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Impacts of climate change on nutrient enrichment

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EXECUTIVE SUMMARY

Nutrient enrichment has been identified as one of the major threats to coastal and marine ecosystems, because of potential risks of eutrophication and impacts such as oxygen depletion and blooms of nuisance macro-algae. Demonstrating causal links between disturbances and nutrient enrichment is challenging, and complicated by other pressures. Climate change, for example, may have similar effects on biological communities and biogeochemical cycling of nutrients and oxygen. In the UK, sources and cycling of nutrients are reasonably well understood, but ongoing research is aimed at improving this understanding, and validating and developing models to predict future impacts of climate change. Impacts of climate change on nutrient enrichment and eutrophication are likely to be complex, and a holistic ecosystem-based approach taking account of multiple anthropogenic pressures is required in order to improve our understanding of the cycling of nutrients in the water column and the coupling between water column and seabed processes. Such an approach requires ongoing research and monitoring, and the use of simulation models for examining fluxes and inter-annual variability in these fluxes. Studies to date have shown that improvements are needed in field measurements and models, and on boundary conditions used in these models.

INTRODUCTION

Nutrient enrichment of estuarine, coastal and marine waters due to human activity has been identified as one of the major threats to the health of these ecosystems around the world. This is largely because of potential risks of eutrophication, which is defined as 'the enrichment of water by nutrients causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned' (from the Urban Waste Water Treatment Directive, UWWTD, 91/271/EEC, see also Tett *et al.*, 2007; de Jonge and Elliott, 2001). Undesirable disturbances may include depletion of dissolved oxygen due to decomposition of accumulated biomass, shifts in species composition, increased occurrence of red tides, water discolouration and foaming, blooms of nuisance and toxic algae and macroalgae, increased growth of epiphytic algae, loss of submerged vegetation due to shading, and changes in benthic community structure due to oxygen deficiency or the presence of toxic phytoplankton species. However, demonstrating causal links between these disturbances and nutrient enrichment is often equivocal, and complicated by other pressures. Cumulative effects of global change, including climate change, may similarly affect biological communities and biogeochemical cycling of nutrients and dissolved oxygen in shelf seas (Rabalais *et al.*, 2009), further complicating efforts to demonstrate casual links.

Sources of nutrients into UK shelf seas and key biogeochemical processes affecting the cycling of key macro-nutrients (nitrate, ammonia, phosphate and silicate) are reasonably well understood (Hydes *et al.*, 2008; Heath, 2010). However, ongoing research is aimed at improving this understanding and quantifying key fluxes (e.g. the current NERC Shelf Sea Biogeochemistry Programme, http://www.nerc.ac.uk/research/programmes/shelfsea/), as well as the transport and fate of these nutrients (see below). A key aspect of this work is the validation and further development of biogeochemical models which can be used to predict potential impacts of direct anthropogenic pressures and climate change. This work is supported by monitoring programmes which provide the data required for quantifying nutrient enrichment attributable to different sources, and potential impacts of nutrient enrichment in coastal and marine waters (e.g. OSPAR, 2003; 2008).

Nutrient sources and trends

Nutrient sources include inputs from rivers, adjacent oceans and the atmosphere. Inputs such as those from agriculture (e.g. fertiliser and manure) and atmospheric deposition of nitrogen are typically 'diffuse'; inputs such as those from industry, caged fish farms and waste water treatment (sewage) discharges typically occur at fixed locations, referred to as 'point' sources. Anthropogenic input of dissolved nutrients into coastal waters via rivers and point sources (notably sewage outlets and industrial discharges) are monitored under the Riverine Inputs and Direct Discharges (RID) programme for reporting to OSPAR (Oslo and Paris Conventions for the protection of the marine environment of the North-East Atlantic). Nutrient loads are calculated for OSPAR regions (Nedwell *et al*., 2002; Foden *et al*., 2011), which are similar to regions adopted for Charting Progress 2 (Figure 1), and given as total loads (Figure 2, see also Baxter *et al*., 2011) and separately for riverine, industrial and sewage sources.

Analysis of RID data from 1990 to 2007 (Defra, 2010) indicated that the highest inputs of dissolved inorganic nitrogen (as nitrate + nitrate, also referred to as total oxidised nitrogen, TOxN) to coastal waters was via rivers, with lowest loads into the Atlantic region (regions 6 and 7, Figure 1) and highest loads into the southern North Sea. Analyses of significant trends indicated decreases in industrial loads in most regions, in sewage loads in the Irish and Celtic Seas, and in riverine loads (flow corrected) in the Channel and Atlantic regions. Significant increases were observed in sewage loads in the Atlantic region (Charting Progress 2, Defra 2010, see http://chartingprogress.defra.gov.uk/feeder/CSSEG-section-3-3-eutrophication.pdf; see also Scotland's Marine Atlas, Baxter *et al*., 2011, http://www.scotland.gov.uk/Publications/2011/03/16182005/38)

For dissolved phosphorus, analysis of RID data from 1990 to 2007 indicated that the main sources of phosphate were sewage inputs into the Channel and northern North Sea, and both riverine and sewage inputs into the southern North Sea and the Atlantic. In the Irish Sea, relative loads indicated that industrial loads were the main input in the early 1990s whereas riverine loads provided the dominant inputs from the late 1990s onwards. Analyses of significant trends (1998 to 2007) indicate that sewage and riverine inputs of phosphate have decreased in all regions except the Atlantic, while industry inputs have decreased in the Irish Sea and the Celtic Sea (Table 1).

Analysis of trends in total loads (1998 to 2007, Table 1) indicate that total inputs of dissolved inorganic nitrogen decreased significantly by 2% per year in the northern North Sea and the Irish Sea, and that total inputs of phosphate decreased significantly by 6 to 9% per year in all regions except the Atlantic (see also OSPAR 2009a; b; 2010a; 2011; Nolan *et al*., 2010). In all other regions (Figure 1), no significant trends were observed in the data (Defra, 2010).

The RID data do not include estimates of nitrogen and phosphorus inputs from particulate material. Recent estimates from the caged fish farm industry to the north and west of Scotland suggest that they may be a significant source of nutrients into the north and west of Scotland where freshwater inputs are low (Figure 1), and comparable to riverine inputs (Baxter *et al*., 2011), which are relatively low. These nutrient inputs are mainly in the form of faecal and particulate organic matter deposited on the seabed. While they may not be available for immediate use by algae or higher forms of plant life they are likely to make an important contribution to biogeochemical cycling in the region.

Analysis of trends in nutrient loads in 20 major Irish rivers between 1990 and 2010 (data not shown) indicate a statistically downward trend in total phosphorus and ammonia in the majority of rivers, and a downward trend in total nitrogen in nearly half the rivers. No statistical upward trend in nutrient load was detected in any of the rivers.

Atmospheric discharges are also an important source of nitrogen into our seas (Defra, 2010). Nitrogen is emitted into the atmosphere by industry, transport (including shipping) and from agricultural practices. Agriculture accounted for 37–44% of atmospheric nitrogen deposited into the UK's seas (OSPAR, 2010b).

***In-situ* nutrient concentrations**

In-situ nutrient concentrations in estuarine, coastal and offshore UK waters are measured during research studies and

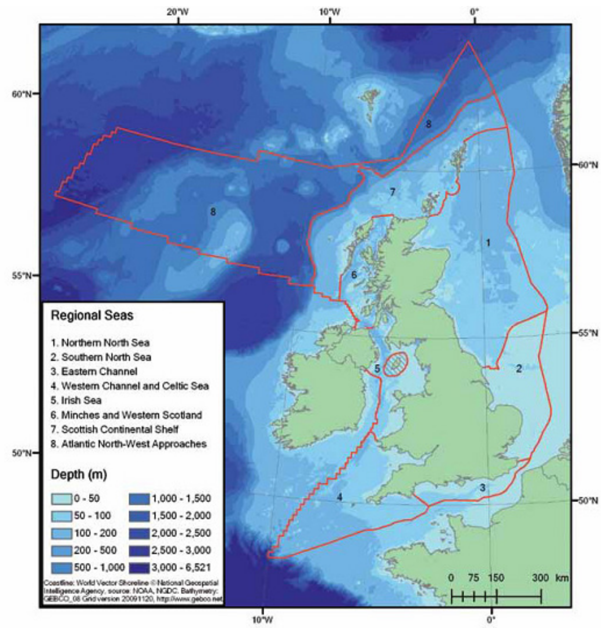


Figure 1: Sea areas used in Charting Progress 2 (CP2, Defra 2010).

