**Viewpoint**

# Diagnostic monitoring of a changing environment: An alternative UK perspective

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**Abstract**

Adaptive management of the marine environment requires an understanding of the complex interactions within it. Establishing levels of natural variability within and between marine ecosystems is a necessary prerequisite to this process and requires a monitoring programme which takes account of the issues of time, space and scale. In this paper, we argue that an ecosystem approach to managing the marine environment should take direct account of climate change indicators at a regional level if it is to cope with the unprecedented change expected as a result of human impacts on the earth climate system. We discuss the purpose of environmental monitoring and the importance of maintaining long-term time series. Recommendations are made on the use of these data in conjunction with modern extrapolation and integration tools (e.g. ecosystem models, remote sensing) to provide a diagnostic approach to the management of marine ecosystems, based on adaptive indicators and dynamic baselines.

**Keywords**

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Ecosystem, indicators, monitoring, baselines, time series, modelling.

## Introduction

In their viewpoint article "A UK perspective on the development of marine ecosystem indicators", Rogers and Greenaway (2005) reviewed the suite of marine ecosystem indicators currently in use or, to their knowledge, under development in the UK to support major national and international biodiversity and ecosystem policies. This article raised a number of issues regarding the development of indicators and how to address the issue of climate change, that we feel require deeper discussion. In this article we present an alternative approach, also being developed within the UK, that can incorporate systematic changes and natural variability into an adaptive ecosystem-based monitoring strategy.

Management of the marine environment requires an understanding of the complex interactions within it. The way in which ecosystem processes and functions interrelate is complex and clearly confounded by their interaction with anthropogenic factors. The potential effects that these may have in terms of sustainability and socio-economic stability adds a further level of complexity. The recent adoption by UK government departments and agencies of an *ecosystem* or *ecosystem-based* approach to managing the seas (Defra, 2002; Laffoley et al., 2004) is a step towards addressing these complexities. The central tenet of such an approach is the holistic assessment of impacts of human activities on the marine ecosystem and the development of integrated management measures.

To manage human impacts on ecosystems successfully, we need to understand issues of scale and natural variability. Ecosystems, by their very nature are dynamic, changing in space, time and composition over a range of scales. For example, short-lived extreme events can have widely distributed impacts on marine communities that can last for decades: the very cold winter of 1962 reduced ranges of many intertidal species by hundreds of kilometres (Crisp, 1964). It is also essential to be able to separate anthropogenic impacts from natural fluctuations. Consequently, a management approach is needed that attempts to incorporate this range of variability and the reasons for them.

The term adaptive management refers to management systems that can adapt to changes in their initial conditions and has been identified as a key mechanism for delivering an ecosystem approach (UNEP, 2004.; Laffoley et al., 2004). Establishing natural levels of variability within and between marine ecosystems is a necessary prerequisite to implementing adaptive management for the marine environment and requires a monitoring programme which takes account of the issues of time, space and scale. Climate change is a key issue in this regard, as there is much evidence globally that climatic changes are impacting marine ecosystems on a range of geographic scales, from the local and regional, through national, basin scale and global scales. Other long-term impacts such as fishing and nutrient run-off are also having effects and the combination of the different impacts is leading to complex changes (Lubchenco et al., 1993; Fields et al., 1993; Paine et al., 1993; Barry et al., 1995; Sagarin et al., 1999; Beaugrand et al., 2002; Root et al., 2003).

In their article, Rogers and Greenaway (2005) state that "At a UK level, climate indicators have *no direct role* in marine ecosystem management" (italics added), and can only provide contextual information. In this paper, we argue that an ecosystem approach to managing the marine environment should take direct account of climatic and other long-term 'contextual' information at a regional (e.g. UK) level if it is to cope with the unprecedented change expected as a result of human impacts on the earth climate system. We discuss the purpose of environmental monitoring, along with ways in which long-term monitoring can be used in conjunction with modern management tools to provide a diagnostic approach to the management of marine ecosystems.

## Why monitor the environment?

Monitoring is an essential component of any environmental management framework and is undertaken for a number of reasons:

- To detect and document the rate, nature and extent of change;
- To establish a baseline of reference conditions from which changes can be detected;
- To attribute change to natural or anthropogenic agents and inform the management process accordingly;
- To improve understanding of the environment so future changes can be predicted and planning put into place.

