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Indications of Change in the Marine Flora of the North Sea in the 1990s

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This paper gives an up-date of the scientific knowledge of changes that occurred in the flora of the North Sea since the Quality Status Report of the North Sea was published in 1994, and the Dobris Assessment (Europe's Environment) was published in 1995. It shows that, as an epi-continental semi-enclosed marine ecosystem, the North Sea conditions create complex interactions between the flora and the marine environment. Plankton distribution and succession are considered in the light of recent research, with a focus on ecosystem modelling. Changes in macrophyte biodiversity are reviewed in connection with pollution. Symptoms of eutrophication are believed to be responses to increases in primary production. Community changes in plankton, seaweeds, and eelgrass also influence lower and higher levels in the food web. The possible effects of predicted climate changes on the flora of the North Sea are investigated. The review demonstrates that, in the future, potential changes could affect the flora in relation to changes in solar radiation and temperature. Finally, attention is paid to crucial needs in related research, education, and conservation of species and habitats. © 1999 Elsevier Science Ltd. All rights reserved

Conditions in the North Sea are characterised by a high degree of variability, both spatially and temporally. This variability in environmental conditions and processes has a strong influence on biological systems, which in turn may affect the marine ecosystem. Due to international commitment to reduce the negative effects of certain human activities, it is important to understand how such a complex system reacts to measures taken. There is now a large body of information on the ecology of the North Sea, but it remains essential that certain gaps in knowledge be identified in view of better management. This paper attempts to review changes in the distribution and abundance of marine macrophytes (excluding salt-marsh plants) in the last few decades, known causes for observed changes and changes in the knowledge of the ecology of the plants

in the North Sea. The present review mainly concentrates on the period 1993–1998, building on the 1993 Quality Status Report (QSR) which was published in 1994 (NSTF, 1994) and the Dobris Assessment (Europe's Environment) which was published in 1995 (Ducrotoy, 1995).

The Context of the North Sea

Geographically, the North Sea was defined by the North Sea Task Force as including the English Channel, the Scandinavian straits (the Skagerrak and the Kattegat) and the northern North Sea south of 62°N (NSTF, 1994). The North Sea is a large epi-continental sea (750 000 km²) of the north-east Atlantic. It consists of a shallow (mean-depth of 90 m) semi-enclosed coastal marine ecosystem situated in north-west Europe. The Southern Bight is relatively shallow, with strong tidal currents; the depth increases progressively towards the North where the basin largely opens to the Atlantic Ocean. Its greatest depth is found in the Norwegian Trench (about 725 m) off the south coast of Norway.

The North Sea is one of the few major marine ecosystems to have been formed by a recent flooding of a landmass, which took place 20 000 years ago. From a bio-geographical point of view, it is therefore a rather young ecosystem. Particularly the western coasts are still being colonised by in-coming species through the Dover Strait and around Scotland. The coastal zones contain a variety of rocky shores, sandy beaches, estuaries, and fjords with a diversity of fauna and flora. There is a complex interaction between algal abundance and productivity, nutrients, light availability and the degree of mixing in the water column. This interaction and its natural variability play an essential rôle in the geographic heterogeneity of phytoplankton and seaweeds distribution in the North Sea. Land-based inputs from human habitations (164 million people in the catchment area), industries and agriculture also influence the distribution and survival of organisms. Offshore oil and gas production and intense shipping add to those activities an associated risk of accidents.

Plankton

Plankton distribution and succession

The Continuous Plankton Recorder (CPR, 1992) survey provides a unique data set on the abundance of plankton in the North Sea and North Atlantic. The CPR is a sampling tool, which filters and traps plankton between two constantly winding lengths of 280 μm mesh silk. Maps of the tows made and details of the species identified since 1931 to the present are documented in Warner and Hays (1994). CPRs equipped with a suite of sensors were towed by merchant vessels in the North Sea in the 1980s and 1990s, recording a range of environmental variables. Correlations were found between the biota and the environmental variables. The tidal front off the north-east coast of the UK and the front between the low salinity water in the Kattegat and the higher salinity water in the Skagerrak were dominant factors correlating with the distribution of the plankton assemblages. Discontinuities, defining the positions of the fronts, in the values of physical variables (temperature and, where measured, salinity and turbidity) were closely identified with geographical divisions between plankton assemblages. Measures of irradiance were found important on several occasions, presumably due to diel migrations of the zooplankton (Lindley and William, 1994).

