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PERSPECTIVE

Nitrogen Inputs from Agriculture: Towards Better Assessments of Eutrophication Status in Marine Waters

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Abstract Nutrient enrichment of coastal marine waters caused by losses of nitrate (NO_3^-) from agriculture is an increasing global problem. In the European Union, the Nitrates Directive (ND) of 1991 was meant to be a cornerstone in reducing eutrophication effects in coastal waters downstream from intensively farmed catchments. Although reductions in losses of nitrate have been attained, very few Member States have yet been able to reduce eutrophication effects caused by inputs of NO_3^- from agriculture. We report trends in concentrations of NO_3^- and chlorophyll-*a* (Chl-*a*) in Danish coastal and open marine waters during the period from 1996 to 2011 together with an assessment of eutrophication status based on multiple indicators (e.g. nutrient concentrations, Chl-*a*, submerged aquatic vegetation and benthic macroinvertebrates). Despite decreasing concentrations of both NO_3^- and Chl-*a*, Danish coastal waters are not yet to be classified as 'unaffected by eutrophication'. In order to improve future pan-European evaluations of the effectiveness of the ND, we argue for the added value of including indicators and assessment principles from other European Directives, i.e. the Water Framework Directive and the Marine Strategy Framework Directive.

Keywords Nitrates Directive · Nutrient enrichment · Eutrophication · Assessment · Water Framework Directive · Marine Strategy Framework Directive

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INTRODUCTION

European countries have over the last decade focused strongly on the interpretation and implementation of the Water Framework Directive (WFD, Anon. 2000). As a result, numerous pan-European guidelines and national interpretation manuals have been developed together with the first generation of River Basin Management Plans. However, the above mentioned work has unintentionally reduced efforts to support evidence-based implementation of the *Nitrates Directive* (ND). Full implementation of this directive is a basic measure under the *Water Framework Directive*, and the ND is therefore in our opinion a corner stone in European water policies in regard to mitigation of nutrient enrichment and eutrophication in estuaries and coastal waters downstream from catchment areas with nitrogen vulnerable zones.

The ND, or in full '*Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agriculture*' was adopted in 1991. The objective of the ND is to reduce water pollution caused or induced by nitrates from agricultural sources and to prevent further such pollution (Anon. 1991a). EU Member States shall according to the ND designate nitrate-vulnerable zones, which are areas of land draining into waters affected by pollution and which contribute to pollution or, if appropriate, apply a nationwide approach. Further, Member States shall where necessary establish action programs promoting the application of the ND's codes of good agricultural practices. They shall also carry out monitoring and assessments of inland waters, freshwater, estuaries and coastal waters in order to make an assessment of eutrophication status every 4 years.

Member States have recently delivered national summary reports to the European Commission on status and trends in water quality and agricultural practice in accordance with

