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Searching for undesirable disturbance: an application of the OSPAR eutrophication assessment method to marine waters of England and Wales

Jo Foden · Michelle J. Devlin · David K. Mills · Stephen J. Malcolm

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Abstract The OSPAR Eutrophication Strategy requires assessment of eutrophication to be based on the ecological consequences of nutrient enrichment and not just on nutrient enrichment alone, i.e. finding reliable evidence for accelerated growth of algae and higher forms of plant life caused by anthropogenic nutrient enrichment, leading to undesirable disturbance. Fully flushed marine waters of England and Wales (salinity >30) were assessed against OSPAR's harmonised criteria of nutrient concentration and ratios, chlorophyll concentrations, phytoplankton indicator species, macrophytes, dissolved oxygen (DO) levels, incidence of fish kills and changes in the zoobenthos, using region specific thresholds. None of the thirteen assessment areas, including six nutrient enriched areas, exhibited evidence for undesirable disturbance. This paper details the methods and the overall outcome of the assessment. It presents evidence that undesirable disturbance caused by nutrient enrichment was not detected in English and Welsh marine waters assessed under the OSPAR procedure. The main reasons for the lack of eutrophication problems, such as the underwater light climate limiting the accelerated growth of algae, which might otherwise result from nutrient enrichment, are discussed.

Keywords Accelerated growth · Eutrophication · Assessment criteria · Marine · OSPAR · Undesirable disturbance

J. Foden · M. J. Devlin · D. K. Mills · S. J. Malcolm
Environment and Ecosystems, Centre for Environment, Fisheries and Aquaculture Science (Cefas), Pakefield Road, Lowestoft, Suffolk NR33 0HT, UK
e-mail: michelle.devlin@jcu.edu.au

D. K. Mills
e-mail: david.mills@cefas.co.uk

S. J. Malcolm
e-mail: stephen.malcolm@cefas.co.uk

J. Foden (✉)
School of Environmental Sciences, University of East Anglia, Norwich, Norfolk NR4 7TJ, UK
e-mail: jo.m.foden@uea.ac.uk

Present Address:
M. J. Devlin
Catchment to Reef Research Group, ACTFR, James Cook University, Douglas Drive, Townsville, QLD, Australia

Introduction

The OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic—the 'OSPAR Convention'—is the current instrument guiding international cooperation on the protection of the marine environment of the North-East Atlantic. The OSPAR Strategy to Combat Eutrophication seeks to achieve 'a healthy marine environment where eutrophication does not occur, by 2010' by identifying eutrophication status of the maritime area through OSPAR's Common Procedure (COMP)

(OSPAR Commission 2005). The first application of the OSPAR COMP by Contracting Parties was for the period 1996–2000, inclusive (OSPAR Commission 2003). The outcomes of the second application of the COMP to estuaries, coastal and offshore waters in the jurisdiction of the United Kingdom, for the period 2001–2005, were reported to the OSPAR Commission (2008). This paper presents the results of this second application to marine waters of England and Wales (salinity >30). The purpose of the COMP was to assess the status of waters with regard to the detection of anthropogenic eutrophication. The OSPAR Commission (2003) definition is, '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'. Therefore, the focus is detection of the potential undesirable ecological consequences of nutrient enrichment, rather than the desirable attributes of a well-balanced naturally enriched system (Tett et al. 2007).

OSPAR's definition, which is the same as European legal definitions, is supported in the scientific literature. Nixon (1995) defined eutrophication as 'an increase in the rate of supply of organic matter to an ecosystem'. Nutrient enrichment or hypernutrification is not indicative of eutrophication without accompanying undesirable effects (de Jonge and Elliott 2001). These definitions effectively separate elevated nutrient concentrations from direct effects such as accelerated growth (indicated by enhanced chlorophyll levels) and from consequences such as hypoxia or fish kills (Nixon 2009). Furthermore Duarte (2009) called for an integrated ecosystem perspective to be embraced, so that impacts beyond primary production are examined. As nutrient enrichment and accelerated algal growth are not of themselves indicative of undesirable change they are not adequate for identifying harmful consequences of enrichment (Nixon 1995, 2009; Tett et al. 2007). Indeed the recent European Court of Justice Ruling dismissed the argument that elevated chlorophyll alone must be considered an undesirable disturbance (ECJ 2009).

Undesirable disturbance has been defined as a perturbation of a marine ecosystem that appreciably degrades the health or threatens the sustainable human use of that ecosystem (Tett et al. 2007). An ecosystem perturbation may manifest in a variety of symptoms including, *inter alia*, increased abundance of opportunistic macroalgae, loss of seagrass, increased incidence of toxin producing algae (TPA), harmful algal bloom (HAB) events, deep water deoxygenation, benthic mortalities, and potential harm to fisheries and sustainable human use (de Jonge et al. 2002; Gowen et al. 2008). Therefore, we set out to test whether eutrophication exists in the marine waters of England and Wales by seeking evidence for undesirable disturbance in which the measurements were unambiguously linked to anthropogenic nutrient enrichment. As there are no unequivocal indicators of disturbance caused by marine eutrophication, a multi-step method using several parameters has been recommended (Bricker et al. 1999; Painting et al. 2007; Tett et al. 2007; ECJ 2009). To identify whether the Irish Sea is eutrophic, Gowen et al. (2008) sought evidence for three stages of eutrophication implicit in the OSPAR definition; eutrophication having occurred if there is evidence for all of the stages shown in Fig. 1 and of causal links between them. This approach was adopted in the application of the OSPAR COMP to marine waters of England and Wales, described herein.

For the first stage, nutrient levels in English and Welsh waters were compared against thresholds calculated from reference conditions (OSPAR Commission 2003, 2005). For stage two primary production and elevated biomass were measured. However, the role of nutrient inputs in controlling phytoplankton biomass has been generally oversimplified as other intrinsic and extrinsic factors also play a role (Duarte et al. 2009). Primary production and biomass measurements alone provide limited information on the biological response to drivers of change and disturbance to the balance of organisms, as they cannot adequately identify harmful consequences of nutrient enrichment (Tett et al. 2007). Rather it is the potential impact of increased production and biomass on the ecosystem structure and function which is of concern (Gowen et al. 2008), i.e. the third stage in Fig. 1. OSPAR's definition of eutrophication is based on the ecological consequences of nutrient enrichment, necessitating this multi-step approach with the focus on detection of undesirable disturbance. However, the prescribed COMP method does not fully align with the definition or approach. The COMP specifies the criteria to be measured and the method

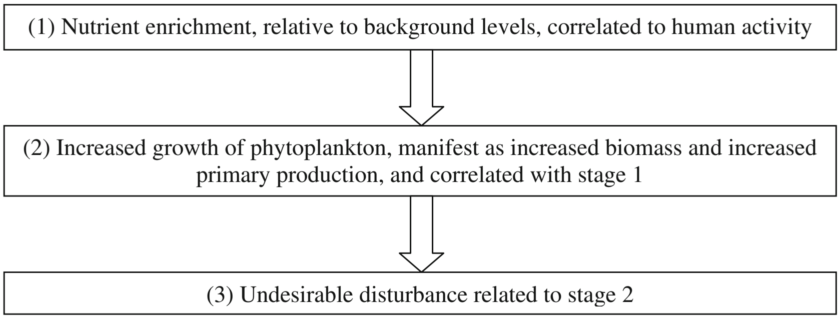

Fig. 1 Three stages in the identification of eutrophication (after OSPAR Commission 2003; Gowen et al. 2008)

for combining data in an overall assessment, but the links between some of these criteria (e.g. TPA) and eutrophication are unclear, or even contradictory.

The COMP characterises areas as problem areas, potential problem areas or non-problem areas (OSPAR Commission 2003): problem areas are those for which there is evidence of an undesirable disturbance to the marine ecosystem due to anthropogenic nutrient enrichment; potential problem areas are those for which there are reasonable grounds for concern that anthropogenic enrichment may be causing or may lead to an undesirable disturbance; and non-problem areas are those for which there are no grounds for concern that anthropogenic enrichment has disturbed or may in the future disturb the marine ecosystem.

