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A global review of the ecosystem services provided by bivalve aquaculture

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Abstract

Bivalve shellfish aquaculture provides many benefits to society, beyond their traditional market value. This study collates the evidence available on the provisioning, regulating and cultural ecosystem services provided by the bivalve species commonly used in aquaculture. For the first time, it synthesises this evidence to provide a global assessment of the potential market and non-market economic value of bivalve aquaculture. Bivalves are filter feeders, filtering water and particulates, creating substrates which provide habitat to act as nursery grounds for other species. Goods from provisioning services include meat, worth an estimated $23.9 billion as well as, pearls, shell and poultry grit, with oyster shell being the most important, with a global potential worth of $5.2 billion. The most important regulating services are nutrient remediation. Cultivated bivalves remove 49,000 tonnes of nitrogen and 6,000 tonnes of phosphorus, worth a potential $1.20 billion. Currently, there is little evidence on the cultural services per year of bivalve aquaculture, but we argue that these cultural values are broad ranging, although difficult to quantify. Our assessment indicates that the global, non-food bivalve aquaculture services are worth $6.47 billion ($2.95 billion–9.99 billion) per annum. However, this is likely to be an underestimate of the true value of bivalve aquaculture as there are significant gaps in evidence of the value for a number of key services. The analysis presented here can be used to indicate the likely scale of payments for ecosystem services provided by bivalve aquaculture, prior to more detailed assessments.

Key words: bivalves, blue carbon sequestration, cultural services, nutrient removal, regulating services, valuation.

Introduction

There has been consistent growth in aquaculture production in recent decades, which in 2016 represented 41% of global fisheries and aquaculture food production (SAPEA 2017). Lower trophic species, including shellfish and algae, currently make up about half of all aquaculture production and offer potential for significant contribution to sustainable growth in the global aquatic food supply (Science Advice for Policy by European Academies 2017). Bivalves (primarily clams, mussels and oysters) accounted for 16 million tonnes of coastal and marine animal aquaculture in 2015, with an estimated market value of $17.1 billion (FAO 2016).

In addition to food supply (provisioning services), there is a growing recognition of the wider ecosystem benefits of bivalve aquaculture in coastal waters, including regulating services such as carbon sequestration, nutrient remediation, coastal defence and indirect benefits arising from shellfish beds and reefs (Shumway *et al.* 2003; Lindahl *et al.* 2005; Rönnbäck *et al.* 2007; Northern Economics 2009; Herbert *et al.* 2012; Seitz *et al.* 2014). However, there remain substantial gaps in the published literature on non-market benefits, and some services remain largely unquantified. For example, the majority of studies focus on only a few regulating services such as carbon sequestration (Filgueira *et al.* 2015) or nutrient remediation (Newell *et al.* 2005). Quantifying cultural services is an acknowledged challenge in many domains (Chan *et al.* 2012) and the cultural services of bivalve aquaculture have not been assessed in any capacity. Meanwhile, the literature on provisioning services is dominated by a focus on constraints to production and the possibilities for expansion (Gentry *et al.* 2017).

Previous reviews of ecosystem services associated with bivalve aquaculture (Newell 2004; Coen *et al.* 2007; Northern Economics 2009; Herbert *et al.* 2012; Rose *et al.* 2014), have focused on oysters (Herbert *et al.* 2012) and mussels (Lindahl *et al.* 2005), with few data published on other major commercially important species, such as clams (Nizzoli *et al.* 2006). There are also strong geographical biases in the literature to date, with many studies from North America and the Baltic, but relatively few from other parts of the globe such as other parts of Europe, South America and Asia. Furthermore, with a few exceptions (e.g. Northern Economics 2009; Beseres Pollack *et al.* 2013), there is a distinct lack of quantification of the services and their economic value.

Coupled with growing interest in the ecosystem services provided by aquaculture, there is an increasing policy focus on this area. For example, in Europe, under the EU's biodiversity strategy member states had an obligation to map and assess the state of ecosystems and their services in their national territory by 2014, assess the economic value of such services, and promote the integration of these values into accounting and reporting systems at EU and national level by 2020 (Bourguignon 2015).

In this paper, we aim to quantify and value of the ecosystem services provided by bivalve aquaculture, focussing on species which are commercially harvested (e.g. mussels and oysters). We follow the Common International Classification of Ecosystem Services (CICES) typology (European Environment Agency 2012), which provides a hierarchical system, building on the Millennium Ecosystem Assessment (MEA) and The Economics of Ecosystem and Biodiversity (TEEB) classifications but tailored to accounting (Bateman *et al.* 2011; Boerema *et al.* 2016), allowing us to look at the economic value where possible. Although, CICES does not classify supporting services, we provide evidence on these supporting services as these underpin the delivery of the final services, to which an economic value can be assigned (Bateman *et al.* 2011).

The structure of the paper is as follows. Firstly, we describe the supporting services provided by bivalve aquaculture. We then synthesise the evidence that quantifies and values the three categories of final ecosystem services (Provisioning, Regulation and Maintenance and Cultural). In each section, we briefly introduce the services, referring to the processes and mechanisms that underpin them. This is followed by a review of quantitative evidence of both the scale of ecosystem services and key underlying mechanisms. Next, we use these data to conduct a global assessment of the potential value of ecosystem services from bivalves. Finally, we discuss challenges raised in this assessment, and provide an overview of knowledge gaps.

Methods

Our analysis is based on keyword searches of literature databases using Google Scholar and Web of Knowledge. Keywords for searches were based on terms often used in bivalve aquaculture, including searches for species names (e.g. mussel, *Mytilus*, oyster, *Crassostrea,* etc.) and services and functions (e.g. provisioning, regulating, cultural, filtration, carbon, nutrient remediation, carbon trading, coastal defence, etc.) on publications between 1918 and 2018. We also searched for grey literature using web searches and databases available on websites of trade bodies, non-governmental and conservation organisations. From the studies identified through literature searches, we selected those where bivalve aquaculture and/or restoration projects had quantified activities, processes or functions which fell within the CICES sections of Provisioning, Regulation and Maintenance and Cultural services.