Plankton and nutrients

In general terms, the main natural source of nutrients to the North Sea is from the Atlantic Ocean, from European rivers and from atmospheric origin. The main rivers loading the surface waters in the south-eastern North Sea account for a major part of the riverine inputs of nutrients. The QSR mentioned that, for instance, about 50% of the total nitrogen load comes from the Rhine and Meuse together (NSTF, 1994).

In 1989–1992, the German Federal Maritime and Hydrographic Agency (BSH) carried out surveys of major physical and chemical parameters in the German Bight in connection with the TUVAS (Transport, transfer and variability of contaminants and nutrients in the German Bight) project. During roughly the same period, the interdisciplinary research project PRISMA (Processes influencing contaminant fluxes in the North Sea) performed continuous measurements of atmospheric nutrient and contaminant deposition and numerical experiments with atmospheric, hydrodynamic and ecosystem models. Results from both projects, together with available information on river loads and data from the literature on sediment fluxes made it possible to construct nitrogen budgets for the German Bight during the period of the TUVAS surveys. Comparing the mean annual input fluxes, the major nitrogen flux into the water of the German Bight was from rivers (around 70%) The atmospheric contribution was around 30%. (Beddig et al., 1997).

As part of the MAST I-Flux Manche initiative, a sampling programme was carried out in the Dover Strait in 1990–1991. Results demonstrated that although nutrient concentrations were lower in the central English Channel waters than in the coastal zone, the dissolved nutrient flux to the North Sea was more important for stations of the central part of the Dover Strait. Long term investigations did not show a more important increase than inter-annual variability did ($+0.85$ μmol l^{-1} N–NO_2 + NO_3, $+0.1$ μmol l^{-1} P–PO_4, $+1.1$ μmol l^{-1} Si from 1979–1980 to 1990–1991) (Bentley et al., 1993; Laane et al., 1993). As a consequence of strong hydrodynamic conditions and currents in the English Channel, the planktonic biomass showed a maximum of only 8 mg C m^{-3} h^{-1} (Lefevre-Lehoerff et al., 1993).

The ecosystem model ERSEM (European Regional Seas Ecosystem Model) was established to simulate the biogeochemical seasonal cycling of carbon, nitrogen, phosphorous and silicon in the whole of the North Sea. The model gave good correlations with the main dissolved nutrients, such as silicate, phosphate, or nitrate (Varela et al., 1995). Both for the phosphorous and for the nitrogen budget, the nutrient uptake by phytoplankton was the dominant flux taking place. The southern North Sea had the highest ecological activity, in the nutrient uptake as well as in the pelagic and benthic remineralisation (Lenhart et al., 1997). From the coastal areas, there was a nutrient flow towards the central North Sea, enhancing the growth of plankton in the central areas (Radach and Lenhart, 1995). For this reason, the ecology of the Dogger Bank, a shallow area in the central southern North Sea, is different from other regions in the North Sea; phytoplankton production occurs there throughout the year (Kronk and Knust, 1995).

The ERSEM model further showed that the flagellate/ diatom interaction and competitive behaviour for inorganic nutrients were also important concerning grazing losses (Varela et al., 1995). The effects of nitrogen and phosphorus discharges were documented but it is only recently that studies have paid attention to the role of silicates in causing changes in the plankton composition. A combination of phosphate increase and silicate decrease was shown to lead to a shift in composition of functional groups with decreasing diatom biomass and increasing flagellate biomass. These results suggest that the indirect effect of silicate reduction in coastal waters favours strong flagellate bloom because of higher availability of river borne nutrient loads (Dippner, 1998).

Seaweeds and Sea Grasses

Disappearance of vegetation

Several types of plants have apparently disappeared from parts of the North Sea coast in the last few decades and this has been documented in various scientific reports, in addition to the QSR (NSTF, 1994). The QSR

mentioned that red macroalgae disappeared from the tidal creeks of the northern German Wadden Sea progressively up to the 1980s but knowledge on the distribution, abundance, and species richness of intertidal macroalgae occurring on sandy and muddy flats of the German Wadden Sea is still incomplete. At Konigshafen Bay (island of Sylt), one of the more extensively studied areas of the Wadden Sea, a total of 46 green algal species, 36 brown algal species and 26 red algal species have now been recorded within the last 120 years on soft and hard substrata. Significant long-term changes in species abundances have occurred in all three major groups of algae: a general decrease of brown and red algae was documented. Two red algal species, *Gracilaria verrucosa* and its epiphyte *Callithamnion corymbosum*, were conspicuous members of the macroflora until the middle of this century. Although present in the 1980s, they have now disappeared completely (Schories *et al.*, 1997).

