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Aquaculture & Good Environmental Status: Assessing Impacts in England & Northern Ireland

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Date:
20/03/2025

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Executive Summary

Aquaculture plays an increasingly significant role in global seafood production, now supplying over half of the world's aquatic food. In England and Northern Ireland, the sector is primarily focused on shellfish farming, with growing interest in seaweed cultivation. Unlike Scotland, where large-scale salmon farming dominates, aquaculture in these areas operates on a smaller scale and presents different environmental considerations. This report assesses how aquaculture in England and Northern Ireland interacts with Good Environmental Status (GES), evaluating both its risks and potential benefits.

The findings indicate that aquaculture in England and Northern Ireland has a relatively minor environmental footprint compared to Scotland's finfish-dominated sector. In some cases, it may even contribute positively to GES. Shellfish and seaweed farming, for example, can improve water quality by filtering excess nutrients from the marine environment, while shellfish reefs provide habitat that supports biodiversity. However, some localised risks remain, including the spread of non-indigenous species, the accumulation of contaminants in shellfish, and the contribution of aquaculture infrastructure to marine litter. Pacific oysters, Manila clams, and northern quahogs, all of which are classified as non-native species, have established populations in certain areas, raising concerns over their potential impacts on ecosystem stability. Meanwhile, shellfish farming's reliance on clean water leaves it vulnerable to contamination from external pollution sources, requiring rigorous monitoring to ensure food safety compliance. The loss or abandonment of plastic aquaculture gear, particularly from shellfish farming, further contributes to localised marine litter issues, highlighting a need for improved waste management practices.

Despite these concerns, aquaculture in England and Northern Ireland has the potential to actively support environmental recovery. Restorative aquaculture initiatives, such as native oyster restoration projects, could enhance biodiversity by re-establishing important marine habitats. Shellfish and seaweed farming may also play a role in mitigating nutrient pollution, though more research is needed to understand how large-scale nutrient extraction affects marine ecosystems. By offering a low-carbon seafood option, aquaculture can reduce pressure on wild fisheries and contribute to a more sustainable food system.

The report also identifies several key constraints limiting the sustainable growth of the sector. Regulatory complexity and lengthy licensing processes continue to hinder expansion, while public opposition to new developments remains a challenge. Marine spatial competition is increasing as aquaculture sites overlap with offshore wind farms, protected*[1] areas, and other marine activities, requiring better integration into

*[1] Protected areas refer to designated marine or coastal zones in the UK that are legally established to conserve biodiversity and ecosystem function.

broader marine spatial planning. Brexit-related trade restrictions have also created additional barriers, particularly for the export of live shellfish to the EU. Limited investment and research support have further slowed the development of the industry, preventing the widespread adoption of innovative solutions that could improve environmental outcomes.

Looking ahead, the future of aquaculture in England and Northern Ireland will be shaped by technological advancements, regulatory changes, and evolving market conditions. The increasing use of AI-driven environmental monitoring, alternative feed sources such as insect-based proteins, and advances in offshore aquaculture technology are likely to improve sustainability. Restorative aquaculture projects focusing on habitat restoration and biodiversity enhancement are gaining momentum, while colocation with offshore wind farms presents new opportunities for optimising marine space use. The pace of innovation in the sector is increasingly driven by technology transfer from other industries, including automation, bioengineering, and digital monitoring, which are being refined for aquaculture-specific applications.

This report finds that aquaculture in England and Northern Ireland does not present a significant obstacle to achieving GES, though certain environmental risks require ongoing attention. Targeted regulatory improvements enhanced environmental monitoring, and strategic investment in innovation will be critical to ensuring that aquaculture develops in a way that aligns with sustainability objectives. Expanding research into nutrient cycling, bioaccumulation, and habitat interactions will help address existing knowledge gaps and support evidence-based policy decisions. With the right regulatory framework and industry incentives, aquaculture in England and Northern Ireland has the potential to not only meet sustainability targets but also contribute positively to the long-term health of marine ecosystems.

The Global Role of Aquaculture

Aquaculture is one of the fastest-growing food production sectors globally, now supplying over 50% of the world's seafood (Figure 1). In the period 1990–2020, total world aquaculture expanded by over 600% in annual output, with an average growth rate of 6.7%[1]. Its expansion has been driven by rising global demand for aquatic foods, advancements in technology that have enhanced production efficiency, and the need to support wild capture fisheries as they face increasing sustainability challenges (Figure 2). Estimates from the Food and Agriculture Organization of the United Nations (FAO) indicate that global aquaculture production exceeded 130 million metric tonnes (MMT) in 2022[2]. Further growth is anticipated; projections indicate that by 2032 aquaculture will account for 60% of all aquatic foods consumed by humans[*2].

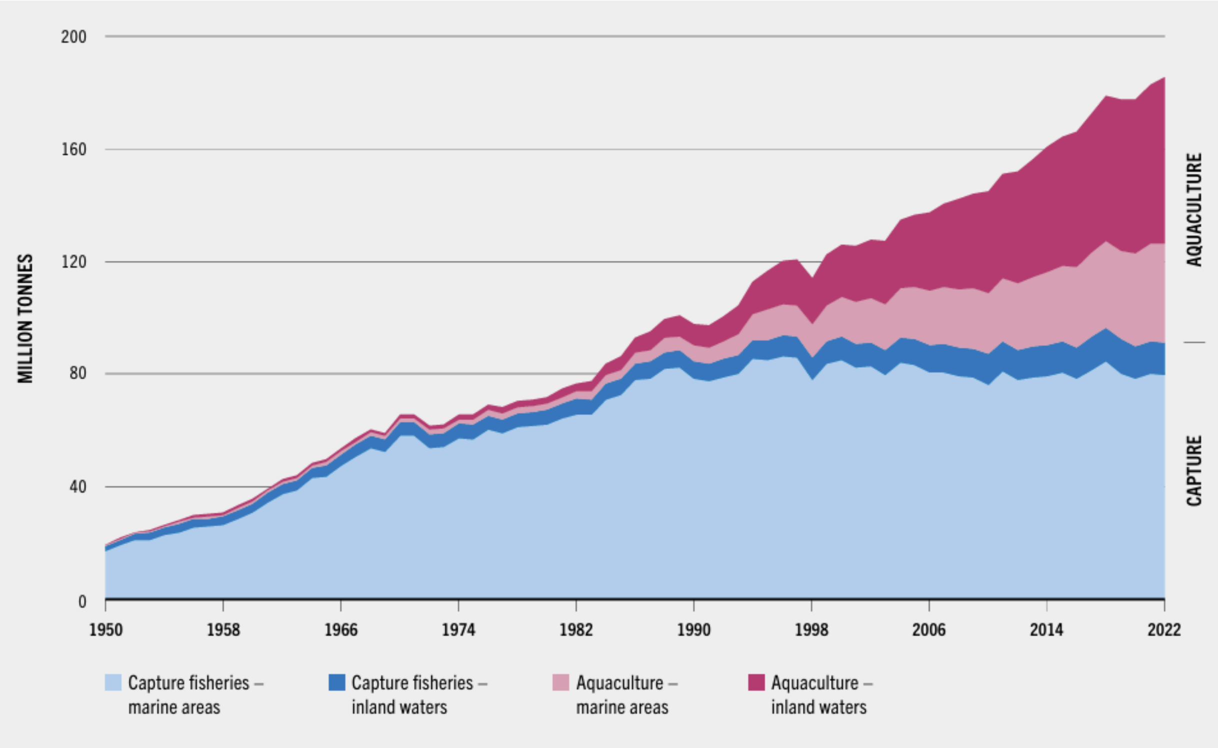

Figure 1. Graph showing total production over time of world fisheries and aquaculture production of aquatic animals. Notes: Aquatic animals excluding mammals, crocodiles, alligators, aquatic products (corals, pearls, and sponges) and algae. Data expressed in live weight equivalent. Source FAO 2024 FishStatJ.

[*2] Comprised of 94.4 MMT of aquatic animals and 36.5 MMT algae

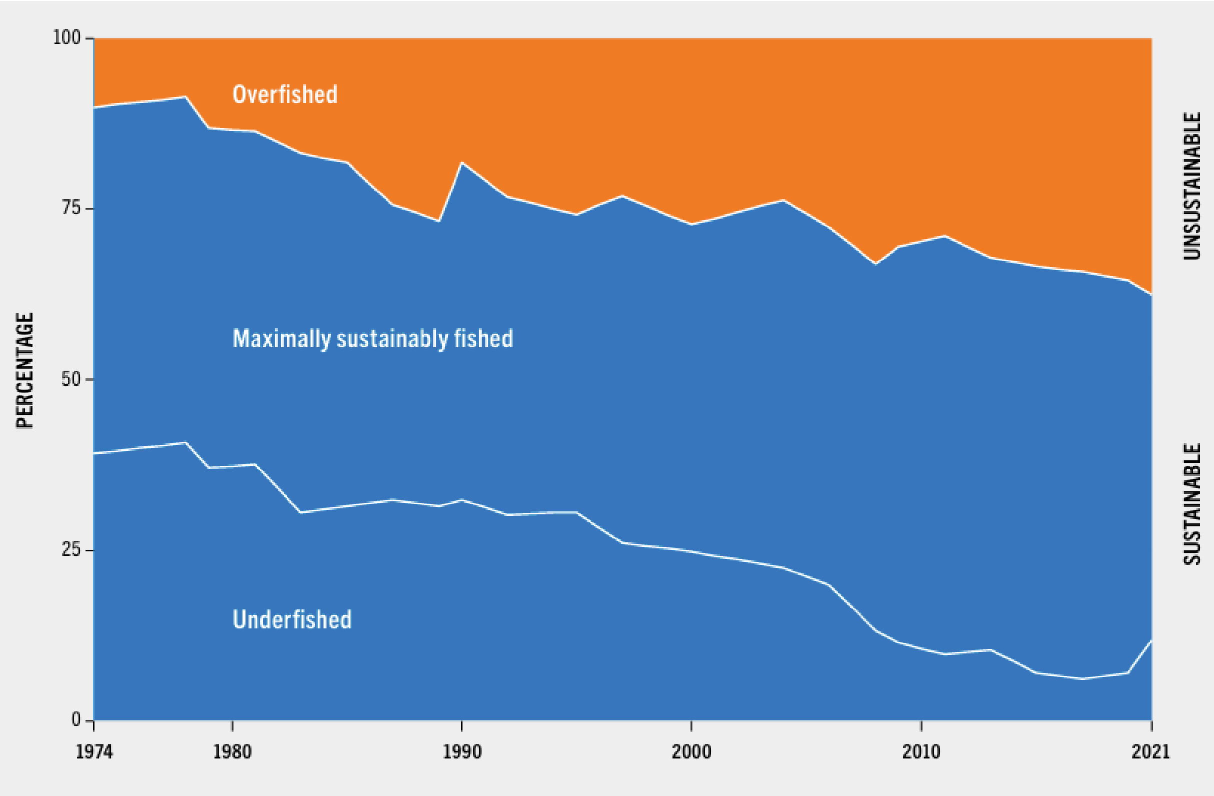

Figure 2. Graph showing global trends in the state of the world's marine fishery stocks, 1974 – 2021. Source FAO estimates.

Expansion of the aquaculture industry presents both opportunities and challenges. On one hand, aquaculture can help to reduce pressure on wild fishery stocks and support economic resilience in coastal communities, while contributing to food security [3,4]. On the other hand, it also introduces environmental pressures, including nutrient loading, habitat modification, the potential introduction of non-native species, and disease transmission, all of which require effective management to ensure long-term sustainability[5,6].

Good Environmental Status

The concept of GES is a core principle of the UK Marine Strategy (UKMS), as set out in the Marine Strategy Regulations 2010[7]. It aims to ensure that the marine environment is protected, maintained, and, where necessary, restored. GES is defined as the state in which marine ecosystems function healthily, supporting biodiversity, sustainable resource use, and minimal human-induced degradation[8].

GES is assessed through 11 qualitative descriptors, each of which addresses a different aspect of marine ecosystem health (Table 1). These descriptors are measured through specific indicators (28 in total), which provide targets to assess the extent to which the UK is achieving GES. For instance, Indicator 5.1 (Nutrient Levels) evaluates the impact of human activities—such as agriculture — on marine nutrient cycles, while Indicator 8.1 (Concentration of Contaminants) examines the presence of pollutants in the water column and sediments.

While aquaculture has both positive and negative environmental effects, its interactions with GES indicators are complex. Certain aquaculture practices—such as bivalve and seaweed farming—can enhance marine ecosystem services by filtering nutrients and improving water quality (D5). However, finfish aquaculture can introduce contaminants (D8, D9) and alter biodiversity and food web structures (D1, D4) through nutrient enrichment, disease transmission, and habitat modification.

As aquaculture continues to evolve, it is critical to understand, monitor, and mitigate its environmental impacts to ensure it contributes positively to the sustainable use of marine resources and aligns with GES objectives.

Table 1. All MSFD GES descriptors along with their respective indicators split into two columns - those most relevant to aquaculture (green) and those considered secondary – or which are covered under other descriptors due to overlaps - (orange).

GES Descriptor	Definition	Indicators relevant to aquaculture	Indicators not discussed herein
D1 – Biodiversity	Ensuring marine species and habitats are maintained at natural levels.	1.2: Population condition, 1.5: Habitat condition	1.1: Species distribution, 1.3: Population demographic characteristics, 1.4: Species distributional range, 1.6: Habitat extent, 1.7: Habitat distribution, 1.8: Ecosystem structure
D2 – Non-Indigenous Species	Preventing the introduction and spread of invasive species that could disrupt ecosystems.	2.2: Impacts of non-indigenous species	2.1: Abundance and state characterization of non-indigenous species
D3 – Commercial Fish and Shellfish	Maintaining fish and shellfish populations within safe biological limits.	3.1: Level of pressure from fishing activity, 3.2: Reproductive capacity of the stock	3.3: Population age and size distribution
D4 – Food Webs	Ensuring all elements of marine food webs are present and function normally.	No specific indicators listed, but overlaps with D3 and D5	4.1: Productivity (production per unit biomass) of key species or trophic groups, 4.2: Proportion of selected species at the top of food webs, 4.3: Abundance/distribution of key trophic groups/species
D5 – Eutrophication	Minimizing human-induced nutrient enrichment and associated negative impacts like algal blooms and oxygen depletion.	5.1: Nutrient levels, 5.2: Direct effects of nutrient enrichment	5.3: Indirect effects of nutrient enrichment
D6 – Seafloor Integrity	Preserving the physical and biological integrity of seabed habitats.	6.1: Physical damage	6.2: Condition of benthic community
D7 – Hydrographical Conditions	Ensuring that human-induced changes to marine currents and conditions do not negatively impact ecosystems.	No specific indicators listed, but minimal relevance to aquaculture in England & NI	7.1: Spatial characterisation of permanent alterations, 7.2: Impact of permanent hydrographical changes
D8 – Contaminants	Keeping chemical pollutants at levels that do not harm marine life.	8.1: Concentration of contaminants, 8.2: Effects of contaminants	None
D9 – Contaminants in Fish and Shellfish	Ensuring that seafood remains safe for human consumption.	9.2: Frequency of exceeding regulatory levels	9.1: Levels of contaminants
D10 – Marine Litter **D11 – Energy, Including**	Preventing and reducing plastic and other waste pollution in marine environments. Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment.	10.1: Characteristics of litter in the marine and coastal environment No specific indicators listed, but minimal relevance to aquaculture in England & NI	10.2: Impacts of marine litter on marine life and ecosystems 11.1: Distribution in time and place of loud, low, and mid-frequency impulsive sounds

Underwater Noise			Indicator 11.2: Continuous low-frequency sound

This Report

This report provides an evidence-based assessment of the relationship between marine aquaculture and the achievement of GES in England and Northern Ireland. It evaluates how different marine aquaculture sectors[*3]—including shellfish, seaweed, and finfish farming—interact with the 11 GES descriptors and their respective indicators.

This report was developed using a multi-method approach, combining spatial analysis, literature review, discussions with the authors' wider network, and data synthesis to assess the relationship between aquaculture and the achievement of GES in England and Northern Ireland. The findings presented in this report are intended to provide a science-based assessment of how aquaculture interacts with marine ecosystem health, contributing to informed decision-making for sustainable aquaculture management.

The analysis is structured as follows:

- A review of current aquaculture activities in England and Northern Ireland, including species farmed and production scales.
- A descriptor-by-descriptor evaluation, examining how aquaculture influences key GES indicators
- A synthesis of key findings, highlighting knowledge gaps, and recommendations to improve aquaculture's alignment with GES targets.
- An overview of future trends, discussing potential growth scenarios, regulatory challenges, and emerging innovations that may mitigate aquaculture's environmental footprint.

Unlike previous assessments of aquaculture, which have focused primarily on economic growth and industry development[9–12], this report provides a holistic environmental perspective. By identifying the risks and benefits through descriptions of the relationship between aquaculture and GES, it aims to inform policymakers, regulators, and industry stakeholders on how aquaculture can be considered within the UKMS and how any negative impacts associated with English and Northern Irish aquaculture operations can be mitigated.

[*3] The report does not assess freshwater aquaculture's impact on GES, as its influence on marine systems is considered minimal. However, it includes some freshwater data and a brief discussion of its indirect effects on marine environments, which are minor compared to impacts from things like farming runoff and industrial pollution.

Overview of Aquaculture in England & Northern Ireland

UK aquaculture is dominated by industrial-scale salmon farming almost entirely based in Scotland. While smaller in scale than Scotland, aquaculture in England and Northern Ireland plays a strategic role in local economies, supporting employment and contributing to domestic seafood production[6]. The marine aquaculture industry can be divided into three primary sectors: shellfish, seaweed, and finfish farming, each with distinct environmental, economic, and social considerations. Whilst the species that are currently farmed in England and Northern Ireland are diverse and geographically spread, shellfish dominates marine production in these regions (Table 2) and finfish dominate freshwater operations (Figure 3). Freshwater aquaculture species in England and Northern Ireland are included in the Annex, as is an illustration of the total volume and value of all aquaculture production for 2022 across England and Wales.

