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Ecosystem Services of Commercially Important Bivalves in the UK: Nutrient removal services.

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This report has been prepared by Seafish, in collaboration with AFBI.

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Summary

Residents of the UK benefit from numerous goods and services provided by nature valued at £211 billion for UK waters (ONS, 2021). Bivalve cultivation, due to its lowered ecological impact, and low food-web nutritional requirements, stands out as a prime example of nature-based intensification supporting blue growth. Bivalves offer multiple environmental services (habitat and ecosystem engineering, source of calcium carbonate, catalysts in the production of biodiesel, feed for livestock etc), including water quality improvement. As they naturally consume algae, they contribute to the removal of nutrients from the water column. This is particularly valuable in areas prone to eutrophication[1], where additional management of non-point nutrient sources is needed. Despite these benefits, several questions remain regarding the scale of national capacity for bivalve nitrogen removal, societal acceptance, and the financial benefits to be gained. Further, the UK shellfish aquaculture sector is diverse and comprises quite a few bivalve species including blue mussels, Pacific oysters, Native oysters, and Manila clam, although the former two dominate the sector. This range introduces variability to the estimates of extraction volumes and financial forecasts. To address some of these questions, this research gathered information on the ecosystem services provided by bivalves in the context of water quality improvement. The scale of those services for the UK was evaluated using proximate analysis and simulation through the Farm Aquaculture Resource Management (FARM) model, and explored options for the valuation of those services for the UK.

The report's methodology involved three key components. First, a comprehensive literature review employed specific criteria to select relevant publications regarding bivalves' nutrient removal capacities and assessment methods. Second, data on nutrient sources in UK waters between 2000 and 2021 were collected, categorising inputs from various sources. Third, the study investigated bivalve-driven nutrient removal through proximate analysis and the FARM model, focusing on four commercially important species. Proximate analysis estimated removal based on bivalve weight and elemental composition, while the simulation through the FARM model considered environmental factors and farming approach. Finally, an avoided cost analysis was used to estimate the value of shellfish farms' nutrient removal. This value was compared with alternative mitigation methods and explored within a nutrient credit trading program.

Primarily, the focus of existing bivalve-mediated nutrient removal research was on bioremediation (83%), targeting water quality issues, eutrophication, and fish farming impacts, with a strong emphasis (82%) on nitrogen removal over phosphorus. Oysters and mussels dominated (86% of cases) due to their popularity and scientific

[1]a process in which a waterbody becomes overly enriched with nutrients, resulting in the overgrowth of simple plant life.

familiarity. Investigations primarily occurred in commercial aquaculture, using diverse methods like modelling (35.7%) and field surveys (23.8%). Global interest surged recently, with the USA leading in research output. According to 81% of publications, the presence of bivalves has a positive impact on water quality. Findings consistently showed bivalves' effectiveness in nutrient removal, with some cases reporting high removal rates of local nutrient loading. However, nuances like biogeochemical processes and varying efficiencies over time and conditions indicate the need for site-specific analyses for accurate nutrient removal assessments. Overall, the consensus strongly supports bivalves' role in enhancing water quality and reducing nutrient concentrations in aquatic systems.

The UK's nitrogen and phosphorus loadings (OSPAR RID[2] dataset 2000-2021) revealed significant variations across regions. England and Scotland emerged as major contributors, primarily through riverine inputs. Despite challenges in recent-year analysis due to data gaps, previous reports suggest improvements in water quality due to governmental measures. The majority of UK coastal waters are non-problem areas for eutrophication, with around 300 km^2 of problem and potential problem areas along the coast, mostly in estuaries with restricted water circulation. However, it is important to consider that some regions still experience significant nutrient levels that can impact their Water Framework Directive (WFD) classification, particularly during seasonal spikes in nutrient or chlorophyll-a levels. Considering ongoing land development, offshore aquaculture, and environmental shifts, exploring additional bioremediation approaches such as bivalve bioextraction is recommended for nutrient management in areas prone to eutrophication as well as high nutrient levels.

The UK shellfish industry is focused on blue mussels, Pacific oysters, and Manila clams, which constituted 99.8% of the reported industry worth of nearly £22 million in 2019. Despite consistently ranking among the top 20 oyster and mussel producers globally and top 10 in Europe between 2015-2021, there was an overall decline in UK bivalve production from 24,149 tonnes in 2015 to 15,936 tonnes in 2019. This decline was notable for blue mussels in particular, but was also evident for Manila clams and Native oysters, in contrast to a significant increase of 111.8% in Pacific oyster production. Scotland has consistently maintained its position as the top shellfish producer in the UK, contributing between 26.3% and 44.0% of farmed species between 2013 and 2019. Conversely, Wales experienced a stark decline in total shellfish production, dropping from 31.61% of the total in 2013 to 18.5% in 2019 due to decreased blue mussel yields. England's contribution ranged from 26.2% to 29.0% in the same period. Northern Ireland saw a decrease in overall production, mainly due to

[2] OSPAR RID - The Riverine Inputs and Direct Discharges (RID) programme has been established by the OSPAR commission. It aims to monitor and assess all inputs and discharges of selected contaminants to the OSPAR maritime area and its regions that are carried via rivers into tidal waters or are discharged directly into the sea.

a decline in blue mussel yields although there was an increase in Pacific oyster production. Conservation efforts in England and Scotland might have contributed to shifts in Native oyster production, with declines in Scotland and increases in England, reflecting different conservation strategies. Regulatory constraints, market challenges, access to finance, and biological events, especially in Scotland, have contributed to production declines, impacting smaller companies and remote regions.

The analysis conducted on shellfish production in 2019 revealed significant nitrogen and carbon removal at harvest, with mussels accounting for 92.2% and 83.5% of the total nitrogen and carbon removed by shellfish, respectively. This dominance is due to both, the higher nitrogen content in mussels compared to other bivalves as well as their substantial production levels. While a tonne of nitrogen could be removed by 113 tonnes of blue mussels, 270 tonnes of Pacific oysters would be required to achieve the same result. For Manila clam and Native oysters 312 tonnes and 344 tonnes respectively would have to be produced in order to remove one tonne of nitrogen at harvest.

Notably, Scotland and England were the primary contributors to nitrogen and carbon removal at harvest, aligning with their status as major aquaculture producers. The trends in removal capacity over time mirror the production decline in Northern Ireland, Wales, and Scotland, particularly in mussel and Native oyster yields. Despite increased Pacific oyster production in Northern Ireland, the decrease in mussel production lessens the nutrient removal in local waters. Recent favourable yields in mussels and oysters in England have positively impacted nutrient removal services.

The comparison between estimated nitrogen removal from proximate analysis in 2019 and nitrogen loadings in UK waters in 2014 reveals that bivalve aquaculture could potentially remove 0.034% of the nitrogen loadings. While this percentage may seem small, in the context of the 15,931 tonnes of bivalves produced in 2019, it holds significant promise for bivalve bioremediation in UK waters. As there has been a substantial decline in the overall bivalve production, the most recent removal estimates do not reflect the capacity of the country and production potential. Considering the highest harvest on our record (2013), 203 tonnes of nitrogen could be removed if bivalve production is returned to over 20 thousand tonnes a year. As the UK has substantial potential for bivalve aquaculture, expansion of the industry would bring greater benefits in terms of nitrogen removal and other ecosystem services offered by shellfish. While bivalves alone cannot address all nutrient excess issues, they play an essential role in nutrient cycling and can be a part of a holistic approach to water quality management. Bivalve bioremediation could support other nature-based solutions and enhance the overall effectiveness of nutrient control strategies. This would be best suited for areas prone to eutrophication and in the removal of nitrogen from more challenging, non-point sources, such as agricultural or stormwater runoff.

On a regional scale, Wales and Northern Ireland exhibit the most potential, removing 0.12% and 0.11% of their respective nitrogen loads. For instance, in England, bivalve harvest-related bioextraction alone could offset 2.5% of industrial effluents, while in

Northern Ireland, it could more than compensate for the industrial nitrogen (when considering the reported nitrogen loadings). This signifies a tangible improvement in water quality, adding to the existing suite of ecosystem services from bivalves and benefits derived from the food and by-product industry.

In terms of potential saved costs, extrapolating data from water treatment facilities suggests that the national-scale cumulative avoided costs for nitrogen removal in 2019 could exceed £7 million annually (for 126 nitrogen tonnes removed by bivalves). Combined efforts for effective catchment management could contribute an additional £1.1 million in savings. Using regional examples, the average cost of reducing a tonne of nitrogen could range from between £32,884 and £139 million. These savings underline the potential for cost-effective nitrogen removal methods and pave the way for innovative mechanisms like nutrient credit trading (NCT). However, establishing NCT frameworks would require comprehensive regulatory structures, collaboration among stakeholders, public awareness, and acceptance. It is crucial to ensure that consumers perceive bivalve nitrogen removal as safe and reliable, that it does not by itself impact the quality or safety of products destined for eventual human consumption and that it does not introduce pollution concerns, but rather is a natural process that is being expanded through aquaculture. Nevertheless, it is important to note that any repayments for nitrogen or nutrient removal will most likely be based on a least-cost comparison and the repayments will not equal the saved costs but rather a proportion of the costs saved.

This research contributes valuable insights to discussions regarding the significance of bivalve aquaculture, not only for seafood but also for water quality. The results of the final report are expected to further the understanding of wider benefits provided by shellfish aquaculture and to help support the promotion of bivalve cultivation across the UK. The authors express hope that this report will encourage future work on including bivalves in nutrient management plans and nutrient credit trading schemes in the UK.

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Introduction

Aquatic ecosystems are under severe strain due to human activities (Poikane et al., 2019), especially near coastal areas where pollution accumulation is greatest (Aly et al., 2013; Critchell and Lambrechts, 2016). This poses a significant threat to various economic activities reliant on good environmental status and water quality, including seafood production, tourism, recreation and other marine ecosystem services and societal benefits. Collectively these ecosystem services and societal benefits have been estimated to be worth over £211 billion in UK waters (Culhane et al., 2019; Grizzetti et al., 2016; O'Higgins and Gilbert, 2014; ONS, 2021).

Eutrophication, or nutrient pollution, is caused by an overload of nutrients such as nitrogen and phosphorus. This can further lead to an imbalance in the elemental ratio in the water and the changes to the natural nutrient cycle, which results in a cascade of environmental effects (Billen and Garnier, 2007; Defra, 2019; Grizzetti et al., 2016; Romero et al., 2013). Nutrient excess results in increased algal biomass, which blocks sunlight from reaching submerged vegetation, such as seagrass beds, preventing their growth (Burkholder et al., 2007; Han and Liu, 2014). Eutrophication can also lead to the decline or even loss of native species, as it favours the growth of invasive species that thrive in such nutrient-rich environments (Alexander et al., 2017; Byers, 2002). Moreover, as algae die and decompose, they expend more oxygen, causing hypoxia or 'dead zones', which have a harmful effect on aquatic organisms, can lead to reduced biodiversity, and ecological imbalance (Diaz and Rosenberg, 2008; Howarth et al., 2011; Romero et al., 2013).

Although aquatic systems have the capacity to self-regulate, the rate and volume of nutrient input can exceed this capacity. Therefore, management systems are required (wastewater treatment procedures, best management practice guides, investment in control and prevention measures), which all incur costs and pose difficulties in their administration. Even with continued improvements in technology and a rise in the eco-awareness of society, maintaining good ecosystem health on the fundamental level – water quality - is frequently still challenging and costly. For example, the environmental protection expenditure incurred by UK businesses (mining and quarrying, manufacturing, energy production, water supply) reached £2 billion in 2020, including costs of hiring external organisations for their environmental services (Defra, 2019; ONS, 2022). Although most of the UK coastal waters are considered non-problem areas (NPA), there are over 300 km^2 of problem and potential problem areas for eutrophication, mainly estuaries with restricted water circulation (Axe et al., 2017). Moreover, there are many regions that still experience significant nutrient and chlorophyll-a levels during winter and summer months, which can affect their Water

Framework Directive (WFD)[3] classification. In these regions, research into innovative and cost-effective solutions is crucial to maintain and incentivise water quality improvement processes. The UK also has commitments to the sustainable development of the blue economy and the implementation of nature-based solutions such as implementing the 25-Year Environment Plan and the UK Marine strategy, being a member of the OSPAR commission and the Convention on Biological Diversity.

A bioremediation method that has been gaining momentum is the bioextraction of nutrient pollution using organisms that directly or indirectly extract and accumulate nutrients from the water body in an environmentally safe and minimally invasive way. Bivalves, with their filter-feeding lifestyle and low food-web position, present a sustainable and multi-faceted solution. As they feed, they remove algae and suspended organic matter, leading to lower nutrient concentration in the water (Fig. 1). Some of the nitrogen is assimilated into their tissue, while the excess is excreted back into the water. It is then further transformed by other organisms into nitrogen gas, completing the nitrogen cycle (Fig. 1). Nitrogen is removed from the system through shellfish harvest and by background biochemical processes. While the bivalves alone cannot address all nutrient excess issues, they play a crucial role in nutrient cycling and can be a part of a holistic approach to water quality improvement. By integrating bivalves into nutrient management strategies, we could leverage their natural abilities to support healthier ecosystems and communities.

This path has already been embraced by some states in the United States, where additional income can be earned by producers through nutrient credit trading schemes that consider the least avoided cost of water treatment through traditional purification measures (Bricker et al., 2018, 2020; Ferreira and Bricker, 2016; Wheeler, 2020). However, it is important to note that these programs are still in their set-up phase. In Virginia, no payments have been made to the growers yet, despite recognising the services of bivalves (Wheeler, 2020). In Maryland, two growers have been paid based on the Chesapeake Bay NCT Program (Wheeler, 2020).

In the UK, shellfish aquaculture of blue mussels, Native oysters (also known as European flat oysters), Pacific oysters and Manila clams is worth approximately £22 million for the 16 thousand tonnes produced (2019), offering a nutritious, healthy protein source for humans. Within the blue economy framework, bivalve cultivation is perceived as a sustainable food production venture, providing a nutritious food source, a wide range of ecosystem services and economic potential (Bateman and Bishop, 2017; Gallardi, 2014; Lillebø et al., 2017). While within their natural aquatic environments, bivalves act as habitat and ecosystem engineers, providing sediment

[3] The Water Framework Directive (WFD), established by the European Union in 2000, aims to protect and enhance the quality of water bodies across Europe. The concentrations of Chlorophyll-a and nutrients are considered under the Ecological Status and Chemical Status classifications.

stabilisation, preventing coastline erosion, serving as settlement and nursery areas for other species (including many of commercial importance) and contributing to the expansion of hard substrate and increasing biodiversity (Bateman and Bishop, 2017; McLeod et al., 2019; Sheehan et al., 2019; Smaal et al., 2019; Sousa et al., 2009; zu Ermgassen et al., 2020). Recent studies in Lyme Bay (UK) show that offshore bivalve aquaculture structures contribute to the recovery of benthic habitats, increase biodiversity and boost abundance of mobile taxa (Bridger et al., 2022; Mascorda-Cabre et al., 2023).

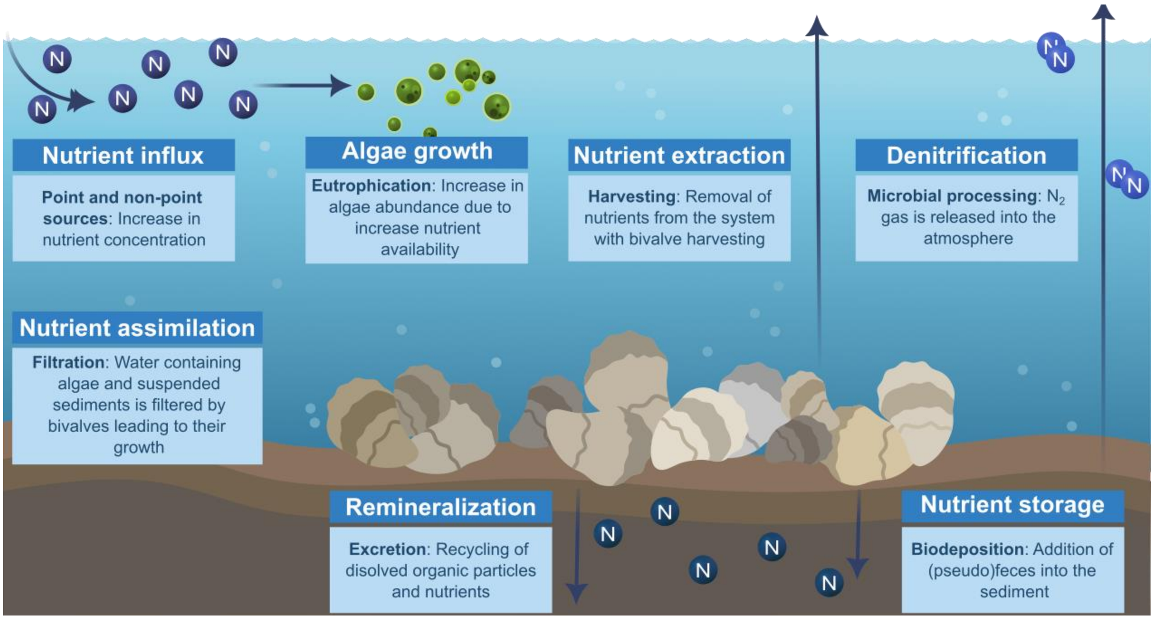


Figure 1: Simplified illustration of nutrient removal removed by bivalves.

Further down the processing chain, bivalve by-products are used as part of the circular economy. The discarded shells, for example, can be used as a source of calcium carbonate in the egg industry and construction, for conditioning and ameliorating acidic soils, as catalysts in the production of biodiesel, as inorganic fillers in polymers as bactericidal and dehalogenation agent and medically in artificial bones (Lee et al., 2008; Spångberg et al., 2013; Summa et al., 2022; Yao et al., 2014). Bivalves that do not reach the human market can be repurposed as feed for livestock as well as farmed finish. Mussel meal has become an alternative feed with reduced carbon emissions and agricultural land use (McLaughlan et al., 2014; Nagel et al., 2014; van der Heide et al., 2021). However, knowledge gaps still exist on the extent to which these services affect the ecosystem and their value in the socio-economic context.

There are many unanswered questions regarding the national capacity for bivalve nitrogen removal, societal acceptance of the approach and resulting seafood products, and the financial benefits to be gained. The scale and net balance of nutrient removal through the entire bivalve lifecycle is yet to be fully ascertained. The UK shellfish aquaculture sector is diverse and comprises quite a few bivalve species including blue mussels and Native oysters and, to a lesser extent but equally valuable, scallops, cockles and clams and the non-native species such as the Manila clam or

Pacific oyster. Shellfish production methods differ substantially, both in methods of production and scale of the aquaculture farms. This range introduces variability to the estimates of extraction volumes and financial forecasts. This report aims to address that by:

i) gathering information on the ecosystem services provided by bivalves in the context of water quality improvement,
ii) evaluating the scale of those services for England, Wales, Northern Ireland, and Scotland using proximate analysis and simulation through the Farm Aquaculture Resource Management (FARM) model and
iii) exploring ways for the valuation of those services using regional examples from the UK.

