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Ecosystem Services, Goods and Benefits Derived From UK Commercially Important Shellfish

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Executive Summary

Nature supports humanity through the provision of food and raw materials, the maintenance of clean air and water, and the creation of spiritual and cultural connections that foster health and well-being. Collectively these valuable functions are known as ecosystem services, which in turn lead to the public goods and benefits we derive from them.

In 2019 Seafish undertook an initial assessment of the ecosystem services and the benefits provided by important commercial marine species. The aim of this report is to build on that work using a literature review to provide a robust evidence base for the ecosystem services and the public goods and benefits provided by shellfish. This literature review was undertaken using a Boolean key word search of the bibliographic database of peer-reviewed literature ISI Web of Science. This database was chosen because it provides a catalogue of the highest level of reliable cited journal articles, provides easy third-party access, and allows for repeatability of searches. This review was further enhanced with industry knowledge gathered through a workshop held on 4 March 2020.

This review revealed that there has been a considerable focus on the ecosystem services and benefits provided by mussels and oysters by academia whilst relatively little consideration has been given to infaunal bivalves (cockles and clams) and crustaceans (crabs, lobsters and prawns). Although focus on these other species has increased recently. Similarly, the industry knowledge and understanding from the shellfish culture sector was focused on mussels and oysters. In contrast, the wild capture industry knowledge and understanding was largely focused toward crustaceans, as well as the cultural goods and benefits derived from the fisheries.

The provision of food is the most obvious, and often the only ecosystem service, attributed to commercially important shellfish species. Beyond this, there are, however, a wide variety of other ecosystem services that shellfish provide. These include raw material provision, nutrient and water cycling, sediment quality and stabilisation, and carbon and nitrogen sequestration. Such ecosystem services provide societal goods and benefits in terms of reduced coastal erosion, clean water, improved climate health and cultural benefits related to aesthetics, education and research. The delivery of ecosystem services can be highly variable on a spatial basis, depending on the hydrodynamics of the habitat and also upon the accessibility of the site to humans in order to access the benefits. Additionally, interactions occur between the different ecosystem services which in turn influences the goods and benefits derived. Understanding these interactions is essential for sustainable management.

The evidence provided in this literature review will contribute to decision-making in relation to marine planning and also aid decision making for inshore fisheries management, permitted activities within marine protected areas and other management policies in order to make the case for increased shellfish production where appropriate. The fishing and aquaculture industries depend on a healthy and functioning marine ecosystem. A thriving seafood industry requires clean, healthy and productive seas. The ecosystem services approach, with its emphasis on the give and take relationship with the natural world, can therefore help provide a balanced seafood story for the future.

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1. Purpose of Report

Humans receive significant natural goods and benefits such as food and raw material provision, the maintenance of clean air and water, and the creation of spiritual and cultural connections that foster well-being. Until recently, these ecosystem services have been taken for granted and their value gone unrecognised. These ecosystem services, leading to the goods and benefits that humans derive from the marine environment, has been values at £211 billion for UK waters (Office for National Statistics, 2021). As a result of such evaluations, there is now a much greater appreciation of what nature does for us, as well as the interdependencies between humans, the natural environment and biodiversity.

Fishing and aquaculture depend on a healthy and functioning marine ecosystem. In recent decades, however, the degradation of the marine ecosystem as a result of human pressures has become an important concern. The Seafish report ‘Ecosystem services and the UK seafood industry’ (Garrett, 2019) highlighted a lack of evidence in how the UK seafood industry draws on and contributes to marine ecosystem services and the good/benefits to society that arise from that. This lack of evidence for the seafood industry undermines efforts being made to make the case for seafood related public goods in marine policymaking.

The purpose of this report is to build upon that initial work and to provide a more informed understanding of the ecosystem services, goods and benefits derived from the fishing and aquaculture industries. Initially, an academic literature review was undertaken in order to provide a basis for an industry workshop held on 4 March 2020. The outputs of that workshop provided an opportunity to incorporate additional undocumented industry knowledge and understanding of ecosystem services into the review. Subsequently, the literature review was further updated as the consideration of ecosystem services is a very active area of academic research and has become a significant focus for policy.

Specifically, this report focuses on shellfish and presents a synthesis of the available evidence to provide crucial connections between research, policy and practice.

2. Introduction

In recent years there has been an increasing national and international policy focus on the blue economy, i.e. the growth of marine sectors such as energy production, aquaculture, cruise tourism, marine mineral resources, and biotechnology. In this context, there has been an increased emphasis on the contribution of marine and coastal environments to the economy (Lillebø et al., 2017). These economic activities depend on a healthy and functioning marine ecosystem and, in particular, a thriving seafood industry requires clean, healthy and productive seas. In recent decades, however, the degradation of the marine ecosystem as a result of human pressures, has become an important concern. This was evidenced by the first assessment of the UK's Marine Strategy undertaken in 2018 (Defra, 2019; UKMASS, 2019), in which very few indicators had met their environmental targets (Figure 1). Similar failures were noted for the wider European region (Maes et al., 2020).

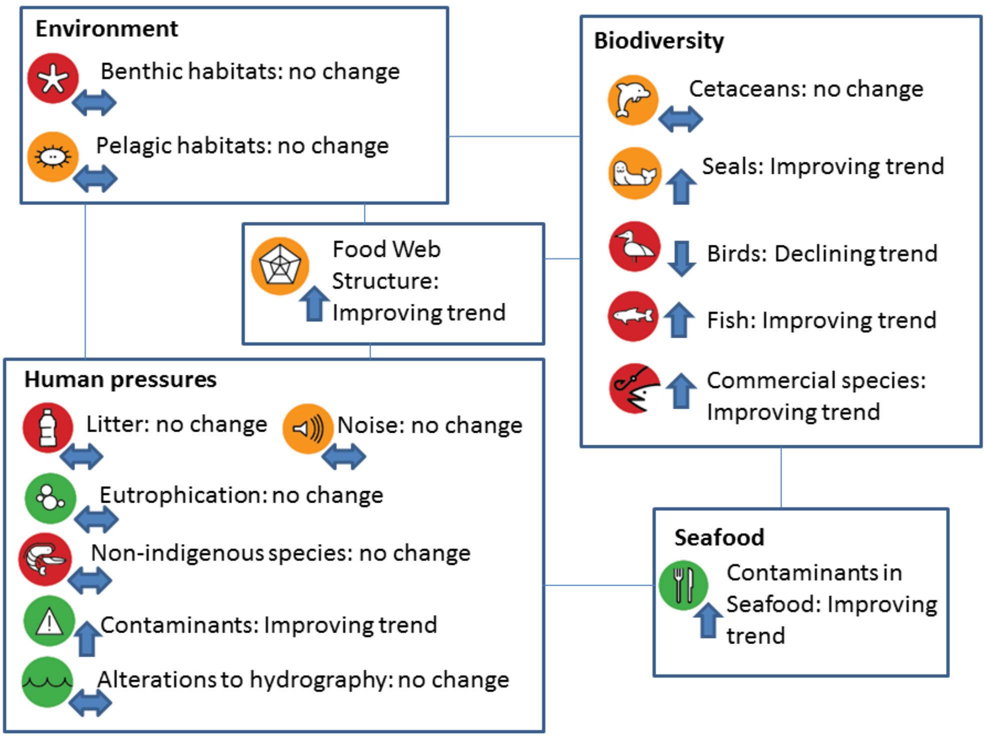

Figure 1: Summary of 2018 UK Marine Strategy Assessment. (key: Green – environmental status met, orange – environmental status partially met, red – environmental status not met; direction of arrows indicate whether there has been any improvement since initial assessment undertaken in 2012).

At the interface of land and sea, coastal ecosystems are reservoirs of high levels of biodiversity, play a central role in biogeochemical cycling of carbon and nitrogen, and are places of a significant biological production that support economic activities such as aquaculture and fisheries which rely on a functioning ecosystem in order to remain viable in the long term. Further development of the blue economy requires an appreciation and understanding of the trade-offs between the use we make of the sea with the environmental functioning necessary to meet those uses.

The concept of ecosystem based management, initially enshrined in 12 principles by the United Nations (UN) Convention on Biological Diversity (CBD, 2000; Figure 2), was proposed to manage our activities in a more sustainable way, taking account of our impact on the natural world. Such a management approach, by its very nature, has to be holistic and adaptive (Elliott et al., 2017). Consideration of ecosystem services provides a mechanism for demonstrating the dependence of human societies on the natural world, and the indispensable contribution that nature makes to all economic activities and social systems (Lebreton et al., 2019).

The Twelve Principles of the Ecosystem Approach

Principle 1*: The objectives of management of land, water and living resources are a matter of societal choice.*

Principle 2*: Management should be decentralized to the lowest appropriate level.*

Principle 3*: Ecosystem managers should consider the effects (actual or potential) of their activities on adjacent and other ecosystems.*

Principle 4*: Recognizing potential gains from management, there is usually a need to understand and manage the ecosystem in an economic context. Any such ecosystem-management programme should:*
(a) Reduce those market distortions that adversely affect biological diversity;
(b) Align incentives to promote biodiversity conservation and sustainable use;
(c) Internalize costs and benefits in the given ecosystem to the extent feasible.

Principle 5*: Conservation of ecosystem structure and functioning, in order to maintain ecosystem services, should be a priority target of the ecosystem approach.*

Principle 6*: Ecosystems must be managed within the limits of their functioning.*

Principle 7*: The ecosystem approach should be undertaken at the appropriate spatial and temporal scales.*

Principle 8*: Recognizing the varying temporal scales and lag-effects that characterize ecosystem processes, objectives for ecosystem management should be set for the long term.*

Principle 9*: Management must recognize that change is inevitable.*

Principle 10*: The ecosystem approach should seek the appropriate balance between, and integration of, conservation and use of biological diversity.*

Principle 11*: The ecosystem approach should consider all forms of relevant information, including scientific and indigenous and local knowledge, innovations and practices.*

Principle 12*: The ecosystem approach should involve all relevant sectors of society and scientific disciplines.*

Source: CBD Guidelines – The Ecosystem Approach

Figure 2: The twelve guiding principles of the ecosystem approach to management from the UN Convention on Biological Diversity.

2.1 Definitions

Ecosystem services are the '*functions and products from nature that can be turned into benefits with varying degrees of human input*' (NCC, 2017). These ecosystem services would continue to take place regardless of human presence.

The benefits derived from the ecosystem services are defined as the '*changes in human welfare (or well-being) that results from the use or consumption of goods, or from the knowledge that something exists (for example, from knowing that a rare or charismatic species exists even though an individual may never see it)*' (NCC, 2017).

Natural capital can be defined as '*the elements of nature that directly or indirectly produce value to people, including ecosystems, species, freshwater, land, minerals, the air and oceans, as well as natural processes and functions. Natural capital is simply those assets provided by nature which has the capacity to generate goods and services. In fact, natural capital can be regarded as the source of all other types of capital: whether manufactured, financial, human or social*' (NCC, 2017).

Put simply, natural capital is the stock of renewable and non-renewable resources (e.g. plants, animals, air, water, soils, minerals) that provide a flow of ecosystem services that benefit people (Figure 3). It is worth noting that within the schematic, biodiversity underlies the stocks of natural capital.

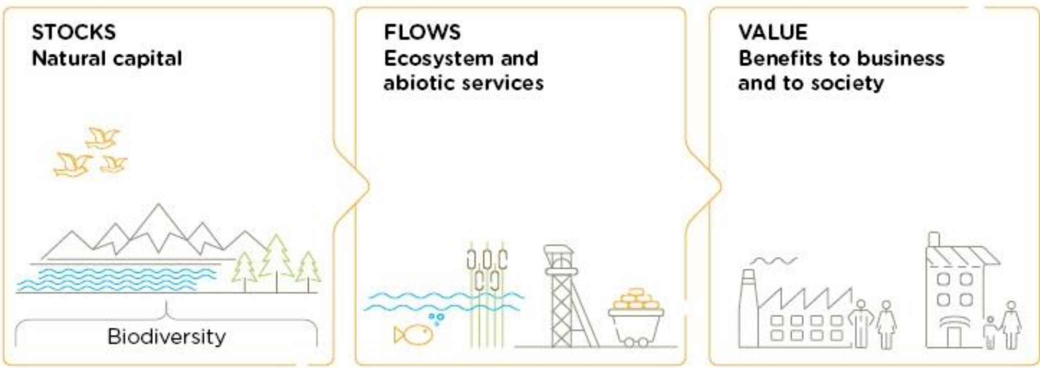

Figure 3: Natural capital, ecosystem services and benefits (From Natural Capital Coalition).

The links between the marine environment and its functioning, the ecosystem services provided and the benefits we derive are further outlined in Figure 4. Through a variety of processes, the marine ecosystem contributes services such as food production, climate regulation, protection from natural hazards and so on, from which society can benefit following an input of built, human and/or social capital.

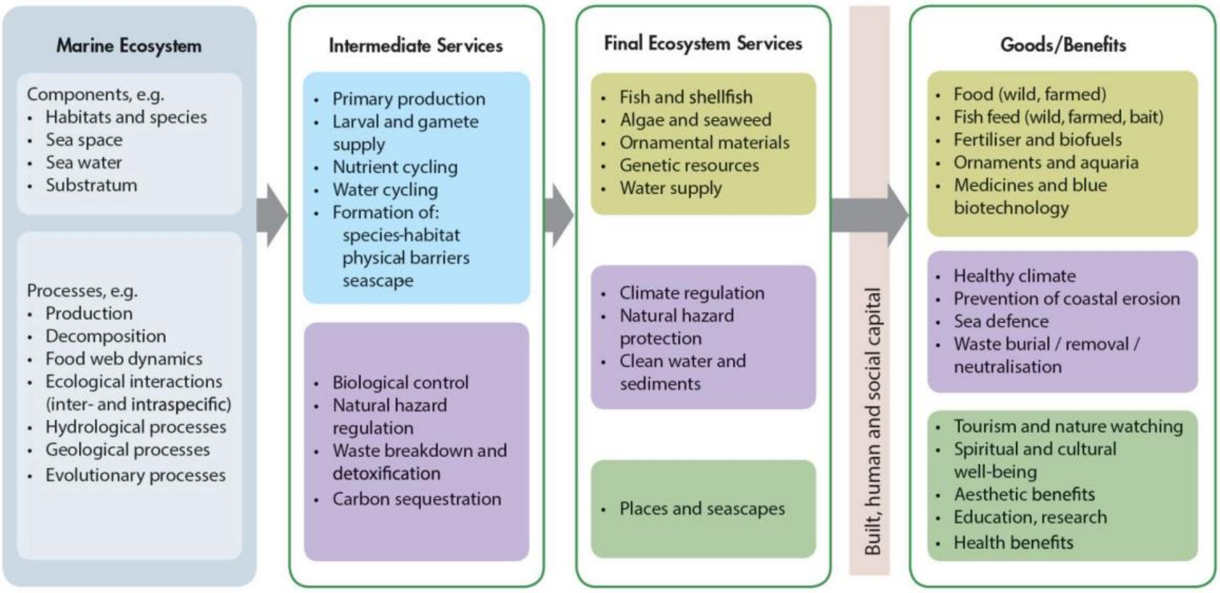

Figure 4: The links between the marine environment, the ecosystem services provided and the benefits we derive (from Turner et al., 2014).