This paper presents the outcomes of the application of the COMP to those marine waters of England and Wales considered at risk of eutrophication. English and Welsh coastal and offshore waters with salinity >30 are well flushed, defined as meso- (1–5 m) or macro- (>5 m) tidal ranges (Rogers et al. 2003). Much of the marine waters are turbid and optically complex, with light limitation influencing the maximum rate of primary production (Devlin et al. 2008, 2009). In coastal waters (salinity 30–34.5) suspended particulate matter (SPM) concentrations have been recorded between 3.0 and 95.0 mg l^{-1}, and in offshore waters (salinity >34.5) 2.8–33.3 mg l^{-1}. Consequently, a dose–response relationship between nutrient enrichment, accelerated growth and undesirable disturbance is not appropriate in these conditions. In such limited light regimes nutrient levels are not necessarily indicative of the system's ability to sustain production (Cloern 2001; de Jonge and Elliott 2001). The final determination of eutrophication was founded on evidence for undesirable disturbance. In conducting the assessment we attempt to highlight where the OSPAR definition of eutrophication and the COMP are misaligned.

Methods

Determination of area boundaries

The division into areas was designed to encompass the range of English and Welsh marine waters (salinity ≥30) that might be subject to eutrophication as a result of land-based anthropogenic nutrient input, where there is a risk that an undesirable disturbance may occur. Boundaries were also set on the basis of national jurisdiction, e.g. the median line in the North Sea and Channel. Thirteen marine water areas were delineated, as shown in Fig. 2a.

Nutrient enrichment is closely associated with freshwater inputs, so two salinity regimes were identified showing different degrees of freshwater influence:

Coastal: Irish Sea—salinity range 30 to <34
North Sea and English Channel—salinity range 30 to <34.5
Offshore: Irish Sea—salinity range ≥34.0
North Sea and English Channel—salinity range ≥34.5

The narrower coastal salinity band for the Irish Sea is a reflection of fully marine waters rarely exceeding 34.5 in this small (2430 km^3) coastal sea, which is partially landlocked by England and Ireland (Gowen and Stewart 2005). According to the dominant salinity regime each assessment area was delineated either as 'coastal' with significant freshwater input, or 'offshore' areas, either well mixed or seasonally stratified. The designated regime then formed the basis of the assessment.

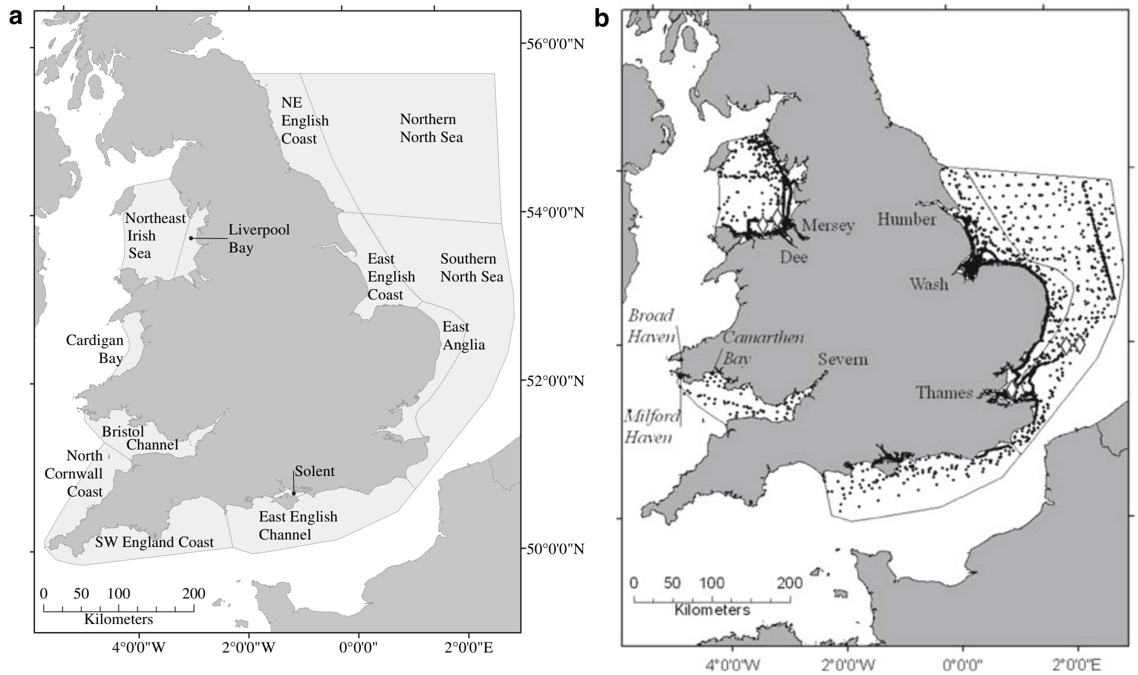

Fig. 2 OSPAR areas in England and Wales: **a** 13 marine areas assessed for eutrophication under OSPAR, **b** the eight areas subject to the full Comprehensive Procedure after screening, with surface water sample sites 2001–2005 (*filled circle*) and Cefas SmartBuoys (*open diamond*). The six major river catchments, which were analysed for riverine and direct DIN discharges, are indicated (*plain text*), and three locations (*italicised text*) where shellfish incidents were recorded

Screening areas and the eutrophication assessment process

Firstly areas were screened; a procedure that allows for the designation of areas with no or limited nutrient enrichment as obvious non-problem areas. Secondly, a full eutrophication assessment (the OSPAR Comprehensive Procedure) was conducted in remaining areas, following the three-stage process shown in Fig. 1.

Winter dissolved inorganic nitrogen (DIN = $NO_2 + NO_3 + NH_4$) concentrations were used to screen those areas least susceptible to eutrophication impacts from nutrient enrichment. Data originated from five main sources: (a) spatial nutrient data were obtained from the National Marine Monitoring Program (NMMP) database held by the Centre for Environment, Fisheries and Aquaculture Science (Cefas, http://www.cefas.co.uk/data/marine-monitoring/national-marine-monitoring-programme-(nmmp).aspx); (b) the Water Framework Directive (WFD) nutrient and chlorophyll database held by the UK Environment Agency (EA), (c) nutrient loading data from the EA; (d) high frequency temporal data from Cefas SmartBuoys moorings (www.cefas.co.uk/monitoring) in the Thames embayment, Liverpool Bay, northeast Irish Sea and the Southern North Sea (locations in Fig. 2b), and; (e) supplementary data from local sources, e.g. Kennington et al. (2003, 2004, 2005) in the northeast Irish Sea. SmartBuoys are fixed moorings housing a suite of autonomous instruments providing high frequency (hourly and daily) observations of physical, chemical and biological parameters (Mills et al. 2003). Regions with concentrations below 15 μM during the period 2001–2005 were screened out (OSPAR Commission 2003). This threshold was used in the first application of the OSPAR COMP and is justified in the following section. Remaining areas with mean winter nutrients in excess of 15 μM were subject to the full eutrophication assessment under the OSPAR Comprehensive Procedure methods.

For the full eutrophication assessment relevant parameters from OSPAR's criteria (Table 1) were selected and applied to areas for each of the 5 years. This enabled trends to be identified within regions.