Methodology

The project comprised three parts:

1. a literature review to investigate the knowledge of the nutrient removal services provided by bivalves and explore methods used for the bioextraction assessment,
2. a proximate analysis accompanied by modelling to provide the estimation of Nitrogen and Carbon removal by different bivalve species across the UK and
3. an avoided cost analysis to calculate a possible financial value of nutrient removal by shellfish aquaculture.

Literature Review

An advanced search within all Web of Science (WoS) databases and collections was conducted (Web of Science Core Collection, BIOSIS Citation Index, KCI-Korean Journal Database, MEDLINE®, SciELO Citation Index), encompassing all years (1900 - 2022) and using TS (topic) field tag which covers title, abstract and keywords. The focus of the search was the water quality improvement services provided by bivalves through nutrient reduction. To fulfil this scope, the question was broken down and analysed in terms of PICO inclusion criteria (Population, Issue, Comparator, Outcome) to formulate individual substrings (Table 1). The traditional Intervention category was replaced with the Issue category to better encompass the focus of the study. The Issue and Outcome categories as well as the Boolean search string (Table 1) were compiled based on information and keywords from reviews relevant to the field of bivalve aquaculture ecosystem services. The review had a global coverage and considered all bivalve species available, not only the ones currently cultivated in the UK as inferences can be made between species with similar life histories.

For the eligibility of the article, it had to fulfil the following criteria:

- focus on bivalves (P),
- research nutrient removal capabilities of bivalves as a part of field or laboratory study (I),
- compare the effect of bivalve-mediated water quality improvement (C),
- investigate the effects of bivalve-mediated nutrient removal on water quality indicators (O),
- for context, the research had to concentrate on bivalve presence in marine and brackish waters rather than purely freshwater species in ponds or rivers (C).

Table 1: Search string used in Web of Science (topic fields; all databases; all years). Publications were required to contain at least one term from each category.

Aquatic term	Population term	Issue term	Comparison term	Outcome term
marine OR coastal OR catchment OR basin OR estuarine OR bay OR aquaculture OR sea	shellfish OR bivalve OR mussel OR oyster OR scallop OR clam	eutrophication OR restor* OR ecosystem services OR “wastewater treatment” OR “runoff treatment” OR bioextraction OR biodeposition OR denitrification	improve* OR change OR effect OR impact OR decrease OR contribute OR support OR mitigat*	“water quality improvement” OR “nutrient removal” OR “nitrogen removal” OR “phosphorus removal” OR biodiversity improvement OR “algal bloom mitigation” OR “algae removal” OR “pollution mitigation” OR “water clarity” OR resilience

If the species is freshwater but its presence has been recorded and investigated in the context of marine or brackish habitat, the article was retained. Only English, peer-reviewed, primary data publications were retained (reviews and meta-analyses excluded). Expanded criteria rules are available in Appendix 1.

The WoS search produced 597 articles that were screened in two stages: abstract/title screening and full-text screening (Appendix 1 Fig. 1). The abstracts and titles of each article were assessed for compliance with the PICOC criteria using the WoS interface. Uncertain articles were kept for full-text evaluation to avoid potential false exclusion. Eighty-five publications accepted for full-text screening were uploaded to Zotero for review. Exclusion reasons were recorded based on the PICOC category. This resulted in the final 42 articles for review (Appendix 1 Fig. 1). The process and analysis are reported following PRISMA. The study information included but was not limited to, geographic specifications relevant to the research, type of study conducted (field or lab experiment, modelling), aquatic setting, species or organism groups, issue addressed, effect measurement approach and observed outcome. For a full scope of the data extracted, see Appendix 1. Studies covering the analysis of more than one species or species group (hereafter combined articles) were treated as separate instances for the analysis.

Nutrient loading in the UK waters

The primary sources of nutrient influx into water bodies include agricultural activities (fertilizers, manure runoff), urban runoff (stormwater runoff, pet waste, domestic wastewater), industrial discharges (manufacturing and mining), and inadequate wastewater treatment systems.

The nutrient loadings of the UK waters (Celtic Seas, Channel, Atlantic, Irish Sea and North Sea) between 2000 and 2021 were sourced from the OSPAR RID dataset (OSPAR, 2023) and separated based on the source into point sources: aquaculture discharges, industry effluents, sewage effluents and summarised in total direct discharges as well as diffuse sources which here comprised total riverine inputs from monitored and unmonitored sources. Total Riverine Inputs are the contaminants that are carried via rivers into tidal waters, originating from various sources in the river's catchment while the Total direct discharges are the contaminants that are discharged directly into the sea and do not pass through a river system before entering the sea. These categories followed the data classification utilised by OSPAR in their data collection.

Nutrient removal

Bivalves filter particles from the water, removing nutrients and utilising the digested material for tissue and shell growth, while the rest is expelled as faeces, pseudofaeces, and ammonia (Bricker et al., 2018; Carmichael et al., 2012; Thomsen et al., 2016; Weihrauch and Allen, 2018). However, their efficiency and filtration rates depend on environmental factors such as temperature, salinity, dissolved oxygen, food resources and the species type. Larger species are expected to have higher filtration rates.

In order to assess the nutrient removal capacity of bivalves, two distinct approaches were employed: proximate nutrient removal analysis and the FARM model. The proximate analysis is based on data concerning the amounts of carbon (C) and nitrogen (N) present in the wet weight of bivalve, while the FARM model estimates removal based on a mass balance of intake and excretion of particulates (phytoplankton and detritus i.e., food) by the population of bivalves in the farm. The two approaches are complementary, and the results of both analyses are upscaled to the level of UK production to show the range of the nutrient removal potential. Our analysis focused on four bivalve species (Table 2): the blue mussel (*Mytilus edulis*), Pacific oyster (*Magallana gigas*, formerly *Crassostrea gigas*), Native oyster (*Ostrea edulis*), and Manila clam (*Ruditapes philippinarum*). Due to a lack of information on the nitrogen content and the parametrisation within the FARM software for common cockle and Queen scallop and Great Atlantic Scallop, it was not possible to undertake an analysis for these species.

The corresponding bivalve production between 2013 and 2021 was sourced from Cefas (Cefas, 2023), and Marine Scotland (Scottish Government, 2023) for national and, where possible, regional scale. The data was aggregated on a national level for all countries.

Figure 2: UK Riverine and Direct Discharges Areas in relation to OSPAR Sea areas.

Proximate analysis

The first approach in estimating the nitrogen and carbon removal by bivalves was through a function of their weight and N or C content. The elemental composition of the bivalves was procured from combustion elemental analysis performed as a part of the Green Aquaculture Intensification in Europe (GAIN) project (Ferreira et al., 2020). In the process, the elemental composition is determined for a pre-weighed sample by flash combustion and separation of the resulting gaseous products. The full description of the methodology can be found in the project's report (Ferreira et al., 2020).

To calculate the removal on a national scale, the percentage value of N content in the live weight of each species (Table 2) was scaled up to the corresponding national production (Table 2; Equation 1):

$$N_{removed(p)} = N_{bivalves}\ X\ Production_{National}$$ Equation 1

Table 2: Bivalve species considered in the proximate analysis with the percentage content of nitrogen (N) and carbon (C) in their shell and flesh (% of live weight, in fresh mass) presented originally in the Green Aquaculture Intensification in Europe (GAIN) project report as mean elemental composition. TFW stands for Total Fresh Weight (live weight).

Species	Latin name	Origin	% of N in TFW	% of C in TFW
Blue mussel	*Mytilus edulis*	Belfast Louch (Northern Ireland)	0.88	11.1
Pacific oyster	*Magallana gigas*	Dundrum Bay (Northern Ireland)	0.37	10.9
Native oyster/ European flat oyster	*Ostrea edulis*	Lough Foyle (Northern Ireland)	0.29	8.80
Manila clam/ Japanese carpet shell	*Ruditapes philippinarum*	Venice Lagoon (Italy)	0.32	8.50

FARM model implementation

The second approach utilised was to provide the nutrient removal estimates through the Farm Aquaculture Resource Management (FARM) model. The FARM local-scale model has been used previously in diverse scenarios involving different types of finfish and shellfish species, geographical regions, and aquaculture practices such as bottom culture, trestles, cages, and suspended culture (Bricker et al., 2020, 2018; Dvarskas et al., 2020; Ferreira et al., 2020, 2007a, 2007b). Based on food supply, aquaculture farm size, shellfish density and various environmental parameters (e.g., current velocity, temperature, salinity, concentration of organic particles), the FARM model provides estimates of the number and biomass of harvestable shellfish and potential levels of production.

FARM can provide estimates based on two modes: the physiology-based population dynamic model used in this project or the individual-based model (IBM). First, an individual bivalve growth model (WinShell) is developed, parametrised and validated for the individual bivalve species, based on a generic AquaShell™ framework (Bricker et al., 2015, 2020b, 2018; Ferreira, 2007; Ferreira et al., 2008; Nobre et al., 2010; Saurel et al., 2014; Sequeira et al., 2008). The AquaShell model operates using WinShell and FARM. Overall, WinShell checks how well one organism performs and tracks the mass balance of various substances related to ecosystem services. The FARM model simulates farming on a larger scale. Individual-based population simulations (IBM) are created based on the object-oriented paradigm used in ecological modelling (Ferreira, 1995; Silvert, 1993), where each individual in the population possesses various attributes related to growth performance and interactions with the environment, such as food consumption, organic waste production and mortality (however, events such as disease outbreaks were not included). These models are deterministic, but to accurately simulate the variability within a cultivated population (e.g., some individuals do not survive to be harvested), individuals are stochastically assigned a fitness parameter in terms of assimilation efficiency (AE), which introduces genetic diversity within the cohort determining survival rates. Fitness is determined at runtime, ensuring a minimal probability of two model runs being identical. The IBM framework operates with the Net Energy Balance (NEB) approach and uses bioenergetic models to predict bivalve growth, reproductive effort and mass balance for the culture cycle at the level of the individual (Ferreira et al., 2014, 2012, 2010). This provides a more accurate estimation of nutrient removal across a broad range of environments and the regulatory ecosystem services of bivalves. After integrating the individual bivalve models into FARM, the production, and environmental effects at the local scale of a farm are simulated over one culture cycle. Taking into consideration environmental parameters such as advective water flow, transport of particulate and dissolved material, temperature and salinity, the model estimates the removal of particulate suspended particles, particulate organic waste, excretion of dissolved nitrogen, oxygen consumption as well as the removal of phytoplankton and detrital carbon and nitrogen by bivalves (Fig. 3). The net removal is calculated by subtracting losses caused by faeces, pseudofaeces, excretion, mortality, and spawning.

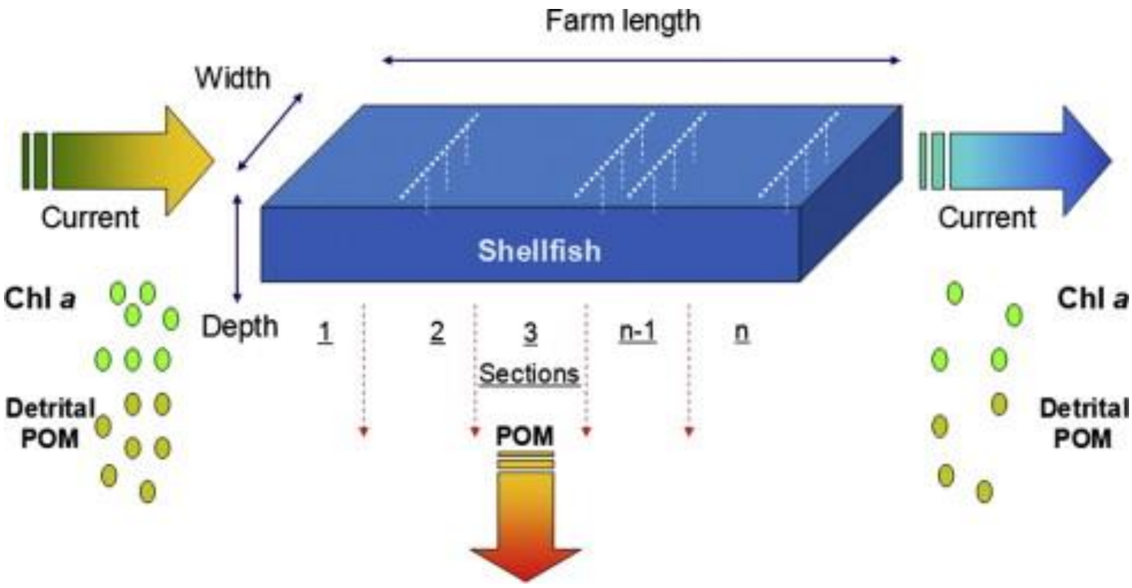


Figure 3: Conceptual diagram of the FARM model (Ferreira et al., 2007a).

The net removal is calculated by subtracting losses caused by pseudofaeces, faeces, excretion, mortality, and spawning. To be more reflective of realistic shellfish farm operations, the 'Harvest When Ready' option was chosen for the IBM model runs, rather than assuming that the shellfish would only be harvested at the end of the culture period. For the regular runs of the model, this option is not available.

Population dynamics in the simulation were defined by culture strategies, with natural mortality within each national model parametrised using pre-defined "typical farms" that were chosen to be representative of each species. The data used to parametrise the models was sourced from governmental reports, scientific literature as well and data made available by shellfish farms and hatcheries. Due to a wide range of cultivation approaches, sizes of ventures, and periods of cultivation, each species was considered on a similar basis in all countries that naturally cultivate it, with average farm and shellfish practice parameters.

The environmental conditions were distinct for each country. Environmental parameters driving the models were sourced from scientific publications, personal communications, openly available data from OSPAR (OSPAR, 2023), EA Water quality data archive (EA, 2023), as well as satellite data from Copernicus Marine Services (CMEMS, 2023). However, it is crucial to note that those drivers were not sourced from the same year or regions and hence the results should be interpreted as a general potential. For UK waters, particularly data on chlorophyll and particulate matter concentrations, the datasets available were limited with substantial gaps between the years and between months which hinders interpolation. It was previously noted by the 2017 report provided by OSPAR, whereby the data availability for the northern North Sea coast (Norwegian and United Kingdom coasts) was limited, with gaps in the observations as well as high clusters of observations in space and time.

The results of the model were scaled up to the national production as below (Equation 2):

$$N_{removed(m)} = \frac{\frac{Production_{national}}{TPP}}{1000} x\ Nremoval \qquad \text{Equation 2}$$

Where $N_{removed(m)}$ represents the total N removed by the estimated live weight

Production in tonnes. $Production_{national}$ (tonnes) is the corresponding species production for each nation, while TPP (tonnes) is the estimated FARM-modelled production for each species at the farm scale and N removal (kg y^{-1}) is the N removed by each species at the local (farm) - scale.

Avoided cost analysis

The economic value of nutrient removal by shellfish farms can be estimated by considering it as a water cleaning service. In the avoided or replacement cost analysis method, the economic value of nutrient removal or eutrophication avoidance is estimated based on the cost of the alternative mitigation methods such as stormwater control measures, chemical and manual wastewater treatment, and approved agricultural Best Management Practices (BMP) (Barrett et al., 2022). It has been successfully applied in coastal regions of the United States for oysters (Bricker et al., 2020; Dvarskas et al., 2020; Parker and Bricker, 2020), clams ((Dvarskas et al., 2020)) and for mussels of the Baltic Sea (Gren, 2019). In the UK, such a valuation has been conducted for oyster populations of the Solent (England) (Watson et al., 2020) and Dundrum Bay (Northern Ireland) (Ferreira et al., 2020). This method can also provide an estimate of potential compensation in a nutrient credit trading program.

By applying the cost required to remove one kilogram of N (£/kg N) or C (£/kg C) through traditional methods, the cost savings achieved through bivalve bioextraction can be estimated. Only the costs directly related to nitrogen or carbon removal were used in calculations, rather than more general estimates for eutrophication mitigation measures or general water improvement costs. These would further increase the value of bivalve aquaculture, outside of water quality aspect.

Trends in bivalve-mediated bioremediation research

Bivalve bioextraction, proposed as a nutrient removal method since at least 1994 (Mackie, 1994), has regained attention in scientific and industrial circles. The primary focus (83%) of reviewed research has been bioremediation, addressing water quality issues, eutrophication, and mitigating the environmental impact of fish farming. Nutrient dynamics was another cause behind the research, followed by reef restoration and associated nitrogen dynamics as motivation for future projects. As noted previously, the focus in this study is nitrogen though where possible carbon and phosphorus results will also be included.

There was a clear dominance of nitrogen removal studies (82%), in contrast with phosphorus, which was not studied independently; it was only examined alongside nitrogen (18%). While carbon removal was not the main focus of the review, two publications included consideration for carbon bioassimilation by oysters and mussels. In the UK context, one publication explored phosphorus and carbon removal through mussel aquaculture and field surveys. Nitrogen is perceived as the limiting nutrient for algal growth in marine, brackish and estuarine habitats, particularly if they are heavily polluted (Fang et al., 1993; Forsberg, 1976; Pedersen and Borum, 1996), which explains the emphasis being placed on nitrogen rather than phosphorus. Moreover, considering the focus of the review (water quality improvement), carbon studies were not as common. However, it is worth noting that regardless of the study's focus and removal calculated, bivalves participate in the uptake of both, nitrogen, and phosphorus, as part of their natural feeding cycle. Moreover, in the absence of nitrogen, phosphorus fertilisation can exacerbate the algae bloom issues (Carpenter, 2008; Ryther and Dunstan, 1971; Schindler et al., 2008) and the limiting nutrient can change seasonally, based on freshwater inflow (Malone et al., 1996). As both elements are important in eutrophication dynamics, estimates inclusive of phosphorus removal would benefit the understanding of the ecosystem services of bivalves and further ecosystem dynamics modelling.

Species of interest

A high proportion of oysters (50%) and mussels (36%; mainly *Mytilus edulis* - 25% of studies) in the investigated cases reflects the global popularity of these shellfish groups, contributing 33% and 13% of global production respectively (food and non-food uses; Wijsman et al., 2019) as well as the relative ease in field and laboratory work using those organisms. *Crassostrea virginica*, *Magallana gigas* and *Mytilus edulis* are major contributors to global aquaculture, with annual aquaculture production of 135.7, 643.5, and 164.5 thousand tonnes respectively (FAO, 2023). However much of the global oyster production is reported under broader categories of 'cupped oysters' and 'sea mussels' which accounted for an additional 6 million tonnes of oysters and nearly 1 million tonnes of mussels in 2022 (FAO, 2023).

In the UK, only *M. edulis* and *M. gigas* were included, which contribute to the 14,800 and 2,325 tonnes of mussels and oysters produced (Seafish, 2023a, 2023b). In addition to being in high demand, these species have experienced substantial scientific coverage concerning their anatomy, habitat preferences and functional ecology, which facilitates the evaluations of their bioextractive capabilities and use in modelling studies.

