Shifting sands of Marine eutrophication: revisiting and rethinking our approach for the UK

Date: March 2024

Author(s): Michelle Devlin[1] Naomi Greenwood[1], Carolyn Graves[1], Mike Best[2]

[1]Centre for Environment, Fisheries and Aquaculture Science, Lowestoft, UK. NR33 0HT.

[2]Environment Agency

Cover sheet:

Programme	Marine Natural Capital and Ecosystem Assessment (mNCEA)
Programme lead organisation	Department for Environment, Food and Rural Affairs
Project ID and title	NC34: PELCAP
Other reference numbers	
Project lead organisation	*Michelle Devlin (CEFAS)*
Project start date	01/04/2023
Project end date	31/03/2024
Work package number and title	Work Package (WP)2: An improved ability to take an ecosystem approach to nutrient pollution.
Output title	Shifting sands of Marine eutrophication: revisiting and rethinking our approach for the UK
Output lead organisation	*Cefas*
Contributing organisations	*Cefas and Environment Agency*
Lead author	*Michelle Devlin*

This project was funded by the Department for the Environment, Food and Rural Affairs (Defra) as part of the marine Natural Capital and Ecosystem Assessment (NCEA) programme. The marine NCEA programme is leading the way in supporting Government ambition to integrate natural capital approaches into decision making for the marine environment.

Find out more at https://www.gov.uk/government/publications/natural-capital-and-ecosystem-assessment-programme.

Any enquiries regarding this publication should be sent to us at

marineNCEA@defra.gov.uk

Contents

1 Abstract 5

2 Introduction 5

2.1 Eutrophication assessments in the UK 6

2.2 Eutrophication indicators 7

3 Eutrophication assessments – what is needed. 9

3.1 Knowledge gaps 9

3.1.1 DATA 9

3.1.2 ALIGNMENT 12

3.1.3 INDICATORS 14

3.1.4 PELAGIC 16

3.1.5 CLIMATE 18

4 Prioritisation exercise 19

5 Tracking progress to achieve recommendations 19

6 Conclusions 22

7 Acknowledgements 23

8 References 24

1 Abstract

The assessment of water quality, and in particular eutrophication, has been a core strategy to disseminate and communicate the impact of anthropogenic influences on our coastal and marine waters in the UK. Initial assessments focused heavily on single metrics associated with a numerical threshold, where the supporting science concentrated on understanding the importance of that threshold and relating exceedances to a management action. As our understanding of the complexity of processes occurring in the coastal zone, in terms of variability, time lags, ecological interactions and resilience has evolved, so has the structure of our water quality reporting and the composition of the reporting metrics. Water quality reporting should now consider the importance of cumulative impacts, in terms of water quality changes within a warming world and recognise that the bottom up and top-down processes are needed to inform and direct our understanding of what constitutes an acceptable and sustainable level of use. This paper will present a review of approaches for eutrophication assessment, identifying the pathways required to progress our assessments to fully encapsulate complexity, embed new indicators and improve understanding of a shifting baseline.

2 Introduction

Excess nutrients from fertiliser application, pollution discharge, urban wastewater and sewage treatment plant outflow through rivers from lands to oceans, impacting on the coastal water quality and coastal ecosystems (Devlin & Brodie, 2023; Paerl & Piehler, 2008; Painting et al., 2007). Terrestrial runoff of waters polluted with nutrients (primarily nitrogen [N] and phosphorus [P] compounds) from point sources, such as sewage treatment plant (STP) discharges, and diffuse sources via river discharges, such as fertiliser losses, have had devastating adverse effects in coastal and marine ecosystems globally (Ngatia et al., 2019; Ryther & Dunstan, 1971; Smith, 2003). Biomass production of plant matter in coastal waters is often limited by the availability of nitrogen and/or phosphorus (light is a limiting factor in turbid zones). Increased anthropogenic inputs of these substances can lead to increased biomass production that disturbs the natural ecological balance in marine ecosystems (de Raús Maúre et al., 2021). This disturbance, the process of eutrophication, is seen globally as one of the biggest threats to marine ecosystem health. Eutrophication, like climate change, is a global issue with coastal regions throughout the world being impacted through the input of elevated nutrients (Laurent et al., 2018; Meier et al., 2019)

Eutrophication has a substantial impact on our coastal and marine systems and can limit access to ecosystem services by acting as a pressure on biodiversity and the ecosystem (Kermagoret et al., 2019; Rhodes et al., 2017). Even at a low level, increased nutrient loads and changing proportions of nutrients result in phytoplankton biomass and species shifts which affect higher trophic level species (Carstensen et al., 2011; Duarte, 2009; Duarte et al., 2009). Species shifts are frequently characterized by bloom events which have significant economic impacts as they reduce attractiveness and amenity value of coastal waters. Increased phytoplankton biomass reduces light penetration which in turn causes habitat loss by limiting areas where seaweeds and seagrasses can grow (Carolina, 2002; Foden et al., 2005). These habitats are important for maintaining nursery populations of fish. More serious eutrophication involves hypoxic events which harm many organisms but are particularly damaging to sessile benthic fauna, whose loss again affects the food web and biotic water quality regulation. Extreme hypoxia and anoxia lead to a loss of both biotic and abiotic water quality regulation, as previously sequestered nutrients are lost from sediment surfaces and bacterial denitrification processes change (Devlin and Brodie, 2023). Well-documented adverse ecological responses of increased nutrient discharge to coastal and marine waters include harmful algal blooms (HABs) (Glibert and Burford, 2017; Hudnell, 2008), changed preponderance and dominance of certain types of algae over other benthic plants (seagrass, coral, other algae) (Lapointe et al., 2018; Lapointe et al., 2019) hypoxia and subsequent “dead zones” (Diaz and Rosenberg, 2008) habitat degradation, and adverse changes in aquatic food webs (Carpenter et al., 1998; Gross and Hagy, 2017).

Eutrophication in the 1970’s was related to point source pollution with program of measures focused primarily on the reduction of phosphorus and management of nitrogen from sewage treatment. Whilst there were catchment-based programs such as the Nitrogen Vulnerable Zones (NVZ), the abatement of diffuse nitrogen and other agricultural pollutants has been less effective. Diffuse nitrogen losses are now the main sources of nitrogen loading into coastal and marine waters.

Mitigation of eutrophication presents many layers of complexity, needing multiple, often cumulative actions over large spatio-temporal scales (Thornton et al., 2013). Solutions to tackle eutrophication need to address the entire land-sea continuum and to measure a whole range of complex interactions and impacts. Our previous way of thinking needs a re-analysis of the issues, and an updating of how we approach the problems, and a rethinking of the solutions.

2.1 Eutrophication assessments in the UK

Our eutrophication assessments in the United Kingdom have changed politically in multiple ways and in multiple directions. The shift from reporting under EU environmental directives to a more nationally based marine strategy is challenging but has also acted as a catalyst to rethink how we manage our environment in respect to eutrophication. This is particularly relevant given our reporting to OSPAR for eutrophication and chemical contamination (Claussen et al., 2009; Devlin et al., 2023; Foden et al., 2011; Malcolm et al., 2002). However, previous assessments have identified ongoing issues with the eutrophication assessment approach with a disconnect between geographical boundaries and thresholds still hindering our understanding of eutrophication state across coastal and marine waters. Progress was made under the recent OSPAR eutrophication thematic report with harmonizing of assessment areas, integration of common indicators for the assessment of eutrophication, agreement on harmonized area-specific assessment levels and integrated data assessment via an online data tool (Devlin et al., 2023).

National work has focused on developing improved assessments under the UK Marine Strategy, developing ecologically relevant assessment areas, which are not constrained by geographical boundaries, developing assessment levels based on historical scenarios and modelling and applying a harmonised assessment across the North-East Atlantic and much stronger alignment with nearshore and coastal marine waters under [The Water Environment (Water Framework Directive) (England and Wales) Regulations 2017 (legislation.gov.uk)](https://www.legislation.gov.uk).