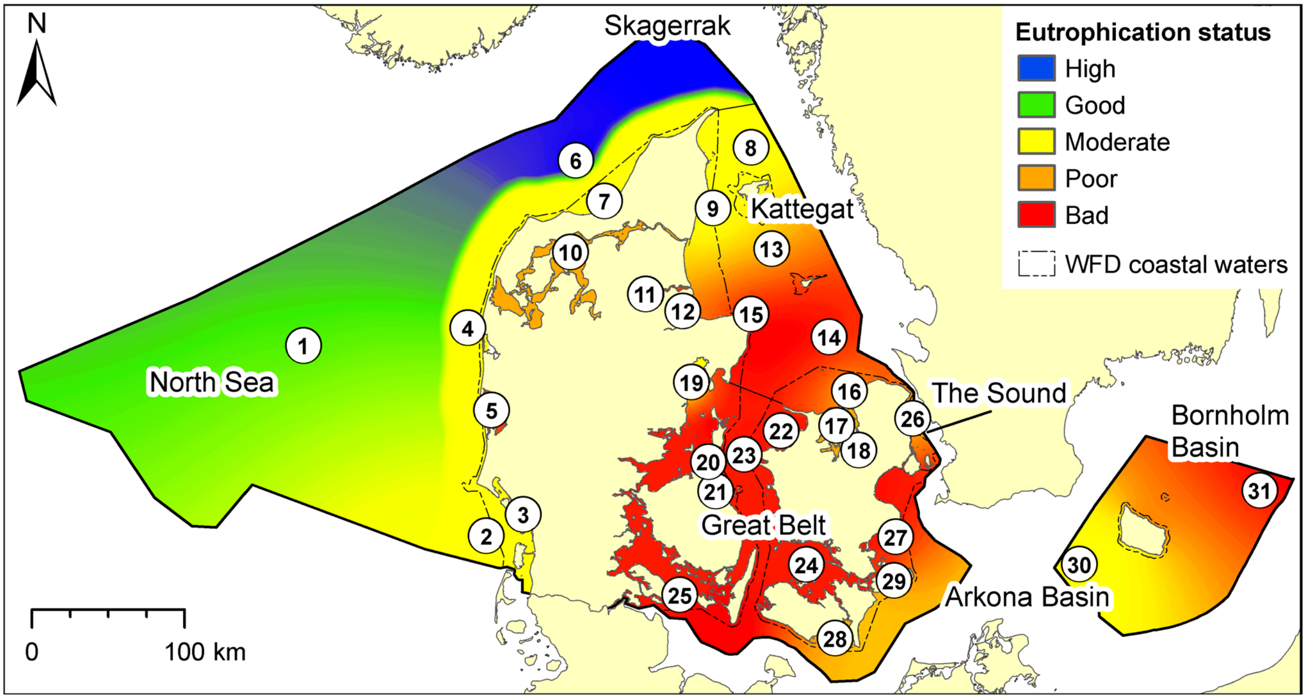

Fig. 1 Classifications of eutrophication status in Danish marine waters. The assessment is based on the multimetric assessment tool HEAT described in Andersen et al. (2010, 2011). The numbers (*1–31*) refer to the assessment units used in Andersen et al. (2012), which is the basis for this map

the ND for the fifth reporting period 2008–2011. The national reports are prepared according to pan-European guidelines and focus on (1) water quality in surface and ground waters; (2) measures implemented in the national action program; (3) evaluation of progress made (i.e. based on statistical trend analyses); and (4) expected future trends in water quality.

Here, we report trends in water quality in Danish marine waters. The indicators used are nitrate (NO_3^-) concentrations and chlorophyll-*a* (Chl-*a*) concentrations, the latter used as a proxy for phytoplankton biomass and thus indirectly primary production. We believe the Danish examples are of general interest because (1) all Danish coastal waters are prone to excess inputs of nutrients and hence classified as affected by eutrophication (Fig. 1), (2) Denmark in 1987 was amongst the first EU Member States to adopt a national action plan which focused on losses, discharges and emissions of nutrients and in particular nitrogen from agricultural practices (Ærtebjerg et al. 2003; Andersen 2012), and (3) the 1987 *Danish Action Plan on the Aquatic Environment* is to our knowledge the only national nutrient management strategy that so far has been documented to be successful in regard to both diffuse sources and point sources.

Further, we apply a simple indicator-based tool for assessment of eutrophication status, which in combination with a source apportionment, can be used to assess whether or not the status is caused by inputs of nitrates from agriculture. This tool represents in our opinion a step forward from simple trend assessments to integrated assessments of eutrophication status. In this way, we link assessment under the ND to assessments of ‘ecological status’ under the WFD (Anon. 2000; Andersen et al. 2012), assessments of ‘eutrophication status’ under the Marine Strategy Framework Directive (MSFD, Anon. 2008), the Helsinki Convention for the Baltic Sea (HELCOM 2009, 2010), and the OSPAR Convention for the Northeast Atlantic (OSPAR 2003, 2008). Such a convergence in assessment methodologies is in our opinion worth pursuing as it leads to both a harmonization and coordination of work and reduces the risks of duplicating efforts.

ASSESSMENTS *SENSU* THE ND

According to the ND, reporting must be made every four years and in agreement with the guidelines in Anon (2011). For marine waters, this implies that focus is on concentrations of NO_3^- [in practice concentrations of dissolved inorganic nitrogen (DIN)] and Chl-*a* in surface waters.

