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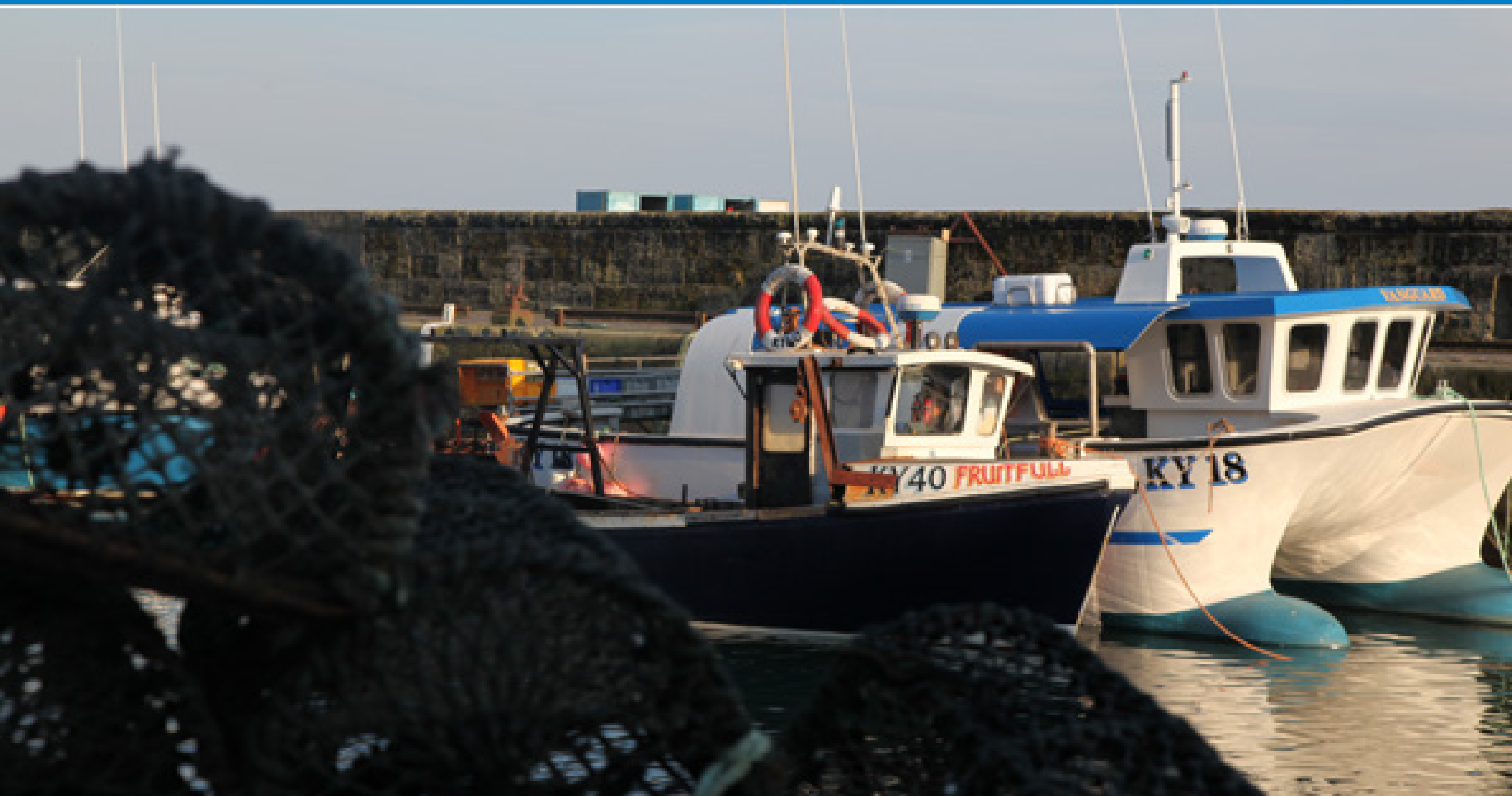
The UK shellfish industry's role in supporting shellfish ecosystem services and public goods and benefits



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Contents

Introduction

In 2019, Seafish began work to explore the seafood industry's contribution to Ecosystem Services (ES) and public goods and benefits (PGBs). The first phase of this work culminated in the published report *Ecosystem Services and the UK Seafood Industry* (Garrett, 2019). Building on this initial research, Seafish then commenced work to explore the relationship between shellfish fishing and aquaculture activity and the impact that this has on the maintenance and enhancement of ES and the provision of PGBs. The research focused on key commercial wild harvested and farmed shellfish species, including blue mussels (*Mytilus edulis*), Pacific and native oysters (*Magallana gigas* and *Ostrea edulis*), king and queen scallops (*Pecten maximus* and *Aequipecten opercularis*), brown crab (*Cancer pagurus*) and Nephrops (*Nephrops norvegicus*) (see also Appendix 1.).

The first stage of this work involved a comprehensive scientific literature review on the topic, "*Ecosystem Services, Goods and Benefits Derived From UK Commercially Important Shellfish"* (Pinn, 2021). In this review, Seafish concluded that there is limited academic research into the role that fishing, and aquaculture sectors play in supporting marine ES and delivering PGBs. Alongside the literature review, in March 2020, Seafish held a multi-stakeholder workshop which brought together policymakers, industry, and the research community to consider what role fishing and aquaculture activity play concerning ES and PGBs, and the relevance of this to future marine policy development.

This report summarises the literature review and workshop findings and consolidates the knowledge and understanding to date on the subject. Specifically, it is intended for key stakeholders across industry, policy, and the scientific community. It provides a robust evidence base to contribute to marine policy discussions and business decision making. The information within this report provides an entry point into understanding marine ES and PGBs for many, and insight into the UK seafood industry's contribution to them. Consequently, the report is structured as follows:

- Section 1 provides an overview of the key concepts and definitions, including natural capital, ecosystem services and public goods and benefits.
- Section 2 contextualises the ES and PGBs associated with key commercial UK shellfish species. It then outlines how shellfish fishing and aquaculture activity impacts, maintains, and enhances shellfish ES and contributes to the delivery of PGBs. The positive role of the seafood industry is acknowledged through research examples that outline where shellfish fishing and aquaculture activities are already maintaining and enhancing shellfish ES and providing PGBs. Case studies are also used to provide real-world examples and signpost extra reading whilst also discussing the negative impacts of commercial seafood capture and production.

- Section 3 discusses how key stakeholders (policymakers, industry, and the scientific community) can use the information within this report to better support the shellfish industry's role in contributing to ES and providing PGBs moving forward. Divided by stakeholder groups for ease of use, the section provides practical suggestions for consideration to see marine policy and business decisions reflect the ES and PGBs narrative associated with farming in the UK.

In summary, by highlighting these key aspects, readers will better understand (1) the role that shellfish fishing and aquaculture play in maintaining and enhancing ES and providing PGB and (2) the potential opportunities to ensure this is reflected in marine policy and wider decision making.

Background context

ES and PGBs in terrestrial policy

There is a clear narrative around the ES and PGBs provided by land-based ecosystems and the contribution of agriculture in enhancing terrestrial ES and delivering PGBs through a well-managed landscape (Dwyer et al., 2015; Power, 2010; Rodgers, 2019). This influences policy and supports the subsidies and incentives given to farmers and land managers to enable sustainable management practices.

Specifically, policy interventions incentivise farmers and landowners to practice management that provides recreational and ecological benefits such as improved water and soil quality or reduced fertiliser use and greenhouse gas (GHG) emissions (Department for Food Environment and Rural Affairs and Government Statistical Service, 2021). Financial incentives for the provision of PGBs in the terrestrial setting include subsidies or direct payments that offer income security and remunerate farmers and landowners for environmentally friendly practices that deliver public goods not typically paid for by the markets (Table 1) (Department for Food Environment and Rural Affairs, 2020).

Following the UK's vote to leave the European Union on the 23rd of June 2016, a heavy debate surrounded the development of land management policy that should replace the EU's Common Agricultural Policy (CAP) (European Commission, 2020). The UK government received over 44,000 responses to the consultation on developing appropriate land management policy (Department for Food Environment and Rural Affairs, 2018). Scientific research conducted to inform the debate focused on answering critical questions to aid land policy development that supports society, industry, and the environment, including:

- *What are the farm-related public goods that public money should support?*
- *How should public money be allocated to support farm-related public goods?*
- *How much public money should the UK government allocate to supporting farm-related public goods?*

The UK government considered the science and, in 2019, announced its intention to formulate an agricultural policy that restricts public funding to the provision of public goods instead of providing income support for farmers (Bateman and Balmford, 2018). In 2020, the Agriculture Act 2020 was passed, aiming to steer food production in England in an environmentally sustainable way. Common Agricultural Policy direct payments made to farmers based on the size of land farmed will be phased out over seven years (starting in 2021) and eventually replaced by a new scheme that focuses on paying farmers to produce 'public goods' (Coe and Finlay, 2020).

Table 1. Examples of the various financial incentives UK farmers can receive through UK land management policy to support ecosystem services and the delivery of public goods and benefits. The examples outline the practical ways farmers can support/enhance ecosystem services and deliver public goods/benefits through land management. The approximate financial payment farmers receive from the government are also listed.

Farmers can support ecosystem services and deliver public goods/benefits by:	Practical actions used to support ecosystem services and deliver public goods/benefits.	Payments farmers will receive from the government
Providing supplements for threatened species	Payments for providing food supplements on their land for threatened species such as turtle doves (GOV.UK, 2021a).	£120 per hectare (ha)
Planting flower-rich margins and plots	Payment for sowing a seed mix of grass and wildflowers along margins or plots during spring/summer to provide an abundant supply of pollen and nectar, habitats, and foraging grounds (GOV.UK, 2021b).	£539 per ha
Constructing wetlands	Construct and maintain wetlands on their land to treat pollution generated from normal agricultural activities. Wetlands help to reduce the risk of pollutants entering nearby watercourses (GOV.UK, 2017).	50% of the actual cost to install and maintain.
Creating and maintaining a woodland	Creation of woodland and support towards its maintenance (GOV.UK, 2021c).	Eighteen funding initiatives/subsidies are available: £6,800 per (ha) for complete woodland creation and £100 per hectare (ha) per year to improve the biodiversity of an existing woodland (GOV.UK, 2020) and its resilience to climate change (GOV.UK, 2021d).

ES and PGBs in marine policy

The discussion and debate surrounding public money for public goods and the subsequent policy outcomes that apply in UK farming are not mirrored for UK wild fisheries and aquaculture. This absence is apparent in both legislation and marine funding schemes.

The new UK Fisheries Act 2020, which replaces the Common Fisheries Policy (CFP), reflects this lack of consideration regarding the spending of public money for public goods in UK fisheries (UK Parliament, 2020), focusing more broadly on sustainability issues for UK fisheries and aquaculture policy. In April 2021, the UK government launched the Fisheries and Seafood scheme via the Marine Management Organisation (MMO) to support England's seafood sector, coastal communities, and marine environment (Department for Food Environment and Rural Affairs, 2021a). The scheme provided £6.1 million in funding through to April 2022 and focuses on providing grants to businesses to help them adapt to life outside the EU's CFP and recover from the impacts of Covid-19 (Marine Management Organisation, 2021).

The scheme also supported the UK government's commitment to tackle climate change across industries by matching funding for projects that support sustainable innovation and protect the environment (Marine Management Organisation, 2021). The scheme has recently been relaunched and adapted to incorporate ES. However, whilst projects aimed at maintaining and/or recovering biodiversity and ecosystem services are acceptable, the scheme still does not fully recognise or reward the seafood industry's role in supporting ES and delivering PGBs. Policy support for UK fishing and aquaculture sectors certainly does not equal that offered to the farming sector for land management.

The UK is currently in the early stages of considering the true economic value of its coastal waters. As of April 2021, UK marine natural capital assets, which account for ES for UK marine and coastal areas, were estimated to be worth £211 billion (Office for National Statistics, 2021). This estimation accounts for a wide range of marine ES that bring PGBs to society (Office for National Statistics, 2021).