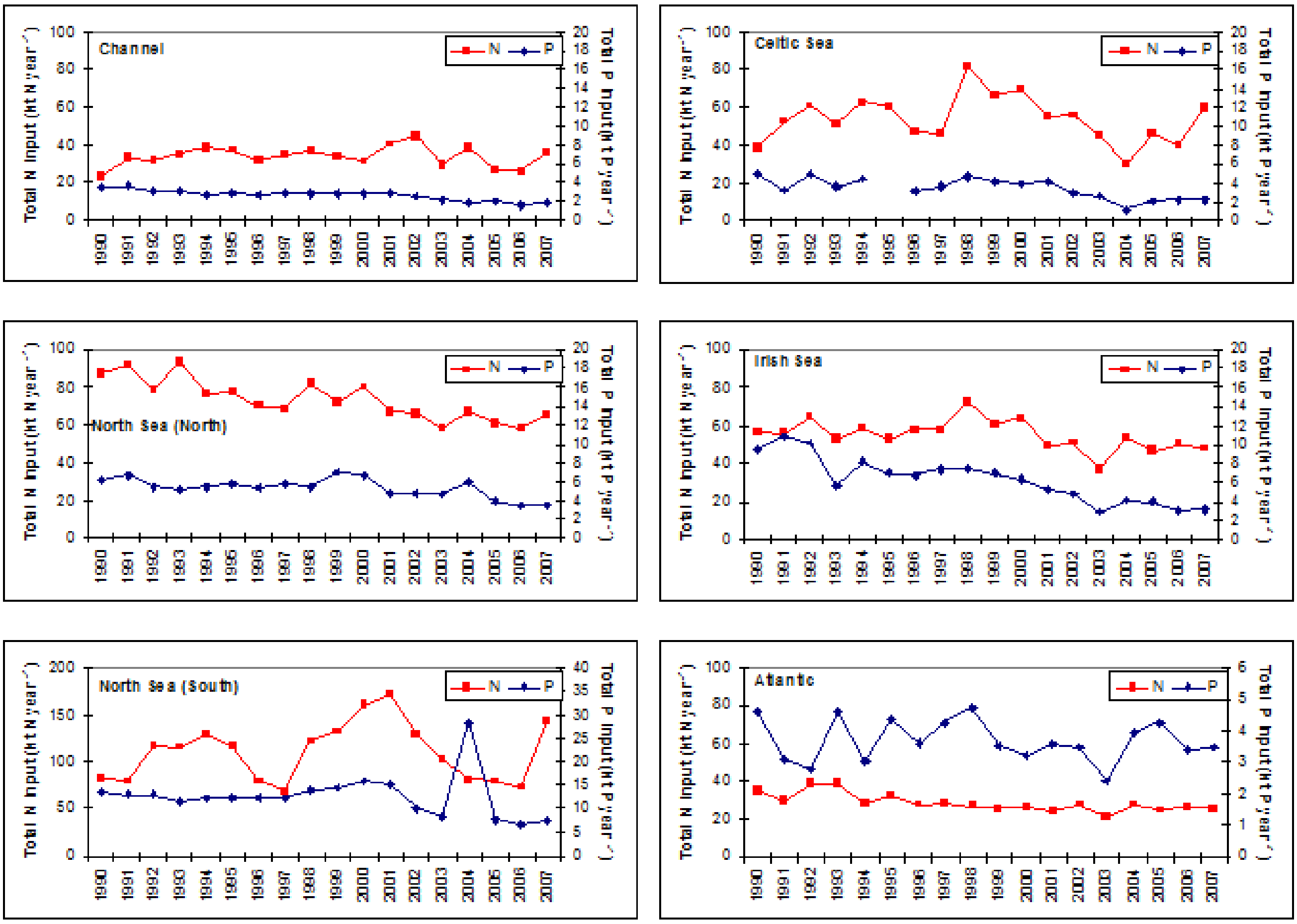


Figure 2: Total annual loads (1980 to 2007) of dissolved inorganic nitrogen (as total oxidised nitrogen, TOxN, kt y^{-1}) and phosphorus (P, kt y^{-1}) to OSPAR areas, which are broadly similar to areas shown in Figure 1. TOxN = nitrate + nitrite.

Table 1: Estimated percentage annual change in loadings of dissolved inorganic nitrogen and phosphorus over a ten year period (1998 to 2007). Negative numbers indicate downward trends; positive numbers indicate upward trends. Shading indicates that the change is significant at the 5% level. Riverine loads are shown with and without corrections for flow rates.

REGION	DISSOLVED INORGANIC NITROGEN					DISSOLVED INORGANIC PHOSPHATE				
	Total Load	Industry Load	Sewage Load	Riverine Load - no flow correction	Rivers- flow corrected	Total Load	Industry Load	Sewage Load	Riverine Load - no flow correction	Rivers- flow corrected
North Sea - North	-2	-10	-1	-2	-2	-6	+4	-10	-7	-7
North Sea - South	-1	-14	-1	-1	0	-8	-1	-6	-9	-8
Channel	-2	+9	+1	-3	-4	-6	-4	-7	-5	-6
Irish Sea	-2	-24	-3	-1	-2	-9	-34	-12	-4	-5
Celtic Sea	-2	-36	-12	-1	-2	-8	-29	-9	-7	-8
Atlantic	0	0	+7	-3	-3	-1	+38	0	-3	-4

monitoring programmes, such as those carried out under the Clean Safe Seas Environmental Monitoring Programme (CSSEMP, see Defra, 2010). These measurements are vital to assessments of the risks and impacts of nutrient enrichment (e.g. see Foden *et al.* 2011, Baxter *et al.* 2011), as well as for research, e.g. on biogeochemical cycling, and for development, parameterisation and confirmation of models. Assessments such as the OSPAR Comprehensive Procedure (COMPP, Foden *et al.*, 2011) use data on nutrient concentrations during winter to indicate nutrients available

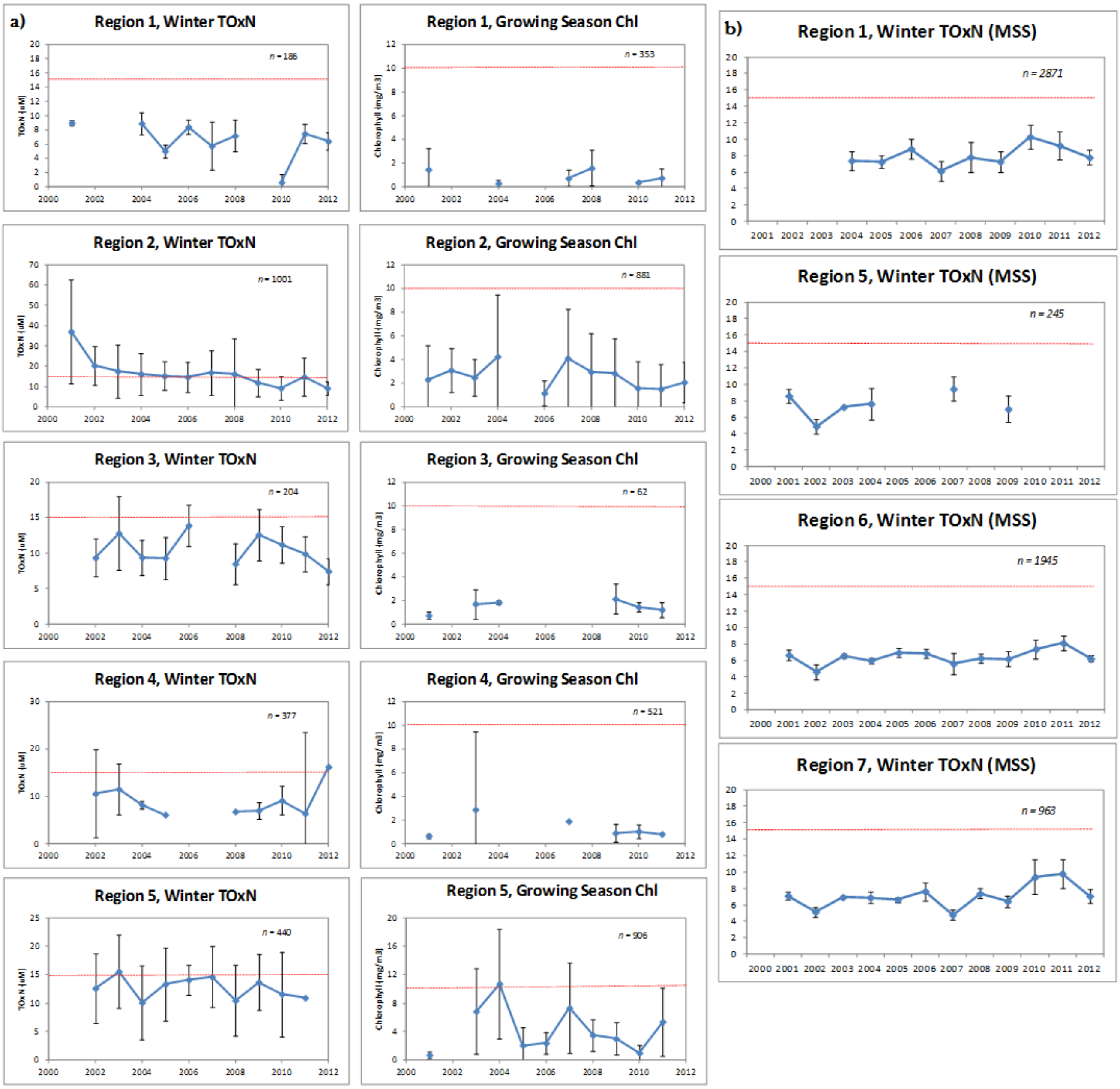


Figure 3: Changes (2000 to 2012) in annual concentrations of winter nutrients (TOxN) in CP2 regions, given as averages ± standard deviations. n = total number of samples. Data were obtained during coastal and offshore sampling (salinity >30) using surveys and/or moorings, by (a) Cefas (winter = November to February) and (b) Marine Scotland Science (MSS, winter = November to March). TOxN = total oxidised nitrogen (nitrate + nitrite); concentrations in coastal water (30-34.5μM) were not normalised to salinity 32 (e.g. as for OSPAR assessments). Growing season chlorophyll concentrations (March to September), an indicator of direct effects of nutrient enrichment, are also shown in (a). Red lines indicate 15μM TOxN and 10 mg chlorophyll m^{-3}; these are shown for illustrative purposes only, but are comparable with UK OSPAR thresholds for offshore waters (see Foden et al.*, 2011)..*

to primary producers such as phytoplankton during the spring-summer growing season in temperate waters.

Annual averages (2000 to 2012) in *in-situ* concentrations of dissolved winter nutrients (such as total oxidised nitrogen, TOxN, Figure 3) in coastal and offshore waters (salinity >30) indicate relative nutrient availability in CP2 regions. Concentrations are lowest in regions 1, 6 and 7 (generally <10μM TOxN) and highest (≥15μM) in region 2 (southern North Sea). These concentrations are likely to reflect relative nutrient loads in each region during winter (November to February, inclusive). Standard deviations indicate considerable variability around these means, in all regions. In the southern North Sea, winter averages show a gradual decline from 2000 to 2012. Growing season chlorophyll concentrations in CP2 regions 1 to 5 are also shown on Figure 3. These are used as an indicator of the direct effects of nutrient enrichment in assessments such as the OSPAR COMPP (see also Baxter *et al.*, 2011; Devlin *et al.*, 2011, Ferreira *et al.*, 2011). In all the regions, mean values are generally <10 mg m^{-3}. As for nutrients, standard deviations indicate considerable variability around the means in all regions.