Danish marine waters cover the eastern North Sea, the southern part of Skagerrak, the western part of Kattegat, The Sound, Great Belt and Little Belt (Belt Sea), the western part of the Arkona Basin (Baltic Sea) and the Danish territorial waters around the island Bornholm (Baltic Sea) (Fig. 1). The western part of Kattegat, The Sound and Belt Sea are collectively named inner Danish

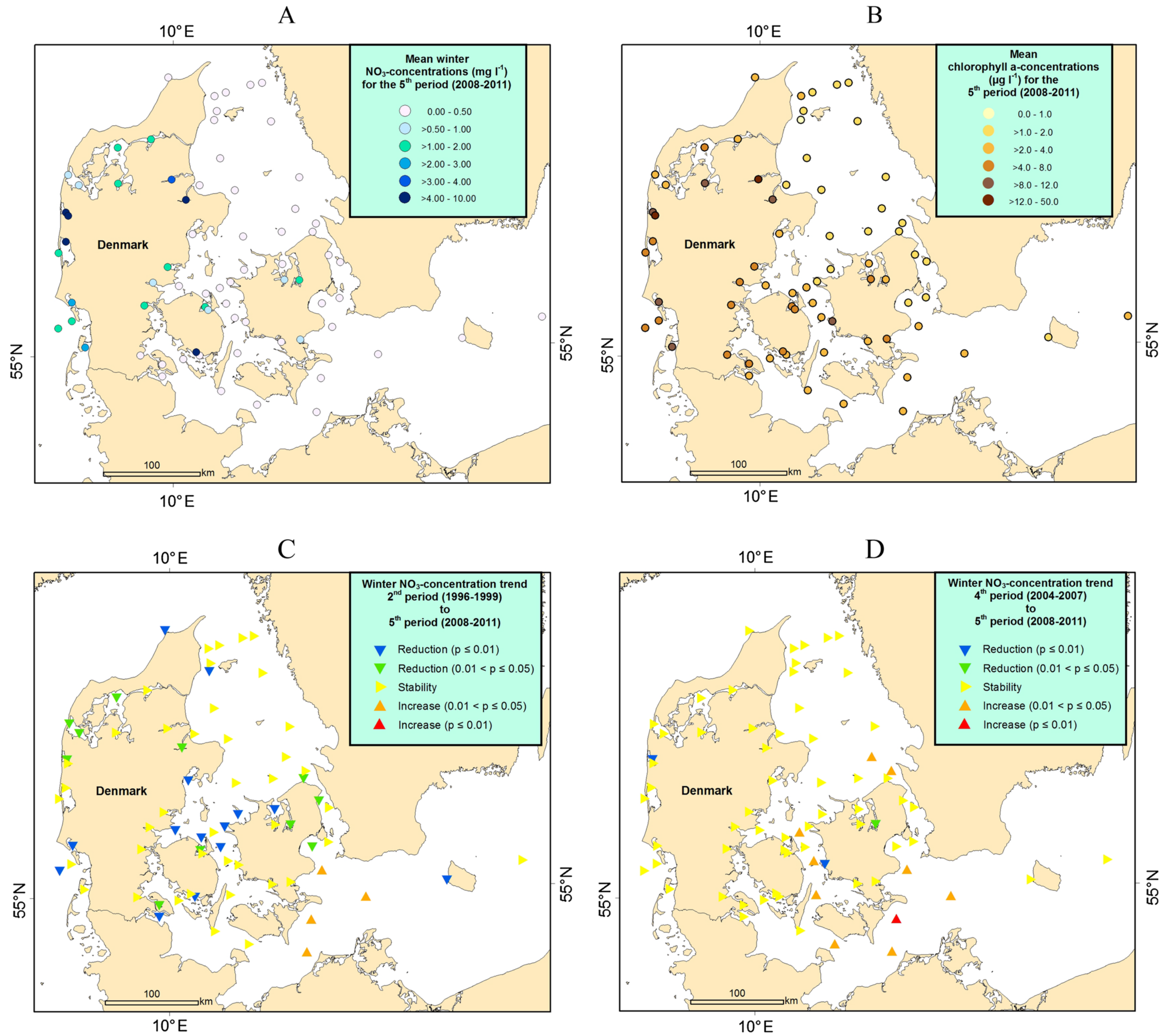

Fig. 2 Surface (0–10 m) winter (January–February) mean concentrations of NO_3^- and summer (May–September) mean concentrations of Chl-*a* for the period 2008–2011 (**a**, **b**, respectively). Trends in winter concentrations of NO_3^- from 1996–1999 to 2008–2011 and 2004–2007 to 2008–2011 (**c**, **d**, respectively). Additional maps are annexed as Electronic Supplementary Material