The assessment of water quality has been a core strategy to disseminate and communicate the impact of anthropogenic influences on our coastal and marine waters. Initial assessments focused heavily on single metrics associated with a numerical threshold, where the supporting science concentrated on understanding the importance of that threshold and relating exceedances to a management action. As our understanding of the complexity of the coastal zone, in terms of variability, time lags, ecological interactions and resilience has evolved, so has the structure of our water quality reporting and the composition of the reporting metrics. Water quality reporting now considers the importance of cumulative impacts, in terms of water quality changes within a warming world and recognise that both bottom up and top-down processes are needed to inform and direct our understanding of what constitutes an acceptable and sustainable level of use. This paper will present the outcomes of a prioritisation exercise, looking at the urgency required to shift our eutrophication programs and assessment frameworks to better encapsulate a changing baselines and increased understanding. The outcomes of the prioritisation will be presented and discussed in terms of failures and successes and discusses the options for future decision makers.

2.2 Eutrophication indicators

Assessment of eutrophication has typically focused on the measurements of three primary indicators, which typically include dissolved nutrients (nitrogen and phosphorus), phytoplankton biomass (typically measured as chlorophyll-a) and dissolved oxygen. However, various eutrophication assessments apply additional assessments, focusing on measures that indicate if the increased nutrients are impacting on ecosystem state. These measures or metrics can include phytoplankton community, harmful algal blooms and fish kills. The type of primary and secondary metrics varies depending on the water type, geographical area and monitoring program (Table 1). Dissolved inorganic nitrogen, phosphorus and silicate concentrations are measured in winter when biological activity and uptake of nutrients by phytoplankton is low. Chlorophyll-a concentrations, measured as a proxy for the (carbon) biomass of phytoplankton, are the net result of several processes: the production of phytoplankton biomass which is determined by nutrient concentrations but also by light and temperature, and the loss of phytoplankton biomass which is determined by mortality, sinking and grazing. Due to these many interacting factors, the response of phytoplankton biomass to changes in nutrient input is complex and system specific. While there are examples of water systems within the OSPAR Maritime Area where reduced nutrient inputs have resulted in lowered phytoplankton biomass or production this is not always the case due to the complexity of interacting processes. Nevertheless, this parameter is a useful direct effect assessment parameter of nutrient enrichment.

Table 1: Summary of current eutrophication indicators, identifying the metrics used within each of the three UK frameworks (Water Framework Regulation (England) or Water Framework Directive (Wales, Scotland), UK Marine Strategy and the OSPAR Comprehensive Procedure. NI = Not implemented.

Category	Indicator	**UK assessment frameworks**		
		Water Environment (Water Framework Directive) Regulations	UK Marine Strategy	OSPAR Comprehensive procedure
Category 1				
Physico-chemical	**Nutrient concentrations -** Elevated level(s) of winter DIN and/or DIP	Winter Mean DIN, DIP	Winter Mean DIN	Winter Mean DIN
	N/P ratio - Elevated winter N/P ratio	NI	NI	Partly
	TN & TP - Total nitrogen and phosphorus	NI	NI	Partly
Category 2				
Direct biological impacts	**Chlorophyll-*a* concentration** 90 percentile level or mean	Growing Season 90th %	Mix GS 90th % and GS Mean	Growing Season Mean
	Phytoplankton indicator species (area-specific) • Elevated levels of nuisance/toxic indicator species • increased duration of blooms • **Elevated counts**	Single Species and total taxa count	Partly	NI
	Macrophytes including macroalgae (area-specific) Shift from long-lived to short-lived nuisance species, Elevated levels (biomass or area covered) opportunistic green macroalgae)	Opportunistic macroalgae	Partly	NI
Category 3				
Indirect Biological impacts	**Oxygen deficiency** Decreased levels (< 2 mg l^{-1}: acute toxicity; 2 - 6 mg l^{-1}: deficiency) and lowered % oxygen saturation	Surface DO	Mix of Surface DO and Bottom DO.	Bottom DO
	Zoobenthos and fish	NI	NI	NI
	Organic carbon/organic matter (area-specific)	NI	NI	NI
	Photic limit (transparency of the water column	Turbidity Used in TWs		

3 Eutrophication assessments – what is needed.

One of our current challenges has been to respond to shifts in our understanding of eutrophication and a shifting baseline. We need to explore how we can become more confident in the outcomes of national assessments by better use of high frequency data, improved technology, modelling, mapping, and working across the catchment to coast continuum - the area across which nutrients move from their place of use or place of discharge to the sea. Through discussions with relevant government agencies who are responsible for some aspect of eutrophication monitoring and/or assessment, priorities for future work were identified for five broad knowledge areas, ranging across five themes. The five themes are DATA, ALIGNMENT, INDICATORS, PELAGIC and CLIMATE covering 12 recommendations identified to improve eutrophication monitoring and assessment.

3.1 Knowledge gaps

3.1.1 DATA

3.1.1.1 High Frequency data

High frequency data from new and improved technology is now creating high volumes of data and is changing the shape of data in our coastal and marine assessments (Bean et al., 2017; Mills et al., 2004). These shifts need to consider data streams that can fully integrate novel and high frequency data to improve understanding of the complex coastal and marine processes (Addison et al., 2018; Dafforn et al., 2016).

One of our challenges in improving our understanding of eutrophication, and progress in our national assessments is through better use of high frequency data and improved technology. For example, under the recent OSPAR comprehensive assessment (Devlin et al,.2023a; Devlin et al., 2023b) earth observation data has been used in the assessment for the first time (van Leeuwen et al., 2023). Higher data frequency over these reporting areas and through different time periods makes it easier to understand if changes are occurring and what we need to do to mitigate problems and to protect areas that have high ecological value.

The use of multiple instruments such as the growth in sensor technology, ecosystem models, uptake of remote sensing and high frequency autonomous data have resulted in a rapid increase in the amount of data that is collected across spatial and temporal scales. Although many of these instruments are still reliant on some form of discrete sampling to calibrate measurements, a comparison between these indicators (chlorophyll and dissolved oxygen), and one that relies solely on discrete sampling (nutrients) demonstrates the increase in spatial coverage that multiple sources of data can provide.

Recommendation 1: High frequency data is incorporated into the assessment. High frequency data encompasses BIG data, autonomous sensors, satellite data, depth profile data (CTD) and other innovative approaches to measuring high spatial and temporal water quality data.

3.1.1.2 Targeted and increased sampling in low or limited data areas

Many of the waterbodies in the UK have limited or no data, and thus, even areas in good and high status can have very low confidence due to limited or low data collection. For some parameters, we are very reliant on the in-situ and discrete sampling, such as nutrients, and it is difficult (currently) to increase data frequency through earth observation data. This is particularly relevant when you have a short assessment period for winter nutrients (from November to February) that limits sampling and requires in-situ sampling at logistically difficult times of the year. Current monitoring data is relatively sparse leading to minimal assessment options and requires a revised approach.

Another major issue with data in our eutrophication assessments is the lack of confidence in the nutrient load program and our ability to accurately assess long-term nutrient load trend, Accurate and timely information on nutrient concentrations and loads is integral to strategies designed to improve human well-being and successfully manage the underlying drivers of water quality impairment and inform our program of measures (Joo et al., 2012; Pellerin et al., 2016). This is an ongoing problem, where limited (or no) data frequency is impacting on our ability to understand if our river systems are changing. Recent studies have identified a common problem for many coastal waters, where abatement of phosphorus loads has occurred at a much faster rate than nitrogen abatement and mitigation (Devlin & Brodie, 2023b; Lu & Tian, 2017; Ngatia et al., 2019). This has led to imbalanced nutrient ratios, where rivers and coastal systems are experiencing a reduction of P, but stable or increases in N (most likely due to diffuse N from agriculture) with these imbalances impacting on plankton communities in coastal waters (Romero et al., 2012). But there is a lack of understanding of the extent of this issue, coupled with changing climate and shifts in seasonality mean that we are not tracking these changes with confidence.