Although commercial aquaculture was the dominant site of investigation, oyster reefs (Ayvazian et al., 2022; Cerco, 2015; Onorevole et al., 2018; Smyth et al., 2016, 2015; Westbrook et al., 2019), and to a lesser degree, natural mussel beds (Neves et al., 2020; Sea et al., 2021) were also investigated for their participation in nutrient dynamics and their extractive capabilities. Three studies considered a comparison between shellfish aquaculture and natural bivalve populations. This research is also beneficial for the analysis of farmed shellfish bioextraction, as it focuses on biochemical processes such as denitrification and biodeposition that are not always considered in some of the aquaculture models focused on nutrient removal through harvest.

Some studies looked at shellfish more generally, with nine unspecified species from mussel, oyster, and clam groups investigated (Fig. 4) and the six combined studies provided 23 combinations of species and locations, (38% of studies). While the proportion of clam (9.8%) and scallop (1.6%) cases were low compared to their global production (38% and 17%; Wijsman et al., 2019), they were more common in combined papers, particularly using modelling. This might be due to the difficulties in conducting work with species such as clams which bury themselves in the substrate or sediment.

Investigation methods

To assess and compare the outcomes of bivalves for nutrient removal, examined articles employed variations of field and laboratory studies, historical data analysis and modelling. Modelling (35.7%) and combined field surveys (23.8%) were the dominant modes of investigation. Models provide a valuable tool to estimate and predict changes on wider spatial scales, largely unattainable through field experiments, and can be applied to more than one species. Amongst the diversified modelling approaches (numerical models, GIS, 3D models, combinations of hydrodynamic and ecological modelling), the Farm Aquaculture Resource Management (FARM) model emerged frequently for bivalve production (Bricker et al., 2020; Dvarskas et al., 2020; Ferreira et al., 2007b; Parker and Bricker, 2020; Rose et al., 2015; Silva et al., 2012). Integrating physical, biogeochemical, growth, and eutrophication models, FARM assessed harvest, eutrophication changes, and costs (Ferreira et al., 2007a). It featured in 43% of modelling publications and 60% of individual cases in China, Europe, and the United States. In the UK it has been used for example in the case of *Magallana gigas* in Loch Creran (Scotland) in a combined study of 6 other species across 9 countries (Rose et al., 2015) and provided encouraging results with annual nitrogen removal at 23 g m^{-2}. FARM software has also been used in the Green Aquaculture Intensification (GAIN) project, which included examples from the UK and bioextraction estimates based on the UK mussel industry (Ferreira et al., 2020). However, the parameters required for FARM are site-specific, other areas of the UK require separate analysis, and in the case of neighbouring farms, would require a system-scale rather than a farm-scale model (Rose et al., 2015).

Elemental analysis of tissue and shell offers a simplified approach for nitrogen removal estimation and can be appropriately upscaled to the population harvested from the system (Kotta et al., 2020; Olivier et al., 2021). While lacking consideration for certain biogeochemical processes (denitrification, biodeposition or excretion) that contribute to the final net balance of nutrient dynamics, it provides a faster, simpler and less data-demanding solution. This simplified approach can help identify ventures of particular value to bioremediation or inform on the minimal harvest necessary for the improvement of water quality.

Laboratory and field experiments involved repeated water quality monitoring, followed by calculations of estimated nutrient removal through biodeposition and harvest. One study used stable isotope analysis to track the journey of anthropogenic nitrogen. A mixture of nutrient dynamics and harvest balance was also used to estimate the nutrient removal capacity of bivalves. In field and laboratory studies, the nutrient removal capacity and nutrient dynamics were compared based on divergent study designs, while for modelling different scenarios were applied.

Global interest distribution

A surge in interest in bivalve-mediated nutrient bioextraction is evident from the increased publication activity in the last 7 years (Fig. 6). This growing interest can be attributed to concerns for food security (Jennings et al., 2016; Pradeepkiran, 2019) and sustainable protein provision, combined with a growing need for ecologically neutral or friendly management methods (Ferreira and Bricker, 2016; Olivier et al., 2020; Smaal et al., 2019; Vaughn and Hoellein, 2018). Nature-based solutions have also been gaining traction and have reached the mariculture world not only in terms of bioextraction but also coastal protection (Zhu et al., 2020), biodiversity enhancement (Hughes, 2021) and habitat improvement (Nanou et al., 2022). The UK has committed to OSPAR's Biodiversity and Ecosystems Strategy aims to protect and conserve marine biodiversity and ecosystems in the North-East Atlantic which can be supported by implementing nature-based solutions. In this context, shellfish cultivation is being promoted and contributes to the safeguarding of the UK's marine ecosystems' natural capacity to sequester nutrients.

The review had a global scope, identifying 18 countries and one larger study area (Baltic Sea) which was not country-specific. Most countries had only one or two papers each between 1996 and 2022. The overall limited amount of research could stem from the relative novelty of bioremediation research, even though reports of mussel-based nitrogen bioextraction date back to 1996 (Haamer, 1996) and the concept itself is older (Goldman et al., 1974; Mackie, 1994). Of the countries identified (Fig. 5), the United States stood out with the highest number of cases (36%) and consistent annual article output since 2011. Eastern (*Crassostrea virginica*) and Pacific oysters (*Magallana gigas*) were the primary species investigated in the USA, along with three species of clams. This spike in academic interest could be linked to the significant role the USA plays in global marine bivalve production whilst experiencing a decline in bivalve yields (Wijsman et al., 2019). Particularly, the decline in the US oyster fisheries by nearly 30% between 1970 and 2015 combined with a nearly 34% increase in aquaculture production between 1999 and 2015 (Wijsman et al., 2019) could have sparked more interest in the additional benefits of oyster farming.

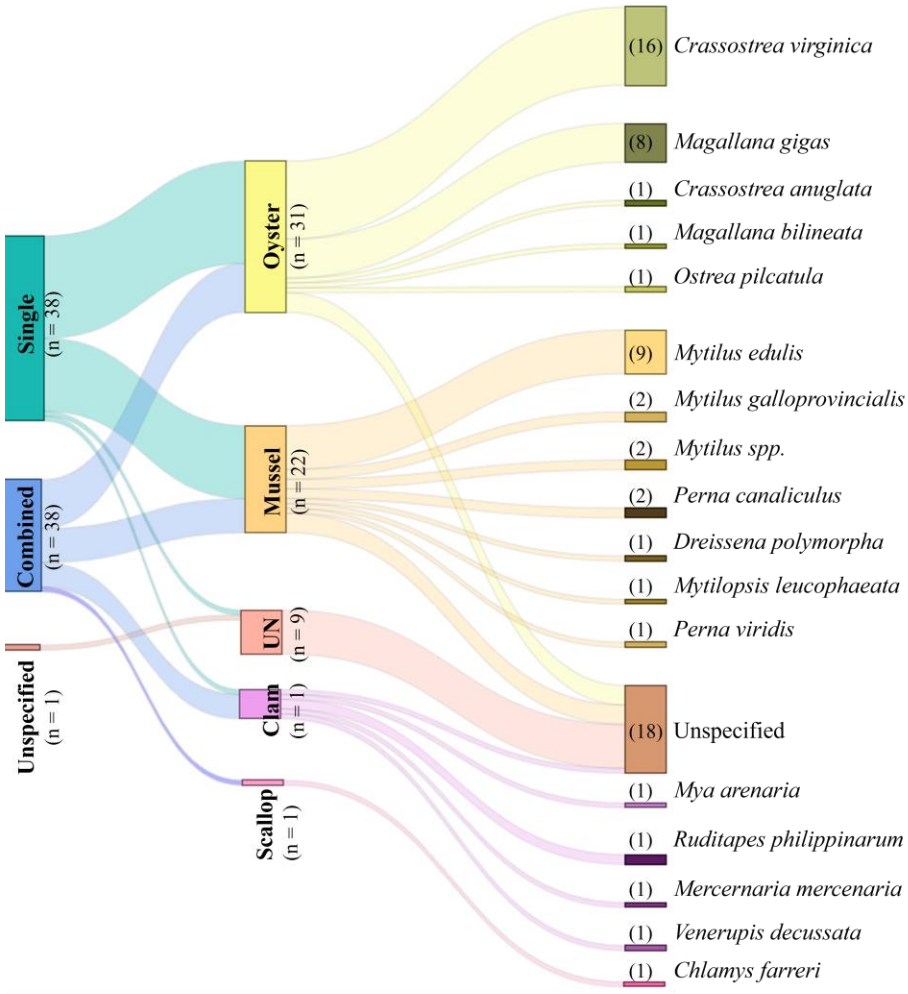


Figure 4: Sankey diagram of publications' focus (single, combined species) and the species investigated. The number of database entries for each group is included in the brackets. Articles studying multiple species were counted separately. Unspecified species or shellfish types were labelled as UN.

In contrast, the United Kingdom was involved in only two publications, both originating in the last 10 years and investigating *Mytilus edulis* and *Magallana gigas* (Fig. 5, 6). This period coincides with an increase in publication output observed since 2015 (Fig. 6). The highlighted gaps between global efforts and the state of research in the UK on bivalve bioextraction should stimulate further studies efforts and possibly lead to the expansion of the bioremediation and nutrient credit initiatives on a wider scale. As the UK consistently placed in the top 20 oyster and mussel producers in the world and the top 10 in Europe between 2015-2021 (FAO, 2023c; Seafish, 2023b, 2023a; Wijsman et al., 2019), it is a prime location for research into bivalve bioextraction and nutrient credit trading.

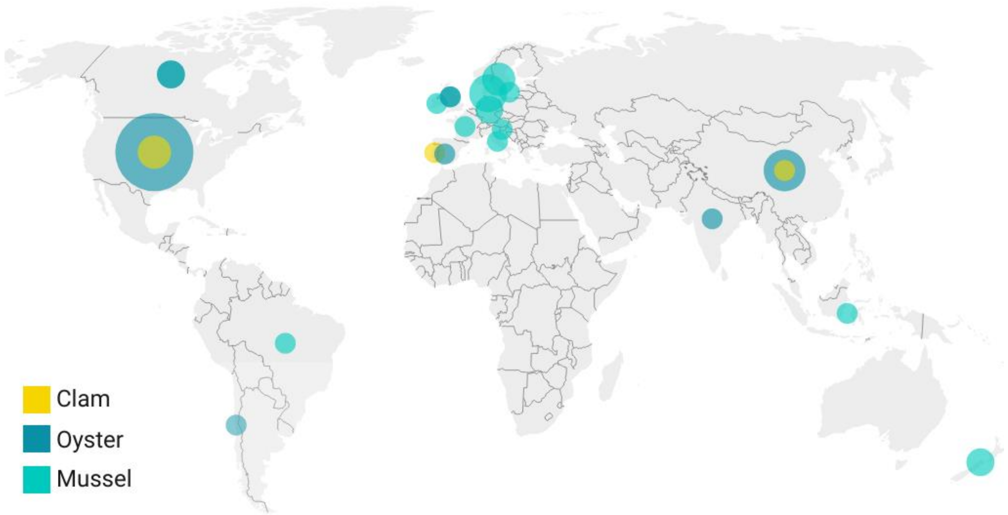


Figure 5: Distribution map of publications registered in the literature database between 1996 and 2022. Three shellfish groups, clam, oyster, and mussels are separated with the size of the bubble representing the number of publications. The map was generated via Datawrapper (Lorenz et al. 2012).

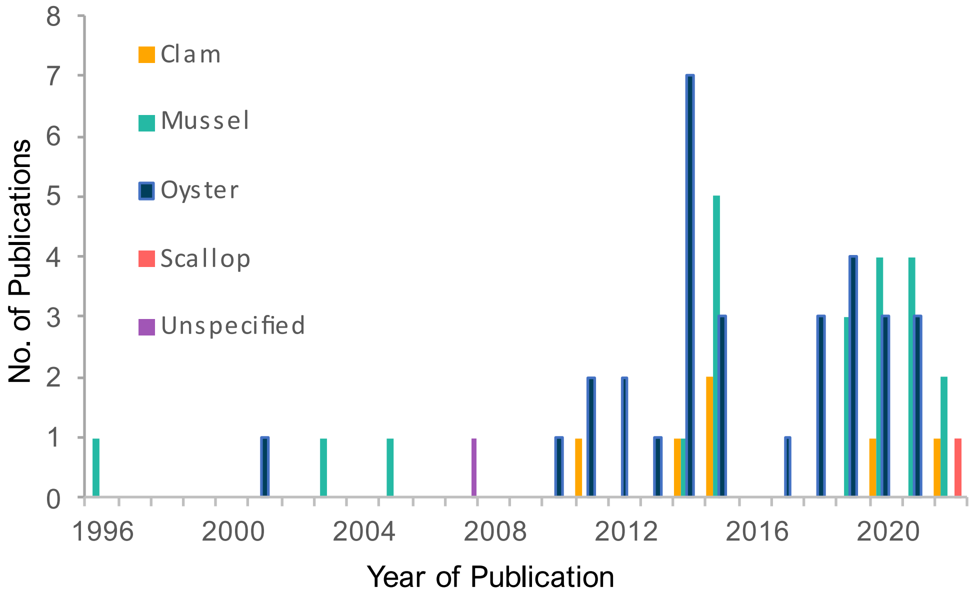


Figure 6: Number of publications registered in the literature database between 1996 and 2022 with a focus on bivalve bioremediation. Four shellfish groups, scallops (purple), clams (yellow), oysters (blue) and mussels (green), are separated together with the unspecified shellfish (pink).

Outcomes

The vast majority of the reviewed publications (81%) concluded that the presence of bivalves, and as such, their commercial cultivation, has an overall positive effect on water quality and nutrient removal from the system. While some studies reported mixed results, it is worth noting that none reported a solely negative impact of bivalve bioremediation - only limited effects.

FARM model assessments from around the world have reported bivalve-mediated nutrient removal as favourable over best management practices and stormwater treatment (Rose et al., 2015). Field studies consistently reported net positive nutrient removal and little to no negative effects observed which is encouraging and reinforces theoretical and model predictions. Some studies placed the net nitrogen removal of oysters between 10% to 20% of the total N load to the studied waterbody (Carmichael et al., 2012; Cerco, 2015; Clements and Comeau, 2019). Higher rates could be found for clams, with 28.7% and 43.3% of the external nitrogen and phosphorous input being removed by the manila clam (Zan Xiaoxiao et al., 2014). A minority of studies reported a higher nutrient removal capacity, that could compensate from 86% up to 100% of the local nutrient loading if the production site is established at an optimal growth location and density and if the nutrient load is relatively low (Clements and Comeau, 2019; Kotta et al., 2020). In the context of the UK, cultivation of *M. gigas* has been estimated to remove 23 g m^{-2} and 74 g m^{-2} of nitrogen annually in the Scottish Loch Creran and Irish Lough Ireland respectively (Rose et al., 2015) and from 5 to 8.50 kg of nitrogen per tonne (mean) of live *M. edulis* based on upscaled elemental analysis (Olivier et al., 2021). The estimates of phosphorus removal for the UK, also important in managing the health of marine ecosystems (Carpenter, 2008; Ryther and Dunstan, 1971; Schindler et al., 2008), were placed between 0.43 kg of phosphorus per tonne of *M. edulis* from bottom cultures and 0.95 kg of phosphorus per tonne from rope cultures (Olivier et al., 2021).

The denitrification process is also important for net positive nitrogen removal and in live oysters, denitrification can be three times higher than nitrification (Caffrey et al., 2016), supporting the positive net effect of restored oyster reefs as well as oyster aquaculture. Studies conducted in the Chesapeake Bay reveal that bivalve-mediated denitrification can remove significantly more nitrogen than is achieved solely through bivalve harvest (Golen, 2007; Mykoniatis and Ready, 2020). The stimulation of denitrification has been also demonstrated in a recent meta-analysis of oyster habitats in comparison to bare sediments (Ray and Fulweiler, 2021). Denitrification efficiency of 50% to 75% was reported for oyster reefs which indicates net nitrogen removal (Onorevole et al., 2018). High denitrification rates have also been reported within and between natural green-lipped mussel beds (Sea et al., 2021), suggesting a wider spatial impact of bivalve presence. Whilst comparing natural reefs and beds to cultivated ones, it is important to take into account the higher tissue:shell ratio of farmed bivalves which translates to a higher level of nitrogen removal (Ayvazian et al., 2022).

However, not all ventures have the potential to maintain the same efficiency in nitrogen removal within or across the years. Consideration of biogeochemical dynamics (biodeposition and excretion) is necessary to avoid overestimating nutrient removal potential (Olivier et al., 2021). For example, the removal of nitrogen through oyster harvesting may be offset through the excretion of ammonia (NH_4), as was noted through studies of combined seaweed-bivalve aquaculture of *Magallana gigas* in China (Liu et al., 2021; Yu and Gan, 2021). Another study placed the return of the ingested nitrogen through excretion and elimination between 40% and 73% (Ferreira et al., 2007b). Moreover, the biodeposition process has the potential to further offset the nutrient removal potential (Silva et al., 2012). Holmer et al (2015) observed that the net removal of nitrogen from the blue mussel was maintained only through the first year, with the mussels converting into a nitrogen source thereafter. This time dependency was not recorded in other studies but could be attributed to the increased biodeposition outweighing denitrification stimulation and an increase in excretion rate with growth, which lowers the net removal efficiency. In areas characterised by little to no tidal currents or where bivalve stocking densities are high, over-enrichment and biodeposition can lead to dissolved oxygen depletion and eventually, the release of nitrogen into the water column as organic matter decomposes (Bricker et al., 2020; Higgins et al., 2013; Lindahl et al., 2005; Ritzenhofen et al., 2021).

Variability in nutrient removal estimates is due to site- and species-specificity and the true potential of any farm can only be ascertained with the inclusion of the particular circumstances of the planned venture (Rose et al., 2015). Nutrient removal further varied between culture systems, with rope-cultured blue mussels capturing more nitrogen and phosphorus than bottom-cultured ones (Olivier et al., 2021). However, cultivation on ropes and longlines can cause higher mineralization rates in the sediment below, where nitrate is converted to ammonium which would conserve the nitrogen within the system rather than remove it (Christensen et al., 2003). Climate change impacts can alter the capacity of a farm for nutrient extraction. On one hand ocean acidification will have a negative impact on bivalve growth and survival (Waldbusser et al., 2015) while higher water temperatures were associated with reduced phosphorus content in the tissue (Olivier et al., 2021), which would reduce the nutrient removal capacity of bivalves. However, this could be balanced by a faster production cycle expected with the increase in the seawater temperatures and therefore a higher nutrient removal (Olivier et al., 2021).

While there may be some variability in the efficiency and levels of nutrient removal by bivalves depending on specific circumstances, the overarching consensus is clear: bivalve bioremediation positively impacts nutrient removal from aquatic systems. At the same time, the process of nitrogen uptake and assimilation or enhanced denitrification was not directly connected to the safety of bivalve consumption. The safety of consuming bivalves is more related to their potential to accumulate bacteria, viruses, and toxins in their bodies due to their filter-feeding behaviour (Seafish, 2024). Overall, the majority of reviewed publications demonstrate the substantial potential of bivalves in enhancing water quality and reducing nutrient concentrations and eutrophication.

Bivalve-mediated bioremediation in the UK waters

This section considers the state of the UK's bivalve industry, aquatic ecosystems, and the capacity of the farmed populations to remove nitrogen and carbon from the water based on two estimates: proximate analysis and modelling, with the potential implications of bivalve cultivation for nutrient management in the future.