Table 1 OSPAR harmonised assessment criteria and their respective assessment thresholds for the Comprehensive Procedure

Category	Harmonised criteria
I	*Degree of nutrient enrichment*
	Riverine total N and total P inputs and direct discharges (RID): elevated inputs and/or increased trends (compared with previous years)
	Winter DIN and/or DIP concentrations: elevated level(s) (defined as concentration >50% above salinity related and/or region specific background concentration)
	Increased winter N/P ratio (Redfield N/P = 16): elevated cf. Redfield (>24)
II	*Direct effects of nutrient enrichment (during growing season)*
	Maximum and mean chlorophyll concentration: elevated level (defined as concentration >50% above spatial (offshore)/ historical background concentrations)
	Region/area specific phytoplankton indicator species: elevated levels (and increased duration)
	Macrophytes including macroalgae (region specific): Shift from long-lived to short-lived nuisance species (e.g. *Ulva* spp.)
III	*Indirect effects of nutrient enrichment (during growing season)*
	Degree of oxygen deficiency: decreased levels (<2 mg l^{-1}: acute toxicity; 2–6 mg l^{-1}: deficiency)
	Changes/kills in zoobenthos and fish kills: kills (in relation to oxygen deficiency and/or toxic algae); long term changes in zoobenthos biomass and species composition
	Organic carbon/organic matter: elevated levels (relevant in sedimentation areas)
IV	*Other possible effects of nutrient enrichment (during growing season)*
	Algal toxins (DSP/PSP mussel infection events) incidence, related to Category III criteria

Note: Parameters found at levels above the assessment level are considered as ‘elevated levels’ and entail scoring of the relevant parameter category as (+). For concentrations, the assessment level is defined as a justified area-specific % deviation from background, not exceeding 50% (OSPAR Commission 2005)

Data sets for 2001–2005 were statistically analysed to establish whether parameters were found at levels exceeding a criterion’s assessment threshold, entailing scoring as ‘+’, or within the threshold as ‘−’. Using the three-stage approach (Fig. 1) an initial classification was reached for each area. All relevant information concerning the harmonised assessment criteria and supporting environmental factors was appraised to provide a sufficiently sound and transparent account of the reasons for assigning a particular status to an area. This process resulted in an enormous quantity of data, which it is both impractical and unnecessary to reproduce here as full area reports are available from http://www.cefas.co.uk/publications/scientific-series/ospar-eutrophication-assessments.aspx.

Assessment criteria and thresholds

To establish whether areas were eutrophic the Comprehensive Procedure categories of harmonised assessment criteria (Table 1) were aligned with the three-stage approach shown in Fig. 1, as follows. For the first stage, Category I criteria determined anthropogenic nutrient enrichment relative to background levels. Increased chlorophyll and primary production, the second stage of eutrophication, were assessed through the Category II criteria. Evidence for undesirable disturbance used Category III and IV criteria for the third stage. Threshold values were set for criteria, against which the available data for each area were assessed, as described below.

In most European waters the historic record is limited and derived values were used to set assessment standards and thresholds. Atlantic water entering the shelf seas of northern Europe provides a suitable background condition from which to derive standards (Gowen et al. 2002; OSPAR Commission 2003). Standards for nutrient concentrations, nutrient ratios, chlorophyll concentration and the potential level of primary production in waters of full marine salinity (>34) were set from Atlantic water values. Salinity gradients exist in coastal systems due to riverine influences and must be taken into account in any assessment of nutrient enrichment (Devlin et al. 2007a). In order to compensate, OSPAR requires nutrient concentrations to be normalised for salinity (OSPAR Commission 2005). This normalised estimate could then be compared with the region-specific background level. Presented below are the methods used for each criterion, as they appear in Table 1. Descriptions are given of the standards specific to English and Welsh marine waters and the calculated thresholds for each assessment criterion.

Nutrient enrichment

OSPAR specifies three nutrient criteria: trends in annual nutrient loadings, winter nutrient concentrations and N:P ratios. Although the assessment period of the application of the COMP was 2001–2005, OSPAR requires nutrient trends to be compared with previous years of data. Therefore, annual DIN data from 1992 to 2005 were analysed for input trends from major English and Welsh catchments: the Bristol Channel, Liverpool Bay, Humber-Wash and the Thames (six of the major rivers contributing to these catchments are shown in Fig. 2b). A trend was defined as any change of more than 5% over a period ≥10 years (OSPAR Commission 2005). Using data collected for the Riverine Inputs and Direct Discharges survey statistical trend analysis was conducted for major catchments (Fryer and Nicholson 1999). This helped in determining whether the present status is likely to improve or worsen and whether the risk of undesirable disturbance might increase.

Work in UK waters has shown that dissolved nitrogen is the limiting nutrient in marine waters (e.g. Gibson et al. 1997; Gowen et al. 2008), therefore DIN analysis was prioritised. Elevated levels of DIN concentrations during the winter months of November–February 2001–2005, inclusive, were assessed from 'mixing diagrams'. Concentrations of DIN were plotted against salinity creating mixing curves and normalised to a single value of the salinity. Dissolved inorganic nitrogen was normalised to specific salinities for coastal (32) or offshore (34 or 34.5) waters and compared to the region-specific background concentration. In order to allow for natural variability, and in the absence of more specific information, the assessment level was defined as the concentration 50% above the salinity-related area-specific background concentration (OSPAR Commission 2003, 2005). Background concentrations for offshore waters were identified as the mean winter nutrient concentrations in Atlantic seawater (Table 2a), derived from the shelf break in February 1994, 1998 and January 1999 (Gowen et al. 2002). Thresholds for nutrients in coastal waters were based on the reference freshwater end point of 42 μM at 0 salinity (UKTAG 2008) and fully marine reference concentration of 10 μM at salinity 35. These reference values for freshwater and salt-water ends provided the mixing curve relationship for DIN against salinity. Thresholds were then normalised to specific salinity (Table 2b).

The behaviour of winter DIP (dissolved inorganic phosphorous) is complex in areas with fine sediment (House et al. 1998), therefore phosphorous was assessed as part of the N:P ratio. Increased winter N:P ratios may indicate an increased risk that potentially nuisance and toxic algal species will proliferate during the subsequent growing season (Burkholder et al. 2001). The amount of deviation from the Redfield ratio (C:N:P ratio of 106:16:1) was used to infer changes in the nutrient ratios present within a water body. The deviation indicates which nutrient is first likely to become limiting to algal growth when nutrient concentrations decrease to growth rate limiting concentrations (Tett et al. 1985). The Redfield N:P ratio of 16:1 was used as the standard. Elevated ratios for the period 2001–2005 were judged to be those that exceeded the 16:1 ratio by 50%, i.e. 24:1 (Table 2c). Ratios of N:Si are also considered to have some predictive power in relation to the balance between diatoms and dinoflagellates in the sea (Gillbricht 1988; Tett et al. 2003). A deviation of new observations in the diatom:dinoflagellate balance from a reference envelope would be considered undesirable (Tett et al. 2007, 2008).

Increased growth of phytoplankton and increased primary production

Evidence was sought for accelerated growth and increased primary production caused by anthropogenic enrichment, using chlorophyll concentrations, phytoplankton indices and macrophyte abundance. Data sources included NMMP, Cefas SmartBuoys (Mills et al. 2003), the UK phytoplankton database (WFD Marine Phytoplankton Database) (CEC 2000), the EA and the Countryside Council for Wales (CCW). Cefas samples was determined through the acidification step, which corrects for degradation products, i.e. phaeopigments, but not for presence of chlorophyllide-*a* (Tett 1987). As all the data were

Table 2 Calculations of thresholds for OSPAR Comprehensive Procedure in UK marine waters

(a) Nutrient concentration (Gowen et al. 2002)

Nitrate + Nitrite threshold			*Phosphate threshold*			*Silicate threshold*		
Mean	Range	+50%	Mean	Range	+50%	Mean	Range	+50%
7.20	5.25–9.90	*10.80 µM*	0.45	0.34–0.65	*0.68 µM*	3.27	2.30–5.15	*4.91 µM*

(b) Mean winter (November–February) dissolved inorganic nitrogen (DIN)

	DIN threshold (standard + 50%)
CW; normalised to salinity of 32, reference value = 13 µM	*20 µM*
Offshore; normalised to salinity of 34.5, reference value = 10 µM	*15 µM*

(c) Nutrient ratios

	Standard background ratio value	*Nutrient ratio threshold (standard ±50%)*	
N:P	16:1	*−50% = 8:1*	*+50% = 24:1*
N:Si	2.2:1	*−50% = 1.1:1*	*+50% = 3.3:1*

(d) Chlorophyll—growing season (March–September)

	Standard background ratio value	*Chlorophyll threshold (standard +50%)*
Offshore waters	6.7 µg l^{-1} and C:Chl factor of 0.012	*10 µg l^{-1}*
CW	10 µg l^{-1} and C:Chl factor of 0.02	*15 µg l^{-1}*

(e) Phytoplankton indicator species (Devlin et al. 2007b)