2.2 Policy drivers and development of the ecosystem services approach

The need for a much greater appreciation of the human-nature interdependencies was highlighted by the UN Millennium Ecosystem Assessment (MA, 2005) which assessed the consequences of ecosystem change on human well-being and provided the scientific basis for the need to enhance the conservation and the sustainable use of ecosystems.

The UN Millennium Ecosystem Assessment (MA, 2005) grouped ecosystem services into four areas:

- **Provisioning** services - the products obtained from ecosystems, such as food. This is the most obvious service associated with fisheries and aquaculture.
- **Regulating** services - the benefits obtained from the regulation of ecosystem processes, such as water cycling and purification, and waste treatment. Shellfish, particularly, bivalves filter water in order to feed providing this service.
- **Supporting** services - those necessary for the production of all other ecosystem services such as nutrient cycling, water cycling and provisioning of habitat. Reef building bivalves such as mussels and oysters produce habitat for other species and thereby increase the biodiversity of an area once established.
- **Cultural** services - nonphysical benefits that humans obtain from ecosystems which include recreation and tourism. Rock pooling or non-commercial hand gathering are an examples of cultural services.

Biological diversity (also referred to as biodiversity) underpins ecosystem functioning and the provision of ecosystem services essential for human well-being. It provides for food security, human health, the provision of clean air and water, and it contributes to local livelihoods, and economic development (Figure 5).

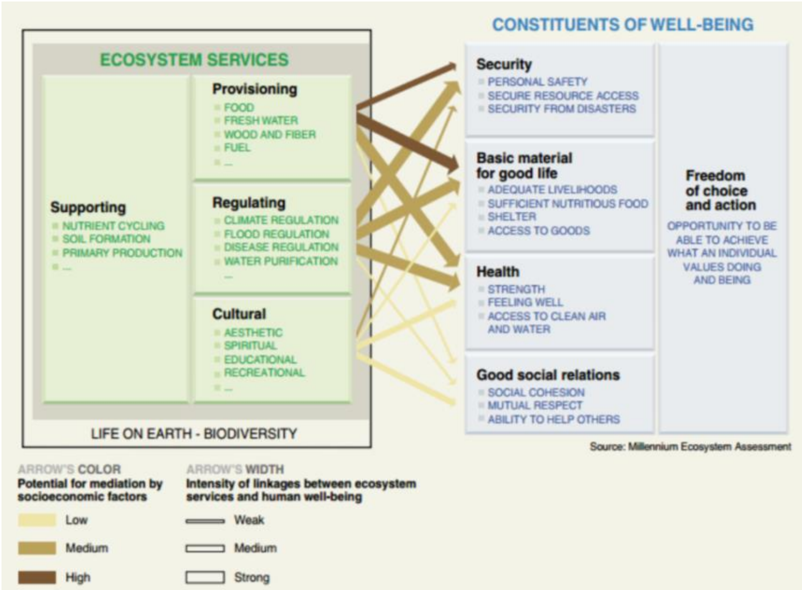

Figure 5: From ecosystem services to human wellbeing (from MA, 2005).

In 2010, Parties to the Convention on Biological Diversity (CBD) adopted the Strategic Plan for Biodiversity 2011-2020 with its 20 Aichi Biodiversity Targets (Figure 6), one of which was to ensure that '*By 2020, at the latest, biodiversity values have been integrated into national and local development and poverty reduction strategies and planning processes and are being incorporated into national accounting, as appropriate, and reporting systems*.'

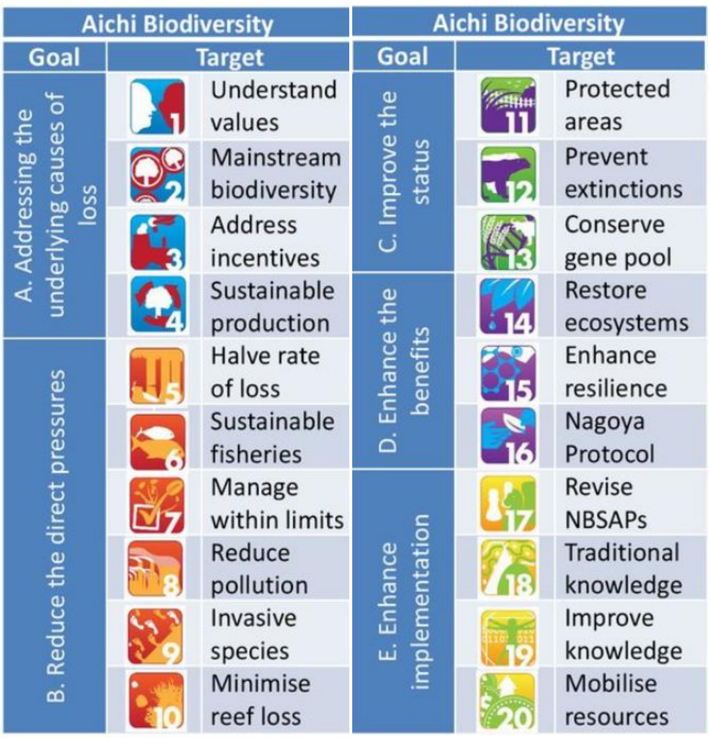

Figure 6: The 20 Aichi Biodiversity Targets of the Strategic Plan for Biodiversity 2011-2020.

The CBD commitments led to the first UK National Ecosystem Assessment in 2011 (UK NEA, 2011) and, subsequently in 2014, a follow on project to adapt the National Ecosystem Assessment (NEA) conceptual framework (Figure 7) to adequately characterise a set of relevant ecosystem services and values for marine and coastal systems (Turner et al., 2014). An adaptive management strategy was recommended to ensure a more sustainable use of UK coasts, while at the same time maintaining the current supply of a set of ecosystem services. Notably, the underlying goal was not to conserve biodiversity at all cost but instead to manage change in ecosystems (structure, species composition, habitats and processes) as the economy and society developed.

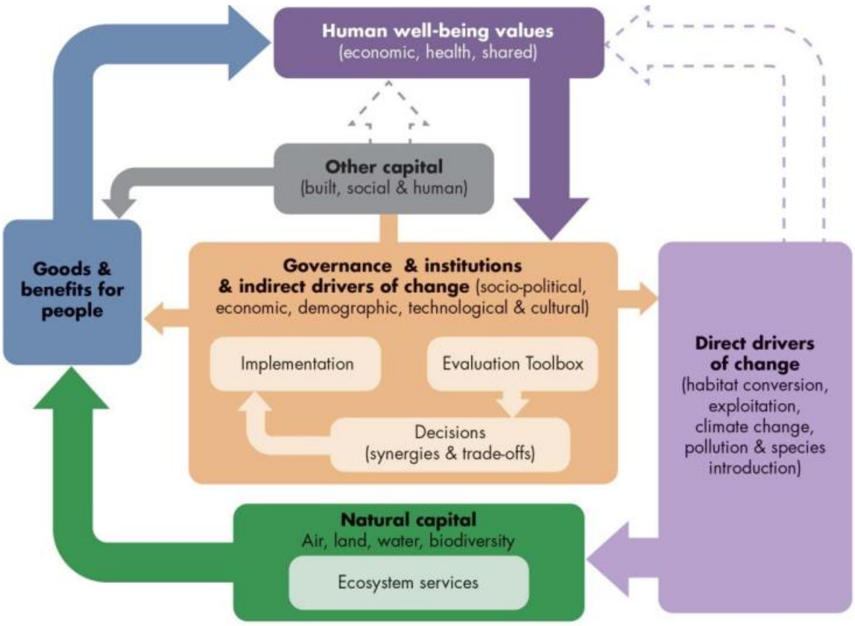

Figure 7: UK National Ecosystem Assessment Follow-On conceptual framework (from Turner et al., 2014).

CBD commitments also led to the formation of the Natural Capital Committee (NCC) in 2012 to provide national scale independent advice on protecting and improving natural capital through the sustainable use of natural assets as well as the benefits derived from them, such as food, recreation, clean water, hazard protection and clean air. NCC (2019) provided the first assessment of ecosystem services and natural capital for the UK marine environment. This report explicitly recommended the incorporation of current scientific understanding on the marine environment into all aspects of policy, which would lead to a variety of benefits including increases in the biomass and productivity of fisheries and improved opportunities for aquaculture.

The marine environment is highly dynamic with interconnections between spatially disparate parts, making such assessments extremely complex. In the context of policy and marine management/governance, the natural capital and ecosystem service approaches available to support environmental decision-making have therefore not been fully realised (Hooper et al., 2019). Linked with CBD commitments, in 2015, the UN adopted the 2030 Agenda for

Sustainable Development which incorporated 17 Sustainable Development Goals (SDG, Figure 8, UN [2015]).

Figure 8: The 17 UN Sustainable Development Goals

The UK has committed to meeting these Sustainable Development Goals (SDGs), a number of which are very pertinent to the ecosystem services and benefits derived from the shellfish catching and culture sectors:

- **SDG Goal 2. Zero hunger**: End hunger, achieve food security and improved nutrition and promote sustainable agriculture
- **SDG Goal 6. Clean water and sanitation**: Ensure availability and sustainable management of water and sanitation for all
- **SDG Goal 8. Decent work and economic growth**: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
- **SDG Goal 12. Responsible consumption and production**: Ensure sustainable consumption and production patterns
- **SDG Goal 13. Climate Action**: Take urgent action to combat climate change and its impacts
- **SDG Goal 14. Life below water**: Conserve and sustainably use the oceans, seas and marine resources for sustainable development
- **SDG Goal 17. Partnerships for the goals:** Strengthen the means of implementation and revitalize the global partnership for sustainable development.

More recently the UK government published its 25 Year Environment Plan (Defra, 2018), further reinforcing these SDGs and, in particular, the ambition to secure clean, healthy, productive and biologically diverse seas which are sustainably managed. The plan explicitly required the development of a comprehensive set of indicators which would measure progress in achieving the plan ambitions. Ten broad themes were identified, one of which is 'Seas and Estuaries'. Under each theme, sit a series of headlines which were identified to provide a high-level overview of progress and to simplify the presentation of a large amount of information (Figure 9). Defra (2019) noted that there was currently insufficient data available to undertake a baseline assessment of the Seas and Estuaries theme.

Themes	Headlines	Goals
A. Air (A1-A7)	1. Air quality (A1,A3)	Clean Air
	2. Greenhouse gas emissions (A2)	Mitigating Climate Change
B. Water (B1-B7)	3. Water and the water environment (B3,B4,B5	Clean and plentiful water
C. Seas and Estuaries (C1-C11)	4. Diversity of our seas (C3,C4,C5)	Thriving plants and wildlife
	5. Health of our seas (C7,C8)	
D. Wildlife (D1-D7)	6. Wildlife and wild places (D2,D5)	
	7. Nature on land and water (D1,D4,D7)	
E. Natural Resources (E1-E9)	8. Production and harvesting of natural resources (E1,E3, E4, E7)	Efficient use of natural resources
F. Resilience (F1-F4)	9. Resilience to natural hazards (F1,F2,F3)	Reduced risk from environmental hazards
G. Natural beauty and engagement (G1-G7)	10. Landscapes and waterscapes (G1,G2,G3)	Enhanced beauty and engagement
	11. People enjoying and caring about the natural environment (G4,G5,G6,G7)	
H. Biosecurity, chemicals and noise (H1-H4)	12. Exotic diseases and invasive non-native species (H1,H2)	Enhancing biosecurity
	13. Exposure of people and wildlife to harmful chemicals (H3,H4)	Managing exposure to chemicals
J. Resource use and waste (J1-J6)	14. Resource efficiency and waste (J2,J4,J5,J6)	Minimising waste
K. International (K1-K4)	15. Impacts on the natural environment overseas (K1)	Global impacts
	16. Improving the environment overseas (K2, K3,K4)	

Figure 9: The relationship between indicator themes, headlines and the 25 Year Environment Plan goals. Global impact is not a goal in the plan but as it is included in the indicators it is listed under the 'goals' column (from Defra, 2019).

2.3 Ecosystem services and benefits derived

The value of marine ecosystem services and the goods and benefits that humans derive has been estimated to be £211 billion (Office for National Statistics, 2021). Valuing ecosystem services helps decision-makers incorporate environmental, social and economic concerns into policy and management. Although the term 'ecosystem service' is scientific jargon to the general public, the phrase is increasingly being used in the public sphere (Norgaard 2010; Thompson et al 2016), and the public do intuitively understand the benefits they gain from the natural environment (Hynes et al., 2013; Kosenius & Ollikainen, 2015; Burdon et al., 2019).

The ecosystem services terminology around fisheries is complex; food provision from wild-capture fisheries is categorised under provisioning ecosystem services, yet there is often little differentiation between indicators of the service, ecosystem function or ecosystem benefit (Atkins et al., 2015; Brooker et al., 2018). The seafood industry clearly draws upon and interacts with a range of ecosystem services and benefits beyond the provision of food. Garrett (2019) specifically identified the need for case studies covering key seafood species which clearly articulate the ecosystem services and benefits they provide in order to contribute effectively to the current policy and management focus on natural capital. However, management that incorporates the ecosystem services and benefits of commercially important fish and shellfish species beyond the economic gain of food is required if our marine and coastal ecosystems are to be resilient to change.

The fishing industry is broadly divided in to three sectors which vary in terms of landings and value:

- pelagic (approximately 25% by value and 52% by volume in 2019, [Quintana et al., 2020]),
- demersal (approximately 34% by value and 25% by volume, [Quintana et al., 2020]) and
- shellfish (approximately 41% by value and 23% by volume, with 3 of the top 5 species by value for the UK fleet being *Nephrops*, brown crab and scallops [Quintana et al., 2020]).

For the purposes of this report, it was decided to focus upon shellfish. The increasing importance of aquaculture in future food security provided further impetus for this. Any commitment to the expansion of sustainable marine cultivation will require an integrated assessment of the value of bivalve shellfish to improve social acceptance, promote food security, economic growth and employment.

3. Methodology

A Quick Scoping Review (QSR) approach has been utilised for this review. QSR provides an informed conclusion on the volume and characteristics of an evidence base and a synthesis of what that evidence indicates. This approach does not provide a critical appraisal of the available evidence. Instead, it incorporates a variety of types of evidence (e.g. quantitative data, economic studies and reviews) and provides an indication of the robustness of the evidence.

Garrett (2019) provided an initial assessment of the ecosystem services and benefits for important commercial species (Table 1). This was based on the matrix approach developed by Potts et al. (2014) and further refined by Burdon et al. (2017). The purpose of this report is to build on the initial work and provided a more robust assessment of the ecosystem services, goods and benefits derived from species of commercial importance.

3.1. Shellfish species

Based on the value of the industry and also the initial work undertaken by Garrett (2019) indicating a greater array of available information, the shellfish sector was chosen for the focus of this review. It is anticipated that similar work will be undertaken for other fisheries sectors in the future.

