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HORIZONS

Coastal eutrophication: recent developments in definitions and implications for monitoring strategies

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The word 'eutrophication' has its root in two Greek words: 'eu' which means 'well' and 'trope' which means 'nourishment'. The modern use of the word eutrophication is related to inputs and effects of nutrients in aquatic systems. Despite a common understanding of its causes and effects, there is no agreed definition of coastal eutrophication. This communication aims to review recent developments in the definitions of coastal eutrophication, all of which focus on 'accelerated growth', and to discuss the implications in relation to monitoring and assessment of ecological status. It is recommended that measurements of primary production, being a sensitive and accurate indicator of eutrophication, should be mandatory when monitoring and assessing the ecological status of coastal waters.

INTRODUCTION

Eutrophication of coastal waters has been considered one of the major threats to the health of marine ecosystems for more than 30 years (Ryther and Dunstan, 1971; Nixon, 1995; Elmgren, 2001; Bachmann *et al.*, 2006). The different processes and effects of coastal eutrophication are well known and documented (Cloern, 2001; Conley *et al.*, 2002; Rönnberg and Bonsdorff, 2004).

In 2000, the European Parliament and the Council adopted the European Union (EU) Water Framework Directive (WFD), which provides a framework for the protection of groundwater, inland surface waters, transitional waters (estuaries) and coastal waters (Anonymous, 2000). The overall aim of the WFD was: (i) to prevent further deterioration, protect and enhance the environmental status of aquatic systems and (ii) to promote the sustainable use of water while progressively decreasing or eliminating discharges, losses and emissions of pollutants and other pressures for the long-term protection and enhancement of the aquatic environment. The WFD is intended to improve the ecological status, including eutrophication status, of all European surface waters of which many are considered to be eutrophic (European Environment Agency, 2001, 2003). The directive provides national and local authorities with a legislative basis for the maintenance and recovery of water quality to achieve good ecological and chemical status for all surface waters and good chemical status for groundwater. Accordingly, the directive can be considered the most significant piece of legislation of the last 20 years, in regard to water policy not only in Europe but also in non-European countries seeing EU legislation as a benchmark for their own legislation.

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However, the WFD lacks a definition of eutrophication. The directive's treatment of eutrophication is indirect, with the boundary between good and moderate ecological status being defined as an environmental management objective. For waters failing to meet the objective of at least good ecological status, the directive requires that competent authorities establish programmes of measures and river basin management plans to secure this status. The measures to be implemented in the context of eutrophication are already required under other existing directives, for example, the Urban Waste Water Treatment (UWWT) Directive (Anonymous, 1991a) and the Nitrates Directive (Anonymous, 1991b). If these are insufficient, then the implementation of supplementary measures is required. The WFD thus acts as an umbrella for the UWWT Directive and the Nitrates Directive, and as such it has to respect the definitions of eutrophication in these directives.

HOW IS EUTROPHICATION DEFINED?

Within the EU, there has been a sound tradition of focusing measures on the sources causing eutrophication (Elliot *et al.*, 1999; Elliot and de Jonge, 2002). Consequently, eutrophication has been defined in relation to sources and/or sectors. For example, the European Commission (EC) UWWT Directive defines eutrophication as 'the enrichment of water by nutrients, especially nitrogen and/or phosphorus, 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 water concerned' (Anonymous, 1991a).

According to the EC Nitrates Directive, eutrophication is defined as 'the enrichment of water by nitrogen compounds 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 water concerned' (Anonymous, 1991b). The difference between the two definitions can be explained by the focus of the Nitrates Directive which, perhaps unsurprisingly, rests on losses of nitrogen from agriculture.