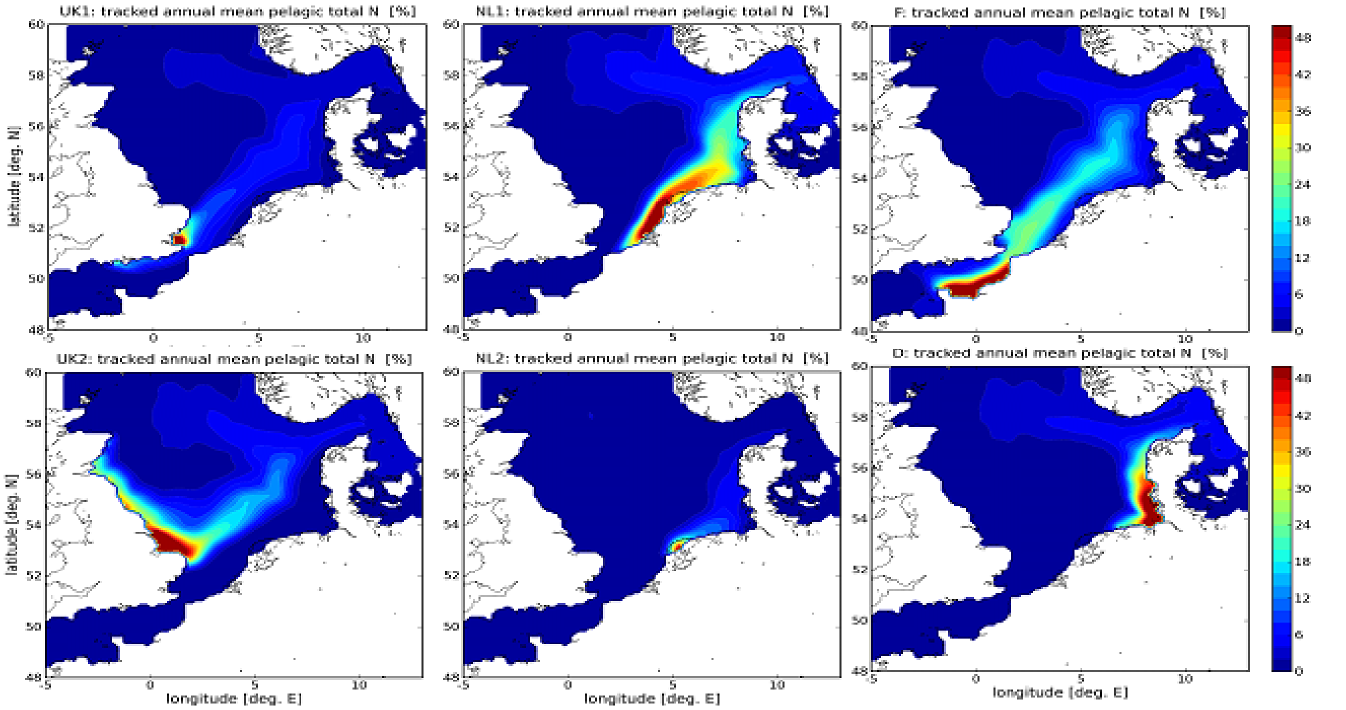


Figure 4: Tracked annual mean pelagic total nitrogen content (i.e. summed over all the compartments in the pelagic part of the ecosystem model) in the year 2002, after 5 years of tracking, from GETM-ERSEM-BFM (see www.nioz.nl/northsea_model), given as a percentage of all pelagic total nitrogen originating from the river groups UK1, UK2, NL1, NL2, F1 and D (NL=Netherlands, F=France, D=Germany). Rivers in group UK1 include all rivers from the middle of the Channel to East Anglia. Rivers in UK2 include all rivers from East Anglia up to north Scotland. Rivers in NL1 include rivers along the Netherlands west coast; rivers in NL2 consist of the Lake IJssel outflows. Rivers in F1 include rivers between Cap de la Hague and Calais. Rivers in group D include all rivers entering the North Sea along the German north-west coast.

Transport and fate of nutrients

A number of studies have been carried out to assess the transport and fate of nutrients. These include recent modelling studies carried out as part of three international ICG-EMO (Inter-sessional Correspondence Group for Eutrophication Modelling) workshops under the auspices of OSPAR. Six coupled hydrodynamics-biogeochemistry models were used to quantify nutrient transport in the North Sea, using various methods to track nutrients through the full suite of biogeochemical calculations in the models (see www.cefas.defra.gov.uk/publications-and-data/miscellaneous-publications.aspx). Transport of nutrients from individual sources cannot at present be quantified from observations. The models demonstrated that specific nutrient sources (in this case groups of rivers) contribute most to the total nutrient burden in plume-shaped areas close to the source (i.e. coastal areas). Figure 4 illustrates some results from the GETM-ERSEM-BFM model run by Cefas. The contributions get progressively smaller with distance away from the sources as waters are transported with the ambient residual circulation, and as the influence of other sources, such as oceanic waters, increases. Nevertheless, nutrients can, over the years, travel over a thousand km away from their source and make a recognisable contribution to local nutrient pools. Reduction measures for a specific source can be expected to have the largest effect on the total nutrient burden within several hundreds of km of the source, and only within the plume to which the source contributes.

Assessing risk and impacts of nutrient enrichment

A number of tools are available for assessing the risks and impacts of nutrient enrichment. In Europe, these include the OSPAR Comprehensive Procedure (COMPP, OSPAR, 2003; Ferreira *et al*., 2011), tools developed under the Water Framework Directive (WFD, CEC, 2000), and the Trophic Index (TRIX, Vollenweider *et al*., 1998; Devlin *et al*. ,2011).

All assessments of the risks and impacts of nutrient enrichment are based on a set of indicators for the direct and indirect impacts of dissolved inorganic nutrients (e.g. Table 2, Gowen *et al*., 2002; OSPAR, 2003; Foden *et al*., 2011), as discussed by a number of authors (e.g. Heath, 2010). For direct impacts, these assessments consider the balance of organisms in algal (phytoplankton) communities, which are the most likely to show the most rapid response to changes in biogeochemical conditions, as well as any changes in the coverage and/or biomass of macrophytes and macroalgae, where they occur, typically in estuarine waters (see example 1 for Scottish waters). Other anthropogenic pressures, such as the removal of top predators (through fishing, Baxter *et al*., 2011), dredging and aggregate extraction, may also affect the balance of organisms, making it essential to establish causal links with nutrient enrichment. Furthermore, anthropogenic activities such as nutrient reduction schemes may affect assessment outcomes, which need to be evaluated carefully. Larger decreases in the input of dissolved inorganic phosphate (P) in coastal waters relative to nitrogen (N) will result in shifts in local N:P ratios, which are likely to be reflected in the relative abundances of different algal species, and therefore the balance of organisms. The impacts are likely to depend on whether the water body is N or P limited. Grizetti *et al.* (2012) have shown that the N to P ratio has increased steadily in the North Sea, as well as in the Mediterranean Sea and Atlantic Ocean. These authors suggest that consequences include losses in biodiversity and reduced ecosystems resilience to future additional anthropogenic stress, such as climate change. Very few studies have considered availability of silicon, which is also likely to influence the balance of organisms. Similarly, few studies have considered communities of other microplankton, such as viruses, cyanobacteria and pico- and nano-plankton (<20um) which may also be sensitive to nutrient enrichment and/or climate change (Brandsma *et al*., 2013; O'Neil, 2012).

1. WHAT IS ALREADY HAPPENING?

Risks and impacts of nutrient enrichment

Recent assessments of the risks and impacts of nutrient enrichment in UK waters have indicated that marine waters (salinity >30) are generally 'Non Problem Areas' (NPAs, OSPAR, 2003; 2008). However, 17 coastal water bodies have been assessed as 'Problem Areas' due to designations as Sensitive Areas or Nitrate Vulnerable Zones under EU directives, such as the Habitats and Nitrates Directives (OSPAR, 2008; Defra, 2010; Baxter *et al*., 2011). Furthermore, assessments under the Water Framework Directive have indicated that some estuarine water bodies may also be impacted by nutrient enrichment. Management measures are in place in all estuarine and coastal water bodies which have been identified as having an ecological or eutrophication status below the target levels.

Indicators of undesirable disturbance in response to nutrient enrichment include depletion of dissolved oxygen (DO) due to decomposition of accumulated biomass. In marine waters (salinity >30), near-bed concentrations of DO are more useful than concentrations in surface water, as it is generally here that excess organic material accumulates and decomposes. Recent studies have, however, shown that concentrations of DO are also affected by warming of bottom water, particularly in regions where the water column stratifies in summer. In the North Sea, for example, studies based on moorings (Greenwood *et al*., 2010) and spatial surveys (Queste *et al*., 2013) have attributed low summer DO concentrations near the sea bed to water temperature as well as processes such as decomposition of organic material. Using historical data (1900 to 2010), Queste *et al*. (2013) showed that trends of increasing near-bed hypoxia after 1990 were associated with trends in increased temperature (Figure 5).

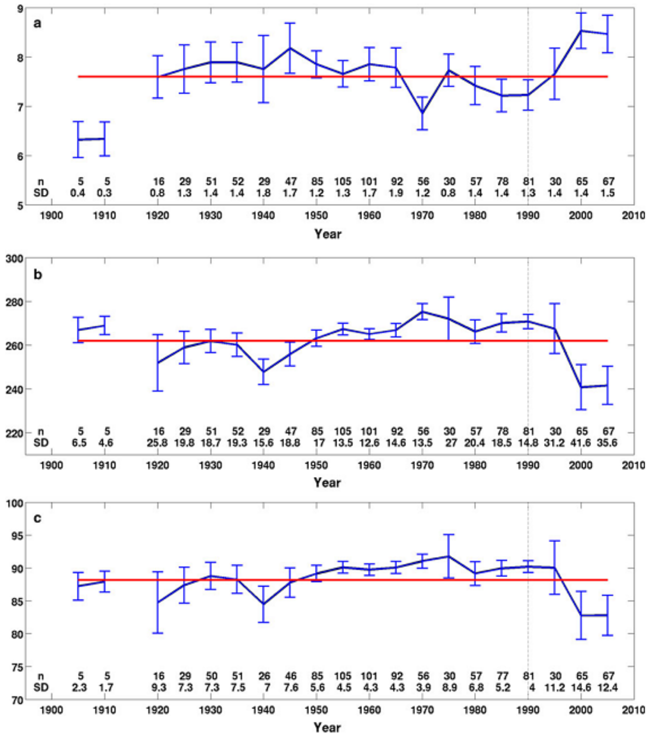


Figure 5: Five-yearly values of an 11-year running mean of (a) summer temperature (°C) in bottom mixed layer, (b) oxygen concentration (μmol dm^{-3}) and (c) oxygen saturation (%) in the stratified central North Sea (from Queste et al., 2013).

Examples of what is already happening in terms of nutrient enrichment (from Defra, 2010; Baxter *et al.*, 2011).