The list of commercially exploited shellfish in the UK comprises of 19 species or species groups. On the basis of fishery landings and value, or aquaculture production and value, this was refined to a list of 9 key species for inclusion in the revised matrix:

- prawns (*Nephrops norvegicus*)
- brown or edible crab (*Cancer pagurus*)
- European lobster (*Homarus gammarus*)
- king scallop (*Pecten maximus*)
- queen scallop (*Aequipecten opercularis*)
- blue mussel (*Mytilus edulis*)
- Pacific oyster (*Magallana gigas*, previously named *Crassostrea gigas*)
- native oyster (*Ostrea edulis*)
- cockles (*Cerastoderma edule*)

3.2 Literature Review

A synthesis of the available evidence that collates primary research on the ecosystem services and benefits provided by commercially important shellfish will provide crucial connections between research, policy and practice.

A literature review was undertaken using key word searches of the bibliographic database of peer-reviewed literature ISI Web of Science which incorporates articles published since 1941. ISI Web of Science was chosen because it provides a catalogue of the highest level of reliable cited journal articles, provides easy third-party access, and allows for repeatability of searches. A Boolean search of the database was undertaken using the primary terms 'ecosystem services' and 'shellfish', whilst secondary terms focused on variations of 'bivalve' and 'crustacean' and tertiary terms including 'mussel', 'oyster', 'cockle', 'crab', 'lobster' and 'prawn'. The literature search was conducted on 25 September 2019 and encompassed the entire dataset available at that time. This process identified 557 articles, which were further refined by reviewing the article title and abstract to exclude those that were not relevant (e.g. papers covering the effects of climate change and impacts such as acidification). This left 151 papers. The reference lists of these remaining papers were also examined to identify additional relevant papers, which lead to a further 109 articles being identified. Subsequently, this bibliographic review process was repeated on 20 April 2021. This identified a further 150 articles, which, after review of the title and abstract for relevancy, was reduced to 68 articles.

It should be noted that these searches had a global coverage and were not restricted to the 9 UK commercially important shellfish species included in the revised matrix. Inferences can be made between species with similar life history strategies.

3.3 Population of the UK commercially important shellfish matrix

Building on the work presented in Garrett (2019), the literature review was used to update and the ecosystem services and benefits matrix specifically for shellfish. Each cell of the matrix is assigned a shade of grey and a symbol. Some commercial shellfish species are more important than others in providing a particular ecosystem service or benefit. The 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. Where a species does not provide the particular ecosystem service or benefit being considered, the symbol NA was used. The symbol within each cell were used to indicate the strength and consistency of the underlying evidence. This was adapted from DfID (2014):

- 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 suggest contrasting conclusions, symbolised as +/-

In addition to the information identified in the literature review, the matrix was further refined incorporating unpublished industry knowledge and understanding gathered during a Seafish workshop held on 4 March 2020.

Table 1: Ecosystem services and the seafood industry: contributions (green dot) and withdrawals (red dot) (From Garrett, 2019).

			Services											Good/benefits														
			Supporting services							Regulating services				from Provisioning services					from Regulating services					from Cultural services				
Seafood system	Main species group	Species	Production	Larval and gamete supply	Nutrient cycling	Water cycling	Formation of species habitat	Formation of physical barriers	Formation of seascape	Biological control	Natural hazard regulation	Regulation of water and sediment quality	Carbon sequestration	Food provision (wild, farmed)	Fish feed (wild, farmed, bait)	Fertiliser and biofuels	Ornaments (including aquaria)	Medicines and blue biotechnology	Healthy climate	Prevention of coastal erosion	Sea defence	Clean water & sediments	Immobilisation of pollutants	Tourism and nature watching	Spirital and cultral wellbeing	Aesthetic benefits	Education, research	Health benefits
Domestic	Seafood	General	red, green				green						green	red, green						green								green
Domestic	Seafood	General	red				red							green														
Domestic	Seafood	General	red				red						red	green										green	red, green			green
Domestic	Pelagic	Blue whiting, herring, others	red											red														
Domestic	Shellfish	Oysters			green	green	green						green	green		green	green			green				green	green		green	
Domestic	Shellfish	Mussels												green										green	green	green		
International	Seafood	General					red							green										green				
International	Seafood	General												green														
International	Seafood	General	red, green											red, green														
International	Seafood	General	red											green														
International	Seafood	General												green										red	green	red		
International	Whitefish	Hake	red											green														
International	Whitefish	Sea bass					green					green	green	green								green		green			green	
International	Pelagic	Tuna	red, green											green														
International	Pelagic	Tuna	red											green														
International	Pelagic	Tuna												green											green			green
International	Pelagic	Sardine, horse mackerel, anchovy, sea bream	red				red							green										red, green	green			green
International	Shellfish	Shrimp	red				red							green														
International	Shellfish	Shrimp					green					green	green	green								green		green			green	
International	Shellfish	Krill																										green
International	Shellfish	Pacific oysters					green					green		green										green				
International	Shellfish	Clams, cockles	red, green		red	red	red			red				green										red, green	green			
International	Shellfish	Octopus					red							green										red, green	green			green

4. Distribution and food production of commercially important shellfish species in UK waters

A broad range of shellfish species are either caught, or cultivated, in UK waters for human food consumption, including:

- mussels (blue mussel *Mytilus edulis*)
- oysters (native oyster *Ostrea edulis* and Pacific oyster *Magallana gigas*, previously named *Crassostrea gigas*)
- scallops (queen scallop *Aequipecten opercularis* and king scallop *Pecten maximus*)
- clams (Manila clam *Ruditapes philippinarum* and razor clams *Ensis spp.*)
- cockles (*Cerastoderma edule*)
- crabs (brown or edible *Cancer pagurus*, spider crab *Maja* spp. and velvet swimming crab *Necora puber*)
- lobster (European lobster *Homarus gammarus* and spiny lobster *Palunirus elegans*)
- prawns (*Nephrops norvegicus*)
- cuttlefish (*Sepia officinalis)*
- squid (*Loligo forbesi*)

The UK production volumes and values of these species are shown in Tables 2 and 3. From a food production perspective, the most important commercial species are crabs, lobsters, *Nephrops*, and scallops from the capture fisheries and mussels, oysters and cockles from cultivation. In 2019, the largest quantity and value of shellfish were captured relatively close to the coast whilst the shellfish species with high prices were typically captured away from coastal areas (MMO, 2020).

Table 2. Shellfish Capture: Landings into major ports in the UK by UK vessels in 2019 (adapted from MMO, 2020).

	TOTAL UK		SCOTLAND		ENGLAND		WALES		NI	
	Vol ('000 t)	Value (£ million)	Vol ('000 t)	Value (£ million)	Vol ('000 t)	Value (£ million)	Vol ('000 t)	Value (£ million)	Vol ('000 t)	Value (£ million)
Cockles	8.0	6.2			8.0	6.2				
Crabs	28.9	69.5	11.6	31.2	14.5	33.1	0.8	1.6	1.3	2.2
Cuttlefish	3.9	14.9			3.9	14.9				
Lobsters	3.0	44.1	1.2	18.5	1.5	21.7	0.2	2.5	0.1	0.7
Mussels	0.7	0.2							0.7	0.2
Nephrops	24.9	79.0	17.6	59.8	2.1	7.1	<0.1	0.1	5.1	11.9
Scallops	28.8	69.7	8.7	21.8	14.9	36.3	1.0	2.4	1.0	2.3
Shrimps and Prawns	1.1	2.7			1.1	2.7				
Squid	2.8	12.8	2.6	11.1	0.3	1.7				
Whelks	17.9	21.9	1.5	1.7	10.8	13.0	4.5	5.9	0.1	0.1
Other Shellfish	1.3	7.1	0.6	4.6	0.5	1.9	<0.1	0.6		
Total Shellfish	**121.3**	**328.1**	**43.8**	**148.8**	**57.8**	**138.6**	**6.6**	**13.2**	**8.1**	**17.4**
Total All Fisheries (including finfish)	**426.0**	**727.2**	**302.8**	**467.6**	**92.7**	**208.7**	**7.5**	**15.5**	**18.5**	**25.2**

Table 3. Volume and value of UK shellfish cultivation 2017[1] (tonnes, £'000) (MSS, 2018; CEFAS pers comm).

	TOTAL UK		SCOTLAND		ENGLAND		WALES		NI	
	Vol (t)	Value (£ '000)	Vol (t)	Value (£ '000)	Vol (t)	Value (£ '000)	Vol (t)	Value (£ '000)	Vol (t)	Value (£ '000)
Mussels	16,178	19,627	8,232	10,093	1,507	1,798	1,520	1,813	4,919	5,924
Pacific oyster	2,249	7,498	403	2,014	909	2,271	25	63	912	3,149
Native oyster	23	145	16	120	7	25				
Queen scallop	11	33	11	30						
King scallop	6	92	6	90						
Manila clam*	20	117			20	117				
Cockles*	5,223	13,059			5,223	13,059				
Northern quahog (=Hard clam)*	1	5			1	5				
Total Shellfish	**23,711**	**40,574**	**8,668**	**12,352**	**7,667**	**17,274**	**1,545**	**1,875**	**5,831**	**9,073**
Total All Species (including finfish)	**227,642**	**1,140,590**	**206,150**	**1,083,900**	**12,635**	**37,945**	**1,779**	**2,928**	**7,078**	**15,816**

[1]Although more recent information was available for shellfish cultivation in Scotland, the data for 2017 were the most recent available for elsewhere in the UK.
*Harvest of wild-seeded production from aquaculture sites

Crabs, scallops and *Nephrops* (langoustines) landed by UK vessels into the UK and abroad accounted for approximately 24% of the weight of landings and 40% of the value in 2019 (MMO, 2020). Lobsters command the highest average price, accounting for 2% of the weight of shellfish landings by the UK fleet, but 12% of the value. For cultivation, Scotland tends to dominate in mussel production, England dominates cockle production and Northern Ireland for oysters.

This report focuses specifically on the following commercially important shellfish species:

- prawns (*Nephrops norvegicus*)
- brown or edible crab (*Cancer pagurus*)
- European lobster (*Homarus gammarus*)
- king scallop (*Pecten maximus*)
- queen scallop (*Aequipecten opercularis*)
- blue mussel (*Mytilus edulis*)
- Pacific oyster (*Magallana gigas*, previously named *Crassostrea gigas*)
- native oyster (*Ostrea edulis*)
- cockles (*Cerastoderma edule*)

The remainder of this section provides a brief summary for each commercially important species covering distribution, and capture and/or culture methods. The information provided has largely been 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.

4.1 Prawns (*Nephrops norvegicus*)

Figure 10: *Nephrops norvegicus* (© Kåre Telnes). Map shows Nephrops landings for the UK fleet by port and volume (© Seafish).

Nephrops norvegicus, also known as the Dublin Bay prawn, Norwegian lobster, langoustine, or scampi, is a decapod crustacean distributed throughout the North East Atlantic. *Nephrops* construct extensive shallow and branching burrows in soft sediments at depths of 20-800 m. They require sediment with silt and clay content of between 10 – 100% to dig burrows, and the locations of suitable sediments defines the distribution of the species with sea temperature also playing a role. Burrows may be up to 10 cm in diameter, over a metre long and penetrate the sediment to a depth of 20-30 cm. *Nephrops* usually remain within their burrows by day, emerging primarily at dusk to forage, although in deeper water individuals can be are more active by day.

Early fisheries investigations revealed marked geographical variability in the abundance and size of individual *Nephrops.* The larvae do not have a high dispersal potential and adult *Nephrops* show no evidence of migration. As a result, potential recruitment from other populations is low.

Nephrops are only caught when outside their burrows. The *Nephrops* fishery has grown rapidly since the 1950s to become one of the most valuable to the UK. They are caught mainly by demersal otter trawls, with larger vessels using multiple rigs. Bycatch and discard rates were initially high in *Nephrops* trawls due to the small cod end mesh requirements of the target species. However, measures to reduce bycatch and discards have been the subject of much research over the years, resulting in technical measures to improve selectivity being implemented as a statutory requirement (Cosgrove et al., 2019). There also features of trawl design which can reduce discards that can be implemented on a non-statutory basis. In some locations, creels or pots are used rather than trawls, which result in a higher quality product. Bycatch is considered a low risk in these fisheries.

In 2017, 25,624t of *Nephrops* were exported from the UK at a total value of £120m (Garrett et al., 2019). 84.5% of this export was mainly to EU countries, primarily France, Spain and Italy. Of the 15.5% going to non-EU Countries, China (including Hong Kong) is the primary recipient.

4.2 Brown or edible crab (*Cancer pagurus*)

Figure 11: *Cancer pagurus* (© Robert Keen). Map shows brown crab landings for the UK fleet by port and volume (© Seafish).

Cancer pagurus is a large crab typical of a wide variety of marine and coastal communities, occurring on the lower shore, through shallow sublittoral and offshore waters to depths in excess of 100m. They are found on bedrock including under boulders, on mixed coarse grounds and on muddy sand. Brown crabs are nocturnal animals with a diet composed of smaller crustaceans and molluscs. Motile prey may be stalked and pounced upon whilst other prey is ambushed from shelters under rocks and *Cancer pagu*rus may also dig large pits to access bivalve molluscs such as razor clams.

Cancer pagurus is caught in pots around most of the UK. Stock boundaries for brown crab remain poorly understood and both sexes move quite widely at times; females in particular have been shown to travel large distances in relation to spawning activity.

Catches have risen steadily over the past 40 years with most of the British catch exported live to France and Spain and, more recently, to Asia. For example, in 2017 18,332t of brown crab were exported with a total value of £72m (Garrett et al., 2019). 75.6% of this was to EU countries and 24.4% (4,063t, valued at £18m) was exported primarily to China (including Hong Kong). Since 2010, brown crab has seen a 12% increase in export volume and 58% increase in value (Garrett et al., 2019). Much of this increase has been driven by demand from China.

4.3 European lobster (*Homarus gammarus*)

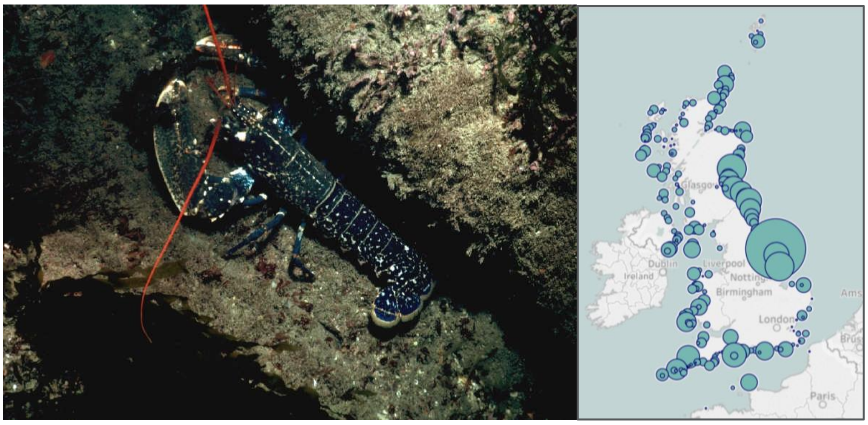

Figure 12: *Homarus gammarus* (© Keith Hiscock). Map shows lobster landings for the UK fleet by port and volume (© Seafish).