Table 2: Marine aquaculture species farmed in England and Northern Ireland and the overall volumes produced in 2022 (Source: Cefas & Scottish Seaweed Industry Association)

Species	England	Northern Ireland	Metric Tonnes (MT)
Shellfish[1]			
Pacific oyster (**Magallana gigas*)	✓	✓	2,212
European flat oyster (*Ostrea edulis*)	✓	✓	7
Blue mussel (*Mytilus spp.*)	✓	✓	4,995
Northern quahog (*Mercenaria mercenaria*)**	✓		6
Manila clam (Japanese carpet clam) (*Ruditapes philippinarum*)**	✓		1
European Lobster (*Homarus gammarus*)	✓		Enhancement
Seaweed			
Sugar kelp *(Saccharina latissima*)	✓	✓	Pilot scale
Winged kelp (*Alaria esculentia*)	✓	✓	Pilot scale
Oarweed *(Laminaria digitata*)	✓	✓	Pilot scale
Tangle, Cuvie *(Laminaria hyperborea)*	✓		Pilot scale
Dulse *(Palmaria palmata*)	✓		Pilot scale
Finfish			
Atlantic salmon (*Salmo salar*)		✓	1,057***
Cleaner fish (*Cyclopterus lumpus*)	✓		

[1]Common edible cockle have been removed from this table as they are considered either wild caught or ranched rather than farmed – recorded by Cefas as "harvest of wild-seeded production from aquaculture sites" = 1,476 tonnes in 2022.

*Previously *Crassostrea gigas.*

**These species are the harvest of wild-seeded production from aquaculture sites.

***Listed under "Salmonids - not elsewhere included", however, other sources corroborate that this is Atlantic salmon[13].

Figure 3. Map of approximate UK aquaculture sites colour-coded into shellfish, marine finfish and freshwater fish. Sites include licensed, active and inactive operations as of 2019 (Source: EMODnet, aquacultureNI and Cefas for freshwater operations in England. No freshwater operations data was available for NI). A full list of spatial datasets pertaining to UK aquaculture is provided in the Annex.

BOX: 1 Regulatory Landscape of Aquaculture in England & Northern Ireland

Aquaculture in England and Northern Ireland is governed by a complex regulatory framework that seeks to balance sectoral growth with environmental protection. The Marine Management Organisation (MMO) oversees licensing and planning for marine-based aquaculture in England, while Natural Resources Wales (NRW), Marine Scotland, and DAERA (Northern Ireland) regulate their respective jurisdictions. These agencies ensure that aquaculture operations comply with marine conservation objectives, but there is no unified national strategy specifically aligning aquaculture policy with GES targets.

Permitting for new aquaculture projects requires Environmental Impact Assessments (EIA) in cases where significant environmental impacts are expected. However, the extent of regulatory oversight varies depending on farm size, location, and production type. Finfish farming operations typically undergo stricter scrutiny due to their potential to contribute to eutrophication and disease transmission, whereas shellfish and seaweed farming have fewer regulatory barriers. Despite existing policies, a lack of clear integration between aquaculture governance and national marine environmental goals remains a challenge[14].

Shellfish Farming

Shellfish farming is the largest and most established aquaculture sector in England & Northern Ireland with an approximate combined production volume of 7,214 metric tonnes (MT) in 2022[*4]. An overview of the different species produced is provided below.

Pacific oyster

The Pacific oyster (*Magallana gigas*[*5]) (also known as the Pacific cupped oyster or rock oyster) is the main oyster species farmed in the UK, accounting for over 99% of oyster production in 2022. Despite this, there is considerable contention regarding its place in the domestic aquaculture sector as it is considered to be a non-native species in the UK. Initially thought to pose negligible conservation risks, due to UK waters being cooler than its native waters in Japan and South-East Asia, the Pacific oyster has established self-sustaining populations in the UK, particularly on the warmer coastal areas in the south of England. While many sources refer to the initial introduction of the Pacific oyster occurring in the 1960s, which occurred through efforts to augment the declining native European oyster industry, other authors contend that the first introduction took place much earlier, in 1890[15–17].

European shellfish farmers also started to culture non-native Pacific oysters in the 1960s. Since then, resident populations have become established in many localities, both in Europe and Scandinavia[18]. In contrast to the UK, European countries such as France, Ireland, Spain, and the Netherlands now consider Pacific oysters to be a naturalised species that can provide environmental as well as socio-economic benefits. The Pacific oyster industry in Europe therefore has strong government support, with some farming even taking place within protected areas. Consequently, production levels of Pacific oyster in Europe are much higher than in the UK, particularly in France[19], which produced 83,428 MT in 2022[20]. By comparison, the UK's total production of this species for the same year accounted for just 3% of that amount (Cefas, 2024).

The Pacific oyster's broadcast spawning capability, combined with its planktonic larval stage, contributes to its ability to spread over vast distances. Due to climate change and warming sea temperatures, the spread of Pacific oysters is expected to continue expanding northwards[19]. Natural England, the government's statutory adviser on the natural environment in England, has raised concerns over the ecological impacts of Pacific oyster expansion, particularly in designated conservation areas. Their recent assessment highlights the challenges of balancing Pacific oyster aquaculture with biodiversity protection, as wild populations continue to establish despite control efforts[21].

[*4] More recent production figures are still undergoing compilation and are due for release in mid-2025.
[*5] Previously named *Crassostrea gigas*.

While feral populations are expanding in some areas, commercial Pacific oyster culture in the UK relies heavily on hatchery production due to the unreliability of natural spatfalls[15]. To regulate this species, the UK has imposed controls on its cultivation, banning expansion of farming north of latitude 52° and restricting existing aquaculture south of this line[*6] [22]. In 2012, Natural England considered additional measures to limit the spread of feral Pacific oysters, including a scenario involving the compulsory use of triploid (sterile) stock in aquaculture operations[23]. However, industry representatives have noted that triploid seed is not always available[24], and currently, Guernsey Sea Farms is the only hatchery in the UK supplying disease-free triploid oyster seed[25]. Furthermore, scientific evidence indicates that while triploid oysters exhibit significantly reduced fecundity, they may still produce viable gametes, and their offspring could become fertile over time, suggesting that this approach may not completely eliminate reproductive risk[26].

To farm oysters, juveniles are placed in nylon mesh bags attached to either trestles ('rack and bag' method) or floating longlines near the water's surface. As the oysters grow, farmers regularly transfer them to bags with larger mesh and lower densities, positioning them where wave action helps develop deep-cupped shells. Before harvest, oysters undergo a two-week 'hardening off' period in the intertidal zone, after which they are cleaned, purified through depuration, and prepared for market[27].

European flat oyster

European flat oysters (*Ostrea edulis*), sometimes also called native oysters, have been a significant part of the human diet for centuries, with historical practices dating back to the Romans. However, their total global production volume has drastically declined from a peak of nearly 30,000 MT in 1961. This has occurred due to over-exploitation, disease outbreaks, and environmental factors. By the 1980s, diseases like *Bonamia ostreae* and *Marteilia refringens* had severely impacted populations of this keystone species, leading to a shift towards the more resilient Pacific oyster. Currently, European flat oyster production remains low, primarily supplying niche markets, with Spain, Ireland and France being the main producers[20,28,29].

In the UK, flat oysters are farmed using both off-bottom and on-bottom techniques. Off-bottom methods include floating trays, rafts, and suspended ropes, while on-bottom techniques involve re-laying oyster spat on subtidal grounds. The main issues in their culture are disease management and low survival rates, which have prompted efforts to develop disease-resistant strains. Despite these challenges, the high market value of European flat oysters sustains their cultivation, although future production is likely to remain limited without significant advancements in disease resistance and breeding practices[28].

Estimates indicate that only 1% of Europe's native flat oysters remain, hence cultivation efforts are now mainly focused on restoration and conservation[30–33]. In the UK and Ireland, such initiatives have been ongoing for several years. Hatcheries play

[*6] Approximately south of the latitude of Fishguard to Felixstowe.

a crucial role in these efforts, providing disease-free juvenile oysters for restoration, ensuring genetic diversity and biosecurity[34].

Blue mussel

The blue mussel complex (*Mytilus* spp.) consists of three species (*Mytilus edulis*, *Mytilus galloprovincialis*, and *Mytilus trossulus*), which hybridise to varying degrees in regions where their geographical distributions overlap. In the UK's mussel farming industry, both *M. edulis* and *M. galloprovincialis* are cultivated, along with their naturally occurring hybrids[35].

Mussel juveniles or 'spat' used for farming are either collected from the wild or settle naturally on farm sites. Seabed culture may involve the dredging of seed mussels from offshore sites and reseeding these in sheltered inshore locations. Mussel farming can be carried out by a variety of methods, either on the seabed or in suspended culture, with rearing methods dependent on both environment factors (tidal range, water depth, temperature, etc.) and farm infrastructure. As with oyster culture, mussels feed mainly by filtering microscopic algae (phytoplankton) and organic detritus in sea water. No feed, chemicals, or medicines are administered[35].

As with all bivalves, since mussels are filter feeders, they are vulnerable to any water borne contaminants and pollution that may affect their growth and health - and ultimately their marketability for human consumption. Poor water quality presents serious constraints for mussel aquaculture producers in the UK. Depuration, where mussels are held in clean water tanks on land prior to sale, can greatly increase production costs. Due to relatively low UK domestic demand, producers in the UK have been reliant primarily on EU export markets, but these have been adversely affected, post Brexit, by stringent EU water quality and depuration regulations[36]. In common with all bivalves, mussel aquaculture can deliver beneficial ecosystem services as well as contribute to biodiversity[37].

Northern quahog

The Northern quahog (*Mercenaria mercenaria*), also known as the American hard-shelled clam, is a non-native species in the UK, having first been introduced during the 19th Century[38]. Subsequent establishment and aquaculture activity, including in Poole Harbour, has been documented[39]. Although production remains very limited (see Table 2), concerns have been raised over its invasive potential. A more detailed assessment of its ecological impacts is provided in Section D2 – Non-Indigenous Species.

Manila clam

The Manila clam (*Ruditapes philippinarum*), also known as the Japanese carpet clam, is a non-native species that can be grown intertidally and was previously trialled in the Exe Estuary. Limited cultivation is ongoing as the subject of a controlled fishery in Poole harbour[11,40]. Despite low production volumes (see Table 2), concerns have been raised over its potential to establish and spread. Further discussion is provided in Section D2 – Non-Indigenous Species.

European lobster

A small number of small-scale hatcheries in England and Northern Ireland cultivate the European or common lobster (*Homarus gammarus*) for restorative purposes with the juveniles being released into the wild for restocking[41–43].

Seaweed Farming

Whilst global farmed macroalgae production reached 36.5 MMT in 2022[44], seaweed farming in both England & Northern Ireland is only now emerging as an aquaculture sub-sector, with potential applications in food production, biofuels, cosmetics, and ecosystem service provision[45]. The main seaweed species currently cultivated at commercially pilot scale in England and Northern Ireland are the kelps, *Saccharina latissima* (sugar kelp) and *Alaria esculenta* (winged kelp). Other species under consideration and being variously trialled include two other kelp varieties - *Laminaria digitata* (oarweed) and *L. hyperborea* (tangle or cuvie) – and *Palmaria palmata* (dulse), amongst others[46].

Seaweed can be farmed using a variety of techniques, ranging from intense land based tank or pond systems to open sea farming systems using long lines or rafts secured with blocks or anchors to the seabed[47]. In long line systems at sea, seaweed spores cultured on twine in seaweed hatcheries are placed along long lines below the surface; these are then raised for cutting during harvest[48].

Given the nascent state of seaweed aquaculture in the UK, no official production figures for this sector are published. However, for reference, the 2017 harvest of *S. latissima* was 20 MT, which at the time was the UK's largest amount of harvested seaweed to date[9]. Pioneer UK seaweed farms include those based in both Northern Ireland (Pers. Comm., Dr. Duncan Smallman, Scottish Seaweed Industry Association, February 2025) and England and the authors of this report are aware of seven small-scale seaweed aquaculture producers currently active in these countries (Pers. Comm., Rhianna Rees, Scottish Seaweed Industry Association).

Finfish Farming

Despite finfish aquaculture being the dominant aquaculture sector in the UK, marine-based finfish farming in England and Northern Ireland is minimal. The vast majority of UK finfish production occurs in Scotland, where ocean-based net pen farming of Atlantic salmon (*Salmo salar*) dominates, accounting for 169,194 MT of production in 2022 (Cefas, 2024). Past attempts to develop at sea marine farming of finfish, particularly in southwest England, have rarely developed past the pilot stage, with inshore water quality issues, high peak water temperatures, and public opposition to cage farming being cited as key constraints[9].

Atlantic salmon

The only active marine finfish farm in England or Northern Ireland is operated by Glenarm Organic Salmon[49], based in County Antrim, Northern Ireland. The farm consists of two sites and produces Atlantic salmon using ocean-based net pens, with an estimated annual production of 500-1,000 MT. However, Cefas production statistics do not disaggregate these figures from other salmonids, likely due to confidentiality constraints.

Cleaner fish

Lumpfish (*Cyclopterus lumpus*) are cultivated in an onshore saltwater hatchery based in Portland Port in Dorset. These ‘cleaner fish’ are used as a biological control method to control sea lice in the Scottish salmon sector. Approximately 850,000 lumpfish are produced per year[11].

Aquaculture Impacts & Good Environmental Status

This section evaluates the relationship between GES and the impacts of aquaculture in England and Northern Ireland. Each descriptor (D) is introduced with an overview of its overarching purpose, followed by an analysis of the indicators most relevant to the aquaculture sector. This analysis draws on the available evidence of aquaculture's impacts on the marine environment in relation to each respective GES descriptor. Where possible, UK-based examples of these impacts are provided, with international references included as needed. Some indicators overlap with others. Therefore, to avoid repetition, overlapping impacts are highlighted where they are relevant but are only discussed under the indicator that has been deemed most pertinent.

Biodiversity (D1) - Purpose: Biological diversity is maintained. The quality and occurrence of habitats and the distribution and abundance of species are in line with natural conditions.

D1 - Indicator 1.2: Population condition

Aquaculture has the potential to affect the population condition of wild species in several ways. While many of these impacts are also implicated in other GES descriptors, the potential for disease spread from aquaculture operations is particularly relevant to this biodiversity/ population condition indicator as are potential impacts upon predator prey dynamics.

Disease Spread from Aquaculture to Wild Populations

Aquaculture operations can serve as a reservoir and transmission hub for infectious diseases, posing risks to wild populations through multiple pathways, including waterborne transmission, escape events, and contact with farmed species. One key mechanism is parasite spillover, where farmed populations may transmit parasites to wild species, affecting their health and survival. Additionally, interspecific spillback occurs when wild species infect farmed stocks, leading to an amplification of pathogen loads, which in turn heightens disease risks for wild populations[50].

Waterborne pathogen transmission is a significant concern in open-water aquaculture systems, where pathogens can be dispersed through currents. For example, salmon lice (*Lepeophtheirus salmonis*) (Figure 4) from farms have been linked to mortality in wild juvenile salmon as they migrate past aquaculture facilities[50].

Figure 4: Atlantic salmon (*Salmo salar*) with visible sea lice (*Lepeophtheirus salmonis*) infestation, highlighting the challenges of parasite management in aquaculture. (Image source: Norwegian Veterinary Institute (2024)[51])

This highlights the importance of managing parasite loads within aquaculture operations to prevent negative impacts on wild stocks. Additionally, live fish transport between aquaculture sites can further spread pathogens. An analysis of UK aquaculture found that 7.2% of all live fish transports cross the England-Scotland border, increasing the risk of disease transmission between regions[52]. Also, diseases such as Infectious Salmon Anaemia Virus (ISAV) and Bacterial Kidney Disease (BKD) have been linked to live fish movements within the industry[52].

In bivalve aquaculture, pathogen outbreaks can impact both farmed and wild populations. The ostreid herpesvirus (*OsHV-1 μVar*) (Figure 5) has caused high mortality rates in farmed Pacific oysters in England and Northern Ireland, raising concerns about potential disease transmission beyond aquaculture sites. Similarly, native oyster populations have been threatened by the spread of *Bonamia ostreae*, a lethal parasite found in aquaculture settings, necessitating strict biosecurity and disease monitoring[53].

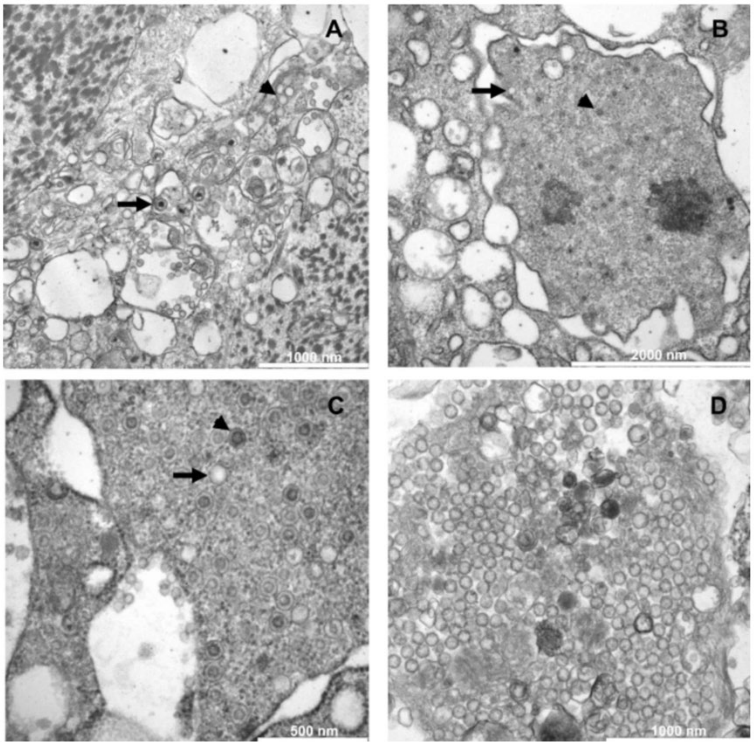

Figure 4. Transmission electron micrographs of Pacific oyster (*Magallana gigas, previously Crassostrea gigas*) tissues infected with Ostreid herpesvirus 1 (OsHV-1)[54].