The toxic algal bloom in the Skagerrak and Kattegat of *Chrysochromulina polylepis* in May–June 1988 resulted in direct drastic effects from the surface and down to at least 15 m on both soft-bottom and hard-bottom organisms. In particular, seaweeds were affected by the bloom. Tissues of several red brown and green algae were bleached due to inhibition of the chlorophyll and the effect was still visible after 2–3 months (Pedersen *et al.*, 1992).

Sea-grass was reduced drastically in the 1930s by the so-called 'wasting disease' (Den Hartog, 1987) and was unable to re-colonise the subtidal regions of the Wadden Sea (Nienhuis, 1996). De Jonge *et al.* (1996) showed that, in the past, *Zostera marina* covered a sublittoral area of 65–150 km² and a eulittoral area of unknown size in the western Dutch Wadden Sea. In the 1960s, it also declined in other areas such as the Danish coast and the coast of Brittany (France) The causes for the decline may be a change in velocity of currents, the effect of cockle and mussel fisheries and competition by green algae (Den Hartog, 1994). Together with the disappearance of the subtidal vegetation, the associated animals (snails, shrimps, and pilefish) disappeared (Reise *et al.*, 1989).

Pollution

In order to evaluate the influence of geographically varying marine ecosystem properties on the uptake of various contaminants in *Fucus vesiculosus* along the North Sea and Baltic Sea coasts several scientists carried out measurements in the mid 1990s. Jayasekera and Rossbach (1996) measured concentrations of a wide range of trace elements (arsenic, cadmium, cobalt, chromium, hafnium, nickel, thorium, uranium, zinc, and the rare earth elements) in the brown alga, *Fucus vesiculosus* from Eckwarder Horne, North Sea and from Rugen, Baltic Sea. Cobalt, chromium and nickel concentrations were highest in *F. vesiculosus* from the North Sea while zinc was highest in samples from the Baltic Sea, reflecting high levels of these elements in coastal

waters of the North Sea and the Baltic Sea. The paper shows that the brown algae used in this study may be used to monitor trace elements in coastal waters but the effect on the seaweed population is not mentioned. Struck *et al.* (1997) measured ecosystem properties such as the geographical position, the salinity, and the concentrations of the macroelements Ca, Fe, K, Mg, Na, P and S in the seaweed. Trace elements studied were As, Cd, Co, Cu, Hg, Mn, Ni, Pb and Zn. Ostapczuk *et al.* (1997), over more than ten years, also determined metal (Hg, As, Se, Cd, Pb, Cu, Na, K, S, P, Zn, Mn, Fe, Sr, Ca, Ba, Mg, Tl, Ni, Co) concentrations in mussels and algae collected in the North Sea and the Baltic Sea. The influence of salinity on the biological uptake of macroelements and trace elements was demonstrated. The three cited studies confirmed modified conditions for the uptake of trace elements in seaweed, in comparison to the uptake of macroelements.

In relation to chemical pollution from sewage and industrial wastes disposal, Hardy *et al.* (1993) showed that brown and red seaweeds have decreased in diversity since the early 1930s in the Tees estuary, and during the past 20 years in the Tyne and Wear estuaries. Other recent studies (Day *et al.*, 1994) have shown a connection between seasonal phytoplankton activity and the generation of atmospheric sulphur products known to contribute towards acid rain. Although anthropogenic sources of sulphur dioxide and sulphate dominate in acid deposition on land surfaces, for some less industrialised areas of Europe, during the summer, there may be a significant contribution from natural marine sources.