However, there is still a lack of acknowledgement of the UK seafood sector's contribution to enhancing, maintaining, and supporting ES and providing PGBs. Consequently, the role of the UK seafood sector in providing public goods is not captured in conventional market economics. Nevertheless, when the sector's role is considered, the contribution of UK fisheries and aquaculture sectors to ES and PGBs is generally limited to food production (Pinn, 2021), which is usually viewed as being at the cost of the environment (Fearnley-Whittingstall, 2021). This common assumption has led to an unreasonably negative narrative that plays to a seafood industry dependent on natural resource exploitation that results in environmental degradation.

Whilst we must not ignore the environmental impacts of food production, the narrative of UK fisheries entirely neglects the ES and PGBs of the marine environment and the positive role the fishing and aquaculture sectors can play when managed sustainably. By failing to acknowledge these contributions, policymakers and businesses miss the opportunity to strengthen the many PGBs that arise from clean, healthy seas and a thriving seafood industry. The opportunity to promote the traditional livelihoods of the UK's coastal and rural communities is also missed, along with the health and well-being benefits associated with consuming seafood and protecting coastal ecosystems (Kundam et al., 2018; Venugopal and Gopakumar, 2017; White et al., 2020).

Despite the current landscape, there is an emerging awareness of the opportunity to re-focus UK fisheries and aquaculture policy so that it incentivises the delivery of PGBs from the ES provided by commercial shellfish fisheries and aquaculture. This will require marine policy makers to learn from land management practices where the acknowledgement of ES and PGBs across the farming industry has helped to re-frame UK agricultural policy. For this to happen there needs to be greater awareness and understanding, through research and discourse, of:

- the ES provided by key UK commercial shellfish and the seafood industry's role in preserving and, in some cases, enhancing these ES and PGBs.
- Interventions to incentivise the delivery of ES and PGBs.

Section 1

1.1. Key terms

The natural world can be considered a form of natural capital or stock that provides valuable goods and services that benefit human health, prosperity, and well-being (Figure 1) (Polasky and Daily, 2021). Many flows (functions or products) that come from natural capital are essential for human life, such as water, food, and clean air. We rely on nature for its intricate biological processes that provide healthy, fertile soil for our crops and complex chemical exchanges for clean air and a stable climate. Nature also provides raw materials that enhance our quality of life through its use across various industries such as healthcare (medicine), construction (building materials), and agriculture (fertilisers). There are also non-material benefits derived from nature such as recreational and spiritual benefits that result from spending time in natural areas, such as parks, wildlife areas and coastlines.

Figure 1. The process of natural capital to ecosystem services and public goods and benefits. The wider natural environment contains stocks (natural capital) and a range of flows (functions or products) that come from these assets (ecosystem services), which we draw on to bring value and benefits to society (public goods and benefits) (©Capitals Coalition).

The flows from natural capital that are essential for human life are known as ecosystem services. The UK National Ecosystem Assessment defines ecosystem services as *"the benefits provided by ecosystems that contribute to making human life both possible and worth living"* (UK National Ecosystem Assessment, 2021). Ecosystem services can be categorised into provisioning, regulating, supporting and cultural services. For example, the provision of food and water, the regulation of the climate and soils, the cultural services that influence our spiritual and cultural well-being and the biological structuring functions that support food webs. The services provided by ecosystems are naturally available to all members of society. People and industry can draw on them to deliver valuable PGBs to society (Capitals Coalition, 2020; Turner et al., 2014).

Public goods are defined as *"goods or services that no one can be stopped from using and where one person's use does not affect another's. For the environment, this includes such goods as an attractive landscape or a public park"* (Department for Food Environment and Rural Affairs and Government Statistical Service, 2021). PGBs provided by ES can sustain and fulfil human life and social welfare (Guerry et al., 2015). Therefore, any loss to PGBs due to the destruction of ecosystems can negatively impact human well-being, such as decreased air quality, water quality and food security.

1.2. ES and PGBs explained

To prevent the destruction of ecosystems and subsequent loss of PGBs essential to human well-being, we must understand the different types of ES and the derived PGBs in more detail. The four main categories of ES, as previously mentioned, are:

1. Provisioning ecosystem services
2. Regulating or maintaining ecosystem services
3. Cultural ecosystem services
4. Supporting ecosystem services

Figure 2 provides an infographic linking these ecosystem services to some of the specific benefits we gain.

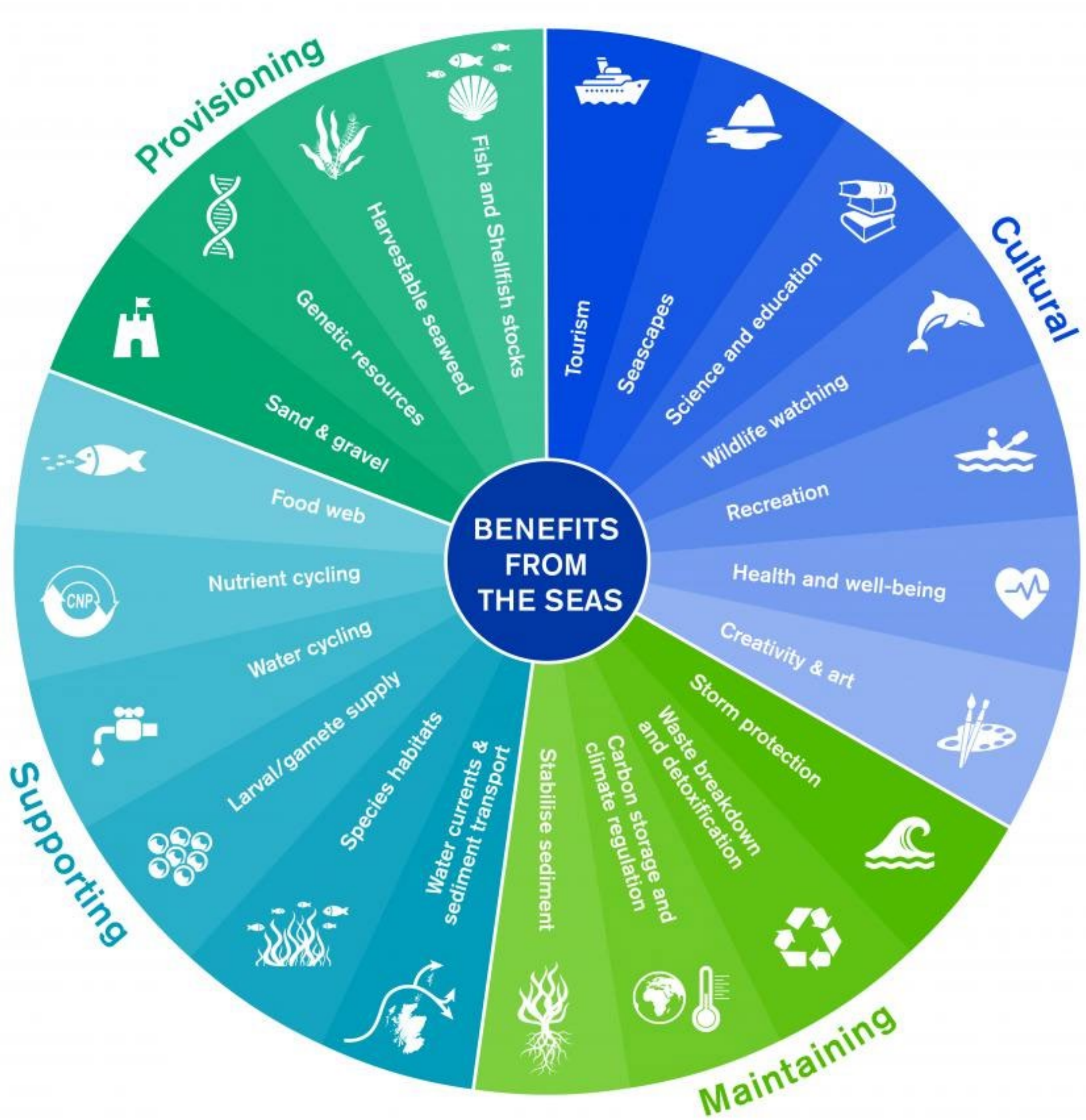

Figure 2: The ecosystem benefits from the we gain from our marine environment (NatureScot ©).

Provisioning Ecosystem Services

Provisioning ES relate to the supply of food, water, and raw materials that we extract from ecosystems for basic human needs. The supply of food by nature is the best-understood example of provisioning ES, with fruit, vegetables, fish, and livestock available as a direct product of ecosystems. However, other provisioning services include food for livestock, bait, drinking water, and industrial materials such as timber, biofuels, fertilisers, and plant and animal fibres used for clothes and product packaging. Certain plants, animals (including marine corals and shellfish) and fungi also have medical value. Through provisioning ES, people can derive many PGBs to society, including:

- Food for human consumption
- Water for human consumption, bathing, and domestic needs
- Feed and water supply for farming and catch sectors

- Water supply for industry sectors
- Agricultural fertiliser and fuels
- Materials for decorative ornaments and displays such as museum exhibitions
- Materials for medical and biotechnology sectors

Regulating Ecosystem Services

Regulating ES, sometimes referred to as Maintaining ES, moderate the natural environment by maintaining environmental conditions that are favourable for life. Forests, for example, influence rainfall and water availability, whilst trees and plants remove carbon dioxide from the atmosphere as they grow, regulating the global climate by storing greenhouse gases (GHG). Trees with strong roots such as mangroves, hold soil in place and absorb wave energy during storm events, reducing damage from erosion, floods, landslides, and tsunamis. Insects pollinate flowers, which is essential for successful crop production, whilst bacteria decompose waste, releasing nutrients back into the environment and maintaining soil fertility. Through regulating services, ecosystems provide many PGBs essential for human life. Examples include:

- Clean air to breathe and fresh water to drink
- Erosion and flooding control
- Buffering against natural disasters
- Rich, fertile soils for good crop yield

Cultural Ecosystem Services

Cultural ES are non-material benefits that people obtain from a connection to nature. They include recreation and tourism, aesthetic enjoyment and spiritual experiences related to the natural environment. The cultural connection that humans have associated with nature over time has led to people deriving many intangible/immaterial benefits from their interaction with the natural environment including:

- Physical and mental well-being
- A sense of place
- Cultural identity
- Social unity
- Inspiration for culture, art, and design

Time spent in green spaces such as parks, woodlands, and private gardens can be positive for mental and physical health whilst stimulating psychological relaxation and alleviating stress. Similar findings have been recorded for coastal environments. The importance of the PGBs provided by cultural ecosystems such as outdoor recreation became apparent during the COVID-19 pandemic and the subsequent national lockdowns and restrictions on travel (Aerts et al., 2021; Holland, 2021). The cultural importance of nature to humans can be traced back to ancient civilisations, where animals, plants, and weather patterns were depicted in cave wall paintings. Furthermore, cultural ES are all deeply interlinked and often connected to provisioning and regulating ES. For example, farming provides food and income to a farmer, as well as a deep connection to their land and traditional farming practices. The same can also be said for fishermen.

Supporting Ecosystem Services

Supporting ES include the consistent, underlying natural processes that sustain the ecosystem themselves, such as providing space for a broad range of species to live, leading to the maintenance of genetic diversity (Food and Agriculture Organization of the United Nations, n.d.). Ecosystems provide habitats for many plants and animal species whilst also maintaining a diversity of other processes that are the foundation of other ES. These ecosystems become 'biodiversity hotspots', where high numbers of diverse species occur, thus supporting a greater diversity of life forms and biodiversity resilience. These processes are fundamental to sustaining all primary forms of life on Earth. Without them, provisioning, regulating, and cultural ES and the PGBs we derive from them would not exist.

Humans and Ecosystem Services

The four categories of ES all occur in the natural environment, regardless of the presence of humans. Consequently, the flow of benefits from ecosystems to humans is often depicted as one-way (Comberti et al., 2015). However, this fails to recognise the role of humans in actively maintaining and enhancing ES through cultivation and management practices.