Recent assessments of eutrophication status indicate that each of the Charting Progress 2 assessment areas do not, as a whole, suffer from eutrophication problems. They were therefore classified as Non-Problem Areas. However, a number of estuarine and coastal areas are nutrient enriched and are at risk from or currently affected by eutrophication. Seventeen water bodies have been identified as sensitive or polluted waters, or conservation areas. These have been classified as Problem Areas. Five water bodies have been classified as Potential Problem Areas. Similarly, the occurrence of eutrophication problem areas in Ireland is almost entirely restricted to estuarine areas located along Ireland's southern coast. Twenty estuarine areas and only two coastal areas were classified as problem areas in the last application of the Common Procedure in Irish waters.

a. CP2 Regions 1, 6 and 7 – Scotland and NE England

Region 1 (northern North Sea): Pressures from nutrient inputs are present due to agriculture and urban waste water treatment in limited areas. The overall pressure is low. The region as a whole does not suffer from eutrophication problems although there are some small estuarine and coastal areas that are assessed as Problem Areas.

Region 6 (Minches and Western Scotland): The overall pressure from nutrient input is low due to the low population density. The pressure is higher in the southern part of the region due to agriculture. The region as a whole does not suffer from eutrophication problems.

Region 7 (Scottish Continental Shelf): The overall pressure from nutrient input is very low due to the low population density. The region as a whole does not suffer from eutrophication problems.

Assessments

The recent assessment of Scottish waters (Baxter *et al*., 2011) showed that the concentration of winter dissolved inorganic

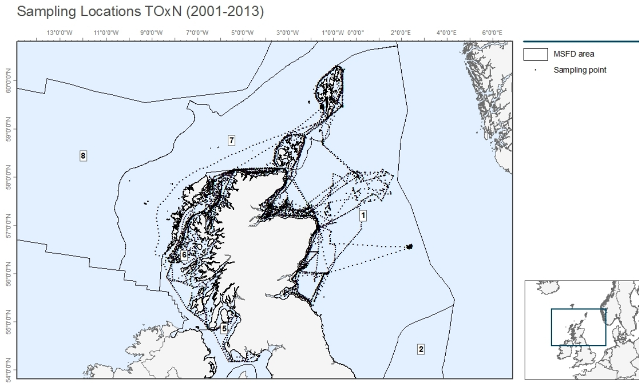


Figure 6a: Sampling locations in Scottish waters, 2001 to 2013

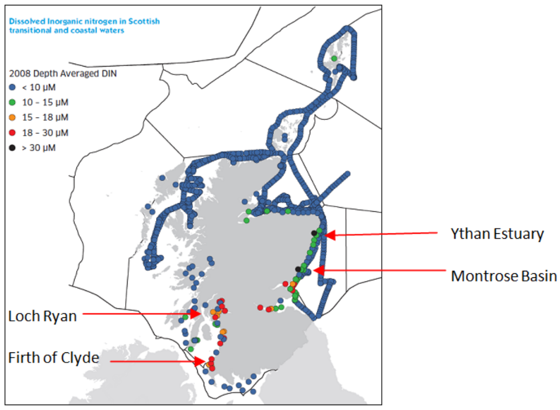


Figure 6b: Dissolved inorganic nitrogen in Scottish transitional and coastal waters in 2008

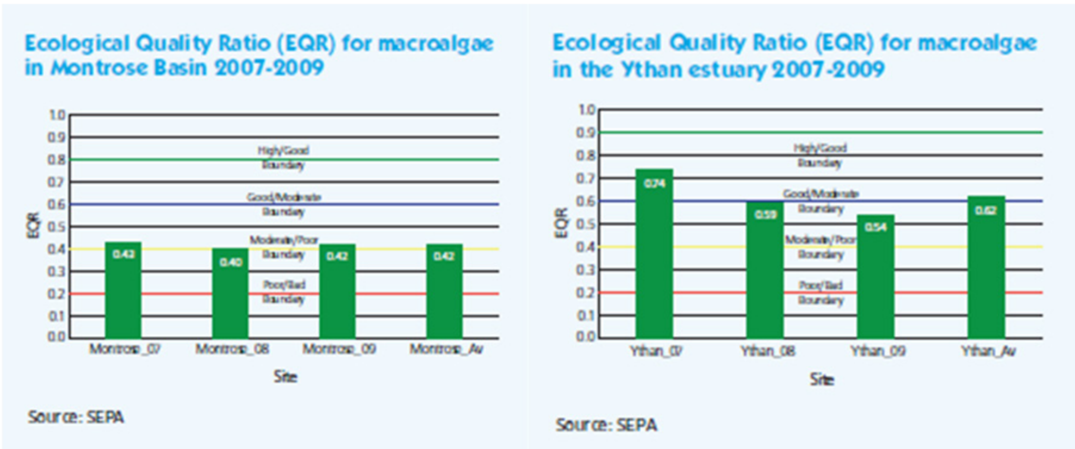


Figure 6c: The Ecological Quality Ratio (EQR) for opportunistic green macroalgae in Montrose Basin and the Ythan estuary, 2007 to 2009. The EQR is an index of excessive growth, as determined from coverage and density of mats in the intertidal areas (see Baxter et al., *2011).*

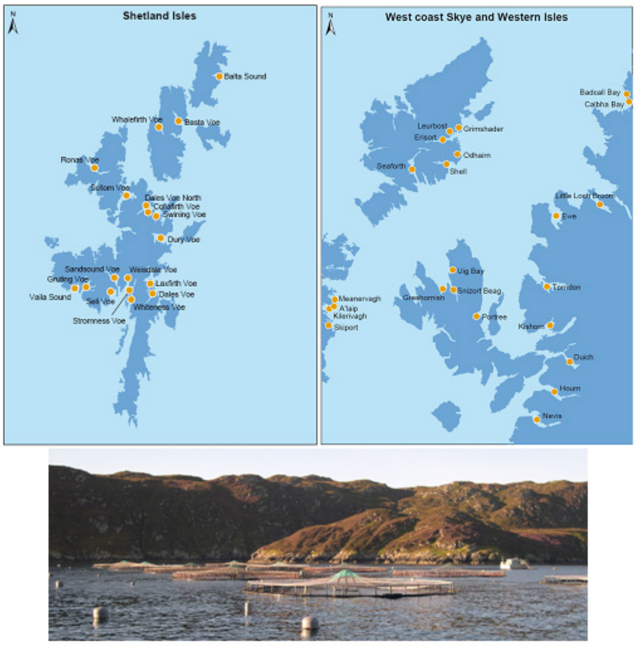


Figure 7: Sea lochs, voes, sounds and bays monitored by Marine Scotland Science during 2002 – 2006 and assessed as 'Non Problem Areas' with respect to the effects of nutrients from fish farms by applying the OSPAR Comprehensive Procedure for eutrophication assessment.

nitrogen (DIN) was less than '50% above background concentrations' (where background concentrations for DIN are 10 µM in offshore waters, 12µM in coastal waters [salinity 32], and 20 µM in estuarine waters [salinity 25]) in offshore and most coastal and estuarine waters (see Figure 6a, Defra, 2008). DIN concentrations were greater than 50% above background concentrations in the coastal waters of the Firth of Clyde and in Loch Ryan, and in two small estuaries on the east coast, the Ythan Estuary (Figure 6b) and Montrose Basin. In these two estuaries, there is evidence of nutrient enrichment leading to excessive growth of opportunistic green algae (Figure 6c). However, there is no evidence that the algal mats cause an undesirable disturbance. Benthic invertebrates are abundant in both of these areas and support populations of wading birds.

Effects of nutrients from fish farms on Scottish sea lochs

The majority of UK marine fish farming takes place in the sheltered waters of sea lochs, and voes, of the west coast, Western and Northern Isles of Scotland. Nutrient discharges from fish farms in these semi-enclosed waters have the potential to result in nutrient enhancement. In order to assess the potential eutrophication status of these regions the UK undertook an extensive programme of monitoring and assessment between 2002 and 2006 covering some 38

Table 2: Summary of results of the application of the OSPAR Comprehensive Procedure, Harmonised Assessment Criteria to 38 Scottish sea lochs supporting aquaculture.

Assessment Parameter	Summary of findings for Scottish sea lochs
Category I	***Degree of nutrient enrichment***
1 Nutrient inputs	In general, nutrient inputs from aquaculture decreased from 2003 – 2005 across Scotland as feeding efficiency improved and production declined over this period. Regulatory restrictions will prevent future increases in nutrient discharges from aquaculture in most hotspot areas.
2 Nutrient concentrations	Winter nutrient concentrations (of dissolved inorganic nitrogen) did not exceed the criteria of 50% above background concentrations of coastal waters for any lochs.
3 Nutrient ratios	Winter N/P ratios did not exceed 50% above background values (16) for any sea lochs.
Category II	***Direct effects of nutrient enrichment***
1 Chlorophyll a concentrations	The 90th percentile of measured values did not exceed 50% above background values for coastal waters at any of the sea lochs surveyed.
2 Phytoplankton indicator species	Potentially toxic and nuisance species were recorded at several lochs at densities typical for Scottish waters. The occurrence of these species is not thought to be related to nutrient inputs from aquaculture.
3 Macrophytes and macroalgae	Percentage area coverage of 'nuisance' green macroalgae in the inter-tidal zone did not exceed the assessment level of 15% at any of the sea lochs surveyed.
Category III	***Indirect effects of nutrient enrichment***
1 Oxygen deficiency	The 5th percentile of measured values never fell below the assessment level of 4 mg/l. Some bottom waters in sea loch basins showed lower values which are a result of the natural hydrography of the lochs and are not caused by nutrients from aquaculture.
2 Fish kills	There are occasional kills of farmed fish caused by jellyfish and harmful phytoplankton in sea lochs. These are not related to eutrophic conditions.
3 Organic carbon	Organic carbon levels in sediments vary naturally with hydrography and are high close to fish farms. Levels are not of concern with respect to eutrophication assessment.
Category IV	***Other effects of nutrient enrichment***
1 Algal toxins	Extensive monitoring reported the presence of amnesic, paralytic and lipophilic shellfish toxins in water, plankton and shellfish from several sea lochs. The occurrence of these toxins is typical for Scottish waters and not thought to be related to nutrient inputs from aquaculture.

water bodies supporting fish farms (Figure 7). Hotspot areas were targeted for the assessment, where according to simple models relating nitrogen discharge rates from fish farms to flushing rates of sea lochs, nitrogen enhancement was predicted to be highest.