To allow comparison between studies, we converted units to a standardised format where possible. For pumping rates of bivalves, the units were converted into litre h^{-1}. Bivalve production was converted to tonnes. Nitrogen or phosphorus removal were respectively converted to t N ha^{-1} yr^{-1} or t P ha^{-1} yr^{-1} and the denitrification rates converted to μmol N m^{-2} h^{-1}, or to kg N t^{-1} shellfish. Where it was not possible to convert the units, they were presented as kg N t^{-1} or as % of N load d^{-1}. Rates of carbon sequestration were converted to t C ha^{-1} yr^{-1}.

All economic values are expressed as US dollars (2017 values). Economic values were adjusted to account for inflation to 2017 and then where necessary converted to USD using purchasing power parities (PPPs) (Hamadeh *et al.* 2017).

To carry out a global upscaling of the potential value of the ecosystem services, we used FAO figures of global aquaculture production (http://www.fao.org/fishery/statistics/global-aquaculture-production/query/en). Species tonnages included those for mussels, oysters, clams, cockles, arkshells, scallops and pectens. We then used meat yields (the ratio of meat to whole weight including shell (Marine Scotland Science 2015)) to approximate the wet tissue weight (Table 1). Shell weight was calculated using condition indices to convert from the total production weights, accounting for wet tissue weight to allow for water (liquor) retained by live bivalves. We used the condition indices (CI = wet meat weight/(Live weight − shell weight) × 100) ((WMW/(LW − SW)) × 100) reported in both Okumuş and Stirling (1998) and Muniz *et al.* (1986) to calculate the shell weight for mussels and oysters.

Table 1 Values extracted from peer reviewed sources used to carry out global upscaling calculation and analysis

	Value			Source
Clam Meat yield	18%			Marine Scotland Science (2015)
Mussel Meat yield	22.06%			Çelik *et al.* (2012)
Oyster Meat yield	10.75%			Stroud (1981)
Scallop Meat yield	13%			Hardy & Smith (2001)
Condition index clam ((MDW/SDW) × 1,000)	66.1			Orban *et al.* (2006a, 2006b)
Condition index Mussel ((WMW/(LW-SW)) × 100)	45.9			Okumuş and Stirling (1998)
Condition index Oyster ((WMW/(LW-SW)) × 100)	72.3			Muniz *et al.* (1986)
	C (% of dry weight)	N (% of dry weight)	P (% of dry weight)	
Clam (Shell/Tissue)	11.41/43.70	0.25/10.28	0.04/0.79	
Mussel (Shell/Tissue)	12.68/45.98	0.84/9.08	0.05/0.92	
Oyster (Shell/Tissue)	11.85/44.81	0.16/7.85	0.04/0.91	
Scallop (Shell/Tissue)	11.72/44.86	0.32/9.28	0.04/0.88	
Shell free wet weight to dry weight conversion	8.7			Ricciardi and Bourget (1998)
Value of N removal	$\$8,996\text{–}31,050\ \mathrm{t}^{-1}$			Beseres Pollack *et al.* (2013); Newell *et al.* (2005)
Value of P removal	$\$13,118\text{–}58,561\ \mathrm{t}^{-1}$			Molinos-Senante *et al.* (2011)
Value of shell aggregate	$\$538\text{–}1,783\ \mathrm{t}^{-1}$			Morris *et al.* (2018)

For clams we used the condition index (CI = (Meat dry weight/Shell dry weight) × 1,000) ((MDW/SDW) × 1,000) reported in Orban *et al.* (2006) to calculate shell weight. Scallops gape when harvested and therefore the landed weight does not include liquor, so it was possible to simply remove the meat weight from total weight to find the weight of shell. Where necessary, wet tissue weight was converted to dry weight using Ricciardi and Bourget (1998) conversion factors.

The C, N and P composition percentages of meat and shell were calculated using values from the literature for each species (Stroud 1981; Hardy & Smith 2001; Çelik *et al.* 2012; Marine Scotland Science 2015). Where data for a species were not available an average of all bivalve species was applied. Carbon content was calculated for shell only, as carbon in meat was considered as non-sequestered. To estimate economic values for nutrient removal, we applied the alternative cost of nitrogen removal ($\$8,996\text{-}31,050\ \mathrm{t}^{-1}$ (Beseres Pollack *et al.* 2013; Newell *et al.* 2005)) and the shadow price (the estimated price of a good or service for which no market price exists) for phosphorus removal ($\$13,118\text{-}58,561\ \mathrm{t}^{-1}$ (Molinos-Senante *et al.* 2011)). Due to a lack of consensus on whether calcification represents a source or a sink of CO_2, the potential value of carbon sequestration was not used in the final valuation. To calculate the potential value of oyster shell, we used the values found for shell aggregate (Morris *et al.* 2018) and applied this to the tonnage of waste oyster shell (Table 1).

Supporting services

Supporting services underpin the delivery of all other ecosystem services, Supporting services provided by shellfish include: the cycling of nutrients through filter feeding and the creation of sediment (Cranford *et al.* 2007); increasing seabed roughness; and providing habitats for other organisms (Seitz *et al.* 2014; Turner & Schaafsma 2015).

Increasing seabed roughness

Shellfish beds impact upon water flows at different scales: (1) at a micro scale (mm to cm) via biomixing created by the jet of water from the exhalant siphons and by increasing bed roughness via the mussel shell shape; and (2) at a macro scale (tens of metres), via the topographic variation of the mussel bed, e.g. alternation between mussel patches and bare patches of sediment (Butman *et al.* 1994; Saurel *et al.* 2013; Folmer *et al.* 2014). This mixing of water underpins several supporting or intermediate services including nutrient cycling, alteration of turbidity, and the accretion of sediments and moderating wave energy.