Nutrient loadings in UK waters

The data for the total mean nitrogen and phosphorus loadings (Table 3, 4) into the UK waters were sourced from the OSPAR RID dataset between 2000 and 2021 although the analysis involves only data from 2014. This was the most recent year with most regions reporting their total nitrogen and total phosphorus loads. A considerable limitation of the dataset was the gaps in the records, resulting from the changes in sampling and record-keeping across the different administrations as well as interruption caused by COVID-19 (2020-21). Although total riverine inputs (RIN), as well as total direct discharges (TDD), were recorded for nearly every year between 2000-2021, the individual sources were not always provided (sewage, industry, and aquaculture effluents). This was particularly evident for aquaculture discharges and reports for Welsh waters, which recently comprised only the information on RIN. The most recent data (2015 onwards) has experienced reduced reporting spatially in England and Wales and changes in the way of reporting the measurements for Northern Ireland and as such was not deemed suitable for this analysis.

Nutrient types considered in the OSPAR reporting system were aquaculture discharges (mainly from fish farming), industry effluents (wastewater discharges) and sewage effluents (domestic and municipal wastewater) which come under the direct discharges, as well as monitored and unmonitored riverine inputs.

There are marked variations within the UK loadings of both, nitrogen, and phosphorus. The biggest UK contributors to nitrogen and phosphorus loadings are England and Scotland. Riverine inputs dominate over direct discharges, with 2014 nitrogen data indicating loadings of 305.22 $x10^3$ tonnes and 63.94 $x10^3$ tonnes, respectively. Phosphorus loadings were more closely matched, with 10.40 $x10^3$ tonnes of RIN and 9.47 $x10^3$ tonnes of TDD. In 2014, the highest nitrogen loadings were recorded for the North Sea South (106.67x10^3 tonnes y^{-1} for RIN), Celtic Sea (58.28x10^3 tonnes y^{-1} for RIN) and Irish Sea (44.79.x10^3 tonnes y^{-1} for RIN). At the same time, in terms of phosphorus, the highest loadings were received by the North Sea South (3.22x10^3 tonnes y^{-1} for TDD, 3.2x10^3 tonnes y^{-1} for RIN), the North Sea north 2.8x10^3 tonnes y^{-1} for TDD) and the Irish Sea (2.13x10^3 tonnes y^{-1} for RIN).

Although the analysis of recent years and trends in nitrogen and phosphorus loadings is difficult to perform due to data limitations, there have been reports of improvements in the water quality and issues of elevated loadings (Defra, 2019; DEFRA, 2012; Maier et al., 2009; Painting et al., 2018). The number of problem areas for eutrophication has decreased from 23 to 21 (2006-2014), which represents 0.41% of UK transitional and coastal waters (Axe et al., 2017). This has been attributed to the measures taken by the UK government to reduce nutrient loadings into surrounding waters (Defra, 2019; DEFRA, 2012; Maier et al., 2009; Painting et al., 2018). Analysis conducted by OSPAR also revealed a significant reduction in nutrient inputs to the OSPAR Maritime Areas, particularly in the Greater North Sea area (Axe et al., 2022). However, inputs of nitrogen oscillate year to year, and a lag resultant from nitrogen reservoirs in soils and sediments as well as confounding effects of environmental change could lead to future changes (Carpenter et al., 1998; Foden et al., 2011; Worrall and Burt, 2001). Considering further land developments, offshore aquaculture farms and environmental changes, implementing more bioremediation methods such as bivalve bioextraction should be considered.

Table 3: Nitrogen (N) and phosphorus (P) loadings* and sources for England, Northern Ireland, Scotland, and Wales for 2014. Loadings in 103 tonnes y-1. Total direct discharges are the sum of Aquaculture discharges, Industry and Sewage effluent.

Country	Source	N-Total	P-Total
England	Industry effluents	1.20	0.11
	Sewage effluents	35.35	4.71
	Total direct discharges	**36.25**	**4.80**
	Total Riverine Inputs (monitored and unmonitored)	**229.84**	**6.62**
Northern Ireland	Industry effluents	0.001	0.0008
	Sewage effluents	0.96	0.11
	Total direct discharges	**0.99**	**0.45**
	Total Riverine Inputs (monitored and unmonitored)	**8.22**	**0.98**
Scotland	Aquaculture discharges	11.11	1.53
	Industry effluents	2.11	1.25
	Sewage effluents	12.21	1.33
	Total direct discharges	**25.32**	**4.00**
	Total Riverine Inputs (monitored and unmonitored)	**46.99**	**2.10**
Wales	Industry effluents		0.002
	Sewage effluents	0.99	0.41
	Total direct discharges	**1.39**	**0.22**
	Total Riverine Inputs (monitored and unmonitored)	**20.17**	**0.69**
UK	**Total direct discharges**	**63.94**	**9.47**
	Total Riverine Inputs (monitored and unmonitored)	**305.22**	**10.40**

*The data in Table 3 should be considered with caution. Although it is supplied by OSAPR RID, the data is collected by many bodies across the UK and collated on many levels, which could introduce error. Some nations do not collect and report data on certain sources which is reflected in the gaps within the table and the graphs. Moreover, certain regions are not always included in the reporting, depending on the yearly monitoring capabilities of the country, as such not all OSPAR regions might be included in this summary.

Table 4: Nitrogen (N) and phosphorus (P) loadings* into the UK waters for 2014. Loadings in 103 y-1. Total direct discharges are the sum of Aquaculture discharges, Industry and Sewage effluent.

Area	Source	N-Total	P-Total
Atlantic	Aquaculture discharges	7.28	1.00
	Industry effluents	0.94	0.33
	Sewage effluents	5.64	0.60
	Total direct discharges	**13.86**	**1.93**
	Total Riverine Inputs (monitored and unmonitored)	**16.27**	**1.47**
Celtic Sea	Industry effluents	0.002	0.002
	Sewage effluents	1.36	0.41
	Total direct discharges	**3.71**	**0.37**
	Total Riverine Inputs (monitored and unmonitored)	**58.28**	**1.40**
Channel	Industry effluents	0.02	0.002
	Sewage effluents	7.03	0.68
	Total direct discharges	**7.04**	**0.69**
	Total Riverine Inputs (monitored and unmonitored)	**40.00**	**0.82**
Irish Sea	Industry effluents	0.09	0.05
	Sewage effluents	3.71	0.37
	Total direct discharges	**1.45**	**0.46**
	Total Riverine Inputs (monitored and unmonitored)	**44.79**	**2.13**
North Sea (North)	Aquaculture discharges	3.84	0.53
	Industry effluents	2.26	0.99
	Sewage effluents	13.26	1.29
	Total direct discharges	**19.35**	**2.80**
	Total Riverine Inputs (monitored and unmonitored)	**39.22**	**1.37**
North Sea (South)	Industry effluents	0.01	0.001
	Sewage effluents	18.51	3.22
	Total direct discharges	**18.52**	**3.22**
	Total Riverine Inputs (monitored and unmonitored)	**106.67**	**3.20**
UK	Aquaculture discharges	11.11	1.53
	Industry effluents	3.32	1.37
	Sewage effluents	49.51	6.56
	Total direct discharges	**63.94**	**9.47**
	Total Riverine Inputs (monitored and unmonitored)	**305.22**	**10.40**

* The data in Table 4 should be considered with caution. Although it is supplied by OSAPR RID, the data is collected by many bodies across the UK and collated on many levels, which could introduce error. Some nations do not collect and report data on certain sources which is reflected in the gaps within the table and the graphs. Moreover, certain regions are not always included in the reporting, depending on the yearly monitoring capabilities of the country, as such not all OSPAR regions might be included in this summary.

Shellfish Production

Scotland remains the top shellfish producer within the UK, contributing between 26.27% (6,935 tonnes; 2013) and 44% (7,061 tonnes; 2019) of farmed species. Wales experienced the most visible decline in total shellfish production, dropping from 8,344 tonnes in 2013 (31.61% of total shellfish production) to 2,946 tonnes in 2019 (18.5%), primarily due to a decline in blue mussel yields. England contributed between 29.02% (7,648 tonnes; 2013) to 26.20% (4,181 tonnes; 2019) of total shellfish production. However, it is important to notice that in 2019, the reported production did not include cockles, which have been a substantial component of English shellfish production (50.90% - 60.70% between 2015 and 2018). The decline in the overall Northern Ireland production from 3,464 tonnes in 2013 (13.12%) to 1,747 in 2019 (11.00%) was caused by the decline in blue mussel yields, although the country has increased its Pacific oyster production by 484 tonnes.

The United Kingdom's for-consumption production focused on the blue mussels, Pacific oyster, Native oyster, Manila clam, queen scallop, Great Atlantic scallop, common cockle, and hard clam, with a combined worth of nearly £22 million in 2019 (CEFAS, 2023). Here, the analysis focuses on the mussels, oysters, and Manila clams, which were responsible for 99.77% of this reported value. Over the past decade, the UK's shellfish industry has consistently placed in the top 20 oyster and mussel producers in the world and the top 10 in Europe between 2015 and 2021 (FAO, 2023; Seafish, 2023b, 2023a; Wijsman et al., 2019). This was achieved despite the overall decline in bivalve production, from 24,149 tonnes in 2015 to 15,936 tonnes in 2019, which was largely due to decreased yields of mussels, particularly in Wales (Fig. 7, 8). Between 2013 and 2019, blue mussel, Manila clam and Native oyster production experienced an overall decline of 41.26%, 36.36% and 62.00% respectively, contrasting with the increase of 111.78% for Pacific oyster production (Fig. 7). However, while discernible patterns were evident for blue mussels, Pacific oysters and Native oysters, production of Manila clam exhibited greater variability in the year-to-year yields. This variability was more pronounced due to the comparatively lower overall production levels of Manila clams, which has only been recorded for England. Native oysters experienced a great decline in Scotland, with a simultaneous increase in yields originating in England. This could be attributed to the widespread conservation and restoration efforts forming part of the restoration works across the country which lead to the expansion of the natural beds and can contribute to greater success of commercial production in England while in Scotland the approach involves restricting fishing to only Loch Ryan, allowing for slow and steady growth of the seabed (Baggett et al., 2014; Kaspar, 2014; NatureScot, 2023; Preston et al., 2020; Zu Ermgassen et al., 2020). Overall production of Pacific oysters was largely consistent, with England and Northern Ireland remaining the top producers and limited yields harvested in Scotland and Wales. Although still the dominant species in UK aquaculture, blue mussels have experienced a 41.23% decline in yields (22,570 - 13,264 between 2015 and 2019), largely due to the decline of production in Welsh waters.

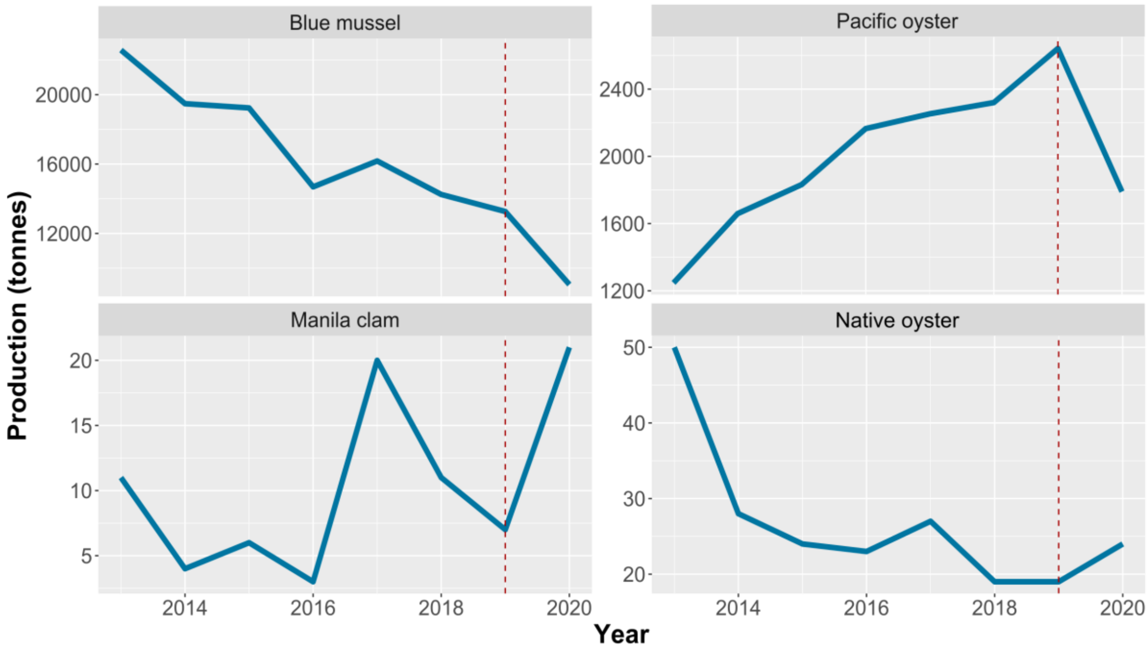


Figure 7: Total aquaculture production (tonnes) of UK all bivalves (mussels, oysters, scallops, clams, and cockles as well as marine molluscs not else identified) between 2013-2020 (note the different scales). The red dashed line indicates 2019, after which the reported production might be biased due to Covid-19 pandemic and should be considered with caution.

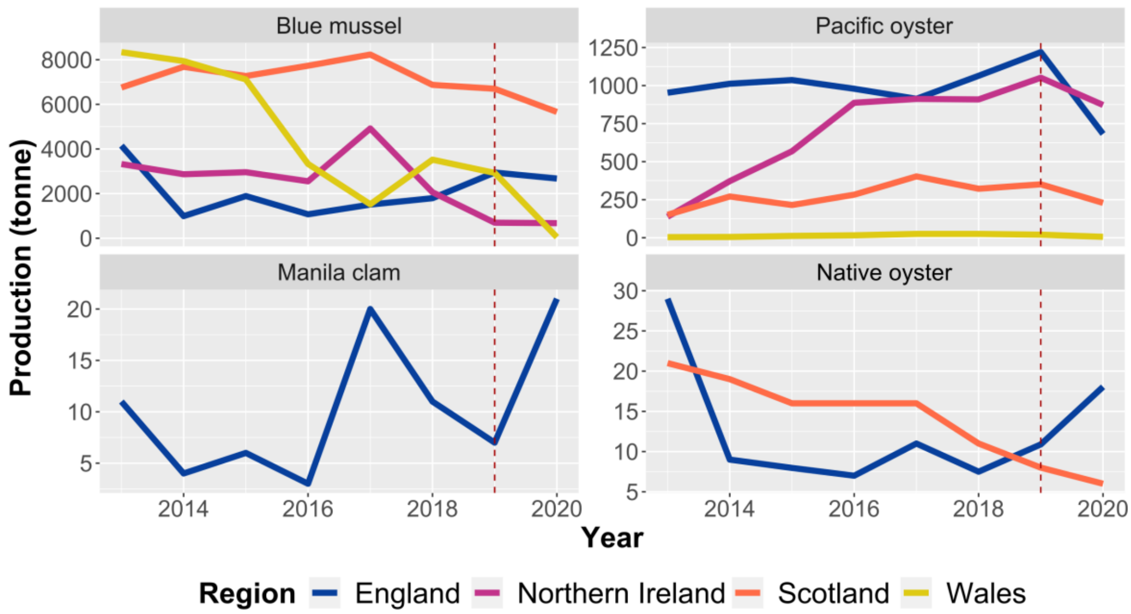


Figure 8: Aquaculture production (tonnes) of UK bivalve species across the countries between 2013-2020 (note the different scales). The red dashed line indicates 2019, after which the reported production might be biased due to Covid-19 pandemic and should be considered with caution.

The decline in production can be related to administration and technical issues such as hindered access to finance for smaller companies due to a long wait (can be as much as three years) before a company starts gaining revenues, exacerbated by unexpected costs, slow domestic market, difficulty in finding employees (particularly in the remote regions of Highlands) and regulatory constraints. Moreover, biological events have contributed to the closing of mussel ventures in locations across Scotland (Crown Estate Scotland and Maritek, 2019).

Nitrogen removal estimates

Proximate analysis on the national level

For nutrient removal, data from shellfish production for 2019 was used to represent the most recent valid year. The estimated removal volumes for nitrogen and carbon using the proximate analysis are available in Table 6. Based on the 126.57 tonnes of nitrogen removed in 2019, mussels were responsible for 92.19% of the nitrogen removed by shellfish, followed by 7.72% removed by Pacific oysters. The dominance of blue mussels in nitrogen removal (Fig. 11; Table 6) can be attributed to their high nitrogen content compared to oysters or clams (Table 3) and higher levels of production (Fig. 7, 8). Although not the primary focus of the study, the removal of carbon was also estimated (Fig. 10, 12). However, it is important to note that this number represents the removal of carbon from the water column following harvest, rather than long-term overall sequestration. Several factors such as bivalve respiration, local conditions and shell dissolution affect the effectiveness of the sequestration and contribute to offsetting it. As such the 1762.49 tonnes removed in 2019 should be considered as an indication of the effect, rather than precise estimates. Similarly to nitrogen, mussels dominated in terms of the proportion of total carbon removed by shellfish (83.51%), with Pacific oysters removing nearly five times less (16.32%). The removal of both elements was not distributed evenly across the UK, with the main aquaculture producers, Scotland, and England, remaining the top contributors in nitrogen and carbon removal (47.68% and 24.09% of nitrogen and 44.35% and 26.14% of carbon removed respectively).

The nitrogen and carbon removal follows the trends in UK production, with lowered capacity in Northern Ireland, Wales, and Scotland in recent years, attributed to the decline in mussel and Native oyster production (Fig. 9, 10). Despite the increase in Pacific oyster production in Northern Ireland, the decline in mussels outweighs it, reducing the nutrient removal capacity of Irish waters. Concomitant favourable mussel and oyster yields in the past two to three years are also reflected in increasing nutrient removal services provided by the English shellfish industry. Comparable results have been seen for the UK based on mussel production in the UK (2018), where 14,247 tonnes of mussels removed 125 tonnes of nitrogen (Ferreira et al., 2020). The removal efficiency is 0.0088 tonnes of nitrogen per tonne of mussel, which is slightly higher than the removal proposed by Olivier et al. (2020), but still shows the greatest bioremediation potential per tonne of shellfish. Comparably, the average oyster removal here was 0.0037 tonnes of nitrogen per tonne of oysters, higher than the estimated 0.00233 tonnes based on global data (Olivier et al., 2020).