The European lobster is found in most areas of the UK from the lower shore to about 150 m depth, particularly off rocky coastlines living in holes and excavated tunnels. Lobsters are very territorial, and will kill or inflict serious damage on other lobsters that come into their space. This high level of site fidelity leads to the possibility of distinct populations within small geographic areas.

Lobsters are predominantly scavengers or predators, hunting at night. Their diet consists of benthic invertebrates such as crabs, molluscs, sea urchins, polychaete worms and starfish, but may also include fish and plants. Lobsters are also highly cannibalistic of smaller individuals.

The majority of lobsters are caught using pots in inshore waters shallower than 30 m. Crabs (both edible and velvet) are taken by the same vessels and gear as lobsters but they are usually targeted on the different grounds and in the different seasons. Approximately 80% of the lobsters caught are exported to France and Spain.

4.4 King scallop (*Pecten maximus*)

Figure 13: *Pecten maximus* (© Sue Scott). Map shows king scallop landings for the UK fleet by port and volume (© Seafish).

King scallops are recorded around most UK coasts, although generally less frequently in the North Sea. The species prefers mixed sediments consisting of muddy sand, sandy gravel or gravel, possibly interspersed with small stones, rocks, boulders and low-lying reef from extreme low-water down to approximately 100m. Most individuals are found between 20-70m and, being highly-adapted filter feeders, they prefer moderately strong tidal flows and reduced exposure to strong wave action.

Both shell valves are fan shaped with an 'ear' on either side of the apex of the valve. The right valve is strongly convex whilst the left valve is flat. If undisturbed, scallops usually lie recessed into the sediments with their flat valve uppermost, often disguised by a layer of sediment with only their eyes and tentacles visible when the valves are open. Scallop eyes are capable of forming an image which, along with other well developed sense organs, make scallops highly sensitive to changes in their immediate surroundings. Although considered to be relatively sedentary, they can swim using water jets ejected around the hinge of the shell to escape predation.

Adult scallops have a limited mobility and rely on the dispersal of larvae in terms of geographic distribution. The extent of this distribution will in turn be affected by factors including local hydrographic regimes and the survival of larvae. Consequently, all scallops have an aggregated distribution within their geographic range and the major fishing grounds are generally widely separated so much so that respective environmental conditions produce marked differences in population parameters. If all the scallops are fished out of an area, future recruitment should not be expected from contiguous areas within the time frame of interest to fisheries management and therefore some minimum spawning stock must remain in each area to ensure long term harvesting potential.

Fishing takes place all year round with vessels using an array of specialised dredges attached to bars towed from either side of the vessel. Many vessels utilise Newhaven dredges with a chain mail collecting bag. The scallop fleet is roughly divided into two groups: smaller vessels that tend to work locally in inshore waters; and fewer larger nomadic vessels (up to about 30m in length) with the capability to fish offshore grounds and venture more widely around the UK. Scallops are also fished commercially by divers, accounting for about 5% of the landings. This fishery involves around 40-50 full-time divers that are mainly located in the west Coast of Scotland and in Orkney.

29,507t of scallops (both King and Queen) were exported in 2017, with a total value of £103m (Garrett et al., 2019). 99.6% of this was to the EU, primarily France. The UK is particularly well positioned to supply high quality, fresh, roe-on king scallops (Coquille St Jacques), which command high prices in the French market.

4.5 Queen scallop (*Aequipecten opercularis*)

Figure 14: *Aequipecten opercularis* (© Keith Hiscock). Map shows queen scallop landings for the UK fleet by port and volume (© Seafish).

The Queen scallop, *Aequipecten opercularis*, is a medium-sized scallop species found all round UK coasts. It occurs from the shallow subtidal to about 180 m but is most common in water of 20-45m depths. Adults are free living on sandy to shelly seabed types. Young scallops initially settle and attach themselves with byssus, later becoming free swimming.

Queen scallop fisheries are mostly concentrated in the Irish Sea and off the west coast of Scotland, although some are taken in the English Channel. Queen scallops are considered to have specific substrate type requirements and most trawling for scallops therefore occurs within ‘core’ areas where yields are high. Throughout the West of Scotland, Irish Sea and the English Channel they are targeted using scallop dredges. In the Northern Irish Sea, they are targeted with otter trawls. This gear is designed to move over the seabed and catch swimming queen scallops.

29,507t of scallops (both King and Queen) were exported in 2017, with a total value of £103m (Garrett et al., 2019), almost all of it to EU countries, primarily France.

4.6 Blue mussel (*Mytilus edulis*)

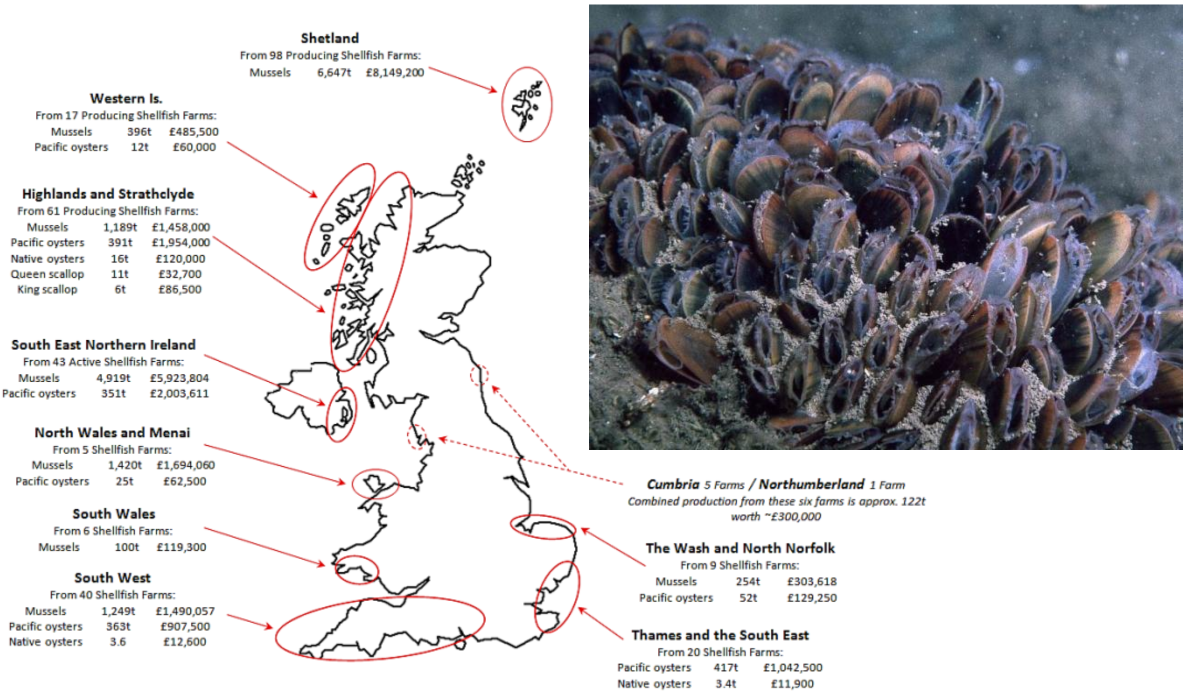

Figure 15: *Mytilus edulis* (© B.E. Picton). Map shows mussel and oyster production areas, volumes and values for 2017 (© Seafish).

Mussels are sessile bivalve molluscs and are attached to the substratum or one another by byssus threads. The byssus threads resemble a matrix of hairs and are secreted by the mussel's foot. The species is widely distributed on all coasts, living in the intertidal on a wide range of habitats from rocky shores to estuaries on any substratum providing a secure anchorage such as rocks, stones, and dead shell. They can also be found in the sublittoral to depths of 200m. In soft bottom areas mussels form stabilised beds of interconnected mussels and dead shells.

In the UK there has been a move away from exploitation of wild mussel stocks to cultivation. Mussels are cultivated using two main techniques:

- Bottom culture which uses the re-laying of seed mussels collected from wild sources onto 'lays' which provide improved growth and survival (primarily in England, Wales and Northern Ireland). The seed mussels are collected using a mussel dredge. Mussel dredges are designed to remove the mussels in clumps with minimal force and penetration into the substrate.
- Grown on ropes suspended from rafts and buoyed long-line systems (primarily in Scotland)

No feed is supplied and no chemicals or medicines are administered.

In 2017, 11,155t of blue mussels were exported from the UK with a value of £4m (Garrett et al., 2019). This was all almost exclusively to EU countries, primarily to the Netherlands for relaying purposes prior to the mussels going into the food chain.

4.7 Pacific oyster (*Magallana gigas*, previously named *Crassostrea gigas*)

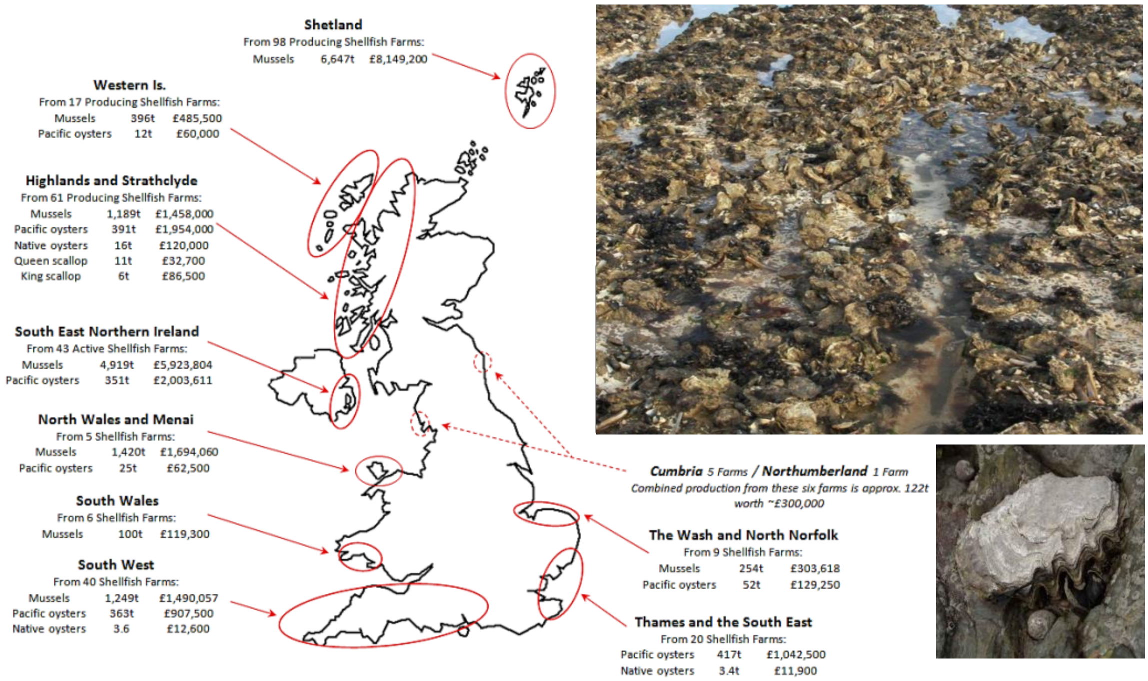

Figure 16: *Magallana gigas* (© W. McKnight [top right] and © Guy Baker [bottom right]). Map shows mussel and oyster production areas, volumes and values for 2017 (© Seafish).

The Pacific oyster is sometimes referred to as the Portuguese, Japanese, cupped or rock oyster. The shell is elongated in shape, with rough and fluted shells that include a deep cupped bottom shell and a flat top shell. The species prefers estuarine conditions, but can be found on the lower shore and shallow sublittoral to a depth of around 80m.

The Pacific oyster is the most 'globalised' bivalve, having been introduced to 66 countries primarily for aquaculture purposes. It was originally 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. Oyster farms are now widespread around the coasts of UK except for the northeast coast of England and east coast of Scotland. 'Escapees' have also established wild populations in some locations. The species is listed as an invasive non-native species in the UK. This is in part constraining the development of the industry, preventing expansion and development of new farms (Adamson et al., 2018).

Pacific oysters are usually cultivated in bags affixed to trestles (the traditional 'rack and bag' method) or floating long line systems. The oysters, bags and trestles are situated at or near the surface of the water, where there is more nutrient and oxygen rich surface water; and the wave motion tumbles the oysters about which helps to shape the shells. The bags are also turned regularly during cultivation. Pacific oysters from Poole Harbour are, however, produced using sea bed cultivation (Adamson et al., 2018). Pacific oysters can be eaten year round, however in spawning periods during the summer months, the meat content becomes very milky.

The UK exports approximately 60% of its Pacific oyster production to France and Spain (Humphreys et al., 2014).

4.8. Native or European flat oyster (*Ostrea edulis*)

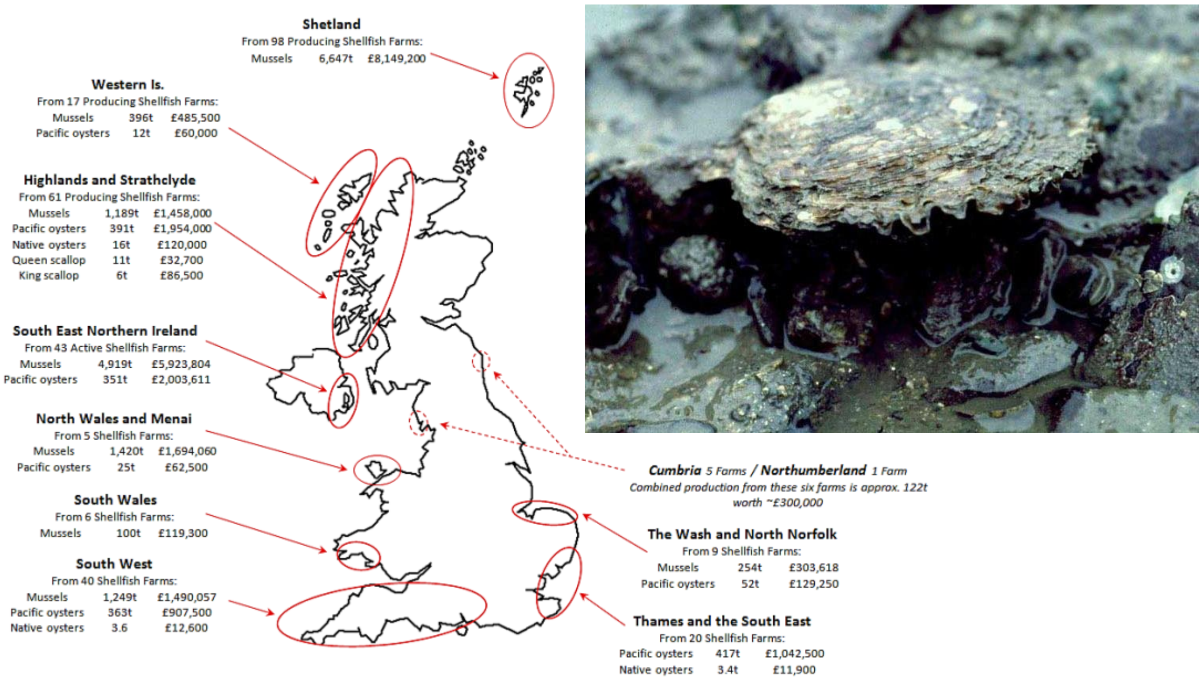

Figure 17: *Ostera edulis* (© Keith Hiscock). Map shows mussel and oyster production areas, volumes and values for 2017 (© Seafish).