waters. A detailed description of the study area is annexed as Electronic Supplementary Material.

Data originate from the *Danish Marine Monitoring and Assessment Programme* (DANMAP) which has been in operation since 1988 (Kronvang et al. 1993; Conley et al. 2000; Ærtebjerg et al. 2003; Carstensen et al. 2006; Naturstyrelsen 2011). The measurements of nutrients and Chl-*a* are carried out in accordance with HELCOM COMBINE (www.helcom.fi) and OSPAR CEMP (www.ospar.org).

Here, we discuss the monitoring observations of NO_3^- and Chl-*a* for the fifth reporting period (2008–2011) of the ND (see Carstensen et al. 2006 for a description of the methodology) as well as trends in loads and eutrophication during 1996 through 2011. Carstensen et al. (2006) report temporal trends using annual averages, while we in this study combine data for the different reporting periods (1992–1995, 1996–1999, 2000–2003, 2004–2007, and 2008–2011). Further, the discussion is limited to monitoring data from the inner Danish waters as only stations from these waters have been continuously monitored, i.e. at least three times per year, during this period. Further, we compare these observations to the assessments of eutrophication status carried out in regard to the WFD and MSFD.

The number of monitoring stations in the inner Danish waters has decreased markedly over the periods from

Table 1 Development over time of surface winter nitrate concentrations (January–February) in Danish waters (western part of Kattegat, The Sound, Great Belt, Little Belt, and the western part of the Arkona Basin, see also Fig. 1 and text). Percentage of stations with mean concentrations of nitrate increasing, stable or decreasing. Number of stations: 36 for coastal waters and 34 for open waters

Trend	Significance	Second period to fifth period (1996–1999 to 2008–2011)		Fourth period to fifth period (2004–2007 to 2008–2011)	
		Coastal waters (%)	Open waters (%)	Coastal waters (%)	Open waters (%)
Increasing	$p \leq 0.01$	0	0	3	0
	$0.01 < p \leq 0.05$	0	3	26	12
Stable		47	92	71	70
Decreasing	$p \leq 0.01$	25	5	0	15
	$0.01 < p \leq 0.05$	28	0	0	3

2004–2007 to 2008–2011. The locations of stations and monitoring results for surface (0–10 m) 'winter' (January–February) NO_3^- and 'summer' (May–September) Chl-*a* concentrations can be seen in Fig. 2 together with the temporal trends for NO_3^-. The trends for inner Danish waters are summarized in Table 1. Additional information is annexed as Electronic Supplementary Material.

The highest winter nitrate concentrations in the fifth reporting period were observed in coastal waters, whereas the lowest winter NO_3^- concentrations were found in the Bornholm Basin, the Kattegat and the Belt Sea (see Electronic Supplementary Material for details). In Danish coastal waters, 47 % of the stations show no change in winter NO_3^- concentrations over the last 15 years, i.e. from the second to the fifth reporting period (Table 1), while 53 % showed a decrease, and no stations showed an increase. In the inner Danish open waters, 70 % showed no development, 12 % showed increases, and concentrations decreased in 18 % of the stations (Table 1).

Out of 36 monitoring stations in coastal waters, the vast majority of stations (92 %) showed no change in winter NO_3^- concentrations from the fourth to the fifth period, while 3 % of stations showed a weak yet statistically significant increase and 5 % showed a significant strong decrease (Table 1). Out of 34 stations in Danish open marine waters, 71 % of stations reported stable winter nitrate concentrations (Table 1). Concentrations showed weak and strong increases at 26 and 3 % of the stations, respectively, whereas a decrease was not observed at any of the stations.