Surveys of these regions were conducted at key times of the year by research vessel and parameters monitored according to the OSPAR Comprehensive Procedure (COMPP) and assessed against the Harmonised Assessment Criteria. A summary of results is shown in Table 2. An overall assessment of the parameters according to the COMPP was undertaken and resulted in Non-Problem Area classifications for all the sea lochs assessed with respect to nutrient inputs from aquaculture (see also the section on nutrient sources and trends, above, and Baxter *et al.*, 2011).

b. CP2 Regions 2, 3 and 4 – England and Wales

Region 2 (southern North Sea): There is significant pressure due to nutrient input from agriculture which covers large areas of eastern England and from urban waste water due to the high population density. The coastal and offshore areas of the region are assessed as Non-Problem Areas even though there is nutrient enrichment and some evidence of accelerated growth, particularly in coastal waters. The physical nature of this region (tidal hydrodynamics, inorganic turbidity restricting light), especially in coastal areas, makes it resistant to developing eutrophication problems.

Region 3 (Eastern Channel): There is some pressure due to nutrient input from agriculture which covers large areas of eastern England and from urban waste water due to the high population density. The offshore waters are Non-Problem, being influenced predominantly by the inflow of water from the Atlantic. There are several areas at the coast that have very restricted exchange and are Problem Areas. The pressures associated with the specific problem areas are being managed.

Region 4 (Western Channel and Celtic Sea): Relatively low population density, although this varies seasonally and

Table 3: Site-specific data for assessing the susceptibility of 5 east coast estuaries to nutrient enrichment using a simple box model. WFD data were used to estimate the total area (km^2), and the intertidal area available for macroalgal growth. Average depths (m) were obtained from mean sea level and used to calculate estuary volumes and exchange rates (E, d^{-1}, using the tidal prism method). The values for average light attenuation (Kd, m^{-1}) were obtained from previous work (see Devlin et al.*, 2008).*

Estuary	Area (km^2)	Average depth (km)	Available intertidal area (%)	Exchange rate (E), (d^{-1})	Mean Kd (m^{-1})
Humber	326.5	7.4	11.3	0.08	8.52
Wash	611.6	6.9	8.8	0.07	4.62
Thames	453.2	6.9	5.9	0.07	4.3
Colne	7.0	2.9	28.9	0.13	2.69
Blackwater/ Colne	52.3	3.4	28.9	0.13	2.3
Deben	7.8	3.1	29.0	0.09	3.84

is high in summer. Significant intensive agriculture but confined to a few areas. Overall pressure is low. There is no nutrient enrichment in this area with the exception of small estuaries and lagoons which are Problem Areas and the specific sources of the enrichment are being managed.

East coast estuaries

A simple box model was used to predict the magnitude of growth by the phytoplankton and macroalgal communities in five east coast estuaries (the Humber, Wash, Thames, Colne/Blackwater and Deben) in response to nutrient input. This Combined Phytoplankton Macroalgal (CPM) model was developed by combining two earlier models, one for phytoplankton (see Painting *et al.*, 2007), based on the CSTT approach, and one for macroalgae (Aldridge *et al.* unpubl, Cefas). In the model, growth is strongly influenced by a number of factors, including the retention time of water, relative light regimes, estuary depth, and the extent of the intertidal area suitable for macroalgal growth (see Table 3).

The model was run using average (2000-2005) catchment-corrected loads of dissolved inorganic nitrogen (N, Figure 8) and precautionary site-specific data per estuary (e.g. slowest water exchange rates, zero losses of N due to denitrification). Model results (Figure 7a) showed no phytoplankton production in the Humber, the Wash or the Thames. This was attributed to light limitation, which was enhanced by the mean depth of the estuaries. Observed phytoplankton biomass (chlorophyll) was considered to have been advected in from adjacent coastal water. In the absence of phytoplankton growth in the Humber, Wash and Thames, the model predicted growth by macroalgae, with highest production rates (245 g C m^{-2} y^{-1}) in the Humber. These results were sensitive to estimates of the intertidal area available for macroalgal growth, which are influenced by factors such as substratum type and exposure.

For the Colne, Blackwater and Deben, model results indicated relatively high levels of production by phytoplankton, largely attributable to more favourable light conditions in these estuaries (see Table 3, smaller values for light attenuation, Kd). Relatively high nutrient concentrations in these estuaries (Figure 8) were attributable to their relatively small volumes compared with the Humber, Thames and Wash where higher nitrogen loads were diluted by larger estuary volumes.

CPM model results were compared with the scale proposed by Nixon (1995) for assessing trophic status from net annual primary production estimates i.e. oligotrophic: 0 - 100 g C m^{-2} y^{-1}, mesotrophic: 101 - 300 g C m^{-2} y^{-1}, eutrophic: 301 - 500 g C m^{-2} y^{-1} or hypertrophic: >500 g C m^{-2} y^{-1}. Estuaries identified as being eutrophic by this scale may not show any signs of eutrophication as defined by the UWWTD (C.E.C., 2000). Additional attributes need to be considered to assess negative impacts. None of the predicted levels of production exceeded Nixon's threshold for eutrophic status.

c. CP2 Region 5 – Irish Sea

Region 5 (Irish Sea): There is significant pressure in the eastern part of the region due to nutrient input from

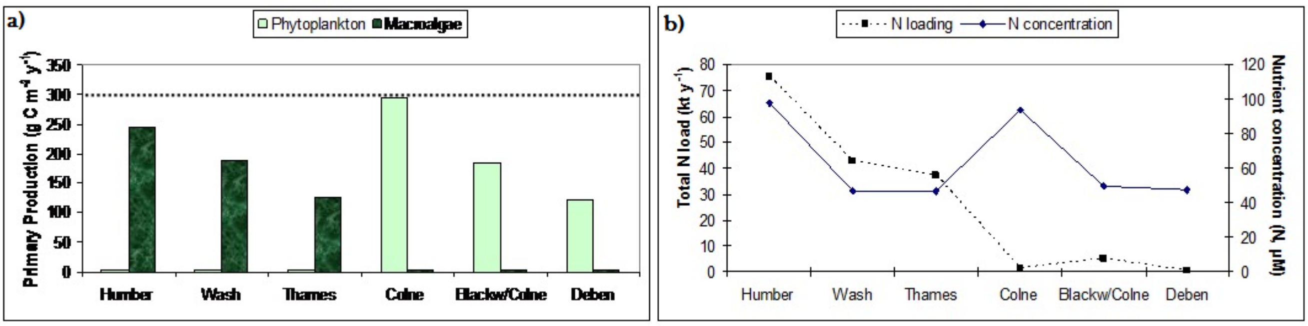


Figure 8: (a) Summary of results from a simple model (CPM, see text) used to assess susceptibility of east coast estuaries to the input of dissolved inorganic nitrogen (N). Average loads (b) were calculated using catchment corrected data from 2000 to 2005. The model calculates in situ nutrient concentrations from data on estuary volume, and predicts primary production (g C m^{-2} y^{-1}) by both phytoplankton and macroalgae. The dashed line in (a) indicates a threshold of 300 g C m^{-2} y^{-1}, proposed by Nixon (1995) for assessing eutrophic status, but not necessarily eutrophication as defined by the UWWTD.

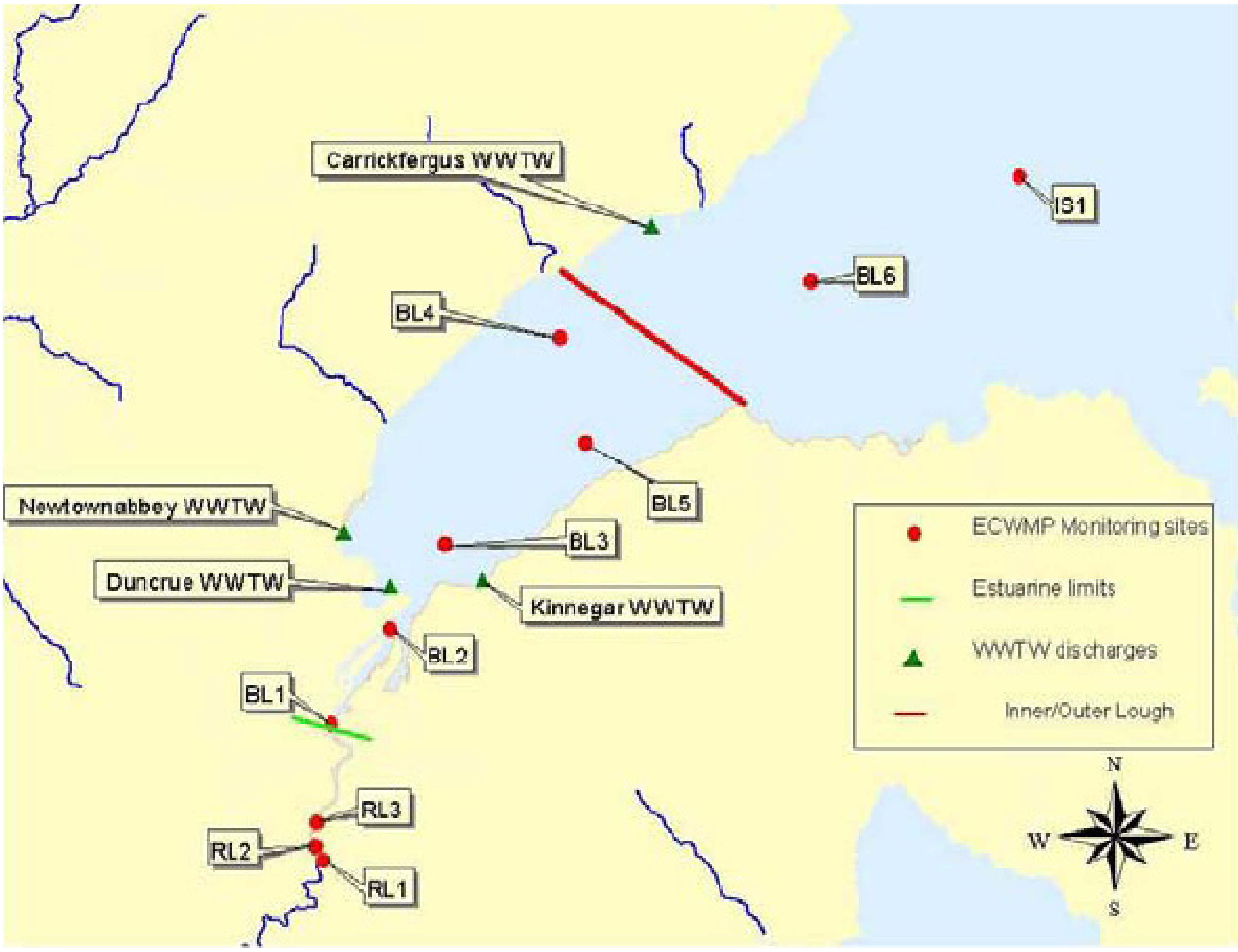


Figure 9: Belfast Lough showing the Northern Ireland Environment Agency (NIEA) monitoring locations.

agriculture and from urban waste water due to the high population density. The coastal and offshore areas of the region are assessed as Non-Problem Areas even though there is nutrient enrichment and some evidence of accelerated growth, particularly in coastal waters.