There has been some justifiable discussion of these definitions, in particular their focus on nutrients, and also the need to clarify what constitutes an 'undesirable disturbance' and an 'accelerated growth'. Is 'accelerated' the right word to use in this context? No, accelerated, meaning speed up, is in our opinion the wrong word and should be replaced by 'increased'. Nixon (Nixon, 1995) defines eutrophication as 'an increase in the rate of supply of organic matter to an ecosystem'. This definition is short and consistent with historical usage and emphasizes eutrophication as a process rather than a trophic state. Nixon also notes that the increase of the supply of organic matter to coastal systems may have various causes, but the common factor is clearly nutrient enrichment. The supply of organic matter to an ecosystem is not restricted to pelagic primary production, even though such an interpretation leads to a convenient operational definition. It also includes primary production of higher plants and benthic microalgae as well as inputs of organic matter from adjacent waters or from land, via rivers or point sources. Having such a broad interpretation of the term 'supply' makes the definition, despite its obvious strengths, difficult to apply in a monitoring and management context.

Eutrophication and definition(s) of eutrophication are much discussed topics as indicated above and also pointed out by Jørgensen and Richardson (Jørgensen and Richardson, 1996). The most common use of the term is related to inputs of mineral nutrients, primarily nitrogen and phosphorus, to specific waters. Consequently, eutrophication deals with both the process as such, the associated effects of nutrient enrichment and natural versus cultural caused eutrophication. And as prudently pointed out by Jørgensen and Richardson, when we speak of eutrophication, it is anthropogenic eutrophication that is of interest.

Within the OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic, the definition of eutrophication follows the above definitions and thoughts and defines eutrophication similar to the UWWT Directive and continues 'and therefore refers to the undesirable effects resulting from anthropogenic enrichment by nutrients described in the Common Procedure' (OSPAR, 2003).

The implementation of the WFD has revealed the need for a common understanding and definition of eutrophication as well as a need for stronger coordination between directives dealing directly or indirectly with eutrophication. The EC has initiated a process with the aim of developing a pan-European conceptual framework for eutrophication assessment in the context of all European waters and policies. At a workshop in September 2004, hosted by the EC and Joint Research Centre in Ispra, Italy, draft guidance on a pan-European framework for assessment of eutrophication was presented and discussed. The objective of the workshop was to coordinate different activities under the EU WFD and other eutrophication-related directives (e.g. UWWT Directive and Nitrates Directive). The workshop concluded that a draft pan-European definition of eutrophication could use the UWWT Directive as a starting point for further developments on the issue of eutrophication. Taking the comments put forward at the workshop into consideration, eutrophication can be defined as 'the enrichment of water by nutrients, especially nitrogen and/or phosphorus and organic matter' (Anonymous, 2004). Work is ongoing and expected to be reported in the spring 2006 in the form of an interim guidance document. Revision of the guidance is planned in 2007, following the WFD inter-calibration exercise and some on-going activities by the conventions for the protection of the marine environment of Baltic Sea and the North-East Atlantic.

TOWARDS A PROCESS-ORIENTED MONITORING AND ASSESSMENT STRATEGY

How are member states of the EU obliged to monitor and assess the ecological status of coastal waters? Monitoring networks should be established to create a coherent and comprehensive overview of ecological and chemical status and ecological potential. The networks should be operational by 20 December 2006 or by 1 January 2007 at the latest. Monitoring networks should in principle be based on variables/indicators that are indicative of the status of each relevant quality element [biological (e.g. phytoplankton, submerged aquatic vegetation and invertebrate benthic fauna), hydromorphological or physiochemical]. In addition, the networks should permit classification of water bodies in five classes consistent with the normative definitions of ecological status.

In a North European perspective, there are at least two or three important drivers for the design, execution and reporting of monitoring activities. These are the WFD including the WFD Common Implementation Strategy guidance on monitoring (Anonymous, 2000, 2003a), the HELCOM COMBINE Programme (Co-operative Monitoring in the Baltic Sea Environment) (HELCOM, 2003) and the OSPAR Joint Assessment and Monitoring Programme (JAMP), including the Eutrophication Monitoring Programme, which describes the indicators and sampling methods (OSPAR, 2004, 2005). So far, the pan-European process for development of a conceptual framework for eutrophication assessment has not included discussion of specific monitoring guidance. This will take place at a later stage. The only available guideline for selection of indicators is a draft holistic checklist (Anonymous, 2004).