Biodiversity

In some regions of the North Sea, it would seem that no changes have taken place in the macroalgal flora. For instance, at Helgoland, the *Laminaria hyperborea* forest and deepest coralline crust occupied the same levels in the 1990s as they did in 1960s (NSTF, 1994). Brown seaweeds would then appear to be less vulnerable to human-induced changes than the reds but it may also be that their diversity is not yet fully understood. Scott and Hardy (1994) observed the occurrence of hybrids between two sympatric species of fucoid algae in the Firth of Clyde (Scotland). They showed that the hybrid forms between *Fucus spiralis* and *Fucus vesiculosus* may be more frequent than recognised earlier. From a study carried out on the Yorkshire Coast, Anderson and Scott (1998) have demonstrated the existence of small geographic scale mosaics of formae of *Fucus spiralis*, which are apparently independent of environmental conditions. Similarly, Mundai and Kremer (1997) studied the rocky eulittoral of Helgoland in the German Bight and its populations of fucoids, *Fucus spiralis*, *Fucus vesiculosus*, and *Fucus serratus*. Several differences from the *Fucus* populations of the North European mainland shores were obvious, regarding both the population structure and form variations within the individual

species. In general, the *Fucus* species do not form distinct belts, but build up mixed populations. At Helgoland, *Fucus vesiculosus* occurred in two morphologically distinct forms; this cannot be attributed to particular habitat conditions. On the average, the fronds of the Helgoland *Fucus* species were longer and significantly narrower than in specimens from other coastal sites of Western Europe. It could be suggested that the observed insular endemism could be related to the recent geological development and geographic position of Helgoland.

Genetic variation was examined by Vanoppen *et al.* (1995) within and among North Atlantic, North Sea and Baltic populations of the benthic red alga *Phycodrys rubens* using allozymes and random amplified polymorphic DNA (RAPD) markers. Along the European coasts, two genetic groups were distinguished by fixed allelic differences: an outer oceanic group and a North Sea/Baltic group.

In the course of the past century, various alien seaweeds have found their way to the North Sea: *Sargassum muticum* and *Undaria pinnatifida* (1973), *Grateloupia doryphora* and *G. filicina* (1990), *Heterosigma akashiwo* (1996). The brown alga *Sargassum muticum* has now begun to colonize mussel beds in Konigshafen Bay as recently presented by Schories *et al.* (1997). In most instances, the introduction of non-native species may increase the biological diversity of the area but native organisms may also be killed by the alien plant. As stressed by Hiscock (1997), it is therefore sensible to prevent the introduction of non-natives.

Increases in numbers

Since the late 1970s, accumulations of drift seaweeds have been mentioned and studied in several coastal areas in the North Sea. Dense green algal mats dominated by *Ulva* spp. were studied by Piriou *et al.* (1991) in Brittany (France). Another well-known example, also cited in the QSR (NSTF, 1994), was studied in England at Langstone Harbour where *Enteromorpha* spp. and *Ulva* spp. growths developed into a nuisance in the 1980s. Large quantities of filamentous green algae (*Enteromorpha flexuosa*, *E. radiata* and *E. prolifera*) have also regularly occurred on muddy and sandy tidal flats in Konigshafen, on the island of Sylt, since 1979, covering the sediments in thick mats during the summer months (Schories *et al.*, 1997). While spores of *Enteromorpha* were encountered in both mud and sand, germling formation was restricted to sand. However, mud snails (*Hydrobia ulvae* Pennant) were overgrown with small *Enteromorpha* filaments in both habitats, about 50% of them at a muddy site and 20% at a sandy one. Filaments, several cm in length and still adhering to the snails, became tangled into clusters. At the sandy site, with abundant *Arenicola marina* L., these clusters slid into the feeding funnels of lugworm burrows (Schories and Reise, 1993).

Filamentous red algae are also mentioned in the literature as posing problems. Lundalv *et al.* (1986) reported that red algae increased in 1971–1976 at 5–10 m depth in the Skagerrak while *Halidrys siliquosa* (brown) declined in 1977. Generally speaking, accumulations of filamentous algae appear to be a local management problem, connected to inorganic nutrients enrichment in simultaneity with specific hydrological and climatic conditions. These aspects will be presented below under the heading eutrophication.