Native oysters, also known as European flat oysters, are fixed to the substratum by their left concave valve. The right is flat and sits inside the left. As a result of these oysters cementing themselves to the substratum on settlement, their size and shape can be extremely variable if neighbouring individuals have to compete for space.

Native oysters used to be widely distributed around the British Isles, but are now severely depleted (especially in the North Sea). Wild native oyster beds are probably one of the most endangered marine habitats in Europe, with 95% of beds having been lost in the UK. *Ostrea* *edulis* is associated with highly productive estuarine and shallow coastal water habitats to 50m depth on firm bottoms of mud, rocks, muddy sand, muddy gravel with shells and hard silt where they can form dense beds or reefs. The main stocks are now in the west coast of Scotland, the south-east and Thames Estuary, the Solent, the River Fal, and Lough Foyle.

Native oysters are almost always wild caught through licensed fisheries in areas such as River Blackwater in Essex; Whitstable Bay in Kent; River Fal in Cornwall; and Loch Ryan in Dumfries and Galloway. Many of the fisheries are governed by ancient laws; e.g. participants in the Truro Oyster Fishery must use sail or oar vessels, and haul their catch aboard by hand or hand winch. No motor or mechanical power is allowed. Part-grown or 'half-ware' oysters may also be fished from the wild under licence. This stock is then relayed to submerged on-growing beds and reared to harvest size. As with mussel cultivation, no feed is supplied and no chemical or medicines are administered. Native oysters are traditionally only harvested when there is an 'r' in the month i.e. from September to April. This avoids the periods when they are spawning and meat quality is at its lowest.

4.9 Cockle (*Cerastoderma edule*)

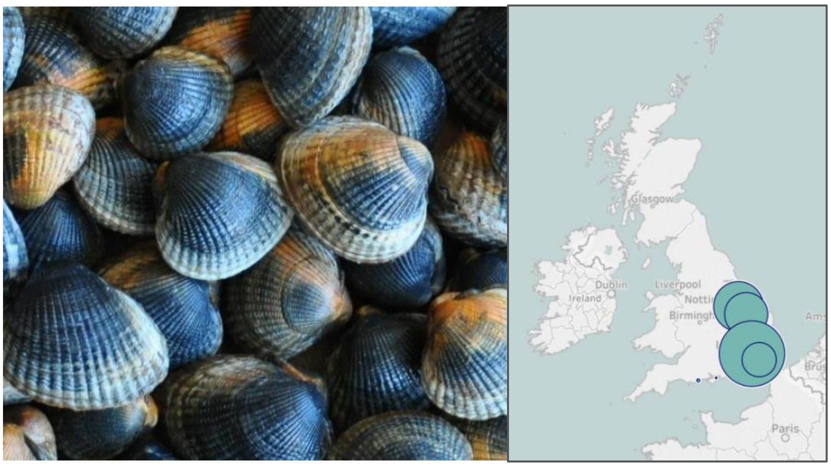

Figure 18: *Cerastoderma edule* (© Simply Oysters Ltd). Map shows cockle landings for the UK fleet by port and volume (© Seafish).

Cockles are a benthic (sea bed residing) bivalve. The species is widespread around the UK. It is found living intertidally or shallow sublittoral, usually buried in sand and muddy sand.

Commercial beds of the edible cockle *Cerastoderma edule* are fished in the Wash, Thames Estuary, Morecambe Bay, Dee estuary, and Ribble Estuary in England, the Burry Inlet, South Wales, and Solway Firth, Scotland. Traditional hand raking collection methods have been superseded by mechanised methods such as tractor dredging or hydraulic dredging techniques, except in the Burry Inlet, South Wales. Mechanised methods are more efficient than hand raking and capable of exploiting lower density beds but have the potential to over-fish the cockle stocks without adequate management. Demand for cockle meat in the

Netherlands and Spain, has increased, especially since the collapse of stocks in Wadden Sea in the late 1980s.

Concerns about over-exploitation and large scale dredging operations on cockle stocks has led to restrictions on the numbers collected and/or methods used. For example, dredging by any vehicle is prohibited in Scotland, whilst in England the type or design of equipment may be specified or hand gathering is the only permitted method.

5. Ecosystem services of shellfish and the revised matrix

The ecosystem services and benefits provided by shellfish, particularly bivalves, is probably better understood than it is for other seafood groups (McLeod and McLeod, 2019; van der Schatte Olivier et al., 2020). Focusing specifically on shellfish species, Rullens et al. (2019) reviewed the links between four key ecosystem functions, the processes required to fulfil these functions and the resulting ecosystem services and benefits derived (Figure 19).

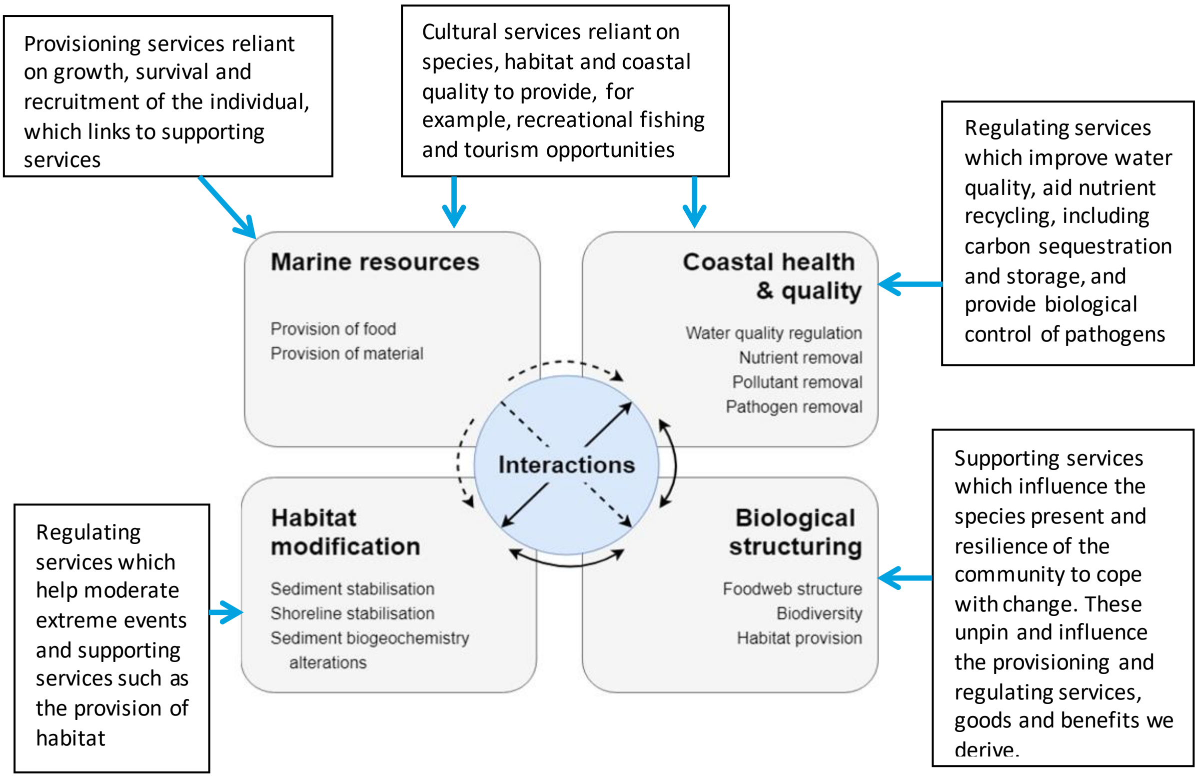

Figure 19: Four key ecosystem functions and the links to ecosystem services provided by shellfish. Arrows between the boxes in the centre of the figure indicate the interactions between boxes either as synergies (black bi-directional arrows) or trade-offs (dashed one-directional arrows). The blue arrows indicate the key ecosystem service type associated with the box (adapted from Rullens et al., 2019).

These four ecosystem functions are explicitly related to the ecosystem services, goods and benefits categories utilised in the matrix:

- Marine resources are explicitly linked to provisioning services and the goods we derive from that:
    - larval and gamete supply,
    - food provision (wild and farmed)
    - fish feed (wild, farmed and bait)
    - fertilizer and biofuels
    - ornaments (including aquaria)

    - medicines and blue biotechnology
- Coastal health and quality is explicitly linked to regulating services and the benefits we derive:
    - Nutrient cycling
    - Water cycling
    - Biological control
    - Clean water and sediments (waste breakdown and detoxification)
    - Carbon sequestration/climate regulation
    - Prevention of coastal erosion
    - Sea defence
    - Waste burial/removal/neutralisation and immobilisation of pollutants
    - Healthy climate through the storage of carbon
- Habitat modification is explicitly linked to regulating services and the benefits we derive:
    - Formation of species habitat
    - Formation of physical barriers
    - Formation of seascape
    - Natural hazard regulation
- Biological structuring underpins the entire ecosystem through its supporting services:
    - Influences on food webs and biodiversity which links to the availability of marine resources and the goods and benefits we obtain from the sea.

In addition to these ecosystem goods and services, there is a flow of cultural benefits. For example, shellfish play an important role in tourism, leisure and local food culture. They have held a significant role, both historically and today, as products used for decoration, fashion and as souvenirs. They also contribute to education, research and wider aesthetic and health benefits.

Because of the biological linkages between different ecosystem functions, many of the examples identified in the literature provided evidence for more than one ecosystem service or benefit. As a result, the evidence has been grouped by ecosystem function as described above in order to avoid repetition, with additional consideration given to the cultural aspects.

5.1 Marine Resources and the provision of food and materials

The provision of food is the most obvious, and often the only ecosystem service, attributed to commercially important species (Williams et al., 2018). Shellfish, and bivalves in particular, provide a high protein, low fat meat that is rich in marine lipids and minerals (Menon & Gopakumar, 2017; Silva et al., 2021). Despite this beneficial food value, shellfish do not receive the same attention as finfish regarding health consciousness in the media (Grant and Strand, 2019).

Production is strongly reliant on the biomass produced in the system and yield for the region, which is underpinned by individual survival, growth and recruitment. Sustainable harvesting either by wild caught fisheries or through aquaculture requires sufficient biomass to be available for our use. The growth rate of individuals determines how much biomass can be generated in a particular region and can be affected by density of individuals (Merder et al., 2019). Growth rates are also dependent upon environmental variables, which change both spatially and temporally (Li et al., 2012; Bergstom et al., 2015). For example, the growth rate of mussels is higher in off bottom culture than in on bottom culture, and is also higher when grown submerged rather than in the intertidal zone (Kamermans & Capelle, 2019).

Similarly, survival of the individual also influences the amount of biomass available, with high survival meaning greater provision. Environmental variables can be important here too with, for example, high or low temperatures causing physical stress or death (Steeves et al., 2018), and algal blooms or hypoxia causing infaunal shellfish to emerge from the sediment (Lewis & DeWitt, 2017). Natural recruitment to the population affects the biomass available for harvest in the future (Marsden & Adkins, 2010). However, the settlement ecology and preferences of different shellfish species are poorly understood (Guy et al., 2019). Our harvesting activities have been shown to influence the settlement and future recruitment of some shellfish species (Toupoint et al., 2016). Disease outbreaks are also important, effecting shellfish survival and, potentially, human health (Wilkie et al., 2013; Carass et al., 2020). The prevalence of disease and its movement through the population can be influenced by environmental variables such as temperature (Callaway et al., 2013; Burdon et al., 2014; Guillotreau et al., 2018; Carass et al., 2020).

Shellfish aquaculture is viewed as being increasingly important for protein production (Kluger et al., 2017). Non-native species can be used in aquaculture (e.g. the Pacific oyster in the UK), and may produce higher yields than native species (Ruesink et al., 2006). The success of the global mussel aquaculture industry relies heavily on high natural settlement rates and the retention of spat for on-growing (Hickman, 1992; Carl et al., 2012; Kamermans and Capelle, 2019). Their position low in the food chain with no addition of feed and medicine makes bivalve aquaculture eminently future-proof (Grant & Strand, 2019).

In addition to being a food resource, shellfish can also be used as bait and in the production of animal feed. For example, a market for brown crab as whelk bait developed using crab that did not meet full commercial quality requirements (Nautilus Consultants, 2009). Whilst this originally started as a means of disposing of the small quantities of crab that did not meet commercial specifications for landing to port, a significant market developed for whelk bait, which in turn has led to reduced quality grading of crab onboard where crab could easily be returned to the sea. This in turn raised concerns for the future of brown crab fisheries. As a result, the use of brown crab as bait for the whelk fishery has now been banned in approximately half of the English IFCAs as part of a suite of measures aimed at improving inshore crustacean fisheries. Crushed oyster shells have been used as a calcium source for egg producing poultry for decades (NRC, 1994). More recently, mussel meal is being used as an alternative protein source in poultry diets (Wilhelmsson et al., 2019; van der Heide et al., 2021).

Besides being a source of food, bivalves and their microorganism communities produce a variety of bioactive peptides, proteins and metabolites which are potentially anti-microbial and anti-cancer candidates. For example, antimicrobial peptides have been identified in the Mediterranean mussel which likely contribute to its vigour and could assist with the identification of innovative pharmaceuticals and other products (Wiese et al., 2018; Venier et al., 2019). Mussels have also been investigated as a possible source renewable energy source through the production of biogas (Wollak et al., 2018).

Rullens et al. (2019) identified the provision of materials as an important resource from shellfish. For example, bivalve shells are generally regarded as a waste material once the flesh has been harvested. Due to the calcium carbonate present, they can be used for conditioning and ameliorating acidic soils, as adsorbents to remove acidic gases in flues, in construction, as catalysts in the production of biodiesel, as inorganic fillers in polymers, as a bactericidal and dehalogenating agent and in artificial bone (Lee et al., 2008; Spångberg et al., 2013; Yao et al., 2014). Crab and shrimp shell waste are used as the primary source of biomass for the industrial production of chitin and chitosan. Chitosan is used in the food industry as a dietary additive and as a natural preservative for meat and other food products against fungal spoilage, in the pharmaceutical and medical industries as a carrier for various active agents, as an antibacterial agent and as a coating for medical implants, for water purification and environmental protection and to produce sustainable 'plastic' films (Galvis-Sánchez et al., 2018; Bakshi et al., 2019). Brown crab waste has also been used as a constituent in industrial scale compost production suitable for agricultural use (Pérez et al., 2015).