Belfast Lough

Belfast Lough (Figure 9) is a shallow semi-enclosed marine bay in which the principal watercourse is the River Lagan which enters at Stranmillis (RL3). The total catchment of Belfast Lough is 900 km2 and freshwater input from the River Lagan is augmented by several streams along its shores. The sea bed of the Lough slopes gradually from Belfast where there are extensive mud-flats, to a depth of approximately 20 m at the outer limit. The total area of the Lough has a flushing time of 1.44 days with higher flushing rates in the Outer Lough. Tidal currents are weak and oscillatory in the Inner Lough resulting in a predominantly sheltered area where the currents are dominated by tides. The Outer Lough is exposed and water exchange with the North Channel is rapid. A clockwise rotatory current has been documented in the Outer Lough (Parker *et al.*, 1988) and these physical conditions result in less potential for eutrophication. The physical oceanography of the Inner and Outer Lough results in significant chemical and biological differences.

The UK originally issued guidance for identifying sensitive areas (eutrophic) under UWWTD in March 1993. This guidance has been used alongside the Comprehensive Studies Task Team guidance issued by the UK authorities in 1997 (MPMMG, 1997). In 1993 there was insufficient evidence to warrant identification of Inner Belfast Lough as a sensitive area according to the definition of eutrophication (Article 2, 11) and the criteria in Annex IIA (a) of Directive 91/271/EEC.

A four year study (1992-96) was completed by Service and Durrant (1996) and concluded that Inner Belfast Lough was eutrophic. However, the area was not designated as sensitive under UWWTD in 1997 primarily because the main source of nutrients to the Inner Lough was not from waste water treatment works but from an industrial discharge. The Environment and Heritage Service (EHS), the predecessor organisation to the Northern Ireland Environment Agency (NEEA), delayed identification, awaiting the outcome of a further trophic status study and modelling. The purpose of these further studies was to determine whether management of the industrial nutrient discharge would be sufficient to return Inner Belfast Lough to a more normal trophic status.

The Inner Lough was designated as a sensitive area under UWWT Directive in 2001 following a recommendation from a study by Charlesworth and Service (1999). Supplementary

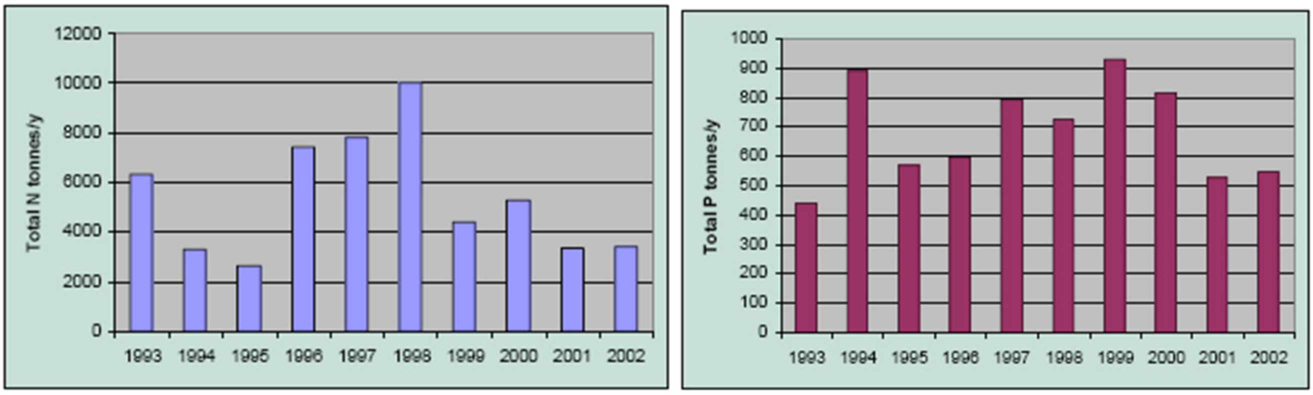


Figure 10: Total loadings of N and P (tonnes y^{-1}) to Belfast Lough (data source: NIEA OSPAR RID Programme).

guidance under the UWWTD was issued in May 2002, this was closely aligned with the OSPAR Common Assessment Criteria for Eutrophication. A report in 2003 confirmed the trophic status of Inner and Outer Belfast Lough using this methodology (issued in 1993 and supplemented in May 2002) for identifying eutrophic waters. All data sources are described in the detailed report, which is included as part of the second application of the OSPAR Compp (see.www. cefas.co.uk/ospardocs). The report documented a number of changes in Inner Belfast Lough from 1998 to 2002 which resulted in a reduction of nutrient inputs, concentrations and an overall improvement in trophic status. These include: the introduction of full secondary treatment with nutrient (N) removal at Belfast (Duncrue. See Figure 6) waste water treatment works (WWTW) from December 1998; secondary treatment at Kinnegar WWTW operational from December 2000, with nitrogen reduction operational from June 2001; a progressive tightening of the discharge consent of a major industrial discharger (fertilizer plant) and the eventual closure of the plant in December 2002; and the rapid development of a shellfishery (largely bottom culture mussels) in Inner Belfast Lough since 2000. Total loads of N and P (tonnes y^{-1}) to Belfast Lough (Figure 10) show considerable variability between years. For nitrogen, total loads appeared to decrease after 1998. Similar trends were not observed for phosphorus.

The conclusions from the updated assessment in 2003 were that the Inner Belfast Lough was eutrophic although there was evidence of reduced nutrient inputs which resulted in improvements in this area. The Inner Lough was still enriched in nutrient concentrations; there was still evidence of accelerated algal growth on occasions; there was still evidence of an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned.

Physical conditions in the Outer Lough do not favour eutrophication because of the rapid exchange of waters with the waters of the North Channel. The waters were nutrient enriched, and showed signs of accelerated growth of algae during the 1990s. However, there was no evidence of an undesirable disturbance to the balance of organisms present in the water and water quality during this period. Therefore the Lough was not designated as sensitive. The conclusions from the updated assessment in 2003 were that the Outer Lough was not enriched with nutrients, there was no evidence of accelerated algal growth or higher plant forms, and no evidence of an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned. The Outer Lough was therefore assessed to be not eutrophic or likely to become eutrophic in the near future if protective action was not taken within the terms of Annex IIA(a) of the Directive.

Liverpool Bay

Liverpool Bay is a coastal region of freshwater influence (salinity 30 – 34) that receives waters from the Mersey, Ribble and Dee estuaries. There is clear evidence of nutrient enrichment in Liverpool Bay but there is also robust evidence that neither accelerated growth of phytoplankton nor undesirable disturbance to the balance of organisms occurred during the assessment period (2001 and 2005, see Gowen *et al*., 2002; Tett *et al*., 2008).

Since November 2002, high frequency fixed point observations obtained by deployment of a Cefas SmartBuoy have formed a key part of the monitoring strategy in Liverpool Bay. This has resulted in a large volume of data leading to more robust conclusions about eutrophication status. Figure 11 shows a time series of daily TOxN concentrations measured at 2-hourly intervals using an *in-situ* nutrient analyser and in the laboratory from water samples collected 3-4 times each week and stored automatically on the SmartBuoy. These data are used to calculate the over-winter DIN (dissolved inorganic nitrogen) concentration and determine whether Liverpool Bay is enriched with nutrients (Figure 12).

Evidence of accelerated growth is provided by increased phytoplankton biomass (as indicated by increased chlorophyll concentrations) during the growing season (March – September). Assessment of this parameter has been improved by using measurements from SmartBuoy. A high frequency time series of SmartBuoy chlorophyll concentration is shown in Figure 11. SmartBuoy chlorophyll data augment the dataset that is assessed against an appropriate threshold (Figure 13 a and b). For the assessment period 2001 – 2005 there was judged to be no evidence of accelerated growth.

The use of SmartBuoy high frequency time series measurements has not only improved the quality of the

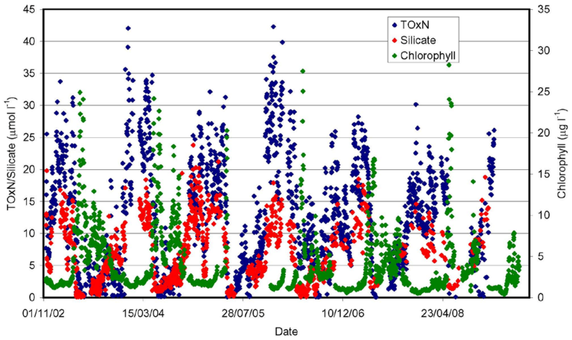


Figure 11: A time series of daily TOxN (nitrate + nitrite), silicate (micro M) and chlorophyll (micro g l^{-1}) concentration from the Cefas Liverpool Bay SmartBuoy. Measurements are made every 2 hours using an in situ nutrient analyser for TOxN and several times a week with a waters sampler for TOxN and silicate. Chlorophyll is measured twice an hour for 10 minute periods using a fluorometer.

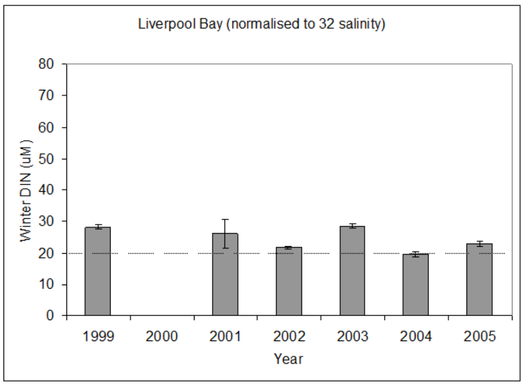


Figure 12: Winter (November to March) nutrients in waters of coastal salinity (30 – 34) in Liverpool Bay, as mean DIN concentrations normalised to 32 salinity. Error bars are 95% confidence limits; the dashed line shows the threshold value for normalised data. SmartBuoy measurements began in November 2002.