Providing habitat for other organisms

Both mussels and oysters can naturally form reefs, which perform a wide range of ecological functions. They provide refuge between the shells (Snover & Commito 1998) and a hard substrate for other species of invertebrates and algae to settle (Brumbaugh *et al.* 2006). Studies have shown that species diversity can be greater on Pacific oyster reefs than within the habitat on which the oysters settle (Herbert *et al.* 2012) and act to facilitate biodiversity and re-establish benthic communities on shores where *Ostrea edulis* has become extinct (Zwerschke *et al.* 2018). The artificial structures used in bivalve aquaculture also provide a habitat for organisms to adhere to, with racks, cages, nets, ropes and the shells themselves all providing a suitable substrate for colonisation (Shumway *et al.* 2003). This can lead to richer ecological communities, supporting numerous trophic levels not only at the reefs themselves, but in the surrounding area (Ragnarsson & Raffaelli 1999; Brumbaugh *et al.* 2006; Koivisto & Westerbom 2010). In the northern Baltic Sea, mussel beds support a range of suspension feeders such as barnacles, polychaetes and ascidians. The mussels themselves are often encrusted in barnacles. The mussels are predated on by crabs and starfish and several species of wading birds (Mainwaring *et al.* 2014). Intertidal mussel beds support a high taxonomic diversity and abundance of benthic organisms and are important foraging grounds for many avian species (Waser *et al.* 2016). The reef itself forms accumulations of 'mussel mud', composed of faeces, pseudofaeces and sediment, which also supports a diverse range of infauna (Mainwaring *et al.* 2014). In the northern Baltic, mussel mud increased the abundance of soft-bottom species such as polychaetes and nemerteans (Bick & Zettler 1994; Koivisto & Westerbom 2010).

Indirect economic benefits to other services/habitats

Structured habitats provided by bivalves can lead to measurable increases in production of finfish and invertebrates that are important for commercial and recreational fisheries (Coen *et al.* 2007), with an economic benefit (Northern Economics 2009). Peterson *et al.* (2003) used both demographical and growth models to estimate that in the southeast United States, oyster reef restoration yielded an additional 2,600 kg ha^{-1} yr^{-1} of fish and large mobile crustacean produce. Grabowski and Peterson (2007) then showed that the long-term commercial value of the fish and crab species in the same area was greater than the value of oyster production and using commercial landing values of each species demonstrated that the added value from oyster reefs equated to \$3,811 ha^{-1} yr^{-1}. The increase in fish numbers also benefits recreational fishers; Isaacs *et al.* (2004) estimated the value of recreational fishing over oyster reefs in Louisiana using contingent valuation and found the average net willingness to pay among resident saltwater recreational fishers was \$13.61, giving a median value of \$3 million for sports fishing provided by oyster beds in Louisiana.

Provisioning services

Provisioning services include all material and energy outputs from an ecosystem that may be exchanged or traded, as well as consumed or used directly in manufacturing (European Environment Agency 2012). Within bivalve aquaculture provisioning services are split between two divisions: the provision of nutrition (food), and provision of materials such as fertiliser, construction, grit for poultry and in jewellery (Table 2).

Food production (nutrition, biomass, reared animals)

The value of bivalve aquaculture has most frequently been calculated as the market value of the meat that is produced. The value fluctuates as aquaculture production increase and decrease, and as market demands change. The total aquaculture production of bivalves for human consumption in 2015, was 14.65 million tonnes (Table 3), with an estimated market value of \$23.92 billion (http://www.fao.org/fishery/statistics/global-aquaculture-production/query/en). (FAO 2016) Asia is the largest regional global producer, dominated by China, with 12.4 million tonnes of bivalves produced in 2015. On a much smaller scale of

Table 2 Provisioning services of shellfish aquaculture using the CICES system for classification

Division	Group	Class	Examples and indicative benefits
Nutrition	Biomass	Reared animals and their outputs	Food production e.g., shellfish meat produced through aquaculture production
Materials	Biomass	Materials from plants, algae and animals for agricultural use	Crushed shells used in the poultry industry
			Using the ground flesh or associated nutrient rich mud's as sources of fertiliser. Crushed shell as a source of lime
		Fibres and other materials from plants, algae and animals for direct use or processing	Shells used as construction materials (aggregate and lime)
			Pearls/mother of pearl

Table 3 Annual aquaculture production by continent, showing top three countries and dominant aquaculture species in 2015. Values adjusted for inflation to 2017. FAO [online] [Accessed 26 June 2017]

Region	Country	Predominant species farmed	National total for all Species (Tonnes)	Value ($ 000)
Africa		**Mussels, Oysters**	**8,703**	**8,703**
	South Africa	*Mytilus galloprovincialis*	3,987	3,987
	Namibia	*Crassostrea gigas*	1,850	1,850
	Senegal	*Crassostrea gigas*	1,798	1,851
Americas		**Mussels, Oysters, Clams, Cockles, Arkshells, Scallops, Pectens**	**463,419**	**2,300,788**
	Chile	*Mytilus chilensis*	214,531	1,783,157
	United States of America	*Crassostrea virginica*	159,175	257,083
	Canada	*Mytilus edulis*	36,311	69,852
Asia		**Mussels, Oysters, Clams, Cockles, Arkshells, Scallops, Pectens**	**13,479,192**	**19,983,869**
	China	*Crassostrea spp*	12,389,502	18,459,094
	Japan	*Patinopecten yessoensis*	413,028	825,029
	Taiwan	*Crassostrea gigas*	323,926	309,876
Europe		**Mussels, Oysters, Clams, Cockles, Arkshells, Scallops, Pectens**	**608,957**	**1,106,374**
	Spain	*Mytilus galloprovincialis*	227,805	144,860
	France	*Crassostrea gigas*	124,481	513,317
	Italy	*Mytilus galloprovincialis*	100,345	173,728
Oceania		**Mussels, Oysters, Clams, Cockles, Arkshells, Scallops, Pectens**	**95,054**	**605,693**
	New Zealand	*Perna canaliculus*	78,720	507,576
	Australia	*Crassostrea gigas*	16,320	77,601
	Cook Islands	*Tridacna* spp	5	16
World			**14,649,532**	**23,919,193**

production, Europe is the next largest producer, with only 0.6 million tonnes and then the Americas with 0.46 million tonnes.