To achieve these objectives, the type of monitoring undertaken and the framework in which data are interpreted are crucial. The framework which has been implemented by the European Environment Agency (EEA, 2003) and adopted in the UK (EA, 1999; Defra, 2003) is DPSIR (Driving force, Pressure on system, State of system, Impact of pressures on system, Response of society/management to remediate the impacts; IIED, 2002), implemented as an indicator-based reporting system with reference points to aid interpretation.

## Detecting change – Indicators

The traditional approach to monitoring environmental quality has been to measure particular indicators and to judge them against set targets. Such monitoring is designed to demonstrate compliance with national and international policy. While it may provide a useful measure of performance against environmental quality standards (performance indicators), the approach tends not to produce much understanding of how and why changes have taken place, or what knock-on effects such changes may have for the ecosystem. Simply expressing the state of an individual biological, chemical or physical variable (e.g. winter nitrate level) provides little understanding about the health of the ecosystem as a whole and no predictive knowledge of possible future changes. We can report if the variable is higher or lower than last year's value but such changes do not necessarily indicate whether the condition of the environment is becoming more or less favourable.

More recently, attempts have been made to construct a series of simple indicators that reflect the present status of the marine environment, termed *state indicators*. This approach has been championed by Rogers and Greenaway (2005) and has been adopted by the UK Department for Environment, Food and Rural Affairs (Defra) in their Charting Progress report (Defra, 2005). While these have the advantage of reflecting changes relevant to ecosystem status and processes, and are important for managing according to the DPSIR framework, they still only provide information on the current status of the ecosystem (S in DPSIR)[1], not on forcing processes (D in DPSIR). Without understanding the causes of change it is difficult to either undertake remedial action in the short term or set longer term objectives. For example, a localised change in the benthos might be the result of changes in pollution status, but it might equally result from natural changes in productivity, nutrient flux, water temperature or a host of other variables. Without knowledge of the way in which the whole ecosystem is changing it is difficult to take any remedial action. Successful ecosystem-based management needs to

[1] Some indicators of pressures (P) and impacts (I) have been suggested in Rogers and Greenaway (2005) to supplement the state (S) indicators.

understand the nature of changes within context, that is by determining their physical, chemical or biological drivers and the rate (i.e. time scales) and extent (incl. spatial scales) to which these factors cause perturbations from "acceptable" ecosystem conditions. This presents another challenge: how do we determine "acceptable" ecosystem conditions?

**Evaluating Change – Environmental Baselines**

What does the detection of a change mean in, for example, the temperature of seawater or the species composition of a nature reserve? Not much - unless such changes are placed in spatial and temporal context. We need to know what the environment should be like naturally and how far from this *baseline* it has deviated. We also need to know the circumstances (e.g. geographic extent) to which this baseline applies and the levels of naturally occurring variability that fluctuate around the baseline. Problems with defining the baseline status of ecosystems have been widely discussed but, essentially, knowledge of levels of variability in the pre-impacted state is required, necessitating the collection of considerable data covering long time periods. Unfortunately, such information does not exist for the majority of ecosystems, so later baselines reflecting an impacted state of the ecosystem are often used. This problem has been defined as the 'shifting baseline syndrome' (Pauly, 1995; Sheppard, 1995) and arises because, for management purposes, it is often not practicable to define a true baseline for an ecosystem. As a result "acceptable" target conditions have been set using reference conditions calculated from limited data sets of short duration and inadequate sampling frequency that do not adequately reflect the pre-impacted state and longer-term natural variability of an ecosystem.

An alternative approach, adopted by Defra in their Charting Progress report (Defra, 2005), uses current conditions to define a reference status level for the ecosystem. This can be adequate for the evaluation of future change, but gives no information on past status so is insufficient if restoration is a target. As such, it should not be confused with the environmental baseline. The European Commission's Water Framework Directive (WFD) calls for a restoration of all aquatic ecosystems in Europe to meet "high status" or "good status" by 2015, with "high status" corresponding to totally, or near totally, undisturbed conditions and "good status" corresponding to low levels of distortion resulting from human activity, but deviating only slightly from those normally associated with undisturbed conditions (EU, 2003). This requires information on baseline states for all ecosystems.