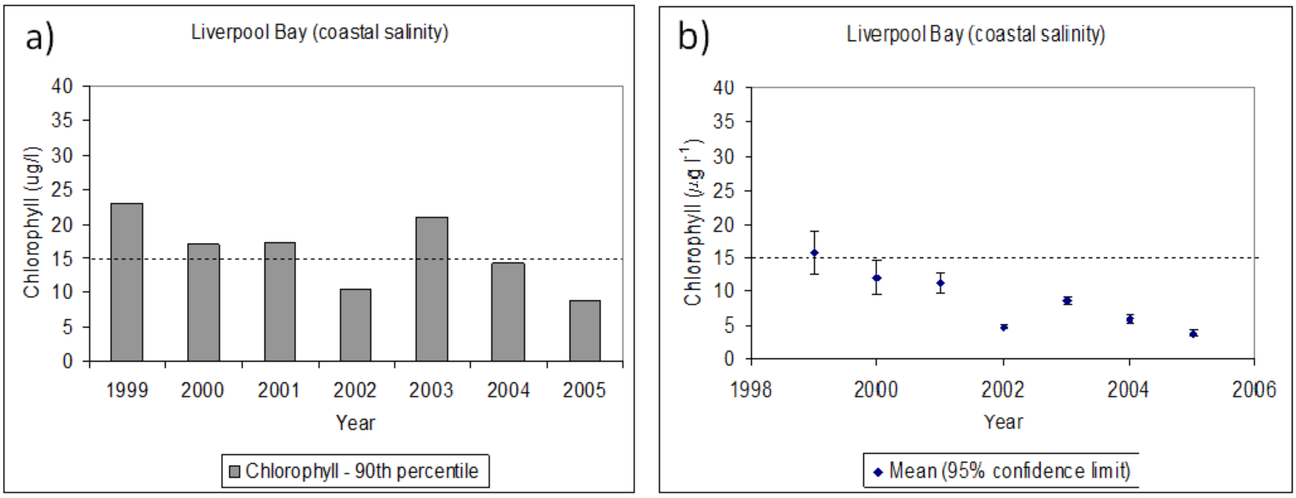


Figure 13: Chlorophyll concentrations during the growing season in coastal waters (salinity 30 – 34) in Liverpool Bay, from spatial (ship based) and SmartBuoy observations. (a) 90th percentiles and (b) means and 95 % confidence limits.

evidence base used in the assessment of the eutrophication status of Liverpool Bay but provided insights into the dynamic nature of the region. Figure 11 shows the large degree of variability of nutrients (TOxN and silicate) and chlorophyll on a variety of time scales. Short scale (hours to days) variability in nutrients is strongly driven by tides and episodic inputs of freshwater due increased runoff. The winter build up of nutrient concentrations is followed by a rapid draw down in the spring associated with the timing of the spring bloom that is a prominent feature in Liverpool Bay. Significant inter-annual variability is also apparent in all of these time series demonstrating the challenge faced by traditional monitoring approaches in resolving the variability of key ecosystem variables that are used as indicators of eutrophication status.

As well as spatial information from ships, satellite remote sensing is beginning to provide more robust information on chlorophyll in turbid coastal waters. Figure 14 shows a map of chlorophyll in Liverpool Bay derived from satellite together with surface concentration of chlorophyll measured along a track sailed by a research vessel. There is good agreement between the different datasets and this provides a way of establishing good confidence in the information used to derive status assessment. The Ferrybox and satellite data together shows that at this time of year chlorophyll shows high concentrations along the north Wales coastline.

d. CP2 regions 8 and 9 – Scottish continental Shelf and Atlantic North-West Approaches

Regions 8 and 9: There are no nutrient pressures in this region. The region as a whole is unlikely to suffer from impacts of anthropogenic nutrient enrichment.

2. WHAT COULD HAPPEN?

Forecasting the likely impacts of climate change on nutrient enrichment and the subsequent risks and impacts of undesirable disturbance to the balance of organisms and water quality, i.e. eutrophication, is complex and challenging. Firstly, there is no simple dose-response relationship between nutrient enrichment, primary production and undesirable

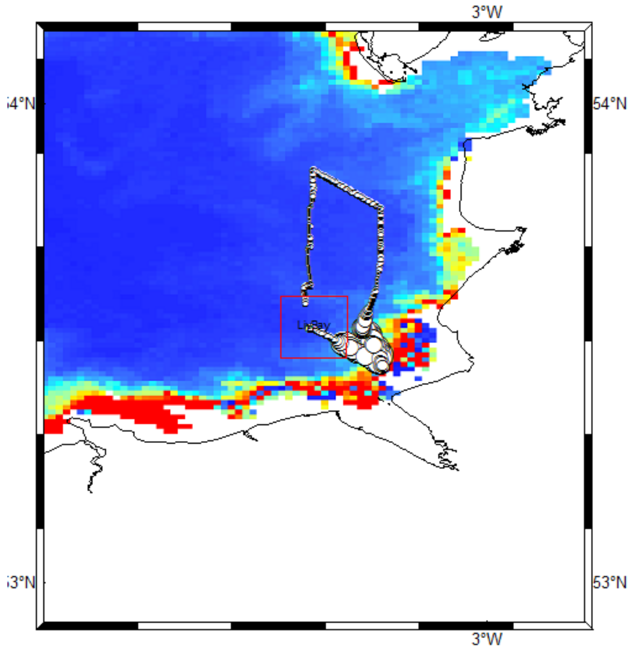


Figure 14: Satellite remote sensing of chlorophyll derived from ocean colour measurements in Liverpool Bay on 10th May 2006 derived from MODIS radiance measurements using the OC5 algorithm for case-II waters. Blue represents low and red high values of chlorophyll. The track of the research vessel and the relative surface concentration of fluorescence is also plotted. In this image higher surface concentrations are visible inshore by remote sensing and from underway surface chlorophyll fluorescence measurements compared to those offshore and in the region of the SmartBuoy indicated by the red box.

disturbance. This is because of system attributes that 'filter' responses to changes in nutrient loading, including the underwater light climate, horizontal exchange, tidal mixing, grazing and biogeochemical processes (Cloern, 2001; de Jonge and Elliott, 2001). In addition, some symptoms of eutrophication such as accelerated algal growth, changes in the phytoplankton community and hypoxia (oxygen depletion) in bottom water can also be the result of climate variability and the two causes are difficult to separate (McQuatters-Gollop *et al*., 2009).

Furthermore, forecasts and future assessments need to take account of multiple pressures, including fisheries, population growth, and increases in industrialisation and agri-business (Rabalais *et al*., 2009). Various approaches are currently being adopted to examine future scenarios. These include the use of complex statistical techniques and simulation modelling (see Heath 2010) and regional assessments and evaluations, such as those carried out by the Marine Climate Change Impacts Partnership (MCCIP), the Intergovernmental Panel on Climate Change (IPCC), the BALTEX assessment of Climate Change for the Baltic Sea (BACC), and the North Sea Region Climate Change Assessment (NOSCCA, http://www.hzg.de/institute/coastal_research/projects/noscaa/index.html).

Potential impacts of climate change include changes in the magnitude of nutrient enrichment in estuarine, coastal and offshore waters, in the physical and chemical oceanography (e.g. circulation patterns, acidification and light) and in rates of biogeochemical cycling in these waters (see CLAMER, 2011; Statham, 2012). These are likely to be driven by changes in atmospheric forcing and atmospheric warming. A key question is whether these changes will result in increases in eutrophication-related undesirable disturbance, and whether these changes should be attributed to climate change or to nutrient enrichment, or both.

In Europe, the North Atlantic Oscillation (NAO) and the Eastern Atlantic Pattern (EAP) are important influences on the ocean and climate (Nolan *et al*., 2010). The EAP naturally exhibits strong multi-decadal variability without a defined periodicity. Since 1970 there has been a measurable trend towards more positive phase NAO conditions, with particularly strong and persistent positive values during the 1997 to 2007 period. The positive phase of the EAP is associated with a more direct storm track across the Atlantic and has been linked to an increased intensity of winter storms and shifts in temperature and salinity throughout the North Atlantic Ocean. It is associated with above average surface air temperatures in Europe throughout the year and with above average rainfall over northern Europe and Scandinavia, but below average rainfall across southern Europe (Nolan *et al*., 2010). Increased precipitation over Europe and Scandinavia will increase freshwater discharges into the North-east Atlantic coasts and sea, and may result either in increased nutrient loads or dilution of these loads (CLAMER, 2011). Bouraoui and Grizzetti (2011) found that annual fluctuations in nutrient loads correspond to variations in water flow In European seas. Certainly, precipitation rates are changing globally, with wet regions generally becoming wetter and dry areas becoming drier. There are also changes between seasons in different regions. For example, rainfall in the UK during summer is decreasing, while in winter it is increasing (MetOffice, http://www.metoffice.gov.uk/climate-change/). Overall, more rain and increased flooding as a result of climate change are expected to enhance nutrient enrichment through increased freshwater input and run-off from land (Cloern, 2001; Rabalais, 2004; OSPAR, 2010a; b), indicating that natural variability in climate is likely to have a greater effect on diffuse sources of nutrients than on point sources.

Climate change scenarios for the 21st Century, such as those from the Met Office (2008; see also Collins, 2007; Murphy *et al*., 2007; Pope *et al*., 2007), indicate atmospheric warming due to greenhouse gas emissions. A recent North Sea study of potential impacts of climate change and demersal trawling (and not nutrient enrichment) on biogoechemical fluxes, using the coupled physical-biogeochemical flux model (ERSEM) and atmospheric forcing from the HadRM3-PPE-UK unperturbed ensemble member, showed long-term increases of 10-20% in gross primary production by algal communities at study sites in three ecohydrodyamically distinct regions by the year 2100 (van der Molen *et al*., 2013). This was considered to be largely due to temperature-dependent growth rates and enhanced nutrient recycling in the pelagic domain. Model results indicated greatest changes in the southern North Sea, where the water column is well mixed all year round, making nutrients available to algal communities at all times. Model results indicated smaller changes in gross primary production in the seasonally stratified central North Sea, where vertical stratification of the water column during summer limited the availability of nutrients to algae in surface waters. Other models using climate change scenarios have indicated that an additional effect of atmospheric warming is enhanced stratification in those sea areas which stratify seasonally, in response to summer warming of surface layers (see Heath 2010). Results such as these indicate that the combined effects of climate change and nutrient enrichment may have most effect on primary production of algal communities in the well-mixed shelf seas, rather than in stratified waters. However, studies on near-bed concentrations of dissolved oxygen (Greenwood *et al*., 2010; Queste *et al.,* 2013) in seasonally stratified waters suggest that DO concentrations in these regions are affected by warming of bottom water, as well as by decomposition of organic material (Meire *et al*., 2013). Additional studies and an ongoing monitoring programme are therefore needed to further quantify the impacts of climate change on nutrient enrichment.