In the fifth reporting period, the highest summer Chl-*a* concentrations in the uppermost 10 m were observed in the semi-enclosed coastal waters and in the Danish parts of the Wadden Sea, followed by the Belt Sea (see Electronic Supplementary Material). The lowest summer Chl-*a* concentrations were observed in the Kattegat and the western Baltic Sea. Out of 36 stations in the Danish coastal waters, 59 % showed no significant change in the summer Chl-*a* concentration from the fourth to the fifth reporting period, while 33 % of the stations showed statistically significant strong or weak decreases, and 8 % showed a weak increase. In the open waters, 94 % of the 34 stations showed no change, while concentrations have shown significant strong increases at 3 % of the stations (1 station), and 3 % have shown a weak decrease.

Nitrogen load to the Danish marine waters and the resulting winter concentrations of NO_3^- are closely correlated to runoff from land (Ærtebjerg et al. 2003). Runoff, which depends primarily on the annual precipitation, varies by a factor of 2–3. For example, nutrient loading to marine waters around Denmark has varied from about 50 000 tons of N during years of low precipitation (e.g. 1996 and 1997) to about 130 000 tons during a wet year like 1994 (Hansen 2013). These annual variations in nutrient loads due to changes in climatology (freshwater discharge) strongly influence the reported trends. Therefore, the main reason that NO_3^- concentrations decreased sharply from the first reporting period (1992–1994) to the second period (1996–1999) was probably the two dry years of 1996 and 1997 that strongly influenced the mean NO_3^- concentrations. Detailed information in regard to spatial and temporal variations in runoff can be found in Wiberg-Larsen et al. (2012).

Changes in NO_3^- concentrations following the reduction measures that have been taken in Denmark to reduce nutrient loads are partly concealed by inter-annual variations in freshwater discharge. However, if data are corrected for the variation in river runoff, then the normalized concentration of DIN concentrations have significantly decreased both in Danish coastal and open waters during the period 1989–2011 (Hansen 2013). The phosphorus loads and thus concentrations have also decreased significantly in Danish coastal waters during the period from 1989 to 2011, and both nitrogen and phosphorus have become increasingly potentially limiting for phytoplankton growth (Hansen 2013). Now nitrogen and phosphorus are potentially limiting for phytoplankton growth in approximately 60 and 50 %, respectively, of the productive period (March–September) in Danish coastal waters.

These first indications of environmental recovery are most pronounced in the coastal waters, but are also apparent in the open waters of the Kattegat, the Sound and the Belt Sea, and document significant decreases in nutrient concentrations on a large regional scale as a result of an active management strategy to reduce nutrients from both diffuse and point sources (Carstensen et al. 2006).

Despite these very first signs of recovery, we are still far from fulfilling the objectives of coastal waters 'unaffected

by eutrophication' or having a 'good ecological status' (Fig. 1). For better document recovery, we believe the reporting of the ND should be improved in regard to (1) the indicators used, (2) the WFD assessment principles, and (3) the assessment tools applied, the latter including also the methods used to assess both trends in NO_3^- loads and source apportionment, the latter indicating whether the load originates from agricultural activities or from other sectors. Further, the reporting should be based on continuous monitoring (i.e. every year), not on snapshots (i.e. every 4 or 6 years). By monitoring every year, the temporal trend analysis will be more powerful, and Member States can assess year-to-year variations which, in many cases, are directly linked to year-to-year variations in precipitation and runoff.

NEXT STEPS TO CONVERGE ASSESSMENT PROCESSES

The fact that the ND has been in operation for more than two decades without alleviating the eutrophication status of the most European coastal waters should not be interpreted as a failure in its implementation, but merely that changes in agricultural practices are not necessarily recorded as instant improvements of downstream water quality.

Other eutrophication-related Directives such as the Urban Waste Water Treatment Directive (Anon. 1991b), the WFD, and the recently adopted MSFD should not be disregarded. Our key message is that the ND ought to be linked closer to the implementation of especially the WFD. In the WFD, articles 10 and 11.3 provide a direct link to the ND, but this has so far been used only partially. Such convergence should not only be made in regard to reduction of losses and discharges of nitrates from agriculture, but also in regard to target setting and assessment procedures.