Historical records are very important in the establishment of reasonable baselines, but such records are rare. For areas where records do not exist, proxy baselines can sometimes be defined. In some cases this is reasonably easy; for example, one can safely assume that the pristine baseline state for PCBs in mussels is going to be zero (Sheppard, 1995). In most cases, however, it is very difficult to establish a robust proxy baseline without some historical information, although extrapolation from laboratory studies, modelling and expert assessment can play an important role.

## Moving targets – the challenge of dynamic ecosystems

The management approach so far described, comparing static indicators against pre-determined standards, is implicitly dependent on the assumption of relative constancy in the marine environment. This assumption of a constant background is scientifically tenuous (Southward, 1980; Scheffer et al., 2001) and becomes completely invalid when one or more of the dominant factors forcing the system begins to shift systematically rather than simply varying around a mean value.

Although biological systems may appear to exist in a steady state over short periods, they are dynamic in nature, with many changes only evident over longer time scales (e.g. sardine-anchovy or sardine-herring oscillations; Southward et al., 1988; Baumgartner et al., 1992; Alheit and Hagen, 1997; Schwartzlose et al., 1999). Errors are introduced when assumptions are made that, for example, habitats and species distributions do not vary through time (Pearson & Dawson, 2003; Parmesan et al., 2005). Some changes are oscillatory in nature, while others can be systematic. Quasi-decadal fluctuations in the biology of the ocean have been observed for many years and the influence of the North Atlantic Oscillation (NAO) on the ecology of European waters has been well documented. Synchronous changes in plankton and benthos, for example, were observed in long-term data throughout the North Sea as changes in the inflow of Atlantic water occurred between the 1970s and 1980s (Buchanan, 1993; Evans and Edwards, 1993; Josefson et al., 1993). However in recent years such decadal patterns have been overridden by a systematic increase in global oceanic temperatures and these have been accompanied by well documented changes in species distributions world-wide (e.g. Beaugrand et al., 2002; Walther et al., 2002; Parmesan and Yohe, 2003; Mieszkowska et al., in press).

Current trends suggest that $CO_2$ emissions could easily be 50% higher by 2030. Already 48% of anthropogenic $CO_2$ has been taken up by the oceans (Sabine et al., 2004). Consequently the oceans act as a buffer for atmospheric $CO_2$ concentrations. Given that atmospheric $CO_2$ causes global warming and climate change there are observed and predicted ramifications for the marine system: warming, increased stratification and changes to weather induced mixing, circulation and freshwater inputs. Temperature is a fundamental variable that controls the composition of marine assemblages and the biology of their constituent species. As the climate warms, species close to their range edges are likely to shift their distribution polewards;

increasing in abundance at present poleward, near-range edge locations while decreasing close to equatorward range edges. As the distributions of species change, so the community composition of individual sites will be altered.

Additionally while $CO_2$ is relatively inert in the atmosphere, when dissolved in seawater it becomes highly reactive and induces ocean acidification. It is predicted that the continued release of fossil fuel $CO_2$ could lead to a reduction in surface ocean pH of up to 0.4 units by the end of the century. This will affect many biogeochemical processes in potentially complex ways. Both positive and negative feedback mechanisms exist, making the prediction of the consequences of changing $CO_2$ levels difficult. Integrating the net effect of these processes on regional and basin scales is an outstanding challenge for the marine research community, however it is expected that the physiology of many species will be adversely affected, particularly those with calcareous structures (e.g. hard corals, calcifying phytoplankton, some molluscs, echinoderms and crustaceans). Sites designated as being of nature conservation importance may well loose their most important features and changes observed in indicators designed to detect direct anthropogenic impacts may actually reflect changes in marine climate. Established baselines will no longer represent the ecosystem in the region to which they are being applied.

If adaptive ecosystem management is to be implemented, these fluctuations and systematic changes must be taken account of when evaluating ecosystem status in relation to other anthropogenic impacts. Dynamic baselines are needed which reflect both the full range of natural variability and the ecological feasibility of reference conditions; the impacts of increased temperature and reduced pH may create a substantially different ecological niche in a region to that which currently exists (see example box 1).