5.2 Improved coastal health and quality through water regulation and nutrient cycling

Water quality regulation, removal of pathogens and pollutants and nutrient recycling are important for improving coastal health and quality. The provision of improved water quality by filter feeding of bivalves, e.g. oysters, mussels and clams, has gained increasing attention as a mechanism to mitigate the adverse effects of excess nutrient loading from human activities, such as agriculture and sewage discharge (Lindahl et al., 2005; Ferreira & Bricker 2016; (Reitsma et al., 2017; Hedberg et al., 2018; Clements and Comeau, 2019; Petersen et al., 2019; Buer et al., 2020; Gravestock et al., 2020; Kotta et al., 2020; Parker & Bricker, 2020; Sonier et al., 2021). Nitrogen is considered the primary nutrient limiting phytoplankton growth in coastal waters (Rose et al., 2015; Petersen et al., 2019) and is, therefore, associated with euthrophication and algal blooms when abundant.

By removing phytoplankton and suspended sediment particles from the water column, bivalves act as biofilters, improving water clarity, reducing turbidity and increasing light penetration. Filtration rates are dependent upon the size and density of the individuals, vary by species and also with changes in environmental variables such as the phytoplankton species present, organic matter and oxygen concentration, salinity and temperature (Dame et al., 1991; Riisgård et al., 2003, 2011; Li et al., 2012; Zu Ermgassen et al, 2013a; Forster et al., 2015; Nielsen et al. 2016; Galimany et al., 2017a; Gray & Langdon, 2018; Cranford, 2019; Preston, 2019; Theuerkauf et al., 2019; Buelow & Waltham, 2020; Galimany et al., 2020; Moody & Kreeger, 2020; Leite et al., 2021).

Nutrient extraction by bivalves occurs through two mechanisms: (i) harvest/removal leading to the nutrients being returned to land and (ii) through increased denitrification in proximity to dense bivalve aggregations, leading to loss of nitrogen to the atmosphere and carbon sequestration (Talmage & Gobler, 2010; Volety et al., 2014; Sebastiano et al., 2015; Galimany et al., 2017b; Reitsma et al., 2017; Bricker et al., 2018; Petersen et al., 2019). This nutrient uptake leads to partial transformation of particulate-bound nutrients into dissolved nutrients via bivalve excretion or enhanced mineralization of faecal material (Jansen et al., 2019; Petersen et al., 2019). During these processes, 40–50% of the nutrients are regenerated and made available again for phytoplankton growth, and 10–50% of the filtered nutrients are stored in tissue to be removed from the system by harvest (Higgins et al., 2011; Rose et al., 2015; Jansen et al., 2019).

The water clarification capacity of natural and cultured bivalve populations could provide a bioengineering tool for mitigating the major symptoms of human induced eutrophication and thereby providing positive ecosystem-scale benefit (Cranford, 2019; Bricker et al., 2020). For example, the improved water quality of Liverpool Docks, required as part of the redevelopment of the area, was the result of mussel settlement and recolonisation (Wilkinson et al., 1996).

Globally 85% of native oyster (*Ostrea edulis*) populations and their associated habitat have been lost (Beck et al., 2011). This decline rises to 96% in some locations in the UK (Helmer et al., 2019). Similar declines and concerns have been raised regarding other reef or bed forming species, e.g. American oyster (*Crassostrea virginica*) (Lenihan, 1999; Powers et al., 2009; Grizzle & Ward, 2016; Weissberg & Pagano, 2021), Olympia oyster (*Ostrea lurida*) (Brumbaugh &, Coen, 2009; Pritchard et al., 2015; Zacheri et al., 2015), Australian flat oyster (*Ostrea angasi*) (Alleway & Connell, 2015; Gillies et al., 2020), Sydney rock oyster (*Saccostrea glomerata*) (Mcleod et al., 2019; Gillies et al., 2020; McAfee et al., 2020), horse mussel (*Modiolus modiolus*) (Fariñas-Franco et al., 2013) and blue mussel (*Mytilus edulis*) (Dankers et al., 2001; Dolmer & Frandsen, 2002; McDermott et al., 2008; Kristensen et al., 2015).

With the global decline of biogenic reefs, restoration efforts have been growing in momentum and scope (Bromley et al., 2016; Fariñas-Franco et al., 2018; Reeves et al., 2020). Recently, reef restoration projects have been initiated in various locations as a mechanism for improving water quality (Zu Ermgassen et al., 2013b; Baggett et al., 2015; Milbrandt et al., 2015; Harding et al., 2016; Buer et al., 2020; Kotta et al., 2020) as well as stabilising the shoreline and enhancing estuarine habitat for fish and invertebrates (LaPeyre et al., 2014) and for carbon sequestration (Lee et al., 2020). However, progressively increasing the standing stock of bivalves to achieve greater water clarification benefits will lead to inefficiencies in bivalve feeding. This is related to increased flow reduction from structure drag, which facilitates an increase in water re-filtration, thereby constraining the maximum water clarification capacity of the population (Cranford, 2019). When restoring biogenic reefs, consideration needs to be given to bivalve density, as well as positive interactions with other species and habitats in order to increase restoration success (Fariñas-Franco et al., 2013; Carranza & zu Ermgassen, 2020; Reeves et al., 2020).

Whilst filter feeding, bivalves also move particles from the water column to the sediments as biodeposits, which contributes to nutrient exchange between the benthic and pelagic environments (Petersen et al., 2014, 2016; Filgueira et al., 2016; Kent et al, 2017a; Buelow & Waltham, 2020; Isdell et al., 2020) and can bury organic carbon thereby contributing to carbon sequestration (Fodrie et al., 2017; Strand & Ferreira, 2019; Lee et al., 2020). These biodeposits also induce denitrification, which helps counteract eutrophication by releasing nitrogen into the atmosphere (Williams et al., 2018; Rose et al., 2021).

Marine and coastal environments play a vital role in regulating the global climate via the carbon cycle. When carbon is incorporated into shell, it is generally considered to represent carbon sequestration. When it is incorporated into tissue, however, it will be consumed and recycled. Bottom cultured mussels remove and store more carbon in their shells than to rope cultured mussels, whilst the opposite was found for nitrogen (van der Schatte Olivier et al., 2021). In addition, biodeposition increases sedimentation rates and modifies physical, chemical and bacterial composition (Karlson et al., 2010; Kanaya, 2014). This alters nutrient cycling rates including denitrification and also leads to burial (Cerco, 2015; Filgueira et al., 2016; Fodrie et al.., 2017; Kent et al., 2017a). Associated with this activity is the removal of pollutants and pathogens from the system through deposition/burial, biotransformation or bioassimilation (Volety et al., 2014; Broszeit et al., 2016; Burge et al., 2016).

Infaunal species contribute to sediment turnover and bioturbation through their burrowing activities, which in turn stimulates nutrient cycling and the removal of nutrients from the sediment to the water column through changes in ammonia fluxes (Thrush et al., 2006; Jones et al., 2011; Kellog et al., 2013; Venter et al., 2020; Otero et al., 2020) and burial of plant material (Rani et al., 2021). For example, the burrowing activity and movement of cockles results in the mixing of particulate material, whilst their filtration and valve movements enhance pore water displacement and solute exchanges across the sediment-water interface (Mermillod-Blondin et al., 2005). *Nephrops norvegicus* burrows create habitat heterogeneity and stimulate ecosystem functions that involve sediment-water fluxes (Tuck et al., 1994; Johnson et al., 2013) whilst burrow construction and filtration by the sandprawn *Callichirus kraussi* can reduce phytoplankton biomass by 70% (Venter et al., 2020).

Eutrophication leading to phytoplankton blooms can have direct negative impacts on the ecosystem which can be mitigated to some extent by filter feeding bivalves (Ferreira & Bricker, 2016). The capacity of bivalves for improving water quality, makes them good candidates for inclusion in integrated aquaculture (Soto & Jara, 2007; Visch et al., 2020). For example, bivalves can use degraded fragments derived from cultured kelp or phytoplankton grown in the effluent water from fish farming or shrimp ponds and increase biogeochemical processing of the waste products (Richard, 2004; Nobre et al. 2010; Ferreira et al. 2012; Li et al., 2019; Strand et al., 2019; Sanz-Lazaro & Sanchez-Jerez, 2020). Similarly, lobsters have been shown to reduce the organic waste generated by salmon farms (Baltadakis et al., 2020) whilst mussels have been successfully trialled as an additional food source for the wrasse used in salmon aquaculture for the biological control of sea lice (Holmyard, 2019). When mussels are also made available as a food resource, sea lice consumption by wrasse was more efficient.

5.3 Habitat modification, sediment stabilization and coastal protection

Shellfish are ecosystem engineers, i.e. they modify the habitat through their interactions with physical environment. Their influence, however, varies depending on the species and their activities, e.g. reef formation by bivalves or the bioturbation of the sediment by borrowing crustaceans. These activities provide ecosystem services related to sediment biogeochemistry, sediment stabilisation and shoreline stabilisation.

Because bivalves such as oysters and mussels typically display aggregating behaviour during settlement, i.e. pelagic juveniles preferentially choose sites where conspecific individuals are already present, they can form biogenic habitats (Rodriguez-Perez et al., 2019; Smyth et al., 2020). These complex reefs can exert strong influences on local hydro- and morpho-dynamics as well as surrounding habitats and associated species (Fariñas-Franco et al., 2013; Baggett et al., 2015; Walles et al., 2015; Lovelock & Duarte 2019; Chowdhury et al., 2020; Liversage, 2020). The spatial impact of the ecosystem engineering effects of reef-building bivalves is much larger than the size of the reef. For example, by influencing hydrodynamics oysters and mussels modify the sedimentary environment up to several hundreds of meters beyond the boundaries of the reef, affecting morphological and ecological processes (Ysebaert et al., 2019). Conversely, the sedimentary environment, e.g. salt marsh shoreline geomorphology or presence of boulder reefs, influences the stability of biogenic reef and how other fauna utilise it (Keller et al., 2019; Liversage, 2020).

Due to their wave dampening effects, bivalve reefs are increasingly being used for shoreline protection and erosion control as an alternative to artificial shoreline hardening (Scyphers et al., 2011; Pogoda et al., 2019; Lovelock & Duarte 2019; Rodriguez Perez et al., 2019; Branigan et al., 2020; Zu Ermgassen et al., 2020; Fivash et al., 2021; Gregg et al., 2021). Alternatively, breakwaters created from oysters shells provide similar shoreline stabilising services to artificial breakwaters but also create a greater variety and availability of habitat for other species (Scyphers et al., 2015). Suspended bivalve aquaculture can expand habitat availability, not only of the cultured species beyond its natural benthic occurrence but also for many other associated species (Grant & Stand, 2019; McLeod & McLeod, 2019; Sheehan et al., 2019).

Sediment reworking through bioturbation and burrow construction leads to alterations of the sediment biogeochemistry through the burial of organic matter (Kanaya, 2014; Sarker et al., 2020), influences nutrient fluxes at the sediment-water interface (Sandwell et al., 2009; Lohrer et al., 2010; Norkko et al., 2013; Premo & Tyler, 2013; Carass et al., 2020) and cause changes in the depth at which sediment moves from being oxygenated to anoxic (Clare et al., 2016; Sarker et al., 2020). Changes in the sediment biogeochemistry are affected by species composition and density (Sandwell et al., 2009; Clare et al., 2016; Sospedra et al., 2017; Sarker et al., 2020), feeding behaviour of the species present (Marie et al., 2006; Karlson et al., 2010) and predators affecting the burrowing behaviour of their prey (Marie et al., 2010).

Where sediment is reworked, its erosion potential is altered through changes in near-bed flow dynamics, alterations in the distribution of sedimentary grain sizes and associated microbial activity and surface topography. Shellfish can either stabilise or destabilise sediments depending on the species present, the densities present and size distribution

(Brumbaugh & Coen, 2009; Eriksson et al., 2010; Donadi et al., 2013; Harris et al., 2015; Carass et al., 2020; Williams & Johnson, 2021).

5.4 Biological structuring, food webs and biodiversity

The influence of shellfish on the structure of the biological community links to ecosystem services such as foodweb structure and habitat provision. The intrinsic value of any ecosystem is based on the species present and resilience of the community as a whole to deal with change. It should be noted, based on cultural determination, that biodiversity may or may not be considered an ecosystem service (Mace et al., 2012). Biodiversity, however, underpins a range of critical ecosystem services. Changes in the composition and abundance of species, genes and habitats will affect processes such as the biogeochemical cycles of nutrients and carbon at different scales (Naeem et al., 2012; Frid & Caswell, 2015).

The suspension feeding activities of bivalves plays a major role in phytoplankton dynamics and biomass in coastal regions (Beadman et al., 2004; Cranford, 2019; Andriana et al., 2021). Habitat alterations and provision (e.g. biogenic reefs) leads to the creation of feeding opportunities, as well as refuge and nursery areas (Guidetti & Boero, 2004; Volety et al., 2014; Sheehan et al., 2015; Rees et al., 2016; Zu Ermgassen et al., 2016; Glaspie & Seitz, 2017; Craeymeersch & Jansen, 2019). The biogenic reefs created by bivalves are complex environments with layers of habitat, e.g. the surfaces provided by the shells for attachment and the crevices between the shells where mobile or sedentary fauna can live, as well as the opportunity for larger mobile fauna moving across the surface of the reef (Dinesen & Morton, 2014; Crawford et al., 2020).

In addition, the biodeposits produced from filter feeding support a high density and diversity of macroinvertebrates, many of which form prey resources for fish (McLeod et al., 2014). An indirect result of this habitat creation can be increased secondary production of fish and crabs leading to food provision for commercial fishers and recreational anglers (Coen et al., 2007; Volety et al., 2014; Kirstensen et al., 2015; Norling et al., 2015; Kent et al., 2017b; Blomberg et al., 2018; Ayvazian et al., 2020; Lai et al., 2020). This will be lost if a reef is destroyed and replaced by unstructured sediment (Cook et al., 2013; Hancock & Zu Ermgassen, 2019). It is the combination of shelter and protection from predation, combined with the biodeposits which drive a greater abundance of prey, leading to enhanced fish production (Humphries et al., 2011; Kesler, 2015).

Infauna shellfish can also alter and provide habitat through their bioturbatory activities, changing the sedimentary characteristics and thereby influencing community composition (Queiros et al., 2011; Moore, 2019). Macrofaunal, meiofaunal and microbial communities of sediments are altered by the presence of shellfish, which can lead to changes in community assemblages and species richness (Liu et al., 2009; Boldina et al., 2014; Winberg & Davis, 2014; van der Zee et al., 2015; Abdullah & Lee, 2016; Kluger et al., 2016). Clam restoration projects have also recorded increased biodiversity, species richness and abundance, particularly for some environmentally sensitive groups such as crustaceans, which in turn alters community structure of the resident infauna (Shantharam et al., 2019).