In general, the biological responses to altered nutrient loads, and any potential negative impacts, are likely to be affected by other factors responding simultaneously to climate change, such as changes in water temperatures and changes in physical and/or chemical oceanographic processes. Changes in the colour index derived from continuous plankton recorder observations have been attributed to climatic trends (McQuatters-Gollop *et al*., 2007; Defra, 2010). Depending on whether the water body is mixed or stratifed, warming of surface waters can be expected to contribute to increased or decreased growth rates of phytoplankton and other primary producers, which could alter the eutrophication responses to potentially increased nutrient availability during spring and summer months, particularly in some regions. These may be offset by similarly increased growth rates of zooplankton grazing communities. These responses are, however, likely to be complicated by shifts in species composition of plankton communities which have been attributed to changes in water temperature and to changes in chemical and physical oceanography. The distribution, abundance and species composition of both phytoplankton and zooplankton communities is strongly influenced by regional oceanographic processes (Defra, 2010).

Is there a range of noteworthy opinions on the impacts of climate change on nutrient enrichment? If so, you discuss the main arguments for the range of views expressed?

Whilst expert opinions may differ on quantities of nutrient enrichment, there is a general consensus of opinion on the overall cause, patterns and trends in nutrient enrichment. Improved knowledge of nutrient loads and concentrations is urgently needed, because at present our knowledge and understanding has not moved forwards to any great degree since the previous MCCIP reports.

Furthermore, there is general consensus that the impacts of climate change on nutrient enrichment and eutrophication are likely to be complex, and that a holistic ecosystem-based approach is required in order to improve our understanding of the cycling of nutrients in the water column and the coupling between water column and seabed processes (Painting *et al*., 2013; Statham, 2012). Such an approach requires ongoing research and monitoring, and the use of simulation models (Heath, 2010; Salihoglu *et al*., 2013) for examining fluxes and inter-annual variability in these fluxes. Studies to date have shown that improvements are needed in field measurements and models (Kelly-Gerryn *et al*., 2001; van der Molen *et al*., 2013), and on boundary conditions used in these models (Lenhart *et al*., 2010).

Examples of what could happen (from Heath 2010)

Heath (2010) assessed the relative impacts of natural variability in nutrient sources and concentrations (see also Figure 3, above) and the likely impacts of climate change, as summarised below:

Region 1 (Northern North Sea)

Runoff from land (precipitation–evaporation and transpiration) is high (approximately 1000mm year^{-1}) and contains high concentrations of silicate due to catchment geology. Nutrient loads are moderate for nitrogen and phosphorus, but high for silicate. Atmospheric deposition of nitrate is of similar magnitude to river inputs. The largest impact on variability in nutrient concentrations in this region is from ocean inputs. Therefore the impact of climate change on the nutrient status will be principally determined by processes (such as winter mixing) which affect concentrations in the upper layers of the ocean.

Region 2 (Southern North Sea)

Runoff from land is the lowest in the UK (<300mm year^{-1}), but the concentration of nitrogen, phosphorus and silicate is high. Region 2 is also influenced by nutrients from continental European rivers. Variability in the nutrient status of region 2 waters is strongly driven by precipitation patterns and river runoff. Simulated concentrations respond strongly to weather forcing patterns which may be similar to expected future climate conditions, with improved water quality due to dilution of river nutrient loads in winter runoff, and increased flushing rates.

Region 3 (Eastern Channel)

UK runoff is low, but concentrations of nitrogen and phosphorus in runoff waters are high. UK inputs of nitrate have been stable or decreasing over time, but the area is strongly influenced by nutrient inputs from the River Seine, which have been steadily increasing with time. Variability in the nutrient status of region 3 is likely to be most strongly influenced by runoff from continental Europe. Current models have difficulty predicting water quality in region 3 due to the bathymetry and the poor availability of detailed river input data.

Region 4 (Western Channel and Celtic Sea)

Runoff to region 4 is similar to region 1 (approximately 1000 mm year^{-1}), but concentrations of nitrogen and phosphorus in runoff waters are much higher. Transport of ocean water from across the shelf edge is an important component of oceanographic variability. Little is known about the likely consequences of climate change for this process, so predictions of likely climate impacts on nutrient concentrations are very uncertain.

Region 5 (Irish Sea)

Region 5 receives large inputs of nutrient from rivers, especially silicates. Simulated nutrient concentrations respond strongly to weather forcing, with conditions which may be similar to future climate predictions resulting in improved water quality. However, the future nutrient state of area 5 is most likely to depend mainly on future trends in anthropogenic inputs.

Region 6 (Minches and Western Scotland)

Runoff from the catchments discharging into region 6 is the highest in the UK, with values exceeding 2000 mm year^{-1}. However, concentrations of nitrogen, phosphorus and silicate in these waters are the lowest of all of the CP2 catchments, and consequently the river nutrient inputs are small. Winter concentrations will be primarily influenced by on-shelf mixing of ocean water and along-shelf transport from the Irish Sea (Region 5). The factors affecting variability in these processes are well understood. The impact of climate change on nutrient status of region 6 is very uncertain, but not likely to be greatly influenced by precipitation patterns despite the fact that the catchment is forecast to experience the greatest change in winter rainfall. Anthropogenic inputs of nutrient are only a small component of the regional nutrient budget, though at the inshore local scale nutrient inputs from aquaculture are important in some areas.

Region 7 (Scottish Continental Shelf)

Freshwater inputs, and runoff nutrient concentrations, are small for region 7 and annual inputs of nitrogen and phosphorus are among the lowest in the UK. Winter nitrate concentrations are probably mainly influenced by mixing from the ocean. Simulated nutrient status indicators were relatively insensitive to weather conditions which may represent future climate conditions, though these do not accurately reflect variability in either oceanic nutrient concentrations or the processes affecting exchange across the shelf edge. Hence, the nutrient status of region 7 with respect to climate change is uncertain.

Region 8 (Atlantic Northwest approaches)

There is little information on which to conduct an assessment of the eutrophication status of this region. However, it receives no land inputs of nutrient, so external inputs are entirely due to atmospheric deposition, upwelling and vertical mixing, and ocean transport. All of these factors may vary with expected patterns of climate change. Hence, we can suggest that the nutrient status of region 8 may be subject to influence by climate change, but that the sensitivity is very uncertain.

3. KNOWLEDGE GAPS

Although progress has been made since the last report card was published, the top priority knowledge gaps are similar to those given in previous years (Hydes *et al*., 2008; Heath, 2010):

a. Likely changes in riverine inputs - research is ongoing. Improved estimates of loading are required to improve boundary conditions used in models. This may be achieved through efforts such as E-HYPE, a pan European application of the Hydrological model, HYPE, (http://www.waterdiss.eu/http%3A/%252Fwaterdiss.eu/node/61)

b. Better understanding of the role of denitrification - few additional studies have been done since the last report. Neubacher *et al*. (2011; 2013) have considered the impact of oxygen deficiency on nitrogen cycling in North Sea sediments

c. Cross-shelf exchange of Atlantic water – research is underway through NERC and NERC/Defra research on physics and shelf sea biogeochemistry

d. The relative effects of increased storminess and increased stratification - these have not been addressed through targeted studies. High frequency data from moorings deployed at three depths at two sites in the stratified North Sea (Greenwood *et al*., 2010) provided some evidence of the impacts of stratification and sea water temperatures on chlorophyll and dissolved oxygen concentrations in these regions, and the relative impacts of storms on biogeochemical cycling at these sites.

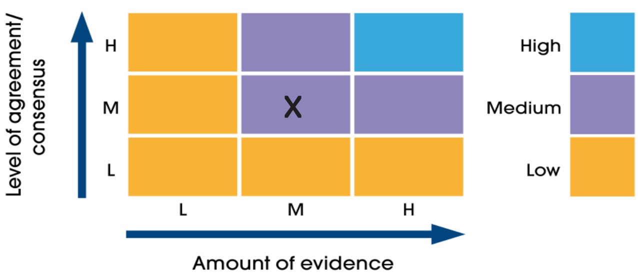
Continued collection of data remains a high priority, for validation and parameterisation of coupled physical-biogeochemical models which are increasingly being used to predict the impacts of direct anthropogenic pressures and climate change. Also, for statistical analyses of trends in nutrient loading and ecosystem state. Moreover, Tett *et al*. (2013) have highlighted the need for institutional time series of data to monitor ecosystem state for assessments of ecosystem health.

4. SOCIO-ECONOMIC IMPACTS

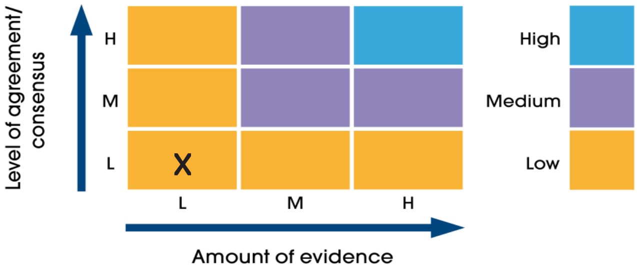
Undesirable disturbance to water quality and the balance of organisms that may result from anthropogenic nutrient enrichment can have considerable socio-economic impacts. For example, the development of nuisance macroalgae or harmful algal blooms, deoxygenation of water, and/or damage to benthic fauna has the potential to impact upon recreational use of water bodies and economic activities such as commercial fisheries. Furthermore, levels of nutrient enrichment which result in eutrophication in estuarine, coastal or offshore water bodies result in significant costs for water treatment authorities, and for agriculture, in relation to measures for the reduction of nutrient loads.

5. CONFIDENCE ASSESSMENT

What is already happening?



What could happen?



Analyses of trends in anthropogenic nutrient inputs to coastal waters and assessments of the eutrophication or ecological status in UK water bodies show that the majority of these water bodies are non-problem areas. However, we are still not able to say with any confidence what the impacts of climate change on nutrient enrichment are likely to be.

The levels of confidence in what is happening now has improved since the last report card, as the amount of evidence has improved, and there is consensus on the current state and assessment status. The level of confidence in what could happen remains unchanged.

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