Recommendation 2: Increase data collection in areas with limited or no data, areas with low confidence assessment outcomes and for nutrients in the load monitoring program.

3.1.1.3 Inclusion of riverine influenced areas to understand transport and fate in assessments.

To date, water quality assessments made under UK Marine Strategy and OSPAR Comp Procedure have used assessment areas defined by geographical or political boundaries rather than those which are ecologically coherent and fully represent the extent of terrestrial influence in marine waters. The UK coastal zone has a large extent with dynamic spatial and temporal fluctuations with tides, areas with a seasonally stratified water column, wind, river discharges all influencing the behaviour of the eutrophication indicators. Whilst the WER (WFD) did develop an approach to defining transitional and coastal typologies that were characterised by tidal range, mixing, salinity and depth, the edge of the coastal assessment areas were defined by an arbitrary 1nm offshore for England, Wales and NI and by 3nm for Scotland, leading to abrupt changes over the nearshore to coastal assessment areas. There is a need to reconsider the assessment areas and increase our understanding of the role of the riverine influenced area that lies between the UK transitional and coastal waters, riverine plume areas and further offshore assessment areas.

Riverine freshwater plumes are the major transport mechanism for nutrients, sediments and pollutants and connect the land with the receiving coastal and marine waters. Knowledge of the variability of the freshwater extent into UK marine waters is relevant for environmental management to develop strategies for improving ecosystem health and risk assessments (Devlin et al., 2011; Schroeder et al., 2010). The area of the riverine influence has been mapped previously with salinity and SPM (Desmit et al., 2024; Fettweis et al., 2022) and salinity (Ivanov et al., 2020) but whilst useful for understanding hydrodynamic variability, it is difficult to extract imagery of the plume extent. Sea surface salinity is the most traditional conservative tracer of freshwater discharge however, it can be difficult to extract direct satellite-based salinity measurements in sufficient spatial resolution for coastal applications (Schroeder et al., 2010). A new approach defining the water quality assessments, using satellite derived particulate matter (SPM) and in situ salinity can be a better reflection of the physical, chemical and biological processes present in the water (Greenwood et al., 2019). Although this method can provide assessments across ecologically homogeneous areas, defining river plumes seasonally and on a relatively high resolution in the coastal areas is still required to assess the water quality conditions across estuarine and intertidal habitats (Fronkova et al., 2022; Heal et al., 2023). Plume mapping of UK waters has now progressed through deriving and mapping the Forel Ule colour scale, as determined from Sentinel-3 satellite imagery. Using the relationship between ocean colour and water quality parameters, recent work has now developed geographically defined assessment areas through the mapping of ocean colour (Fronkova et al., 2022; Greenwood et al., 2019; Heal et al., 2023). Improved mapping of riverine extent has provided new "plume" areas within UK assessment areas and were used for the first time in the recent OPSAR eutrophication thematic assessment and the UK marine Strategy assessing environmental status across transitional to marine waters (Devlin et al., 2023).

Recommendation 3: Reporting of riverine plume extent as part of eutrophication assessments and use of ocean colour to define the full riverine extent for UK rivers. Harmonisation between coastal waterbodies, plumes and offshore waters is also required.

3.1.1.4 Improve knowledge around natural variability.

To allow for natural variability, the original OSPAR assessment procedure for eutrophication (Comprehensive Procedure) sets the threshold between Non-Problem/Problem Area (elevated levels) at 50% above natural background concentrations, which is equivalent to the boundary setting good/moderate for the EU Water Framework Directive (WFD). The 50% level corresponds to the recent natural variability of nutrient gradients in coastal and estuarine waters in the UK. For eutrophication effects such as oxygen deficiency, reduced transparency and increased transboundary loads, especially for offshore regions, 50% (Maas-Hebner et al., 2015) exceedance of the natural background surpasses ‘slight differences’ as recommended by the boundary good/moderate for the WFD (Claussen et al., 2009; Topcu et al., 2009).

Recommendation 4: Analysis of long-term data to assess natural variability, looking at values that represent different areas, different parameters, and different seasons. Calculate new values for the difference between non-problem and problem areas that represent natural variability.

3.1.1.5 Trend analysis within eutrophication assessments

Assessments typically share monitoring data across geographic and jurisdictional boundaries. Doing so improves their abilities to assess local, regional-, and landscape-level environmental conditions, particularly status and trends, and to improve their ability to make short- and long-term management decisions (Maas-Hebner et al., 2015). Status monitoring assesses the current condition of a population or environmental condition across an area. Monitoring for trends aims at monitoring changes in populations or environmental condition through time. Our assessments, with a multimetric approach using several indicators is based on a status assessment (so a value aggregated over 6-year cycle) but associated trend assessments are not presented as part of the quantitative assessment. We need to incorporate understanding the trends within our assessments with a consideration of state and trend to fully encapsulate not only current state, but the trajectory of change and future predictions.

Recommendation 5: Incorporate trend analysis into assessment, identifying trajectory of change and prediction of future state.

3.1.2 ALIGNMENT

3.1.2.1 Harmonising assessment areas, indicators, and thresholds

Area-specific assessment levels have been established based on levels of increased concentrations and trends as well as on shifts, changes, or occurrence. Assessment levels are defined in general terms as a percentage above an area-specific reference condition. This reflects natural variability and allows for a ‘slight disturbance’ as is also the case for assessment under the Water Framework Directive. Under the recent OSPAR comprehensive assessment (Devlin et al., 2023) there has been a move to a more harmonised approach in the development of common indicators, data, and assessment areas for our reporting and to achieve greater spatial coverage of all our marine reporting regions (Devlin et al., 2023). The harmonisation under OSPAR has not translated into our UK eutrophication assessment, where there is a disconnect between thresholds developed for transitional and coastal waters and those developed for plumes and offshore. Despite this, the gradient between inshore to offshore reflects a reducing concentration gradient against salinity, but more work is required to ensure that the indicators and thresholds are linked across the political boundaries between UKMS and WFR/WFD.

Recommendation 6: Harmonise assessment areas and thresholds across the UK eutrophication assessments.

3.1.2.2 Integration across ecological boundaries from catchment to coast

Historically, UK marine and terrestrial environmental policies have been largely delivered in isolation despite the marine system being explicitly connected to the land with most of the marine pollution originating from terrestrial sources. This has resulted in a disconnect between inshore and offshore assessments. Furthermore, this disaggregated approach can negatively impact on our understanding of how land-based management measures need to consider and assess climate change related changes. A fully integrated catchment to coast approach has greater potential to change the input of terrestrial contaminants into our marine environment with subsequent positive effects on the coastal ecosystem.

Eutrophication assessment for the UK Marine Strategy (hereafter UKMS) still relies strongly on adding in two different assessments – OSPAR and the Water Environment (Water Framework Directive) Regulation (WFD/WER) (Devlin et al., 2009, 2023; Foden et al., 2011). Whilst there is some compatibility between the approaches, there are more differences than similarities. For example, we report nutrients in the UKMS collated from both WFD/WER and OSPAR assessment, but there are small but significant differences in how both approaches derive an outcome from nutrients. The WFD/WER nutrient assessment is an aggregation of two indicators for Winter DIN and Winter DIP, whilst the OSPAR nutrient is based on DIN and DIP measured separately. The biggest difference is how the overall “eutrophication” is calculated, meaning that the read across in coastal to offshore areas is not seamless. WFD/WER use the physico-chemical assessment to identify high risk areas for eutrophication whilst the outcome of the Winter DIN and Winter DIP in OSPAR is not accounted for in the final assessment. There are other differences between the chlorophyll and dissolved oxygen assessment, again, small but significant, and result in multiple differences between the two approaches for the final assessment of eutrophication. Ultimately there is a disconnect between the catchment to coast, with an arbitrary policy line at 1nm, that separates out coastal water bodies under WFD/WER and our riverine plume areas and further offshore assessment areas under OSPAR and UKMS. It also means we struggle with data frequency in those very important plume areas as over past few years, agencies such as Cefas tend to focus more offshore and agencies such as Environment Agency are monitoring estuarine and inshore, with limited sampling in the plume areas.