Given these risks, effective disease management strategies are essential to mitigate aquaculture-related disease transmission. Surveillance programs and biosecurity protocols have been implemented to reduce the spread of pathogens within and beyond aquaculture sites in England and Northern Ireland[55]. These findings underscore the need for continued monitoring, adaptive management, and robust biosecurity measures to minimise the risks of disease spillover from aquaculture to wild populations while ensuring sustainable production practices.

Predator-Prey Interactions Linked to Aquaculture

The presence of aquaculture infrastructure can modify natural predator-prey interactions, leading to potential shifts in population condition for wild species. Fish farms are known to aggregate wild fish, often increasing local fish abundance and potentially altering predator-prey dynamics[56,57]. For example, a large-scale offshore mussel farm in Lyme Bay, England, has been described as acting as a fish aggregation device (FAD), enhancing marine biodiversity by increasing species diversity and abundance, supporting habitat restoration, and promoting the formation of biogenic reefs[56]. Conversely, literature notes that aggregations around fish farm facilities can create ecological traps, where fish are drawn to farm sites due to increased food availability but may also experience heightened predation risk or other negative fitness consequences[58]. Additionally, escaped farmed salmon may influence wild predator-prey relationships, as they often display altered behaviours compared to their wild counterparts, which can disrupt natural predator-prey interactions in receiving ecosystems[59]. Beyond acting as FADs, bivalve aquaculture structures can provide habitat complexity, further influencing local trophic interactions[58]. These interactions underscore the need for careful site selection and monitoring to mitigate unintended ecological impacts.

D1 - Indicator 1.5: Habitat condition

Aquaculture has the potential to impact marine habitat conditions through both direct and indirect mechanisms. While some of these effects are localised to farm sites, others can have broader implications for ecosystem structure and function. Key concerns include changes to benthic conditions from organic waste accumulation, habitat modification due to aquaculture infrastructure and shading effects, particularly from large-scale seaweed farming and suspended mussel culture. Additionally, aquaculture may alter habitat quality by influencing sediment chemistry, promoting bacterial mat formation, and affecting the carrying capacity of marine environments. Conversely, certain forms of aquaculture, such as shellfish farming, can enhance habitats by improving water quality and providing structural habitat for marine organisms. However, the ecological consequences of habitat creation vary depending on the species involved and the environmental context.

Habitat Alteration from Infrastructure and Shading Effects

Seaweed farms, depending on their size and density, have the potential to reduce light penetration to the seabed, potentially affecting sensitive habitats, such as seagrass beds, and altering benthic productivity[60]. Aquaculture can also alter local hydrodynamics and sediment deposition patterns, particularly in estuarine systems in which shellfish farms influence water flow and sediment stability. However, these effects can be managed through careful site selection and appropriate farm layout[61].

Potential Benefits of Aquaculture and Habitat Enhancement

Not all aquaculture impacts on habitat condition are negative. Shellfish and seaweed aquaculture can provide ecosystem services that can enhance local habitat quality[62]. Oyster cultivation has been shown to contribute to habitat complexity, increasing species diversity and supporting local fish and invertebrate populations. Moreover, oysters act as natural filter-feeders, removing organic particles from the water, which results in clearer and cleaner water, thereby further improving habitat quality[31], as do restored oyster reefs[34]. Similarly, mussel farming can improve benthic conditions by providing substrate for marine organisms and increasing local biodiversity, offering potential habitat benefits[63]. By filtering excess nutrients from the water column, bivalve aquaculture can reduce eutrophication risks, creating a more stable and resilient benthic environment[64]. Shellfish aquaculture has been recognised for its role in marine habitat conservation, promoting biodiversity while acting as a natural biofilter that improves water quality[65].

However, Natural England, in a published report, highlights that while Pacific oyster reefs may provide structural complexity like native oyster beds, their spread in protected areas raises concerns over biodiversity trade-offs. These reefs can alter intertidal habitats and displace native species, particularly in sensitive or protected sites. For example, a survey of the North East Kent European Marine Sites documented substantial intertidal populations of Pacific oysters, with particularly dense aggregations around Ramsgate's Western Undercliff. These sites fall within designated Special Areas of Conservation (SACs) and Special Protection Areas (SPAs)—collectively known as European Marine Sites (EMSs)—and are protected for their habitat and species features[21].

Natural England has also identified the presence of Pacific oysters as a pressure on the designated features of nearby protected areas, including the Thanet Coast SPA, where their proliferation could contribute to assessments of unfavourable condition — particularly where they interact with native mussel beds, which are integral to the SPA's supporting habitats[66]. Continued monitoring is therefore recommended to assess the long-term ecological implications of reef development in protected sites.

Overlaps: Aquaculture-related biodiversity pressures intersect with multiple GES descriptors. The introduction of non-indigenous species and their potential ecological impacts on biodiversity are considered in D2. The potential for aquaculture to reduce commercial fishing pressure on wild stocks is explored in D3, as are the possible impacts of genetic introgression posed by aquaculture escapees. The potential for restorative aquaculture and stock enhancement initiatives, such as native oyster restoration projects, to enhance habitat complexity and indirectly support commercial fish and shellfish species is also considered in D3. Predator-prey interactions linked to aquaculture are also relevant to both D2 and D3, as well as broader food web dynamics, which are of relevance to D4. Nutrient and contaminant-driven biodiversity impacts are assessed in D5 and D8, respectively, while entanglement risks from aquaculture infrastructure are addressed in D10.

Regarding habitat condition, potential seabed disturbance from aquaculture infrastructure, such as mooring systems and bottom-culture shellfish farming, is examined under D6, which considers seabed integrity. Additionally, while harmful algal blooms (HABs) and bacterial mat formation can affect habitat condition, these processes are primarily driven by nutrient enrichment and are therefore assessed in D5. Conversely, the potential for aquaculture, particularly shellfish and seaweed farming, to enhance habitat condition through water filtration and structural habitat provision is further considered in D5.

Non-Indigenous Species (D2)

– Purpose: Non-indigenous species (NIS) introduced by human activities are at levels that do not adversely alter the ecosystems.

D2 - Indicator 2.2: Impacts of non-indigenous species

The introduction of NIS can cause disruption in local ecosystems and impact native stocks through competition for resources. Aquaculture activities can contribute to the introduction and spread of NIS through several pathways, including escapes from farmed stock, unintentional transport of associated species (e.g., parasites, fouling organisms), and the movement of aquaculture equipment. Additionally, aquaculture may act as a secondary vector for the spread of invasive species already present in UK waters, should stocks be translocated domestically. Understanding these interactions is critical for assessing the risks posed by NIS and developing appropriate management measures to ensure that aquaculture activities do not hinder the achievement of GES.

Introduction of Non-Indigenous Species via Aquaculture

Historically, several NIS marine species have been introduced for aquaculture in the UK. Notably, Pacific oysters (Figure 5) were introduced for commercial aquaculture in the 1960s and now account for more than 99% of UK oyster production (Cefas UK aquaculture production data, 2022). Since their introduction, Pacific oysters have established self-sustaining wild populations, predominantly in southern England, with further populations recorded in Northern Ireland, Wales, and as far north as Shetland in Scotland. This has raised concerns over their impact on native habitats and ecosystem functions[6,16,67]. Natural England, in a recent report, highlights the continued expansion of wild Pacific oyster populations despite control efforts, particularly in protected areas. The report underscores the need for site-specific management strategies to mitigate ecological risks while balancing potential ecosystem service benefits[21].

While some view the establishment of Pacific oysters as an ecosystem benefit due to their ability to improve water quality and enhance habitat complexity, concerns remain regarding their potential to outcompete native species[68]. Literature notes that aquaculture may play a significant role in the persistence and spread of Pacific oysters in new areas. External recruitment from farmed stocks and established feral populations may sustain or increase wild oyster densities, even in the absence of regular spawning[69].

Figure 5. Pacific oyster (*Magallana gigas*, previously known as *Crassostrea gigas*) (Photo credit: Plymouth Marine Laboratory)[70].

Other shellfish species that have been introduced for aquaculture include the Manila clam and the northern quahog. Originally introduced in 1988, by 2010 the Manila clam had become naturalised in at least 11 estuaries in southern England, most notably in Poole Harbour. Literature notes that this species is not presently viewed as an aggressive invasive and does not present a major threat to native biodiversity or ecosystem function. This classification is supported by its medium invasiveness score under the Marine Invertebrate Invasiveness Screening Kit (MI-ISK), which evaluates ecological impact, potential for spread, and management difficulty[71]. Some positive impacts have also been documented in relation to Manila clams, such as support for a productive local fishery and a prey resource for oystercatchers in Poole Harbour. Distribution of this species is expected to gradually expand as sea temperatures increase, hence ongoing monitoring and research is warranted[40,71].

Similarly, the northern quahog was successfully introduced to Southampton Water in 1925 and has since become naturalised in several regions across the UK, including the south coast of England, Burnham-on-Crouch in Essex, Pembrokeshire in Wales, and Loch Sunart in Scotland, with further deliberate introductions recorded in Poole Harbour and Newtown Creek on the Isle of Wight[39]. Literature notes that the northern quahog has been documented to displace native clam species and is assessed as being moderately invasive, based on MI-ISK, which evaluates ecological impact, potential for spread, and management difficulty. Future projections indicate that its suitable habitat will shift poleward by approximately 620 km globally by the end of the century[71].

Associated Species and 'Fellow Travellers'

Alongside the deliberate introduction of aquaculture species, biofouling organisms and parasites can be unintentionally introduced and spread through aquaculture operations. For example, the American slipper limpet (*Crepidula fornicata*) made its way into European waters in the late 19th century as an unintended fellow traveller on American oysters (*Crassostrea virginica*), which were imported for aquaculture[72]. Similarly, the invasive colonial tunicate *Didemnum vexillum* has also been associated with the translocation of oyster stock[73]. UK shellfish aquaculture may also have played a potential role in the introduction of NIS such as the Asian clubbed tunicate (*Styela clava*) and the Japanese or Asian oyster drill (*Ocenebra inornata*)[72].

Similarly, seaweed farming, while emerging as a promising industry, potentially carries risks related to non-native epibionts and associated microbiota. Cultivated seaweeds can inadvertently introduce non-native/ non-local invertebrates or microorganisms that may affect local biodiversity[60]. The role of biosecurity protocols in preventing these introductions is therefore critical.

Globalisation and the Risk of Increased NIS Spread

While the increasing globalisation of aquaculture trade, including the movement of live aquaculture stock and equipment, is a primary concern for the spread of invasive species, a key vector for the translocation of marine species is international shipping. Ballast water from shipping is a widely recognised vector for marine invasive species. The leathery sea squirt (*Styela clava*), for example, is a known biofouling species on aquaculture equipment, but it was most likely first introduced to the UK in 1952 via hull fouling on warships returning from the Korean War[74]. This highlights the need for integrated biosecurity measures that account for multiple introduction pathways beyond aquaculture operations alone.

Overlaps: Some of the pressures related to NIS introductions intersect with other GES descriptors. The spread of invasive species and parasites through aquaculture operations is relevant to Indicator 1.2 (Population Condition) and Indicator 3.2 (Reproductive Capacity of the Stock). However, since this topic is most relevant to this indicator, it is solely discussed here in D2.

Commercial Fish and Shellfish (D3) – Purpose: Populations of all commercially exploited fish and shellfish are within safe biological limits, with a healthy population age and size distribution.

While aquaculture is often presented as a solution to overfishing by reducing pressure on wild stocks, it can also contribute to fishing pressure if feeds containing wild-sourced fishmeal and fish oil are used. However, most aquaculture in England and Northern Ireland is unfed, with the only marine-based fed aquaculture being a single salmon farming operation in Northern Ireland. This contrasts sharply with Scotland, where large-scale salmon farming dominates the sector.

This section examines two key interactions between aquaculture and fisheries: its role in reducing or increasing pressure on wild fish stocks, and its potential impact on the reproductive capacity of commercially important species.

D3 - Indicator 3.1: Level of pressure from fishing activity

Although aquaculture can reduce reliance on wild-caught fish, it still exerts pressure on wild fisheries through feed sourcing. Understanding these dynamics is essential for assessing aquaculture's contribution to the achievement of GES.

Aquaculture's Dependence on Wild Fisheries for Feed

Most finfish aquaculture relies to some degree on fishmeal and fish oil inputs derived from wild fisheries[75]. A study of feed mills supplying the salmon sector in Scotland indicates that fishmeal and fish oil are primarily sourced from Peru and Denmark[76]. However, as the study was limited to Scottish feed mills, it does not account for other imported diets, which may source these ingredients from additional locations.

Until recently, one of the notable industrial forage fisheries in UK waters targeted sandeels (Figure 7) in North Sea waters off England and Scotland. This fishery was predominantly operated by Danish vessels, with no UK quota allocated since 2021. In early 2024, the UK and Scottish governments implemented a ban on industrial sandeel fishing in their respective waters to protect marine biodiversity and food web integrity[77].

Figure 6. Sandeels (*Ammodytes marinus*).
Source: https://commons.wikimedia.org/wiki/Image:Atlantic_puffin_with_fresh_catch_of_sand_eels.jpg Nature Scot – David Steele.

While this closure of the sandeel fishery removed a high-profile industrial forage fishery from UK waters, quotas remain for other forage species, including blue whiting[78]. However, given the very limited scale of marine finfish aquaculture in

England and Northern Ireland—where only two farming sites exist, both located in Northern Ireland and managed by one operator—the impact of local forage fish extraction on GES remains minimal in this context.

Transition to Alternative Feed Ingredients

To reduce reliance on marine-derived feedstocks, the aquaculture industry is increasingly exploring alternative ingredients such as insect meal, algal oils, and microbial proteins. If widely adopted, these innovations could significantly lessen aquaculture's indirect contribution to fishing pressure. However, widespread commercial adoption is still in progress, and fishmeal and fish oil remains an important feed component in salmon farming[79,80].

D3 - Indicator 3.2: Reproductive capacity of the stock

Aquaculture can influence the reproductive success of wild fish and shellfish populations through habitat modification, nutrient loading, and species interactions. These effects can be both positive and negative, depending on species, farming methods, and local ecosystem conditions. Some aquaculture activities may support wild stock recruitment, while others can disrupt natural spawning and genetic integrity.

Escapees, Genetic Interactions, and Hatchery Stock

Farmed species that escape into the wild can compete with native stocks for food, habitat, and breeding grounds, and in some cases, may interbreed with wild populations, which can reduce genetic diversity and adaptability. While salmon escapees have been a key concern in Scotland[55,81], the risk is significantly lower in Northern Ireland due to the limited scale of marine finfish farming. In England there is no marine fish farming. Nevertheless, in October 2024, the Department of Agriculture, Environment and Rural Affairs (DAERA) reported a possible escape of up to 5,000 farmed salmon from Northern Ireland's only marine-based salmon farm, highlighting that even small-scale operations can pose risks[82].

In addition to concerns about escapees, aquaculture can also influence the reproductive success of wild populations through stock enhancement initiatives. Oyster restoration projects, for example, introduce hatchery-reared individuals into the wild to support population recovery. While these efforts aim to support wild stock recovery, they may also affect genetic diversity and lead to competition with natural populations for habitat and resources[34].

Aquaculture Infrastructure and Reproductive Habitat

Aquaculture modifies local habitat conditions in ways that can either support or hinder wild stock reproductive success. Finfish cages and some large-scale aquaculture structures may alter movement patterns, particularly for migratory species[55]. Conversely, shellfish and seaweed farms can increase habitat complexity, creating refuge areas and potentially enhancing spawning and recruitment for some species. Research suggests that bivalve aquaculture can support commercially valuable species by improving local habitat conditions[31].

Restorative Aquaculture and Stock Enhancement

Certain aquaculture-based conservation initiatives directly aim to improve wild stock reproductive capacity and support GES objectives. Oyster reef restoration efforts are designed to increase spawning success and rebuild historically overfished populations[34]. Similarly, hatchery-based stock enhancement programs introduce juvenile shellfish to support depleted fisheries and enhance long-term sustainability[31]. While stock enhancement projects aim to restore natural populations, their effectiveness depends on local environmental conditions and the genetic diversity of hatchery-raised individuals. Oyster restoration projects are currently underway in various parts of the UK, including the Essex Native Oyster Restoration Initiative (ENORI) and the Solent Oyster Restoration Project in England, as well as the Native Oyster Restoration Northern Ireland (NONI) project in Northern Ireland[83–85].

Overlaps: As discussed above, aquaculture escapees can impact the reproductive success of commercial fish and shellfish stocks. Where these escapees are NIS, their presence may have additional implications for wild stock reproduction. Since the introduction of NIS through aquaculture is primarily addressed under D2, this topic is discussed in more detail there. While nutrient loading from aquaculture is typically considered a pressure, in some cases, moderate enrichment may benefit the reproductive success of certain commercial fish and shellfish by increasing primary productivity and food availability. This is explored further in D5.

Food Webs (D4)

– Purpose: All elements of the marine food webs occur at normal abundance and diversity, ensuring the long-term abundance of species and retention of reproductive capacity.

For the assessment of aquaculture in England and Northern Ireland, this descriptor is not a priority in terms of its impact on achieving GES. Aquaculture in these regions primarily consists of shellfish farming, with limited seaweed or fed finfish production. As a result, such operations are unlikely to significantly alter marine food web structure, and any potential interactions are minimal. Where relevant, these interactions are already considered under other GES descriptors.

Overlaps: The potential effects of aquaculture on food web dynamics are addressed within other GES descriptors. The relationship between aquaculture and forage fish dependency, stock enhancement, and its potential to reduce fishing pressure is discussed in D3. The influence of shellfish farming on habitat modification and associated species is examined in D6. The role of non-indigenous species, such as Pacific oysters, in shaping food web interactions is explored under D2.

