigated to increase coverage of the ecosystem components that are currently not well reported. This is appropriate for any LME, not just the North Sea. In addition, a more robust time-series analysis is likely to be generated if based upon sub-regional divisions (or eco-hydrodynamic units) of the North Sea as indicated in the present study rather than using the previously defined ICES (sub)-divisions.

The ICES Regional Ecosystem Study Group for the North Sea (REGNS) process has demonstrated that it is possible to create a credible assessment database to support integrated ecosystem assessments and that it is possible to generate new insights and hypothesis into the relationships between a number of state and pressure outputs of value in supporting an ecosystem advisory process. However, the challenge is how to use and interpret the analysis and how to make the process operational and sufficiently comprehensive to support the on-going assessment and policy needs for an EA to the management of the North Sea ecosystem.

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