Recommendation 7: Better integration of WER (WFD), UKMS and OSPAR to ensure indicators, assessment areas and thresholds are harmonised across ecological and geographical boundaries.

3.1.3 INDICATORS

3.1.3.1 Consider complex interactions that define susceptibility into the assessment.

Traditionally eutrophication indicators have relied on nutrients, phytoplankton biomass (measured as chlorophyll) and dissolved oxygen. These parameters are, and continue to be, highly relevant indicators when measuring the extent and impact of eutrophication issues.

However, the use of these indicators can limit understanding of impacts, and there is an urgent need to expand, both in the improvement of our current indicators and development of new indicators. Measures of light attenuation, coastal darkening, and ocean colour are all measures that provide information on the clarity and composition of the water column and can help informed susceptibility of the coastal and marine waters to eutrophication.

Chromophoric dissolved organic matter (CDOM) offshore originates predominantly from bacterial decomposition of phytoplankton cells, whereas in coastal waters, CDOM is dominated by humic and fulvic acids of terrestrial origin and transported to the seas through freshwater runoff from the land as well as autochthonous CDOM from salt marshes, mangroves, inter- and sub tidal benthic microalgae, seagrasses, macro-algae and corals (Carder et al., 1989). CDOM is a useful surrogate for salinity in coastal waters and an important component of light attenuation. Vertical attenuation of light through the water column is attributable to the optically active components of phytoplankton, suspended particulate material (SPM) and (CDOM) with CDOM not routinely measured in UK waters (Foden et al., 2008).

The use of ocean colour has been incorporated into a risk framework to assess the impact of river plume exposure on marine ecosystems in English waters. This can be used to identify ecosystems which may experience acute or chronic high exposure to contaminants in river plumes and help evaluate the susceptibility of coastal ecosystems to land-sourced contaminants and track long term changes related to flow and pollution loads. Such an approach can be used to enhance the link between marine management and environmental land management schemes.

CDOM, ocean colour, light attenuation, turbidity and suspended particulate matter are all important components to measure to understand both freshwater extent and the dynamics of the light conditions. Foden et al., 2008 discusses how a simple dose-response model of nutrient enrichment to risk of eutrophication does not consider the important role light plays in marine waters, and limits understanding of the complex interactions at play. Cloern (2001) recognises system attributes that ‘filter’ responses to changes in nutrient loading, including: the underwater light climate, horizontal exchange, tidal mixing, grazing and biogeochemical processes. This complex response determines susceptibility, which influences the assessment of eutrophication status. The light climate is highly variable in UK waters and therefore of particular significance regarding the risk of eutrophication (Devlin et al., 2008; Foden et al., 2008, 2011).

Over the last century, the world oceans and coastal regions have seen marine lightscapes changing in two fundamental ways. Firstly, some regions have experienced a long-term reduction in water clarity, referred to as Coastal Darkening (Aksnes et al. 2009), with large-scale drivers connected to effects of climate change (more frequent and intense rainfall, increased temperatures, melting permafrost and glaciers) and other human activities, such as changes in catchments' properties and activities that increase erosion (Dupont and Aksnes, 2013; Frigstad et al., 2023, Organelli et al., 2017). A reduction in the light availability will affect all organisms that are dependent on light for photosynthesis, such as phytoplankton, benthic macroalgae and seagrasses, in addition to animals' dependent on light for feeding or other purposes (Opdal et al., 2019; Capuzzo et al., 2015; Wollschlaeger et al., 2021). Secondly, some coastal regions are experiencing a brightening of the night-time light environment linked to urbanisation, on- and offshore infrastructures, fisheries, and shipping (Davies et al., 2014; Davies et al., 2020; Smyth et al., 2021). Knowledge of coastal darkening and other changes in natural light conditions needs to be a key part of eutrophication (and climate change) assessments into the future.

Recommendation 8: Develop indicators that measure components of light attenuation, ocean colour and coastal darkening. Consider complex interactions that influence susceptibility in the eutrophication assessment.

3.1.3.2 Reset of traditional approach to eutrophication

Positive environmental and societal change related to monitoring and assessment entails a move away from a single pressure-state response through to the development of integrated frameworks across ecosystems, pressures, stakeholders, and policy.

Improvements that could be beneficial for eutrophication assessments include quantification of economic and environmental connections, greater integration of the reporting of complex interactions between social, economic, and ecological factors, multi-disciplinary frameworks and enhanced community engagement. Processes or programs that deliver these improvements have been identified for programs that cost environmental successes as marine natural capital and holistic approaches that consider health between the environment and humanity as intrinsically linked in terms of water quality improvements. Additionally, programs that include clear elucidation between cause and consequence, socio-economic pathways, and greater levels of engagement with communities are all attributes of successful monitoring and evaluation programs that could be applicable to UK coastal and marine systems.

Incorporation of natural capital into monitoring programs has been a successful way to incorporate the system flows between ecology, goods and services, and benefits to human wellbeing. In the recent marine natural and ecosystem assessment for the UK (mNCEA), there are several projects exploring these links between environmental assets, flow and human wellbeing (Rhodes et al., 2017). Fully integrated assessments such as the One Health approach where the multiple interconnections that exist between environmental, animal and human health are also considered as a technique to incorporate multiple benefits to multiple end-users (Backer & Miller, 2016; Cork et al., 2016; Stentiford et al., 2020). A greater understanding of the relationship between ecological and economic production for these beneficiaries will also be important for understanding the magnitude of changes in human well-being (Rhodes et al., 2017).

Greater engagement of the community, not only through data collection, but as an important part of the evaluation side, and by becoming embedded in decision making around policy and governance should be a key requirement of greater success in monitoring and evaluation programs.

Recommendation 9: Continue to incorporate marine Natural Capital into national monitoring programs, align assessments with integrated ecological approaches such as DPSIR and One Health. Re-engage and renew ecosystem approach within the eutrophication assessments.

3.1.4 PELAGIC

3.1.4.1 Embed linkages with plankton indicators and long-term trends.

Collecting information on pelagic data will provide will move our reliance from common indicators (nutrients, chlorophyll, dissolved oxygen) to better estimates of community shifts such as nutrient imbalances, plankton lifeforms, and ecosystem functioning.

Shifts in species composition from diatoms to flagellates may indicate a shift in the balance of organisms due to eutrophication. The composition of the phytoplankton community could be compared with area-specific reference conditions and be expressed by the ratio of diatoms to flagellates. This approach can be picked up as part of PH1 under OSPAR and UKMS biodiversity assessments. Eutrophication is a complex process and often associated with not only a change in overall algal biomass but also with a change in biodiversity. Common metrics of eutrophication (e.g., chlorophyll a), total nitrogen (TN) and phosphorus (TP) are not adequate for understanding biodiversity changes, especially those associated with harmful algal bloom (HAB) proliferations (Glibert, 2017). To maximise the utility of the plankton lifeform approach for informing the management of marine ecosystems, changes in the abundance of lifeforms need to be attributed to drivers of change. These drivers may include 'directly manageable' anthropogenic pressures (such as eutrophication caused by nutrient loading) as well as larger-scale and longer-term changes in climate and oceanography (Bedford et al., 2018). Ecological time-series are critical for understanding the drivers of change, especially of climatic factors such as changing thermal regimes (Edwards et al., 2010; Giron-Nava et al., 2017).