Total cell count—assessment of occurrences over 250,000	*Phytoplankton threshold = All exceedance counts less than 25% of all sampling times over 5 years*
Phaeocystis cell count—occurrences over 10^6	
Any single taxa—occurrences over 10^7	
Counts of chlorophyll—occurrences exceeding 10 µg l^{-1}	

(f) Macroalgae (Scanlan et al. 2007)

Macroalgal biomass	Macroalgal cover	*Macroalgae threshold = 500 g m^{-2} wet weight and 15% of intertidal area*
<500 g m^{-2} wet weight	<15% of intertidal area	
>500 g m^{-2} wet weight	>15% of intertidal area	

(g) Dissolved oxygen (Best et al. 2007)

≥5.7 mg l^{-1}	All life-stages of salmonids and estuarine fish	*Dissolved oxygen threshold 4.0 mg l^{-1}*
≥4.0 <5.7 mg l^{-1}	Presence of salmonids and estuarine fish	
≥2.4 <4.0 mg l^{-1}	Most life-stages of non-salmonid adults	
≥1.6 <2.4 mg l^{-1}	Presence of non-salmonids, poor survival of salmonids	
<1.6 mg l^{-1}	No salmonids present marginal survival of resident species	

(h) Zoobenthos and fish kills

Zoobenthos and fish kill thresholds = Incidence of fish kills or documented changes in zoobenthos to assess disturbance, related to eutrophication

(i) Toxin levels in bivalve mollusc tissue (Shellfish Hygiene Directive 91/492/EEC)

Toxin	Maximum permitted levels	*TPA threshold = Proportion of failed tissue samples; whichever was most for ASP/PSP/DSP.*
PSP	80 µg per 100 g flesh	*<10% no undesirable disturbance*
DSP	Presence in flesh	
ASP	20 µg per g flesh	

Thresholds in italics

CW coastal waters

combined, results are reported as measurements of extracted chlorophyll and not chlorophyll *a*. The result is a likely over-estimation of chlorophyll *a*, which may be considered a more precautionary approach. Other OSPAR Contracting Parties report a mixture of chlorophyll or chlorophyll *a*. Ireland recognised the problem of employing different chlorophyll extraction techniques and OSPAR's recommendations include further harmonisation in methodological aspects of chlorophyll measurements (OSPAR Commission 2008).

An appropriate standard for assessing chlorophyll (Chl) concentration was derived from background nutrient concentrations by making reasonable assumptions about nutrient conversion to plant biomass. Algal C:N ratios remain relatively consistent with the Redfield ratio of 6.6:1 (Geider and La Roche 2002). In contrast, variability of the Chl:C ratio owing to physiological acclimation, light environment and taxonomic composition has been recognised as a major source of uncertainty (Geider et al. 1998). The Chl:C ratio is inversely correlated with irradiance and positively related to growth rate, contributing to the variability found in the Chl:C ratio. Ratios of Chl:C range from <0.01 to 0.06 g g^{-1} (Geider et al. 1998; Zonneveld 1998). For offshore waters a reasonable C:Chl factor of 0.012 determined the background value of 6.7 μg l^{-1} and for coastal waters, where the level of production may be expected to be higher, a C:Chl factor of 0.02 set the background value of 10 μg l^{-1} chlorophyll (OSPAR Commission 2003; Painting et al. 2005). To allow for natural variability the assessment level was defined as the concentration plus 50% above the salinity-related and/or area-specific background concentration (OSPAR Commission 2005), so that threshold values were 10 μg l^{-1} chlorophyll in offshore waters and 15 μg l^{-1} in coastal waters (Table 2d).

The salinity gradient of coastal waters complicated the derivation of chlorophyll standards. For such particulate material it was not possible to use the same approach as that used for dissolved substances. The OSPAR assessment period was the March–September growing season, which inevitably included high spring-bloom chlorophyll values. The statistical treatment applied was calculation of 90th percentile because chlorophyll data are non-parametric. This is a recognised statistic which encompasses the spread of chlorophyll data omitting highly skewed values that can be present during bloom periods (Aitchison 1986; Clarke and Warwick 1994; Bricker et al. 2003; Devlin et al. 2007b). The maximum and mean levels were reported as specified in the harmonised assessment criteria (Table 1), though these were deemed to be of limited value because of the non-normal distributed data and difficulties involved in sampling the maximum concentration, even when using high frequency sampling platforms. There is consensus among Contracting Parties that the 90th percentile is appropriate for reporting chlorophyll and in future will replace measurement of chlorophyll maximum (OSPAR Commission 2008).

Known consequences of marine eutrophication on the phytoplankton community include: increased production, in particular of the rapid growth of opportunistic, fast growing primary producers, linked to detrimental effects (Devlin et al. 2007b); red tides; water discolouration and foaming, such as that caused by the colonial flagellate *Phaeocystis pouchetii* in the southern North Sea (Lancelot et al. 1987). For phytoplankton indicator species, rather than assessing region/area specific species as stated in Table 1, an integrated tool was used, designed to encompass these consequences of nutrient enrichment. The index was developed by Devlin et al. (2007b) for the purposed of WFD ecological status classification. It includes measures of *Phaeocystis* spp. and any phytoplankton taxa with abundance over a defined threshold. The overall index (I_E, Eq. 1) is composed of counts of the four attributes within the tool. The index is a summary of the frequency of elevated biomass and phytoplankton taxa counts within a whole population. Samples during the growing season between March and September were assessed against this index.

$$I_E = \{\mathrm{SUM}\ [T] + [P] + [S] + [\mathrm{CHL}]/4\} * 100 \quad (1)$$

where T is the sum of the occurrence of any species at >250,000 (excluding *Phaeocystis*), P is *Phaeocystis* cell counts $>10^6$, S is total cell counts $>10^7$, and CHL is counts of chlorophyll >10 μg l^{-1} over a 6 year period. Chlorophyll counts are included in this index because the frequency of occurrence is a different measure from chlorophyll concentration per year which is used in the specific threshold assessment described above to assess increased primary production. The WFD boundary between Good and Moderate equates to the phytoplankton indicator species' threshold for the OSPAR Comprehensive Procedure (Devlin et al. 2007b), summarised in Table 2e.

The OSPAR Commission (2008) states in particular the shift from long-lived to short-lived nuisance species like *Ulva* spp. is a relevant assessment of macrophytes for coastal areas. This was interpreted as the existence of excessive blooms of these opportunistic macroalgae. It is not a relevant parameter for offshore regions with no coast. Macroalgae data were assessed using thresholds developed by Scanlan et al. (2007), simplified for the derivation of OSPAR Comprehensive Procedure thresholds (Table 2f). The thresholds of 500 g m^{-2} biomass and 15% cover of available intertidal area were determined as the limit of acceptable abundance, above which deleterious effects to biota and sediments occur (Scanlan et al. 2007).

Undesirable disturbance

Indirect effects of nutrient enrichment causing an undesirable disturbance include: reductions in dissolved oxygen (DO) concentrations; changes to fish and zoobenthos communities; organic carbon or organic matter enrichment; and algal toxins (DSP/PSP mussel infection events) incidence (OSPAR Commission 2005). For each area the relevant criteria were assessed and scored as '+' if the threshold had been exceeded, or '−' where it had not.

Increased production may give rise to extra biochemical oxygen demand and hence increased removal of oxygen in enclosed waters, resulting in local anoxia (Tett et al. 1986). Fish and crustacea are sensitive to reduced DO, in particular the early life stages of fish and migratory salmonids (Stiff et al. 1992; Nixon et al. 1995). Thresholds for hypoxia need to be precautionary because once breached, ecosystems are more prone to experience future hypoxia (Conley et al. 2009). Best et al. (2007) reviewed the effects of reduced DO levels on fish and this determined the DO standards for eutrophication assessment (Table 2g). Regions were deemed as having exceeded the threshold (scoring '+') where DO levels were <4 mg l^{-1}, using the 5th percentile of samples during the growing season of early summer (May) to early autumn (September). The <4 mg l^{-1} threshold applies to atmospherically ventilated layers of waters and where the bottom water is rapidly replaced, not naturally deoxygenated waters of deep basins (Best et al. 2007). The use of the 5th percentile statistic is compatible with national standards, established by Stiff et al. (1992) and used by the UK EA, and extant European legislation, e.g. Shellfish Waters Directive (CEC 2006), WFD (CEC 2000). DO data were available from the EA and Cefas SmartBuoys.