Usage of shell (materials, biomass, agricultural uses)

While the tissue is consumed and respired, the shell is usually discarded and these shells act as a long-term carbon store (Mangerud & Gulliksen 1975). Currently waste disposal of shell costs up to \$290 t^{-1} in Australia (Yan & Chen 2015), however, using shell as a product could provide income instead of a cost. Annually 4.5 million tonnes of oyster shell is produced which has multiple potential uses. One potential trade-off is that destructive uses of shell such as for poultry grit or agricultural lime will prevent their use as a carbon store, so not all of the non-food services are compatible. For this reason, in our analysis of potential uses of shell, we only valued the use of shell as aggregate and not as poultry grit.

Poultry grit (materials, biomass, agricultural uses)

Global poultry production is estimated to be approximately 21 billion birds per year, producing 1.1 trillion eggs and approximately 90 million tonnes of meat annually (Blake & Tomley 2014). Bivalve shells are used in some poultry grit (ground-up shell is mixed with ground granite and fed to poultry to help digestion and to provide calcium for egg shells). The main species used are oyster and cockle shells because their shells do not break down into sharp shards: unlike mussel and scallop shells. Little information is available on the contribution of shell to poultry grit. Values for oyster shell sold as poultry grit range between \$320 and \$2,400 per tonne (Morris *et al.* 2018).

Fertiliser and lime (materials, biomass, agricultural uses)

Agricultural crops require macro-nutrients such as nitrogen, phosphorus and potassium, of which nitrogen is the most important, as it has the largest effect on crop yield and quality (Campbell 1996). Other important nutrients include magnesium (Bot & Benites 2005) and, due to improvements in air quality, in some regions it has become necessary to add sulphur-containing fertilisers to replace sulphur previously provided by air pollution (ADAS UK Ltd 2006; Jones *et al.* 2014).

Shellfish waste is nutrient rich, containing many of the macro- and micro-nutrients required for agriculture. ADAS (2006) compared nutrient contents of shellfish waste with other organic manures which have been used in agriculture (Appendix I). The ratio of nitrogen, phosphate and potash in the shellfish-based compost is approximately 2:1:1, which closely matches the nutrient requirement of many crops.

Agricultural improvement of acid soils involves application of lime or other calcareous materials (Yao *et al.* 2014). Crushed oyster shell can be used as a soil conditioner, stimulating the growth of soil and rhizospheric microorganisms. Addition of 0.3 t ha^{-1} doubled the number of bacteria, actinomyces and nitrogen-fixing bacteria (Guoliang *et al.* 2003). In Korea, oyster-shell meal, was tested as a soil liming material (Lee *et al.* 2008) and significantly increased soil pH and soil nutrients such as soil organic matter, available phosphorus and exchangeable cations in silt loam and sandy loam soils, when applied at rates of up to 16 t ha^{-1} although this is currently not a common practice.

Shucked shells used as construction materials (materials, biomass, construction uses)

Oyster shell is used as a construction material in sea defences in North America. This is because the shells become tightly packed and are more lightweight than traditional shoreline protection materials (Piazza *et al.* 2005; Borsje *et al.* 2011). Oyster shells have been used throughout history for construction of buildings, most commonly in their burnt form as lime, also known as quicklime (calcium oxide) (Sheehan & Sickels-Taves 2002). More recently, there has been growing research into the use of crushed shells in place of sand, aggregate and cement (Ohimain *et al.* 2009; Kumar *et al.* 2016). Environmentally friendly methods of aggregate extraction and material selection are in demand, because over-extraction of natural aggregate can lead to the destruction of ecosystems associated with marine sediments (Yoon *et al.* 2004). Kumar *et al.* (2016) found that replacing 10% of standard aggregate in concrete with shell and lime created a product with the same strength, however, at 20–30% replacement this led to gradually decreasing strength. Two billion tons of aggregate are produced each year in the United States and production is expected to increase to more than 2.5 billion tons per by the year 2020 (Kumar *et al.* 2016). In terms of economic value, shell aggregate can cost between $240 and $2,400 t^{-1} (Morris *et al.* 2018) therefore providing a potential use for waste products of the aquaculture industry.

Pearls and mother of pearl (materials, biomass, fibres and other materials from animals)

Pearls have long been valued for their lustre, and made into earrings, necklaces, pendants, bracelets, rings and other jewellery. Pearl production in 2009, yielded around 40 tons of pearls (Cariño & Monteforte 2009). Another product derived from bivalves is mother of pearl or nacre, this is a naturally occurring layer that lines some mollusc shells. Throughout history has been used to make pearl buttons and jewellery. It was also commonly inlaid into boxes and other furniture, particularly in China (Southgate & Lucas 2008). We could find no figures on the quantity traded or its value. The pearl industry has declined in recent years, with production in 2009 being half of what it was in 1993. From an estimated $912 million in 1993, the wholesale value of pearls dropped to approximately $570 million in 1999; and for 2009, the value was estimated to be approximately $422 million, although we could not find current valuations for the industry. This decrease has been attributed to competition between producers, increasing cost of production and to a lesser degree marine pollution affecting the health of the oyster populations used (Müller 2013).