The requirement relating to the monitoring of pelagic biological and chemical indicators in EU WFD, HELCOM COMBINE, OSPAR JAMP/Coordinated Environmental Monitoring Programme (CEMP) and the ongoing pan-European process is summarized in Table I. Measurements of phytoplankton species abundance, composition and biomass are mandatory in most monitoring networks. Measurements of chlorophyll *a* (Chl *a*) and nutrients are mandatory within HELCOM and OSPAR but considered a recommended supporting indicator by European drivers. Measurements of primary production are not mandatory at present.

How to assess ecological status?

The WFD requires EU member states to develop classification systems to describe the ecological status of a given water body at a given time. The results of the monitoring programmes are the basis for an assessment of ecological status of a given water body that according to the directive will fall into one of five classes (categories): high, good, moderate, poor or bad. The status classes high and good are in general considered to be acceptable.

An important step in assessing ecological status is the setting of reference condition standards with the objective of enabling the assessment of ecological quality against these standards. Reference condition is in this context defined as a description of the biological quality elements that exist, or would exist, at high status, that is, with no, or very minor, disturbance from human activities (Anonymous, 2003b).

Another important step is to define what constitutes an acceptable deviation. An acceptable deviation *sensu* the WFD is to us equivalent to high and good ecological status, the latter defined as a status where the values of the biological quality elements show low levels of distortion resulting from human activity. An unacceptable deviation is in our understanding equivalent to bad, poor or moderate ecological status, where values of the biological quality elements deviate moderately or more from those normally associated with the coastal water body type under undisturbed conditions *sensu* the WFD definition of reference conditions.

The approach employed in the so-called OSPAR Comprehensive Procedure (COMPP) is very pragmatic and straightforward. On the basis of background values, in practice identical to reference conditions, a water body is considered an 'Eutrophication Problem Area' if actual status deviates 50% or more from reference conditions (OSPAR, 2003). It should be noted that the choice of 50% is arbitrary, not based on any scientific considerations about ecological changes caused by nutrient enrichment. The application of percentages lower than

Table I: Selection of relevant quality elements and indicators by WFD, HELCOM COMBINE, OSPAR COMPP and the draft holistic checklist of the pan-European conceptual framework for eutrophication assessment

Quality elements and indicators	EU WFD	HELCOM	OSPAR	pan-European
Phytoplankton				
Abundance	M	M	(R)	(R)
Composition	M	M	M	(R)
Diversity	M	(R)	(R)	(R)
Biomass	M	M	(R)	R
Primary production	n.i.	R	n.i.	R
Chlorophyll a	R	M	M	R
Fluorescence	n.i.	R	n.i.	n.i
Transparency				
Secchi depth	R	M	R	n.i.
Light attenuation	n.i.	M[a]	n.i.	R
Turbidity	R	n.i.	n.i.	R
Color	R	R	n.i.	n.i.
Nutrients				
Total P	R	M	M	R
Soluble reactive P	R	M	M	R
Total N	R	M	M	R
Nitrate + nitrite	R	M	M	R
Ammonium	R	M	M	R
Silicate	n.i.	M	n.i.	R

COMPP, Comprehensive Procedure; EU WFD, European Union Water Framework Directive; M, mandatory; R, recommended; (R), recommended indirectly; n.i., no information. Compiled from Anonymous (Anonymous, 2003a; Anonymous, 2003b; Anonymous, 2004), HELCOM (HELCOM, 2003) and OSPAR (OSPAR, 2005).

[a]Mandatory when primary production is measured.