Temperature change and eutrophication are known to affect phytoplankton communities (McQuatters-Gollop et al., 2007), but we have limited information on the effects of interactions between simultaneous changes of temperature and nutrient loading in coastal ecosystems. Such interactions have been key in driving diatom-dinoflagellate dynamics in coastal systems such as the East China Sea. Diatoms preferred lower temperature and higher nutrient concentrations, while dinoflagellates were less sensitive to temperature and nutrient concentrations but tended to prevail at low phosphorus and high N:P ratio conditions (Xiao et al., 2018). These different traits of diatoms and dinoflagellates can cause different responses, with both the effect of warming resulting in nutrients decline as a consequence of increasing stratification and the effect of increasing terrestrial nutrient input as a result of eutrophication promoting dinoflagellates over diatoms (Xiao et al., 2018). Thus, with warming and eutrophication combined might promote dinoflagellates over diatoms.

Within the phytoplankton community, the consequences for diatoms and dinoflagellates are a major concern because these taxa play key roles in ecosystem processes and form the basis of many aquatic food webs (Agusti et al., 2014, Menden-Deuer and Lessard, 2000). Diatoms and dinoflagellates are two typical groups that form harmful phytoplankton blooms, which can adversely affect human health as well as marine fisheries and aquaculture (Anderson et al., 2002, Moore et al., 2008). In fact, dinoflagellates and diatoms account for 75% and 5% of all harmful phytoplankton species, respectively (Smayda and Reynolds, 2003). Regime shifts in the diatom–dinoflagellate composition has occurred in the Baltic Sea (BS) and Bohai Sea (BHS) under eutrophication and have affected the entire coastal ecosystem, damaging the regulatory, provisioning, cultural, and supporting service functions of marine ecosystems (Chen et al., 2024).

Larger plankton have long been used to monitor ecosystem productivity and biodiversity due to their identification via traditional light microscopy. In contrast, the regular monitoring of pico- and nanoplankton (<20 μm; “tiny plankton”) only started with the development of flow cytometry techniques, which has limited their inclusion as ecosystem health indicators. However, McQuatter-Gallop et al., 2024 recently showed strong correlations between the clustering of the tiny plankton with environmental variables, including nutrients. Thus, future monitoring for ecosystem impacts from eutrophication should include tiny plankton groups as plankton lifeforms, either individually or in combination, to inform biodiversity indicators that meet policy obligations under the EU Marine Strategy Framework Directive (MSFD), (Oslo-Paris Convention) OSPAR strategies, and the UK Marine Strategy (Bedford et al., 2018; McQuatters-Gollop et al., 2024)

Many countries have reported undergone regime shifts in phytoplankton community composition; the proportion of diatoms has decreased, whereas that of non-diatoms such as dinoflagellates and cyanobacteria has increased (Bologa et al., 1995; Chen et al., 2024; Granéli & Turner, 2002; Lehtinen et al., 2017; Lu et al., 2023; Moon et al., 2021; Romero et al., 2012) . A shift in the phytoplankton community composition from diatoms, which have traditionally been dominant, to non-diatoms, can increase jellyfish abundance (Chen et al., 2024; Granéli & Turner, 2002) . This change can have several consequences, including reduced energy transfer, higher respiration rates (higher oxygen consumption and CO2 production), and accumulation of economically fewer valuable organisms Yunev et al., 2017). The diatom–dinoflagellate ratio” is one of indicators to implement in the Marine Strategic Framework Directive (MSFD) (HELCOM, 2018). United Nations Decade of Ocean Science for Sustainable Development (2021–2030) (UN, 2017) emphasizes the need for a “quantitative understanding of marine ecosystems” to guide their management and adaptation. Therefore, elucidating the driving mechanisms behind the regime shift in marine phytoplankton community composition and proposing viable strategies for its effective management are extremely important.

Recommendation 10: Incorporate pelagic indicators (specifically lifeforms, ratio of diatoms and dinoflagellates) in eutrophication assessments.

3.1.4.2 Connect nutrient imbalances with pelagic community indicators.

Human-induced inputs of N and P into the biosphere have reached unprecedented levels, particularly N, leading to an escalating global anthropogenic N:P ratio. This ratio has emerged as a significant driver of environmental change, impacting organisms, ecosystems, and global food security (Penuelas & Sardans, 2023). Historically, P has been the priority nutrient controlling upstream freshwater productivity, whereas N) limitation has characterized coastal waters. However, changing anthropogenic activities have caused imbalances in N and P loading, making it difficult to control eutrophication by reducing only one nutrient. Furthermore, upstream nutrient reduction controls can impact downstream nutrient limitation characteristics. Recently, it was suggested that only reducing P will effectively control eutrophication in both freshwater and coastal ecosystems. However, controls on production and nutrient cycling in estuarine and coastal systems are physically and chemically distinct from those in freshwater counterparts, and upstream nutrient management actions (exclusive P controls) have exacerbated N-limited downstream eutrophication (Paerl, 2009). Controls on both nutrients are needed for long-term management of eutrophication along the continuum.

Different species of phytoplankton have different traits (Bedford et al., 2018, 2020; Graves et al., 2023; Holland et al., 2023; McQuatters-Gollop et al., 2017), most notably size and shape, growth rate, life history, and behaviour such as motility that together determine their ecological niche and preferred environmental conditions.In additionphytoplankton are a major driver for global carbon fixation and biogeochemical cycles. There has been concern about shifting nutrient ratios for some time, with a review by Gilbert et al., (2017) who describes the impact from the increase in global nutrient loads with export of nitrogen increasing faster than phosphorus. The different proportions of nutrients affect HABs, their toxicity and the food web. In addition, forms of nitrogen are changing, also affecting HABs, their biodiversity and toxicity. Most importantly, this review and many others highlight that P control without N control has unintended consequences for HABs and the food web (Bedford et al., 2020; Glibert, 2017; Graves et al., 2023).

Recommendation 11: Report N:P ratios in nutrient loads, transitional and coastal waters and offshore alongside pelagic community and food web indicators. Strong alignment between UKMS eutrophication and biodiversity indicators.

3.1.5 CLIMATE

3.1.5.1 Improve knowledge on interactions between eutrophication and climate resilience.

Climate change is impacting on our environmental baseline, with the impacts of climate change affecting the delivery of freshwater and associated nutrients and sediment to the coastal marine environment and the subsequent effect on ecosystem processes. This creates an urgency to identify the relative importance of climate change and catchment management measures on future compliance (Gudmundsson et al., 2021; Kay et al., 2021) . Existing research demonstrates that climate change has the potential to impact nutrient run off, algal growth and the interactions between planktonic and pelagic organisms (Elsworth et al., 2020; Henson et al., 2021; Holland et al., 2023). Being able to predict the impact of climate change and understand potential mitigation measures are important to successfully managing the marine environment (Martiny et al., 2022). By linking catchment models with high resolution coastal mapping, we can explore the combined effects of climate change and land management on the delivery of terrestrial nutrients and sediment into the coastal zone.

Recommendation 12: Improve knowledge of climate and eutrophication interactions. Consider shifting baselines in the development of eutrophication assessments.

4 Prioritisation exercise

The Eutrophication steering group is made up of a cross selection of UK environmental agencies working on water quality issues from the catchment to coast to offshore waters. Agencies from across the devolved administrations are responsible for the collection and analysis of water quality data that is used for eutrophication assessments and four of the agencies are responsible for the reporting of eutrophication for the UKMS and OSPAR. The main knowledge gaps with a subset of priority areas were sent out to the members of the UK Marine Strategy and asked to rank the priority areas in terms of three factors (i) importance in increasing our understanding of eutrophication impacts, (ii) importance in increasing our confidence in the eutrophication assessment outcome (iii) importance in achieving harmonisation across agencies and directives. Each member was asked to comment on reasoning on top 2 priorities for each factor. The responses, alongside the literature review and consultations, were used to develop the recommendations in Section 5.

5 Tracking progress to achieve recommendations.

Whilst this review has focused on what could be done to improve the eutrophication monitoring and assessment for the UK, many activities are already underway. We have now modified our sampling – supported by national monitoring funding and the mNCEA program, and now have more regular inshore sampling trips in the English plume areas, but this needs to be structured better across UK. The key recommendations from the review and consultation are listed in Table 3. Progress towards the key recommendations is reported against effort, complexity, costs, politics, impact, and progress. Definition of each factor and ranking is described in Table 2.