Regional Sea Fisheries Commission provided data on incidence of fish kills. Benthic data has been gathered as part of the NMMP, though it has not been directly targeted at assessment of eutrophication: the Benthic Ecology of the Western North Sea (Law et al. 2005) study was used, which compared species assemblages of samples from 2001 to 2002 with assemblage data from the ICES North Sea Benthos Survey (Künitzer et al. 1992); the UK infaunal trophic index (ITI) uses a system in which ≥60.0 indicates unchanged and 30–60 indicates changed biota (Codling and Ashley 1992); and in the AZTI-Tecnalia Foundation's Marine Biotic Index (AMBI) system, ≤3.3 indicates undisturbed or slightly disturbed communities and <5.0 indicates moderately disturbed (Borja et al. 2000). Death of benthic animals or fish as a result of oxygen deficiency (or from toxic poisoning by algae) and long term changes in the biomass and taxa composition of the benthos can indicate an impact of sustained organic enrichment. This can be very obvious in the vicinity of specific sewage or industrial discharges but it is difficult to link such changes in wider sea areas to nutrient enrichment, given the background climatic variability. Where there was incidence of fish kills or changes in zoobenthos indicative of disturbance related to eutrophication (Table 2h), areas were scored '+'.

The link between nutrient enrichment and incidence of toxic algae is still under investigation. HAB events often coincide with distorted nitrate: phosphate ratios (e.g. Burkholder et al. 2001) and low turbulence (e.g. Dahl and Tangen 1993), but there is a history of toxic algal problems occurring in areas where there are low or no significant nutrient inputs; for example on the west coast of Scotland (Fehling et al. 2006). Indeed the OSPAR Commission (2008) concludes there is an emerging consensus that the link between nutrient enrichment and toxin producing algal blooms is not sufficiently robust for this parameter to be used in the Comprehensive Procedure assessment and research is needed to justify it as an indicator for eutrophication. However, the incidence of algal toxins causing diarrhetic, amnesic or paralytic shellfish poisoning (DSP, ASP and PSP) mussel infection events was still considered, as required at the time of applying the Comprehensive Procedure. Assessment was based on the frequency of positive toxicity tests in bivalve mollusc tissue that exceeded Food Standards Agency (FSA) limits for PSP, ASP and DSP in shellfish flesh as specified by the European Commission Shellfish Hygiene Directive 91/492/EEC (Food Hygiene (England) Regulations 2006). In fulfilment of the these regulations the UK already has monitoring and management programmes in place to ensure the protection of the public from the harmful effects of consuming shellfish that have been contaminated by toxic algae or toxins. The number of bivalve mollusc tissue samples taken within each OSPAR area during the assessment period was counted, and the percentage of samples failing the FSA standards for PSP, ASP and DSP in shellfish tissue, i.e. exceeded the Action Level, was calculated. If analyses showed samples above the FSA Action Levels in more than 10% of cases, the site was deemed to have exceeded threshold limits (Table 2i), scoring '+'.

Adequacy of data and confidence in assessment

Levels of confidence in the data were assigned to the OSPAR assessment, in a scheme similar to that used by Bricker et al. (2007), who reported on eutrophication symptom variables. The adequacy of the data was analysed in respect of its quantity, spatial coverage and temporal resolution. The final classification included an assessment of confidence for each of the three stages of eutrophication assessment—nutrient enrichment, accelerated growth and undesirable disturbance (Fig. 1)—ranked as high, medium or low, and an overall confidence in each area's final assessment.

In the first instance confidence was assessed with regards to the consistency of patterns in the data for each criterion. For example, areas with nutrient concentrations consistently in excess of the threshold in every year would be at high confidence, whereas areas with variable annual concentrations above and below threshold would be at medium confidence. Figure 3 gives examples of confidence levels for different combinations of annual results. For 'data consistency' there were five outcomes, one for each year of assessment, which were above (+) or below (−) threshold. Secondly, confidence in 'data quantity' was based on the number of years with sufficient data. Inadequate or absent data would result in low confidence (example combinations in Fig. 3). This technique worked well for nutrient enrichment and accelerated growth criteria, but was more difficult to apply for undesirable disturbance, relying on an expert opinion of robustness regarding data types and coverage. The final classification was determined on the basis of combining confidence estimates for the three stages of eutrophication. So for nutrient enrichment, accelerated growth and undesirable disturbance, respectively, the examples in the last section of Fig. 3 illustrate the approach. Extra weighting was given to undesirable disturbance in the determination of overall confidence.

Results

Screening defined areas

The screening procedure was carried out for all areas considered to be at risk of eutrophication (Fig. 2a). The procedure identified five coastal and offshore areas with low dissolved inorganic nutrient concentrations; DIN range 6.0 to <15 μM. These were categorised as non-problem areas. The eight coastal and offshore areas which exceeded the 15 μM DIN threshold were subject to the full eutrophication assessment (Fig. 2b).

Variations in the data coverage reflect the current level of perceived risk and the practicalities of monitoring (Fig. 2b). Sampling variations existed between the different parameters where, for example, there were more data available for winter nutrient concentrations and chlorophyll than for phytoplankton species.

Assessment criteria and thresholds

Data for each criterion were analysed for annual levels and trends in the eight assessed areas. The outcomes were reported to the OSPAR Commission (2008) in individual area reports and a national report. Reproducing the annual data for every criterion for each area would be both impractical and unnecessary here. Rather, the results for the eight areas have been summarised across the 5 year assessment period for this paper. These mean values are reasonable reflections of the final outcomes as detailed in the reports. Individual area reports are

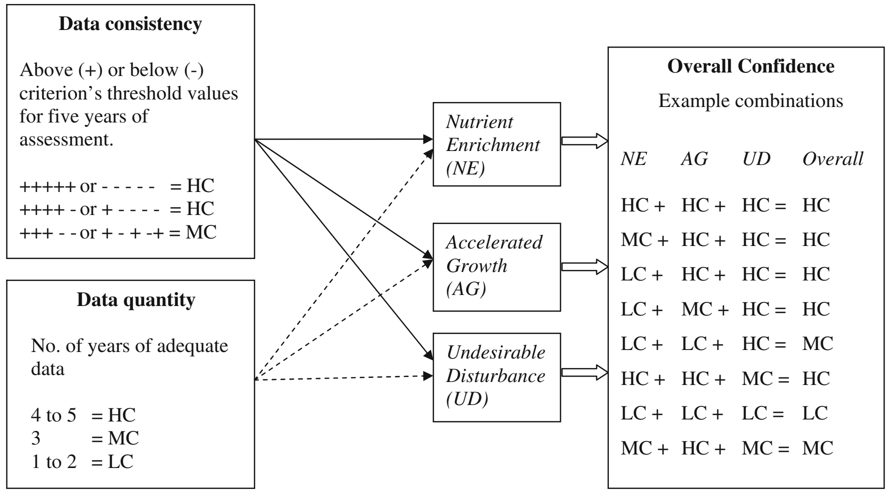

Fig. 3 Assigning levels of confidences in assessment; *HC* high, *MC* medium, *LC* low confidence. Example combinations are given in the final 'Overall Confidence' box

available at http://www.cefas.co.uk/publications/scientific-series/ospar-eutrophication-assessments.aspx.

Nutrient enrichment

Annual riverine and direct inputs of DIN from 1992 to 2005 varied between 1500 tonnes measured into the Solent in 1997, and 68000 tonnes into the east English Coast area in 1998. There were neither statistically significant changes nor identifiable trends in DIN inputs, in any individual area.

Figure 4a shows the mean winter (November–February) DIN concentrations of assessed areas, normalised to coastal or offshore salinity, 2001–2005. The east English Channel and southern North Sea areas had mean winter DIN less than the 15 µM threshold for waters of salinity >34.5. All other areas had mean winter DIN in excess of their relevant salinity-type thresholds. Similarly, the east English Channel and southern North Sea had mean DIN:DIP ratios below the threshold (24:1), as Fig. 4b shows. The mean DIN:DIP ratios of East Anglia, Liverpool Bay and the northeast Irish Sea were also all <24:1. Only the east English coast, the Solent and the Bristol Channel areas had mean ratios >24:1.