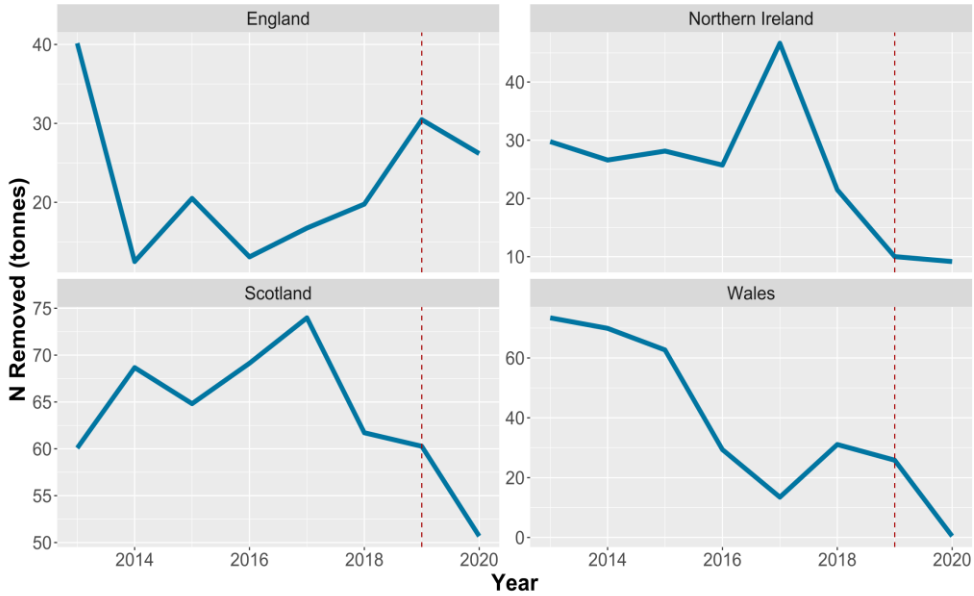


Figure 9: Nitrogen removal (tonnes) estimates based on aquaculture harvest of UK bivalve species (blue mussel, European flat oyster, Pacific oyster, Manila clam) for England, Northern Ireland, Scotland, and Wales between 2013-2020, estimated by proximate analysis (note the different scales). The red dashed line indicates 2019, after which the reported production might be biased due to Covid-19 pandemic and should be considered with caution.

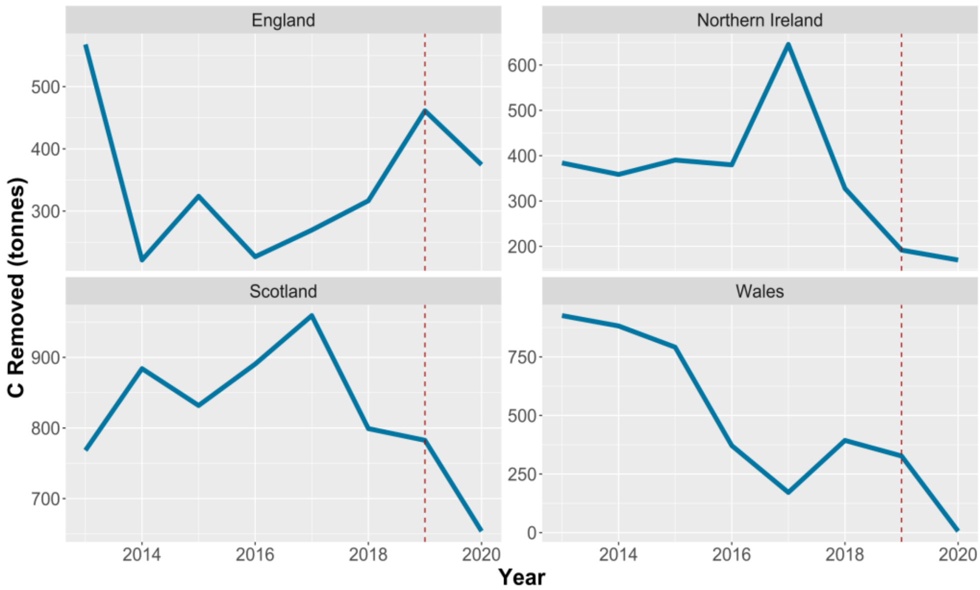


Figure 10: Carbon removal (tonnes) estimates based on aquaculture harvest of UK bivalve species (blue mussel, European flat oyster, Pacific oyster, Manila clam) for England, Northern Ireland, Scotland, and Wales between 2013-2020, estimated by proximate analysis (note the different scales). The red dashed line indicates 2019, after which the reported production might be biased due to Covid-19 pandemic and should be considered with caution.

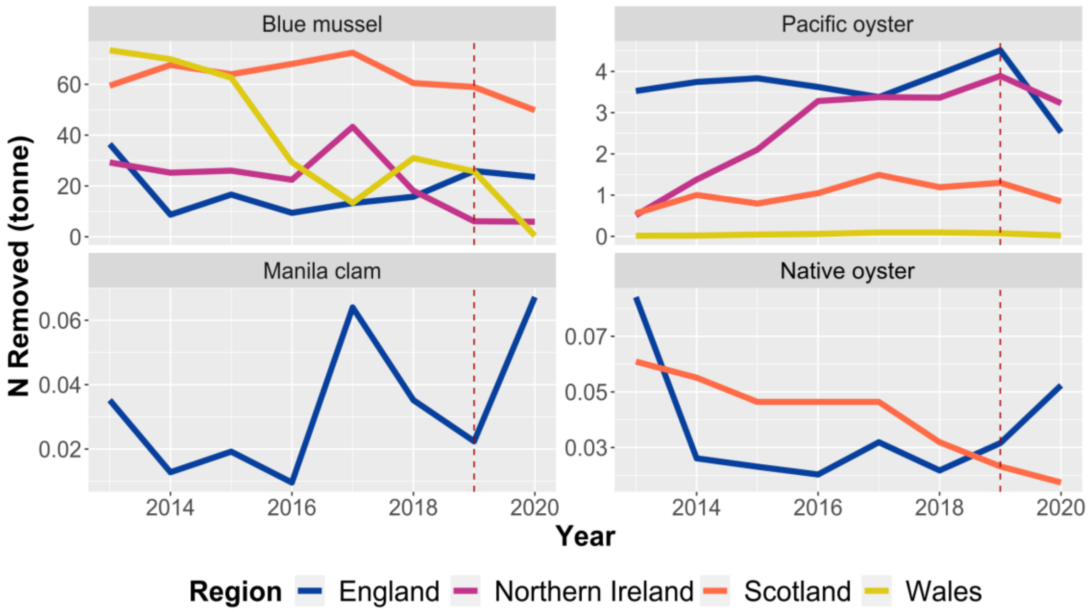


Figure 11: Nitrogen removal (tonnes) estimates based on aquaculture harvest of UK bivalve species for England, Northern Ireland, Scotland, and Wales between 2013-2020, estimated by proximate analysis (note the different scales). The red dashed line indicates 2019, after which the reported production might be biased due to Covid-19 pandemic and should be considered with caution.

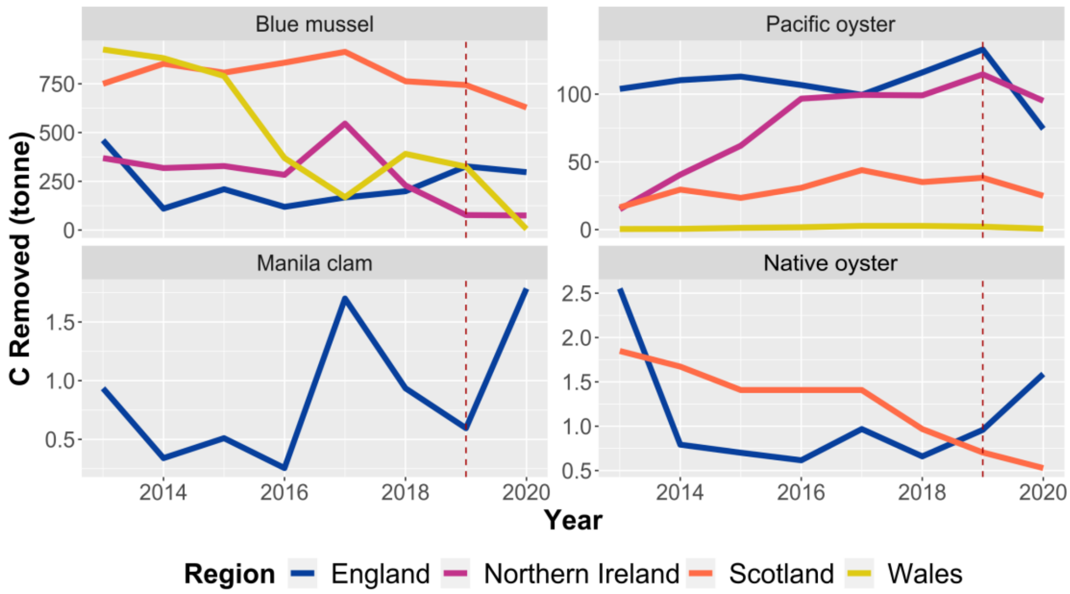


Figure 12: Carbon removal (tonnes) estimates based on aquaculture harvest of UK bivalve species for England, Northern Ireland, Scotland, and Wales between 2013-2020, estimated by proximate removal (note the different scales). The red dashed line indicates 2019, after which the reported production might be biased due to Covid-19 pandemic and should be considered with caution. Note should be taken of the different carbon removal scales.

FARM model

Similarly, to the proximate analysis, in the scaling up of the FARM estimates, data from 2019 for shellfish production was used. The estimated removal volumes for nitrogen using the scaled-up FARM outputs are available in Table 6. Before considering the data, it is important to note that the outputs are generated based on general and averaged farm and environmental parameters and as such provide an overview of potential rather than a detailed estimate for each country. Outputs are presented for the regular model and the IBM model. The estimates for both, diploid Pacific oysters, and triploid Pacific oysters are available in Table 6.

After summarising the data, FARM estimated the removal of between 285.15 (IBM) and 362.65 tonnes of nitrogen. Similar to the proximate analysis, mussels were responsible for most of the removal (91.23% - 92.66%), followed by Pacific oysters (7.35% - 8.71%), which reflects their high production in Scotland, England, and Wales. In comparison to the proximate analysis, the estimated N removal is universally higher for FARM outputs, between 2 to 4 times higher, which has been observed before (Ferreira et al., 2020). The proximate analysis considers only harvested individuals using nitrogen content based on an average individual. In contrast, the model considers the N removal contribution of the entire population (harvestable and undersized individuals) as well as the individuals that were not harvested and did not survive which contributes to the higher estimates.

Mass balance and financial valuation

The estimated nitrogen removal for 2019 compared against the nitrogen loadings for 2014 in the UK waters is available in Table 5. Although the changes in loadings can be significant year-to-year, and shellfish production also changed between 2014 and 2019, this comparison allows for the use of the most recent complete data. Based on that, bivalve aquaculture would have been able to remove between 0.034% to 0.098% (FARM) of the nitrogen loadings in the UK waters. The nitrogen removal capacity reflects the size of the industry in each of the countries (Figure 10; Table 6). However, in terms of removal of their individual nitrogen loads, Wales (0.12% and ca. 0.30% (FARM) of N loading into local waters) and Northern Ireland (0.11%; ca. 0.29% FARM) have shown the biggest potential.

Although 126.57 tonnes of nitrogen (ca. 324.12 tonnes, FARM), or 0.03% (0.09%; FARM) of nitrogen load removed, might not appear as substantial, in the context of the 15931 tonnes of bivalves produced in 2019, that removal level highlights the great potential for bivalve bioremediation in UK waters. Current production levels are at least eight thousand tonnes below the potential 2013 harvest, due to a combination of socio-economic and political challenges. As such, the 2019 removal estimates do not reflect the capacity of the country and production potential. By expanding current production to at least 2013 levels, 203 tonnes of nitrogen could be removed. Considering that the UK has substantial potential for bivalve aquaculture (MMO, 2019), expanding the industry would bring greater benefits in terms of nitrogen removal and other ecosystem services offered by shellfish. While not a complete solution on its own, our estimates illustrate that bivalve bioremediation could support other nature-based solutions and enhance the overall effectiveness of nutrient management strategies. In England, just the harvest-related bivalve bioextraction would offset 2.50% of industrial effluents (ca. 6.52%; FARM), while in Northern Ireland it would more than compensate for them. This translates to tangible benefits for water quality improvement, which already stand on top of other ecosystem services of bivalves and gains from the food and by-product industry (Olivier et al., 2020). Moreover, it is a cost-efficient mitigation measure compared to most of the other mitigation or purification measures (Petersen et al., 2014, 2012; Pretty et al., 2003; Watson et al., 2020).

Table 5: Nitrogen loadings (tonnes) in the UK waters (2014) and nitrogen removal (tonnes) by each of the countries (with the percentage of the total nitrogen loads for the respective UK waters in brackets) calculated through proximate analysis and FARM software (t stands for estimates where triploid oysters were used for Pacific oyster instead of diploid oysters) using 2019 production data.

Country	N-Total input	N-removal		
		Proximate analysis	FARM	FARM IBM
England	266 088.31	30.47 (0.01%)	88.00 (t) – 88.17 (0.03%)	68.87 (t) – 68.31 (0.03%)
Northern Ireland	9 206.83	10.01 (0.11%)	29.82 (t) – 29.97 (0.32% - 0.33%)	22.48 (t) – 21.99 (0.24%)
Scotland	72 305.60	60.27 (0.08%)	171.26 (t) – 171.31 (0.24%)	136.53 (t) – 136.36 (0.19%)
Wales	21 561.33	25.82 (0.12%)	73.20 (t) – 73.20 (0.34%)	58.51 (t) – 58.50 (0.27%)
Total	**369 162.10**	**126.57 (0.03%)**	**362.28 (t) – 362.65 (0.10%)**	**286.39 (t) – 285.15 (0.08%)**

Table 6: Nitrogen and carbon removed (tonnes) by each species in the UK, estimated through scaling up of proximate analysis and FARM results based on production from 2019 reported by Cefas. For FARM, the results are based on the regular and IBM versions of the model and provide only nitrogen estimates. For Pacific oysters, the estimates are available for diploid and triploid organisms (t).

Proximate analysis										
	Blue mussel		Pacific oyster		Native oyster		Manila clam		Total N	Total C
Country	N	C	N	C	N	C	N	C		
England	25.90	326.73	4.51	132.94	0.03	0.96	0.02	0.60	30.47	461.22
Northern Ireland	6.12	77.15	3.89	114.61	-	-	-	-	10.01	191.76
Scotland	58.95	743.59	1.30	38.26	0.02	0.70	-	-	60.27	782.55
Wales	25.75	324.79	0.07	2.18	-	-	-	-	25.82	326.97
UK Total	**116.72**	**1472.25**	**9.78**	**287.99**	**0.05**	**1.66**	**0.02**	**0.60**	**126.57**	**1762.49**
FARM										
	Blue mussel		Pacific oyster		Native oyster		Manila clam		Total N	
Country	Regular	IBM	Regular	IBM	Regular	IBM	Regular	IBM	Regular	IBM
England	73.40	56.69	14.66 14.49 (t)	9.43 10.00 (t)	0.06	0.10	0.05	0.08	88.17 88.00 (t)	68.31 68.87 (t)
Northern Ireland	17.33	13.86	12.64 12.49 (t)	8.13 8.62 (t)	-	-	-	-	29.97 29.82 (t)	21.99 22.48 (t)
Scotland	167.05	133.57	4.22 4.17 (t)	2.71 2.88 (t)	0.04	0.07	-	-	171.31 171.26 (t)	136.36 136.53 (t)
Wales	72.96	58.34	0.24 0.24 (t)	0.15 0.16 (t)	-	-	-	-	73.20 73.20 (t)	58.50 58.50 (t)
UK Total	**330.74**	**264.46**	**31.75 31.38 (t)**	**20.43 21.66 (t)**	**0.10**	**0.18**	**0.05**	**0.08**	**362.65 362.28 (t)**	**285.15 286.39 (t)**

Economic valuation and credit trading potential

Having analysed the nutrient removal capabilities of bivalves, and the variability involved in their efficiency, the question of financial value remains. The approach with the highest potential, due to its simplicity and wider availability of necessary data, is the avoided or replacement cost method, where the economic value is estimated based on the cost of the alternative, least-cost mitigation methods and nutrient removal strategies such as stormwater control measures, chemical and manual wastewater treatment and approved agricultural Best Management Practices (BMP) (Barrett et al., 2022). It has been successfully applied before in coastal regions of the United States for oysters (Bricker et al., 2020; Dvarskas et al., 2020; Parker and Bricker, 2020), as well as for mussels of the Baltic Sea (Gren, 2019). In the UK, such valuation has been conducted for oyster populations of the Solent (Watson et al., 2020) and Dundrum Bay (Northern Ireland) (Ferreira et al., 2020).

The assessment of nitrogen removal costs, as outlined in Table 7, provides valuable insights into potential cost savings and the viability of nutrient credit trading. By extrapolating data from the Poole Harbour water treatment facility, which indicates a cost of approximately £58,000 per tonne of nitrogen removed through methanol dosing and tertiary denitrifying sand filters (Wessex Water, 2023), the cumulative savings on a national scale could surpass £7 million (or £16 - 21 million; FARM) annually for the 126.57 tonnes (ca. 285.77 - 362.46 tonnes; FARM) of nitrogen removed in 2019. Further collaborative efforts with local farmers, landowners, and businesses for effective catchment management aimed at reducing nitrogen influx (improving farming practices, reducing fertiliser wastage, improving biodiversity, reducing runoff) could contribute an additional £1.1 million (£2.5 - 3.2 million; FARM) in savings. Using another regional valuation example from data based on Solent replacement and abatement costs, the average cost of reducing a tonne of nitrogen could be around £295,000 (Watson et al., 2020), suggesting over £37 million (£84 - 106 million; FARM) in savings, but could reach as much as £139 million (£398 million; FARM) considering the highest potential avoided cost of £1,100,000 per tonne of nitrogen. This substantial range, between £32,884 and £139 million (£74,300 and £398 million; FARM) underscores the significant potential for cost savings in nitrogen removal. However, it is crucial to remember that any potential remuneration for the services provided by bivalves would most likely be based on the least cost approach (i.e. method of nitrogen removal or mitigation that is the lowest cost alternative) and adjusted for the needs of the market. Quantifying cost-saving implications of including bivalve aquaculture as means of nitrogen removal in water quality management schemes are pivotal in laying the groundwork for innovative mechanisms like nutrient credit trading, a concept advocated by the Aquaculture Advisory Council (AAC, 2023) and explored by projects such as GAIN (Ferreira et al., 2020). It would not only help achieve substantial cost savings in water management efforts but also address critical environmental concerns, propelling the UK towards a more sustainable and economically efficient future. UK has also committed to promoting nature-based solutions to protect the marine environment, including nutrient removal, through joining the OSPAR Convention.

Table 7: Costs for various aspects of nitrogen and eutrophication removal, monitoring and mitigation measures. Values are provided for the UK nitrogen (N) removal: 126.57 tonnes from proximate analysis (PA), 362.46 tonnes from FARM and 285.77 FARM IBM estimates.