Table 2: Qualitative ranking of different factors for measuring difficulty and complexity of each recommendation.

Factor in reporting progress	Ranking		
	High	Medium	Low
Effort	Requires multi-agency input,	Multi-agency input but with some agreed positioning in place. Stakeholders informed of work	Agreed positioning from all agencies, work already started.
Complexity	Complex, dynamic systems requiring multi-layered data analysis	Complex interactions, but can be analysed on single variables with high data usability	Less complex system, with minimal processing and analysis required.
Costs	High, ongoing costs and significant staff, vessel, and field time	Medium, intermittent costs, significant staff, vessel and field time	Low start up costs, some staff, vessel and field time
Politics	Requires agreement across agencies with risk of stakeholder conflict	Requires agreement across agencies with medium risk of stakeholder conflict	Requires agreement across agencies with stakeholders informed and already participating
Impact	Significant improvement to current monitoring, high confidence in assessment outputs	Some improvement to current monitoring, medium to high confidence in assessment outputs	Some improvement to current monitoring, low to medium confidence in assessment outputs

Table 3: Summary of each key recommendation against effort required, complexity of approach, costs associated to complete task, the political and geographical challenges to achieve the recommendation and the impact of success. A measure of progress is also presented which is split into “partly” or “no” with partly identifying that some work or progress to deliver recommendation has been initiated.

	Key Recommendations for improving assessment	Effort	Complexity	Costs	Politics	Impact	Progress
DATA	High frequency data incorporated into assessment	High	High	Medium	Medium	High	Partly
DATA	Targeted data collection in low data areas and monitoring programs	High	Medium	Medium	Low	High	Partly
DATA	Inclusion of riverine influenced areas in transport and fate and assessment	Medium	Medium	Low	Medium	High	Partly
DATA	Update thinking on natural variability - 50% variability no longer fit for purpose	Medium	Low	Low	High	Medium	NO
DATA	Incorporate trend analysis and trajectory of change into assessments	Medium	Low	Low	Medium	Medium	Partly
ALIGNMENT	Harmonise assessment areas, indicators & thresholds between environment directives	Medium	Medium	Low	High	Medium	Partly
ALIGNMENT	Integration across ecological boundaries from catchment to coast	Medium	Medium	Low	High	Medium	Partly
INDICATORS	Consider complex interactions that influence susceptibility (light, darkening)	High	Medium	High	High	High	NO
INDICATORS	Re-engage ecosystem approach, embed marine Natural Capital. Align with One Health approach	High	High	High	High	High	NO
PELAGIC	Incorporate plankton indicators into eutrophication assessment	Medium	High	Medium	Medium	High	Partly
PELAGIC	Connect nutrient imbalances with pelagic indicators & food webs	Medium	High	Medium	Medium	High	Partly
CLIMATE	Improve knowledge on interactions between eutrophication and climate resilience	Low	Medium	Low	Medium	Medium	Partly

6 Conclusions

In summary, disaggregation between the natural gradient of coast to sea, limited and no data collection in the full riverine plumes and riverine load monitoring, the disconnect between the indicators and the low confidence in our assessments make it difficult to understand how and why our coastal systems are changing. There are many positive improvements, with our national monitoring now increasing our data frequency in more transitional and coastal waterbodies and plume areas. We cannot collect all data all the time, that is not feasible or affordable. There could be a more strategic way to collect high density data alongside the routine monitoring, but focused on a few high priority rivers, sub-catchments, and waterbodies – which could be extrapolated to the rest of the UK. This would need a focused work package to determine those high priority waterbodies which could represent the types of waterbodies and coastal systems which are present across the UK and would need modelling and land use data.

Nutrient pollution is more often related to diffuse sources, making it difficult to identify and mitigate a single source. Le Moal et al., (2019) recognises these difficulties and urges a different approach to diffuse and large ranging nutrient sources where we need to address: i) the long term cumulative impact of far reach anthropogenic activities, ii) the consequences of multiple, and often cumulative, actions which can be very distant both in space and time, iii) the difficulty to disentangle past and present causes from past anthropogenic legacy (Le Moal et al., 2019).

The consequence of multiple, often cumulative actions, which can be very remote both in space and time from the visible impact, the uniqueness of each aquatic ecosystem, its resistance, resilience and trajectory, the difficulty to disentangle past and present causes from legacy of the past anthropogenic activities fulfil many attributes of a wicked or complex problem facing society (Thornton et al., 2013). The development of eutrophication exemplifies the linkages between physical and biogeochemical processes along the land-sea continuum. However, from headwater catchments to coast areas, several, often antagonistic interests prevail, while scientists are often specialized in one domain, with limited interactions and shared methods, tools or models. There is a need for interdisciplinary approach calling for several disciplines of agronomy, engineering, biogeochemistry, ecology, hydrology, economy, political sciences and sociology to provide ways and approaches for remediation of aquatic ecosystems from this world-wide and pervasive problem of eutrophication.

UK marine agencies need to continue to look for new ways to sample high frequency measurements of water quality parameters. As the world changes, and there are multiple pressures impacting on our marine environment on a daily and long-term basis, it becomes more important to measure, monitor and assess the health of our marine environment. We still need to sample through traditional methods such as the discrete, in-situ sampling but will do so hand in hand with new and novel ways to collect the water quality measurements we need at the right frequency and the right place. Accessible large, data rich collection methods, such as FerryBox, modelling and satellite data will all play an important part in the future of UK water quality monitoring.

7 Acknowledgements

Support for this work was funded under the Defra Marine Natural Capital and Ecosystem Assessment Programme (nNCEA). The Marine Natural Capital and Ecosystem Assessment Programme (mNCEA) - Marine Science (blog.gov.uk)

8 References

Addison, P. F. E., Collins, D. J., Trebilco, R., Howe, S., Bax, N., Hedge, P., Jones, G., Miloslavich, P., Roelfsema, C., Sams, M., Stuart-Smith, R. D., Scanes, P., Von Baumgarten, P., & McQuatters-Gollop, A. (2018). A new wave of marine evidence-based management: Emerging challenges and solutions to transform monitoring, evaluating, and reporting. ICES Journal of Marine Science, 75(3). https://doi.org/10.1093/icesjms/fsx216

Bean, T. P., Greenwood, N., Beckett, R., Biermann, L., Bignell, J. P., Brant, J. L., Copp, G. H., Devlin, M. J., Dye, S., Feist, S. W., Fernand, L., Foden, D., Hyder, K., Jenkins, C. M., van der Kooij, J., Kröger, S., Kupschus, S., Leech, C., Leonard, K. S., … Righton, D. (2017). a review of the tools used for marine monitoring in the UK: Combining historic and contemporary methods with modeling and socioeconomics to fulfill legislative needs and scientific ambitions. In Frontiers in Marine Science (Vol. 4, Issue AUG). https://doi.org/10.3389/fmars.2017.00263

Bedford, J., Johns, D., Greenstreet, S., & McQuatters-Gollop, A. (2018). Plankton as prevailing conditions: A surveillance role for plankton indicators within the Marine Strategy Framework Directive. Marine Policy, 89. https://doi.org/10.1016/j.marpol.2017.12.021

Bedford, J., Ostle, C., Johns, D. G., Atkinson, A., Best, M., Bresnan, E., Machairopoulou, M., Graves, C. A., Devlin, M., Milligan, A., Pitois, S., Mellor, A., Tett, P., & McQuatters-Gollop, A. (2020). Lifeform indicators reveal large-scale shifts in plankton across the North-West European shelf. Global Change Biology, 26(6). https://doi.org/10.1111/gcb.15066

Carolina, N. (2002). Harmful Algal Blooms and Eutrophication Nutrient Sources , Composition , and Consequences. Estuaries, 25(4), 704–726.