Changes in Productivity

Production

In general, phytoplankton production is not as high in the open North Sea as in the coastal zone. There are, however, a number of recent reports that suggest that the area on and near the Dogger Bank, for example, may exhibit higher primary production and more efficient energy transfer within the food chain than other regions of the open North Sea (Heip *et al.*, 1992). This may be due to the particular features that dominate in this area. In general, well-lit rocky bottoms are often covered by macroalgae whilst poorly lit regions are dominated by sessile macrofauna. Due to difficulty of access, little is known about sublittoral hard substrata productivity of communities dominated by kelps and the associated red algae.

The processes of benthic–pelagic coupling are specific to the shelf sea environment and work together to make the North Sea very productive. The production of organic compounds from inorganic sea water constituents is brought about by the photosynthetic activity of marine plants using energy derived from sunlight. Most of these organic compounds are incorporated as plant tissue, which is of major importance as the primary source of food for animals. The minimum light intensity for photosynthesis is about 1% of irradiation at the sea surface. Such intensity occurs down to 30 m water depth in the clear waters of the central North Sea, but not deeper than 10–15 m in the less transparent coastal waters. As most parts of the North Sea benthos lie deeper, phytobenthos (macroalgae, sea-grasses and microphytobenthos) contributes only little to the primary production of the North Sea (NSTF, 1994). Therefore, the majority of the primary production in the North Sea is performed by the phytoplankton although large marine algae growing in the shallows contribute. It should be noted, however, that the flow of energy to the highest trophic levels could be more or less efficient within the food chains depending largely on the composition of the plankton community present.

Estimates of the production at all levels of the marine food chains are imprecise because of difficulties with methods and definitions and because of variability between areas and seasons. There have been no surveys to estimate primary production for the whole North Sea over an annual cycle, although the area south of 55°30′

N was covered recently. The average annual primary production of the North Sea is probably in the range 150–250 g C m^{-2} yr^{-1}. In the coastal areas, the annual production can reach values of 300–400 g C m^{-2} yr^{-1} (Cadée, 1992; Joint and Pomroy, 1993). However, the phytoplankton biomass and production off the north-east English coast is clearly much less than in the central regions (ca 79 g C m^{-2} yr^{-1}), but the reasons are not clear (Joint, 1997).

Eutrophication

A general increase in nutrient discharges during the last few decades has caused various changes in the algal community structure along the European continental coasts. At the same time, the food web structure, and functioning has changed in local areas. Eutrophication will therefore be understood here as the process of increasing concentration and load of nutrients, inducing communities changes. Notably, unusual phytoplanktonic blooms have aroused public concern. This concern can be caused by water discoloration (e.g. *Noctiluca* spp.), foam production (e.g. *Phaeosystis* spp.), fish or invertebrate mortality (e.g. *Chrychromulina* spp., *Gyrodinium* spp.) or toxicity to humans (e.g. *Alexandrium* spp., *Dinophysis* spp.) in the form of paralytic and diarrheic shellfish poisoning (PSP and DSP). Those changes have recently been interpreted in relation to key mechanisms such as resource competition and selective grazing of phytoplankton and phytobenthos (Riegman, 1995). Diatoms are particularly affected by nutrient enrichment. Primary production of phytobenthos in the Dutch Wadden Sea increased dramatically in relation to nutrient concentration increase (Cadee, 1984) with a positive effect on the zoobenthos productivity and some commercial fish species (Beukema. and Cadee, 1986).

Along the Dutch coastal zone of the North Sea eutrophication has caused a doubling of the yearly averaged algal biomass during the past three decades (Cadee, 1992). The sudden appearance of *Phaeocystis* spp. summer blooms coincided with a shift from P-limitation towards N-limitation in the Dutch coastal area due to a stronger increase in P-discharge relative to the increase in N-discharge. Competition experiments in continuous cultures showed *Phaeocystis* spp. to becoming dominant under N-limitation. Additionally, the large *Phaeocystis* spp. colonies, which can reach a diameter up to one centimetre, escaped from microzooplankton grazing. A shift from bottom-up towards top-down control in the Dutch coastal zone was further demonstrated to take place by Riegman (1995) when the pelagic environment became eutrophicated. Implementation of this concept in a size-differential phytoplankton control model generated the prediction that algal blooms are dominated by species that escape from grazing by those zooplankton species which have a high potential numerical response, i.e. microzooplankton species. These organisms mainly feed on cyanobacteria,

prochlorophytes and some nano-algal species. One of the consequences for food web structure and the carbon fluxes in marine food webs is that eutrophication will lead to the dominance of poorly edible algal species (Davies *et al.*, 1992). Eutrophication favours the downward transport of carbon and nutrients towards the sediments not only due to higher algal biomasses but also as a consequence of a shift towards larger algal species with higher sedimentation characteristics (Riegman, 1995). Deposition areas, not only at the coast are under the direct influence of eutrophication but, against prevailing opinions, the Dogger Bank, an offshore region, seems also to be affected by eutrophication and pollution (Kronk and Knust, 1995).