50% has been discussed, for example, by Ærtebjerg *et al.* (Ærtebjerg *et al.*, 2003), Andersen *et al.* (Andersen *et al.*, 2004) and Krause-Jensen *et al.* (Krause-Jensen *et al.*, 2005). Recently, the OSPAR Eutrophication Committee amended the procedures of the next application of the Comprehensive Procedure, so that the acceptable deviation should be justified but not exceed 50% (OSPAR, 2005).

How can primary production be estimated?

With the development in relation to a pan-European definition of eutrophication, it would be logical to focus monitoring on relevant biological indicators including measurement of 'increased growth'. In our understanding, measurement of primary production is a relevant indicator that can indicate if algal growth is increased.

Primary production is a fundamental ecological indicator (variable), because it is a measure of the extent to which primary energy input (solar energy) to the aquatic environment is transformed into the biological/ecological sphere. It is defined as the flux of inorganic carbon into planktonic algae per unit time. It has significant capability to indicate and characterize the status of a particular water body. Primary production can conveniently be measured using the so-called ^{14}C method (Steemann Nielsen, 1952). When adding a known quantity of the radioactive isotope ^{14}C to a water sample, the planktonic algae will take up ^{14}C along with 'native' ^{12}C present in water. After a short incubation period (2 h), the ^{14}C incorporated into the algal cells can be measured by liquid scintillation counting. The total carbon uptake, which is a good approximation of net production (Jespersen *et al.*, 1995), can then be calculated by:

$$^{12}CO_2 \text{ uptake} = (^{14}CO_2 \text{ uptake}/^{14}CO_2 \text{ added}) \times {}^{12}CO_2 \text{ concentration}$$

Primary production can either be determined as particulate production or total production. For particulate production, only the ^{14}C uptake in the algae cells is determined, whereas total production also includes the ^{14}C incorporated into the organic matter, which can be lost to the environment outside the cell during incubation. The method is very sensitive, and primary production is a widely used method when assessing eutrophication effects in coastal waters (e.g. Pinckney *et al.*, 1999; Prins *et al.*, 1999; Bonsdorff *et al.*, 2002). Primary production is also used as an important indicator when modelling how changes in loads impact upon the environment.

Various research activities and monitoring networks have made use of the ^{14}C method and have documented considerable changes in the levels of the primary production since the 1950s (e.g. Richardson and Heilmann, 1995; Bonsdorff *et al.*, 2002). In the central Great Belt, Denmark (55° 22′ 36″ N, 11°00′ E), the annual primary production, averaged over each decade, has roughly doubled from the 1950s to the 1980s and 1990s (Fig. 1). In the central Kattegat, the average monthly primary production at four different depths in the water column through the year is compared for the two periods 1954–60 and 1984–93 (Fig. 2). It can be seen that both the spring bloom and the algal production during the summer months increased significantly from the 1950s to 1984–93, as a consequence of eutrophication (Jørgensen and Richardson, 1996).

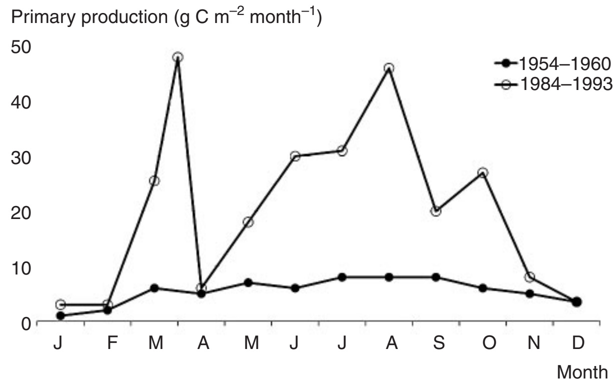

Fig. 2. Primary production in the Kattegat, Denmark, through the year as estimated by Steemann Nielsen (Steemann Nielsen, 1964) and Richardson and Heilmann (Richardson and Heilmann, 1995) [From Jørgensen and Richardson (1996). Copyright 1996 American Geophysical Union. Modified by kind permission of American Geophysical Union].