[Example box 1: MarClim dynamic baseline]

**Understanding change: The case for long-term time series**

The FAO (1999) guidelines on indicators state that their fluctuation should reveal key elements of a system, while the position and trend of indicators in relation to reference points or values should indicate the present state and dynamics of the system. Therefore, to develop adequate indicators and baselines, extensive data representing the long-term behaviour of key elements of the system are required.

Long-term data sets are rare but give a unique and invaluable perspective on environmental change. In recent years, data from the Continuous Plankton Recorder (CPR) survey, which extend back to the 1930s, have provided much evidence of broad scale changes in the distribution of planktonic communities that relate closely to changes in sea temperatures (e.g. Beaugrand et al., 2002; Richardson and Schoeman, 2004). Similarly, data from the rocky intertidal, which also span over 50 years (e.g. Southward et al., 2004), have been used to show the way in which crustaceans and molluscs on the seashore have reacted to increased temperatures by expanding their ranges (Herbert et al., 2003; Mieszowska et al., in press). In both cases, it is the spatial and temporal extent of the observations, coupled to the strictly comparable methods of data collection, that have allowed the separation of trends from the noise of natural variability, making it possible to clearly identify the impacts of a changing climate.

Such long-term time series are clearly of utmost importance and are generally relatively inexpensive to maintain, so it is strange that they are constantly under threat from a lack of commitment to sustained funding. This can partly be explained because often the purposes they were started for have long since been concluded. For example, the benthos in Tees Bay, on the east coast of the UK, was monitored twice a year between 1973 and 1996 using a comprehensive sampling design tailored to detect spatial changes related to activities of the chemical industry in the Tees Estuary. The intention was not to track changes through time, but over the years a valuable standardised time series emerged. Analyses of the dataset as a whole (Warwick et al., 2002) showed major changes in the benthic community associated with a change in the North Sea ecosystem which occurred in the mid-to-late 1980s, of sufficient magnitude to have been termed a "regime shift" (Reid et al., 2001; Reid and Edwards, in press). Although the time series was clearly developing a value greatly exceeding its original purpose, sampling in the bay was terminated in 1996 following perceived improvements in the estuary, and in the estuary itself in 1999 following major changes in the organisation funding the work. Similar stories have been reported around the UK (e.g. time series in the English Channel documented by Southward et al., 2004) and the situation may soon be repeated on the Isle of Man, with closure of the Port Erin Marine Laboratory, ending over 100 years of uninterrupted time series measurements there.

In the UK, the Department for Environment, Food and Rural Affairs (Defra) has recently funded (from 2002) a pilot project to establish a network of long-term marine time series (Marine Environmental Change Network, MECN – see http://www.mecn.org.uk for details). This network provides information on long-term changes in marine ecosystems around the British Isles in order to provide understanding and context for the interpretation of changes identified from compliance monitoring. To provide this understanding, the long-term time series in MECN aim to monitor key components of marine ecosystems for which historical records exist (e.g. temperature, salinity, nutrients, benthos, zooplankton and phytoplankton communities). Comparison of these data across the network can show whether changes are due to broad-scale or local effects. This understanding can then improve interpretation of measurements taken from sites established for compliance monitoring purposes, by placing them within the context of wider scale changes.

Time series which measure fundamental properties of marine ecosystems continue to address issues that were not envisaged when they were initiated, such as climate change. One way they can be used adaptively is to calculate indices for novel indicators retrospectively. For example, a useful indicator of warming in the North Sea is the ratio of occurrence of the warm-temperate copepod *Calanus helgolandicus* to the cold-temperate copepod *C. finmarchicus* in the CPR survey, so this index was been back-calculated to 1958 to show changes over a prolonged period (see fig. 2; Edwards et al., 2005). These adaptive indicators can only be calculated if historical data series are fully funded, rigidly standardised through time and adequately maintained over the long-term.

[Insert Fig. 2 about here]

There are relatively few multi-decadal time series globally and it is essential that these are sustained if we are to understand current variability. They are an invaluable resource both for current management and for providing answers to future issues. Sustained observations also allow new problems or questions to be identified, so can help to focus management activities. Termination of an established long-term time series should only be considered after extensively reviewing whether it is likely to provide any useful information in the future. It must not be forgotten that there are many examples of long-term time series allowing questions to be addressed which could not have been formulated when the series were begun.