Regulating services

Regulating services are the ways in which ecosystems control or modify biotic or abiotic parameters that define the environment of people. These are ecosystem outputs that are not consumed but affect the performance of individuals, communities and populations as well as their activities (European Environment Agency 2012). A wide variety of specific regulating services are performed by bivalve beds, which include biochemical accumulation, biological accumulation, carbon sequestration, nutrient removal and coastal defence (Table 4).

Cycling of nutrients, creation of sediment, biochemical accumulation of nitrogen and phosphorus and deposition into sediments (regulation of biophysical environment, mediation of waste, biochemical accumulation)

Bivalves are filter-feeding organisms, and are able to modify biogeochemical cycles by filtering large quantities of organic matter from the water column (Kellog *et al.* 2013). Phytoplankton use dissolved inorganic nitrogen for their growth, and when they are filtered from the water column by bivalves, along with other organic matter, the nutrients they contain are partly incorporated within the bivalves and partly deposited onto the surface of the sediment as faeces or psuedofaeces. Nitrogen in these biodeposits can also be transformed into unreactive nitrogen gas through denitrification and diffuse out of the sediment and back to the atmosphere (Newell *et al.* 2005; Kellog *et al.* 2013). Individual bivalves can filter large volumes of water ((Dame 2011; Jørgensen *et al.* 1990; Saurel *et al.* 2013) Appendix II). The greatest pumping rates are carried out by oyster species (26 to 34 l h^{-1}), with other species ranging from 0.12 to 2.07 l h^{-1}. This filtration removes large quantities of chlorophyll, ranging between 28 and 92% (Appendix III). Grabowski *et al.* (2012), Koivisto and

Table 4 Regulating services of shellfish aquaculture using the CICES system for classification

Division	Group	Class	Examples and indicative benefits
Regulation of biophysical environment	Mediation of waste, toxics and other nuisances	Bioremediation by microorganisms, algae, plants and animals	Cycling of nutrients, creation of sediment, biochemical accumulation of nitrogen and phosphorus and deposition into sediments Biological accumulation e.g. *E. coli* into shellfish, pathogen deposition into sediments
		Filtration/sequestration/storage/accumulation by microorganisms, algae, plants and animals	Carbon sequestration in the form of calcium carbonate in shells, removing CO_2 from the system, Carbon deposition
Mediation of flows	Liquid flows	Hydrological cycle and water flow maintenance	Increased seabed roughness, introducing turbulence and reducing erosive potential of laminar flow of water; increased food transport
	Mass flows	Mass stabilisation and control of erosion rates	Reduced rates of shoreline and bed erosion Regulation of transport and storage of sediment

Westerbom (2010) and Saurel *et al.* (2014) are good examples where chlorophyll α filtration rates in models can calculate the nitrogen removal through consumption of phytoplankton and detritus. This makes it possible to calculate the quantity of biological material and therefore nutrients being transferred from the water column, into the benthos.

Eutrophication of the aquatic environment has become an issue around the world (Kellogg *et al.* 2014). It is caused by excess nutrients (primarily nitrogen and phosphorus) leading to hypoxia, fish kills, loss of habitats such as submerged aquatic vegetation, and/or toxic blooms of algae (Bricker *et al.*, 1999, 2008; Rose *et al.* 2014). Nitrogen is considered the primary limiting factor in phytoplankton growth in the coastal environment and therefore has been the main focus in eutrophication management (Ryther & Dunstan 1971; Ryther *et al.* 1972; Rose *et al.* 2014). The restoration of bivalve beds in Chesapeake Bay was recommended to mitigate environmental changes associated with eutrophication (Newell 1988; Rose *et al.* 2014), using bivalves as 'ecosystem engineers' (Waldbusser *et al.* 2013). Nitrogen and phosphorus are taken up and used for both shell and tissue growth, and this is removed from the marine ecosystem when the animals are harvested (Cerco & Noel 2007; Carmichael *et al.* 2012). Table 5 summarises quantities of nitrogen and phosphorus in tissue and shell of a number of species, while Table 6 summarises shell size. Together these can be used to estimate rates of removal of nutrients from the marine environment by harvesting bivalves. On average, the dry weight of bivalve tissue contains 44.9% carbon, 9.3% nitrogen and 0.9% phosphorus, while shell contains 11.7% carbon, 0.3% nitrogen and 0.04% phosphorus (Table 6). Bivalves harvested in different seasons may have different contents of nitrogen and phosphorus, and the magnitude of these seasonal effects are unknown (Rose *et al.* 2014).

Bivalves also immobilise or remove these nutrients through the production of biodeposits. These biodeposits increase the denitrification potential by providing anoxic environments for denitrifying bacteria (Newell *et al.* 2005). Denitrification transforms biologically available N and releases it to the atmosphere as either N_2 or N_2O which has been identified as an important removal mechanism for nitrogen in coastal waters (Piehler & Smyth 2011). This process makes it possible to limit the nutrient availability for algae and prevents aspects of eutrophication in the nearshore environment (Petersen *et al.* 2014).

There is a growing trend to use bivalves within integrated multi-trophic aquaculture (IMTA). Fed aquaculture systems leak considerable amounts of nutrients to the surroundings, which could lead to eutrophication and deterioration of the environment. Large-scale intensive mariculture such as those in China, lead to undesirable biological and biochemical characteristics in coastal waters, which may have consequences on natural ecosystems (Liu & Su 2017). Recently, the idea of using seaweeds and mussels as extractive species to clean the effluents from fish farms has grown considerably (Chopin 2012). Bivalves are also themselves used to provide nutrients to assist in the culture of seaweeds within the IMTA systems (Fang *et al.* 2016). Using chemical or biological methods of nutrient removal from wastewater and in estuaries has proven to be expensive. As the concentration of nitrogen in wastewater becomes lower, the cost of removing it mechanically increases. It costs $6.20 kg^{-1} to reduce nitrogen to 8 mg l^{-1}, but $19.13 kg^{-1} to reduce nitrogen to 3 mg l^{-1} (Evans 2008; Rose *et al.* 2014). Beseres Pollack *et al.* (2013) estimated that to remove 1 tonne of nitrogen would cost $8,996, while Newell *et al.* (2005) previously estimated it could cost as much as $31,050. Nutrient removal by bivalve harvest is being used as a nature-based solution alternative to upgrading sewage works in Denmark (Petersen *et al.*