Seascapes are defined as the patches or mosaics of interacting ecosystems (e.g. sandflats, seagrass beds or biogenic reefs) that are dynamic and variable at multiple spatial and temporal scales. Seascapes that contain a wider variety of patch types, topographies or habitats, tend to support greater diversity. The connectivity and ecological flows are key features of seascapes that strongly influence the composition and diversity of marine organisms. Foodweb structure is determined by the transfer of carbon and energy from primary producers to higher tropic levels. Bivalves provide an important link between the phytoplankton and microphytobenthos (i.e. the primary producers) and top predators such as fish and shorebirds (Vinagre et al., 2015; Ferriss et al., 2016; Christianen et al., 2017; Carass et al., 2020). Energy transfer to the benthic communities through biodeposition is also important as it stimulates the microbial community (Franzo et al., 2016; Andriana et al., 2021). At the other end of the trophic interactions, the presence of predators influences the behaviour of their prey species and so on down the system, which can have the benefit of reduced bivalve predation (Barrios-O'Neill et al., 2017).

5.5 Cultural ecosystem services for local communities and well-being

Cultural ecosystem services provided by marine shellfish are more difficult to quantify than the supporting, regulating and provisioning services more closely linked to biology. Cultural services are often associated with non-materiality, and are intangible, subjective and/or nebulous (Chan et al., 2012). They can be understood as being life-enriching and life-affirming contributions to human well-being, encompassing a broad range of human interactions and understandings of the natural environment (Fish et al., 2016). Cultural services in general change over time, and can be modified by social influences, as well as human perceptions including emotions and senses (Church et al., 2014; Jones et al., 2016). Most examples of the cultural services provided by shellfish relate to bivalves (van der Schatte Olivier et al., 2020). For example,

The collection of shellfish and in particular harvesting of bivalves have been part of human cultures for thousands of years (Smaal & Strand, 2019; Muething et al., 2020). For example, Stone Age hunter gatherers from as early as 8700 BC harvested native oysters, the Romans ate them and valuable oyster beds are recorded in the 1086 Domesday book (Gamble, 2020). Consequently, bivalve shells can provide a valuable archaeological resource for studies of food habits, patterns of seasonal site occupation, migration, tool use, ornamentation, and also the dating of archaeological sites (Waselkov, 1987; Light, 2013; Thomas, 2015a, b; van der Schatte Olivier et al., 2020; Garcia-Escarzaga & Gutierrez-Zugasti, 2021; Ritchison et al., 2021). Shellfish likely played a key enabling role in early human dispersal (Hausmann et al., 2021).

Shellfish can be of spiritual importance. For example, the Camino de Santiago, also known as the Way of St James, was one of the most important Christian pilgrimages during the Middle Ages. It became customary for those who undertook the pilgrimage to bring back a scallop shell as proof of the journey (Waldron, 1979). The Camino de Santiago comprises a network of pilgrims' ways to the shrine of Saint James in the cathedral of Santiago de Compostela (Galicia, Spain). Today, these pilgrimage routes are included in the UNESCO

World Heritage list. Also in Galicia, the 12th century church, Capilla de las Conchas (chapel of the shells) or Ermita de San Sebastian, on Isla de la Toja, is covered in scallop shells (Figure 20). The shell covering was the result of the remodelling carried out in the 19th century and, in part, symbolises the natural richness of the marine environment. Shells have been used to provide a protective covering and/or decoration to buildings all over the world for well over a century (Figure 20).

The well-defined and time-delimited (usually daily, tidal or annual) banding patterns developed as bivalves lay down their shells can also provide a long term record of changes in geochemistry and climatic events (Butler et al., 2019). Because bivalves are hardy, fast growing and some species can reach sexual maturity within a year (e.g. mussels), they are frequently used in scientific investigations (van der Schatte Olivier et al., 2020).

Figure 20: Capilla de las Conchas, Spain (© J.A. del Pino [top left]), the 19th Century Shell House, Cornwall UK (© R. Croft [top right]), a 1920s scallop shanty house, USA (© A. Kennedy [bottom left]) and a house constructed of oyster shells, China (© People's Daily, [bottom right]).

Collecting seashore shells is worldwide leisure activity, and an organised profession through the scientific discipline of malacology. Pearls have been used for adornment and as a symbol of material wealth in many cultures throughout human history (Warsh, 2018; Zhu et al., 2019). Pearls and mother of pearl shells can also function as collector's items (Duncan & Ghys, 2019) and as inlays in furniture and musical instruments (Grant & Strand, 2019). Historically they were used as buttons, a notable example of which are the iconic Pearly Kings and Queens of London. Easily recognised by their distinctive suits and accessories covered in mother-of-pearl buttons, the Pearly Kings and Queens originated in the 1880s (Kelly, 2019). Over 150 years later, the tradition still continues today (Figure 21).

Figure 21: Henry Croft c1900, founder of the Pearly Kings and Queens (© Pearly Kings and Queens Guild, [left]), Pearly Kings and Queens of the 1960s and at the London Olympics 2012 (© G. Graham).

Fishing and aquaculture contribute to the physical landscape and existence of numerous towns today. The value of these industries to the social and cultural well-being of coastal communities is, however, often overlooked (Chan et al., 2012; Urquhart & Acott, 2014; Michaelis et al., 2020). For example, fishing and its role in defining identity can account for the reluctance of some fishers to diversify into new activities when fishing becomes unviable, i.e. the cultural significance of fishing takes precedence over economic interests (van Ginkel, 2001; Urquhart & Acott, 2014). Fishing and shellfish aquaculture are seen as a way of life rather than a job. In fishing communities, the loss of fishing as a career not only leads to higher unemployment, but also changes the social structure of the community with young people leaving to find non-fishing related employment (Urquhart et al. 2011). Conversely, a focus on small scale vessels in lobster fisheries, whilst excluding large-scale fisheries, can boost social equity whilst encouraging long-term economic growth and supporting ecological sustainability (Ward et al., 2018). Local inshore fisheries can also support communities through direct vessel-level expenditures and onshore processing (Carruthers et al., 2019).

The development of sustainable fisheries and aquaculture provides cultural services and benefits to coastal rural communities, enabling people to stay in their familiar environment for employment rather than moving away. Sustainable aquaculture and fisheries help shape the cultural identities of a place and ownership (Urquhart & Acott, 2014; Michaelis et al., 2020; van der Schatte Olivier et al., 2020). This can lead to job satisfaction, provide a 'way of life', opportunities for lifelong learning, spiritual value of 'being out there', and the knowledge of doing something *with* and *for* the marine environment, as well as sustaining healthy food production which extends into tourism and local food culture (Krause et al., 2019). The physical objects linked to fishing, such as the boats and gear, such as pots and creels used by *Nephrops*, crab and lobster fisheries, are important identifiers for community cohesion and as an attraction for tourism (Urquhart & Acott, 2014).

The aesthetic benefits of ecosystems are the primary responses derived from experiences of the natural environment (Cooper et al., 2016). Special landscapes, including the sea, are often deemed as being noteworthily pretty, and may be designated as Areas of Outstanding Natural Beauty (e.g. Cornwall ANOB incorporating picturesque fishing villages and Arnside & Silverdale AONB incorporating Morecambe Bay) or National Nature Reserves (e.g. the Wash). Such areas are important for tourism, with tourists perceiving fishing vessels as being more attractive and charming than yachts or other vessels in the harbour. In many rural locations, food has also become a recognised part of cultural tourism through seafood festivals (Lee & Arcodia, 2011; van der Schatte Olivier et al., 2020). Annex 2 provides a list of over 40 UK seafood festivals, many focused specifically on oysters, crabs or lobsters.

Community-based shellfish restoration efforts provide benefits that aid community cohesion and help connect people with local foods and traditions. For example, the Chichester Harbour Oyster Partnership Initiative brought together statutory bodies, biologists and fishermen to develop innovative management approaches to address issues affecting the native oyster fishery (Williams et al., 2018). This approach was also adopted by the Southern Inshore Fisheries and Conservation Authority for bivalve fisheries in the Solent area (Harding et al., 2016; Williams and Davies, 2018). Through such initiatives shellfish fisheries and aquaculture can indirectly bring local environmental problems (e.g. water quality) to the attention of the local community and serve as a starting point for wider engagement into environmental issues (Williams et al., 2018; Zu Ermgassen et al., 2020).

Restoration projects can also serve as opportunities for engaging community volunteers, incorporating student or citizen science, and/or broad-scale education and outreach. Restoration projects can benefit from community participation via an added labour force and by fostering community investment and support, which is critical for project success and future restoration investments. Community participants gain physically and psychologically rewarding experiences from being a part of such projects, while fostering an environmental ethos (DeAngelis et al., 2019). An example of such a project is the Dornoch Environmental Enhancement Project (DEEP) which is restoring 40 hectares of native oyster reef to provide a bioengineering solution to treatment of the last 5% of biological oxygen demand pollution from the Glenmorangie Distillery (Allen, 2019). Although much of the shellfish reef restoration activity undertaken to date has been focused on oysters, there is rapidly growing interest in restoring mussel and other habitat-building shellfish reefs (Fitzsimons et al., 2020; Gillies et al., 2020; McAfee et al., 2020; Weissberg & Pagano, 2021).

Time spent outside 'in nature' can benefit psychological well-being and increase social engagement. Mental health, especially psycho-social wellbeing, can be improved with access to blue space (Pasanen et al., 2019; Britton et al., 2020). 1.8 million visits to the English coasts occur for the purposes of recreational fishing for health, social and relaxation motivations (Elliott et al., 2018).

5.6 The revised matrix

The shellfish elements of the matrix presented in Table 3 (from Garrett, 2019) have been further updated, with a specific focus on the UK shellfish wild capture and culture industries, in light of this literature review as well as the industry knowledge and understanding (Table 4). Garrett (2019) only covered the shellfish groups oysters, mussels and cockles. This literature review and the workshop have strengthened our understanding of the ecosystem services, goods and benefits derived from these species. In addition, additional evidence for the ecosystem services, goods and benefits provided by scallops, brown crab, lobster and *Nephrops* have also been identified. A wide variety of ecosystem services and benefits are associated with commercially important shellfish species including food and material provision, nutrient and water cycling, sediment quality and stabilisation, and carbon and nitrogen sequestration. These provide societal goods and benefits in terms of reduced coastal erosion, clean water and cultural benefits related to community, tourism, education and research.

It is clear that there has been a considerable focus on the ecosystem services and benefits provided by mussels and oysters by academia whilst relatively little consideration has been given to infaunal bivalves (cockles and clams) and crustaceans (crabs, lobsters and prawns). Although focus on these species has increased recently. Similarly, the industry knowledge and understanding from the shellfish culture sector was focused on mussels and oysters. In contrast, the wild capture industry knowledge and understanding was largely focused toward crustaceans, as well as the cultural goods and benefits derived from the fisheries.

Different shellfish species contribute to different ecosystem services, goods and benefits to different degrees. For example *Nephrops* will play a lesser role in shoreline stabilisation or water quality improvement when compared to mussels or native oysters. Whilst the evidence for the contribution of cockles to water and nutrient cycling as well as habitat formation was contradictory, i.e. both positive and negative contributions were noted.

The good and services identified for bivalve cultivation are generally more apparent than those for wild capture shellfisheries. The wider benefits for wild capture fisheries are more easily attributed to the fishers, through food provision, material by-products and the cultural benefits associated with communities, heritage, tourism and so on. For example, the fishing vessels and associated gear, such as pots and creels, used by *Nephrops*, crab and lobster fisheries play a significant role in community cohesion and tourism. In contrast, seafood festivals are either broadly focussed across all types of seafood or maybe be specific to a single species or group of species, primarily oysters, crabs and lobsters.

5.6.1 Interpretation of the matrix

For the revised matrix (Table 4), 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 (from both the literature review and industry knowledge) point to identical, or similar conclusions, symbolised as ++
- Some evidence = there is some evidence from either the literature review or industry knowledge on which a conclusion can be drawn, symbolised as +
- Mixed evidence = Some evidence sources indicate a particular conclusion, whilst other evidence suggest contrasting conclusions, symbolised as +/-

Table 4: Matrix of the ecosystem services that UK commercially important shellfish provide based on the literature review.

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	+/-	+	++		+	++

5.7 The links between the different ecosystem services and the goods and benefits we derive.

The ecological functions and processes which shellfish provide contribute to human wellbeing. However, it is often the food resource provided that is accounted for whilst many of the other ecosystem services go unrecognised (Williams et al., 2018; McLeod and McLeod, 2019). The management of shellfish and shellfish habitats for objectives beyond commercial and recreational fisheries does not generally occur. Failure to consider the true costs of degrading these ecosystems results in a reduction of the benefits that humans derive. The ecosystem services framework enables us to appreciate the wide variety of beneficial contributions that shellfish make. This will, in turn, enable regulation and investment to protect, conserve and sustainably manage these benefits.

The sustainable delivery of ecosystem services is closely linked to a good condition of the ecosystems providing them (Maes et al., 2020). That delivery of ecosystem services can also be highly variable on a spatial basis, depending on the hydrodynamics of the habitat and also upon the accessibility of the site to humans to access the benefits (Grabowski et al., 2012; La Peyre et al., 2014; Pogoda, 2019; Theuerkauf et al., 2019; Thorngren et al., 2019). For example, the value of coastal protection provided by oyster reefs is thought to be orders of magnitude greater than the value of any harvest and the cost of restoration (Grabowski et al., 2012). Additionally, interactions occur between the different ecosystem services which in turn influences the goods and benefits derived. Understanding these interactions is essential for sustainable management (Hattam et al., 2015; Lee & Lautenbach, 2016; Rullens et al., 2019). These interactions can operate through trade-offs, i.e. one ecosystem service or benefit can have a negative impact on another. Fishing and aquaculture harvesting shellfish generally remove biomass which will result in the loss of other services, e.g. the removal of mussels will reduce water regulation services. Scallop dredging can cause irreversible damage to benthic habitats, particularly biogenic habitats such as horse mussel reefs (Bryce & Howarth, 2016). Policy makers and regulators need to understand the effects of different management strategies on the provision of ecosystem services and, therefore, the goods and benefits we derive (Cobacho et al., 2020).

In a review of ecosystem services in relation to aquaculture, Weitzman (2019) noted that crustacean farming (mostly shrimp and prawn species) lead to a loss of mangroves, wetlands and deltas. Loss of such habitats in turn leads to a reduction in nursery grounds for fisheries (Zavalloni et al., 2014), reduced carbon storage (Ahmed & Glaser, 2016; Eid et al., 2019), and a loss of coastal buffering (Gunawardena & Rowan, 2005). Salinity intrusion due to shrimp farming has also been shown to significantly reduce local crops and livestock production (Islam & Tabeta, 2019), although prawn-rice farming systems or rice-crab systems can reduce the need for fertilizer inputs whilst increasing yields, as well as creating versatile employment opportunities (Loc et al., 2017; Islam & Tabeta, 2019; Hu et al., 2020).