**Modern management tools for extrapolation and integration of monitoring**

Clearly, long-term data do not exist for all components of all ecosystems, so knowledge-based extrapolation and integration are essential for providing meaningful, dynamic baselines and for the interpretation of indicators. Spatial extrapolation requires knowledge of the spatial extent of different ecosystems and how representative individual sampling locations are for the whole. This information can be provided by comparing detailed information from point locations with coarser resolution data from repeat surveys covering broad spatial scales, such as satellite remote sensing and the CPR survey (probably the longest running large-scale marine biological survey in the world, see http://www.sahfos.org). Integration of individual point samples can also provide a level of spatial understanding. One example is the HadISST data set produced by the UK Met Office's Hadley Centre from voluntary merchant ship sea surface temperature measurements combined with satellite measurements. This data set provides SST data globally at 1° spatial resolution from 1870 to present (see http://badc.nerc.ac.uk/data/hadisst/). Networks of data collectors, such as the MECN, also allow for integration. The EU-funded network-of-excellence in Marine Biodiversity and Ecosystem Functioning (MarBEF) is bringing together data holders and researchers from across the European Union (http://www.marbef.org) with an aim of addressing long-term, large-scale changes in marine ecosystems.

In the absence of limitless resources for sampling the real world, statistical and numerical modelling techniques are essential tools for extrapolation in space and time. Recent developments in complex 3-D coupled ecosystem circulation models mean they can be used to fill knowledge gaps using the full range of available information. Shelf-seas marine ecosystem models are developing rapidly to the point that some are currently being run in nowcast and forecast mode. For example, pre-operational, 7-day hindcasts of the NW European Shelf ecosystem (http://www.metoffice.gov.uk/research/ncof/mrcs/browser.html) with coupling to ocean and meteorological forecast models are currently being evaluated to assess the forecast potential of such systems within the National Centre for Ocean Forecasting (NCOF), a new initiative with the role of further developing all aspects of ocean forecasting for the UK as part of the national infrastructure (http://www.ncof.gov.uk).

[Example box 2: Modelling of indicators in MERSEA]

The current generation of ecosystem models do not incorporate the full wealth of complexity associated with, for example, species' distributions or community interactions. Neither do models reduce the requirement for adequate monitoring. On the contrary, they rely heavily on data for parameterization, assimilation and validation. Their utility lies in their ability to provide a more complete picture, extrapolating from existing data to fill in the gaps where data collection is currently unfeasible, including the past and the future. This extrapolation is essential for calculating dynamic baselines.

**Recommendations**

In recent years, European environmental management systems have undergone substantial adaptation to the demands of changing policy targets. These now need to become adaptive to, and predictive of, systematic changes in environmental forcing and knock-on effects for ecosystems. To achieve this, effective, integrated monitoring is needed. By combining the approaches described in this article (adaptive indicators and dynamic baselines from long-term, ecosystem based monitoring; extrapolation and integration from modelling and remote sensing), we propose a diagnostic approach to ecosystem-based management and environmental monitoring which moves beyond just detecting change towards an understanding of its causes and wider impacts, thereby providing a diagnosis of the long-term health of ecosystems.

Indicators are essential tools for adaptive management, but the indicators required will change over time, whereas the fundamental building blocks of marine ecosystems stay the same. Multi-decadal time series observations of key ecosystem components and pathways, together with forcing processes, provide the basis for many of the indicators required and can be repackaged into new indicators to answer new questions when they arise. This ensures a continuity of methodology for the observations, so novel indicators required to solve future problems can be calculated retrospectively. These long-term data are also needed to create dynamic baselines, representing the range of natural variability within a changing climate. They need to be maintained in a variety of locations, representative of different marine ecosystems, to provide geographical context and to allow the separation of local perturbations from broad scale trends.

In summary, we recommend the following:

- State indicators need to be supplemented by indicators of forcing and need to be adaptive but based on consistent, long-term monitoring of key ecosystem components and pathways.
- Mobile baselines are needed which reflect what can be expected as a realistic environmental baseline under different climatic conditions.
- Extrapolation and integration tools, such as remote sensing and modelling, should be used more widely for ecosystem-based management.

- Long-term data series are invaluable for providing understanding of natural variability and systematic change and are essential for developing the above management tools so need sustained, adequate funding over the long term.