In recent years, symptoms of eutrophication in the form of increased frequency and intensity of oxygen depletion events in bottom waters and unusual algal blooms have been observed notably in the Kattegat. In general, such symptoms are believed to be responses to increases in primary production and the evidence was examined by Richardson and Heilmann (1995) by comparing primary production measurements from the 1950s and measurements made in the period 1984–1993 in the Kattegat. They concluded that primary production did increase from less than 100 g C m^{-2} yr^{-1} to about 200 g C m^{-2} yr^{-1} since the 1950s to the 1990s. This increase was observable from the spring bloom and throughout the summer period when nutrients were predicted to be limiting for primary production. They further showed that the primary production values recorded in the 1950s and in the period 1984–1993 were related to nitrogen loading in the two periods (Richardson and Heilmann, 1995).

Eutrophication-related macrophyte accumulations, especially filamentous seaweeds were described earlier in this paper. Increased occurrence is known to take place in Brittany (France), in some estuaries (for instance Langstone Harbour) and in the north-eastern North Sea. Roughly 50 000 tons are removed each year from North Sea beaches (NSTF, 1994). The distribution and cover density of macroalgae (Chlorophyta, Ulvaceae) were estimated by means of aerial surveys in 1990–1992 in the Wadden Sea off Niedersachsen on the German coast. Each year, up to a maximum of 15% of the total area was covered by algae. In some subregions the macroalgal carpets covered from 30% up to 60% of the tidal flats. The cover density was at its peak in 1990 (Kolbe *et al.*, 1995). A general shift from long-lived macrophytes (kelp, wrack, eelgrass) to short-lived nuisance algal species was demonstrated in the QSR to have taken place at various sites on the North Sea coasts (NSTF, 1994). It is assumed that the observed macroalgal blooms have to be regarded as a response to eutrophication, and will presumably remain a chronic problem for many years to come (Kolbe *et al.*, 1995). Oxygen depletion is one of the consequences through the decomposition of the algal biomass in excess, with possible resulting benthos and fish kills. The Oslo and

Paris Commission has published maps of the most badly affected areas in the North Sea.

In a review, Reise *et al.* (1989) summarised a number of possible causes for the changes in eelgrass distribution and abundance in the Wadden Sea. Some of the more recent declines have been linked to nutrient enrichment, which has caused decreased transparency and massive epiphytal growth. It was furthermore suggested that declines in *Zostera marina* coincided with a run of warm summers and mild winters. The authors concluded that the pattern of changes in eelgrass distribution and abundance is complex and that no conclusive interpretation can yet be offered.

Community Changes

The boundary between terrestrial and marine ecosystems is inhabited by communities which are influenced by the sea only when very high tides or high onshore winds occur. Therefore, intertidal rocky shore communities include a restricted variety of species, except on the lower shore and show a marked zonation in relation to the degree of tidal immersion. Salt marshes are found in the upper reaches of sheltered intertidal areas. They display rich and often unique populations of marine plants but they are not considered in the present paper.

Communities vary both in time and space. Recently, Tobin (1997) adopted an interesting approach to rocky shore vegetation. Rocky intertidal shores exhibit a mosaic of habitats with patchiness at a range of spatial scales. With a view to understanding how changes may take place over time, she suggested the use of functional groups (Dayton, 1975; Steneck and Dethier, 1994). Preliminary work showed that patch dynamic could be better understood in relation to environmental factors and competition (Ducrotoy and Pickaert, in preparation).