Eutrophication (D5) – Purpose: Human-induced eutrophication is minimized, especially adverse effects like losses in biodiversity, harmful algal blooms, and oxygen deficiency in waters.

Aquaculture activities in England and Northern Ireland have a relatively limited impact on nutrient loading compared to other anthropogenic sources such as agricultural runoff and wastewater discharges. However, localised effects can still occur, particularly in areas with high aquaculture activity and limited water exchange, contributing to human-induced eutrophication and its associated effects, such as biodiversity loss, harmful algal blooms, and oxygen deficiency in waters.

D5 - Indicator 5.1: Nutrient levels

Nutrient discharges from finfish farms can lead to localised nutrient enrichment. Conversely, shellfish and seaweed farming can play a role in nutrient mitigation.

Aquaculture's Role in Nutrient Cycling

Aquaculture contributes to marine nutrient dynamics in different ways depending on the production type. Fed aquaculture, such as finfish farming, releases nitrogen (N) and phosphorus (P) into the surrounding environment, whereas unfed aquaculture, including shellfish and seaweed farming, can help reduce nutrient levels by filtering and assimilating organic matter[86,87].

The impact of nutrient loading from finfish aquaculture is highly dependent on site conditions, particularly water circulation and flushing rates. Appropriate site selection is therefore crucial to mitigating impacts, ensuring that nutrient discharges do not exceed the carrying capacity of the local environment[88]. Despite this, nutrient contributions from marine finfish aquaculture in England and Northern Ireland are minimal due to the limited scale of the industry; in Northern Ireland, there are only two salmon farming sites, while in England, there are no marine finfish farming operations[6].

In contrast to finfish farming, bivalves such as oysters and mussels remove nitrogen through filter-feeding, reducing phytoplankton levels and improving water clarity[89]. Large-scale seaweed cultivation can also absorb dissolved nitrogen and phosphorus, potentially offsetting anthropogenic nutrient inputs. Natural England, in a recent assessment, notes that while shellfish aquaculture and wild Pacific oyster reefs can contribute to nutrient removal, their broader ecological effects remain uncertain. The extent to which these reefs influence nutrient cycling varies by location, necessitating further site-specific research[21]. While these processes can have positive effects, excessive extraction of nutrients through shellfish and seaweed farming can potentially deplete essential resources for primary production and alter nutrient cycling dynamics[86]. However, evidence from an offshore mussel farm in Lyme Bay, England, found no significant depletion of zooplankton in the surrounding waters[56].

Importantly, achieving GES requires consideration of all nutrient inputs, including those from terrestrial sources such as agricultural runoff and wastewater discharges, which contribute significantly to marine eutrophication. Notably, in the UK, N and P inputs are responsible for more water bodies failing to achieve good ecological status under the Water Framework Directive[*7] (WFD) than any other pollutants apart from polybrominated diphenyl ethers (PBDEs)[91]. Agricultural land alone accounts for 50–60% of all Dissolved Available Inorganic Nitrogen (DAIN) inputs to the water environment, highlighting the significant role of terrestrial sources in nutrient loading[91].

D5 - Indicator 5.2: Direct effects of nutrient enrichment

Nutrient loading from aquaculture can have significant direct impacts on marine ecosystems, particularly through eutrophication, HABs and oxygen depletion. In addition to its effects on water quality, excessive organic deposition can alter sediment chemistry and contribute to benthic degradation though hypoxia-driven impacts. Given the importance of minimising human-induced eutrophication to achieve GES, the potential for these direct effects to occur must be carefully considered in management decisions.

Water Column Impacts: Eutrophication, HABs and Oxygen Depletion

The accumulation of organic waste from finfish farms, including uneaten feed and fish excretion, can contribute to nutrient enrichment in the surrounding water column, which, in poorly flushed or enclosed environments, has been linked to localised eutrophication[6]. When aquaculture facilities are appropriately sited and managed, waste disperses effectively, minimising local impacts; however, excessive waste accumulation in areas with limited water exchange can result in hypoxic conditions that disrupt benthic ecosystems[55,88], and stimulate excessive phytoplankton growth, increasing the likelihood of HAB formation[92].

Many HABs are natural events that occur as part of the seasonal cycles of planktonic micro-organisms (Figure 7) and can develop naturally offshore without human influence. However, human activities like nutrient runoff and habitat disruption can intensify their frequency and severity, especially in coastal regions with limited water circulation. The toxins that HABs produce can impact marine life and human health, disrupt shellfish aquaculture, and contribute to oxygen depletion through decomposition processes[92,93]. The depletion of oxygen due to decaying algal blooms can lead to mass fish mortality and the loss of sediment-dwelling organisms, representing a significant ecological disturbance[94].

[*7] The WFD assesses the impact of human activities in estuarine and coastal waters[90].

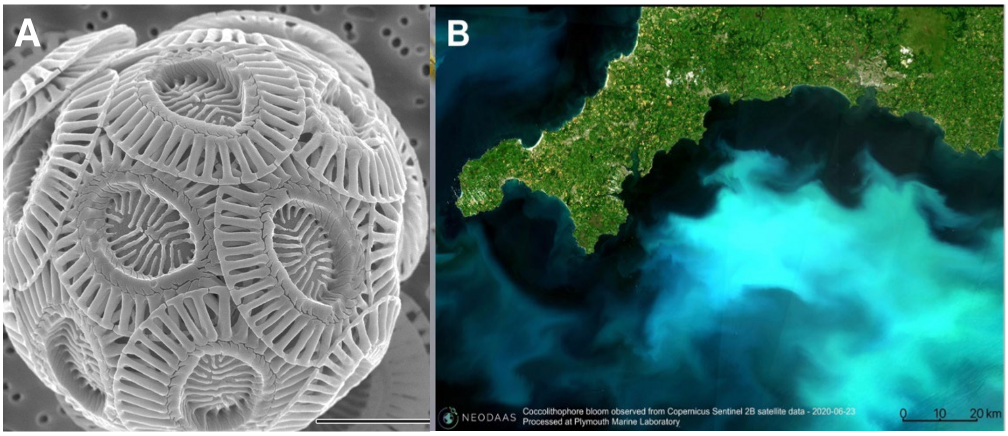

Figure 7. Microscopic view of the coccolithophore *Emiliania huxleyi* organisms (Image A) that contribute to algal blooms such as the one shown in the satellite image (Image B). Source: Alison R. Taylor, University of North Caroline Wilmington Microscopy Facility (A) and the Marine Science Blog, UK Government (B)[95].

Organic Deposition and Benthic Degradation

Benthic habitat condition can be significantly influenced by aquaculture wastes, particularly in high-density finfish farming. Organic waste from aquaculture can result in bacterial mat formation on the seafloor, reducing oxygen penetration into sediments and altering the composition of benthic communities. Bacterial mats are indicative of high organic load environments, often dominated by sulfide-oxidizing bacteria that thrive under hypoxic conditions. Beggiatoa-like bacterial mats are a well-documented indicator of eutrophication-driven benthic degradation and serve as a warning sign of excessive nutrient loading[6,96,97]. Organic deposition from farms can alter sediment chemistry, leading to shifts in benthic community structure, often favouring opportunistic species over sensitive benthic fauna[98].

Although shellfish and seaweed farming generally have a lower impact on benthic habitats, localised effects can occur. Shellfish biodeposits may increase sedimentation rates, altering oxygen penetration and microbial composition in the seafloor environment[6]. However, these systems can also provide a counterbalance to nutrient enrichment by improving water clarity and stabilising sediments, mitigating some of the negative effects associated with organic deposition[89].

The extent of these impacts depends on site-specific factors such as depth, current speeds, and farm management practices[98]. Ensuring that aquaculture sites are selected based on environmental carrying capacity is essential for sustainable development, as is assessing their potential impact on habitats[88]. In addition, EIAs are an integral part of the regulatory process for certain aquaculture developments, helping to determine appropriate production levels, acceptable environmental impact, and suitable farm locations through initial assessments and environmental capacity modelling[14]. Predictive models, such as DEPOMOD[*8], play a key role in estimating organic waste

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[*8] DEPOMOD is a model used to predict the deposition and dispersion of particulate waste from marine fish farms, particularly those using open-net pen aquaculture systems. It was developed by the Scottish Association for

dispersion and deposition from finfish farms, helping to inform decision-making and regulatory compliance[99], which in turn support the achievement of GES.

Overlaps: Due to the significance of eutrophication as a pressure on marine ecosystems, many of the topics discussed in this descriptor are also relevant to other GES descriptors. To avoid redundancy, nutrient-related impacts have been primarily addressed here under D5.

Sea-Floor Integrity (D6) – Purpose: Sea-floor integrity is maintained at a level that safeguards the structure and functions of ecosystems, particularly benthic ecosystems.

D6 - Indicator 6.1: Physical damage

Aquaculture activities can physically impact seabed habitats through infrastructure placement, sediment disturbance, and harvesting practices. The extent of these impacts depends on the farming method, site conditions, and farm management practices. While these effects are generally localised, aquaculture infrastructure—such as anchoring systems for finfish cages and bottom-culture shellfish farming—can alter seabed habitats. Some aquaculture activities may also provide habitat benefits, highlighting the importance of site selection and best practices in minimising disturbance.

Bottom-Culture Shellfish Farming and Dredging

Bottom-culture shellfish farming, particularly for mussels and oysters, can cause physical disturbance through dredging for seed collection and harvesting. These activities may alter sediment structure, impact benthic communities, and contribute to localised habitat modification[55]. In Belfast Lough, Northern Ireland, mussel dredging was shown to leave visible seabed scars that persisted for over a year in softer sediments, highlighting the potential for long-term disturbance. While most dredging remained within licensed aquaculture zones, some activity extended beyond designated areas, demonstrating the need for effective spatial management to minimise habitat impacts. Additionally, routine aquaculture practices such as seeding, re-laying, and harvesting contribute to seabed modification. In Belfast Lough, some dredge marks observed between licensed sites were speculated to be linked to starfish mopping— a method used to control predation on mussel beds. This highlights the importance of effective spatial management to minimise unintended habitat impacts[100].

Mooring and Infrastructure Impacts

Mooring systems used in finfish and shellfish aquaculture can physically disturb the seabed during installation, operation, and decommissioning. Anchoring methods, including concrete blocks, screw anchors, and weighted lines, can result in abrasion,

Marine Science (SAMS) and is widely used by regulatory agencies, environmental consultants, and aquaculture companies to assess the potential impact of fish farm waste on the seabed.

penetration, and compression of sediments, altering habitat conditions and potentially displacing benthic organisms. The extent of these impacts depends on substrate type, hydrodynamic conditions, and the scale of aquaculture operations[101].

Additionally, wave and current interactions with aquaculture infrastructure can influence sediment transport dynamics, leading to localised scouring or deposition that affects seabed stability. In some cases, prolonged anchoring may create bare patches or fragmented habitats, which can expand over time due to ongoing erosion and sediment redistribution. Increased turbidity from disturbed sediments may further impact light-dependent benthic communities, such as seagrass meadows, by reducing photosynthetic efficiency[55,101]. While these physical impacts are generally localised, appropriate site selection and mooring design can help mitigate seabed impacts.

Seabed Modification and Habitat Influence

Some shellfish farms have been observed to enhance seabed habitats by excluding destructive fishing activities and creating habitat for demersal species[37]. For example, research on an offshore mussel farm in England, found that the deployment of mussel farm infrastructure led to the accumulation of mussel shells and clumps on the seabed, increasing structural complexity and providing new microhabitats that support benthic communities and commercially valuable species. European lobster (*Homarus gammarus*) actively used both the farm anchors and mussel shell accumulations for refuge, while brown crab (*Cancer pagurus*) showed no strong preference for either habitat type, suggesting varied responses to aquaculture habitat modifications[102].

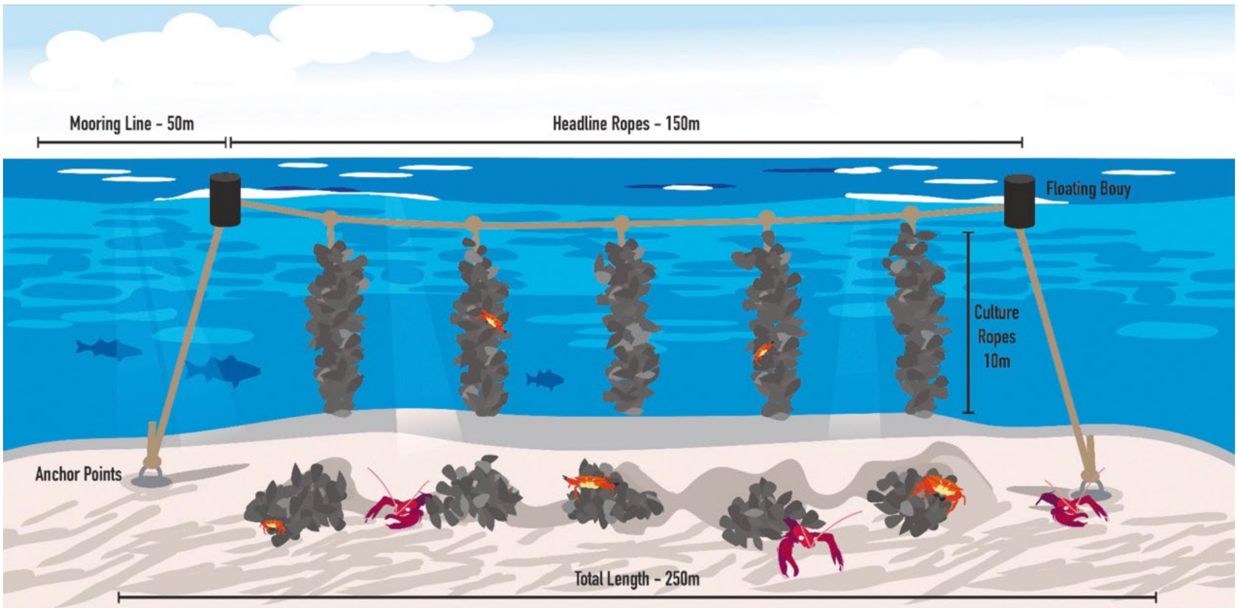

Figure 8. Offshore longline mussel farm providing structural habitat that supports demersal and commercially important species[102].

The extent to which aquaculture activities modify the seabed depends on site-specific factors such as hydrodynamic conditions, sediment type, and farm design[103]. Strategic site selection and farm configuration can help mitigate physical impacts while supporting habitat structure, ensuring aquaculture development is compatible with the achievement of GES.

Natural England, in a recent assessment, notes that wild Pacific oyster settlement—while occurring independently of aquaculture in some locations—has been significant in the vicinity of certain farming sites, while other farms show little to no associated wild settlement. This variation underscores the need for site-specific monitoring to assess the role of aquaculture in the spread of Pacific oysters and its potential ecological consequences. Where large-scale wild reefs have developed, particularly in Protected Areas, these reefs may alter sediment composition, modify hydrodynamic processes, and impact native benthic communities. Natural England's report emphasises the importance of understanding these habitat changes in the context of conservation management[21].

Overlaps: Nutrient-related impacts on the seabed from aquaculture waste are relevant to this indicator but have been primarily addressed in D5.

Hydrographical Conditions (D7) – Purpose: Permanent alterations of hydrographical conditions do not adversely affect marine ecosystems.

For aquaculture in England and Northern Ireland, this descriptor is not considered a priority indicator. While some localised hydrographical changes may occur around aquaculture sites, such as minor reductions in water flow near finfish cages or sediment resuspension from shellfish farming, these effects are highly localised and most unlikely to be permanent. Given the scale and type of aquaculture in these regions, there is no strong evidence that it leads to permanent hydrographical alterations that adversely affect marine ecosystems.

Overlaps: There are no notable overlaps with other descriptors.

Contaminants (D8) – Purpose: Concentrations of contaminants are at levels not giving rise to pollution effects.

Aquaculture has the potential to introduce chemical contaminants into the marine environment through the use of antifoulants, antibiotics, pesticides, diesel spills, and microplastics. These substances may enter the water column through direct application, leaching, or accidental discharge, with potential consequences for marine ecosystems. However, certain forms of aquaculture, such as shellfish and seaweed farming, may play a role in mitigating contamination by filtering pollutants from the water column.

D8 - Indicator 8.1: Concentration of contaminants

Understanding the types and concentration of contaminants involved in aquaculture production is key to assessing their potential impact on the achievement of GES. This section examines potential aquaculture contaminant sources and how they enter the marine environment.

Antifouling Paints and Chemical Leaching

Antifouling paints, used to prevent biofouling on aquaculture structures and vessels, have traditionally included toxic compounds such as tributyltin (TBT), though this has now been banned and phased out in favour of copper-based alternatives. Despite this regulatory shift, concerns remain regarding copper accumulation in sediments and its long-term environmental impact. Copper is a naturally occurring element essential for marine life in small amounts. However, at elevated levels from sources like antifouling paints, it becomes toxic, affecting gill function, growth, and stress levels in fish. While copper accumulation in sediments near boatyards and areas with high antifouling use can pose a risk to benthic organisms, studies indicate that wild fish populations in the vicinity of fish farms generally exhibit low copper levels and are not significantly impacted by antifoulant-related contamination because of aquaculture activities[104,105].

Antimicrobial Use and the Risk of Antimicrobial Resistance (AMR)

Globally, the use of antimicrobials in aquaculture is a recognised concern, as residues can persist in the marine environment and contribute to AMR in marine microbial communities[106,107]. According to the 2024 Responsible Use of Medicines in Agriculture Alliance (RUMA) report, the salmon sector is the primary user of antimicrobials in UK aquaculture. However, the report notes that antimicrobial treatments were limited to a small number of farms, with 7.5% of freshwater farms and 9.8% of marine farms using antibiotics in 2023[108]. Given the limited scale of ocean-based finfish production in England and Northern Ireland, limited to two sites producing salmon in Northern Ireland, the potential impact of antimicrobial use from aquaculture on the achievement of GES in these localities is relatively small. Of note, shellfish and seaweed aquaculture in the UK does not use antimicrobials or other chemicals[35,109].