Issue addressed	Method	Cost	Source	Location	Value (PA)	Value (FARM; FARM IBM)
Nitrogen	Methanol dosing; tertiary denitrifying sand filters	£58,300/tonne of N yr^{-1}	Wessex Water, 2023	Poole Harbour	£7,378,051 yr^{-1}	£21,131,460 yr^{-1}; £16,660,391 yr^{-1} (IBM)
	Catchment management	£8,750/ tonne of N yr^{-1}			£1,107,487 yr^{-1}	£3,171,531 yr^{-1}; £2,500,487 yr^{-1} (IBM)
	Mixed methods	£0.26 kg^{-1} N	Brink et al., 2011 (adapted from Pretty et al., 2003)	England and Wales	£32,884	£94,239 £74,300 (IBM)
	Change of agricultural land use to less intensive grass production through direct land purchase or Payments for Ecosystem Services schemes	£295–895 kg^{-1} N	Watson et al., 2020	Solent	£37,351,150 - 113,325,150	£106,925,913 - 324,402,346 £84,302,150 - 255,764,150 (IBM)
	Upgrades to existing wastewater treatment plants and associated drainage infrastructure	£282–1100 kg^{-1} N			£35,781,540 - 139,227,000	£102,213,923 - 398,706,794 £80,587,140 - 314,347,000 (IBM)
	Application of Catchment Sensitive Farming measures	£5 - 23 kg^{-1} N			£632,850 - 2,913,110	£1,812,303 - 8,336,596 £1,428,850 - 6,572,710 (IBM)

Other cost estimates				
Not Eutrophication	Treatment of algal blooms and in-water preventative measures	£0.5m yr^{-1}	Pretty et al., 2003	England and Wales
	Adopting new farm practices that emit fewer nutrients	£3.39m yr^{-1}		
	Monitoring costs for water and air	£0.44m yr^{-1}		
	Developing eutrophication control policies and strategies	£0.2m yr^{-1}		
	Stormwater control measures	£2,914 kg^{-1} N	Rose et al., 2015	USA-based estimates
	Approved agricultural BMP	£374 kg^{-1} N		
	Wastewater treatment upgrades	£7047 kg^{-1} N		
Nitrate	Costs to the agricultural sector of complying with the NVZ regulations	£44m - £65m yr^{-1}	Environment Agency, 2021	UK
	Company led catchment schemes to reduce nitrate concentrations in their abstractions in SgZ	£95m - £115m yr^{-1}		

The research from the GAIN project can be translated into additional, innovative revenue streams for aquaculture resulting in a nutrient credit trading policy framework for Europe and could provide an evaluation of the water quality improvement services provided by commercially important bivalve species present in the EU waters, including blue mussels in the UK (Ferreira et al., 2020). The use of nutrient credit trading has been considered for the USA and implemented in some states (Ferreira et al., 2007b; Jones et al., 2010; Newell and Mann, 2012; Rose et al., 2015; Stephenson et al., 2010; Wheeler, 2020). It has the potential for profitable aquaculture ventures as well as in areas where bivalve cultivation might not be profitable on its own (Ritzenhofen et al., 2021). There, the economic value for bivalve aquaculture nitrogen removal was placed between £82,522 (current) and £318,299 (prospective) for oysters in the Great Bay Piscataqua (Bricker et al., 2020), with annual revenue between £439.92 to £9.82 million in Chesapeake Bay (Parker and Bricker, 2020) and £129 to £325 per kilogram of nitrogen annually at Greenwich Bay (USA) (Dvarskas et al., 2020). In the Long Island Sound, 1.3% of the nutrients entering the system could be removed by the present shellfish reefs, with avoided costs placed between £6.68 million and £180 million annually (Bricker et al. 2018). Mussel farming in Limfjorden (Denmark) provided avoided costs in the range of £1.34 million to £1.62 million (Filippelli et al., 2020) whilst in the Solent area (UK) Native oysters were estimated to have provided an annual bioextractive value of £37.44 million for nitrogen and £6.77 million for phosphorus (Watson et al., 2020). Moreover, there is also a consideration for the damage costs associated with nutrient enrichment and eutrophication (i.e.: reduced value of waterside dwellings and of the water bodies for commercial uses, losses for tourist industry and aquaculture etc.), placed at £82.52 million to £125.75 million annually for England and Wales (Pretty et al., 2003). Visibly, the valuation estimates are varied (Table 7) and show a vast range of magnitude. As such it is imperative to provide bioextraction and economic value analysis on a regionalised basis.

In the case of the UK, implementation of any nutrient credit trading (NCT) would be dependent on the availability of information on removal costs through methods currently available in specific regions. Moreover, due to the intricate dynamics of aquatic ecosystems and biochemical processes involved in nitrogen cycles, a national NCT would most likely be based on harvestable biomass such as the Chesapeake example (Ferreira and Bricker, 2019; Rose et al., 2021). However, the inclusion of processes such as denitrification and burial can be implemented on a regional, catchment basis using modelling approaches outlined in the GAIN framework (Ferreira and Bricker, 2019; Ferreira et al., 2020). Nevertheless, it still requires a comprehensive regulatory framework, encompassing credit calculations, monitoring protocols, and enforcement mechanisms, which demands the collaboration of governmental bodies, aquaculture operators and environmental advocates. Furthermore, fostering public awareness and acceptance is necessary to maintain interest in the food provisioning services of bivalves. It is crucial to ensure that consumers understand that bivalve nitrogen removal stands as a safe and reliable approach, assuring the suitability of these bivalves for eventual human consumption and does not in itself introduce concerns related to pollution through heavy metals or other contaminants. Once NCT frameworks in the UK take hold and encompass bivalve producers, the result would be the eco-intensification of existing sites, enhanced yields, improved profitability, and the generation of employment opportunities across the country with concomitant benefits for the ecosystem reaching through multiple industries and cultural services. It is important to note that any potential repayments for the removal of nitrogen or nutrients would be based on a least-cost comparison, rather than the range of avoided costs from different measures. Moreover, regional demand of the market and the availability of bivalve-related credits would factor into the final value of the nitrogen credit (Bricker et al., 2015, 2020b, 2018). Additionally, farmers should be aware that the repayments would not be equal to the saved costs, but rather a proportion of the costs saved from the least cost analysis.

Table 8: Summary of nitrogen removal valuations based on costs saved.

Nitrogen Removal Value	Location	Source
£82,522 - £318,299	Great Bay Piscataqua (USA)	Bricker et al., 2020
£439.92 - £9.82 million	Chesapeake Bay (USA)	Parker and Bricker, 2020
£1.34 million - £1.62 million	Limfjorden (Denmark)	Filippelli et al., 2020
£129 - £325 annually	Greenwich Bay (USA)	Dvarskas et al., 2020
£6.68 million - £180 million annually	Long Island Sound	Bricker et al., 2018
£37.44 million	Solent area (UK)	Watson et al., 2020

Conclusions

As nutrient enrichment and elemental imbalance promote eutrophication, bivalve bioextraction offers a promising nature-based solution to address this issue. While bivalves alone cannot mitigate nutrient pollution, they could play a critical role in removing nitrogen from the system, particularly in relation to the more challenging, non-point diffuse sources, such as agricultural or stormwater runoff. This bioremediation strategy has gained more academic attention, particularly in the last seven years, focused on the nitrogen and phosphorous balance. Oysters (*C. virginica*, *M. gigas*) and mussels (*M. edulis*) are the predominant study species, with clams and scallops contributing to a lesser extent. Modelling approaches have gained more popularity in the analyses of nutrient removal. Particularly the FARM model, which combines several biogeochemical, physical and growth models to provide eutrophication and financial benefits estimates.

Our analysis using the FARM model and proximate analysis provides encouraging results for the bioextraction potential of UK bivalves – 126.57 tonnes (285.77 - 362.46 tonnes; FARM) of nitrogen removed in 2019. This aligns with reviewed research, highlighting positive effects on water quality and net nutrient removal from the system. The range of provided estimates is wide, indicating the importance of site and species-specific variables. However, bivalve-mediated nutrient removal compared favourably with best management practices and stormwater treatment. Nitrogen removal cost assessments reveal substantial savings potential, ranging from £32,884 to £139 million (£74,300 and £398 million; FARM) based on the cost of alternatives such as improved catchment management, wastewater treatments and changes in agricultural land use.

Important aspects for consideration when estimating the removal capacity of shellfish farms are biochemical processes, denitrification, nitrification, biodeposition and excretion. These factors contribute to the net balance of nutrients removed and can tip the scale from positive to negative net removal. Research points to the stimulation of denitrification through bivalve presence, yet high densities and biodeposition can offset nutrient removal. The choice of the right cultivation method and location for the farm is imperative to offset the potential negative environmental effect of biodeposition, salinity and pathogen spread, in order to create a net positive nutrient removal effect. When considering frameworks for implementing bivalve bioremediation into market mechanics such as nutrient credit trading on a national scale, it will be important to focus on the quantifiable removal pathways such as removal via harvest whilst local management efforts should assist in estimating the potential of burying and denitrification removal.

As the UK remains in the top 20 global aquaculture producers for bivalves, it is well-positioned for research into bivalve bioextraction and nutrient credit trading. While bivalves alone cannot fully resolve the problem of excess nutrients, they are an integral part of a multifaceted approach, particularly in areas experiencing high nutrient influx and eutrophication. Bivalve bioremediation complements other strategies aimed at improving water quality and ecosystem health and offers additional benefits, such as habitat enhancement and carbon sequestration, which also build ecosystem resilience.

This research illustrates the potential of this bivalve nutrient management approach by quantifying the water quality benefits on a national scale. By recognising and harnessing the full capacity of bivalve ecosystem services, we can advance environmental sustainability and economic resilience while contributing to a sustainable food source. There is potential in using harvest removal estimates, followed by widely tested methods like the FARM model, for a more comprehensive understanding of site-specific nutrient removal capacity. Expanding this knowledge and financially evaluating nutrient bioextraction in the context of nutrient trading is necessary to fully realise the potential of the UK's shellfish sector. However, successful implementation hinges on robust regulations, stakeholder collaboration, and public awareness, fostering economic benefits and sustainable practices. Future work in this direction will require collaborating with aquaculture producers to perform case studies on individual farms across the nation and adapting the NCT schemes implemented around the globe to fit the unique socio-economic and environmental conditions of the UK.

References

AAC, 2023. AAC Recommendation on shellfish farming as a nitrogen sink. Aquaculture Advisory Council.

Alexander, T.J., Vonlanthen, P., Seehausen, O., 2017. Does eutrophication-driven evolution change aquatic ecosystems? Phil. Trans. R. Soc. B 372, 20160041. https://doi.org/10.1098/rstb.2016.0041

Aly, W., Williams, I.D., Hudson, M.D., 2013. Metal contamination in water, sediment and biota from a semi-enclosed coastal area. Environ Monit Assess 185, 3879–3895. https://doi.org/10.1007/s10661-012-2837-0

Axe, P., Clausen, U., Leujak, W., Malcolm, S., Harvey, E.T., 2017. Eutrophication status of the OSPAR maritime area. Third Integrated Report on the Eutrophication Status of the OSPAR Maritime Area.

Axe, P., Sonesten, L., Skarbövik, E., Leujak, W., Nielsen, L., 2022. Inputs of Nutrients to the OSPAR Maritime Area.In OSPAR, 2023: The 2023 Quality Status Report for the North-East Atlantic. OSPAR Commission, London.

Ayvazian, S.G., Ray, N.E., Gerber-Williams, A., Grabbert, S., Pimenta, A., Hancock, B., Cobb, D., Strobel, C., Fulweiler, R.W., 2022. Evaluating Connections Between Nitrogen Cycling and the Macrofauna in Native Oyster Beds in a New England Estuary. ESTUARIES AND COASTS 45, 196–212. https://doi.org/10.1007/s12237-021-00954-x

Baggett, L.P., Powers, S.P., Brumbaugh, R., Coen, L.D., DeAngelis, B., Greene, J., Hancock, B., Morlock, S., 2014. Oyster habitat restoration monitoring and assessment handbook The Nature Conservancy: Arlington. VA, USA.

Barrett, L.T., Theuerkauf, S.J., Rose, J.M., Alleway, H.K., Bricker, S.B., Parker, M., Petrolia, D.R., Jones, R.C., 2022. Sustainable growth of non-fed aquaculture can generate valuable ecosystem benefits. ECOSYSTEM SERVICES 53. https://doi.org/10.1016/j.ecoser.2021.101396

Bateman, D., Bishop, M., 2017. The environmental context and traits of habitat-forming bivalves influence the magnitude of their ecosystem engineering. Mar. Ecol. Prog. Ser. 563, 95–110. https://doi.org/10.3354/meps11959

Billen, G., Garnier, J., 2007. River basin nutrient delivery to the coastal sea: Assessing its potential to sustain new production of non-siliceous algae. Marine Chemistry 106, 148–160. https://doi.org/10.1016/j.marchem.2006.12.017

Bricker, S., Ferreira, J., Zhu, C., Rose, J.M., Galimany, E., Wikfors, G.H., 1954-, Saurel, C., Miller, R.L., Wands, J., Trowbridge, P., Grizzle, R.E., Wellman, K.F., Rheault, R.B., Steinberg, J., Jacob, A.P., Davenport, E.D., Ayvazian, S., Chintala, M., Tedesco, M.A., 2015. An ecosystem services assessment using bioextraction technologies for removal of nitrogen and other substances in Long Island Sound and the Great Bay/Piscataqua Region Estuaries. https://doi.org/10.25923/PW15-KX66

Bricker, S.B., Ferreira, J.G., Zhu, C., Rose, J.M., Galimany, E., Wikfors, G., Saurel, C., Miller, R.L., Wands, J., Trowbridge, P., Grizzle, R., Wellman, K., Rheault, R., Steinberg, J., Jacob, A., Davenport, E.D., Ayvazian, S., Chintala, M., Tedesco, M.A., 2018. Role of

Shellfish Aquaculture in the Reduction of Eutrophication in an Urban Estuary. Environ. Sci. Technol. 52, 173–183. https://doi.org/10.1021/acs.est.7b03970

Bricker, S.B., Grizzle, R.E., Trowbridge, P., Rose, J.M., Ferreira, J.G., Wellman, K., Zhu, C., Galimany, E., Wikfors, G.H., Saurel, C., Landeck Miller, R., Wands, J., Rheault, R., Steinberg, J., Jacob, A.P., Davenport, E.D., Ayvazian, S., Chintala, M., Tedesco, M.A., 2020a. Bioextractive Removal of Nitrogen by Oysters in Great Bay Piscataqua River Estuary, New Hampshire, USA. ESTUARIES AND COASTS 43, 23–38. https://doi.org/10.1007/s12237-019-00661-8

Bridger, D., Attrill, M.J., Davies, B.F.R., Holmes, L.A., Cartwright, A., Rees, S.E., Cabre, L.M., Sheehan, E.V., 2022. The restoration potential of offshore mussel farming on degraded seabed habitat. Aquaculture Fish & Fisheries 2, 437–449. https://doi.org/10.1002/aff2.77

Brink, C., Van Grinsven, H., Jacobsen, B.H., Rabl, A., Gren, I.-M., Holland, M., Klimont, Z., Hicks, K., Brouwer, R., Dickens, R., Willems, J., Termansen, M., Velthof, G., Alkemade, R., Van Oorschot, M., Webb, J., 2011. Costs and benefits of nitrogen in the environment, in: Sutton, M.A., Howard, C.M., Erisman, J.W., Billen, G., Bleeker, A., Grennfelt, P., Van Grinsven, H., Grizzetti, B. (Eds.), The European Nitrogen Assessment. Cambridge University Press, pp. 513–540. https://doi.org/10.1017/CBO9780511976988.025

Burkholder, J.M., Tomasko, D.A., Touchette, B.W., 2007. Seagrasses and eutrophication. Journal of Experimental Marine Biology and Ecology 350, 46–72. https://doi.org/10.1016/j.jembe.2007.06.024

Byers, J.E., 2002. Impact of non-indigenous species on natives enhanced by anthropogenic alteration of selection regimes. Oikos 97, 449–458. https://doi.org/10.1034/j.1600-0706.2002.970316.x

Caffrey, J.M., Hollibaugh, J.T., Mortazavi, B., 2016. Living oysters and their shells as sites of nitrification and denitrification. MARINE POLLUTION BULLETIN 112, 86–90. https://doi.org/10.1016/j.marpolbul.2016.08.038

Carmichael, R.H., Walton, W., Clark, H., 2012. Bivalve-enhanced nitrogen removal from coastal estuaries. CANADIAN JOURNAL OF FISHERIES AND AQUATIC SCIENCES 69, 1131–1149. https://doi.org/10.1139/F2012-057

Carpenter, S.R., 2008. Phosphorus control is critical to mitigating eutrophication. Proc. Natl. Acad. Sci. U.S.A. 105, 11039–11040. https://doi.org/10.1073/pnas.0806112105

Carpenter, S.R., Caraco, N.F., Correll, D.L., Howarth, R.W., Sharpley, A.N., Smith, V.H., 1998. NONPOINT POLLUTION OF SURFACE WATERS WITH PHOSPHORUS AND NITROGEN. Ecological Applications 8, 559–568. https://doi.org/10.1890/1051-0761(1998)008[0559:NPOSWW]2.0.CO;2

Cerco, C.F., 2015. A Multi-module Approach to Calculation of Oyster (Crassostrea virginica) Environmental Benefits. ENVIRONMENTAL MANAGEMENT 56, 467–479. https://doi.org/10.1007/s00267-015-0511-3

Christensen, P., Glud, R., Dalsgaard, T., Gillespie, P., 2003. Impacts of longline mussel farming on oxygen and nitrogen dynamics and biological communities of coastal sediments. AQUACULTURE 218, 567–588. https://doi.org/10.1016/S0044-8486(02)00587-2

Clements, J.C., Comeau, L.A., 2019. Nitrogen removal potential of shellfish aquaculture harvests in eastern Canada: A comparison of culture methods. AQUACULTURE REPORTS 13. https://doi.org/10.1016/j.aqrep.2019.100183

CMEMS, 2023. Copernicus Marine Data Store [WWW Document]. URL https://data.marine.copernicus.eu/products (accessed 11.23.23).

Critchell, K., Lambrechts, J., 2016. Modelling accumulation of marine plastics in the coastal zone; what are the dominant physical processes? Estuarine, Coastal and Shelf Science 171, 111–122. https://doi.org/10.1016/j.ecss.2016.01.036

Crown Estate Scotland, Maritek, 2019. Shellfish Critical Mass Development Plan Pilot - Clyde; WP 3: Development Planning Process Template.

Culhane, F., Teixeira, H., Nogueira, A.J.A., Borgwardt, F., Trauner, D., Lillebø, A., Piet, G., Kuemmerlen, M., McDonald, H., O'Higgins, T., Barbosa, A.L., van der Wal, J.T., Iglesias-Campos, A., Arevalo-Torres, J., Barbière, J., Robinson, L.A., 2019. Risk to the supply of ecosystem services across aquatic ecosystems. Science of The Total Environment 660, 611–621. https://doi.org/10.1016/j.scitotenv.2018.12.346

Defra, 2019. Marine strategy part one: UK updated assessment and Good Environmental Status. Department for Environment, Food & Rural Affairs.

DEFRA, 2012. Marine Strategy Part One: UK Initial Assessment and Good Environmental Status.

Diaz, R.J., Rosenberg, R., 2008. Spreading Dead Zones and Consequences for Marine Ecosystems. Science 321, 926–929. https://doi.org/10.1126/science.1156401

Dvarskas, A., Bricker, S.B., Wikfors, G.H., Bohorquez, J.J., Dixon, M.S., Rose, J.M., 2020. Quantification and Valuation of Nitrogen Removal Services Provided by Commercial Shellfish Aquaculture at the Subwatershed Scale. Environ. Sci. Technol. 54, 16156–16165. https://doi.org/10.1021/acs.est.0c03066

EA, 2023. Water Quality Archive; Open WIMS data [WWW Document]. URL https://environment.data.gov.uk/water-quality/view/landing (accessed 11.23.23).