Albrecht and Reise (1994) investigated the patchy growth of *Fucus vesiculosus* forma mytili (Nienburg) and its influence on mussel (*Mytilus edulis*) beds in the intertidal Wadden Sea. They showed that the algae affected mussels and their epibionts negatively, but supported various herbivores and helped to increase overall benthic diversity .The brown alga covered about 70% of mussel bed surface area. On experimental mussel beds, fucoid cover enhanced mud accumulation and decreased mussel density. On natural beds, barnacles (Balanidae), periwinkles (*Littorina littorea*) and crabs (particularly juveniles of *Carcinus maenas*) were significantly less abundant in the presence of fucoids, presumably because most of the mussels were covered with sediment, whereas in the absence of fucoids, epibenthic mussel clumps provided substratum as well as interstitial hiding places. The endobenthic macrofauna showed little difference between covered and uncovered mussel beds. On the other hand, grazing herbivores such as the flat periwinkle *Littorina mariae*, the isopod *Jaera albif-*

rons and the amphipods *Gammarus* spp. were more abundant at equivalent sites with fucoid cover.

From high tide to about 30 m water depth the water column remains fully mixed all year round and live plankton is transported continuously by turbulence from the surface layers to the bottom and back, coming within reach of the benthos. A variety of different benthic communities exists in this zone. The impact of phytoplankton bloom magnitude on the microbial food web of the Dutch pelagic coastal zone (Southern Bight of the North Sea) was studied by Brussaard *et al.* (1996). Light availability and temperature were the key factors for the timing of the diatom spring bloom. Differences in *Phaeocystis* bloom magnitude were, as a consequence of algal cell lysis, reflected in bacterial production (up to 90 μg C l^{-1} d^{-1}; Brussaard *et al.*, 1996) and grazing activity of members of the microbial food web (Billen *et al.*, 1990).

The role played by algae in the deeper North Sea is indirect, in particular in the north-west, in a small area of the "Oceanic Province", where waters are deeper than 700 m (NSTF, 1994). Organic detritus produced by phytoplankton and zooplankton in the surface layers of the oceanic province, if not broken down in the water column, sinks to the deep-sea bottom where mineralisation by deep-sea bacteria and deep-sea fauna takes place. Raaphorst *et al.* (1997) showed that the fate of the plankton and particulate matter arriving at the sea floor is determined by the particle deposition flux, the reworking process in the surficial sediment and either burial in deeper sediment layers or resuspension, showing, there again, the importance of the microbial loop. The resultant carbon dioxide, nutrients, and trace elements are then transported ocean-wide in the deep-water circulation and there is no direct recycling back to the surface of the North Sea. Transfer of energy within the water column is through consumption of phytoplankton by zooplankton and, in turn, planktivorous fish to carnivorous fish. Additionally, bacteria relying on organic matter are consumed by small flagellates, which are fed on by microzooplankton and in turn by larger zooplankton. Defecation and death at all stages in the planktonic food web supply organic detritus to bottom feeders. This organic matter is utilised by bacteria, microfauna, meiofauna and, in turn, macrofauna. Deposit feeders are consumed by predatory worms in the sediment and by predators and scavengers amongst bottom-feeding fish and mobile epifaunal species including crabs, bivalve molluscs and starfish. Large stocks of pelagic copepods only develop in the northern North Sea. They consume the summer production of phytoplankton. This could explain the low biomass of infauna in the northern North Sea.

Possible Future Changes

In this section, the possible effects of predicted climate changes are investigated. Recent experiments

have shown the sensitivity of certain algal species to changes in temperature, the length of the photoperiod or solar radiation intensity. The seasonality of *Delesseria sanguinea, Membranoptera alata,* and *Phycodrys rubens* (Rhodophyta) was studied at Helgoland (Germany) and Roscoff (Brittany, France). Growth and reproduction were monitored. Adequate timing of the history events (e.g. appearance of juveniles in spring) appeared more important than maximal growth and reproduction of adults during the season with the most favourable temperatures (Molenaar and Breeman, 1997).

The influence of varying temperatures on growth and survival of isolates of the cool temperature red alga *Phycodrys rubens* from different latitudes along the NE Atlantic coasts were investigated by Voskoboinikov *et al.* (1996). A slight increase in tolerance to high temperatures appeared to have evolved independently at southern localities in both recognised genetic groups. Tolerance to high temperatures of the northernmost isolates and growth potential at low temperatures of the southernmost isolates were far in excess of temperature extremes experienced in nature. Most isolates had the capacity to grow for most of the year under local temperature regimes. This is in conflict with the marked spring peak in growth reported for the species (Voskoboinikov *et al.*, 1996).