Increased growth of phytoplankton and increased primary production

Chlorophyll concentrations, phytoplankton indices and macrophyte abundance were analysed for the second stage in determining eutrophication caused by anthropogenic enrichment (Fig. 1).

Figure 5 shows the mean March–September chlorophyll 90th percentiles for each area. Offshore waters of the east English Channel and southern North Sea had chlorophyll 90th percentiles $<10\ \mu g\ l^{-1}$. The coastal salinity waters of the Solent, Bristol Channel, Liverpool Bay and the northeast Irish Sea had chlorophyll 90th percentiles $\leq 15\ \mu g\ l^{-1}$ (the threshold for waters of coastal salinity). The mean percentiles in East Anglia and eastern English coast waters were well in excess of the $15\ \mu g\ l^{-1}$ threshold; 34.2 and $36.7\ \mu g\ l^{-1}$, respectively.

The percentage frequency of elevated phytoplankton taxa counts within each OSPAR area's population was calculated for the assessment period and the results are illustrated in Fig. 6. There were no data for the southern North Sea as samples are primarily collected in estuarine or coastal waters. The frequency of elevated phytoplankton count events over the assessment period was below the 25% threshold in the remaining seven areas.

The EA and CCW conduct intertidal surveys where opportunistic macroalgae are present. As no opportunistic macroalgae blooms have been found requiring monitoring in the eastern English coast, Solent and Liverpool Bay areas, no surveys are conducted. The east English Channel and southern North Sea areas are offshore waters and therefore this criterion is not applicable. During 2001–2005 three macroalgae surveys were conducted in the intertidal of the Northeast Irish Sea, five in East Anglia and five in the Bristol Channel areas. None were in excess of the thresholds as described in Table 2.

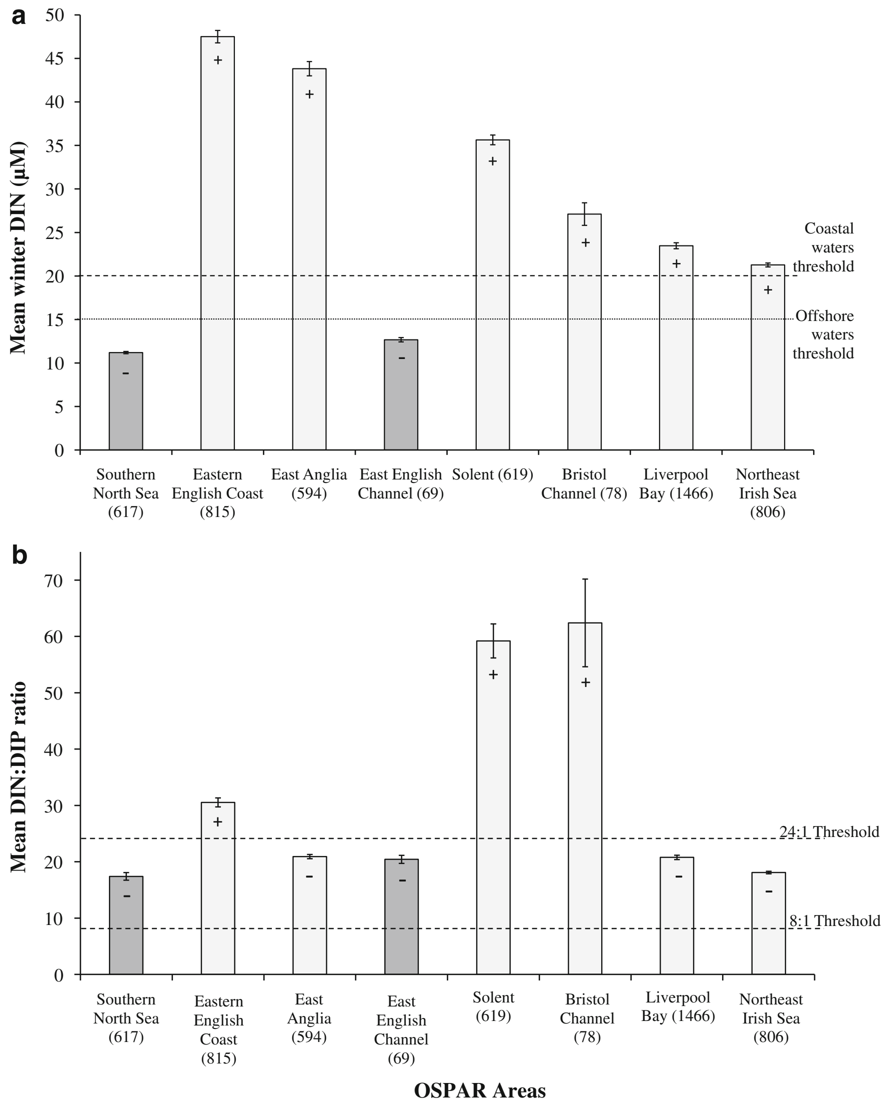

Fig. 4 Nutrient values for eight OSPAR areas, for the assessment period 2001–2005, inclusive (*dark column* offshore and *light column* coastal): **a** mean winter DIN normalised to salinity, and **b** mean DIN:DIP ratios, with standard error bars. *N* for each area shown in *parentheses*. *Dashed lines* are thresholds, '+' indicates values exceed threshold and '−' indicates values within threshold

Undesirable disturbance

The results for the criteria used in determining indirect effects of nutrient enrichment are shown in Table 3. These constitute indicators of undesirable disturbance in the third stage of the process of searching for evidence of eutrophication. DO concentrations did not indicate depletion in the assessed areas (Table 3a). In seven areas DO was never observed at less than 4 mg l^{-1} during 2001–2005. Only one sample was measured at less than 4 mg l^{-1} in the East Anglia area, constituting 0.26% of records which was below the threshold, so all areas were scored '−'.

There were no finfish kills in any area during 2001–2005. Only in the Bristol Channel were there records of shellfish incidents; cockle mortality in Carmarthen Bay, *Bonamia* sp. in Milford Haven and algal scums (creating a froth or film on the water surface) in Broad Haven, Wales (Fig. 2b). A causal link between these incidents and increases in anthropogenic nutrient enrichment has not been found. Table 3b summarises the findings for three indices used to identify changes to the zoobenthos. There were no clear patterns in any area. Outcomes for ITI and AMBI were inconclusive in terms of change linked to anthropogenic nutrient enrichment. Importantly, the Benthic Ecology of the Western North Sea

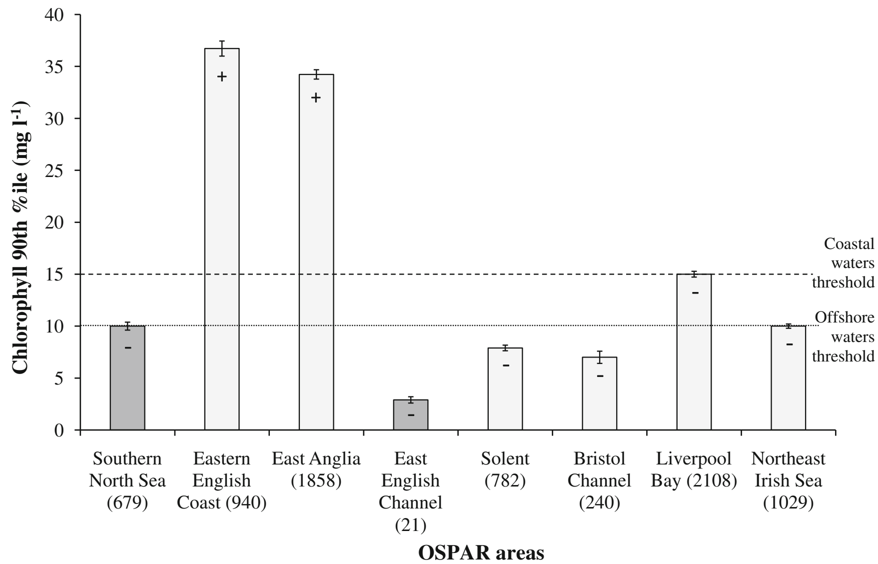

Fig. 5 Chlorophyll 90th percentiles for eight OSPAR areas for the assessment period 2001–2005, inclusive (*dark column* coastal and *light column* offshore), and 95% confidence limits. *N* for each area shown in *parentheses*. Coastal and offshore chlorophyll thresholds are shown as *dashed lines* (15 and 10 µg l^{-1}, respectively). *Dashed lines* are thresholds, '+' indicates values exceed threshold and '−' indicates values within threshold