Despite decreasing trends in nutrient inputs to Danish coastal waters, we still have a large-scale eutrophication problem caused mostly by agricultural activities.

Both nitrogen and phosphorus play a key role in nutrient enrichment of coastal waters, resulting in accelerated growth of primary producers and concomitant increase in the supply of organic matter to coastal ecosystems (Nixon 1995; Conley et al. 2009). However, in all open and in most temperate coastal waters, the key limiting nutrient for primary production is nitrogen (Howarth et al. 2011). Efforts to abate eutrophication thus need to focus on the nutrients controlling eutrophication in order to reverse the eutrophication trends which regarding nitrogen justifies the importance of the ND.

The first step in the assessments of the effectiveness of any nutrient management strategy [being an EU Directive or a regional or national Action Plan such as the HELCOM Baltic Sea Action Plan (HELCOM 2007) or the Danish Action Plans on the Aquatic Environment (Ærtebjerg et al. 2003)] is the monitoring of nutrient inputs to coastal waters. Good examples of how to check temporal trends and source apportionment of nutrient inputs can be found in Conley et al. (2007), OSPAR (2010) and HELCOM (2012). The trends in total nitrogen (TN) inputs to Danish coastal waters are shown in Fig. 3. The inputs are indicative of what controls eutrophication in a given water body. If the majority of the inputs of controlling nutrients originate from agricultural activities in upstream catchment, then the eutrophication signals can be concluded to be caused by agricultural activities.

The second step is to assess eutrophication status. However, if such an assessment should be evaluated as 'state of the art', we argue that the currently used two indicators (NO_3^- and Chl-*a*) are insufficient. During the last decade, several multimetric indicator-based eutrophication tools have been developed. The first of these tools was the OSPAR Comprehensive Procedure, which led to the assessment of eutrophication status in the OSPAR convention area in the years 2003 and 2008 (OSPAR 2003, 2008). This tool is widely used in Northern and Western Europe, and has been the basis, together with WFD, for the *HELCOM Eutrophication Assessment Tool* (HEAT), which has been used for assessment of eutrophication status in the Baltic Sea (HELCOM 2009; Andersen et al. 2011) and recently in the North Sea (Andersen et al. 2012).

Converging lessons learned from assessments under the WFD and recently in the Baltic Sea can be done as shown in Table 2. Here, we present an assessment of temporal trends in eutrophication status in four major Danish estuaries with upstream catchments dominated by agricultural activities. We argue that this type of integrated assessment would represent an important step forward compared to the current reporting under the ND. The added value is in our opinion twofold. Firstly, there will be more confidence in the assessments of eutrophication status (i.e. ecological status) compared to assessments based on nutrient concentrations and Chl-*a* only. Secondly, temporal trends assessments can be made irrespective of changes in the number of parameters (indicators) being monitored.

The improvements in eutrophication/ecological status in Randers Fjord are triggered by reduced inputs of nitrogen and subsequent improvements in light conditions, whereas the improvement in Ringkøbing Fjord is mostly a response to a change in salinity leading to colonization by soft clams which, through their filtration of the water, have improved the light conditions (Petersen et al. 2008).

OUTLOOK

The ND is a Directive in its own right and with specific implementation guidance and reporting formats. However,