Since the agricultural revolution, humans have modified ecosystems to enhance the quality and quantity of ES and PGBs available to people. Whilst human cultivation of ecosystems can damage the environment if managed unsustainability, people, and industry generally work to maintain ecosystem health to ensure a sustained flow of benefits. People also work to mitigate any loss of ES due to human impact through sustainable cultivation, management, and restoration practices that value and protect the ES provided by nature. Consequently, human intervention in nature for the benefit of people, when properly managed, can positively enhance and maintain ES and deliver many PGBs.

Section 2

ES and PGBs associated with key commercial UK shellfish species

The marine environment provides a rich stock of natural capital that brings many ES and PGBs to people (Figure 3). The fishing and aquaculture sectors can play a positive role in supporting, enhancing, and maintaining these ES when managed sustainably. Many PGBs can be attributed directly to the activity of the fishing and aquaculture sectors through responsible catch and cultivation practices, habitat restoration and research projects.

Commercial shellfish in their natural state generate many ES, which deliver various PGBs essential to human life (Table 2). The following section will focus on the ES and PGBs associated with key commercial UK wild caught and farmed shellfish species in their natural state; including blue mussels (*Mytilus edulis*), Pacific and native oysters (*Magallana gigas* and *Ostrea edulis*), king and queen scallops (*Pecten maximus* and *Aequipecten opercularis*), brown crab (*Cancer pagurus*) and Nephrops (*Nephrops norvegicus*). The ES for each of these shellfish species are summarized in a supplementary matrix taken from previous Seafish work which led up to this report (see Appendix 2). The following section then gives an overview of the role of the shellfish farmed (aquaculture) and capture (wild fishing) sectors in supporting, maintaining, and enhancing these ES and PGBs. Research examples highlight the PGBs derived from ES that result from the positive intervention of shellfish catch and farm sectors.

It is noteworthy that there is still a lack of meaningful evidence on the role of the wild capture shellfish sector in supporting ES and delivering PGBs, compared to the aquaculture sector. As such, the evidence in this report largely revolves around the aquaculture sector. Nevertheless, the information in this report does provide useful baseline evidence for future reference that can contribute to marine planning and aid decision making for inshore fisheries and cultivation management, permitted activities within marine protected areas and other management policies. It also highlights areas for future research.

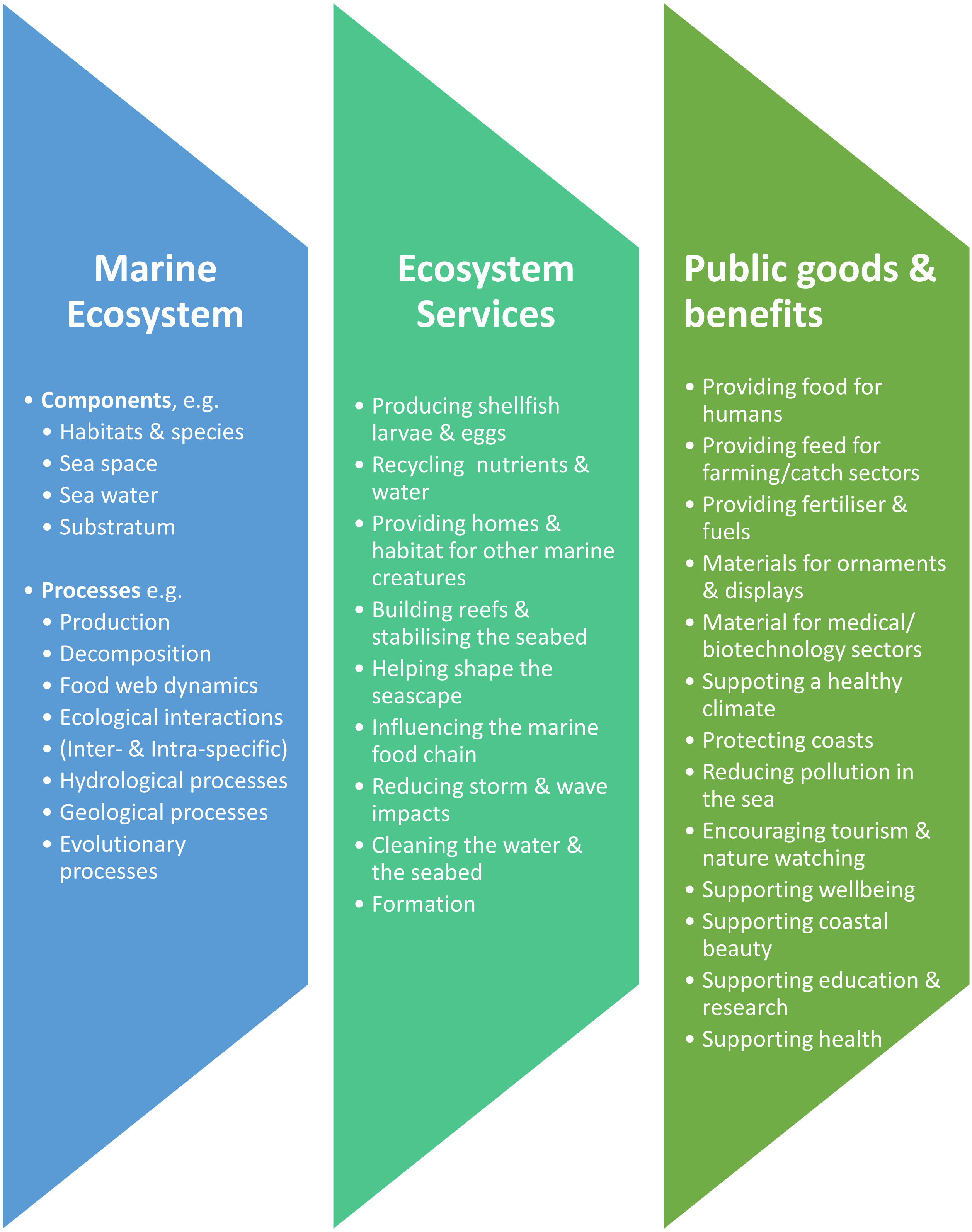

Figure 3. Flow diagram of the links between the marine environment, the various ecosystem services provided, and the public goods and benefits provided to society (produced by MarFishEco).

Table 2. Table categorises the four types of ecosystem services provided by key commercial UK wild harvested and farmed shellfish species: provisioning, regulating, cultural and supporting ecosystem services. Each ecosystem service provided by UK shellfish in their natural state is listed, along with the public goods/ benefits delivered essential to human life.

Ecosystem Service type	Commercial shellfish ecosystem service	Public goods/benefits derived
Provisioning service	Through reproductive activities, shellfish provide marine resources through the supply of larvae and eggs	• Wild and farmed food for humans • Feed for farming and catch sectors • Fertilisers and biofuels for industry • Materials for medical / biotechnology sectors • Materials for decorative ornaments and displays such as museum exhibitions
Regulating service	Through their feed activities, shellfish regulate the marine environment by: • Recycling water • Recycling nutrients • Storing carbon and reducing climate change impacts Through habitat modification, shellfish also regulate the marine environment by: • Building reefs and stabilising the seabed • Reducing storm and wave impacts	• Reduced pollutants in the sea • Improved coastal health and water quality • Supporting a healthy climate • Reducing storm and wave energy • Protecting coastlines against erosion and flooding
Cultural service	Through the human connection, UK commercial shellfish provide services that relate to culture including: • Encouraging tourism and visitors • Supporting coastal beauty • Supporting spiritual experiences • Supporting education and research	These cultural ecosystem services provide PGBs that support human ways of life, such as: • Providing a sense of place • Providing aesthetic enjoyment • Supporting physical and mental health benefits • Employment opportunities • Economic wealth • Maintenance of traditional skills • Supporting life satisfaction
Supporting service	Shellfish provide supporting ecosystem services that are necessary to produce all other ecosystem services including: • Providing homes and habitats for other marine creatures • Feeding activities that influence the marine food chain	Supporting ecosystem services provide the foundation for provisioning, regulating and cultural ecosystem services public goods / benefits, including: • Supporting biological control of the ecosystem • Enhancement of greater genetic diversity and thus species richness

2.1. The provision of marine resources

Food provision (wild and farmed)

Marine shellfish species, both wild-caught and farmed, contribute to food provision for human consumption. Many shellfish species also have a high nutrient profile making them particularly beneficial to human health (Carboni et al., 2019). As of 2020, the most commercially important UK shellfish species in human food consumption were wild-caught crabs, Nephrops, scallops and farmed and cultivated mussels, oysters, and cockles (Marine Management Organisation and National Statistics, 2019).

Bivalve shellfish such as mussels and oysters provide a particularly high protein source, low in fat yet rich in marine lipids and minerals (Venugopal and Gopakumar, 2017). Nevertheless, finfish often dominate media attention surrounding the health benefits of seafood (Grant and Strand, 2019) and the nutritional benefits of consuming shellfish are less widely recognised. Despite this, landings of UK shellfish have increased by more than 300% over the last 80 years (from 32,000 tonnes in 1939 to almost 140,000 tonnes in 2019) (Marine Management Organisation and National Statistics, 2019), highlighting a significant increase in the number of people choosing to eat shellfish. The rise in shellfish consumption is positive for human health and seafood economies in the UK.

Bivalve shellfish aquaculture also requires no feed supply, fertilisers or medicines as they obtain all their nutrients by filtering mainly microscopic algae in the surrounding water column (Grant and Strand, 2019; Marine Conservation Society, 2020). This means fewer negative environmental impacts for the marine environment compared to finfish cultivation that can, if not carefully managed, contaminate the water column through pesticides, fish-feed, and faeces, leading to poor water and sediment quality that can impact the surrounding marine life (Read and Fernandes, 2003; Sustain, n.d.). UK commercial shellfish also receive a higher price on average than finfish, bringing more money into the industry per tonne. In 2019, shellfish landings averaged £2,714 per tonne compared to £2,166 and £854 for demersal and pelagic species, respectively (Marine Management Organisation and National Statistics, 2019). Bivalve shellfish can play an essential role in solving future human health and food security issues, environmental health, and economic stability for seafood supply chains.

Responsible shellfish aquaculture can enhance these PGBs, increasing protein production and food availability (Kluger et al., 2017), whilst causing less environmental harm than other farming and finfish aquaculture practices. Shellfish aquaculture could also provide significant food production by moving farms offshore where there is more space and less conflict with coastal industries (Case study 1. Offshore Shellfish Brixham). The shellfish sector can also utilise specific cultivation methods to enhance the ES provision of shellfish for human health and future food security. For example, rope grown and bottom cultured blue mussels (*Mytilus edulis*) are globally acknowledged as sustainable forms of seafood production and are recommended as a 'best choice' (level 1 categorised - "The most sustainably caught or responsibly farmed seafood") in the Marine Conservation Society 'Good Fish Guide' (Marine Conservation Society, n.d.).

To ensure shellfish continue providing a secure and sustainable source of food for humans, it is important that marine management acknowledges the contribution of commercial shellfish to human health and food security and the economic benefits associated with their low environmental impact cultivation. Financial incentives/subsidies made available to farms that use shellfish cultivation/capture methods to produce a stable source of low ecological impact food for humans may be an option for consideration. Such an incentive system would be like UK terrestrial farms that receive a percentage of the costs to develop woodlands that provide rich habitats for improved biodiversity (Table 1). Finance / subsidy programs could potentially lead to a positive shift in management focus across the seafood sector, better acknowledging the value of the ES provided by commercial shellfish and protecting the PGBs that they provide.

Case study 1. Offshore Shellfish Ltd

Offshore Shellfish Ltd is the UK's first large-scale, fully offshore, rope cultured, blue mussel (*Mytilus edulis*) farm off the coast of South Devon in Lyme Bay (Offshore Shellfish Ltd, n.d.). The mussel farm is spread over three sites, covering 15.4 square km between 3 and 6 miles offshore. When fully operational, the farm is projected to produce around 10,000 tonnes of blue mussels per year, providing a sustainable food source for human consumption and the delivery of PGBs such as nutrition and food security (Offshore Shellfish Ltd, n.d.).

