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Perspective

Blue Nitrogen: A Nature-Based Solution in the Blue Economy as a Tool to Manage Terrestrial Nutrient Neutrality

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Abstract: There is growing concern about the impact of rising nutrient loading on aquatic ecosystems and on human health, due to increased urbanisation and associated sewage effluents. This has led to a policy focus on land-use change or agricultural practice change as nutrient mitigation strategies, but these fail to consider the ultimate downstream receiving environments such as marine ecosystems. Within the UK there has been increasing recognition that housing density in certain sensitive locations is impacting the conservation status of marine features, through the increase in nutrient loading to the marine environment. In order to comply with the statutory obligations to protect these marine features, the competent authorities have required developers to mitigate the impact of these additional nutrients. Current approaches include converting agricultural land to woodland and wetland habitats that release less nitrogen than the agricultural land they replace. This difference is used to offset the nutrient loading from the new development, but such a terrestrial-focused catchment-based mass balance approach has a number of limitations. Current solutions for nutrient neutrality in the UK take a narrow land-focused approach that fails to acknowledge the potential contribution of the marine environments to mitigate nutrient enrichment. We propose that marine nature-based solutions offer an economically and ecologically viable alternative to terrestrial schemes, that can reduce the nitrogen loading to the marine environment, increase ecosystem service provision and increase biodiversity.

Keywords: NbS; low trophic aquaculture; blue economy; nutrient neutrality; nitrogen; urban planning; marine policy

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1. Introduction

The seas and oceans are the receiving environment for multiple terrestrial nutrients and it is estimated that approximately 20% of human-controlled nitrogen inputs to any area are exported to the marine environment [1]. These excess nutrients can have a deleterious effect on the local environment and have been characterised as a predominantly human-derived disruption of the marine environment [2]. This increased flux of nutrients into the sea has a wide range of impacts, such as shifts in phytoplankton species, proliferation of harmful algal blooms, an increase in nuisance macroalgal blooms and a reduction in water clarity [3]. This can directly impact protected areas and reduce or downgrade their conservation status [4]. In this perspective piece, we argue that as well as being the receiving environment for nutrient pollution, the marine environment can, through the enhancement of ecosystem services, host to a range of nature-based solutions that will help mitigate these issues, and we name this approach Blue Nitrogen in a way that is analogous to the current Blue Carbon paradigm. In this paper we examine a particular case study from the UK, where the current policy framework is in place for the direct valorisation of Blue Nitrogen and place this approach within the framework of the IUCN's Global Standard for Nature-based Solutions (NbS) and its related typology.

Nutrient accumulation in aquatic systems poses risks to human health, eutrophication of freshwater (including ground water) and marine environments [5,6]. Agriculture and sewage effluent are the two key sources of nitrogen and phosphorous in aquatic environments in the UK, and the main focus of current control measures. These measures are aimed at either reducing nitrate diffuse pollution from agricultural practices, through Nitrate Vulnerable Zones, the Reduction and Prevention of Agricultural Diffuse Pollution (England) Regulation, various voluntary schemes (e.g., Environmental Land Management scheme, Catchment Sensitive Farming, Environmental Stewardship Schemes, Nutrient Management Plans and the Catchment Based Approach), or to regulate nitrate and phosphorous pollution from point sources, through permits for discharges from sewage treatment works (STW) and industry sites. Despite the number of directives and domestic regulations relevant to nitrogen and phosphorous control, notably the Urban Waste Water Treatment Directive (UWWTD, 91/271/EC), the Nitrates Directive (91/676/EEC), the Water Framework Directive (WFD, 2000/60/EC), Drinking Water Directive (98/83/EC) and the Groundwater Directive (GWD; 2006/118/EC), most water bodies in England fail WFD objectives and nitrogen and phosphorous standards for good ecological status: 93% of estuaries and 47% of coastal waters exceed the nitrogen standards for Good Environmental Status (GES), while 55% of rivers and 73% of lakes exceed phosphorus standards for GES [5,6].