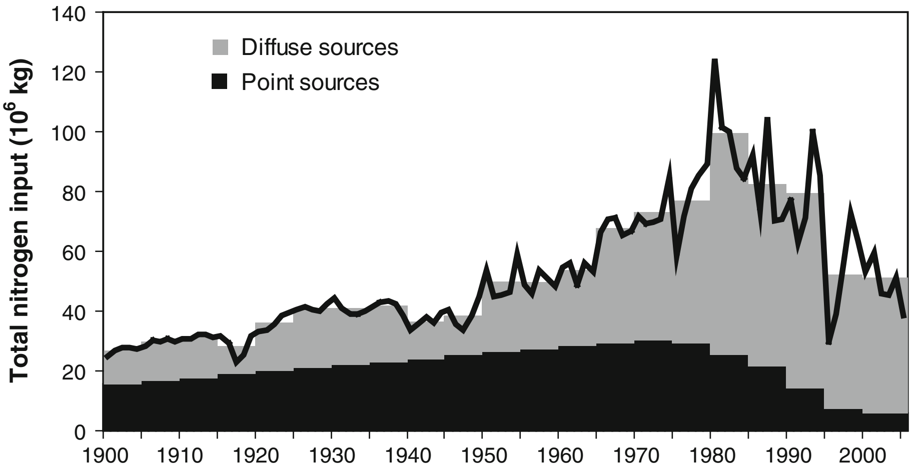

Fig. 3 An example of temporal trend assessment of estimated total nitrogen (TN) inputs (*solid line*) from Denmark to the Danish Straits including the Kattegat since 1900, with 5-year averages of point and diffuse sources. Since the mid-sixties, inputs to the Danish Straits have been dominated by diffuse sources, predominantly agricultural activities. Year-to-year variations are correlated to changes in precipitation and run off. Long-term trends are correlated to human activities, especially agricultural practices and treatment and subsequent discharge of waste water from point sources. From Andersen and Conley (2009), based on Conley et al. (2007)

Table 2 Classification of temporal trends in eutrophication status in four Danish estuaries, all with upstream catchments dominated by agricultural activities. The assessments are in principle based on indicators representing the following three criteria: (1) causative factors, (2) primary effects and (3) secondary effects of eutrophication and based on Andersen et al. (2012). In practice, the indicators used most are related to concentrations of nutrients (N and P), chlorophyll-*a*, and depth limit of submerged aquatic vegetation. The classifications ($n = 20$) are annexed as Electronic Supplementary Material

Assessment unit	Assessment period				
	1992–1995	1996–1999	2000–2003	2004–2007	2008–2011
Ringkøbing Fjord (No. 5)	Bad	Poor	Bad	Bad	Moderate[a]
Limfjorden (No. 10)	Bad	Bad	Bad	Bad	Bad[a]
Randers Fjord (No. 12)	Bad	Bad	Bad	Bad	Moderate[a]
Odense Fjord (No. 21)	Bad	Bad	Bad	Bad	Bad
Average no. of indicators	6.5	7.5	7.5	7.5	7.3

[a] The differences compared to Fig. 1 are due to different assessment periods (2005–2009 vs. 2008–2011) as well as variations in the indicators used; please confer with annexes to Andersen et al. (2012) and the Electronic Supplementary Material to this study

more than ten years of experience with the implementation of the WFD and with the recent implementation of the MSFD have proven that these three Directives share a lot of common ground and mutually support each other. We are convinced that these well-known links should be taken more seriously in order to increase harmonization and coordination. Such coordination will reduce the risk of duplicate work and also increase the accuracy of the assessments being made and thus support fulfilment of the objective of all the three Directives.

A recent pan-European review of Member States River Basin Management Plans (Anon. 2012) has not surprisingly revealed that attainment of good status may take more time than expected in some coastal waters, e.g. those affected by eutrophication caused by nitrates from agriculture. Further, the review concludes that despite considerable progress, some countries show important gaps in both monitoring activities and in the development and application of assessment methods (Anon. 2012). The review recommends that Member States improve and expand monitoring and assessment tools to ensure a statistically robust and comprehensive picture of the status of the aquatic environment for the purpose of further planning.

Therefore, we suggest, with reference to the ND, improving the current reporting process by application of a multimetric indicator-based eutrophication assessment tools. Hence, (1) inputs of NO_3^- (and other N compounds) to the aquatic environment should be monitored and assessed every year, not every four years, in order to identify year-to-year changes and to carry out source apportionment on an annual basis; and (2) eutrophication status with regard to the ND should be assessed using multiple indicators representing key ecological features in the water bodies assessed, e.g. by the use of the indicators and assessment principles in the WFD. This suggested procedure for assessment of eutrophication status and trends will in our opinion lead to better and more evidence-based River Basin Management Plans *sensu* WFD, but also to a better implementation of the ND.

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