Through a mutualistic association with saltmarsh plants, bivalves help to stablise sediments, thereby contributing to saltmarsh resilience (Isdell et al., 2020; Fivash et al., 2021) whilst the presence of burrowing crustaceans influences carbon and nitrogen cycling and sequestration (Moore, 2019). The agricultural grazing on saltmarshes can lead to reductions in blue carbon storage, compromise coastal protection and the provision of a nursery habitat for fish, but can lead to increased wildfowl abundance (Davidson et al., 2017). Historically, bivalve shells were returned to the seafloor after harvesting in order to replenish the underlying habitat, but a market for crushed shells as a soil conditioner has been implicated in both the overexploitation of oyster fisheries and a driver of decline of the oysters through a reduction in settlement sites (Blake & zu Ermgassen, 2015).

The interactions between different ecosystem services may, however, be synergistic. For example, biogenic reef development stabilises sediments and shorelines which reduces sediment resuspension, thereby improving water clarity, but also providing new habitat for the development of seagrass meadows and saltmarsh. Such habitats provide important nature based solutions for sea defence, mitigating the impact of flooding and storing carbon (Gregg et al., 2021).

Spatial protection measures such as Marine Protected Areas (MPAs) provide a diversity of ecosystem services and benefits. For example, the Moray Firth SAC, Scotland, has been designed for its sandbank habitats and bottlenose dolphins. The sub-tidal sandbanks support various algal and invertebrate species (i.e. formation of species habitat), provide natural hazard regulation (i.e. erosion control), nutrient cycling, fish feed, as well as spawning grounds and nursery areas for sandeels and juvenile fish, many of which are commercially exploited. This productivity in turn forms an important food source for marine mammals and sea birds which offer cultural services via tourism/nature watching and education (Potts et al., 2014). In Poole Harbour, a large natural harbour comprising of extensive tidal mudflats, seagrass beds and saltmarsh, together with associated reedbed and freshwater marshes, a condition assessment of the MPA highlighted issues related to eutrophication, including extensive algal mat growth across mudflats leading to negative impacts on prey availability and bird foraging behaviour (Natural England, 2015). Shellfish aquaculture within the MPA has resulted in improved water quality and led to improvements in site condition (Gravestock et al., 2020). Understanding the ecosystem services provided can also be an important factor in stakeholder engagement and, therefore, be a deciding factor in the success of marine protected areas (Brooker et al., 2018; Giakoumi et al., 2018).

Understanding the ecosystem services, goods and benefits that are derived from shellfish will aid better management and planning decisions to be made (Cobacho et al., 2020; Colletti et al., 2020; Pinsky et al., 2021). For example, the non-market values of shellfish ecosystem services is estimated to be at least 50% of their global market production value (Coen et al., 2007; Grabowski and Peterson, 2007; Clements and Comeau, 2019; Gentry et al., 2020; van der Schatte Olivier et al., 2020). Consideration of ecosystem services, goods and benefits will, therefore, help enable a sustainable future for the fishing and aquaculture industries with healthy economies, people and environments (Ward et al., 2018; Custódio et al., 2020; Pinsky et al., 2021). Afterall, shellfish aquaculture is considered one of the most ecologically sustainable sources of animal protein (Shumway et al. 2003, Ray et al. 2019; Gray et al., 2021).

Recently there has been considerable policy focus on the public goods delivered by farming with a policy change in the way subsides are paid to farmers (Bateman & Balmford, 2018). From 2021, as part of a move to higher regulatory standards, farmers will receive payments for enhancing the environment and protecting the countryside, for better animal and plant health and animal welfare, and for improved productivity (Defra, 2020).

Although not currently proposed, a similar approach could be applied to the UK's fishing and aquaculture industry. Such an approach has been successfully trialled for bivalve aquaculture in Scandinavia (Schultz-Zehden & de Grunt, 2019; Schultz-Zehden et al., 2019) and the USA (Miller, 2020) in relation to reducing nutrient loads. For the UK, Gray & Gray (2018) identified a series of equivalent public goods provided by the fishing and aquaculture industries, including:

- provision of fisheries data to inform stock assessments,
- modification of fishing gear to reduce discards and reduce environmental damage,
- collection of environmental data on protected marine species and habitats, invasive non-native species, and pollution;
- strict food safety practices, and
- improvements in water quality and carbon sequestration
- preserving resilience of coastal communities, traditional skills and culture through employment

Such an approach is likely to be essential if the UK is to implement an effective ecosystem based approach to fisheries management.

The fishing and aquaculture industries depend on a healthy and functioning marine ecosystem. A thriving seafood industry requires clean, healthy and productive seas. Too often the narrative about seafood industry practices focusses on the negative; usually concerned with overfishing and environmental damage. The ecosystem services approach, with its emphasis on the give and take relationship with the natural world, can therefore help reframe and provide a more balanced seafood story for the future.

6. Conclusions

Decades of sustained population and economic growth has resulted in significant pressure being placed on natural resources, leading to degradation and a reduction in the natural environment's ability to support human life. Consideration of ecosystem services associated with seafood will help enable a sustainable future for the industry, supporting healthy economies, people and environments.

In 2020, there was been a significant shift in the UK's land management and farming policy from production to a focus on natural capital and the ecosystem services and the public goods and benefits delivered. Similar consideration has not yet been given the fishing, aquaculture and wider seafood industries. The aim of this literature review was to begin to develop a robust evidence base for that could aid such a transition.

The review revealed that there has been a considerable focus on the ecosystem services and benefits provided by mussels and oysters by academia whilst relatively little consideration has been given to infaunal bivalves (cockles and clams) and crustaceans (crabs, lobsters and prawns). Although focus on these other species has increased recently. Similarly, the industry knowledge and understanding from the shellfish culture sector was focused on mussels and oysters. In contrast, the wild capture industry knowledge and understanding was largely focused toward crustaceans, as well as the cultural goods and benefits derived from the fisheries.

The provision of food is the most obvious benefit we derive, and is often the only ecosystem service attributed to commercially important shellfish species. Beyond this, there are, however, a wide variety of other ecosystem services and benefits. These include material provision, nutrient and water cycling, sediment quality and stabilisation, as well as carbon and nitrogen sequestration. Such ecosystem services provide societal goods and benefits in terms of reduced coastal erosion, clean water, improved climate health and cultural benefits related to community, tourism, education and research.

The delivery of ecosystem services can be highly variable on a spatial basis, depending on the hydrodynamics of the habitat and also upon the accessibility of the site to humans to access the benefits. Additionally, interactions occur between the different ecosystem services which in turn influences the goods and benefits derived. Understanding these interactions is essential for sustainable management.

The evidence provided in this literature review will contribute to decision-making in relation to marine planning and to aid decision making for inshore fisheries management, permitted activities within marine protected areas and other management policies in order to make the case for increased shellfish production where appropriate. The fishing and aquaculture industries depend on a healthy and functioning marine ecosystem. A thriving seafood industry requires clean, healthy and productive seas. The ecosystem services approach, with its emphasis on the give and take relationship with the natural world, can therefore help provide a balanced seafood story for the future.

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Annex 1: Definitions of ecosystem services, good and benefits (adapted from Turner et al [2014]).

Service	Definition	Example
Larval and gamete supply	The production and supply of larvae and gametes from coastal & marine biota	Quantity and/or quality of larvae or gametes supplied to a given coastal or marine location
Nutrient cycling	The influence of coastal & marine biota on the movement or exchange of organic and inorganic matter	Change in the concentration of nitrates/phosphates in coastal or marine waters/sediments
Water cycling	The influence of coastal & marine biota on the movement or exchange of water between the coastal & marine environment and adjacent environments (including the atmosphere)	Exchange of water between the sediment and the overlying water column due to burrow irrigation or bioturbatory activity.
Formation of species habitat	The contribution of coastal & marine biota to habitat formed by one species but providing suitable niches for other species	Change in the formation of mussel beds, kelp forests, or cold-water coral reefs
Formation of physical barriers	The contribution of coastal & marine biota to the formation of physical barriers	Changes in reef extent by reef-forming organisms (e.g. *Sabellaria* spp.), impacting on the local hydrographic regime
Formation of seascape	The contribution of coastal & marine biota to supporting the formation of different coastal and marine views ('seascapes')	Changes in area per type of seascape e.g. algae-covered rocky shore, kelp forest, or the designation of protected areas for nationally or international important habitats and species.
Biological control	The contribution of coastal & marine biota to the maintenance of population dynamics, resilience through food web dynamics, disease and pest control	Oystercatchers controlling intertidal cockle population numbers; cleaner fish (e.g. ballan wrasse) removing sea lice from salmon
Natural hazard regulation	The area of suitable coastal & marine habitat which is available to absorb energy, and the contribution of coastal & marine biota to the dampening of the intensity of environmental disturbances such as storms, flooding and erosion.	The reduction in the intensity of environmental disturbances resulting directly from coastal & marine ecosystem structures such as saltmarsh, mudflats and sea grass beds
Clean water and sediments (Waste breakdown and detoxification)	The presence of coastal & marine biota which have the potential to remove anthropogenic contaminants and organic inputs leading to the provision of clean water and sediments	Quantity of waste (tonnes) that is recycled or immobilised by coastal & marine biota over a period of time through the presence of reedbeds, mussels beds, etc.
Carbon sequestration/ climate regulation	The net capture of carbon dioxide by coastal & marine biota and the contribution of coastal & marine biota to the maintenance of a favourable climate through the regulation of greenhouse gases.	Change in the net amount of carbon stored within an area of coastal saltmarsh within a certain period leading to a healthy climate
Goods/benefits	**Definition**	**Example**
Food (wild, farmed)	Extraction of coastal & marine biota for human consumption	Tonnes of cod landed for human consumption
Fish feed (wild, farmed, bait)	Extraction of coastal & marine biota for non-human consumption	Tonnes of sandeel harvested to be processed into fishmeal; volume of mackerel caught for use as bait in crab/lobster pots
Fertiliser and biofuels	Fertiliser (biocides) or energy sourced from coastal & marine biota	Biomass of algae harvested to be processed into fertiliser
Ornaments (including	Extraction of coastal & marine biota for	Number of European lobster extracted

aquaria)	decoration, fashion, handicraft, souvenirs etc. or for display in aquaria	for display in aquarium exhibits; amount of skins, shells, corals, plants, extracted from the coastal & marine environment for decoration, fashion etc.
Medicines and blue biotechnology	Extraction of coastal & marine biota in order to produce medicines, pharmaceuticals, animal and plant breeding and biotechnology	Marine-derived pharmaceuticals such as the use of sea lettuce (Ulva lactuca) in cosmetic and personal care items including make-up remover, shampoo and shaving lotion
Healthy climate	Improvements to human well-being as a result of a healthy climate	Bodily harm avoided as a result of natural carbon sequestration by coastal & marine biota
Prevention of coastal erosion	Reduction in hazards resulting from the natural prevention of coastal erosion by coastal & marine biota	Prevention of gradual damage to property and land by dunes
Sea defence	Reduction in flooding related hazards as a result of the natural protection provided by coastal & marine biota	Saltmarsh providing a natural form of sea defence in the coastal region
Waste burial/removal/ neutralisation/immobil isation of pollutants	Contribution of coastal & marine biota to achieving pre-defined policy standard related to waste levels in water by natural waste burial, removal and neutralisation	Natural waste breakdown by coastal & marine biota such as reedbeds – in contexts in which pre-defined regulations/ standards apply
Tourism and nature watching	Benefits from recreation, leisure driven by coastal seascapes and their associated coastal & marine biota including food tourism	Benefits associated with watching seabirds, marine mammals, seafood festivals
Spiritual and cultural wellbeing	Ability to enjoy preferred lifestyle, culture, heritage, folklore, religion, creative inspiration, and spirituality; sense of place (use- driven) based on ecosystem aspects	The importance of coastal & marine environments in cultural traditions (e.g. traditional cobble fisheries on east coast) or folklore (e.g. sea shanties)
Aesthetic benefits	Enjoyment of the beauty of coastal & marine seascapes	Higher house prices in coastal locations
Education, research	Enjoyment of formal and informal education, research and science, knowledge systems, etc. in which coastal & marine biota play a role and are a source of information	Amount of funding secured for research on coastal & marine biota; number of scientific research papers published which focus on coastal & marine biota
Health benefits	Human physical and psychological health benefits associated with the direct and indirect use of the coastal and marine environment	Increased psychological well-being from direct or indirect experience of the coastal & marine environment; increased physical well-being resulting from engagement with coastal & marine environment, e.g. exercise.

Annex 2: Examples of UK seafood festivals

Event	Month	County	Home nation
Annual Scottish Traditional Boat Festival, Portsoy	June	Aberdeenshire	Scotland
Arbroath Sea Fest	August	Angus	Scotland
Balmoral Show, Lisburn	May	County Antrim / County Down	N. Ireland
Beaumaris Food Festival	August	Isle of Anglesey	Wales
Bridlington Sailing Coble Festival	July	Yorkshire	England
Cardigan Bay Seafood Festival	July	Cardigan	Wales
Clovelly Herring Festival	November	Devon	England
Clovelly Lobster & Crab Feast	September	Devon	England
Crabstock	September	Devon	England
Cromer and Sheringham Crab & Lobster Festival	May	Norfolk	England
Dorset Seafood Festival, Weymouth	July	Dorset	England
East Coast Fish Festival, Johnshaven	August	Aberdeenshire	Scotland
Edinburgh Foodies Festival	August	Edinburgh	Scotland
Falmouth Oyster Festival	October	Cornwall	England
Fishstock, Brixham	September	Devon	England
Flavours of the Foyle Seafood Festival, Derry	July	Londonderry	N. Ireland
Food of the Sea Festival, Lochinver	April	Sutherland	Scotland
Gwledd Conway Feast	October	Conway/Gwynedd	Wales
Hastings Seafood and Wine Festival	September	East Sussex	England
Isle of Man Food and Drink Festival	September	Isle of Man	Isle of Man
Kircudbright Food Festival	October	Dumfries and Galloway	Scotland
Loch Fyne Food Fair, Argyll and Bute	May	Argyll & Bute	Scotland
Menai Food Festival	August	Isle of Anglesey	Wales
Newlyn Fish Festival	August	Cornwall	England
Newquay Fish Fest	September	Cornwall	England
Nyetimber Dorset Seafood Festival	July	Dorset	England
North East Oyster Festival, Sedgefield	September	County Durham	England
Paignton Harbour Festival	July	Devon	England
Pembrokeshire Fish Week, Across Pembrokeshire	June-July	Pembrokeshire	Wales
Peterhead Seafood Festival	September	Aberdeenshire	Scotland
Plymouth Seafood Festival	September	Devon	England
Portavogie Seafood Festival	August	County Down	N. Ireland
Portsmouth Seafood Festival	June	Hampshire	England
Rock Oyster Festival, Rock Town Centre	July	Cornwall	England
Rye Bay Scallop Week	March	East Sussex	England
Stranraer Oyster Festival	September	Dumfries and Galloway	Scotland
Tarbert Seafood Festival	July	Argyll & Bute	Scotland
Taste of Grampian Festival	June	Aberdeenshire	Scotland
Taste of Shetland Festival	November	Highlands & Islands	Scotland

The Crail Food Fest	June	Fife	Scotland
Whitby Fish & Ships Festival	May	Yorkshire	England
Whitstable Oyster Festival	July	Kent	England

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