Table 5 Comparison of bivalve bioremediation-related studies for different rates of nutrient removal from the water column

Nutrient Removal	Location	Density (m^{-2})	Summary of findings	Source
Crassostrea gigas	Various	-	Net N removal 0.02–0.14 t N ha^{-1} yr^{-1} (Modelled)	Rose *et al.* (2015)
Crassostrea gigas	Valdivia estuary, Chile	100	Net N reduction via filtration of between 0.7–1.2 t N ha^{-1} yr^{-1} (Modelled)	Silva *et al.* (2011)
Crassostrea gigas	Hiroshima Bay, Japan	Raft culture	Removed ~10% of N load.day^{-1}	Songsangjinda *et al.* (2000)
Crassostrea virginica	Potomac River, USA	-	Net N removal 0.09 t N ha^{-1} yr^{-1} (Modelled)	Rose *et al.* 2015;
Crassostrea virginica	Mission-Aransas estuary, Texas, USA	408	Net 0.01 t N ha^{-1} yr^{-1} removed by harvest	Beseres Pollack *et al.* (2013)
Crassostrea virginica	Cape Cod, Massachusetts	400	<1%–15% of the total annual nitrogen load, to 25% of all daily nitrogen loads	Carmichael *et al.* (2012)
Crassostrea virginica	Chesapeake Bay, USA	286	Net N removal by harvest 0.17–0.33 t N ha^{-1} yr^{-1} and 0.023–0.047 t P ha^{-1} yr^{-1}	Higgins *et al.* (2011)
Crassostrea virginica	Chesapeake Bay, USA	–	Reduced total N concentration 10%- 15% (Modelled)	Cerco and Noel (2007)
Mytilus edulis	Carlingford Lough, Ireland	–	Net N removal 0.12 t N ha^{-1} yr^{-1} (Modelled)	Rose *et al.* (2015)
Mytilus edulis	Pertuis Breton, France	–	Net N removal 0.11 t N ha^{-1} yr^{-1} (Modelled)	Rose *et al.* (2015)
Mytilus edulis	Skagerrak Strait, Sweden	Long lines	Net N removal by harvest, burial, biogeochemical processes 1.45–1.5 t N ha^{-1} yr^{-1} (Lab based study)	Carlsson *et al.* (2012)
Mytilus edulis	Orust-Tjorn system, Sweden	100 kg, Long lines	Removed 10 kg N t^{-1} of mussel	Haamer (1996)
Mytilus galloprovincialis	Piran, Slovenia	–	Net N removal 0.06 t N ha^{-1} yr^{-1} (Modelled)	Rose *et al.* (2015)
Mytilus galloprovincialis	Chioggia, Italy	–	Net N removal 0.02 t N ha^{-1} yr^{-1} (Modelled)	Rose *et al.* (2015)
Alectryonella plicatula	Huangdun Bay, China	–	Net N removal 0.11 t N ha^{-1} yr^{-1} (Modelled)	Rose *et al.* (2015)
Pinctada imbricata	Port Stephens, Australia	–	Removed 7.5 kg N t^{-1} oyster;	Gifford *et al.* (2005)
Pinctada imbricata	Port Stephens, Australia	–	Removal of 19 kg N t^{-1} oysters	Gifford *et al.* (2004)
Ruditapes philippinarum	Samish Bay, USA	–	Net N removal 0.25 t N ha^{-1} yr^{-1} (Modelled)	Rose *et al.* (2015)
Venerupis decussata	Ria Formosa, Portugal	–	Net N removal 0.06 t N ha^{-1} yr^{-1} (Modelled)	Rose *et al.* (2015)
Denitrification				
Crassostrea virginica	Bogue Sound, USA	–	Denitrification removal 0.02 t N ha^{-1} yr^{-1}	Piehler and Smyth (2011)
Crassostrea virginica	Chesapeake Bay, USA	–	Denitrification removes 5 × 10^{-4} kg N g^{-1} oyster (Modelled)	Newell *et al.* (2005)
Mytilus galloprovincialis	Goro lagoon, Italy	60 kg	Denitrification removal 0.07–0.11 t N ha^{-1} yr^{-1} (Lab based study)	Nizzoli *et al.* (2006)
Perna canaliculus	Kenepuru Sound, New Zealand	Long lines	Denitrification removal 0.03–0.22 t N ha^{-1} yr^{-1}	Kaspar *et al.* (1985)

2014). In order to reduce the nutrient loads in Limfjorden by at least 5,700 tons of nitrogen per year, it was calculated that 9,500 ha of rope mussel aquaculture would be required, which would produce one million tonnes of mussel, although currently the 18.8 ha site is only producing 2,000 tonnes. (Petersen *et al.* 2014). The running costs of this method of nutrient removal were estimated to be between \$128,300–183,300 USD t^{-1} N removed. This estimate does not include the potential income of selling the mussels, which are removed at a small size, and sold for chicken feed.