Scientists from the Marine Institute at Plymouth University have monitored how the farm affects the surrounding marine environment. The company has been able to use the information gathered by the scientists to learn about the ES the mussel farms are providing (Offshore Shellfish ltd, n.d.). To date, evidence collected by the Marine Institute shows that the use of rope installations and elevated biomass within the farm is attracting a wide range of species compared to the surrounding areas. Many of the species attracted to the farms also have commercial value, such as brown crab and lobster (University of Plymouth- Marine Conservation Research Group, n.d.). In addition to acting as an aggregator of existing fish and shellfish, the farm also serves as a nursery area and food provider and, therefore, creates additional production. This is particularly true of brown crab, queen scallops and king scallops. Thousands of larvae will settle on the ropes each year and grow on to a significant size on the ropes away from benthic predators. Subsequently, they drop off and are potentially recruited to the fishery.

Benefits of the use of rope installations and elevated biomass at the farm therefore include increased species richness and improved biodiversity, ecosystem functioning and improved water quality due to filtration from the filter-feeding mussels. These ES can spill over into the surrounding waters, enhancing local fisheries, water quality and the overall commercial value of the farm and the surrounding waters. Furthermore, increased biodiversity, in general, is linked to ecosystems being better able to adapt to stressors in the marine environment. The farm, therefore, has the potential to strengthen local marine ecosystem resilience against climate change impacts and threats from human activities such as pollution (Sumaila and Tai, 2020).

Figure 4. One of the Offshore Shellfish Ltd blue mussel ropes (Mytilus edulis) suspended above the surface, 3-6 miles offshore Lyme Bay, South Devon (© Offshore Shellfish Ltd).

The provision of feed for the farming/catching sectors

In addition to providing food for humans, shellfish also provide further PGBs for non-human consumption purposes. Globally, only 40% of fish and shellfish products are utilised for human consumption, leaving 60% as waste (Malaweera and Wijesundara, 2013). The high nutrients in shellfish waste make it a vital nutrient supply for the animal feed industry intended for human consumption. Therefore, the waste associated with both the shellfish wild catch and cultivation sectors can be utilised and turned into a valuable commodity that brings additional benefits to society in tandem with human food production.

Crushed oyster shells, for instance, have been used for decades as a source of calcium for poultry across the egg industry (National Research Council, 1994). More recently, mussel meal has been used as an alternative protein source in the diets of poultry intended for human consumption (Wilhelmsson et al., 2019). The use of a natural waste product to sustain the poultry sector also provides more environmental benefits than using artificial feed associated with high GHG emissions and agricultural land use (Tallentire et al., 2018), thus, reducing emissions that result from waste degradation on land (Yuvaraj et al., 2019).

Providing fertilisers and biofuels

In addition to using waste shellfish in agricultural feed, it is also an essential source of raw material in fertilisers that can be used to enhance healthy plant growth (Case Study 2. Sea The Change Ltd– Guernsey Crab Shell Fertiliser). For example, the shells of commercial shellfish such as brown crab (*Cancer pagarus*) and Nephrops (*Nephrops norvegicus*) are used in industrial compost production (Domingo Pérez et al., 2015). The shells provide an excellent source of calcium carbonate, an essential element needed for plant health, which can also raise the pH level of soil in acidic areas (Seafish and ADAS UK, 2006). Such shell waste also contains large amounts of chitin and its derivative chitosan**,** a naturally occurring, non-toxic, biodegradable polymer. Chitosan is a natural alternative to synthetic nitrogen fertilisers commonly used in agriculture which is known to leach from soils and pollute waterways (Sebilo et al., 2013). Chitin from waste shellfish shells, therefore, provides a useful solution to minimise the environmental impacts of synthetic fertilisers and provides socioecological benefits through enhanced crop yields and thus improved food security.

Shellfish waste is also a critical component/catalyst in some biofuel formulations (Case study 3. Research into the sustainable production of biofuel from shellfish waste – The University of Alicante). Biofuel/bioenergy is defined as "*the renewable energy derived from recently living biological material called biomass*" (Dahiya, 2020). Biofuels as defined by the FAO are "*Fuel(s) produced directly or indirectly from biomass*" (Food and Agriculture Organization, 2010). Current biofuel production is mainly carried out using yeast from high sugar content plants. However, large areas of cultivated land are needed to produce biofuel crops, which poses serious economic, social, and environmental problems, including land clearance, loss of habitat and increased food prices (University of Alicante, 2016). However, utilising and valuing the wasted material from the shellfish wild capture and aquaculture sectors goes some way to solve these problems. Shellfish waste as an alternative source of biofuel provides an economically viable option using an otherwise wasted product. It further provides an energy source that can be used to sustainably help satisfy society's energy demand without the release of additional GHG emissions (Sánchez et al., 2019).

The provision of biofuels from commercial shellfish waste is a clear PGB provided by the wild shellfish catch and aquaculture sector. As a source of renewable energy, it indirectly increases the quality of life for humans and is an environmentally safe alternative to fossil fuels. The provision of biofuels contributes to broader policy agendas related to net-zero emissions and the industrial transition to circular economy principles. There is, therefore, an opportunity to include the provision of biofuel by commercial waste shellfish in national climate change mitigation efforts. Furthermore, there is scope for the value of shellfish ES and the PGBs derived from the waste of commercially captured and cultivated shellfish to be acknowledged and incentivised. Increased research and investment into the capabilities of shellfish waste as a biofuel would further help maximise its potential to contribute to industry decarbonisation and national GHG emissions reduction targets.

Case Study 2. Sea The Change Ltd– Guernsey Crab Shell Fertiliser

Sea The Change Ltd is a Guernsey and the Channel Islands based business that produces crab shell fertiliser from the waste of the local fishing industry. The fertiliser is made of pure crushed Guernsey crab shell, washed in sea water, and dried in the Guernsey sun. It provides a natural way to nurture plant health and growth without the need for additives, chemicals, or pesticides. To ensure sustainability, Sea The Change Ltd use crab shells from pot caught crabs, ensuring that they support a low impact and sustainable way of fishing that allows bycatch, undersized crabs, or females with eggs to be returned safely to the open water. The company's core aims are to repurpose waste resources, support the Guernsey fishing community and ultimately produce a product that is naturally good for plants.

Figure 5: Managing Director of Sea The Change Ltd seen drying Guernsey crab shell to be turned into Guernsey Crab Shell Fertiliser (©See The Change Ltd).

Case study 3. Research into the sustainable production of biofuel from shellfish waste – The University of Alicante

Promising research into biofuel production (bioethanol) using crab waste from the shellfish industry has been undertaken by the research group of Plant Pathology at the University of Alicante, Spain (University of Alicante, 2016). The group developed a novel process for producing biofuel via ethanol released by fungi (grown in anaerobiosis) feeding on the reducing sugars in crab waste (chitosan, chitin, or their derivatives).

The process is identified as a sustainable way to eliminate the pollution caused by shellfish waste and provides an alternative raw material to crops or agroforestry residues commonly used in biofuel production. The groups research provides good evidence that crab waste (in the form of chitosan) produces bioethanol in a profitable, sustainable, and environmentally friendly manner. However, there are currently no commercial companies using purely shellfish waste for biofuel generation.

Providing material for the medicines and biotechnology sectors

UK commercial shellfish contain several compounds that are sought after in the development of medicines, pharmaceuticals, nutraceuticals, and biotechnology. Bivalves such as blue mussels (*Mytilus edulis*) and Pacific oysters (*Magallana gigas*) are a rich source of bioactive peptides, proteins and metabolites that exhibit anti-cancer and potentially anti-microbial activity (Wang et al., 2017). As a result, the utilisation of peptides from natural shellfish sources are being rapidly developed as alternative anti-cancer agents to conventional therapies like chemotherapy and radiation, which are often associated with severe side effects (Wang et al., 2017).

Studies have identified two novel anti-cancer peptides of the Pacific oyster (*Magallana gigas*) that can kill prostate, breast, and lung cancer cells (Cheong et al., 2013). Further research on isolated peptides from protein hydrolysates in Pacific oysters (*Magallana gigas*) has also demonstrated abilities to inhibit tumour cell growth in mice (Wang et al., 2017). Shrimp species also contain anti-microbial peptides that enhance the anti-cancer activity of certain chemotherapeutic drugs (Wang et al., 2017). Through innovative research, the waste of commercial shellfish sectors (wild capture and aquaculture) benefits human life by contributing to improved health care, quality of life and increased life expectancy. Therefore, commercial shellfish sectors' role in human healthcare, alongside food production, is crucial and accounting for this in marine management may present opportunities to support further research and innovation.

Another biotechnology related application of shellfish is that of extracted chitosan from the shell of brown crab (*Cancer pagarus*) and Nephrops (*Nephrops norvegicus*). Research and developments across many industries now utilise the waste product in various applications.

Chitosan is currently used as an additive and preservative in the food and cosmetics industry, extending the shelf life of certain products. It is also being used across the food packaging industry, providing an environmentally friendly alternative to plastic packaging (Case Study 4. CuanTec Ltd – Scotland) (Bakshi et al., 2020; Galvis-Sánchez et al., 2018). Through biotechnology development, the waste of the commercial sectors can be enhanced to provide additional PGBs to society whilst helping reduce food waste and GHG emissions associated with decomposing shellfish waste.

Case Study 4. CuanTec Ltd – Scotland

CuanTec is a blue biotech company based in Oban, Scotland that produces a compostable, anti-microbial bioplastic film using waste chitosan from the UK's commercial shellfish industry (CuanTec, n.d.). The film is aimed at replacing single use plastic across a wide range of sectors including pharmaceutical, cosmetic and food industries. To further strengthen the products' environmental responsibility and make it a sustainable alternative to the current plastic packaging problem, CuanTech is utilising a Chitosan extraction process that requires significantly less energy and sodium hydroxide than current chitosan chemical processing methods. The company is positively showcasing the opportunities for biotech development alongside the shellfish catch and cultivation sectors and the additional benefits that the industries deliver in tandem, such as food production, research, waste utilisation and sustainable industry materials.

Figure 6. The image shows the New CuanSave™ prototype designed film, an alternative to plastic packaging (©CuanTec).

Ornamentals

The shells of shellfish have long been used for ornamental purposes by humans, bringing benefits such as decoration, fashion, handicraft, and souvenirs. Commonly, the shells of mussels, oysters, scallop, and crab are used for ornaments sourced from the waste of the shellfish wild catch and cultivation sectors. Shellfish species are also captured live and displayed in aquarium exhibits and museums.

However, there is a risk that the benefits of using shellfish for ornamental and display purposes could cause negative impacts on other shellfish ES if overexploited. For example, shells are often used by other marine biotas to form habitats. Fashion trends that use shellfish products can also enhance the demand for ornamental shellfish. Likewise, the spiritual and well-being associations with marine shells can result in people taking shells from beaches as fashion and memorabilia items (discussed further in §2.5. Cultural ecosystem services that support our way of life). The extraction of high numbers of UK shellfish may ultimately reduce and simplify benthic habitats for other aquatic organisms. In recent years, this has prompted local authorities to ask beachgoers to leave shells on beaches to reduce these negative impacts associated with their removal (Goldman, 2014; Kowalewski et al., 2014).

2.2. Regulating coastal health and quality

Recycling water and nutrients

Shellfish that are wild-caught or farmed for human consumption also provide essential ES that improve coastal health and water quality, including recycling water and nutrients in the marine environment. Bivalves such as blue mussels (*Mytilus edulis*) and native and Pacific oysters (*Ostrea edulis* and *Magallana gigas*), are 'filter feeding' species that remove phytoplankton and other suspended sediment particles from the water column. Bivalves naturally contribute to the exchange of nutrients and concentration levels within the marine environment (Preston et al., 2020), helping to improve water clarity and light penetration whilst reducing turbidity and cloudiness. The filtration of water and nutrients by shellfish also aids in the removal of harmful organic matter such as sewage effluent and agricultural runoff (manure and slurry) that are rich in nitrate, that makes its way into the marine and coastal environment (Case Study 5: The Dornoch Environmental Enhancement Project [DEEP]) (Petersen et al., 2019; Rose et al., 2015). Therefore, by recycling water and nutrients, commercial shellfish improve the water quality of contaminated areas, thus delivering PGBs such as reduced risk to human health associated with exposure to polluted waters and improved aesthetic enjoyment of coastal areas.