Environment Agency, 2021. Nitrates: challenges for the water environment. Environment Agency.

Fang, P., Zedler, J.B., Donohoe, R.M., 1993. Nitrogen vs. phosphorus limitation of algal biomass in shallow coastal lagoons. Limnol. Oceanogr. 38, 906–923. https://doi.org/10.4319/lo.1993.38.5.0906

FAO, 2023. Global Aquaculture Production. Fisheries and Aquaculture Division [online].

Ferreira, J. G., Bricker, S.B., 2019. Assessment of Nutrient Trading Services from Bivalve Farming, in: Smaal, A.C., Ferreira, Joao G., Grant, J., Petersen, J.K., Strand, Ø. (Eds.), Goods and Services of Marine Bivalves. Springer International Publishing, Cham, pp. 551–584. https://doi.org/10.1007/978-3-319-96776-9_27

Ferreira, J.G., 2007. SMILE: sustainable mariculture in Northern Irish lough ecosystems. SMILE, Belfast.

Ferreira, J.G., 1995. ECOWIN — an object-oriented ecological model for aquatic ecosystems. Ecological Modelling 79, 21–34. https://doi.org/10.1016/0304-3800(94)00033-E

Ferreira, J.G., Bricker, S.B., 2016. Goods and services of extensive aquaculture: shellfish culture and nutrient trading. Aquacult Int 24, 803–825. https://doi.org/10.1007/s10499-015-9949-9

Ferreira, J.G., Camp, J., Garcés, E., 2010. Marine Strategy Framework Directive: A tool for eutrophication assessment and management in marine waters.

Ferreira, J.G., Cubillo, A.M., Lopes, A.S., Marteleira, R., Service, M., Moore, H., Cromie, H., Bricker, S.B., 2020. GAIN D2.9 – Report & white paper on framework for a nutrient credit trading policy for Europe, integrating shellfish producers. Deliverable 2.9. GAIN - Green Aquaculture INtensification in Europe. EU Horizon 2020 project grant nº. 773330.

Ferreira, J.G., Hawkins, A., Bricker, S.B., 2007a. Farm-scale assessment of shellfish aquaculture in coastal systems—the Farm Aquaculture Resource Management (FARM) model. AQUACULTURE 264, 160–174.

Ferreira, J.G., Hawkins, A.J.S., Bricker, S.B., 2007b. Management of productivity, environmental effects and profitability of shellfish aquaculture — the Farm Aquaculture Resource Management (FARM) model. Aquaculture 264, 160–174. https://doi.org/10.1016/j.aquaculture.2006.12.017

Ferreira, J.G., Hawkins, A.J.S., Monteiro, P., Moore, H., Service, M., Pascoe, P.L., Ramos, L., Sequeira, A., 2008. Integrated assessment of ecosystem-scale carrying capacity in shellfish growing areas. Aquaculture 275, 138–151. https://doi.org/10.1016/j.aquaculture.2007.12.018

Ferreira, J.G., Saurel, C., Ferreira, J.M., 2012. Cultivation of gilthead bream in monoculture and integrated multi-trophic aquaculture. Analysis of production and environmental effects by means of the FARM model. Aquaculture 358–359, 23–34. https://doi.org/10.1016/j.aquaculture.2012.06.015

Ferreira, J.G., Saurel, C., Lencart E Silva, J.D., Nunes, J.P., Vazquez, F., 2014. Modelling of interactions between inshore and offshore aquaculture. Aquaculture 426–427, 154–164. https://doi.org/10.1016/j.aquaculture.2014.01.030

Filippelli, R., Termansen, M., Hasler, B., Timmermann, K., Petersen, J.K., 2020. Cost-effectiveness of mussel farming as a water quality improvement measure: Agricultural, environmental and market drivers. WATER RESOURCES AND ECONOMICS 32. https://doi.org/10.1016/j.wre.2020.100168

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. https://doi.org/10.1007/s10533-010-9475-9

Forsberg, C., 1976. Nitrogen and Phosphorus as Algal Growth-Limiting Nutrients in Waste-Receiving Waters, in: Devik, O. (Ed.), Harvesting Polluted Waters. Springer US, Boston, MA, pp. 27–38. https://doi.org/10.1007/978-1-4613-4328-8_3

Gallardi, D., 2014. Effects of Bivalve Aquaculture on the Environment and Their Possible Mitigation: A Review. Fish Aquac J 05. https://doi.org/10.4172/2150-3508.1000105

Goldman, J.C., Tenore, K.R., Ryther, J.H., Corwin, N., 1974. Inorganic nitrogen removal in a combined tertiary treatment—marine aquaculture system—I. Removal efficiences. Water Research 8, 45–54. https://doi.org/10.1016/0043-1354(74)90007-4

Golen, R.F., 2007. Incorporating Shellfish Bed Restoration into a Nitrogen TMDL Implementation Plan. proc water environ fed 2007, 1056–1068. https://doi.org/10.2175/193864707786619305

Gren, I.-M., 2019. The economic value of mussel farming for uncertain nutrient removal in the Baltic Sea. PLOS ONE 14. https://doi.org/10.1371/journal.pone.0218023

Grizzetti, B., Lanzanova, D., Liquete, C., Reynaud, A., Cardoso, A.C., 2016. Assessing water ecosystem services for water resource management. Environmental Science & Policy 61, 194–203. https://doi.org/10.1016/j.envsci.2016.04.008

Haamer, J., 1996. Improving water quality in a eutrophied fjord system with mussel farming. AMBIO 25, 356–362.

Han, Q., Liu, D., 2014. Macroalgae blooms and their effects on seagrass ecosystems. J. Ocean Univ. China 13, 791–798. https://doi.org/10.1007/s11802-014-2471-2

Higgins, C.B., Tobias, C., Piehler, M.F., Smyth, A.R., Dame, R.F., Stephenson, K., Brown, B.L., 2013. Effect of aquacultured oyster biodeposition on sediment N-2 production in Chesapeake Bay\. MARINE ECOLOGY PROGRESS SERIES 473, 7-+. https://doi.org/10.3354/meps10062

Holmer, M., Thorsen, S.W., Carlsson, M.S., Kjerulf, P.J., 2015. Pelagic and Benthic Nutrient Regeneration Processes in Mussel Cultures (Mytilus edulis) in a Eutrophic Coastal Area (Skive Fjord, Denmark). ESTUARIES AND COASTS 38, 1629–1641. https://doi.org/10.1007/s12237-014-9864-8

Howarth, R., Chan, F., Conley, D.J., Garnier, J., Doney, S.C., Marino, R., Billen, G., 2011. Coupled biogeochemical cycles: eutrophication and hypoxia in temperate estuaries and coastal marine ecosystems. Frontiers in Ecology and the Environment 9, 18–26. https://doi.org/10.1890/100008

Hughes, A.D., 2021. Defining Nature-Based Solutions Within the Blue Economy: The Example of Aquaculture. Front. Mar. Sci. 8, 711443. https://doi.org/10.3389/fmars.2021.711443

Jennings, S., Stentiford, G.D., Leocadio, A.M., Jeffery, K.R., Metcalfe, J.D., Katsiadaki, I., Auchterlonie, N.A., Mangi, S.C., Pinnegar, J.K., Ellis, T., Peeler, E.J., Luisetti, T., Baker-Austin, C., Brown, M., Catchpole, T.L., Clyne, F.J., Dye, S.R., Edmonds, N.J., Hyder, K., Lee, J., Lees, D.N., Morgan, O.C., O'Brien, C.M., Oidtmann, B., Posen, P.E., Santos, A.R., Taylor, N.G.H., Turner, A.D., Townhill, B.L., Verner-Jeffreys, D.W., 2016. Aquatic food security: insights into challenges and solutions from an analysis of interactions between fisheries, aquaculture, food safety, human health, fish and human welfare, economy and environment. Fish Fish 17, 893–938. https://doi.org/10.1111/faf.12152

Jones, C., Branosky, E., Selman, M., Perez, M., 2010. How Nutrient Trading Could Help Restore the Chesapeake Bay.

Kaspar, H., 2014. A multi-species shellfish hatchery as a key asset for the development of Scotland's shellfish aquaculture industry and the restoration of native oyster reefs.

Kotta, J., Futter, M., Kaasik, A., Liversage, K., Ratsep, M., Barboza, F.R., Bergstrom, L., Bergstrom, P., Bobsien, I., Diaz, E., Herkul, K., Jonsson, P.R., Korpinen, S., Kraufvelin, P., Krost, P., Lindahl, O., Lindegarth, M., Lyngsgaard, M.M., Muhl, M., Sandman, A.N., Orav-Kotta, H., Orlova, M., Skov, H., Rissanen, J., Siaulys, A., Vidakovic, A., Virtanen, E., 2020. Cleaning up seas using blue growth initiatives: Mussel farming for eutrophication control in the Baltic Sea. SCIENCE OF THE TOTAL ENVIRONMENT 709. https://doi.org/10.1016/j.scitotenv.2019.136144

Lee, C.H., Lee, D.K., Ali, M.A., Kim, P.J., 2008. Effects of oyster shell on soil chemical and biological properties and cabbage productivity as a liming materials. Waste Management 28, 2702–2708. https://doi.org/10.1016/j.wasman.2007.12.005

Lillebø, A.I., Pita, C., Garcia Rodrigues, J., Ramos, S., Villasante, S., 2017. How can marine ecosystem services support the Blue Growth agenda? Marine Policy 81, 132–142. https://doi.org/10.1016/j.marpol.2017.03.008

Lindahl, O., Hart, R., Hernroth, B., Kollberg, S., Loo, L., Olrog, L., Rehnstam-Holm, A., Svensson, J., Svensson, S., Syversen, U., 2005. Improving marine water quality by mussel farming: A profitable solution for Swedish society. AMBIO 34, 131–138. https://doi.org/10.1639/0044-7447(2005)034[0131:IMWQBM]2.0.CO;2

Liu, M., Wang, Z., Zhang, G., 2021. Nitrogen removal through oyster cultivation: Integration with artificial fertilization makes it more efficient. SCIENCE OF THE TOTAL ENVIRONMENT 792. https://doi.org/10.1016/j.scitotenv.2021.148057

Mackie, G., 1994. Ability of the zebra mussel, Dreissena polymorpha to biodeposit and remove phosphorus and bod from diluted activated sewage sludge. Water Research 28, 1123–1130. https://doi.org/10.1016/0043-1354(94)90199-6

Maier, G., Nimmo-Smith, R.J., Glegg, G.A., Tappin, A.D., Worsfold, P.J., 2009. Estuarine eutrophication in the UK: current incidence and future trends. Aquatic Conserv: Mar. Freshw. Ecosyst. 19, 43–56. https://doi.org/10.1002/aqc.982

Malone, T.C., Conley, D.J., Fisher, T.R., Glibert, P.M., Harding, L.W., Sellner, K.G., 1996. Scales of Nutrient-Limited Phytoplankton Productivity in Chesapeake Bay. Estuaries 19, 371. https://doi.org/10.2307/1352457

Mascorda-Cabre, L., Hosegood, P., Attrill, M.J., Bridger, D., Sheehan, E.V., 2023. Detecting sediment recovery below an offshore longline mussel farm: A macrobenthic Biological Trait Analysis (BTA). Marine Pollution Bulletin 195, 115556. https://doi.org/10.1016/j.marpolbul.2023.115556

McLaughlan, C., Rose, P., Aldridge, D.C., 2014. Making the Best of a Pest: The Potential for Using Invasive Zebra Mussel (Dreissena Polymorpha) Biomass as a Supplement to Commercial Chicken Feed. Environmental Management 54, 1102–1109. https://doi.org/10.1007/s00267-014-0335-6

McLeod, I.M., zu Ermgassen, P.S.E., Gillies, C.L., Hancock, B., Humphries, A., 2019. Can Bivalve Habitat Restoration Improve Degraded Estuaries?, in: Coasts and Estuaries. Elsevier, pp. 427–442. https://doi.org/10.1016/B978-0-12-814003-1.00025-3

MMO, 2019. Identification of Areas of Aquaculture Potential in English Waters, A report produced for the Marine Management Organisation by Centre for Environment Fisheries and Aquaculture Science, MMO Project No: 1184.

Mykoniatis, N., Ready, R., 2020. The potential contribution of oyster management to water quality goals in the Chesapeake Bay. WATER RESOURCES AND ECONOMICS 32. https://doi.org/10.1016/j.wre.2020.100167

Nagel, F., von Danwitz, A., Schlachter, M., Kroeckel, S., Wagner, C., Schulz, C., 2014. Blue mussel meal as feed attractant in rapeseed protein-based diets for turbot (*Psetta maxima* L.). Aquac Res 45, 1964–1978. https://doi.org/10.1111/are.12140

Nanou, G., Peter, B., Elisabeth, D., Klaas, D., Thibaud, M., Alexia, S., Tomas, S., Gert, V.H., 2022. Nature-based solutions in a sandy foreshore: A biological assessment of a longline mussel aquaculture technique to establish subtidal reefs. Ecological Engineering 185, 106807. https://doi.org/10.1016/j.ecoleng.2022.106807

NatureScot, 2023. Native oyster [WWW Document]. NatureScot. URL https://www.nature.scot/plants-animals-and-fungi/invertebrates/marine-invertebrates/native-oyster (accessed 9.15.23).

Neves, R.A.F., Naveira, C., Miyahira, I.C., Portugal, S.G.M., Krepsky, N., Santos, L.N., 2020. Are invasive species always negative to aquatic ecosystem services? The role of dark false mussel for water quality improvement in a multi-impacted urban coastal lagoon. WATER RESEARCH 184. https://doi.org/10.1016/j.watres.2020.116108

Newell, R., Mann, R., 2012. Shellfish aquaculture: ecosystem effects, benthic-pelagic coupling and potential for nutrient trading, Report to the Secretary of Natural Resources, Commonwealth of Virginia, June 21.

Nobre, A.M., Ferreira, J.G., Nunes, J.P., Yan, X., Bricker, S., Corner, R., Groom, S., Gu, H., Hawkins, A.J.S., Hutson, R., Lan, D., Lencart e Silva, J.D., Pascoe, P., Telfer, T., Zhang, X., Zhu, M., 2010. Assessment of coastal management options by means of multilayered ecosystem models. ESTUARINE COASTAL AND SHELF SCIENCE 87, 43–62. https://doi.org/10.1016/j.ecss.2009.12.013

O'Higgins, T.G., Gilbert, A.J., 2014. Embedding ecosystem services into the Marine Strategy Framework Directive: Illustrated by eutrophication in the North Sea. Estuarine, Coastal and Shelf Science 140, 146–152. https://doi.org/10.1016/j.ecss.2013.10.005

Olivier, A. van der S., Jones, L., Le Vay, L., Christie, M., Wilson, J., Malham, S.K., 2020. A global review of the ecosystem services provided by bivalve aquaculture. REVIEWS IN AQUACULTURE 12, 3–25. https://doi.org/10.1111/raq.12301

Olivier, A. van der S., Le Vay, L., Malham, S.K., Christie, M., Wilson, J., Allender, S., Schmidlin, S., Brewin, J.M., Jones, L., 2021. Geographical variation in the carbon, nitrogen, and phosphorus content of blue mussels, Mytilus edulis. MARINE POLLUTION BULLETIN 167. https://doi.org/10.1016/j.marpolbul.2021.112291

Onorevole, K.M., Thompson, S.P., Piehler, M.F., 2018. Living shorelines enhance nitrogen removal capacity over time. ECOLOGICAL ENGINEERING 120, 238–248. https://doi.org/10.1016/j.ecoleng.2018.05.017

ONS, 2022. Environmental protection expenditure, UK. Office for National Statistics.

ONS, 2021. Marine accounts, natural capital, UK, Marine accounts, natural capital, UK – Office for National Statistics. Office for National Statistics.

OSPAR, 2023. Riverine Inputs and Direct Discharges (RID) [WWW Document]. OSPAR Commission. URL https://www.ospar.org/work-areas/hasec/hazardous-substances/rid (accessed 11.22.23).

Painting, S.J., Collingridge, K., Garcia, L., Barry, J., Leaf, S., Best, M., Miles, A., McAliskey, M., Charlesworth, M., Haines, L., Fryer, R., Walsham, P., Webster, L., Bresnan, E., Roberts, A., Scanlan, C., Engelke, C., 2018. Nutrient inputs in water and air. UK Marine Online Assessment Tool.

Parker, M., Bricker, S., 2020. SUSTAINABLE OYSTER AQUACULTURE, WATER QUALITY IMPROVEMENT, AND ECOSYSTEM SERVICE VALUE POTENTIAL IN MARYLAND CHESAPEAKE BAY. JOURNAL OF SHELLFISH RESEARCH 39, 269–281. https://doi.org/10.2983/035.039.0208

Pedersen, M., Borum, J., 1996. Nutrient control of algal growth in estuarine waters. Nutrient limitation and the importance of nitrogen requirements and nitrogen storage among phytoplankton and species of macroalgae. Mar. Ecol. Prog. Ser. 142, 261–272. https://doi.org/10.3354/meps142261

Petersen, J.K., Hasler, B., Timmermann, K., Nielsen, P., Tørring, D.B., Larsen, M.M., Holmer, M., 2014. Mussels as a tool for mitigation of nutrients in the marine environment. Marine Pollution Bulletin 82, 137–143. https://doi.org/10.1016/j.marpolbul.2014.03.006

Petersen, J.K., Timmermann, K., Carlsson, M., Holmer, M., Maar, M., Lindahl, O., 2012. Mussel farming can be used as a mitigation tool - A reply. MARINE POLLUTION BULLETIN 64, 452–454. https://doi.org/10.1016/j.marpolbul.2011.11.027

Poikane, S., Kelly, M.G., Salas Herrero, F., Pitt, J.-A., Jarvie, H.P., Claussen, U., Leujak, W., Lyche Solheim, A., Teixeira, H., Phillips, G., 2019. Nutrient criteria for surface waters under the European Water Framework Directive: Current state-of-the-art, challenges and future outlook. Science of The Total Environment 695, 133888. https://doi.org/10.1016/j.scitotenv.2019.133888

Pradeepkiran, J.A., 2019. Aquaculture role in global food security with nutritional value: a review. Translational Animal Science 3, 903–910. https://doi.org/10.1093/tas/txz012

Preston, J., Gamble, C., Debney, A., Helmer, L., Hancock, B., Zu Ermgassen, P.S., 2020. European Native Oyster Habitat Restoration Handbook. UK & Ireland. The Zoological Society of London, London.

Pretty, J.N., Mason, C.F., Nedwell, D.B., Hine, R.E., Leaf, S., Dils, R., 2003. Environmental Costs of Freshwater Eutrophication in England and Wales. Environ. Sci. Technol. 37, 201–208. https://doi.org/10.1021/es020793k

R Core Team, 2023. R: A language and environment for statistical computing. R Foundation for Statistical Computing.