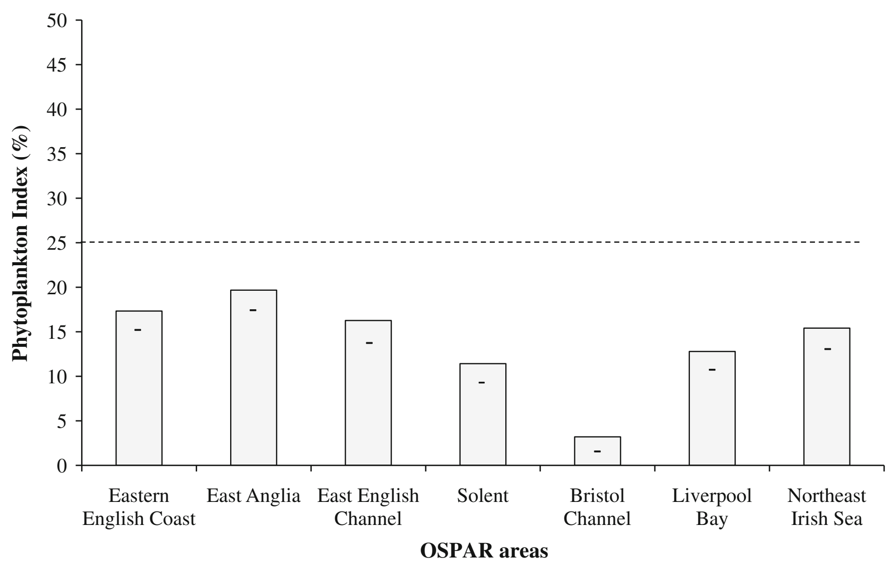

Fig. 6 Phytoplankton Index. Percentage frequency of elevated species counts for 2001–2005, inclusive. *Dashed line* is the 25% threshold. Above this threshold areas would be deemed as having excessive frequency of elevated phytoplankton counts (+). '−' indicates values are within threshold

study (Law et al. 2005) showed there to be a statistically significant correlation between community patterns and water depth or sediment characteristics, but no significant correlation with contaminant levels or enrichment (Marine Environment Monitoring Group (Cefas) 2004). Data were not available for the Solent and Liverpool Bay.

Results of tests for the presence and levels of algal toxins in bivalve mussel flesh are summarised in Table 3c. These tests are conducted in bivalve harvesting areas around the coast of England and Wales and consequently the criterion is not applicable in the southern North Sea area as it has no coastline. For the remaining seven OSPAR areas there have been no positive tests for PSP and ASP toxins. DSP was absent from the east English Channel and Liverpool Bay, but was found in ≤4.1% of samples from five areas. Therefore, the threshold of 10% of all sampling occasions was not exceeded and the seven areas were scored as '−'.

Five of the areas were assessed for all three of the criteria constituting undesirable disturbance. The east English Coast, East Anglia, east English Channel, Bristol Channel and the northeast Irish Sea scored '−' for each criterion, combined to '−' score overall for the third stage of detecting undesirable disturbance.

Table 3 Results for category III and IV criteria for eight OSPAR areas, 2001–2005

(a) Dissolved oxygen (DO) concentrations

OSPAR area	No. samples	Range, mg l^{-1} (no. samples)	Mean	% frequency of samples <4 mg l^{-1}	Score
Southern North Sea	24	6.21–9.15	7.74	0.00	–
Eastern English Coast	242	0.48–10.50	7.69	0.00	–
East Anglia	382	2.55–10.90	7.87	0.26	–
East English Channel	250	6.63–15.00	9.83	0.00	–
Solent	173	6.34–11.00	7.86	0.00	–
Bristol Channel	938	6.28–10.94	7.92	0.00	–
Liverpool Bay	326	4.60–10.95	8.29	0.00	–
Northeast Irish Sea	104	6.92–10.98	8.26	0.00	–

(b) Finfish kills and zoobenthos indices[a]

OSPAR area	Finfish kills	Benthic indices			Score
		Infaunal trophic index (ITI)	AMBI marine biotic index	Benthic Ecology of the Western North Sea	
Southern North Sea	None	Normal	2.5	No long term change	–
Eastern English Coast (four benthic surveys)	None	I; 41.4	I; 2.6	No long term change	–
		II; 65.6	II; 3.1		
		III; 60.3	III; 4.3		
		IV; 38.5	IV; 4.7		
East Anglia	None	31.0	3.4	No long term change	–
East English Channel	None	41.5	3.7	n/a	–
Solent	None	n/d	n/d	n/a	?
Bristol Channel (two benthic surveys)	None	I; 100	I; 0.0	n/a	–
		II; 55.7	II; 2.0		
Liverpool Bay	None	n/d	n/d	n/a	?
Northeast Irish Sea	None	60.0	1.5	n/a	–

(c) Toxin levels in bivalve mollusc tissue; % of flesh samples above FSA limits

OSPAR area	No. samples	FSA limits			Score
		PSP µg 100 g^{-1} flesh	DSP present	ASP µg g^{-1} flesh	
Southern North Sea	0	n/a	n/a	n/a	?
Eastern English Coast	142	0.00	3.52	0.00	–
East Anglia	300	0.00	1.00	0.00	–
East English Channel	78	0.00	0.00	0.00	–
Solent	175	0.00	0.57	0.00	–
Bristol Channel	97	0.00	4.12	0.00	–
Liverpool Bay	50	0.00	0.00	0.00	–
Northeast Irish Sea	142	0.00	3.52	0.00	–

Scores: + indicates a criterion exceeded its assessment threshold, − indicates it was within threshold, ? indicates not enough data to perform an assessment or the data available were not fit for the purpose

n/d no data, *n/a* the criterion was not applicable

[a] See text for explanation of indices

Assessment of the southern North Sea, Solent and Liverpool Bay was based on two of the three criteria. These areas scored '−' in all cases and therefore were classed as '−' overall.

Adequacy of data and confidence in assessment

The levels of confidence in the assessment of each stage of eutrophication in most OSPAR areas were medium or high (Table 4). There were three exceptions. The northeast Irish Sea was assessed as showing evidence of nutrient enrichment with low confidence because winter DIN exceeded the threshold in 3 out of 5 years but DIN:DIP ratios did not. The chlorophyll 90th percentiles in the eastern English Coast area exceeded the threshold in the 3 years with sufficient data, but mean chlorophyll was below the threshold in all years, except 2004. Therefore, it was classed as showing accelerated growth, but with low confidence. There was low confidence in the assessment of the east English Channel as showing no evidence of accelerated growth. Chlorophyll 90th percentiles were below thresholds, but data were only available for 2 years. Overall confidence was high for the majority of OSPAR areas. Levels of confidence were reported in detail in individual area reports and the UK National Report (www.cefas.co.uk/ospardocs).

Discussion

The purpose of this paper was to determine whether the marine waters of England and Wales are eutrophic. Eutrophic ecosystems are anthropogenically nutrient enriched, with subsequent enhanced growth of phytoplankton, leading to undesirable disturbance. Undesirable disturbance may manifest as distortion of food webs, increased abundance of opportunistic macroalgae, loss of seagrass, increased incidence of TPA, HAB events and degradation in water quality causing deep water deoxygenation and benthic mortalities, potentially harming fisheries and sustainable human use. Detection of 'an undesirable disturbance' to the balance of organisms, as caused by nutrient enrichment and accelerated growth of algae, is the essential component of eutrophication. It is undesirable effects that are significant in determining an area's status as problem, non-problem or potential problem area. We used a recommended multi-step approach to assessing undesirable disturbance caused by anthropogenic nutrient enrichment (Bricker et al. 1999; Painting et al. 2007; Tett et al. 2007). The available evidence was considered through the application of the OSPAR Comprehensive Procedure to establish whether the three stages of eutrophication, implicit in the OSPAR definition (Gowen et al. 2008), were extant.