The increased urbanisation of catchments, reflected in new housing has led to a significant reduction in the water quality and increase in the nutrient loading of aquatic environments [7]. These impacts have led to a number of regulators in Europe and the UK to stop or slow developments within certain catchments to prevent further deterioration of water quality [8] and contain subsequent impacts on conservation designated areas. The two main and current EU Directives aimed at maintaining the quality of aquatic ecosystems are the WFD and the Marine Strategy Framework Directive (MSFD), while the Habitats Directive regulates the protection of certain species and habitats. Though the above noted EU Directives no longer apply in the UK, since its withdrawal from the EU, their provisions have however been incorporated into the laws of the UK and its devolved governments through the EU Withdrawal Act 2018 and associated amendments related to EU Exit Regulations, and their principles seem likely to be maintained in the UK. The level playing field provisions in the UK/EU Trade and Cooperation Agreement (EU, 2021) which cover areas of environment and climate law (including aquatic environments) require a non-regression from levels of environmental protection in the UK, to which divergences impacting trade or investment between the parties could trigger appropriate remedial and rebalancing measures. Furthermore, the UK has a commitment to continue respecting internationally recognised environmental principles, notably on environmental protection, preventive action, precautionary approach, rectification of environmental damage at the source and the polluter pays principle.

The focus on reducing the risk from excess nutrients from point sources is more limited than the approach for climate change which focuses on both limiting or preventing emissions and by enhancing activities that remove the target compounds from the environment [9]. Competent authorities recognise that current measures are insufficient to deliver on existing policy objectives unless targeted interventions prevent current deterioration and mitigate additional pressures from climate change and population growth [5,6]. Within the UK, nutrient enrichment as a result of increased urbanisation is impacting a number of marine designated areas. This has led to Natural England (a non-departmental public body that acts as the expert statutory advisor to the UK Government with a remit to protect and restore the natural world), to issue an advice notice in 2019 (this advice carries legal status). This stated "*that planning permission should not be granted unless the impact from a particular development can be appropriately assessed to determine whether the development is compliant with the legislation that protects the Solent and Dorset Coast Special Protection Area.*" This was followed by further advice from Natural England that unless a development could be proven to be nitrate neutral, then planning permission cannot be legally granted [10]. These actions have led to a 60% reduction in housing development in the designated areas [11], and the issue is affecting approximately 10% of English planning authorities. The advice note also gives guidance on how the nitrogen impact (in terms of an increase or decrease in nitrogen (kg/year) into the catchment) of any particular development can be calculated. The advice lists a number of different types of mitigation, if the proposed development would cause additional nitrogen loading to the catchment area, such as conversion of agricultural land for community and wildlife benefits, woodland planting or wetland construction or management.

In response, a number of councils, wildlife trusts and private companies have developed land-use change nature-based nutrient mitigation solutions, through the Solent Nutrient Trading Pilot [12]. This scheme is based on the conversion of current intensive agricultural land (e.g., poultry, dairy, etc.) to other land-uses, such as greenfield, woodland, or lowland grazing, with some uses (e.g., meadows, wood pasture) yet to be confirmed as part of the scheme [13]. This mitigation solution would allow a wildlife trust to sell nitrate credits to developers, and so provide the developers with the required nutrient mitigation [14]. Currently, the estimated price of a nitrogen credit (equivalent to 1 kg of nitrogen per year for the lifetime of the development, generally 80–125 [10] years) is GBP 3000 [15]. While all the schemes included within the guidance are terrestrially based, there is precedence in the trading of nutrient credits for the catchment management of nutrients using marine-based solutions. For example, within Greenwich Bay (USA) the value of nitrogen removal by clams and oysters is estimated annually by the Connecticut Department of Energy and Environmental Protection. A 2016 valuation of one pound of nitrogen was USD 6.70 equating to USD 15 kg N [16]. Further to nutrient trading, examples of payments for ecosystem services (PES) schemes, such as the Lysekil Nutrient Trading Scheme, where mussel farmers sold nitrogen removal services to the local public bodies to mitigate nitrogen enrichment, have proved highly successful and cost-effective in fully offsetting nitrogen in comparison to traditional techniques [17], but also highlighted challenges of economic viability (e.g., insufficient market demand for products) and scope to develop (e.g., nutrient bundling [18]).

The regulation of biogeochemical cycles such as the nitrogen and carbon cycles are important ecosystem services delivered by the marine environment [19,20]. The management of these ecosystems can protect and enhance these ecosystem services. For example the management of mangroves and sea grass meadows can enhance carbon storage and help to mitigate climate change [21] in the form of carbon sequestration and storage in marine habitats. In addition to the Blue Carbon (the ecosystem service of marine habitats to store and sequester carbon) potential of marine sediments, there is also significant potential for marine habitats to store and remove nitrogen from the marine environment (Blue Nitrogen). **It is recognised that marine sediments and biomass are two of the largest storage reservoirs for organic nitrogen in the biospher**e. **As such, marine NbS can be developed around these major nitrogen storage reservoirs. These solutions are based around three main ecosystem services connected to nitrogen regulation.**