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**Example box 1 text: MarClim Dynamic Baseline**

The MarClim project has been using long-term records of intertidal organisms to develop indicators of climate change. Results from MarClim have shown that by sampling multiple sites within a coastal region and having a network of sites spread across a wide geographical area, it is possible to:

1. separate inter-annual fluctuations from longer term environmental changes;
2. distinguish between local noise versus a larger-scale fluctuating baseline;
3. determine over which timescales significant changes in population structures and distributions are occurring.

[Insert Figure 1 about here]

Addressing these questions is essential for the establishment of dynamic baselines. Figure 1a shows intertidal historical and resurvey sites sampled by MarClim. The data from these sites allows detection of changes in range and abundance of intertidal organisms, such as *Gibbula umbilicalis*, a southern species which has extended its range by over 50km in the last two and a half decades (Fig. 1b), in line with rising winter sea temperatures (Mieszkowska et al., in press). Such large range extensions suggest that a shift is occurring in the baseline intertidal community for this coast that will have to be taken account of by future management plans.

**Example box 2 text: Modelling of indicators in MERSEA**

MERSEA-S1 was an EC funded program to evaluate the current status of marine forecast systems for Global Monitoring for Environment and Security (GMES). Within this program, the high resolution POLCOMS-ERSEM coupled hydrodynamic-ecosystem model (Holt et al., 2004; Allen et al., 2001) was evaluated in hindcast mode for 1988-89. This period was chosen because it coincides with the period of the NERC North Sea project enabling us to make a comprehensive validation of the model and to use the simulations to derive useful policy related data products. The model domain used closely matches with the area of comprehensive review chosen by OSPAR. Figure 3 shows a headline indicator traffic light plot derived from model output. The advantage of the model is that we can extrapolate between observations and, in principle, make seasonal forecasts.

[Insert Figure 3 about here]

An important aspect of modeled data is that it allows an expert user to infer from it aspects of the system that the model is not able to simulate directly. In the same way that a weather forecaster takes information about pressure and moisture fields from a numerical weather prediction model to infer what the weather will be, a marine environmental forecaster may be able to take information from a numerical ecosystem prediction model to predict aspects of the ecosystem not directly simulated. For example, we know that Harmful Algal Bloom (HAB) events often coincide with distorted nitrate:phosphate ratios and low turbulence, and that toxin production often occurs when the phytoplankton are nutrient stressed. Currently we cannot make species specific simulations of HABs but we can simulate the aforementioned indicators. In principle, we can combine information from hydrodynamic and ecosystem models to provide probability based 'risk' maps of HAB occurence.

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**Figure Captions**

Figure 1. a) Map showing intertidal sampling locations from 1977-1985, resurveyed from 2002-2004 as part of the MarClim project; b) Inset map showing the range extension of the southern trochid *Gibbula umbilicalis* in Scotland (black line) between these periods, a distance of over 50km from Skerray on the left to Fresgoe on the right.

Figure 2. The abundance of Calanus populations in the North Sea from 1960 to 2003. The percent ratio of *Calanus finmarchicus* (blue) and *Calanus helgolandicus* (red) are shown in relation to total Calanus abundance in each annual bar.

Figure 3. Modelled nitrate:phosphate (N:P) ratio in relation to OSPAR water quality criteria.