Case Study 5: The Dornoch Environmental Enhancement Project (DEEP)

The Dornoch Firth oyster restoration project is a social corporate responsibility programme that collaborates with The Glenmorangie Distillery Co, Heriot-Watt University, Marine Conservation Society, and rural Scottish oyster growers and broodstock providers across

Scotland (Native Oyster Network UK & Ireland, n.d.). It aims to restore a historic 40-hectare native oyster reef in the Dornoch Firth, seeking to establish a self-sustaining reef of four million oysters by 2025. The project is being used as a bioengineering solution to filter organic waste/nutrients from water discharged into the firth from the Glenmorangie Distillery, demonstrating the positive role commercial filter-feeding shellfish can play in water quality regulation (Sanderson, 2017).

The restoration process of the lost native oyster reef also results in the delivery of various other ESs and PGBs working in tandem, such as carbon storage, pollution control and cultural ESs like economic growth and increased social value of the area. Allen (2021) estimated that the restoration of native oyster beds in Scotland has the potential to give a £3.5m boost to the UK economy. It was also estimated that the development of a native oyster aquaculture industry in Scotland could see jobs created in some of the most economically marginal areas of the Western and Northern Highlands and Islands, bringing economic and social value to areas depopulated by migration and an ageing demographic. The DEEP approach and consideration of reef restoration for commercial use has also provided opportunities to enhance the delivery of policy set by the Scottish Government, such as Aquaculture Growth to 2030, Ambition 2030, the Hydro Nation Strategy and the water quality environmental objectives set by SEPA. The Deep project is a clear example of the benefits and opportunities that may arise from valuing commercial native oysters and prioritising their restoration through marine and fisheries management.

Figure 7. Dr Bill Sanderson, Lead scientist of the Dornoch Environmental Enhancement Project (DEEP) surveying reintroduced native oysters in the Dornoch Firth (© nativeoysternetwork.org).

To ensure that shellfish continue to improve the health and quality of our coastal waters, marine management and industry could consider focusing on the growth of bivalve cultivation. Developing competitive funding schemes/initiatives may also assist industry investment in activities that improve shellfish productivity and benefit the environment.

Such a funding scheme would be similar to the Farming Investment Fund, which covers the costs of equipment, technology, and infrastructure needed for farm-related improvements that benefit the environment (Department for Food Environment and Rural Affairs, 2021b). Furthermore, this could work in tandem with the Agricultural sectors new Slurry Investment Scheme (to be launched in 2022) aimed to help farmers invest in new equipment that will reduce pollution from the farming sector (Department for Food Environment and Rural Affairs, 2021b). If implemented, such a scheme could result in the fisheries and agricultural sector taking a collaborative approach to mitigating farm-related pollution entering the coastal environment.

There are opportunities to restore previously lost reefs to maximise the capacity of shellfish to filter coastal waters and sustain associated PGBs, whilst also providing food for human consumption. Several projects of this kind are already underway in UK waters, highlighting the potential of commercial shellfish to mitigate the adverse effects of excess nutrient loading from human activities (Case study 6. Liverpool Docks – Blue Flag Award). Such projects can raise public awareness around the PGBs derived from filter-feeding organisms.

Case study 6. Liverpool Docks – Blue Flag award

In June 2021, the Royal Albert and Salthouse Docks received the Blue Flag award for water quality, a scheme run by the Foundation for Environmental Education (BBC News, 2021; Butcher, 2021). This achievement results from over 40 years of monitoring programs and the introduction of thousands of blue mussel filter-feeders into the docks, required as part of the redevelopment of the area.

Before the late 1980s, the Liverpool docks once contained high concentrations of nutrients due to the pollution of the primary water source, the River Mersey. This pollution encouraged the formation of algal blooms and nuisance species that degraded water quality and marina life (Wilkinson et al., 1996). However, following recolonisation and rewilding projects of mussel beds since the 1980s, the docks water quality improved significantly. Liverpool docks are now home to over 30 different aquatic species and are the first English marina to receive the Blue Flag award.

The success of such projects demonstrates how people can enhance and maintain the ES provided by commercial shellfish to mitigate human degradation. They also showcase the opportunity for similar shellfish-focused projects to develop and maintain farms of filter-feeding shellfish species in UK coastal waters that are prone to pollution.

Figure 8. The waterways and well-being charity Canal & River Trust stand with the Blue Flag logo after being awarded England's first-ever international Blue Flag award for the Royal Albert Dock and Salthouse Dock marinas in Liverpool (June 2021; ©TowPathTalk).

Storing carbon and reducing climate impacts

Shellfish contribute to the vast amount of carbon dioxide captured by the ocean through physical and biological processes (Fodrie et al., 2017). In their natural state, shellfish sequester carbon during shell formation, aiding in climate regulation that humans rely on for well-being and quality of life.

The shells of bivalve shellfish contain calcium carbonate, which requires carbon absorption during growth (Preston et al., 2020). This process isolates and withdraws carbon from the marine environment, known as carbon sequestration. The sequestered carbon is recycled throughout the food chain and eventually stored in the sediment as shells are buried. Unless disturbed, the buried carbon can remain stored for millennia, thereby removing carbon from the atmosphere that would otherwise contribute to GHG levels and the threat of climate change. Therefore, by capturing carbon, shellfish provide an ES that contributes to the ocean's important role in climate change mitigation.

When comparing the carbon footprint of various methods of animal food production, farmed molluscs, such as oysters, mussels and scallops, appear to be the most responsible and sustainable in terms of carbon emissions (Hilborn et al., 2018). Shellfish have a significantly lower carbon footprint than other animal proteins and require no feed supply, fertiliser, or medicine that can negatively impact the marine environment (The Marine Conservation Society and Rewilding Britain, 2021). In addition to being a low carbon form of food production, mollusc aquaculture also produces the least air pollution compared to other food production whilst also absorbing excess nutrients that are harmful to the environment (Hilborn et al., 2018).

The expansion of sustainable shellfish aquaculture such as molluscs provides opportunities to enhance the carbon storage capacity of shellfish whilst increasing the production of a low carbon food source (Coen et al., 2007; The Marine Conservation Society and Rewilding Britain, 2021). The restoration and rewilding of native oyster reefs throughout the UK's coastal waters could also offer a climate change mitigation tool that assists the UK in its goal to reduce national GHG emissions by 2050 (UK Parliament, 2019). A network of native oyster (*Ostrea edulis*) restoration projects has already begun in some areas of the UK (see the Native Oyster Network and Case Study 5 The Dornoch Environmental Enhancement Project [DEEP]), highlighting how industry and research can collaborate to enhance carbon storage capacity provided by UK shellfish.

To ensure that shellfish-focused projects contribute to climate mitigation and future food security, there is scope to consider responsible shellfish aquaculture in broader climate agendas similar to the farming and land management sectors. Sustainable farming practices and protection for terrestrial carbon stores, for example, are considered in the UK's plans to reach Net Zero by 2050 (HM Government, 2021). Marine carbon stores, however, hold significantly greater carbon stores than those on land.

The top 10cm of the English North Sea alone estimated to hold 100.4Mt carbon, nearly 20% of the carbon estimated to be held in UK forests and woodlands (529Mt carbon) (Burrows et al., 2021). The total organic carbon stored in the seabed sediment is significantly higher, with the seabed sediment running tens to hundreds of metres deep (Burrows et al., 2021). Therefore, opportunities to recognise low carbon marine food production through broader climate change agendas such as responsible shellfish acculture, could help the UK meet net zero commitments more effectively. Appropriate payments to support the sectors' role in climate regulation could see greater uptake of responsible aquaculture methods. This again would mirror the funding available to farmers to decarbonise and protect terrestrial carbon stores on land such as peatlands and favour low carbon farming practices (HM Government, 2021).

2.3. Stabilising the seabed and shoreline

Building reefs

Shellfish are ecosystem engineers that modify the marine environment through the formation of complex habitats. Reef-building shellfish such as blue mussels (*Mytilus edulis*) group together during settlement to form dense colonies of underwater reefs. These reefs are held together by byssus threads, becoming rigid physical marine barriers that stabilise the sediment beneath (Ana Rodriguez-Perez et al., 2019). The physical barriers create highly complex habitats for a diverse community of plants and animals to live in and on whilst providing natural shoreline hardening, benefiting society through erosion and flood control (Marine Scotland, 2018).

Shellfish and their shells are increasingly used as a soft engineering alternative to artificial structures such as seawalls that can cause environmental harm through beach narrowing and reduced marine biodiversity (Gittman et al., 2016; Tavares et al., 2020). Utilising the seabed stabilising ES of shellfish in this way is similar to afforestation projects on land, where trees are planted around feeder rivers to slow down floodwaters and reduce the height of flooding in towns further downstream (GOV.UK and Environment Agency, 2019). The stabilising seabed ES provided by shellfish habitats offers a natural alternative to shoreline hardening associated with fewer ecological consequences whilst providing habitats for other species, including commercially important ones (Scyphers et al., 2014).

Regulating natural hazards

During storms, dense colonies of underwater reef-forming bivalves such as oyster and mussel reefs act as natural breakwaters, absorbing wave energy before hitting the shoreline. Therefore, shellfish habitats are a natural form of coastal defence, protecting shorelines from erosion and flooding. However, naturally occurring reef-forming shellfish populations have declined around the UK coast over the last few hundred years, resulting in a significant loss of natural hazard regulation. With climate change predicted to increase the frequency and intensity of storms across the UK, the coastal defence ES provided by shellfish habitats could be considered part of national climate change adaptation tools. Recently reef-forming bivalves have been acknowledged in UK flood and erosion management planning for their coastal defence ES. However, such management projects are still in the trial stages.

To maximise the potential natural hazard regulation provided by commercial shellfish, therefore, coastal flood and erosion management should acknowledge the contribution of shellfish to shoreline stabilisation and coastal defence. There could also be an opportunity to incentivise aquaculture operations that restore lost or declining oyster and mussel reefs for coastal erosion and flood control.

Likewise, it may be beneficial to provide support for developing and expanding sustainable aquaculture farms along vulnerable shorelines, helping to maximise potential shoreline defence as a climate change mitigation tool against intensifying storm events (Case study 7: Stronger Shores Flood and Coastal Resilience Project – North East of England). Such an initiative would be similar to peatland restoration schemes that provide grants to UK landowners to protect and restore peatland areas so that they can hold water and contribute to natural flood management outcomes (IUCN, 2018). Replicating peatland initiatives could lead to a shift in shoreline management that values natural solutions to coastal erosion and flood control.

Case study 7. Stronger Shores flood and coastal resilience project - North East of England

Stronger Shores is one of 25 innovative new projects selected by the UK government to trial a range of marine nature-based solutions to UK coastal flooding and erosion control (South Tyneside Council, 2021). The project, which the South Tyneside Council currently leads, focuses on the English coastline from Blyth in Northumberland down to Redcar and Cleveland in North Yorkshire (South Tyneside Council, 2021; Walker, 2021).

£6.4 million has been secured from the Government's £150 million Flood and Coastal Innovation Resilience Programme to pilot the scheme (Department for Food Environment and Rural Affairs and Environment Agency, 2021; South Tyneside Council, 2021). It aims to improve our understanding of the benefits of UK marine habitats concerning coastal erosion, flood risk, climate change and biodiversity management. The project will involve restoring sub-tidal habitats such as oyster reefs and vegetated marine habitats along the coastline over the next six years. Its findings will measure the costs and benefits of marine nature-based solutions and potentially shape future strategies for managing coastal erosion and flood risk across the UK coastline.

The project demonstrates the interest and investment that is starting to focus on the benefits and opportunities commercial shellfish ES provide. It also suggests that national and localised governments are beginning to recognise the natural hazard regulation potential of marine nature-based solutions like afforestation projects on land.