How to link the definition with monitoring and assessment activities?

Despite positive pan-European developments in defining eutrophication, it is still unclear what an 'undesirable disturbance' is. The phrase is open to interpretation and should be reconsidered. We suggest that an 'undesirable disturbance' in ecological terms is understood as an 'unacceptable deviation from reference conditions'. We realize that an 'unacceptable deviation' is also open to interpretation, but the advantage is 2-fold. First, the definition will be linked to the WFD implementation process, and second, reference conditions *sensu* the WFD will be the starting point.

We also suggest inclusion of primary production measurements in monitoring systems. These should be based on a reasonable and cost-effective approach, that is, monitoring networks should be stratified and based on two types of stations: (i) intensive stations/areas where many indicators are monitored with high frequency and (ii) mapping stations where a few indicators are monitored with lower frequency. This kind of stratification has been used in the HELCOM COMBINE Programme (HELCOM, 2003) and in Danish National Marine Monitoring and Assessment Programme 2003–09 (DNAMAP) (Andersen, 2005).

In our opinion, measurements of primary production should be carried out at all intensive stations or at least one coastal station per type of coastal water or river basin district. Sampling frequency should be based on information on the ecological status and take seasonal variations at the station into account.

We also recommend that primary production measurements should follow the methodology developed within International Council for the Exploration of the Sea (ICES) and currently described in the HELCOM COMBINE Manual (HELCOM, 2003). However, existing time series on primary production should be continued using the original measurement method.

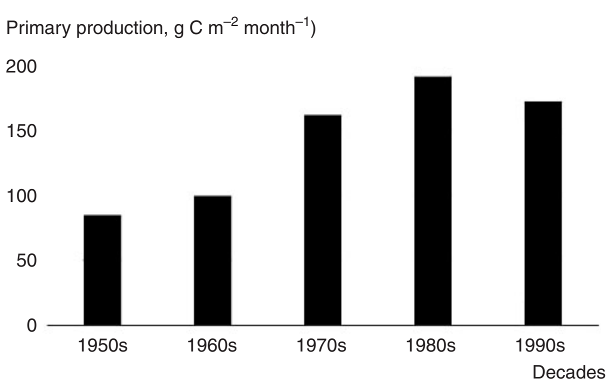

Fig. 1. Examples of observed changes in the primary production in the central Great Belt, Denmark, depicted as averages of the annual primary production of the decades [unpublished data from G. Ærtebjerg, NERI, Denmark].

We are of the opinion that the ^{14}C method allows precise determination of phytoplankton production. However, these measurements are not mandatory in monitoring programmes coordinated on an international level (e.g. HELCOM COMBINE, OSPAR JAMP and WFD related monitoring activities). If our suggestion of including estimates of primary production in the monitoring programmes is followed, then these programmes will be linked directly to both the definition and process of eutrophication. Other methods for determining primary production could be employed, for example, non-isotope method, that is, the oxygen method (Hall and Moll, 1975; Reid and Shulenberger, 1986; Olesen *et al.*, 1999).

An indicator often used for assessment of eutrophication and as a proxy for primary productivity, nutrient status or phytoplankton biomass is Chl *a*. Some caution is recommended when using this indicator, and the information inherent in Chl *a* measurements should be interpreted as what it is: a Chl *a* concentration and nothing more, cf. Kruskopf and Flynn (Kruskopf and Flynn, 2006).

DNAMAP 2003–09, which implements the monitoring requirements of the WFD, was designed according to a principle stating: 'No monitoring without Ecological Quality Objectives, no Ecological Quality Objectives without monitoring' (Svendsen and Norup, 2005). We completely agree with this principle and present a total of nine draft classification scenarios on the basis of percentage deviations for the various boundaries between the classes high, good, moderate, poor and bad (Table II). The scenarios are site specific (The Great Belt, Denmark) and not directly applicable to other coastal waters. They are also specific for the results of primary production measurements and may not be applicable for other indicators. As a cautionary note, we acknowledge that the decision on which of the presented scenarios to implement as an environmental management standard will be political.