The Centre for Environment, Fisheries and Aquaculture Science (CEFAS) has been designated as the FAO Antimicrobial Resistance Reference Centre, reflecting the UK's commitment to minimising AMR risks in aquatic environments[107]. Ongoing monitoring and strict management practices remain essential to mitigating AMR risks in aquaculture and ensuring alignment with the UK’s broader AMR reduction strategies.

Other Potential Contaminants Related to Salmon Aquaculture

Given the limited scale of ocean-based finfish production in England and Northern Ireland—restricted to two salmon farming sites in Northern Ireland—data on contaminant levels from chemical treatments in these regions is scarce. However, insights from the Scottish salmon sector provide a useful proxy to understand potential contaminant sources associated with chemical treatments.

In the Scottish salmon sector, chemical treatments used for sea lice control can introduce contaminants into the marine environment. One key concern is pesticide residues, such as emamectin benzoate (SLICE®) and azamethiphos, which are used to manage sea lice infestations[110]. These substances have differing environmental behaviours. Reviews by the Scottish Environment Protection Agency (SEPA) have assessed environmental quality standards for emamectin benzoate, highlighting its potential to persist in sediments and accumulate over time, potentially affecting non-target benthic organisms[111]. In contrast, azamethiphos remains primarily in the water column, where it degrades through hydrolysis with a half-life of approximately 8.9 days, reducing the likelihood of sediment accumulation[112].

Another potential source of contamination is hydrogen peroxide, which is used as a bath treatment for sea lice and amoebic gill disease. While hydrogen peroxide breaks down into water and oxygen, meaning it does not persist in the marine environment, high concentrations may cause temporary localised effects on marine organisms[113]. Formalin (formaldehyde) is also widely used in aquaculture, including in Atlantic salmon farming, to treat protozoan, oomycete, and monogenean ectoparasites. It is one of the most commonly used and cost-effective treatments used in the aquaculture sector, and while environmental risks from formalin are considered to be limited, concerns have been raised about the health risks it poses to workers handling the substance[114–116]. However, the extent to which these chemicals may be used on Northern Ireland's salmon farms is unclear.

In Northern Ireland, the Department of Agriculture, Environment and Rural Affairs (DAERA) oversees aquaculture licensing and fish health regulations under the Fisheries Act (Northern Ireland) 1966, ensuring compliance with environmental and biosecurity standards[117]. Unlike Scotland's larger salmon sector, where farms are required to report any usage of regulated chemicals to SEPA and this information is made publicly available, no equivalent publicly accessible reporting system exists for Northern Ireland's salmon farms. However, chemical use in Northern Ireland is still subject to regulatory oversight, with compliance monitored through inspections and adherence to EU REACH regulations, which continue to apply under the Northern Ireland Protocol[118].

Diesel Spills and Hydrocarbon Contamination

Operational discharges from aquaculture vessels, including diesel and oil spills, can introduce hydrocarbon contaminants into the marine environment. These spills, whether from routine operations or accidental leaks, pose toxicity risks to marine life and may persist in sediments, where they can impact benthic organisms. For example, in July 2024, a vessel associated with a Scottish salmon farm sank in the Sound of Mull, leading to a fuel spill which required an environmental recovery operation[119].

Marine birds can also be affected by small diesel spills through direct contact, leading to ingestion during preening and hypothermia from matted feathers. While small spills are typically short-lived on the water surface, they can pose a serious risk in areas where birds are concentrated, such as near nesting colonies or migration stopover sites[120,121]. These incidents underscore the importance of stringent operational protocols and emergency response strategies within the aquaculture sector to prevent and address fuel spills.

Microplastics from Aquaculture Infrastructure

Microplastic pollution is an emerging concern in aquaculture environments, with particles originating from infrastructure components such as plastic ropes, nets, and coatings. Microplastics are defined as plastic fragments smaller than 5mm, which may either be intentionally manufactured at this size (e.g., nurdles) or result from the breakdown of larger plastic materials. While microplastics originate from a wide range of human activities, including industrial processes, domestic waste, and fishing, aquaculture can also contribute to their release. Over time, these materials degrade due to factors like sunlight exposure, seawater corrosion, and physical abrasion, releasing microplastics into the surrounding waters. These particles can accumulate in sediments, be ingested by marine organisms, and transfer contaminants through the marine food web. Recent research indicates that microplastic concentrations in UK coastal waters are significantly higher than previously recorded, with some areas containing nearly 100 times more microplastics than data collected six years ago[122–124].

D8 - Indicator 8.2: Effects of contaminants

While D8.1 discusses the presence and sources of contaminants associated with aquaculture, this section evaluates their broader ecological effects. Since shellfish farming is the dominant form of aquaculture in England and Northern Ireland, this sector's susceptibility to contaminant exposure and its potential role in water quality improvement make it the key focus of this indicator. While certain environmental effects—such as those linked to antifoulants and sea lice treatments—were discussed in D8.1 due to their intrinsic link to contaminant concentrations, this section focuses on the bioaccumulation of contaminants in shellfish and their potential ecosystem-level impacts.

Bioaccumulation of Contaminants in Marine Ecosystems

Through their natural filtration processes, shellfish and seaweed aquaculture interact with contaminants, which can potentially lead to the accumulation of pollutants within their tissues. Filter-feeding bivalves, such as mussels and oysters, can absorb heavy metals and persistent organic pollutants (POPs) if they are present in the water. This bioaccumulation can impact species that rely on shellfish beds for feeding and reproduction, with potential consequences for biodiversity and ecosystem stability.

Simultaneously, bivalves and seaweed contribute to contaminant removal by filtering particulates and sequestering pollutants, potentially enhancing local water quality. The extent of this benefit depends on site-specific factors such as farm density, hydrodynamic conditions, and the nature of the contaminants present. While these processes may support the achievement of GES by improving water conditions, they also raise concerns about contaminant accumulation in shellfish and seaweed, which is further addressed in D9 in the context of food safety considerations.

Overlaps: The bioaccumulation of contaminants in commercial fish and shellfish is related to D1 and D3, where potential impacts on stock health are considered. Ecosystem-level effects related to contaminant transfer through trophic interactions is linked to D4. Contaminants from nutrient-driven water quality changes are considered in D5. Meanwhile, contaminant levels in seafood intended for human consumption are examined in D9, where the implications for food safety are considered. Additionally, the contribution of aquaculture to microplastic pollution is relevant to D10, which explores marine litter and its impact on the achievement of GES.

Contaminants in Fish and Seafood (D9) – Purpose: Contaminants in fish and other seafood for human consumption do not exceed levels established by Union legislation or other relevant standards.

Unlike other GES descriptors, which primarily assess marine ecosystem health, D9 focuses on food safety and human health. While aquaculture enables greater control over contaminant monitoring compared to wild fisheries, filter-feeding species such as bivalves and seaweed can accumulate pollutants from surrounding waters. This section examines the regulatory challenges and monitoring efforts required to ensure compliance with food safety standards.

D9 - Indicator 9.2: Frequency of exceeding regulatory levels

Regulatory monitoring ensures that contaminants in aquaculture products remain within safe consumption limits. While UK farmed seafood generally meets food safety standards, environmental contamination and localised pollution events can occasionally lead to regulatory exceedances, impacting trade and consumer confidence.

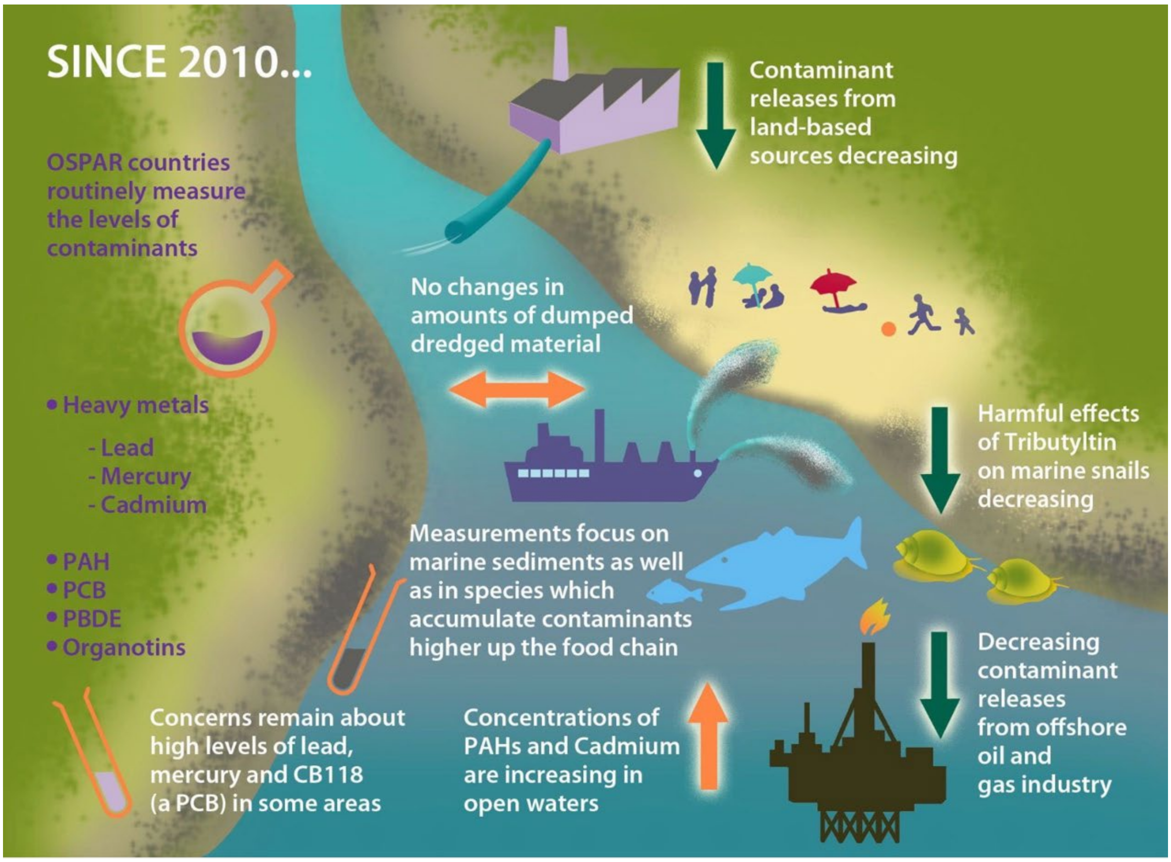

Figure 9. While contaminant discharges across the OSPAR Maritime Area have declined, persistent pollutants such as mercury, lead, and certain PCBs remain above background levels in some regions, continuing to pose risks to marine ecosystems (Source: Scottish Government Marine Scotland Blog[126]).

Bioaccumulation Risks in Shellfish and Seaweed

Shellfish aquaculture is highly sensitive to environmental contamination, because filter-feeding bivalves, such as oysters and mussels, can absorb heavy metals, POPs, microplastics, and other contaminants from surrounding waters[36]. While aquaculture itself is not a source of these pollutants, bivalve production areas can be adversely affected by agricultural runoff, wastewater discharge, and industrial pollutants[91] (Figure 9). Recent research has also highlighted that pharmaceuticals and personal care products (PPCPs), as well as endocrine-disrupting chemicals (EDCs), can accumulate in bivalves, raising additional concerns regarding their potential effects on marine food webs and human health[125].

Similarly, studies indicate that seaweed species can accumulate pollutants such as per- and polyfluoroalkyl substances (PFAS) from the surrounding environment. A study by the University of Portsmouth and the Marine Conservation Society found that sewage discharges contribute significantly to PFAS contamination in marine environments. Notably, seaweed samples collected from Langstone Harbour, a protected marine area in England, exhibited high concentrations of PFBA, a shorter-chain PFAS compound, with bioaccumulation factors 6,000 times greater than surrounding waters[127]. These findings indicate that seaweed in some locations may accumulate PFAS, raising potential concerns for human consumption. Given the increasing use of seaweed in food products, further research and monitoring are essential to assess the potential health risks associated with PFAS accumulation in seaweed[127]. However, aquaculture producers can mitigate these risks by carefully selecting production sites with high water quality, reducing the likelihood of significant contaminant accumulation.

In England and Northern Ireland, routine monitoring of designated shellfish waters ensures that levels of heavy metals, polychlorinated biphenyls (PCBs), and biotoxins remain within regulatory limits. However, sporadic pollution events, such as agricultural runoff spikes, wastewater discharges, and stormwater overflows, can temporarily elevate contaminant concentrations and necessitate targeted mitigation measures[128,129]. Microplastics in bivalves are also a concern because they not only pose direct ingestion risks but can act as vectors for other persistent contaminants, such as PFAS, bisphenols, and phthalates, potentially increasing consumer exposure risks[125].

Regulatory Frameworks and Food Safety Compliance in Aquaculture

UK food safety regulations, aligned with EU food safety standards, set maximum allowable concentrations for contaminants in shellfish[130]. When exceedances occur, they are typically linked to environmental contamination rather than aquaculture practices themselves[36]. To mitigate the food safety risks associated with contaminant exposure, regulatory frameworks classify shellfish harvesting areas based on microbiological water quality and contamination risks, determining whether shellfish require depuration before sale. Depuration—purifying shellfish by holding them in clean water—plays a key role in reducing microbial and chemical contaminant levels before they are sold for consumption[130].

The UK's departure from the EU has further complicated the shellfish export landscape. Post-Brexit regulations have imposed stricter requirements on the export of live bivalve molluscs to the EU, particularly those harvested from waters not classified as the highest quality. As a result, depuration has become an even more critical step in meeting food safety standards, adding logistical and financial burdens for shellfish producers[36].

Despite the effectiveness of depuration for reducing microbiological contaminants, its efficiency in removing chemical pollutants such as heavy metals, microplastics, and pharmaceutical residues remains uncertain. Studies suggest that while some contaminants can be purged over time, others may persist within shellfish tissues, underscoring the need for continued research into the efficacy of depuration for different pollutant types[125].

Contaminant Risks and Consumer Confidence in Shellfish Aquaculture

The accumulation of contaminants in farmed and wild organisms poses both food safety and economic challenges. Within the UK’s shellfish aquaculture sector, concerns regarding water quality and contamination risks have the potential to impact industry growth, particularly where consumer confidence is shaped by perceptions of pollution and safety[36]. While regulatory frameworks help mitigate risks, pollution events—such as spikes in agricultural runoff or illegal sewage discharges—can lead to food safety concerns, influencing market perception and trade opportunities.

Recent research has highlighted that sewage discharges are a significant source of contamination, with pollutants such as PFAS accumulating in shellfish and potentially entering the human food chain[127]. Given the increasing scrutiny on UK water quality and pollution management, maintaining consumer trust in shellfish safety will require continuous monitoring, transparency in regulatory processes, and effective mitigation measures to ensure compliance with food safety standards

Overlaps: The accumulation of contaminants in farmed seafood is inherently linked to environmental contaminant levels, as discussed in D8. The potential bioaccumulation of contaminants in commercial fish stocks is also relevant to D3. Additionally, while microplastic contamination in seafood has been primarily discussed in D8, its implications for food safety and human consumption are also relevant to this descriptor.

Marine Litter (D10) – Purpose: Properties and quantities of marine litter do not cause harm to the coastal and marine environment.

Marine litter is a well-recognised environmental concern, which is contributed to by an array of anthropogenic sources, including aquaculture. This section focuses on macroplastic waste, which can persist in the environment for years, impacting marine ecosystems and biodiversity.

D10 - Indicator 10.1: Characteristics of litter in the marine and coastal environment

Aquaculture-related marine litter originates primarily from plastic-based infrastructure, which can become a source of persistent marine debris, breaking down into smaller plastic fragments over time.

Sources and Types of Aquaculture-Related Marine Litter

Aquaculture contributes to marine litter across UK waters, with plastic waste items such as oyster bags, ropes, fish nets, mussel nets, and crates commonly identified as debris in marine environments[131]. Lost or discarded equipment, whether due to storm damage, wear and tear, or inadequate disposal, can persist in the marine environment, accumulating on shorelines and the seafloor. Research by Cefas has highlighted seabed litter as a hidden threat to UK marine biodiversity, particularly in terms of habitat disruption and the spread of invasive species[132].

While it is challenging to quantify the degree to which marine aquaculture in England and Northern Ireland contributes to this issue, marine litter surveys frequently document aquaculture materials among plastic debris, underscoring the importance of improving waste management practices and promoting gear recovery initiatives within the industry[131]. Notably, industry-led actions are also gaining traction, with some UK aquaculture operators exploring the use of biodegradable ropes and alternative materials to reduce plastic pollution[133]. A survey by the Ellen MacArthur Foundation found that around 80% of marine litter originates from land-based sources, underscoring the importance of effective waste management strategies to reduce pollution at its source[134].

Overlaps: Given the potential for lost aquaculture gear to entangle marine organisms and impact biodiversity, this descriptor is relevant to D1. As literature highlights the potential for marine litter to facilitate the spread of non-indigenous species, this descriptor overlaps with D2. While the contribution of microplastics from aquaculture infrastructure is related to this descriptor, this has been addressed in D8.

Energy, Including Underwater Noise (D11) – Purpose: Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment.

Aquaculture in England and Northern Ireland is not considered a significant contributor to underwater noise or other energy-related pressures and therefore has minimal relevance to this descriptor.

Overlaps: There are no notable overlaps with other descriptors.

BOX 2: Links between freshwater aquaculture & marine systems

Freshwater aquaculture in the UK, particularly trout and salmon farming, may seem separate from marine systems, but the two are closely connected. Nutrient runoff, disease transmission, and water abstraction all create knock-on effects for coastal and marine environments. However, under the MSFD, the impacts of freshwater aquaculture are not considered significant enough to justify a full descriptor-by-descriptor assessment of GES.