**Figures**

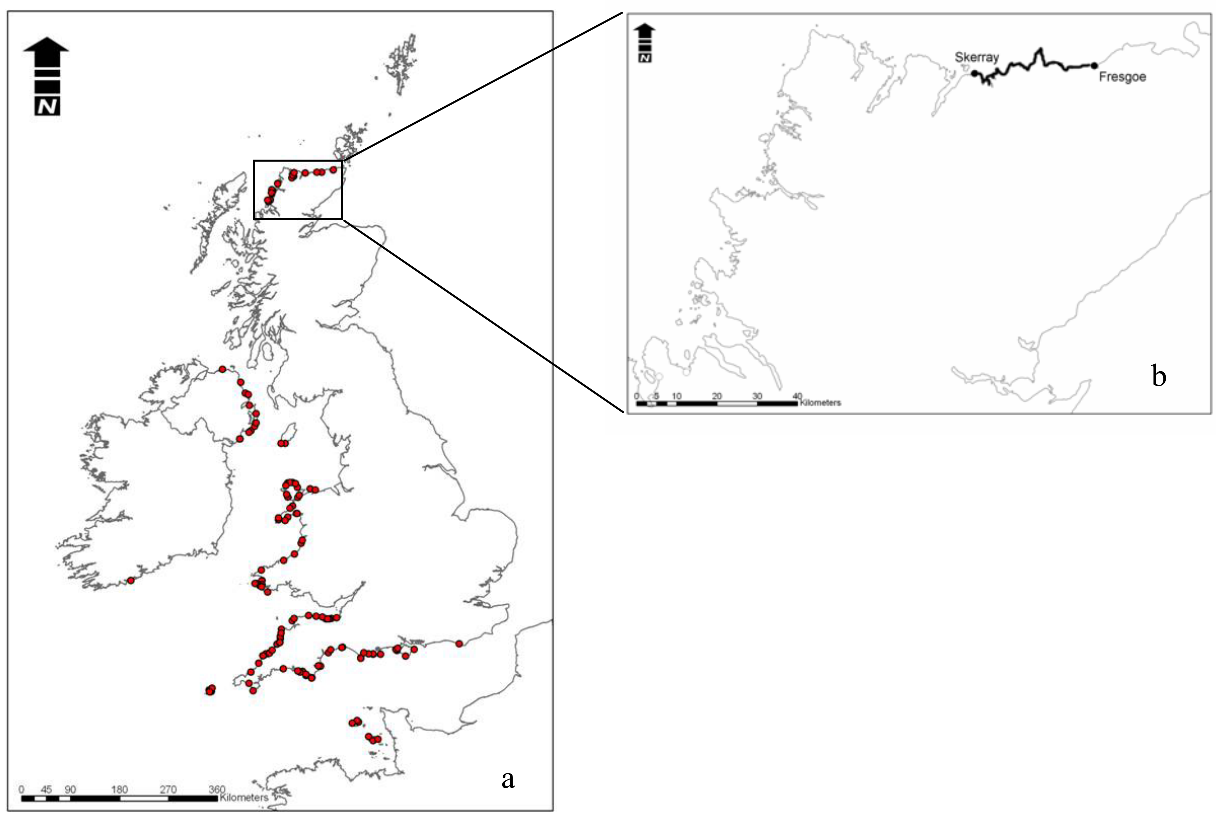
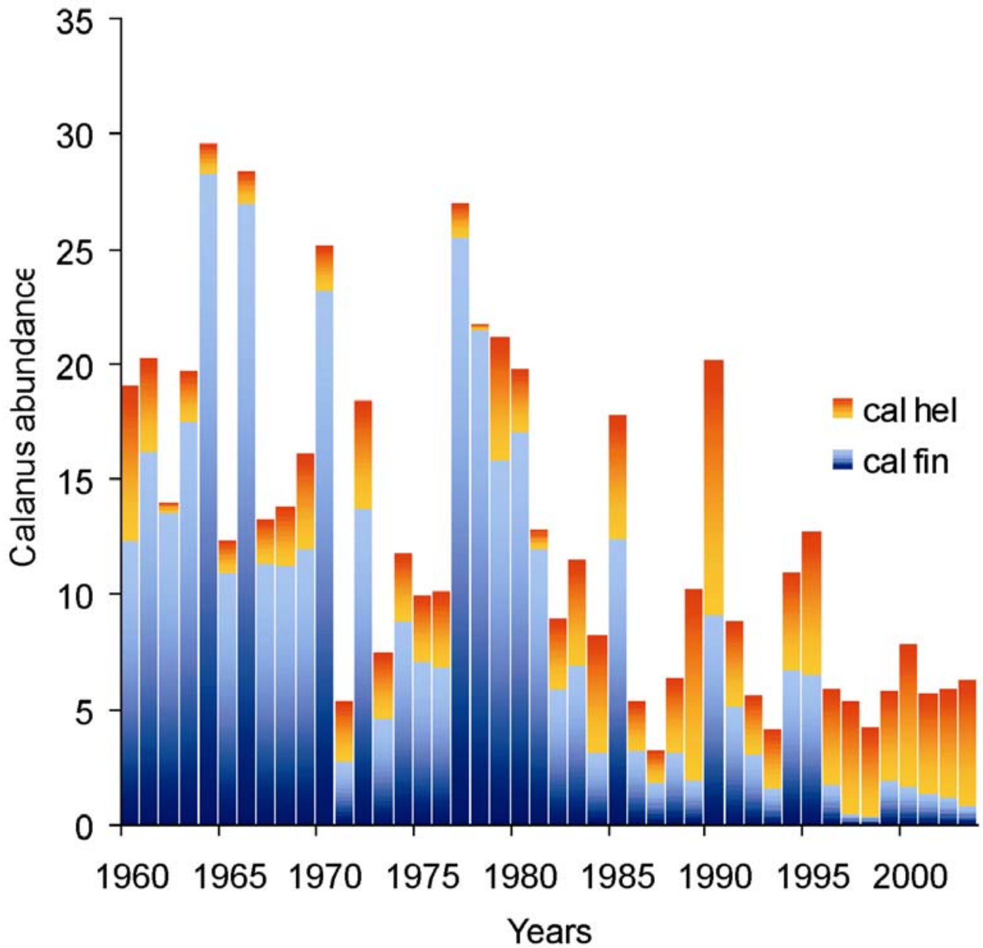