(1) Denitrification: This is an important mechanism to permanently remove excess nitrogen, through the conversion of nitrate to nitrogen gas. This transformation of nitrogen, from a reactive to an inert form, can help to control the rate of eutrophication, particularly in marine coastal ecosystems subject to large inputs of anthropogenic nitrogen.
(2) Assimilation in biomass: Primary producers such as seaweed and phytoplankton (that can be consumed by organisms further up the food chain) represent net sinks for nitrogen. Although globally these might represent a small component, the relative differences between areas with a high biomass and a low biomass can be significant.
(3) Burial within sediments: Although a relatively small sink compared to denitrification the permanent burial of nitrogen containing organic compounds is a well-defined sink for nitrogen in the marine environment [22].

2. Valorising Ecosystem Services

The Blue Carbon potential of coastal and marine habitats is now beginning to be included as nationally determined contributions towards the Paris Climate Agreement and as such is clearly linked to a global market in carbon trading [23]. The management of ecosystems to provide public goods (such as carbon storage) is now a well-accepted paradigm and reflected in a number of management frameworks which have been extensively reviewed [24]. However it has the potential to precipitate trade-offs between management objectives and other outcomes such as biodiversity or human wellbeing [25]. To manage these trade-offs, a number of frameworks have been developed such as the IUCN concept of nature-based solutions which have been defined as "*actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits*".

The development, value and limitations of nature-based solutions to climate change have been recently reviewed [26]. However although NbS for management of the nitrogen cycle is generally well accepted [27] in the terrestrial environment, the use of NbS to manage marine (or Blue) Nitrogen is poorly defined. The use of marine NbS may offer considerable advantage over terrestrial alternatives due to less competition for space, better efficiency per unit area and a more direct connection to the ecosystem which is being impacted by nutrient loading. It also better aligns with the Intergovernmental Panel on Climate Change (IPCC) approach for reducing climate risk through enhancing activities that remove the target compounds from the environment. Using a widely accepted three-part typology of NbS [28], it is possible to map out how the NbS framework can be applied to help manage nitrogen in the marine environment and crucially, to value those ecosystems using the 'nutrient neutrality' concept.

Type 1: Better use and safeguard of natural/protected aquatic ecosystems

Marine Protected Areas (MPAs): MPAs can increase the value of ecosystems goods and services provided by marine ecosystems [29]. For example, protecting an area from trawling can enhance the ecosystem services connected to nitrogen regulation through a number of pathways including increasing benthic and infauna biomass as well as an increase in benthic denitrification. Bottom trawling has a profound impact on the ecosystem services of benthic communities. Trawling can reduce benthic biomass by 56% and reduce nitrogen uptake from the sediments by 63% [30]. Furthermore, trawling significantly reduces denitrification by destroying the complex redox structure of the sediments [31]. It is estimated that trawling induced disturbance can reduce denitrification by 11–50%. If we estimate the denitrification rate of continental shelf sediments as approximately 8000 kg of nitrogen (N) per km^2 per year [32], then protection of the sediments from trawling would increase the denitrification by 880–4000 kg N km^{-2} yr^{-1}. The monetary value of this NbS based on terrestrial nitrogen reduction costs discussed above (extrapolation based on the value of a terrestrial nitrogen credit [15]) would be in the range of GBP 2.2 million (M) to GBP 12 M per km^2, whilst these measures would also protect the biodiversity of the site. It is important to note this is a value for 80–120 years of nitrogen removal.

Type 2: Managed or restored ecosystems

The next step on the typology is to actively restore degraded marine habitats, and although this activity is normally undertaken to restore ecosystem function and increase biodiversity [33] it also has significant potential to be used as a NbS for ecosystem level nitrogen reduction. Structured marine habitats such as seagrass and oyster reefs have higher denitrification rates than subtidal flats [34]. For example, oyster reefs can provide nature-based solutions for nutrient management through assimilation, burial and sediment denitrification [35]. The restoration of oyster reefs increased sediment denitrification by 18–275% when compared to control sites [36], and experiments from restoration projects in Rhode Island showed denitrification rates of up to 60,000 kg N km^{-2} yr^{-1}. Seagrass meadows can be used as a tool for nutrient management both through the burial of nitrogen and denitrification within the sediments. Denitrification rates in vegetated sediments were 3.8 times higher when compared to bare sediments, and removed 620 kg N km^{-2} yr^{-1} [37]. However nitrogen burial may be the principle process of nitrogen removal in seagrass beds, being up to 20 times higher than in bare sediments and giving nitrogen removal rates of up to 3500 kg N km^{-2} yr^{-1} [38].