The tolerance of marine macroalgae from the coastal region of Helgoland Island to ultraviolet and visible radiation was studied by Dring *et al.* (1996) and the content of amino acids in the micosporine group by Yakovleva *et al.* (1998). Dring *et al.* (1996) showed that under exposure to UV_A and UV_B radiation for various periods in the laboratory, the rate of the initial decrease was greater. The extent of recovery was less, in deep subtidal species (e.g. *Delesseria sanguinea, Plocamium cartilagineum*) than in intertidal or shallow subtidal species of other red algae. Littoral algae that contained UV-absorbing substances (micosporine-like amino acids), which act as biological screens, exhibited high tolerance to UV radiation, as found in the intertidal. Deep-sea algae exhibited high sensitivity to UV (particularly to UV_B) radiation. Most sublittoral species that did not occur in the drying zone (on the littoral) had no protective pigments. It is supposed that, during their evolution, these species permanently inhabited deep waters or lost their protective mechanisms. The tolerance of macroalgae to UV radiation depended on their age, germinating spores being the most sensitive growth phase (Yakovleva *et al.* 1998).

The microscopic endophytic brown alga *Laminarionema elsbetiae,* recently described from Japan, was found at Helgoland. Its main host there was *Laminaria saccharina.* They were produced in sporangia embedded in the meristoderm tissue of the host (Peters and Ellertsdottir, 1996). It will be of importance to monitor possible effects in the future.

Education, Research and Conservation

With a view to the protection of living organisms, and in particular the flora of the North Sea, sites, algal communities and species are being identified at national level and in the framework of the European Natura 2000 scheme. A structured approach was required in order to identify sites of interest, to manage designated areas and to protect their features of interest. As underlined by Hiscock (1997), management further requires information on the functioning of ecosystems and on their vulnerability. In particular, coastal communities are complex and vulnerable because they lie at the interface between land and sea. The majority of the North Sea is influenced by nearby land and water depths less than 200 m deep. For instance, the importance of run off from land needs to be understood in terms of carbon fluxes, not only because of pollution from human activities, but also because humic substances from land are needed by the plankton (Loicz, 1997). The QSR mentioned specifically the need to develop surveys using the CPR (NSTF, 1994) in order to understand any changes in the species richness and composition of the phytoplankton. That kind of long-term monitoring is also needed for the macrophytobenthos (Ducrotoy, 1997). There has been a shift away from classical botany and collecting towards ecology and genetics and this should influence monitoring and management in the future (Hardy and Scott, 1994). Recently, Lewis (1996) recommended the implementation of a 'geographical limits strategy' on rocky shorelines in order to monitor any possible effects of globally induced changes such as global warming. Without any doubt, seaweeds would be appropriate bio-indicators to evaluate what changes are acceptable and which are not, in the spirit of a recent paper by Elliott and Lawrence (1998) where the authors recommended self-management with accompanying surveillance. Actually, biological monitoring involving human local communities could meet the requirements for the coverage of long stretches of coasts. In the northeast of England, the monitoring of sensitive marine areas will soon involve the participation of local diving clubs, in collaboration with scientists and managers. Concerning pollution, brown algae may, for example, be used to monitor trace elements in coastal waters (Jayasekera and Rossbach, 1996).

The development of international agreements and other instruments since the late 1980s suggests that major changes in approaching the control of marine pollution compared to those of a decade earlier are taking place (Barnston, 1994; Ducrotoy and Elliott, 1997). There is an increasing degree of legislation and protection for species and habitats at global (UNCED, Rio, 1992), international (CITES), regional (OSPAR) and subregional (Wadden Sea Co-operation) levels (Ducrotoy, 1998). The changing approach can be seen in the development of concepts such as the precautionary principle and approach, best available technology, and

environmental restoration. Nevertheless, this issue is a source of procrastination to scientists because scientific findings are often prevented from being correctly translated to management. It is necessary to question what is the basis and rationale in conservation designation and management, and in this way determine the science required. An international approach is required to collect data and produce scientific information and to develop criteria, to identify and map species and habitats and to further consider the development of EcoQOs (Elliott, 1996). Because of their sensitivity to environmental changes, algal species are to be considered more seriously as potential bio-indicators.

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