Ray, N.E., Fulweiler, R.W., 2021. Meta-analysis of oyster impacts on coastal biogeochemistry. NATURE SUSTAINABILITY 4, 261–269. https://doi.org/10.1038/s41893-020-00644-9

Ritzenhofen, L., Buer, A.-L., Gyraite, G., Dahlke, S., Klemmstein, A., Schernewski, G., 2021. Blue mussel (Mytilus spp.) cultivation in mesohaline eutrophied inner coastal waters: mitigation potential, threats and cost effectiveness. PEERJ 9. https://doi.org/10.7717/peerj.11247

Romero, E., Garnier, J., Lassaletta, L., Billen, G., Le Gendre, R., Riou, P., Cugier, P., 2013. Large-scale patterns of river inputs in southwestern Europe: seasonal and interannual variations and potential eutrophication effects at the coastal zone. Biogeochemistry 113, 481–505. https://doi.org/10.1007/s10533-012-9778-0

Rose, J.M., Bricker, S.B., Ferreira, J.G., 2015. Comparative analysis of modeled nitrogen removal by shellfish farms. Marine Pollution Bulletin 91, 185–190. https://doi.org/10.1016/j.marpolbul.2014.12.006

Rose, J.M., Gosnell, J.S., Bricker, S., Brush, M.J., Colden, A., Harris, L., Karplus, E., Laferriere, A., Merrill, N.H., Murphy, T.B., Reitsma, J., Shockley, J., Stephenson, K., Theuerkauf, S., Ward, D., Fulweiler, R.W., 2021. Opportunities and Challenges for Including Oyster-Mediated Denitrification in Nitrogen Management Plans. Estuaries and Coasts 44, 2041–2055. https://doi.org/10.1007/s12237-021-00936-z

Ryther, J.H., Dunstan, W.M., 1971. Nitrogen, Phosphorus, and Eutrophication in the Coastal Marine Environment. Science 171, 1008–1013. https://doi.org/10.1126/science.171.3975.1008

Saurel, C., Ferreira, J., Cheney, D., Suhrbier, A., Dewey, B., Davis, J., Cordell, J., 2014. Ecosystem goods and services from Manila clam culture in Puget Sound: a modelling analysis. Aquacult. Environ. Interact. 5, 255–270. https://doi.org/10.3354/aei00109

Schindler, D.W., Hecky, R.E., Findlay, D.L., Stainton, M.P., Parker, B.R., Paterson, M.J., Beaty, K.G., Lyng, M., Kasian, S.E.M., 2008. Eutrophication of lakes cannot be controlled by reducing nitrogen input: Results of a 37-year whole-ecosystem experiment. Proc. Natl. Acad. Sci. U.S.A. 105, 11254–11258. https://doi.org/10.1073/pnas.0805108105

Scottish Government, M.D., 2023. Scottish Shellfish Farm Production Survey Data. https://doi.org/10.7489/1917-2

Sea, M.A., Thrush, S.F., Hillman, J.R., 2021. Environmental predictors of sediment denitrification rates within restored green-lipped mussel Perna canaliculus beds. MARINE ECOLOGY PROGRESS SERIES 667, 1–13. https://doi.org/10.3354/meps13727

Seafish, 2024. Bivalve Mollusc Safety [WWW Document]. Seafish. URL https://www.seafish.org/trade-and-regulation/regulation-in-aquaculture/delivering-safe-bivalves-to-the-market/ (accessed 4.8.24).

Seafish, 2023a. Aquatic profiles - Mussels [WWW Document]. Seafish. URL https://www.seafish.org/responsible-sourcing/aquaculture-farming-seafood/species-farmed-in-aquaculture/aquaculture-profiles/mussels/sources-quantities-and-cultivation-methods/ (accessed 1.9.23).

Seafish, 2023b. Aquatic profiles - Oysters [WWW Document]. Seafish. URL https://www.seafish.org/responsible-sourcing/aquaculture-farming-seafood/species-farmed-in-aquaculture/aquaculture-profiles/oysters/escapes-and-introductions/ (accessed 1.9.23).

Sequeira, A., Ferreira, J.G., Hawkins, A.J.S., Nobre, A., Lourenço, P., Zhang, X.L., Yan, X., Nickell, T., 2008. Trade-offs between shellfish aquaculture and benthic biodiversity: A modelling approach for sustainable management. Aquaculture 274, 313–328. https://doi.org/10.1016/j.aquaculture.2007.10.054

Sheehan, E.V., Bridger, D., Mascorda Cabre, L., Cartwright, A., Cox, D., Rees, S., Holmes, L., Pittman, S.J., 2019. Bivalves boost biodiversity. Food Science and Technology 33, 18–21.

Silva, C., Yanez, E., Martin-Diaz, M.L., DelValls, T.A., 2012. Assessing a bioremediation strategy in a shallow coastal system affected by a fish farm culture - Application of GIS and shellfish dynamic models in the Rio San Pedro, SW Spain. MARINE POLLUTION BULLETIN 64, 751–765. https://doi.org/10.1016/j.marpolbul.2012.01.019

Silvert, W., 1993. Object-oriented ecosystem modelling. Ecological Modelling 68, 91–118. https://doi.org/10.1016/0304-3800(93)90110-E

Smaal, A.C., Ferreira, J.G., Grant, J., Petersen, J.K., Strand, Ø. (Eds.), 2019. Goods and Services of Marine Bivalves. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-96776-9

Smyth, A.R., Geraldi, N.R., Thompson, S.P., Piehler, M.F., 2016. Biological activity exceeds biogenic structure in influencing sediment nitrogen cycling in experimental oyster reefs. MARINE ECOLOGY PROGRESS SERIES 560, 173–183. https://doi.org/10.3354/meps11922

Smyth, A.R., Piehler, M.F., Grabowski, J.H., 2015. Habitat context influences nitrogen removal by restored oyster reefs. JOURNAL OF APPLIED ECOLOGY 52, 716–725. https://doi.org/10.1111/1365-2664.12435

Sousa, R., Gutiérrez, J.L., Aldridge, D.C., 2009. Non-indigenous invasive bivalves as ecosystem engineers. Biol Invasions 11, 2367–2385. https://doi.org/10.1007/s10530-009-9422-7

Spångberg, J., Jönsson, H., Tidåker, P., 2013. Bringing nutrients from sea to land – mussels as fertiliser from a life cycle perspective. Journal of Cleaner Production 51, 234–244. https://doi.org/10.1016/j.jclepro.2013.01.011

Stephenson, K., Aultman, S., Metcalfe, T., Miller, A., 2010. An evaluation of nutrient nonpoint offset trading in Virginia: A role for agricultural nonpoint sources?: EVALUATION OF NUTRIENT NONPOINT OFFSET TRADING. Water Resour. Res. 46. https://doi.org/10.1029/2009WR008228

Summa, D., Lanzoni, M., Castaldelli, G., Fano, E.A., Tamburini, E., 2022. Trends and Opportunities of Bivalve Shells' Waste Valorization in a Prospect of Circular Blue Bioeconomy. Resources 11, 48. https://doi.org/10.3390/resources11050048

Thomsen, J., Himmerkus, N., Holland, N., Sartoris, F.J., Bleich, M., Tresguerres, M., 2016. Ammonia excretion in mytilid mussels is facilitated by ciliary beating. Journal of Experimental Biology 219, 2300–2310. https://doi.org/10.1242/jeb.139550

van der Heide, M.E., Johansen, N.F., Kidmose, U., Nørgaard, J.V., Hammershøj, M., 2021. The effect of deshelled and shell-reduced mussel meal on egg quality parameters of organic laying hens under commercial conditions. Journal of Applied Poultry Research 30, 100119. https://doi.org/10.1016/j.japr.2020.100119

Vaughn, C.C., Hoellein, T.J., 2018. Bivalve Impacts in Freshwater and Marine Ecosystems, in: Futuyma, D. (Ed.), ANNUAL REVIEW OF ECOLOGY, EVOLUTION, AND SYSTEMATICS, VOL 49. pp. 183–208. https://doi.org/10.1146/annurev-ecolsys-110617-062703

Waldbusser, G.G., Hales, B., Langdon, C.J., Haley, B.A., Schrader, P., Brunner, E.L., Gray, M.W., Miller, C.A., Gimenez, I., Hutchinson, G., 2015. Ocean Acidification Has Multiple Modes of Action on Bivalve Larvae. PLoS ONE 10, e0128376. https://doi.org/10.1371/journal.pone.0128376

Watson, S.C., Preston, J., Beaumont, N.J., Watson, G.J., 2020. Assessing the natural capital value of water quality and climate regulation in temperate marine systems using a EUNIS biotope classification approach. SCIENCE OF THE TOTAL ENVIRONMENT 744. https://doi.org/10.1016/j.scitotenv.2020.140688

Watson, S.C.L., Watson, G.J., Mellan, J., Sykes, T., Lines, C., Preston, J., 2020. Valuing the Solent Marine Sites Habitats and Species: A Natural Capital Study of Benthic Ecosystem Services and how they Contribute to Water Quality Regulation (Environment Agency R&D Technical Report No. ENV6003066R).

Weihrauch, D., Allen, G.J.P., 2018. Ammonia excretion in aquatic invertebrates: new insights and questions. Journal of Experimental Biology 221, jeb169219. https://doi.org/10.1242/jeb.169219

Westbrook, P., Heffner, L., La Peyre, M.K., 2019. Measuring carbon and nitrogen bioassimilation, burial, and denitrification contributions of oyster reefs in Gulf coast estuaries. MARINE BIOLOGY 166. https://doi.org/10.1007/s00227-018-3449-1

Wheeler, T.B., 2020. Oyster growers hope polluters will shell out for nutrient credits [WWW Document]. Bay Journal. URL https://www.bayjournal.com/news/fisheries/oyster-growers-hope-polluters-will-shell-out-for-nutrient-credits/article_d5d4abac-8e1e-11ea-be85-8f3b710e121b.html (accessed 11.21.23).

Wijsman, J.W.M., Troost, K., Fang, J., Roncarati, A., 2019. Global Production of Marine Bivalves. Trends and Challenges, in: Smaal, A.C., Ferreira, J.G., Grant, J., Petersen, J.K., Strand, Ø. (Eds.), Goods and Services of Marine Bivalves. Springer International Publishing, Cham, pp. 7–26. https://doi.org/10.1007/978-3-319-96776-9_2

Worrall, F., Burt, T.P., 2001. Inter-annual controls on nitrate export from an agricultural catchment — how much land-use change is safe? Journal of Hydrology 243, 228–241. https://doi.org/10.1016/S0022-1694(00)00411-X

Yao, Z., Xia, M., Li, H., Chen, T., Ye, Y., Zheng, H., 2014. Bivalve Shell: Not an Abundant Useless Waste but a Functional and Versatile Biomaterial. Critical Reviews in

Environmental Science and Technology 44, 2502–2530. https://doi.org/10.1080/10643389.2013.829763

Yu, L., Gan, J., 2021. Mitigation of Eutrophication and Hypoxia through Oyster Aquaculture: An Ecosystem Model Evaluation off the Pearl River Estuary. ENVIRONMENTAL SCIENCE & TECHNOLOGY 55, 5506–5514. https://doi.org/10.1021/acs.est.0c06616

Zan Xiaoxiao, Xu Binduo, Zhang Chongliang, Ren Yiping, 2014. Annual Variations of Biogenic Element Contents of Manila Clam (Ruditapes philippinarum) Bottom-Cultivated in Jiaozhou Bay, China. JOURNAL OF OCEAN UNIVERSITY OF CHINA 13, 637–646. https://doi.org/10.1007/s11802-014-2140-5

Zhu, L., Huguenard, K., Zou, Q.-P., Fredriksson, D.W., Xie, D., 2020. Aquaculture farms as nature-based coastal protection: Random wave attenuation by suspended and submerged canopies. Coastal Engineering 160, 103737. https://doi.org/10.1016/j.coastaleng.2020.103737

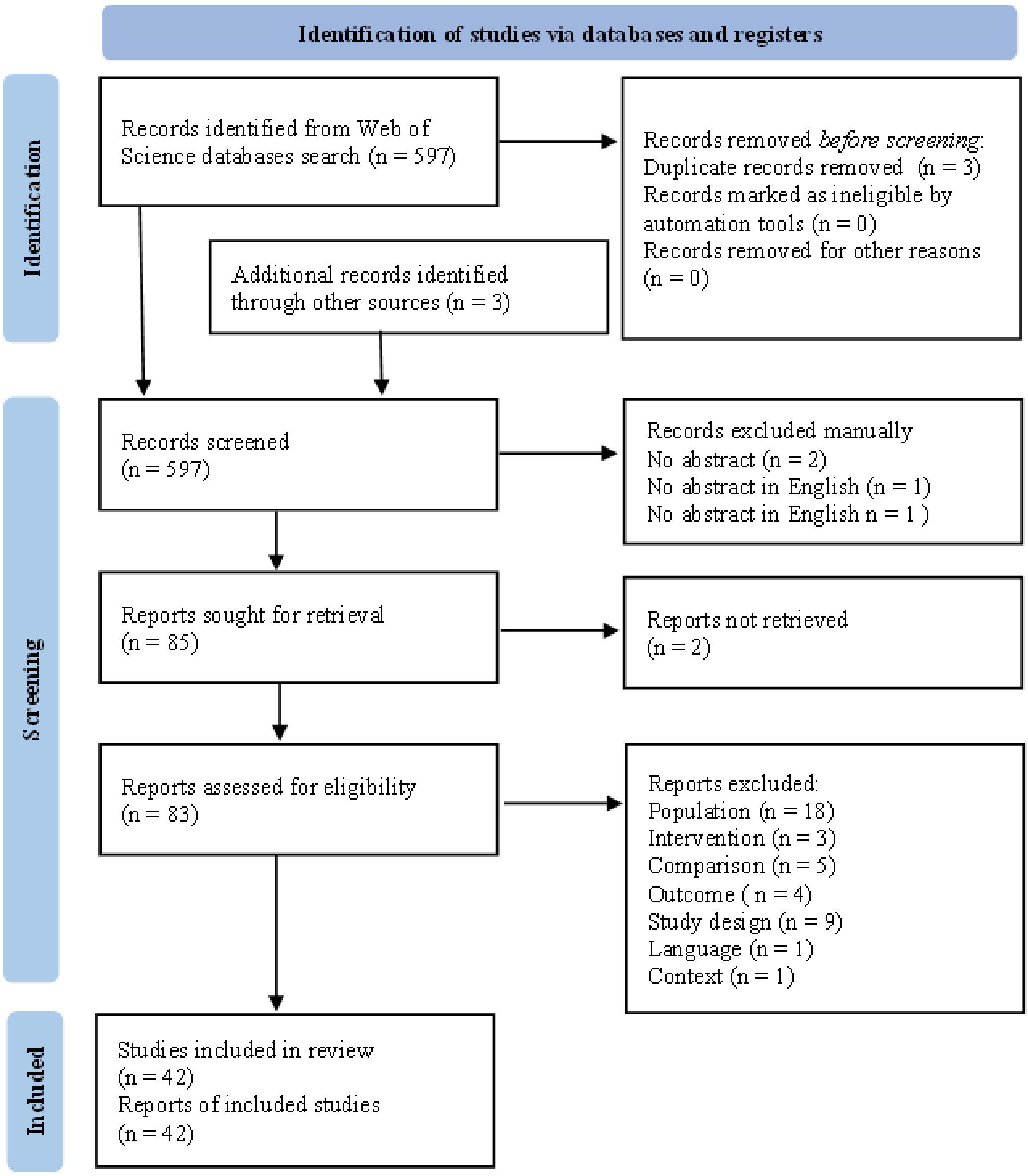
Zu Ermgassen, P.S., Bos, O.G., Debney, A., Gamble, C., Glover, A., Pogoda, B., Pouvreau, S., Sanderson, W.G., Smyth, D., Preston, J., 2020. European native oyster habitat restoration monitoring handbook. The Zoological Society of London.

zu Ermgassen, P.S.E., Thurstan, R.H., Corrales, J., Alleway, H., Carranza, A., Dankers, N., DeAngelis, B., Hancock, B., Kent, F., McLeod, I., Pogoda, B., Liu, Q., Sanderson, W.G., 2020. The benefits of bivalve reef restoration: A global synthesis of underrepresented species. Aquatic Conserv: Mar Freshw Ecosyst 30, 2050–2065. https://doi.org/10.1002/aqc.3410

Appendices

Appendix 1 – Literature Review methodology expanded

Database creation



Appendix 1 Figure 1: Diagram of the review process: search, screening, and full-text assessment. Steps followed were based on the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) reporting protocol.

Eligibility criteria

For the eligibility of the article, screening had to identify the following points of interest:

Population: Focus on (non-freshwater) bivalves, preferably with current or potential commercial aquaculture use. No species-specific limitation was imposed to provide a comprehensive overview of bivalve capabilities, regardless of cultural, commercial, or environmental importance which is not constant through time.

Issue: Research nutrient removal capabilities of bivalves as a part of field or laboratory study.

> If it was not immediately clear based on the title or abstract if the paper investigated nutrient removal or for example other aspects of water quality, the publication was retained for full-text analysis.

Comparator: Compare the effect of bivalve-mediated water quality improvement.

Outcome: Investigate the effects of bivalve-mediated nutrient removal on water quality indicators (direct nutrient content, Chl a concentration, phytoplankton concentration etc.).

Context (aquatic): Concentrate on bivalve presence in marine and brackish waters.

> If the species is freshwater but its presence has been recorded and investigated in the context of marine or brackish habitat, the article was retained for full-text analysis and could be included in the review.

Study design: Must be an English-language, peer-reviewed, primary data publication (reviews and meta-analyses excluded). If it was not immediately clear based on the title or abstract if the paper was a review or primary study, it was retained for full-text analysis.

Data extraction and analysis

The study information included but was not limited to, geographic specifications relevant to the research, type of study conducted (field or lab experiment, modelling) and elements of the PICO inquiry: aquatic setting investigated, species or organism group, issue addressed, effect measurement approach and observed outcome. Studies covering the analysis of more than one species or species group (hereafter combined articles) were treated as separate instances for the analysis. When a specific site was not given by the authors, the study was assigned to the 'Unspecified' category. The issue and outcome data were extracted and categorised based on information sourced from literature reviews published in the field. The study data and bibliographic information from articles retained after the full-text screening were extracted, with a focus on the issue addressed and observed or predicted results based on fieldwork, laboratory experiments or simulation. Extracted research data and publication information were analysed and visualised using RStuido software (R Core Team, 2023). The process and analysis are reported following PRISMA.

Appendix 2 – FARM input data

Appendix 2 Table 1: General information on culture practice for the typical UK shellfish farms across different species. The data were used as a basis to parameterise FARM models for all the species-country combinations in addition to environmental drivers that were specific to each country within the UK.

	Species	Blue mussel	Pacific oyster	Native oyster	Manila clam
Shellfish culture practice	Stocking density (indiv./m^2)	350	75	100	600
Farm layout	Cultivation method	Longlines, bottom	Bottom	Bottom	Bottom
Shellfish cultivation	Mortality (%)	10	20	30	20
	Culture period (days)	1120	700	1500	1220
	Harvest weight (g)	20	80	90	17

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