One of the clearest links is nutrient runoff. Waste from freshwater farms—uneaten feed and fish waste—can flow downstream, contributing to excess nitrogen and phosphorus in estuaries and coastal waters. In some cases, this fuels eutrophication, leading to algal blooms and oxygen depletion, which can negatively impact marine biodiversity. While this is relevant to GES Descriptor 5 (Eutrophication), the scale of impact from freshwater aquaculture is minor compared to agricultural runoff or sewage discharge.

Disease transmission and genetic interactions are also key concerns, particularly in the context of GES Descriptor 1 (Biodiversity) and Descriptor 3 (Commercial Fish and Shellfish). Freshwater hatcheries supplying marine farms can introduce parasites, diseases, or genetic dilution into wild populations when farmed fish escape. In the UK, this is particularly relevant to salmon farming, where interactions between farmed and wild stocks are a long-standing issue.

Hydrological changes from water abstraction and habitat modification also matter, particularly for GES Descriptor 6 (Seafloor Integrity) and Descriptor 7 (Hydrographical Conditions). Freshwater aquaculture often relies on significant water inputs, altering flow regimes and reducing freshwater supply to estuarine environments. This can disrupt natural salinity gradients, affecting key marine habitats such as shellfish beds and juvenile fish nurseries.

While these links highlight how freshwater aquaculture can influence marine health, its overall contribution to GES pressures is small compared to other land-based activities like intensive agriculture or industrial pollution. Freshwater aquaculture should be viewed as part of the broader ecosystem-based management approach, ensuring that best practices—such as improved waste treatment, biosecurity measures, and water management—minimise any unintended marine impacts.

From a policy and regulatory perspective, this means freshwater aquaculture should be monitored for its role in cumulative pressures on marine systems but not treated as a major driver of GES status on its own. The focus should remain on integrated catchment management, balancing sustainable aquaculture growth with the health of marine ecosystems.

Synthesis and Overview of Aquaculture Impacts and GES Findings

Aquaculture is often cited as a sector with the potential to hinder the achievement of GES, particularly in relation to habitat modification, nutrient inputs, the introduction of contaminants, and the spread of non-native species. Many of the environmental risks associated with aquaculture are site-specific, dependent on production type, location, and management practices. England and Northern Ireland's marine aquaculture industry is dominated by shellfish farming, with only two marine finfish sites operating in Northern Ireland. This contrasts with Scotland's much larger marine finfish sector, where many of the more widely discussed environmental concerns—such as nutrient enrichment and the use of chemical treatments—are more pronounced. While findings from Scotland and international studies have been used as proxies where relevant, it is important to acknowledge the lack of England- and Northern Ireland-specific research on many aquaculture-environment interactions.

Despite this, some GES descriptors are more relevant than others when considering the impacts of marine aquaculture in England and Northern Ireland. This synthesis highlights the most significant areas of concern, key knowledge gaps, and where aquaculture may play a role in environmental recovery rather than degradation. In the following synthesis, the topics are arranged in order of greatest to least importance based on the opinion of the authors regarding the extent to which aquaculture influences the achievement of GES. This is based on a snapshot of current production.

Key Findings and Priority GES Descriptors

1. D2 – Non-Indigenous Species

The introduction and spread of NIS is one of the most contentious and well-documented issues linked to aquaculture in England and Northern Ireland. The farming of Pacific oysters represents a key challenge, as this species is classified as non-native but is already well-established due to historical introductions and natural dispersal. Evidence suggests that its spread is inevitable, regardless of aquaculture activities, raising the question of whether its continued farming should be restricted or encouraged for its ecosystem service benefits (e.g., water filtration and habitat creation).

The Natural England report[135] on Pacific oyster populations in Devon and Cornwall reinforces this challenge, highlighting the increasing establishment of self-sustaining populations in Protected Areas and designated conservation sites. The report underscores the urgent need for site-specific management strategies,

particularly in areas where Pacific oyster reefs may alter biodiversity and compete with native species. These findings further support the call for more research into ecological trade-offs and management interventions that balance conservation priorities with ecosystem service benefits.
This issue is particularly relevant in the context of native oyster restoration. With only 1% of native European flat oyster populations remaining in Europe, efforts are now focused on conservation and restoration rather than commercial farming. However, Pacific oysters could provide a functional replacement for lost reef habitats—a perspective that remains highly controversial. More research is needed on the ecological trade-offs of Pacific oyster proliferation in England and Northern Ireland.

2. D8 & D9 – Contaminants and Food Safety

Shellfish aquaculture interacts with contaminants primarily through bioaccumulation rather than direct inputs, with agricultural runoff, wastewater discharge, and industrial pollution posing risks to the sector. The filter-feeding nature of bivalves and seaweed makes them susceptible to contaminants such as heavy metals, POPs, and microplastics, which can impact both ecosystem health and food safety.

The post-Brexit regulatory landscape has created additional challenges for compliance, with stricter EU export standards for live bivalve molluscs. Depuration is widely used to mitigate microbiological risks in bivalve aquaculture; however, its effectiveness in removing chemical contaminants such as heavy metals, microplastics, and PFAS remains underexplored, warranting further research. While international studies suggest that pollutants such as pharmaceutical residues, EDCs, and PFAS are emerging concerns for bivalve aquaculture, comprehensive long-term monitoring specific to England and Northern Ireland is limited, making it difficult to assess local trends in bioaccumulation and depuration capacity. Addressing these knowledge gaps through targeted research and expanded monitoring programs would help ensure that regulatory frameworks remain effective in mitigating contamination risks in shellfish aquaculture.

3. D1 – Biodiversity and Ecosystem Functioning

Shellfish and seaweed aquaculture have the potential to enhance marine biodiversity by providing habitat structure and improving water quality through filtration. However, poorly managed aquaculture infrastructure can also introduce risks, such as spatial competition with wild species or seabed disturbance from farm maintenance activities.

Long-term monitoring of how shellfish and seaweed aquaculture influence native species and ecosystem structure in England and Northern Ireland appears to be limited, particularly in relation to bioaccumulation trends and habitat interactions. While international studies offer insights, empirical data specific to England and

Northern Ireland are less frequently reported in the literature. Expanding research on the ecological interactions of aquaculture in these waters would improve understanding of both its potential benefits and associated risks to biodiversity.

4. D10 – Marine Litter

Plastic debris from aquaculture gear (e.g., ropes, netting, buoys, and flotation devices) is a well-documented source of marine litter in the UK, though the relative contribution from aquaculture in England and Northern Ireland is unclear. Beach clean-up data and seabed litter surveys indicate that aquaculture debris is found in UK waters, but there is a need for more systematic tracking of lost and discarded gear. Industry initiatives promoting biodegradable materials and improved waste management are a positive step, though their uptake is currently limited.

5. D5 – Eutrophication

Unlike in Scotland, where finfish farming can contribute to nutrient enrichment and localised eutrophication, the dominance of shellfish aquaculture in England and Northern Ireland means that nutrient loading from aquaculture is not a significant concern. In fact, shellfish and seaweed farms may help mitigate nutrient pollution by removing excess nitrogen from coastal waters.
However, excessive nutrient removal could pose risks in areas where primary production is already limited, potentially affecting food web dynamics. More research is needed to quantify the net effects of large-scale shellfish and seaweed farming on nutrient cycling in UK waters, particularly in near-shore sites.

6. D4 – Food Webs

Aquaculture's influence on food webs is closely linked to bioaccumulation (D8/D9) and biodiversity (D1), with shellfish and seaweed farming acting as both a filter and a potential contaminant sink. Given the limited scale of aquaculture in England and Northern Ireland, direct trophic impacts are unlikely to be a major concern.

Key Knowledge Gaps and Areas for Further Research

Several key gaps emerged in this assessment, highlighting areas where further research is needed to support evidence-based policymaking:

- Management of Pacific Oyster Spread in England and Northern Ireland: Research has already demonstrated the ecological impacts of Pacific oyster establishment in UK, including habitat alteration and competition with native species. Given that their spread appears to be ongoing despite control efforts, future research should focus on developing site-specific management strategies. This includes assessing the feasibility of containment measures in sensitive areas while also evaluating whether, in some locations, established

Pacific oyster populations could provide certain ecological functions, such as water filtration, that have been lost with the decline of native oysters.

The Natural England report provides crucial insights into the challenges of Pacific oyster management, particularly in protected areas of South Devon and Cornwall, where wild Pacific oyster populations continue to expand despite active control measures. The report also highlights the lack of consensus on management approaches, with some stakeholders advocating for eradication in protected areas, while others explore co-existence strategies that leverage their water filtration benefits. These findings reinforce the importance of targeted, site-specific research to determine appropriate policy interventions for managing Pacific oyster populations in England and Northern Ireland.

Any such considerations should be carefully weighed against conservation priorities and the need to protect native biodiversity.

- Contaminant Monitoring in Shellfish Waters: While international research highlights PFAS, pharmaceutical residues, and EDCs as emerging concerns for bivalve aquaculture, long-term monitoring specific to England and Northern Ireland remains limited. Expanding targeted research and monitoring programs would improve understanding of bioaccumulation risks and help ensure regulatory frameworks effectively address contamination in shellfish waters.

- Microplastic Pollution, Marine Litter, and Sustainable Material Alternatives: Further data collection on aquaculture's contribution to macroplastic and microplastic pollution in UK waters is warranted, particularly in regions with high shellfish farming activity. Additionally, research into viable, sustainable, and biodegradable alternatives to conventional aquaculture materials is needed to mitigate the sector's long-term contribution to marine litter.

- Ecosystem Functions and Nutrient Cycling in Shellfish and Seaweed Farming: More UK-specific research is required on the net ecological benefits and potential trade-offs of bivalve and seaweed aquaculture, particularly in terms of nutrient cycling, habitat provisioning, and carbon sequestration. While these forms of aquaculture are often recognised for their role in removing excess nutrients from the water column, further research is needed to assess the long-term effects of large-scale shellfish and seaweed farming on nutrient balance, particularly in nearshore environments where nutrient depletion or redistribution could influence ecosystem dynamics.

BOX 3: Monitoring & Environmental Data Collection

Monitoring of aquaculture's environmental impacts is inconsistent, with requirements varying by species and location. Water quality monitoring, disease surveillance, and benthic impact assessments are standard for large finfish farms, but there is less structured oversight for shellfish and seaweed farms. While monitoring programmes such as those under the WFD and the MSFD contribute to assessing aquaculture's impact, there is no single, dedicated programme ensuring that aquaculture operations systematically report their nutrient discharge, chemical use, or biodiversity impacts. Expanding long-term monitoring programmes to capture the cumulative effects of aquaculture at a regional scale would provide better insights into its role in achieving GES.

GES and Aquaculture - Synthesis

This assessment of the impact of English and Northern Irish Aquaculture on GES finds that aquaculture in England and Northern Ireland does not represent a major barrier to achieving GES. However, certain site-specific impacts, particularly those related to the bioaccumulation of contaminants in aquaculture products, marine litter, and non-native species, warrant ongoing scrutiny. The sector's potential for environmental enhancement—through nutrient removal, habitat creation, and biodiversity support—is an area that deserves further research. Ensuring that future regulatory decisions are informed by robust, UK-specific data will be critical to achieving GES while also supporting a sustainable aquaculture industry.

Future Growth of Aquaculture in England and Northern Ireland

Seafood Demand

Aquaculture production, as with all food sectors, is closely correlated with consumer demand and trends in consumption. UK seafood demand has varied historically and has seen significant declines in recent years with overall domestic seafood consumption declining 22% between 2006 and 2022, with a continuation of this decline post-Covid equivalent to a 30% reduction every ten years[136]. A recent Seafish report, which reviews developments in UK seafood consumption, comments that, "*Long term consumption per capita is a real concern*,"[136].

Farmed seafood can benefit from competitive advantages over wild caught due to consistent pricing and year-round stability of supply. However, seafood demand is highly price sensitive, and seafood must compete with terrestrial proteins as well as imports on supermarket shelves. Notably, UK seafood demand is highly species specific, with 80% of seafood consumed being from the 'big five,' namely salmon, tuna, haddock, prawns and cod[137]. As the UK is so dependent on a limited range of species, it has become a net importer of seafood[138]. Additionally, there is a widening mismatch between UK seafood production and consumer demand, with both increasing imports and increasing exports since the turn of the century (Figure 10).

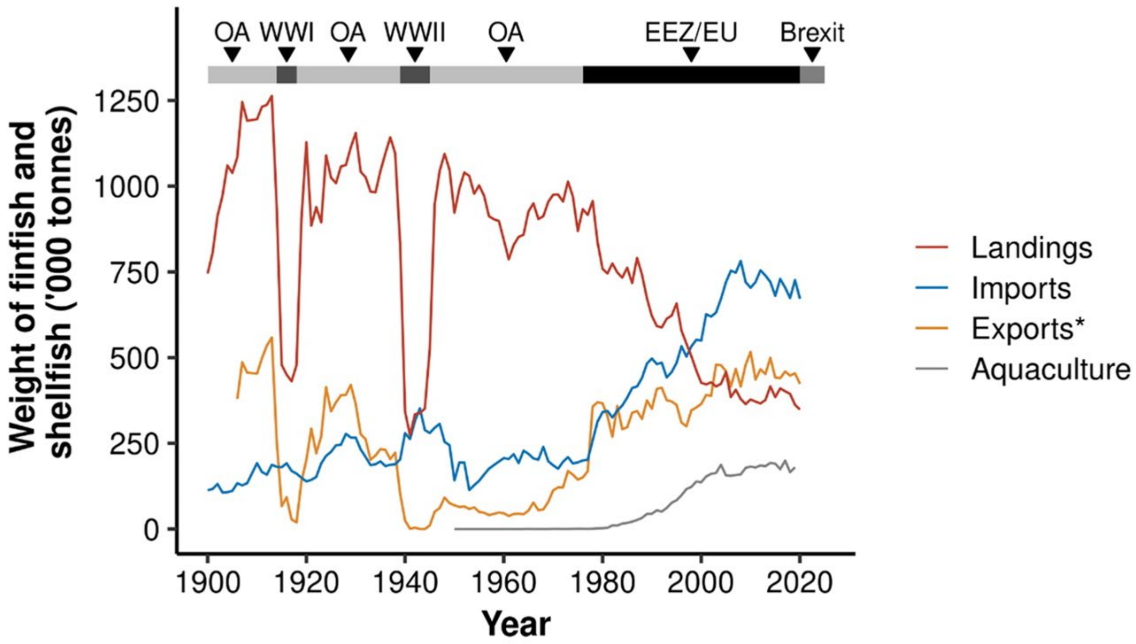

Figure 10. Changes in UK finfish and shellfish domestic landings (red), imports (blue) and exports (yellow), and aquaculture production (grey) between 1900 and 2020. Note that landings and aquaculture represent pre-processed weights, while most imports and exports are processed. Note that export weights (*) are not independent of the other datasets, as UK export data will include some domestic landings, aquaculture and reimports, as well as UK vessel landings abroad. Major periods are

shown above plot (OA = Open access policy, WW = World wars, EEZ/EU = Exclusive Economic Zone and European Union policy).

The one exception to this trend is salmon, largely produced in Scotland, and evidently the UK's 'favourite fish'[139] - and the UK's largest food export[140]. However, the farming of other high-demand species in the UK remains low due to biological or geospatial constraints, and UK domestic per capita consumption of mussels remains one of the lowest in Europe[141]. Conversely, exports of UK produced oysters and mussels have been constrained by EU regulatory measures introduced post-Brexit. The EU only permits import of bivalves from Class A waters or those depurated before shipment, whereas most UK waters are classified as Class B[*9]. Depuration capacity and expense, coupled with EU buyers' preference for localised depuration, have severely hampered UK export potential for mussels and oysters[142].

Supply

Compared to Scottish production and international imports, English and Northern Irish aquaculture production remains at a relatively low level. Between 2010 and 2022, England's aquaculture production of finfish declined by over 50%, with marginal increases in bivalve production (Figure 11). In Northern Ireland, by contrast, finfish production has remained relatively stable, while bivalve production has shown a significant reduction in output. The overall picture for aquaculture in both England and Northern Ireland is one of general decline in production tonnage with a concomitant and significant increase in prices per tonne, particularly for finfish.

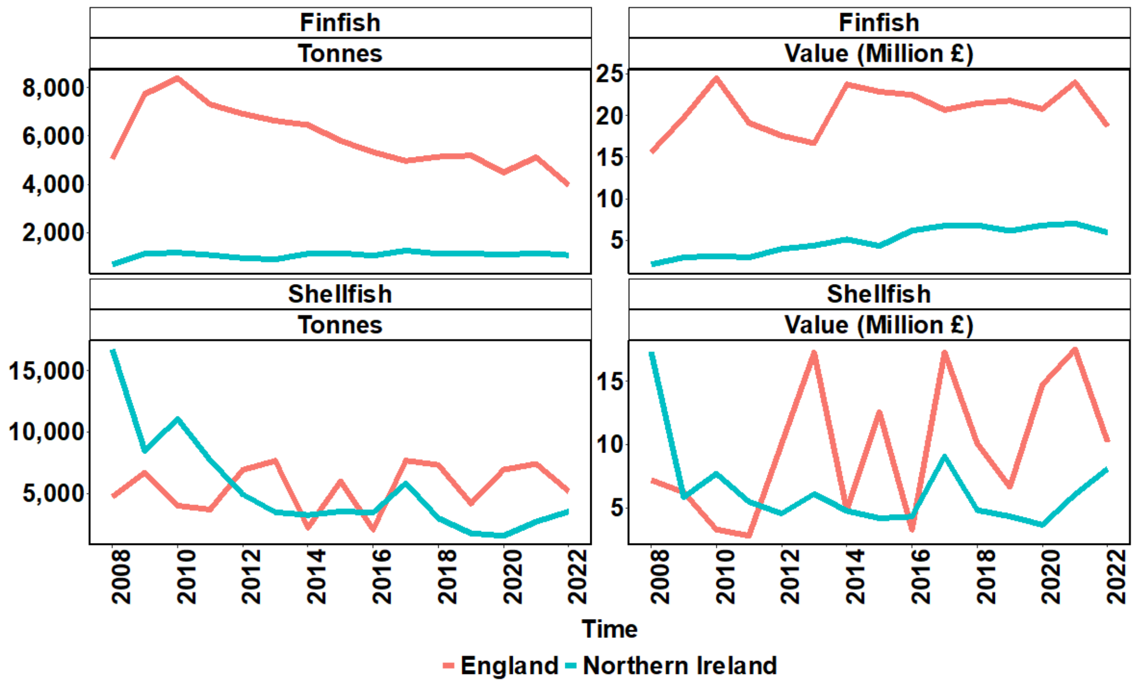

Figure 11: Historic UK production of finfish and shellfish data, 2008 to 2022 (Source Cefas).