2.4. Supporting biological structuring, food webs and biodiversity

Providing homes and habitats for other marine creatures

Shellfish influence the structure of the aquatic biological community through habitat formation and feeding activities. These services affect marine food web structure, influencing biodiversity and shaping the seascape.

Shellfish habitats provide suitable habitats, feeding grounds and nurseries for other marine organisms, including commercially important species (Craeymeersch and Jansen, 2019; Glaspie and Seitz, 2017; Sheehan et al., 2015). Oyster and mussel reefs are complex habitats that offer a variety of places for different marine creatures to live. The shell exterior, for example, provides an ideal surface for barnacles to attach. In contrast, the crevices between neighbouring mussels offer space for both mobile and sedimentary fauna to live (Abdullah and Lee, 2016; Kluger et al., 2016; van der Zee et al., 2015).

Mussel and oyster reefs and shellfish farms also provide shelter and protection for creatures higher up the food web, such as fish and crabs. Protection of higher trophic species can indirectly result in increased secondary production of fish and crabs, leading to a boost in food provision and economic value for the seafood industry (Ayvazian et al., 2020; Lai et al., 2020). The variety of species supported through the structure of shellfish habitats can increase biodiversity, contributing to greater ecological community resilience against disturbances and a sustained flow of seafood for human consumption.

The wild capture of shellfish using heavy gears such as trawlers and dredgers can have significant and unwanted impacts on areas of high biodiversity associated with shellfish habitat formation. However, the use of specific, specialist gear technology can be used to increase target species selectivity and reduce unwanted bycatch that can harm the area's biodiversity. For instance, in Northern Ireland, a 6-year industry-led project is developing and trialling selective fishing gear to eliminate discards and avoid unwatched catches across the Nephrops fishery (Gearing Up, 2018;) (Case study 8. The NOerthen Ireland Gear Trailas Project).

Wild capture fisheries can take various other voluntary actions to support the ES provided by shellfish. For example, nearshore restrictions on trawling could see shellfish habitats protected and the nursey habitats provided for commercially important fish. Although this method has an initial decline in catch, it will likely be offset by future benefits of stock resilience and sustainability if nursery habitats are protected. Larval spillover of juveniles/adults into adjacent fisheries may also occur, strengthening sustainable fish populations and food production (McConnaughey et al., 2020). Freezing the trawling footprint is another voluntary action by the wild capture sector that ensures shellfish ES are sustained. Confining benthic disturbance to previously disturbed areas and minimising benthic impact to unfished areas can preserve the ecosystem integrity of the area and the resilience provided by shellfish ES. These benefits may again spill over into trawled areas (McConnaughey et al., 2020).

Case study 8. The Northern Ireland Gear Trials Project

Set up in 2017, The Northern Ireland Gear Trials Project is a 6-year, industry-led collaborative project that aims to provide the fishing industry with the support to develop more selective fishing gears to increase the selectivity across Northern Ireland's Nephrops fleet. Collaborators in the project include the Anglo-North Irish Fish Producers Organisation (ANIFPO), Northern Ireland Fish Producers' Organisation (NIFPO), The Department of the Environment and Rural Affairs (DAERA), the Agri-Food & Biosciences Institute (AFBI) and Seafish with funding derived from the European Maritime and Fisheries Fund (EMFF).

The gear trials are open to all Northern Ireland Nephrops trawlers and the ideas that have been developed to date originate from discussions with fishermen. NI based gear manufacturers have been commissioned to carry out the gear work with final approval for trials at sea signed off by the project steering group that is composed of the organisations mentioned above. Each year, several gear trials are run using chartered Northern Ireland registered fishing vessels and onboard scientific observers that record catch data (Seafish et al., 2019). Extended trials have also been undertaken by skippers, who were responsible for the recording / collection of data rather than trained observers. This approach aimed to encourage skippers to test things out for themselves over more extended periods and report feedback (The Fish Daily, 2020). A selection of trials carried out so far include two versions of an inclined net grid trawl, coverless trawls, luminous netting in the bottom panel of a SELTRA box section and work with light technology (Seafish et al., 2019). With each trial, fishermen make suggestions on improvements for future trials. Through repeated trialling and analysis of the data, two designs have now shown the ability to reduce the bycatch of unsized whiting whilst not reducing the target catch. The goal is to identify a selective device that can meet conservation objectives but also remains commercially viable to use in the fishery. The project is a clear example of the contribution industry can make to fisheries research and innovation when valued and supported.

Figure 9. Photo showing an experimental net being trialled as part of the Northern Ireland Gear Trials project. The cover of this trawl has been cut out and replaced with a pelagic sized mesh (© Northern Ireland Gear Trial Project 2017-2022).

In wild capture fisheries there are opportunities to make financial incentives/subsidies available to those fisheries that use gear that has less contact with the seabed. Shellfish collection by divers (Figure 10) or through potting and creeling causes minimal damage to the seabed and enables selectivity that helps protect the wider stock. Such financial incentive/subsidy could motivate the smaller scale wild-catch sector to adopt more environmentally sustainable fishing gear, resulting in positive benefits to other ES such as carbon storage.

Figure 10. Hand collection of scallops in West Bay, Dorset (© Saeed Rashid).

Influencing the marine food web

Suspension feeding bivalve shellfish (e.g., mussels and oysters) and brown crab and Nephrops, influence the marine food web structure by moving nutrients through the water column to the seabed. The movement of nutrients by shellfish contributes to nutrient exchange between the pelagic and benthic environments and the transfer of food to different levels of the food web (Buelow and Waltham, 2020; Isdell et al., 2020). The feeding activities of shellfish support a high density and diversity of macroinvertebrates, including sponges, crabs, shrimp, clams, oysters, barnacles and worms, many of which are essential prey resources for fish of commercial value for human consumption (McLeod et al., 2014).

Shellfish feeding activities contribute to the biological control of the ecosystem through the filtration of excess pollutants in the water column. Pollution filtration plays a vital role in controlling the biomass of opportunistic species such as phytoplankton. These species are stress-tolerant and able to adapt to a wide range of food sources. Therefore, without the filtration of nutrients by filter-feeding shellfish, opportunist species can thrive on surplus food sources and quickly colonise ecosystems. Opportunist colonisation can lead to toxically low-oxygen conditions and marine dead zones in extreme cases, where only a few opportunist species can survive. The nutrient exchange promoted by shellfish feeding activities influences the marine food web and contributes to increased species richness and community resilience against change such as diffusing pollution. A rich ecosystem provides a secure and diverse food source for humans, economic value for the seafood industry and a healthy marine environment for human enjoyment and recreation. Sustainable aquaculture could help restore thriving fishing grounds through the positive influence shellfish have on biodiversity and the secondary production of other marine creatures.

2.5. Cultural ecosystem services that support our way of life

Tourism and aesthetic enjoyment

The wild capture and cultivation of shellfish add cultural value that supports our way of life. UK commercial shellfish play an important role in tourism, leisure, and local food culture, bringing health, economic and aesthetic PGBs to society. Iconic UK shellfish such as brown crab (*Cancer pagurus*) is often captured in photography or films, contributing to coastal fishing communities' aesthetic image and tourism success. Likewise, the display of shellfish boats and crab pots in harbours are often considered to add quintessential charm to a place that people consider nostalgic and associate with a simpler time gone by. The shellfish catch and cultivation history of a coastal area is therefore considered part of the beauty of the place, attracting large numbers of visitors and holiday markers. Picturesque fishing villages can often benefit from increased house prices and a strong seafood hospitality presence that brings economic value to the area.

Specific areas across the UK have become associated with local shellfish delicacies recognised as part of local cultural tourism through annual seafood festivals (Case study 9: Cromer and Sheringham Crab and Lobster Festival). Currently, over 100 food festivals occur across the UK every year, several of which specifically celebrate local shellfish (Lee and Arcodia, 2011; van der Schatte Olivier et al., 2018). The 3-day Stranraer Oyster Festival in Scotland celebrates the local native oyster (*Ostrea edulis*) fishery at Loch Ryan, one of the last wild, native oyster beds in Scotland (Figure 11).

In 2018, the event saw over 14,000 visitors come together to celebrate and taste pacific oysters, provided by the Loch Ryan Oyster Fishery Co. The event generated up to £1 million for the local economy and saw families, local businesses, celebrity chefs and live musicians come together (Stranraer Development Trust, n.d.). Many benefits to society are provided and maintained by celebrating captured and cultivated shellfish, including regional economic prosperity, traditional skills, employment, and creating a sense of place through community connection. The connection and association with local, sustainable shellfish farms can therefore build community resilience and life satisfaction.

Figure 11. Loch Ryan Oyster Fishery Co. staff, serving oysters at the Stranraer Oyster Festival 2019. The company's rights to the wild native oyster fishery date back to 1701, with recent generations restoring it to full production. The sustainably caught self-sustaining population at present produces about 20 tonnes a year (© Stranraer Oyster Festival).

Case study 9. Cromer and Sheringham Crab and Lobster Festival

The Cromer and Sheringham Crab and Lobster Festival is a weekend celebration of two former rival Norfolk seaside towns, Cromer and Sheringham (Crab & Lobster Festival, 2022). The festival is dedicated to promoting the areas local seafaring heritage and active fishing community. The local crab and lobster delicacies are the main celebration, bringing economic prosperity to the area through the popular Seafood Trail festivals. Other entertainment, such as lobster pot making, helps keep traditional skills and knowledge alive whilst building connections between the fishing industry and the local community. Live demonstrations of seafood preparation such as fish-filleting and crab-dressing give people the confidence to include local seafood in their diet. The festival helps maintain the local industry's economic prosperity, which in turn contributes to wider local economic stability.

Figure 12. Locals shown enjoying the Cromer & Sheringham Crab & Lobster Festival, Norfolk (© Dalegate Market).

Spiritual experience and cultural well-being

The ornamental value of shellfish shells has long been linked to human spirituality, connecting nature and cultural well-being. For over a century, they have been used to decorate buildings worldwide, symbolising the natural richness of the marine environment. In other areas, shells have provided people with memorabilia of a spiritual journey or as memorabilia of a happy holiday or a peaceful moment by the sea. People often display these shells in their homes, helping to create a unique sense of place through memories.

The Camino de Santiago was one of the most important Christian pilgrimages during the Middle Ages, comprising a network of routes leading to the shrine of Saint James in the cathedral of Santiago de Compostela (Galicia, Spain) (Maria, 2021). It became customary for those who undertook the pilgrimage to bring back the shell of a queen scallop (*Aequipecten opercularis*) as proof of the journey (Waldron, 1979). These pilgrimage routes are now included in the UNESCO World Heritage list and attract hundreds of thousands of tourists and pilgrims each year (UNESCO World Heritage Centre, n.d.). The scallop shell is one of the most iconic symbols of the Camino de Santiago, used as a symbol of direction along the routes and as a link to understanding the history, culture and traditions of the ancient pilgrimage (Wanda, 2021).

Health benefits

Connecting with the marine environment is closely associated with human health benefits (Bell et al., 2017; Gascon et al., 2017). The term 'Blue Health' relates to the idea that human mental health can be improved with access to 'blue spaces' such as the sea, rivers and lakes (Blue Health, 2020; Gascon et al., 2017; Roe, 2019). Time spent in 'blue spaces' can benefit human psychological well-being and increase social engagement that enriches people's lives (Bell et al., 2017; Roe, 2019). People choose to spend time in 'blue spaces' for recreational activities that improve health, such as fishing or water sports, social interaction, and relaxation motivations (Elliott et al., 2018).

The fishing industry, including the shellfish catch and cultivation sectors, has a role in 'Blue Health' by ensuring sound environmental stewardship. Fisheries management should ensure that no industry practices contribute to the degradation of the marine environment that could lead to a decline in access to healthy 'blue spaces'. Shellfish aquaculture, such as rope grown mussel farms, could be acknowledged as a tool to maintain 'blue spaces' by supporting shellfish ES that improve the quality and health of coastal waters, such as water and nutrient recycling. Using shellfish aquaculture to improve the water quality of 'blue spaces' reiterates the importance of the shellfish industry's positive contribution to society outside of food production. This positive narrative could go some way to change the negative associations of environmental damage that often surround the fishing sector.