Phosphate rock is the only economic source of phosphorus for the production of phosphate fertilizers and phosphate chemicals. Currently, the reserves of phosphate rock are estimated at 40 billion tons and are found in the United States, China, Kazakhstan, Morocco, Finland, South Africa and some Pacific Islands, but these reserves are estimated to run out in 60–130 years (van Ginneken *et al.* 2016). Phosphorus recovery from wastewater, therefore, has grown in importance as it is a non-renewable resource and as well as that its discharge into the environment can cause serious negative impacts (Molinos-Senante *et al.* 2011). Each human excretes

Table 6 Chemical composition (carbon (C), nitrogen (N), phosphate (P)) (% dry weight) of shellfish, organised by species and average, minimum and maximum values. A dash indicates no value presented

Species	Tissue			Shell			Reference
	C	N	P	C	N	P	
Oysters							
Crassostrea gigas	–	8.4	–	–	–	–	Ren *et al.* (2003)
Crassostrea gigas	44.90	8.19	–	11.52	0.12	–	Zhou *et al.* (2002)
Crassostrea gigas	–	7.4	–	–	–	–	Linehan *et al.* (1999)
Crassostrea virginica	44.72	7.72	0.83	12.17	0.2	0.04	Higgins *et al.* (2011)
Crassostrea virginica	–	7.54	0.99	–	–	–	Sidwell *et al.* (1973)
Oyster mean (±1 SE)	**44.81 ± 0.09**	**7.85 ± 0.19**	**0.91 ± 0.08**	**11.85 ± 0.33**	**0.16 ± 0.04**	**0.04**	
Mussels							
Mytilus edulis	45.98	11.40	0.708	12.68	0.55	–	Zhou *et al.* (2002)
Mytilus edulis	–	10.6	0.80	–	1.13	0.05	Haamer (1996)
Mytilus edulis	–	8.1	1.24	–	–	–	Cantoni *et al.* (1977)
Mytilus galloprovincialis	–	6.2	–	–	–	–	Miletic *et al.* (1991)
Mussel mean (±1 SE)	**45.98**	**9.08 ± 1.19**	**0.92 ± 0.16**	**12.68**	**0.84 ± 0.29**	**0.05**	
Other spp.							
Arctica islandica	–	–	–	–	0.05	0.003	Westermark *et al.* (1996)
Chlamys farreri	43.87	12.36	0.839	11.44	0.05	0.09	Zhou *et al.* (2002)
Corbicula japonica	–	9.81	–	–	0.22	–	Nakamura *et al.* (1988)
Mactra chinensis	42.21	10.57	–	11.52	0.19	–	Zhou *et al.* (2002)
Mactra veneriformis	–	9.67	–	–	0.09	–	Hiwatari *et al.* (2002)
Macoma baltica	–	–	–	–	0.1	0.03	Seire *et al.* (1996)
Arcuatula senhousia	–	–	–	–	0.82	0.05	Yamamuro *et al.* (2000)
Pinctada imbricata	–	9.82	0.74	–	0.39	0.03	Gifford *et al.* (2005)
Pinctada imbricata	–	10.5	–	–	–	–	Seki (1972)
Ruditapes philippinarum	42.84	10.76	–	11.40	0.56	–	Zhou *et al.* (2002)
Anadara kagoshimensis	45.86	8.71	–	11.29	0.07	–	Zhou *et al.* (2002)
Other spp. Mean (±1 SE)	**44.35 ± 0.80**	**9.95 ± 0.38**	**0.74 ± 0.05**	**11.35 ± 0.05**	**0.46 ± 0.08**	**0.04 ± 0.01**	
Overall mean (±1 SE)	**44.86 ± 0.54**	**9.28 ± 0.40**	**0.88 ± 0.07**	**11.72 ± 0.19**	**0.32 ± 0.09**	**0.04 ± 0.01**	

around 1.5 grams of phosphorus per day into sewage, so with the current population of 7.5 billion an annual excretion of 3.3 billion-kilogram phosphate, which will increase to 5.5 billion-kilogram by 2050. Molinos-Senante *et al.* (2011) found that there was a little economic incentive for the implementation of phosphorus recovery technologies because the selling price of rock phosphate is lower than phosphorus recovered from sewage. They calculated the shadow price of phosphorus, estimating it to be worth between \$13,118–58,561 t^{-1} using a directional distance function to measure the environmental benefits obtained by preventing the discharge of phosphorus into the environment. Despite the current lack of economic incentive, van Ginneken *et al.* (2016) clearly demonstrate that phosphorus recovery from the marine environment will increase in importance, and could be one of the most financially profitable aspects of bivalve aquaculture.

Biological accumulation of pathogens (regulation of biophysical environment, mediation of waste, biological accumulation)

Bivalves are filter feeders, and in areas of lower water quality can bioaccumulate bacteria, protozoa and viruses that are harmful to human health (Roslev *et al.* 2009; Clements *et al.* 2013). Oysters, mussels, clams and cockles are able to concentrate environmental elements and sewage related microbes within their tissues, (Alexander 1976; Daskin *et al.* 2008; Fukumori *et al.* 2008; Kovacs *et al.* 2010; Hassard *et al.* 2017). This causes potential trade-offs with human consumption. However, due to the ability of bivalves to accumulate pathogens (Roslev *et al.* 2009; Clements *et al.* 2013; Aquatic Water Services Ltd 2014), bivalves could possibly be used as sacrificial beds to regulate and safeguard shellfish/finfish production locations, coastal waters and bathing beaches by accumulating pathogens before they reach them.

Carbon sequestration (regulation of biophysical environment, mediation of waste, sequestration)