[*9] Class A and B refer to the concentration of *E.coli.*

Constraints

The primary constraints to the growth of aquaculture in Northern Ireland and England, and those factors which inhibit both industry expansion and investment in the sector include:

Issue	Description
UK seafood consumption	Limited or declining UK domestic seafood consumption coupled with export challenges[130,142].
Social license	Negative public perceptions of marine aquaculture, concerns around visual amenity, and debates surrounding farmed/wild equivalences[143]. High-profile recent examples include objections over a seaweed farm in Cornwall[144] and debates over a land-based salmon farm proposal in Grimsby[145].
General lack of support infrastructure	Poor coordination and resource allocation has been noted in relation to aquaculture developments between industry, research, and government agencies[146].
Marine Spatial Planning considerations	UK seas are at a critical juncture as demand for marine space is projected to increase substantially over the next 10-30 years, including provision for Marine Protected Areas (MPAs), Special Areas of Conservation (SACs), Marine Conservation Zones (MCZs), offshore wind, cabling, and other uses that may compete with aquaculture siting authorisations[147]. Conversely, if permitted, colocation of competing users, such as between seaweed and wind farms, may offer colocation synergies[148].
Authorisations	Difficulty and delays in obtaining the necessary authorisations and permits for aquaculture operations[9].
Investment	Vagaries in the investment climate present challenges for early-stage aquaculture developers[149].
Water quality	As well as classification challenges noted in relation to EU exports, bivalve aquaculture is highly vulnerable to poor water quality[150].
Species limitations	Whilst Pacific oysters as a species may present the greatest potential for the growth of aquaculture in England and Northern Ireland, regulatory hurdles (largely due to their non-indigenous status) may curtail or diminish growth prospects[16].
Temperature and site limitations	High and variable surface temperatures and a lack of suitable sites have prevented the development of marine net pen aquaculture for finfish in southern UK waters[9].

BOX 4: Looking Ahead: The Future of Aquaculture and GES

The environmental pressures on aquaculture in England and Northern Ireland are anticipated to evolve over the coming decades due to factors such as climate change, shifting disease dynamics, competition for space, and increasing global trade. These changes have significant implications for achieving GES[151]. Below, examples of the different risks are briefly described along with the GES descriptors relevant to each (also see Table 3).

Climate Change, Harmful Algal Blooms & Disease Risks (GES Descriptors: D1, D2, D3, D5)

Climate change may exacerbate HABs through mechanisms such as ocean warming, acidification, and deoxygenation. These changes can create conditions that favour the growth and spread of HABs, leading to increased frequency and intensity of these events in coastal areas[152]. Rising sea temperatures are expected to intensify disease risks within aquaculture systems[153]. Warmer waters can favour parasites and bacterial infections, such as *Vibrio* spp., raising concerns for shellfish safety and public health (D9)[154]. Increasing water temperatures and weather anomalies due to climate change are contributing to the rising prevalence of gill diseases in farmed Atlantic salmon in Scottish aquaculture sites, posing significant challenges to fish health and industry productivity[155]. Additionally, sea lice infestations in salmon farms, already a significant issue, may worsen with increasing temperatures[156], potentially leading to greater reliance on chemical treatments (D8). Furthermore, responses to increased bacterial challenges may involve antimicrobial use, exacerbating the risk of AMR[157]. Warmer waters may also expand the range of NIS (D2), which can alter local biodiversity (D1) and food web structures (D4). The introduction and spread of NIS through aquaculture could accelerate under climate change as species adapt to new thermal thresholds[158].

Jellyfish Blooms & Aquaculture Vulnerability (GES Descriptors: D1, D4, D5)

Changes in ocean conditions, overfishing of natural predators, and eutrophication could drive more frequent jellyfish blooms, posing operational and environmental challenges[159]. Large aggregations of jellyfish can clog aquaculture nets, cause mass mortalities in farmed fish, and alter marine food web structures (D4). For example, Scottish salmon farms recently experienced significant losses due to jellyfish blooms, highlighting the industry's vulnerability to such events[160].

Marine Spatial Squeeze (GES Descriptors: D1, D3, D5, D6, D7, D8, D9, D10, D11)

Spatial squeeze in England and Northern Ireland will likely intensify as renewable energy and conservation pressures converge. This increased competition for space poses challenges for achieving GES. Without proactive, integrated planning, traditional users, especially fishers, risk being disproportionately sidelined. However, there are also opportunities for coexistence if careful management and strategic planning are implemented to ensure aquaculture can sustainably contribute to food production and livelihoods[147].

Increased Marine Trade & Biosecurity Risks (GES Descriptors: D2, D8, D10)

As global shipping expands, biosecurity risks will rise due to the movement of invasive species via ballast water[161]. This is a significant concern for shellfish farms, which are particularly vulnerable to biofouling and disease transmission from imported aquaculture stock. Additionally, contaminants (D8), such as oil spills or microplastics (D10) from increased marine traffic, could further impact aquaculture viability.

Extreme Weather Events & Infrastructure Resilience (GES Descriptors: D6, D10)

Climate models predict that storm intensity and frequency will increase[162], posing risks to aquaculture infrastructure. Storms can lead to escaped farmed fish (D3), seabed habitat damage (D6), and lost plastic-based gear, exacerbating marine litter (D10). For instance, a recent incident in Scotland resulted in the escape of approximately 50,000 farmed salmon, raising concerns about the potential genetic and ecological impacts on wild populations[163].

Aquaculture Ambitions

England

Informed by the aforementioned constraints on English Aquaculture, a taskforce called Seafood 2040 was formed to envision England's aquaculture potential and develop an English Aquaculture Strategy (EAS), 2020[9]. The Strategy projects ambitious multi-species production growth in the sector, potentially achievable by 2040. These aspirations are projected along with actual historic production data (), highlighting the considerable challenge industry must meet to have a realistic chance of attaining these aspirations.

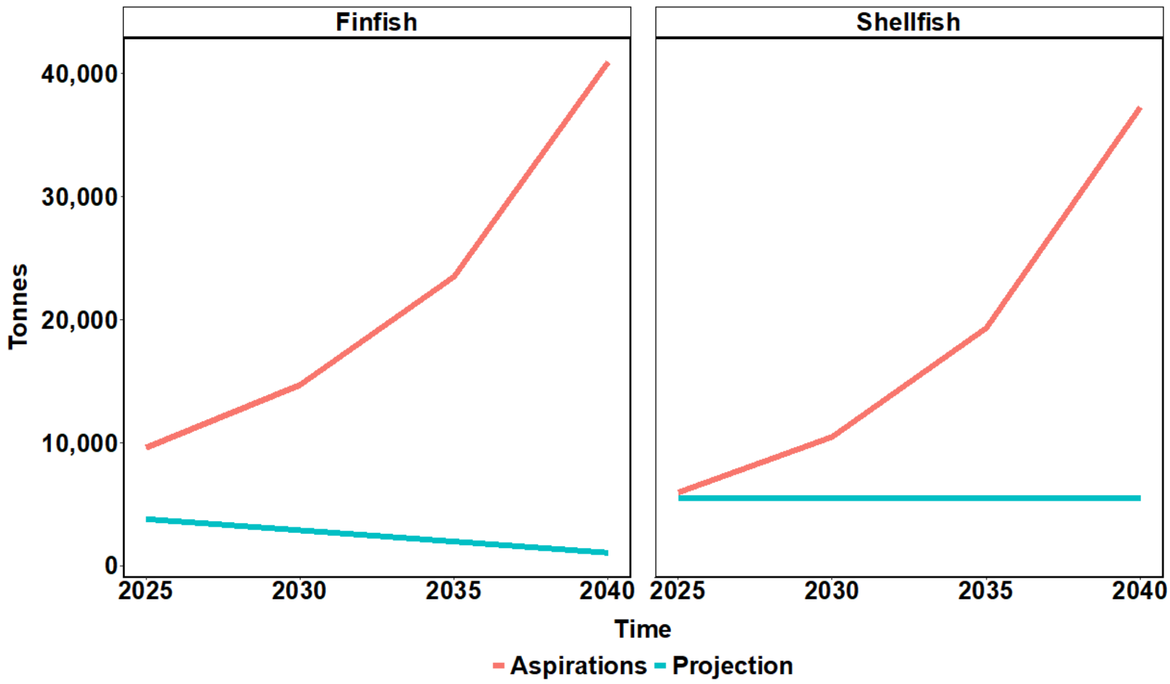

Figure 12. English aquaculture aspirations from the English Aquaculture Strategy[9] red line) and projections based on historic data (Cefas data, 2015 onwards) projected forward (blue line). The projected blue regression line for finfish was significant ($R^2 > 0.5$, $P < 0.05$) whilst for shellfish this line is based on a mean of production since 2015 rather than a regression because of a lack of significance. Results of all regressions are provided in the Annex.

Northern Ireland

The Aquaculture Representative Group for Northern Ireland[164] notes that "*The small yet diverse capacity of Northern Ireland's aquaculture sector, combined with continued access to the EU single market as well as GB, suggests there are a lot of positives for the future of aquaculture in Northern Ireland, yet there are many challenges for operators seeking to grow the sector,*" [165]. With a shift in the main species cultivated from mussels to Pacific oysters, and only a small marine finfish aquaculture sector[6], growth of aquaculture in Northen Ireland may be dependent on developments as they relate to the Pacific oyster sector[166]. This shift may have implications for MPAs, as the expansion of Pacific oyster cultivation has been shown to alter intertidal habitats and affect biodiversity within designated conservation sites[167].

Innovations in aquaculture & relevance to GES

Global aquaculture has expanded significantly in recent years. Between 1990 and 2020 the sector has increased 609%, an average annual increase of 6.7%[168]. During this time, significant investments have been made in research and development in the industry, and notable improvements have been achieved across a range of sustainability indicators[169].

Whilst the UK aquaculture industry only plays a small part in global aquaculture production, it has become a significant hub of aquaculture research and innovation. Notably, the University of Stirling's Institute of Aquaculture is a world-leading aquaculture research centre that includes the National Aquaculture Technology and Innovation Hub[170]. Other UK centres of research and innovation include the Sustainable Aquaculture Innovation Centre[171], Cefas[172], plus various university led initiatives, such as ARCH-UK[173], and the Plymouth Marine Lab[174], amongst others. Additionally, several other government-funded initiatives have incentivised innovation in the seafood sector, such as the UK Seafood Innovation Fund[175].

Cumulatively, public and private investment in research and development in aquaculture has driven an extensive and impressive range of innovations across the sector globally. Much of this innovation is recent and in the commercialisation process. Many may offer potential positives towards achieving GES (Table 3, Table 4, Table 5).

Table 3. Table of technologies that have the potential to help mitigate the negative impacts of aquaculture operations and therefore help contribute to achieving and maintaining GES in England and Northern Ireland. Table contains the top 1/3 of all listed innovations organised by relevance to descriptors (sum) and readiness level. In the column entitled 'Readiness for adoption,' the ranking is as follows: 1 = Conceptual. 2 = In development, 3 = Commercially viable. D1 = Biodiversity, D2 = Non-Indigenous Species, D3 = Commercial Fish and Shellfish, D4 = Food Webs, D5 = Eutrophication, D6 = Sea-Floor Integrity, D7 = Hydrographical Conditions, D8 = Contaminants, D9 = Contaminants in Fish and Shellfish, D10 = Marine Litter, D11 = Energy, Including Underwater Noise.

Technology	Description	Readiness	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	sum
Remote monitoring technology	Real time environmental data collection to safeguard stocks	3	X		X	X	X	X	X	X	X	X		9
Benthic monitoring	New tools for minimising benthic impacts under farms	2	X		X	X	X	X		X	X			7
Bacterial metabarcoding	Methods for better detection and modelling of benthic impacts	1	X		X	X	X	X		X	X			7
Innovations in fish health	Innovations in real-time water quality monitoring	3	X		X	X	X			X	X			6
Workboat technology	Innovations in support vessels including electric & hybrid propulsions	3	X		X	X				X			X	5
Fish feed delivery systems	Waterborne underwater feed delivery systems	3	X		X					X	X	X		5
Nonchemical antifoulants	Replacement of traditionally copper based anti-foulants to control marine biofouling on aquaculture structures including nets	2	X		X	X				X	X			5
Benthic impacts	Advances in understanding of benthic impacts of bivalve aquaculture	3	X		X	X		X						4
AI enabled plankton monitoring	Innovations in monitoring marine plankton	3	X		X	X	X							4
Acoustic deterrents	Innovations in acoustic technology to deter predators	3	X		X	X							X	4
Land based aquaculture	Innovations in Recirculating Aquaculture Systems	3	X	X			X					X		4
Advances in macroalgae aquaculture	Innovations in seaweed farming	2	X			X	X			X				4
New farming techniques for oysters	Innovative flip-farm systems for better growth and disease resistance	3	X		X	X								3
Innovations in fish health	Using robotic lasers to eliminate sea lice from fish	3	X		X	X								3
Satellite detection of HABs	Early detection and warning systems for harmful algal blooms	3	X		X		X							3
Genomic selection	Advances in broodstock selection for growth & disease resistance	3	X		X	X								3

Table 4. Table of technologies that have the potential to help mitigate the negative impacts of aquaculture operations and therefore help contribute to achieving and maintaining GES in England and Northern Ireland. Table contains the middle 1/3 of all listed innovations organised by relevance to descriptors (sum) and readiness level. In the column entitled 'Readiness for adoption,' the ranking is as follows: 1 = Conceptual. 2 = In development, 3 = Commercially viable. D1 = Biodiversity, D2 = Non-Indigenous Species, D3 = Commercial Fish and Shellfish, D4 = Food Webs, D5 = Eutrophication, D6 = Sea-Floor Integrity, D7 = Hydrographical Conditions, D8 = Contaminants, D9 = Contaminants in Fish and Shellfish, D10 = Marine Litter, D11 = Energy, Including Underwater Noise.

Technology	Description	Readiness	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	sum
Farm equipment innovation	Developments in predator proof aquaculture netting	3	X		X	X								3
Semi closed containment aquaculture	Developments in floating semi contained fish farming designs	3	X				X	X						3
Integrated Multi-Trophic Aquaculture (IMTA)	IMTA farming for ecosystem benefits through multi species aquaculture	2	X				X			X				3
New hatcheries for wild oyster restoration	Restoring historically depleted oyster beds	2	X		X	X								3
Alternative proteins in finfish diets	Insect meal to replace wild caught fish inputs in aquaculture diets	2	X		X	X								3
Alternative proteins in finfish diets	Replacement of FMFO in feeds with potential alternative proteins	2	X		X	X								3
Microcontaminant diagnostics	New methods to detect microcontaminants such as PCBs and microplastics	2			X					X	X			3
Benthic monitoring	eDNA techniques for more efficient monitoring under aquaculture sites	2	X			X		X						3
eDNA monitoring	Using environmental DNA to detect aquatic invasive species	2	X	X		X								3
Underwater robots	Underwater tech for net cleaning and other inspections	2	X		X					X				3
Offshore aquaculture	New technology enabling aquaculture in remote exposed locations	2					X	X		X				3
Restorative aquaculture	Tech developing aquaculture techniques to restore natural ecosystems	2	X		X	X								3
New technologies for anchoring and suspending longlines	New farming systems allowing aquaculture in offshore exposed locations	3			X			X						2
In-situ real time environmental monitoring	Real-time in situ monitoring of parameters affecting shellfish growth/quality	3			X		X							2
Advances in processing technology for bivalves	Wide ranging advances provide consumer safety, shelf-life benefits for seafood, particularly oysters and mussels	3			X						X			2

Blockchain technology	Blockchain to increase supply chain transparency and management, particularly in regard to shellfish safety for consumers	3			X						X			2

Table 5. Table of technologies that have the potential to help mitigate the negative impacts of aquaculture operations and therefore help contribute to achieving and maintaining GES in England and Northern Ireland. Table contains the bottom 1/3 of all listed innovations organised by relevance to descriptors (sum) and readiness level. In the column entitled 'Readiness for adoption,' the ranking is as follows: 1 = Conceptual. 2 = In development, 3 = Commercially viable. D1 = Biodiversity, D2 = Non-Indigenous Species, D3 = Commercial Fish and Shellfish, D4 = Food Webs, D5 = Eutrophication, D6 = Sea-Floor Integrity, D7 = Hydrographical Conditions, D8 = Contaminants, D9 = Contaminants in Fish and Shellfish, D10 = Marine Litter, D11 = Energy, Including Underwater Noise.