Following the screening procedure five areas were deemed not to be nutrient enriched and were assigned non-problem area status, leaving eight remaining offshore and coastal areas subject to a full Comprehensive Procedure assessment. The first stage was to determine whether waters were nutrient enriched. The lack of statistically significant trends in the riverine and direct input of DIN, where reduction measures have been taken under EC Directives, may be explained by the long lag time in environmental systems and by the possible confounding effects of environmental change. Experts have indicated that, due to the large existing reservoirs of nitrogen in soils and sediments, it could be decades before measures such as improved agricultural practice with respect to fertilizer and manure use will begin to show measurable improvements in environmental quality (e.g. Carpenter et al. 1998; Worrall and Burt 2001). In six areas winter DIN concentrations and some DIN:DIP ratios were elevated to varying degrees above threshold levels, but as nutrient enrichment is not harmful of itself (de Jonge and Elliott 2001; Tett et al. 2007) evidence was sought for undesirable effects.

The second stage is evidence for direct effects of nutrient enrichment, observed as increased growth of phytoplankton (measured as increases in chlorophyll concentrations), phytoplankton indicator species and macrophytes. Primary productivity is a robust measure of growth, but is not routinely measured in English and Welsh waters because of sampling constraints. However, as primary production is related to phytoplankton biomass, chlorophyll and limiting nutrient concentrations, these are alternative parameters for trophic assessments (Wasmund et al. 2001). Despite elevated nutrient and DIN:DIP ratios, six areas showed no evidence for accelerated growth in chlorophyll, phytoplankton or opportunistic macroalgal blooms. East Anglia and the eastern English Coast had elevated chlorophyll, but phytoplankton

Table 4 Levels of confidence for each eutrophication stage and overall confidence for each OSPAR area assessed

OSPAR area	Three eutrophication stages			Overall confidence
	Nutrient enrichment	Accelerated growth	Undesirable disturbance	
Southern North Sea	HC	MC	MC	HC
Eastern English Coast	HC	LC	HC	HC
East Anglia	HC	MC	HC	MC
East English Channel	MC	LC	MC	MC
Solent	HC	MC	MC	MC
Bristol Channel	MC	HC	HC	HC
Liverpool Bay	HC	MC	HC	HC
Northeast Irish Sea	LC	HC	HC	HC

HC high confidence, *MC* medium confidence, *LC* low confidence

and macroalgae were within threshold limits. System attributes that 'filter' responses to changes in nutrient loading include the underwater light climate, horizontal exchange, tidal mixing, grazing and biogeochemical processes (Cloern 2001; de Jonge and Elliott 2001). Light attenuation in English and Welsh waters is known to be naturally high, predominantly driven by high levels of SPM (Devlin et al. 2008; Foden et al. 2008) and has been identified as a confounding factor in satellite algorithms of Case II waters (Ruddick et al. 2001), in modelling phytoplankton blooms (Allen et al. 2008) and in depressing primary production (Wasmund et al. 2001). There is a gradient of increasing SPM from the west coast to the east coast of Britain, with mean concentrations of approximately 19 mg l^{-1} typical of the east coast of England (Devlin et al. 2008). The limited light availability in English and Welsh marine waters is likely to be a key factor in explaining why phytoplankton indices and opportunistic macroalgal abundance in all areas were low, and chlorophyll was elevated in only two.

Stage three required verification of undesirable disturbance, causally linked to anthropogenic nutrient enrichment and accelerated growth. Detecting disturbance relies on monitoring for changes in ecosystem structure and vigour; the uncoupling of production from pelagic grazing leading to the range of eutrophic symptoms listed above (Tett et al. 2007). There is some debate regarding a link between nutrient enrichment and increases in novel, nuisance and HABs, and recent studies indicate occurrence of such blooms is linked to light, temperature, salinity or climate and weather processes, rather than nutrient flux (e.g. Fehling et al. 2006; Martin et al. 2009). Therefore, the simple occurrence of HABs and TPA is not necessarily indicative of undesirable disturbance (Gowen et al. 2008). Despite elevated chlorophyll concentrations in two areas, all of the marine waters of England and Wales were well oxygenated, with no evidence for any other types of undesirable disturbance linked to nutrient enrichment.

Scientific and legal definitions of eutrophication (Nixon 1995, 2009; de Jonge and Elliott 2001; OSPAR Commission 2003; Gowen et al. 2008) are built on the concept of nutrient enrichment alone not being indicative of eutrophication without accompanying undesirable effects; separating causes of eutrophication from consequences. The simple dose–response model of nutrient enrichment leading to increased growth measured as primary production and consequently undesirable disturbance has been challenged (Cloern 2001; Painting et al. 2007), because nutrient enrichment and accelerated algal growth are not in themselves harmful, and cannot adequately identify harmful consequences of enrichment (Tett et al. 2007). The evidence from our application of the OSPAR COMP to marine waters of England and Wales suggests that enrichment has not brought about an undesirable trophic state. This contrasts with the eutrophication status of some European waters, such as the Baltic; a shallow shelf sea that has limited exchange with the North Sea. Here undesirable disturbance is likely to be more closely coupled to elevated chlorophyll because the open Baltic Proper is permanently stratified with large freshwater flows delivering high nutrient inputs, and very restricted exchange with the open sea

(Wasmund et al. 2001). The fully flushed, high salinity (>30), naturally turbid marine waters of England and Wales were classified as non-problem. Under the requirements of OSPAR non-problem areas will continue to be monitored for any change in status.

Future trends in the assessment criteria are difficult to predict, but consideration was given to the effects of changes in nutrient inputs and climate. Statistical trend analyses of riverine inputs and direct discharges were conducted for the Humber-Wash, Bristol Channel, Liverpool Bay and Thames catchments (Fryer and Nicholson 1999). There were no statistically significant trends identified and this may be due to the long lag time between mitigation measures taken under EC Directives and measurable changes in environmental systems, because of reservoirs of nitrogen in soils and sediments. Taking account of realistic climate change scenarios the delivery of nutrients is expected to change in estuarine and coastal areas, with higher loadings in the winter and a reduction during the summer (Hydes et al. 2007). The direct impact of this change over many decades is difficult to predict and could form the subject of further investigation. Changes in temperature affect phytoplankton physiology and may result in shifts in species composition of phytoplankton (McQuatters-Gollop et al. 2007) as well as affecting the duration and strength of thermal stratification of the deeper (>40 m) shelf seas. The growth response of organisms to nutrient enrichment may change and, for example, deoxygenation of bottom waters in stratified regions may increase. It may be that parts of the seas become more susceptible to the effects of nutrient enrichment, but it is also clear that distinguishing between cause and effect will become more difficult.

Conclusions and perspectives

A three stage approach to eutrophication classification has been applied within the framework of the OSPAR Common Procedure (COMP) to thirteen marine areas (salinity >30) around England and Wales. The result of the classification was non-problem area status for all areas, which was confirmed as robust by an international peer review panel and accepted by OSPAR (OSPAR Commission 2008). The three-stage approach was specifically designed to address OSPAR's definition of eutrophication, as a logical application of the definition's inherent assumptions of cause and effect (Gowen et al. 2008). However, the COMP process did not fully align with the three stage approach. Future modification of the methodology and Harmonised Criteria would be a significant step in aligning the COMP process with the scientific basis for seeking evidence of eutrophication. Following reporting by all OSPAR Contracting Parties of their applications of eutrophication assessment, the need for further development of assessment methods to enhance their robustness was recognised (OSPAR Commission 2008). As a postscript, it is interesting to note that the European Court of Justice recently ruled that diagnosis of eutrophication requires a relationship to be established between the three elements of the definition, in just such a stepwise fashion (ECJ 2009). The exact meaning of undesirable disturbance is still in development as ecosystem perturbations may manifest in a variety ways. It is hoped this eutrophication assessment of English and Welsh marine waters has helped to develop the methods for diagnosing eutrophication, based on improved understanding in the underpinning science

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