Carstensen, J., Sánchez-Camacho, M., Duarte, C. M., Krause-Jensen, D., & Marbà, N. (2011). Connecting the dots: Responses of coastal ecosystems to changing nutrient concentrations. Environmental Science and Technology, 45(21). https://doi.org/10.1021/es202351y

Chen, K., Achterberg, E. P., Li, K., Zhang, J., Xin, M., & Wang, X. (2024). Governance pathway for coastal eutrophication based on regime shifts in diatom–dinoflagellate composition of the Bohai and Baltic Seas. Water Research, 250, 121042.

Claussen, U., Zevenboom, W., Brockmann, U., Topcu, D., & Bot, P. (2009). Assessment of the eutrophication status of transitional, coastal and marine waters within OSPAR. Eutrophication in Coastal Ecosystems: Towards Better Understanding and Management Strategies Selected Papers from the Second International Symposium on Research and Management of Eutrophication in Coastal Ecosystems, 20–23 June 2006, Nyborg, Denmark, 49–58.

Dafforn, K. A., Johnston, E. L., Ferguson, A., Humphrey, C. L., Monk, W., Nichols, S. J., Simpson, S. L., Tulbure, M. G., & Baird, D. J. (2016). Big data opportunities and challenges for assessing multiple stressors across scales in aquatic ecosystems. In Marine and Freshwater Research (Vol. 67, Issue 4). https://doi.org/10.1071/MF15108

de Raús Maúre, E., Terauchi, G., Ishizaka, J., Clinton, N., & DeWitt, M. (2021). Globally consistent assessment of coastal eutrophication. Nature Communications, 12(1). https://doi.org/10.1038/s41467-021-26391-9

Desmit, X., Schartau, M., Riethmüller, R., Terseleer, N., Van der Zande, D., & Fettweis, M. (2024). The transition between coastal and offshore areas in the North Sea unraveled by suspended particle composition. Science of the Total Environment, 915, 169966.

Devlin, M., Barry, Æ. J., & Painting, Æ. S. (2009). Extending the phytoplankton tool kit for the UK Water Framework Directive : indicators of phytoplankton community structure. October, 151–168. https://doi.org/10.1007/s10750-009-9879-5

Devlin, M., & Brodie, J. (2023). Nutrients and Eutrophication. In Marine Pollution–Monitoring, Management and Mitigation (pp. 75–100). Springer.

Devlin, M. J., Barry, J., Mills, D. K., Gowen, R. J., Foden, J., Sivyer, D., & Tett, P. (2008). Relationships between suspended particulate material, light attenuation and Secchi depth in UK marine waters. Estuarine, Coastal and Shelf Science, 79(3). https://doi.org/10.1016/j.ecss.2008.04.024

Devlin, M., Prins, T. C., Enserink, L., Leujak, W., Heyden, B., Axe, P., Ruiter, H., Blauw, A., Bresnan, E., & Collingridge, K. (2023). A first ecological coherent assessment of eutrophication across the North-East Atlantic waters (2015-2020).

Devlin, M., Schroeder, T., Mckinna, L., & Brodie, J. (2011). Monitoring and Mapping of Flood Plumes in the Great Barrier Reef Based on. In Situ, 147–188.

Duarte, C. M. (2009). Coastal eutrophication research: A new awareness. Hydrobiologia, 629(1). https://doi.org/10.1007/s10750-009-9795-8

Duarte, C. M., Conley, D. J., Carstensen, J., & Sánchez-Camacho, M. (2009). Return to Neverland: Shifting baselines affect eutrophication restoration targets. Estuaries and Coasts, 32(1). https://doi.org/10.1007/s12237-008-9111-2

Fettweis, M., Schartau, M., Desmit, X., Lee, B. J., Terseleer, N., Van der Zande, D., Parmentier, K., & Riethmüller, R. (2022). Organic Matter Composition of Biomineral Flocs and Its Influence on Suspended Particulate Matter Dynamics Along a Nearshore to Offshore Transect. Journal of Geophysical Research: Biogeosciences, 127(1). https://doi.org/10.1029/2021JG006332

Foden, J., Devlin, M. J., Mills, D. K., & Malcolm, S. J. (2011). Searching for undesirable disturbance: an application of the OSPAR eutrophication assessment method to marine waters of England and Wales. Biogeochemistry, 106, 157–175.

Foden, J., Scanlan, C., Wells, E., Wood, P., Wilkinson, M., & Best, M. (2005). Opportunistic macroalgal blooms and the water framework directive. Marine Ecology, 3, 2005.

Foden, J., Sivyer, D. B., Mills, D. K., & Devlin, M. J. (2008). Spatial and temporal distribution of chromophoric dissolved organic matter (CDOM) fluorescence and its contribution to light attenuation in UK waterbodies. Estuarine, Coastal and Shelf Science, 79(4), 707–717.

Fronkova, L., Greenwood, N., Martinez, R., Graham, J. A., Harrod, R., Graves, C. A., Devlin, M. J., & Petus, C. (2022). Can Forel–Ule Index Act as a Proxy of Water Quality in Temperate Waters? Application of Plume Mapping in Liverpool Bay, UK. Remote Sensing, 14(10). https://doi.org/10.3390/rs14102375

Glibert, P. M. (2017). Eutrophication, harmful algae and biodiversity — Challenging paradigms in a world of complex nutrient changes. Marine Pollution Bulletin, 124(2), 591–606. https://doi.org/https://doi.org/10.1016/j.marpolbul.2017.04.027

Graves, C. A., Best, M., Atkinson, A., Bear, B., Bresnan, E., Holland, M., Johns, D. G., Machairopoulou, M., McQuatters-Gollop, A., Mellor, A., Ostle, C., Paxman, K., Pitois, S., Tett, P., & Devlin, M. (2023). At what scale should we assess the health of pelagic habitats? Trade-offs between small-scale manageable pressures and the need for regional upscaling. Ecological Indicators, 154. https://doi.org/10.1016/j.ecolind.2023.110571

Greenwood, N., Devlin, M. J., Best, M., Fronkova, L., Graves, C., Milligan, A., Barry, J., & van Leeuwen, S. (2019). Utilising eutrophication assessment directives from freshwater to marine systems in the Thames estuary and Liverpool Bay, UK. Frontiers in Marine Science, 6(FEB). https://doi.org/10.3389/fmars.2019.00116

Heal, R., Fronkova, L., Silva, T., Collingridge, K., Harrod, R., Greenwood, N., & Devlin, M. J. (2023). A Probabilistic Approach to Mapping the Contribution of Individual Riverine Discharges into Liverpool Bay Using Distance Accumulation Cost Methods on Satellite Derived Ocean-Colour Data. Remote Sensing, 15(14). https://doi.org/10.3390/rs15143666

Holland, M. M., Louchart, A., Artigas, L. F., Ostle, C., Atkinson, A., Rombouts, I., Graves, C. A., Devlin, M., Heyden, B., Machairopoulou, M., Bresnan, E., Schilder, J., Jakobsen, H. H., Llody-Hartley, H., Tett, P., Best, M., Goberville, E., & McQuatters-Gollop, A. (2023). Major declines in NE Atlantic plankton contrast with more stable populations in the rapidly warming North Sea. Science of the Total Environment, 898. https://doi.org/10.1016/j.scitotenv.2023.165505

Ivanov, E., Capet, A., Barth, A., Delhez, E. J. M., Soetaert, K., & Grégoire, M. (2020). Hydrodynamic variability in the Southern Bight of the North Sea in response to typical atmospheric and tidal regimes. Benefit of using a high resolution model. Ocean Modelling, 154, 101682.