Contributing to scientific research

The cultivation and wild capture of commercial shellfish can contribute to scientific research. Fishing and shellfish industries often take on data collection and monitoring roles for the scientific community, NGOs, and UK governments. Fishermen also offer invaluable information to scientific research by participating in qualitative research through in-depth interviews and surveys etc (Boase et al., 2019). In recent years, available funding for fisheries and industry science partnerships has seen the UK seafood industry and research institutes come together to improve evidence bases and inform sound management decisions (UK Parliament, 2021) (Case study 10: King scallop stock assessment project). The industry's role in scientific research and data collection therefore supports shellfish ES by contributing to our understanding of the marine environment, which helps to maintain the PGBs we derive from UK waters.

To ensure that the shellfish catch, and cultivation sectors continue to participate in scientific research, the sector should be acknowledged for its contribution to marine scientific understanding. There may also be scope to provide incentives to those fishers participating in scientific collaboration. Such financial incentives could increase the shellfish industry's motivation to participate in fisheries and industry science partnerships, addressing the growing need for evidence in fisheries management (Mackinson et al., 2017).

Case study 10: King scallop stock assessment project

As part of a novel system of fisheries co-management, industry is working collaboratively with researchers to improve the information base for key UK shellfish fisheries. One such project is the king scallop (*Pecten maximus*) stock assessment project, which commenced in 2017, providing an example of how industry can play a central role in improving the availability of data to support evidence-based fisheries management. This work is also contributed to improving our understanding of the contribution shellfish make to blue carbon storage.

Despite being of huge economic importance, UK king scallop stocks have been left vulnerable to overexploitation under a complex management system, which historically lacks coordination across local, national and international boundaries. Prior to 2017 stock units were not subject to routine monitoring or formal assessment. In response to concerns over the long-term sustainability of this fishery, the scallop industry collaborated to provide technical data, operational support and funding to support both the identification of key scallop fishing grounds around the English coast, and the delivery of stock assessments within these areas. This project has been delivered via an innovative data gathering framework by the industry-led Project Steering Board, a subgroup of the Scallop Industry Consultation Group (SICG), in close collaboration with the Shellfish Team at Cefas.

Within each of the seven stock assessment areas located in the English Channel, Bristol Channel Approaches, and the North Sea, the project gathers information on harvestable biomass, fishing pressure, and harvest rates compatible with Maximum Sustainable Yield. Industry facilitated and, at times, directly funded annual dredge surveys to provide the essential biomass data, which is supported by data collected via underwater TV surveys and an industry facilitated biological sampling programme (in which fishers submit part of their catch for scientific sampling, providing data on biological variables such as length frequency distribution).

Stock assessment outputs are expected to be an essential requirement for the development of the king scallop Fisheries Management Plan (FMP), which is currently being produced via close collaboration between industry, government and the scientific community as part of the FMP front runner programme, in recognition of the value and vulnerability of UK scallop stocks. Robust stock assessments will also be a key to the fulfilment of objectives outlined in the Fisheries Act 2020 and Project UK Fisheries Improvement Projects.

By preventing stock over-exploitation, evidence-based management is key to safeguarding the social, economic and environmental sustainability of this valuable fishery. There are also benefits in terms of mitigating against the effects of climate change, as overexploitation would have negative implications in terms of the blue carbon storage potential of shellfish beds. Furthermore, improvements in the sustainability of UK scallop fisheries brings socio-economic benefits throughout the supply chain, from catchers to processors and eventually consumers. The project is a clear example of the contribution industry can make to marine research and innovation.

Section 3

Practical suggestions for stakeholders

This section discusses how key stakeholders (policymakers, industry, and the scientific community) can support the shellfish industry's role in maintaining and enhancing ES and providing PGBs. It provides practical suggestions for consideration to see policy and business decisions reflect the ES and PGBs narrative associated with farming and land management in the UK. The section is structured by stakeholder group.

3.1. Policymakers

In the context of this report, "policymakers" refers to the national UK Government, the devolved administrations, and associated agencies e.g., Marine Management Organisation, the Statutory Nature Conservation Bodies, the Inshore Fisheries and Conservation Authorities and The Crown Estate etc.

Develop a clear understanding of the concepts

To build a policy narrative that acknowledges and supports the contribution of the shellfish industry in a similar way to UK farming policy, a clear understanding of the ES concepts and PGBs associated with the UK seafood industry is needed. The information in this report demonstrates the various ways that the shellfish catch and aquaculture sectors enhance, support, and maintain some shellfish ES while delivering PGBs. Therefore, the evidence provides an opportunity for policymakers to deepen their understanding of ES concepts and shellfish associated PGBs.

Follow similar narratives to farming policy for UK fisheries and aquaculture management

Currently, the UK has a farming system that incentivises PGBs that protect the environment and the benefits society receives from sustainable farm management. Through the UK Fisheries Act 2020, there is an opportunity for policymakers to reassess and rebuild fisheries and aquaculture management to acknowledge and reward practices that support ES and the delivery of PGBs. For instance, there is scope to consider the 'public money for public good' argument paving the future of ES-centred farming subsidies, but in the seafood industry context.

In response, this report begins to address critical questions such as '*What are the seafood industry-related PGBs that public money should support*?' Answers to such questions could help better structure funding so that it recognises actions that enhance shellfish ES. Structuring fisheries funding in this way would reflect the farming policy narrative and see key UK food industries (farming and seafood) align in a management direction that works to secure PGBs for a sustainable, holistic future for the UK.

Consider the contributions of the shellfish industry to other policy agendas

The ES and PGBs provided by UK commercial shellfish demonstrate the seafood industry's indirect contribution to broader policy agenda items, such as water quality and carbon storage. Consequently, there is an opportunity for policymakers to utilise and redirect the industry contributions to PGBs to meet other policy agendas by incentivising aquaculture expansion. The UK seafood industry's role in enhancing bivalve carbon capture capacity through enhanced aquaculture and involvement in restoration projects could be mobilised to help policy priorities such as the Net-Zero agenda, which requires the UK to reduce carbon emissions to zero by 2050.

Likewise, shellfish aquaculture provides a bioengineering tool to increase water quality standards set out by The Water Environment (Water Framework Directive) (England and Wales) Regulations 2017 (UK Parliament, 2017), Water Environment and Water Services (Scotland) Act 2003 (Scottish Government, 2003) and The Water Environment (Miscellaneous) (Scotland) Regulations 2017 (Scottish Government, 2017).

Furthermore, incentivising fishing/cultivation equipment that causes less ecological impact could mitigate reductions in shellfish ES. In this regard, industry could have a much broader role in the future of sustainable marine management. There is an opportunity to capitalise, via policy interventions, on the contributions that the wild capture and farmed shellfish sectors make to climate change mitigation efforts, statutory monitoring of marine climate change indicators, invasive species reduction, and ecosystem service indicator development.

3.2. Industry

In the context of this report, "industry" refers to industry-wide bodies related to fisheries or aquaculture, specific sector groups and associations such as the Shellfish Association of Great Britain, the Scottish White Fish Producers Association, and individual operators such as fishermen and aquaculture producers.

Improve business decision-making to enhance ESs, increase PGBs, and mitigate negative impacts

To support the shellfish industry's crucial role in providing PGBs, industry must first understand its contribution to shellfish ES and PGBs but also the negative impact that certain fishing and farming practices can have. From this understanding, the shellfish catch and cultivation sectors can begin to reassess their role in supporting ES within policy and management discussions. This may lead the sectors to think differently about what is within their control, regardless of fisheries/aquaculture policy and management; business decisions that result in a positive contribution to shellfish ES, increasing the delivery of PGBs, and mitigating any adverse impacts to ES caused by industry activity.

Business decisions could focus on traditional catch and farming methods that help protect healthy commercial stocks, provide a sustainable and high-quality food source, and preserve the resilience of coastal communities, traditional skills, and culture. Practical suggestions could include investing in innovative gear technology so as to modify fishing practices or the type of gear used. Consideration could also be given to the future development of a national nutrient credit trading programme such as has been implemented in Denmark and parts of the USA. Shellfish growers could be credited for the value of the removed nutrients and, as a result of that removal, preventing the consequences such as eutrophication that would otherwise occur unless addressed by alternate management measures. Bivalve production provides a good example of a nature-based solution for improving water quality whilst also representing a sustainable example of blue growth.

Increase industry participation in policy discussions

The information in this report emphasises the benefit of including industry in policy discussions by showcasing the collective knowledge held by the shellfish catch and cultivation sectors. Nevertheless, collective industry knowledge is not always fully utilised in marine governance. To better support the shellfish industry's role in providing PGBs moving forward, possible opportunities to consider include shifting the structure of marine governance towards a more participatory model where the UK shellfish industry takes a more active role in policy management.

A participatory model could take the form of a fisher-directed management system where fishers own the management process, and permission to fish is contingent on the fishers managing their fishery sustainably (Hart, 2021). Access to the fishery through a fisher-directed management system would be a public good, and any degradation of the fishery/public good would receive suitable peer penalties. Ownership of the management process may act as an incentive for fishers to fish sustainably, whilst being held accountable by other fishers may stabilise management and improve compliance with regulation (Hart, 2021).

A more participatory role for fisheries could see concepts of current policy reviewed and developed into a more practical toolbox to help mainstream ecosystem thinking. It could also address overcomplicated language and jargon commonly used in policy, enabling widespread understanding across industry and greater space for industry involvement during seafood-related policy discussions. The shellfish sector may then be better positioned to communicate priorities, share practical knowledge, and increase innovation which should in turn lead to improved marine policy concepts that support shellfish ES and PGBs.

3.3. The Scientific community

In the context of this report, "the scientific community" includes academic institutions, NGOs, and industry funded scientists.

Increased research on industry contributions to PGBs and enhanced ES is needed as the marine space is of a more complex three-dimensional nature than the arguably simpler, two-dimensional terrestrial environment. The challenges to scientific research in the marine space have meant a more significant proportion of unknown factors and a weaker science base surrounding ES and PGBs derived in a marine context. As a result, a more mature scientific understanding of land-based ecosystem interactions has developed, and farming policy and management reflects this (Garrett, 2019).

The solid evidence base surrounding the provision of PGB by UK farming could indicate why the ES and industry enhanced PGBs are acknowledged in the Agriculture Act 2020 in replacing the Common Agricultural Policy but not in the UK Fisheries Act 2020 replacing the Common Fisheries Policy. Therefore, to develop UK fisheries management that replicates the agricultural policy landscape, there is a growing need for dedicated research-led fisheries management policy that focuses on delivering PGBs and rewarding best practices. The information in this report may guide future research that will help drive policy and assess the scale of funding schemes to incentivise the contribution of the UK shellfish sectors to ES and PGBs.

Address scientific knowledge gaps

Researchers may look to this report to identify potential research gaps surrounding evidence of shellfish ES and industry PGBs, indicating where evidence is relatively strong and weak. For example, evidence on the ES and PGBs provided by shellfish is more substantial around bivalves such as mussels and oysters in UK commercial shellfish settings (Carss et al., 2020; Pinn, 2021). While further research on the enhancement of PGBs through bivalve cultivation would be beneficial, this report points to a lack of complete understanding on the contributions that wild capture fisheries make. This should be the focus of dedicated research in the future.

Conclusion

Following the UK's exit from the European Union in January 2020, the UK has set out to restructure the management of its natural resources, focusing on an ecosystem approach to policy. Considerable changes have been made to terrestrial farm policy, where the focus has been shifted toward the benefits of enhancing ES and PGBs. Funding schemes and subsidies have subsequently been developed to support the farming sector in delivering public goods through sustainable farming practices. However, similar consideration has not been given to fishing and aquaculture management and the wider seafood industries. This report aimed to demonstrate the seafood industry's contribution to the ES and PGBs provided by commercially important shellfish, highlighting the need for management and policy development similar to that for terrestrial farming.