Figure 1



35
30
25
20
15
10
5
0
Calanus abundance
cal hel
cal fin
1960
1965
1970
1975
1980
1985
1990
1995
2000
Years


Figure 2.

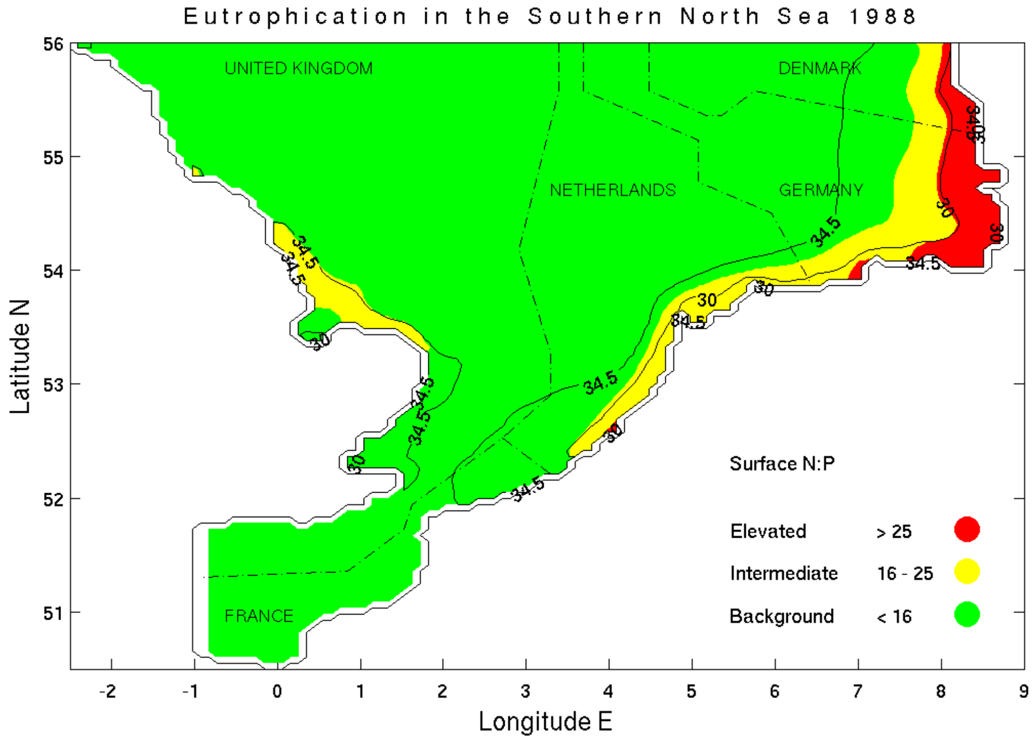

Eutrophication in the Southern North Sea 1988
UNITED KINGDOM
DENMARK
NETHERLANDS
GERMANY
FRANCE
Surface N:P
Elevated > 25
Intermediate 16 - 25
Background < 16
Latitude N
Longitude E

Figure 3