Joo, M., Raymond, M. A. A., McNeil, V. H., Huggins, R., Turner, R. D. R., & Choy, S. (2012). Estimates of sediment and nutrient loads in 10 major catchments draining to the

Great Barrier Reef during 2006-2009. Marine Pollution Bulletin, 65(4–9). https://doi.org/10.1016/j.marpolbul.2012.01.002

Kermagoret, C., Claudet, J., Derolez, V., Nugues, M. M., Ouisse, V., Quillien, N., Baulaz, Y., Le Mao, P., Scemama, P., Vaschalde, D., Bailly, D., & Mongruel, R. (2019). How does eutrophication impact bundles of ecosystem services in multiple coastal habitats using state-and-transition models. Ocean and Coastal Management, 174. https://doi.org/10.1016/j.ocecoaman.2019.03.028

Laurent, A., Fennel, K., Ko, D. S., & Lehrter, J. (2018). Climate change projected to exacerbate impacts of coastal Eutrophication in the Northern Gulf of Mexico. Journal of Geophysical Research: Oceans, 123(5). https://doi.org/10.1002/2017JC013583

Le Moal, M., Gascuel-Odoux, C., Ménesguen, A., Souchon, Y., Étrillard, C., Levain, A., Moatar, F., Pannard, A., Souchu, P., Lefebvre, A., & Pinay, G. (2019). Eutrophication: A new wine in an old bottle? Science of The Total Environment, 651, 1–11. https://doi.org/https://doi.org/10.1016/j.scitotenv.2018.09.139

Lu, C., & Tian, H. (2017). Global nitrogen and phosphorus fertilizer use for agriculture production in the past half century: shifted hot spots and nutrient imbalance. Earth System Science Data, 9(1), 181–192.

Maas-Hebner, K. G., Harte, M. J., Molina, N., Hughes, R. M., Schreck, C., & Yeakley, J. A. (2015). Combining and aggregating environmental data for status and trend assessments: challenges and approaches. Environmental Monitoring and Assessment, 187, 1–16.

Malcolm, S., Nedwell, D., Devlin, M., Hanlon, A., Dare, S., Parker, R., & Mills, D. (2002). First application of the OSPAR comprehensive procedure to waters around England and Wales. Centre for Environment, Fisheries and Aquaculture Report to DEFRA, UK, 1–103.

McQuatters-Gollop, A., Johns, D. G., Bresnan, E., Skinner, J., Rombouts, I., Stern, R., Aubert, A., Johansen, M., Bedford, J., & Knights, A. (2017). From microscope to management: The critical value of plankton taxonomy to marine policy and biodiversity conservation. Marine Policy, 83. https://doi.org/10.1016/j.marpol.2017.05.022

McQuatters-Gollop, A., Raitsos, D. E., Edwards, M., & Attrill, M. J. (2007). Spatial patterns of diatom and dinoflagellate seasonal cycles in the NE Atlantic Ocean. Marine Ecology Progress Series, 339. https://doi.org/10.3354/meps339301

Meier, H. E. M., Eilola, K., Almroth-Rosell, E., Schimanke, S., Kniebusch, M., Höglund, A., Pemberton, P., Liu, Y., Väli, G., & Saraiva, S. (2019). Disentangling the impact of nutrient load and climate changes on Baltic Sea hypoxia and eutrophication since 1850. Climate Dynamics, 53, 1145–1166.

Mills, D. K., Greenwood, N., Kröger, S., Devlin, M., Sivyer, D. B., Pearce, D., Cutchey, S., & Malcolm, S. J. (2004). New approaches to improve the detection of eutrophication in UK coastal waters. USA-Baltic International Symposium: . https://doi.org/10.1109/BALTIC.2004.7296835

Ngatia, L., M. Grace III, J., Moriasi, D., & Taylor, R. (2019). Nitrogen and Phosphorus Eutrophication in Marine Ecosystems. In Monitoring of Marine Pollution. https://doi.org/10.5772/intechopen.81869

Paerl, H. W. (2009). Controlling Eutrophication along the Freshwater–Marine Continuum: Dual Nutrient (N and P) Reductions are Essential. Estuaries and Coasts, 32(4), 593–601. https://doi.org/10.1007/s12237-009-9158-8

Paerl, H. W., & Piehler, M. F. (2008). Nitrogen and marine eutrophication. Nitrogen in the Marine Environment, 2, 529–567.

Painting, S. J., Devlin, M. J., Malcolm, S. J., Parker, E. R., Mills, D. K., Mills, C., Tett, P., Wither, A., Burt, J., Jones, R., & Winpenny, K. (2007). Assessing the impact of nutrient enrichment in estuaries: Susceptibility to eutrophication. Marine Pollution Bulletin, 55(1–6). https://doi.org/10.1016/j.marpolbul.2006.08.020

Pellerin, B. A., Stauffer, B. A., Young, D. A., Sullivan, D. J., Bricker, S. B., Walbridge, M. R., Clyde, G. A., & Shaw, D. M. (2016). Emerging Tools for Continuous Nutrient Monitoring Networks: Sensors Advancing Science and Water Resources Protection. Journal of the American Water Resources Association, 52(4). https://doi.org/10.1111/1752-1688.12386

Penuelas, J., & Sardans, J. (2023). Human-driven global nutrient imbalances increase risks to health. Eco-Environment & Health, 2(4), 246–251. https://doi.org/https://doi.org/10.1016/j.eehl.2023.08.003

Rhodes, C., Bingham, A., Heard, A. M., Hewitt, J., Lynch, J., Waite, R., & Bell, M. D. (2017). Diatoms to human uses: Linking nitrogen deposition, aquatic eutrophication, and ecosystem services. Ecosphere, 8(7). https://doi.org/10.1002/ecs2.1858

Romero, E., Peters, F., & Marrasé, C. (2012). Dynamic forcing of coastal plankton by nutrient imbalances and match-mismatch between nutrients and turbulence. Marine Ecology Progress Series, 464. https://doi.org/10.3354/meps09846

Ryther, J. H., & Dunstan, W. M. (1971). Nitrogen, phosphorus, and eutrophication in the coastal marine environment 1008-1013. Science, 171(3975). https://doi.org/10.1126/science.171.3975.1008

Schroeder, T., Devlin, M., Brando, V. E., Dekker, A. G., & Brodie, J. (2010). Mapping the inter-annual variability of freshwater plume extent in the Great Barrier Reef from ocean colour observations. 1, 4068.

Smith, V. H. (2003). Eutrophication of freshwater and coastal marine ecosystems: A global problem. In Environmental Science and Pollution Research (Vol. 10, Issue 2). https://doi.org/10.1065/espr2002.12.142

Thornton, J. A., Harding, W. R., Dent, M., Hart, R. C., Lin, H., Rast, C. L., Rast, W., Ryding, S. O., & Slawski, T. M. (2013). Eutrophication as a “wicked” problem. Lakes and

Reservoirs: Science, Policy and Management for Sustainable Use, 18(4). https://doi.org/10.1111/lre.12044

Topcu, D., Brockmann, U., & Claussen, U. (2009). Relationship between eutrophication reference conditions and boundary settings considering OSPAR recommendations and the Water Framework Directive-examples from the German Bight. Hydrobiologia, 629(1). https://doi.org/10.1007/s10750-009-9778-9

van Leeuwen, S. M., Lenhart, H. J., Prins, T. C., Blauw, A., Desmit, X., Fernand, L., Friedland, R., Kerimoglu, O., Lacroix, G., van der Linden, A., Lefebvre, A., van der Molen, J., Plus, M., Ruvalcaba Baroni, I., Silva, T., Stegert, C., Troost, T. A., & Vilmin, L. (2023). Deriving pre-eutrophic conditions from an ensemble model approach for the North-West European seas. Frontiers in Marine Science, 10. https://doi.org/10.3389/fmars.2023.1129951

Xiao, W., Liu, X., Irwin, A. J., Laws, E. A., Wang, L., Chen, B., Zeng, Y., & Huang, B. (2018). Warming and eutrophication combine to restructure diatoms and dinoflagellates. Water Research, 128, 206–216. https://doi.org/https://doi.org/10.1016/j.watres.2017.10.051