CONCLUSIONS

Our mission is to propose a better definition of eutrophication and to link the definition with monitoring and assessment systems. By understanding in ecological terms an 'undesirable disturbance' as an 'unacceptable deviation from reference conditions', we arrive at a definition that is consistent with the normative definitions of moderate (and poor/bad) ecological status *sensu* the WFD. Consequently, an acceptable deviation will correspond to the normative definition of high and good ecological status.

Accepting the above suggestions allows a definition of eutrophication as 'the enrichment of water by nutrients, especially nitrogen and/or phosphorus and organic matter, causing an increased growth of algae and higher forms of plant life to produce an unacceptable deviation in structure, function and stability of organisms present

Table II: Scenarios for ecological classification in the Great Belt, Denmark using primary production as an indicator and assuming that deviations of 15% (restrictive), 25% (intermediate) and 50% (non-restrictive) from reference conditions are acceptable deviations

Scenarios	Reference conditions	High (%)	Good (%)	Moderate (%)	Poor (%)	Bad (%)
Restrictive	Primary production	<5	5–15	15–35	35–65	>65
A1	48	<50	50–55	55–65	65–79	>79
A2	67	<70	70–77	77–90	90–111	>111
A3	86	<90	90–99	99–116	116–142	>142
Intermediate		<10	10–25	25–45	45–70	>70
B1	48	<53	53–60	60–70	70–82	>82
B2	67	<74	74–92	92–97	97–114	>114
B3	86	<95	95–108	95–125	125–146	>146
Non-restrictive		<20	20–50	50–70	70–90	>90
C1	48	<58	58–72	72–82	82–91	>91
C2	67	<80	80–100	80–114	114–127	>127
C3	86	<103	103–129	103–146	146–163	>163

The primary production is expressed as g C m^{-2} $year^{-1}$. Reference conditions in scenarios A1, B1 and C1 are defined by Hansen *et al.* (Hansen *et al.*, 2003). Reference conditions in scenarios A3, B3 and C3 are defined by Ærtebjerg (unpublished data). Scenarios A2, B2 and C2, where the reference is 67 g C m^{-2} $year^{-1}$, are an average of 48 and 86 g C m^{-2} $year^{-1}$. The approach used for division in five quality classes is based on Andersen *et al.* (Andersen *et al.*, 2004) and Krause-Jensen *et al.* (Krause-Jensen *et al.*, 2005).

in the water and to the quality of water concerned, compared to reference conditions'.

In our opinion, the proposed definition of eutrophication will lead to revision of existing monitoring strategies. Measurement of primary production, being an indicator of 'increased growth', should be mandatory in monitoring networks and should consequently be included as a monitoring or an assessment indicator in the pan-European guidance on a conceptual framework for eutrophication assessment.

We have raised many rhetorical questions and believe we have answered most of the questions and by doing so promoted the idea of having a process-oriented approach to monitoring and assessment of coastal eutrophication. However, one important question is still to be answered: 'How should primary production be measure or estimated?' Such question requires thorough scientific analyses as well as coordination, otherwise the answer would be up to individual member states meaning that there will be only limited coordination.

The approach to be employed in setting up classifications scenarios is a topic for discussion. Our intention is simply to present some examples of how ecological classification scenarios could be constructed on the basis of measurements of primary production. Further work is needed to verify both the approach and the scenarios. However, we consider it vital that science and management are integrated to ensure that the WFD will be a strong legal instrument for the protection and, where needed, restoration of the ecological status of European waters. Implementation of the WFD is still in its initial phases. The coming years will, therefore, be a learning process. Agreement on a pan-European definition of eutrophication and putting emphasis on primary production will be a good start to this process.

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