Technology	Description	Readiness	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	sum
Innovations in oyster farming methodology	Mechanised and automated oyster trestles for less disease & faster growth	3	X		X									2
Benthic monitoring	Using ROVs to create digital twins of the seabed	3	X					X						2
Underwater image recognition	Innovations in underwater stock assessment	3	X		X									2
Innovations in fish health	Developing biomarkers to monitor water pollution	3			X						X			2
Workboat technology	Increasing sophistication of vessels incl. well boats and support incl. hydrolicers and thermal treatments	3	X		X									2
Non-invasive pathogen diagnostics	New tools to measure and manage disease spread	2	X		X									2
Selective mussel breeding techniques	Selective breeding of mussels for climate resilient spat	2	X		X									2
Diagnostic testing for contaminants	Rapid testing for bacterial contamination in shellfish	2			X						X			2
Bivalve hatchery innovations	Microencapsulated diets for oysters and mussels	2	X		X									2
Innovations in water testing and diagnostics	Water testing to mitigate export risks, depuration requirements for bivalves	2			X						X			2
Nanopore sequencing	Enhancing food safety using molecular sequencing	1			X						X			2
Advances in genetic knowledge	Innovations in genetics allowing better selection in mussel aquaculture	3			X									1
Mapping and modelling wild mussel spat transportation	Enhancing wild mussel spat recruitment	3			X									1
Disease mitigation and standards for oyster aquaculture	ASC certification for oyster hatchery	3			X									1
Smart farming technologies	Novel AI enabled management of fish farming, including remote feeding	3			X									1

Triploid rearing techniques for oysters	Hatchery production of sterile oysters that cannot reproduce	2		X										1
Advances in post-harvest oyster processing	High pressure processing tech to reduce contamination for consumers	2									X			1
Smart technology and management for shellfish farming	Robotics and AI tech to advance to enhancing productivities and profitability	1			X									1

Key Trends in Aquaculture Innovation

The range of innovations emerging in aquaculture reflects both sector-wide priorities and environmental considerations. A strong focus on commercial production efficiency (D3) is evident, particularly in finfish farming, which sees the highest level of investment. Meanwhile, biodiversity (D1) is a recurring theme across innovations, given its broad relevance to aquaculture's environmental footprint.

For shellfish aquaculture, technology development is largely centred on food safety (D9), reflecting the importance of ensuring compliance with human health standards. Across all subsectors, innovations span a wide array of aquaculture operations, from real-time monitoring and disease tracking to sustainable feed alternatives and waste reduction strategies. While finfish technologies dominate, shellfish and seaweed farming are also seeing increased research activity, particularly in relation to environmental monitoring and ecosystem benefits.

The following table (Table 6) provides an example of patterns and trends observed in aquaculture innovations, highlighting the key technologies, their relevance to GES descriptors, and their potential environmental benefits.

Looking ahead, smart technologies and innovations from other industries—such as AI, robotics, and bioengineering—are expected to play an increasing role in aquaculture. The pace of innovation in aquaculture is becoming increasingly reliant on the adoption and adaptation of technologies from other sectors, where cutting-edge advancements—particularly in AI, automation, and digital monitoring—are being refined and configured for aquaculture-specific applications. These advancements have the potential to further enhance efficiency, environmental performance, and resilience across the aquaculture sectors in England and Northern Ireland.

Table 6. Innovations and technology development in aquaculture, estimated readiness levels for each and the overlap with GES descriptors.

Technology	Description	Readiness Level	Relevant GES Descriptors	Environmental Benefit
Remote Monitoring Technology	Real-time environmental data collection to safeguard stocks	3 - Commercially Viable	D1, D3, D5, D8	Improves environmental monitoring and risk response
Genomic Selection	Enhances disease resistance in farmed species	2 - In Development	D1, D2, D3	Strengthens disease resilience in aquaculture
AI-powered Disease Tracking	Predicts pathogen outbreaks in aquaculture	2 - In Development	D1, D2, D5	Reduces pathogen outbreaks and biosecurity risks
Satellite Detection of HABs	Early warning system for harmful algal blooms	3 - Commercially Viable	D1, D4, D5	Minimizes algal bloom impacts on aquaculture
Acoustic Deterrents	Reduces predator pressure on aquaculture sites	3 - Commercially Viable	D1, D4, D6	Protects farmed species from predator losses
eDNA Monitoring	Tracks invasive species spread via genetic monitoring	2 - In Development	D2, D8	Enhances biosecurity and prevents invasive species spread
Blockchain Technology	Enhances seafood traceability and supply chain transparency	3 - Commercially Viable	D8, D10	Improves transparency and consumer confidence
Semi-closed Containment Systems	Reduces fish escape risks and prevents environmental contamination	3 - Commercially Viable	D6, D10	Prevents fish escapes and associated ecosystem risks
Storm-resistant Anchoring Systems	Improves resilience of offshore aquaculture facilities during storms	2 - In Development	D6, D10	Enhances resilience to extreme weather events

English & Northern Irish Aquaculture – Final Appraisal

As aquaculture continues to evolve in England and Northern Ireland, it remains crucial to assess its environmental footprint and its alignment with GES. Unlike Scotland's large-scale finfish sector, aquaculture in these regions is predominantly shellfish-based, with a growing interest in seaweed farming. While its overall environmental impact is relatively low, key challenges such as the spread of non-indigenous species, contaminant accumulation, and marine litter must be addressed.

To provide a structured evaluation, we explore six key questions:

1. How important is aquaculture in England and Northern Ireland to the achievement of GES?

- Aquaculture in England and Northern Ireland plays a relatively minor role in the overall achievement of GES, particularly when compared to Scotland's large-scale finfish sector. However, while the negative environmental impacts of aquaculture in these regions are generally limited, there are some potential net positive contributions.
- For example, shellfish and seaweed farming can support GES objectives by improving water quality (D5) through nutrient removal and enhancing biodiversity (D1) by creating structured habitats. At the same time, aquaculture remains subject to localised risks, which must be monitored and managed.

2. What are the most pressing environmental risks associated with aquaculture in England and Northern Ireland?

Even though aquaculture's overall environmental footprint is relatively small, certain risks remain:

- Non-indigenous species (D2) – The spread of Pacific oysters and other NIS shellfish species remains a management challenge, requiring site-specific control strategies.
- Contaminants & Bioaccumulation (D8, D9) – Shellfish farming is particularly vulnerable to waterborne pollutants, requiring stringent monitoring to ensure food safety compliance.
- Marine Litter (D10) – Lost or discarded aquaculture gear, particularly plastics from shellfish farming, contributes to localised marine debris issues.
- Localised Nutrient Concerns (D5) – While shellfish and seaweed farming generally help improve water quality, there is some concern that excessive nutrient removal could affect primary production in certain areas.

These risks require ongoing monitoring and adaptive management, but they remain relatively low in scale compared to other environmental pressures on the marine environment.

3. How can aquaculture in England and Northern Ireland actively contribute to achieving GES?

While much of the discussion around aquaculture focuses on minimising risks, there are also opportunities for the sector to actively support GES objectives:

- Biodiversity Enhancement (D1) – Restorative aquaculture projects, such as native oyster restoration, can help rebuild lost habitats and improve ecosystem resilience.
- Nutrient Management (D5) – Shellfish and seaweed farming contribute to nutrient uptake, reducing the impact of agricultural runoff in certain areas.
- Sustainable Food Production (D3, D9) – Well-managed aquaculture reduces dependence on wild fisheries and provides a low-carbon protein source, particularly when compared to land-based animal agriculture.

With the right regulatory and industry incentives, aquaculture could become a net contributor to GES, rather than simply being a sector that needs to be managed for compliance.

4. What role does aquaculture play in supporting or hindering marine biodiversity?

Aquaculture has a dual relationship with biodiversity—it can both enhance and challenge ecosystem health depending on how it is managed.

Potential benefits:

- Shellfish and seaweed farms create habitat complexity, providing shelter for marine life.
- Sustainable farming practices can reduce pressure on wild fish stocks by offering an alternative seafood source.

Potential concerns:

- Non-native species introduction (e.g., Pacific oysters) could alter local biodiversity.
- Disease transmission risks (e.g., parasites from farmed species) require careful biosecurity measures.

By prioritising best practices, aquaculture can enhance rather than compromise biodiversity outcomes.

5. What are the key constraints limiting the sustainable growth of aquaculture in England and Northern Ireland?

The growth of aquaculture in these regions is constrained by several interlinked factors:

- Regulatory hurdles – Lengthy and complex licensing requirements limit sector expansion.
- Public perception & social license – Concerns over the visual impact of farms and environmental risks lead to resistance against new developments.
- Marine space competition – Growing pressures from offshore wind, conservation areas, and fisheries restrict available sites.
- Export challenges – Post-Brexit trade restrictions on live shellfish exports to the EU have impacted market access.
- Consumer demand – Demand for seafood in the UK often does not align with domestically produced aquaculture products.
- Limited investment & research – Compared to Scotland, aquaculture in England & Northern Ireland receive less funding and fewer research initiatives, slowing innovation and growth.

Without strategic investment, regulatory clarity, and improved public perception, the potential of aquaculture to contribute positively to GES may remain underutilised.

6. What future trends and innovations could shape the sustainability of aquaculture in England and Northern Ireland?

The future of aquaculture in England and Northern Ireland could be shaped by technological advancements, market shifts, and evolving regulations. Key trends include:

- Smart aquaculture & AI integration – Increased use of real-time monitoring, automation, and AI-driven management systems will improve efficiency and reduce environmental risks.
- Alternative feed sources – The shift away from fishmeal-based diets to sustainable alternatives (e.g., insect proteins, algae-based feeds) could reduce reliance on wild fish stocks.
- Expansion of restorative aquaculture – Initiatives focusing on habitat restoration and ecosystem services (e.g., native oyster restoration, integrated multi-trophic aquaculture) may increase.
- Market & policy shifts – Consumer demand for sustainably certified seafood and regulatory incentives for low-impact aquaculture could drive future investment.
- Colocation with other marine industries – The potential for combining aquaculture with offshore wind farms or other marine infrastructure could optimise space use and improve economic feasibility.

The pace of innovation in aquaculture is increasingly reliant on technology transfer from other industries, where advancements—particularly in AI, automation, and bioengineering—are being refined for aquaculture applications. These developments will be key in shaping how aquaculture interacts with GES objectives, offering pathways to enhance sustainability while meeting the growing demand for seafood.

Conclusion

This report explores the relationship between aquaculture and the achievement of GES in England and Northern Ireland. It provides an in-depth analysis of the sector's environmental impacts and the pressures it faces. The report also examines future trends and emerging technologies that could support improved environmental management related to aquaculture impacts.

Aquaculture in England and Northern Ireland is largely dominated by shellfish farming, with finfish production playing a much smaller role. Aquaculture has varying levels of pressures on marine systems such as habitat modification, nutrient enrichment, and the introduction of non-indigenous species. The spread of species like Pacific oysters and Manila clams has raised concerns about biodiversity and ecosystem stability. Nutrient loading from finfish aquaculture can contribute to localised eutrophication, though shellfish and seaweed farming may help offset these effects by improving water quality. Marine litter from aquaculture infrastructure, along with potential bioaccumulation of contaminants in farmed shellfish, are additional areas of concern.

Future growth in the sector will be influenced by climate change, spatial competition with other marine industries and marine resource users and evolving regulatory requirements. Climate-driven changes to water temperatures and ocean conditions may increase disease risks and affect species distributions. The expansion of offshore wind farms and conservation areas adds further spatial pressures, requiring better integration of aquaculture into marine spatial planning. The potential for seaweed farming and Integrated Multi-Trophic Aquaculture presents opportunities for sustainability, but regulatory and economic barriers remain.

The report highlights several technological advancements that could improve environmental outcomes, including AI-based monitoring systems, alternative feed sources to reduce reliance on wild fish stocks, and innovations in bivalve and seaweed farming to enhance ecosystem services. To align aquaculture more effectively with GES, policy recommendations include improving biosecurity measures, enhancing waste management strategies, expanding long-term environmental monitoring, and refining regulatory frameworks to support sustainable industry growth.

While aquaculture in England and Northern Ireland does not represent a significant obstacle to achieving GES, targeted improvements in regulation, monitoring, and innovation will be essential to ensuring its long-term sustainability and environmental compatibility.

Caveats and limitations within this report

- To ensure a concise summary of the relationship between GES and the impacts of aquaculture, the authors of the report selected the GES indicators they felt were most relevant to the report objectives and therefore warranted further discussion. Whilst this was undertaken pre-literature review and corroborated post-literature review, others may argue that some of the indicators not considered herein have sufficient relevance to be discussed. However, if there are any such arguments, it is unlikely that they would have a significant bearing on the findings presented herein because the report includes no formal quantitative analysis of impact or relevance.
- The sources used to support the ideas presented herein are from a diverse mix of literature including peer review, government and industry reporting. The authors of the report have assumed that all types of literature are equally robust and have not discussed potential weaknesses with using non-peer review material. Based on the expert knowledge of the author team, there is no reason to believe that any materials presented or referenced herein lack the necessary robustness for the conclusions drawn.
- It is noteworthy that the report is not meant to be fully comprehensive covering all relevant material for each GES indicator or aquaculture impact. As such there will be additional materials that could be used to build on the ideas presented herein. However, none of the ideas presented are out of date or inaccurate.
- The production data used herein, whilst appearing to be comprehensive in terms of species produced, has some notable limitations. The most recent year for which data were available from Cefas was 2022, making it difficult to provide up to date values on production for each species. In addition, the classification of some of the species included in these data are inaccurate, such as sea trout being referred to as brown trout. These data should therefore be used with some caution.
- Similarly, the spatial data for aquaculture production sites across England and Northern Ireland is neither up to date, nor deemed accurate because all historic mapping of operations is not well referenced, hence in this report we can only provide an illustrative map of operations across both countries.

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Annex

Annex Table 1. Marine aquaculture species farmed in England and Northern Ireland and the overall volumes produced in 2022 (Source: Cefas).

Species	England	Northern Ireland	Metric Tonnes (MT)
Shellfish			
Pacific oyster (**Magallana gigas*)	✓	✓	2,212
European flat oyster (*Ostrea edulis*)	✓	✓	7
Blue mussel (*Mytilus spp.*)	✓	✓	4,995
Northern quahog (*Mercenaria mercenaria*)**	✓		6
Manila clam (Japanese carpet clam) (*Ruditapes philippinarum*)**	✓		1
European Lobster (*Homarus gammarus*)	✓		Enhancement
Seaweed			
Sugar kelp (*Saccharina latissima*)	✓	✓	Pilot scale
Winged kelp (*Alaria esculentia*)	✓	✓	Pilot scale
Oarweed (*Laminaria digitata*)	✓	✓	Pilot scale
Tangle, Cuvie (*Laminaria hyperborea)*	✓		Pilot scale
Dulse (*Palmaria palmata*)	✓		Pilot scale
Finfish			
Atlantic salmon (*Salmo salar*)		✓	1,057***
Cleaner fish (*Cyclopterus lumpus*)	✓		

Annex Figure 1. Volume and Value of marine and freshwater aquaculture species farmed in England and Northern Ireland and the overall volumes produced in 2022 (Source: Cefas and the Scottish Seaweed Industry Association).

Annex Table 2. UK Data sources related to aquaculture production and operations.

Dataset	Host of Data	Link
Aquaculture License	DAERA	https://www.opendatani.gov.uk/@department-of-agriculture-environment-and-rural-affairs/aquaculture-licences-open-data
Aquaculture License	UK GOV	https://www.data.gov.uk/dataset/9522938c-3397-4857-a46d-17391e604181/aquaculture-licences-open-data2
Public register of Aquaculture Production Businesses in England and Wales	Cefas	https://www.cefas.co.uk/eu-register/?id=3524473&filter=
Aquaculture	Defra / MMO	https://hub.arcgis.com/maps/23017db80d5344c2bc6f6909df0b4d10/about
Dorset & East Devon Fisheries Local Action Group area, 2018-2019	Cefas	https://data.cefas.co.uk/view/20411
Producers Directory	Aquaculture Representative Group NI	https://www.aquacultureni.co.uk/directory/
Classification Zone Maps	Cefas	https://www.cefas.co.uk/data-and-publications/shellfish-classification-and-microbiological-monitoring/england-and-wales/classification-zone-maps/
Shellfish Aquaculture Licensed Sites protected areas under the WFD Finfish, Freshwater, Shellfish Production	EMODnet	https://emodnet.ec.europa.eu/geoviewer/
Fin fish Monthly Biomass and Treatments	NatureScot / SEPA	https://aquaculture.scotland.gov.uk/data/fish_farms_monthly_biomass_and_treatment_reports.aspx
Scotland's Active Aquaculture Sites	NatureScot / SEPA	https://aquaculture.scotland.gov.uk/map/map.aspx
Public register of marine licence applications and decisions	GOV.UK	https://www.gov.uk/check-marine-licence-register
Celtic Seas Ecoregion- Aquaculture Overview. Aquaculture sites for key species groups and countries in the UK	ICES	https://ices-library.figshare.com/articles/report/Celtic_Seas_ecoregion_Aquaculture_Overview/21252294?file=37732320
Licensed Shellfish sites in NI	Queens Uni Belfast	https://pureadmin.qub.ac.uk/ws/portalfiles/portal/217206490/Mitigating.pdf
Factfinding and Future Prospects in UK Aquaculture Scotland Aquaculture sites	Esmee Fairbairn	https://issuu.com/esmeefairbairn/docs/factfinding_and_future_prospects_in_uk_aquaculture
Shellfish Growing Areas	Cefas	https://magic.defra.gov.uk/magicmap.aspx
Strategic Areas of sustainable aquaculture production	MMO	https://explore-marine-plans.marineservices.org.uk/marine-plans-explorer

Annex Table 3. Regression analysis results looking at potential future aquaculture production using the data from 2015 to 2023.

Country	Equation	R squared	P value
Finfish-Tonnes			
England	y = 5820.29 + -182.54 * year	0.65	0.02
Northern Ireland	y = 1144.04 + -6.37 * year	0.06	0.57
Finfish-Value (Million £)			
England	y = 22.72 + -0.25 * year	0.15	0.35
Northern Ireland	y = 5.43 + 0.18 * year	0.26	0.2
Shellfish-Tonnes			
England	y = 5005 + 185.5 * year	0.05	0.58
Northern Ireland	y = 4112.71 + -211.46 * year	0.15	0.34
Shellfish-Value (Million £)			
England	y = 9.21 + 0.52 * year	0.06	0.54
Northern Ireland	y = 4.52 + 0.23 * year	0.08	0.5