The report showcases the ES that UK commercially important shellfish are known to provide, along with the PGBs they deliver to society. The PGBs delivered by shellfish ES are shown to be equally as broad and beneficial to society as those provided by land-based ecosystems, including provisioning, regulating, support and cultural services. Furthermore, the report demonstrates the positive role of the seafood industry in supporting, maintaining, and enhancing shellfish ES along with the action taken to mitigate any negative environmental impacts.

Opportunities to expand the sector's delivery of PGBs are also presented, highlighting the possible opportunities around ES-centred marine management. Current knowledge demonstrates that the catch and aquaculture sectors actively deliver PGBs in a similar way to the farming sector yet are not recognised or rewarded through similar legislation and funding schemes. There is an opportunity for this to be rectified through marine policy development and interventions.

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Appendices

Appendix 1: Overview of key shellfish species wild-caught or cultivated in the UK

A broad range of commercially important shellfish species are caught and cultivated in UK waters for human consumption. From a food production perspective, the most economically important wild-caught commercial species are crabs (brown or edible *Cancer pagurus*, spider crab *Maja spp*. and velvet swimming crab *Necora puber*), lobsters (European lobster (*Homarus gammarus*) and spiny lobster (*Palunirus elegans)*), Nephrops (*Nephrops norvegicus*), and scallops (queen scallop (*Aequipecten opercularis)* and king scallop (*Pecten maximus*)). At the same time, the most economically important cultivated commercial species are mussels (blue mussel (*Mytilus edulis)*), oysters (native oyster (*Ostrea edulis*) and Pacific oyster (*Magallana gigas*)), and cockles (*Cerastoderma edule*) (Marine Management Organisation and National Statistics, 2019).

- Prominent commercial UK species to be discussed include:
- Blue mussel (*Mytilus edulis*)
- Pacific oyster (*Magallana gigas*, previously named *Crassostrea gigas*)
- Native oyster (*Ostrea edulis*)
- king scallop (*Pecten maximus*)
- Queen scallop (*Aequipecten opercularis*)
- Brown or edible crab (*Cancer pagurus*)
- Nephrops (*Nephrops norvegicus*)

The geographic availability of these species varies in and around UK waters, as does their capture/ cultivation methods and export destination, volume, and value. The following section briefly summarises each key UK shellfish species, covering distribution, capture method, and cultivation. This information is synthesised from Seafish's Risk Assessment for Sourcing Seafood (RASS) and associated guides, the UK's Marine Biological Association Marine Life Information Network (MarLIN) and the IUCN Red List of Threatened Species.

Blue mussel (Mytilus edulis)

Mussels are sessile bivalve molluscs that are widely distributed along all UK coasts. Blue mussels (Mytilus edulis) live in the intertidal zone across many habitats, from rocky shores to estuaries. They can also be found in the sublittoral area up to depths of 200 meters. Blue mussels cooperate to form mutual protection by attaching themselves to neighbouring mussels by byssus threads. The group then attaches to substratum that provides a loose anchorage such as rocks, stones, and dead shells whilst still floating and absorbing nutrients in the water (Pinn, 2021).

In 2017, the UK exported £4 million worth (11,155 tonnes) of blue mussels (Mytilus edulis) almost exclusively to EU countries (Garrett, 2019).

Mussels can be caught or cultivated; however, the UK industry has recently moved away from wild mussel stock extraction and now favours cultivation using both bottom culture and rope grown techniques (Pinn, 2021). Bottom culture techniques rely on the re-laying of seed mussels collected by dredge (designed to remove the mussels in clumps with minimal force and penetration into the substrate) from wild sources, which provide improved growth and survival (primarily in England, Wales, and Northern Ireland). Rope grown culture relies on rafts and buoyed long-line systems (primarily in Scotland, however, independent English cultivation has begun significant production (Offshore Shellfish Ltd, n.d.). The culture of blue mussels (Mytilus edulis) requires no feed supply, chemicals, or medicines, making it a sustainable future proof option for the industry.

Pacific oyster (Magallana gigas)

The Pacific oyster (*Magallana gigas*) is listed as an invasive, non-native species in the UK under the Wildlife and Countryside Act 1981 (UK Parliament, 1981) (pacific oysters were introduced into Britain as a response to declining, commercially viable, native oyster stocks in 1890, when oysters from Arcachon, France, were introduced into Poole Harbour, England).

Pacific oyster farms are now widespread around most UK coastal areas (except for the northeast English coast and east coast of Scotland). 'Escapees' have also established wild populations in some locations around the UK. As an invasive non-native UK species, however, the development and expansion of other farms around the UK are constrained to some extent by concerns among conservation organisations that the species may impact negatively on native UK ecosystems (Syvret et al., 2021).

Pacific oysters (*Magallana gigas*) are typically cultivated via the traditional method of bags attached to trestles or floating longline systems. The bags are situated at or near the water's surface, allowing available flows of nutrients and oxygen. Seabed cultivation methods are also used in other areas, such as the Pacific oyster farms found in Poole Harbour (Adamson et al., 2018). As with blue mussel (*Mytilus edulis*) aquaculture, there is no requirement for feed, chemicals, or medicines in pacific oyster cultivation, making it a sustainable future proof option for the industry. Approximately 60% of all UK Pacific oyster exports are shipped to France and Spain (Humphreys et al., 2014).

Native oyster (Ostrea edulis)

Native oysters (*Ostrea edulis*), also known as European flat oysters, attach themselves to the substratum, forming dense beds or reefs. They are typically found within highly productive estuarine environments and shallow coastal water habitats.

Native oysters (*Ostrea edulis*) were once widely distributed around the UK; however, stocks are now severely depleted (especially in the North Sea), with UK populations declining by 95% since the mid-19th century (Preston et al., 2020). Stocks are now substantially reduced to a few important sites within areas of the west coast of Scotland (primarily at Loch Ryan), Lough Foyle in Northern Ireland, and the south-east and the southwest of England (the Thames, the Solent, the River Fal).

Native oysters are almost entirely wild captured through licensed fisheries, many governed by ancient laws that only allow certain fishing practices, e.g., sail or oar vessels and catch hauled aboard by hand or hand winch. Part-grown or half-ware oysters may also be wild captured under licence with stock, then submerged onto growing beds until they reach harvest size. Native oyster cultivation is also a viable option for future-proofing the industry and food supply, as like blue mussel (*Mytilus edulis*) and pacific oyster (*Magallana gigas*) cultivation, no fertilisers, feed or medicine etc. is required.

King scallops (Pecten maximus)

King scallops (*Pecten maximus*) can be found around most UK coasts in areas of mixed sediment, although generally less abundant in the North Sea.

Fishing for king scallops occurs year-round using specialised dredges (generally Newhaven dredges) that tow a chain mail collecting bag. Divers are also used to collect scallops commercially, mainly in the west and southwest coast of Scotland and Orkney. Other smaller-scale sites include Pembrokeshire (Pembrokeshire Scallops, n.d.) and the south coast of Devon (The Hand Picked Company, n.d.). Dive-caught scallops account for approximately 5% of UK landings; however, they often result in a premium market price. This high price is due primarily to dive caught scallops having less environmental impact being perceived to be of better quality compared to dredge caught scallops.

In 2017, the UK exported 29,507 tonnes of scallops (both king and queen), mainly to the EU (99.6%) (primarily to France) with a total value of £103 million (Pinn, 2021). The UK is particularly well-positioned to supply high quality, fresh, roe-on king scallops, which command high prices in the French market.

Queen scallops (Aequipecten opercularis)

Like King scallops (*Pecten maximus*), queen scallops (*Aequipecten opercularis*) are available around most of the UK in coastal areas. They are caught mainly in the Irish Sea and off the west coast of Scotland (although some fisheries are in operation in the English Channel).

Queen scallops are mostly captured using trawlers in high yield (concentrated) areas. Scallop dredgers are utilised throughout the West of Scotland, the Irish Sea and the English Channel, and otter trawls are more frequently used in the Northern Irish Sea.

Brown crab (Cancer pagurus)

Brown crab (*Cancer pagurus*) is widely available around most of the UK coast and is typically captured using bait and pots left on the seabed. Since 2010, brown crab has seen a 12% increase in export volume and a 58% increase in value (Garrett, 2019), primarily driven by increased demand from China. In 2017, £72 million worth of brown crab (18,332 tonnes) was exported from the UK. 75.6% of this was shipped to EU countries, and the remaining 24.4% (4,063 tonnes, valued at £18m) was exported to China (including Hong Kong).

Nephrops (Nephrops norvegicus)

Nephrops norvegicus, also known as the Dublin Bay prawn, Norwegian lobster, langoustine, or scampi, are primarily captured in Scotland, Northern Ireland, and northern England. Capture methods focus on demersal otter trawls; however, creels or pots are used in some locations, resulting in a higher quality catch.

The UK Nephrops industry has grown rapidly over the last 70 years, becoming one of the most valuable fisheries in the UK. In 2017, 25,624 tonnes worth of Nephrops was exported from the UK, valued at £120millon. Roughly 84.5% of this was mainly sent to EU countries, primarily France, Spain, and Italy (Garrett, 2019). The remaining percentage of export going to non-EU countries was primarily exported to China (including Hong Kong).

Appendix 2: Ecosystem Services, Goods and Benefits Derived from UK Commercially Important Shellfish. Based on the literature reviews, the matrix shows the ecosystem services that UK commercially important shellfish provide.

Species	Services										Good/benefits													
	Supporting						Regulating services				from Provisioning services					from Regulating services				from Cultural services				
	Larval and gamete supply	Nutrient cycling	Water cycling	Formation of species habitat	Formation of physical barriers	Formation of seascape	Biological control	Natural hazard regulation	Clean water and sediments (Waste breakdown and detoxification)	Carbon sequestration/climate regulation	Food provision (wild, farmed)	Fish feed (wild, farmed, bait)	Fertiliser and biofuels	Ornaments (including aquaria)	Medicines and blue biotechnology	Healthy climate including carbon storage	Prevention of coastal erosion	Sea defence	Waste burial/removal/neutralisation immobilisation of pollutants	Tourism (including food) and nature watching	Spiritual and cultural wellbeing	Aesthetic benefits	Education, research	Health benefits
mussels	++	++	++	++	+	+	+	++	++	++	++	+	++	++	+	++	++	++	++	++	+	+	++	++
oysters (native and Pacific)	++	++	++	++	+	+	+	++	++	++	++		++	++	+	+	++	++	+	++	+	+	++	++
Scallops (King and queen)	+	+	+	+	NA	NA	+	NA	+	+/-	++		++	++	+	+/-	+	+	+	++	++	+	++	++
cockles	+	+/-	+/-	+/-			+/-		+	+	++			+	+	+	NA		+	+	+		+	+
brown crab	+	+	NA		NA	NA	+	NA		NA	++	++	+	++	++	+/-	NA	NA		++	+	+	+	+/-
lobster	+	+	NA	NA	NA	NA	+	NA		NA	++	NA		++	NA	+/-	NA	NA	NA	++	+	+	+	++
Nephrops	+	++	+	+/-	NA		+	NA	+/-	+/-	++			+	++	+/-	NA	NA	+/-	+	++		+	++

Overview of the Matrix

The matrix incorporates information identified in the previous Seafish literature reviews on shellfish ES and PGBs, along with unpublished industry knowledge and understanding gathered during the Seafish multi-stakeholder workshop held on the 4 March 2020 (Pinn, 2021).

The three shades of grey represent the relative importance of each species in providing the respective ecosystem service or benefit, with the darkest shade representing a more important contribution and lighter grey being less important. The white cells indicate that no evidence was found whilst NA indicates that the species does not provide the particular ecosystem service or benefit. The symbol within each cell relates to the strength and consistency of the underlying evidence:

- Robust, consistent evidence = A range of different forms of evidence point to identical, or similar conclusions, symbolised as ++
- Some evidence = there is some evidence which a conclusion can be drawn, symbolised as +
- Mixed evidence = Some evidence sources indicate a particular conclusion, whilst other evidence suggests contrasting conclusions, symbolised as +/-