Type 3: Creation of new nutrient regulating ecosystems through aquaculture

Low trophic and integrated aquaculture can be planned and developed to function as a NbS [39] that both delivers food and helps regulate nutrients in the marine environment, with most studies to date concentrating on cultivation of low trophic species such as oysters and seaweed. Using modelling studies, it was predicted that 30 hectares of oyster cultivation would remove 3797 kg N yr^{-1}, equating to 12,657 kg N km^{-2} yr^{-1} [40]. Other modelling studies estimate that both blue mussel and seaweed cultivation can remove approximately 60,000 kg N km^{-2} yr^{-1} [41]. At a larger scale, it has been estimated that Chinese seaweed production removes 75,000,000 kg N yr^{-1}, which equates to 60,000 kg N km^{-2} yr^{-1} [42]. It is important to remember that the evaluation framework is based on a value of nitrogen removal over a period of 80–125 years. For aquaculture activities which run on annual cycles, the value of nitrogen removed in a single production cycle would need to be distributed proportionally against this longer time frame. There would also need to be a guarantee that the activity would be persistent on the 80–125 year time frame, which would require a re-consideration of licencing periods for activities falling under this regime and adoption of modelling tools to quantify contribution over time, in consideration of evolving production levels and environmental conditions. With such monetary valuations of these ecosystem services comes the possibility of including the marine NbS within the Blue Economy (BE) [43]. The concept of the BE has been gaining traction for the last two decades and recognises the use of ocean space and its resources as an essential component of global economic growth, with its development reviewed a number of times [44,45]. There is a clear link to the United Nations sustainable development goals (SDGs), specifically to SDG 14 'Life Below Water'[46]. Allowing the direct valuation of ecosystem services within the BE can help drive investment into marine nature-based solutions that deliver multiple societal benefits while protecting marine environments and enhancing biodiversity.

3. Policy Recommendations for Valuing Blue Nitrogen

The requirement for mitigating increased nitrogen loading to a marine water body caused by house building is currently threatening the development of 33,000 homes a year across the south of England [11]. This concept of nutrient neutrality requires that the extra nutrient loading is mitigated either by on-site mitigation, off-site mitigation, or the purchase of nutrient credits from off-site mitigations. It is estimated that this requirement is adding approximately GBP 5,000 to the cost of a new house (Home Builders Federation pers. comm.). These credits are made available to developers in return for a financial contribution paid to an approved mitigation scheme. Currently these off-site mitigations are based on acquiring agricultural land within the catchment and changing the land use in perpetuity (80–125 years), which reduces the nitrogen loss into the marine environment. Our recommendation is to recognise the contribution/capacity of the marine to mitigate nutrient loading and to extend the range of mitigation options to include the marine environment, using the IUCN global standard for nature-based solutions and following the typology of NbS described above. This approach has multiple benefits including:

(1) Avoiding the removal of terrestrial land from food production;
(2) providing financing for marine protected areas and marine habitat restoration;
(3) promoting low trophic aquaculture for food production and other ecosystem services as part of a nature-based solution approach.

Specifically, we propose that marine NbS are considered within financial instruments, such as nutrient credit markets or payment for ecosystem services schemes, as part of an integrated blue-green NbS governance framework. Nitrogen credit trading systems, such as those being established in the Solent, present a timely opportunity for integration and piloting in a UK context, with previous international trials bringing to light the value of such approaches to define scope for additionality. The adoption of policy incentives and instruments to encourage lifecycle approaches that improve secondary material markets, for shellfish and seaweeds aquaculture could also provide an important tool to support longer term nutrient storage within the context of the circular economy. These solutions require both robust approaches to quantify nutrient regulation services and to address existing data gaps, but also to provide an adequate governance landscape which enables long term management of marine ecosystems to both deliver benefit through ecosystem services and provide human well-being and biodiversity benefits in line with the NbS approach.

4. Conclusions

Marine nature-based solutions to help mitigate increased nutrient loading from housing development are viable alternatives to terrestrial-based solutions, which utilise food producing land. These marine-based alternatives have the potential to reduce nitrogen loading through denitrification, assimilation and burial and provide additional ecosystem services such as biodiversity gain, carbon sequestration and possibly food or biomass production. Their market value in terms of nitrogen credits could also provide funding for marine conservation, habitat restoration and low trophic aquaculture production.

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