Bivalve aquaculture is gaining widespread attention because of its role in the carbon cycle (Hickey 2009; Tang *et al.* 2011; Waldbusser *et al.* 2013; Filgueira *et al.* 2015), due to the growing drive to mitigate climate change. Bivalves sequester carbon in the form of calcium carbonate via shell production (Peterson & Lipcius 2003; Hickey 2009). The average carbon in shell is 11.7% produced in the form of calcium carbonate although this varies between species (Table 6). During the calcification process carbon dioxide is formed $(\mathrm{Ca}^{2+} + 2\mathrm{HCO}_3^- \ (\mathrm{aq}) \rightleftharpoons \mathrm{CaCO}_3 + \mathrm{H}_2\mathrm{O} + \mathrm{CO}_2)$, so potentially leading to an increase in $p\mathrm{CO}_2$ in surface waters and evasion of CO_2 to the atmosphere – especially in the shallow well-mixed coastal waters where shellfish are typically farmed. Therefore, the calcification process is considered by some to be a source of atmospheric CO_2 (Fodrie *et al.* 2017). Other authors argue that the C stored in shell represents a long-term sink. Hickey (2009) calculated the amount of carbon sequestered per year in oyster farms, using shell carbon content, spat weight, grow-out time and stocking density to be between 3.81 and 17.94 t C $\mathrm{ha}^{-1}\ \mathrm{yr}^{-1}$. Higgins *et al.* (2011) created a model based on the results of CHN elemental analysis of tissue and shell, which estimated an oyster bed could remove a total of 13.47 ± 1.00 t C $\mathrm{ha}^{-1}\ \mathrm{yr}^{-1}$ in a single growing season at a density of 286 oysters m^{-2}. These studies suggest a higher rate of carbon sequestration than other forms of blue carbon sequestration (Table 7). However, the long-term net effect on carbon storage is still unclear, and further work is required to look at the true potential of shellfish as a store of CO_2.

Table 7 Carbon accumulation rates in different marine habitats. ND – no data. Value ± SE Adapted from (Ouyang & Lee 2014)

Ecosystem type	Rate of carbon sequestration (t C $\mathrm{ha}^{-1}\ \mathrm{yr}^{-1}$)	Number of studies/sites	References
Salt Marshes	2.42 ± 0.26	50/143	Ouyang & Lee (2014)
Mangroves	2.26 ± 0.39	13/34	Ouyang & Lee (2014)
Seagrasses	1.38 ± 0.38	ND/123	Ouyang & Lee (2014)
Oyster Beds	13.47 ± 1.00	1/1	Higgins *et al.* (2011)

Reduced rates of shoreline and bed erosion (Mediation of flows, liquid and mass flows, hydrological cycle and water flow maintenance/Mass stabilisation and control of erosion rates)

Bivalve reefs and beds are able to protect the ecological integrity of other important habitats, such as seagrass beds and marshlands by providing protective structures (Turner *et al.* 1999; Scyphers *et al.* 2011). Many waterways suffer from the introduction of heavy shore defences due to the concentrated load upon soft sediments: the results of which can require additional efforts and funds in order to help maintain the breakwater structures (Piazza *et al.* 2005). Oyster reefs, however, act as biological barriers to reduce erosion, and do not require additional upkeep once established (Scyphers *et al.* 2011; La Peyre *et al.* 2015). Using data from multiple projects over an extended timeframe, La Peyre *et al.* (2015) found that oyster reefs reduced marsh retreat by an average of 1 m yr^{-1} along moderately exposed and highly exposed shores. Location of the oyster reef barriers was crucial for ensuring their effectiveness, the oyster reefs requiring circulation currents suitable for larval recruitment and adequate water quality (Coen & Luckenbach 2000). While marshland retreat was not stopped, the rate of erosion was reduced (La Peyre *et al.* 2015).

Cultural services

Cultural ecosystem services are created by the interactions between humans and the natural world that enable the creation of cultural goods and benefits people obtain from an ecosystem. This interaction changes with time and can be modified through social and cultural influences, and human perceptions that involve memories, emotions and the senses (Church *et al.* 2014; Jones *et al.* 2016). Cultural services offered by bivalve beds include recreational fisheries, historical artisanal fisheries for the public, education and tourism, seafood festivals and symbolic and spiritual benefits (Table 8).

In-situ wildlife watching (physical and intellectual interactions, physical, experiential use of animals)

Birdwatching, or birding, is a form of wildlife observation in which the observation of birds is a recreational activity (Cocker 2002). The number of people participating in this activity, and the contribution of bivalves to that

Table 8 Cultural services of shellfish aquaculture using the CICES system for classification

Division	Group	Class	Examples and indicative benefits
Physical and intellectual interaction with biota, ecosystems and land - / seascapes	Physical	Experiential use of animals and landscapes in different environmental settings	*In situ* wildlife watching (incl. aquatic biodiversity) e.g. birds feeding
	Intellectual and representative interactions	Scientific, educational, entertainment,	Subject matter for research and education both on location and via other media.
		Heritage, cultural, aesthetic	Historic records, cultural heritage; sense of place, artistic representations of nature. Seafood Festivals
Spiritual, symbolic and other interactions with biota, ecosystems, and land-/seascapes (environmental settings)	Spiritual and/or emblematic	Symbolic	Emblematic animals
	Other cultural outputs	Existence	Enjoyment provided by wild species, wilderness, ecosystems
		Bequest	Willingness to preserve plants, animals, ecosystems for the experience and use of future generations; moral/ ethical perspective or belief

activity via their influence on bird numbers are difficult to quantify and therefore value.

Education and research (physical and intellectual interactions, scientific, educational)

Some species of bivalves are frequently used for scientific experiments as they are hardy, fast growing, abundant and in the case of *Mytilus edulis* can reach sexual maturity in their first year (Ackefors & Haamer 1987). A literature search on Google Scholar and Web of Knowledge for articles between 1918 and 2018 returns 511,000 results for shellfish, 254,000 for mussels, 210,000 for oysters and 196,000 for bivalves clearly showing the scale of research involving shellfish.

Heritage (intellectual and representative interactions)

Bivalves have an archaeological and historical value, with empty shells found in midden piles which have been dated to between 8,000 and 7,000 years (Rollins *et al.* 1987; Roosevelt *et al.* 1991). Among the indigenous peoples of the Americas who lived on the eastern coast, they commonly used pieces of shell as wampum (small cylindrical beads strung together). The shells were cut, rolled, polished and drilled before being strung together and used for personal, social and ceremonial purposes as well as currency (Dubin 1999). The Winnebago tribe from Wisconsin had numerous uses for mussels, using them as utensils and tools. They notched them to create knives and graters and carved them into fish hooks and lures as well as powdering shell into

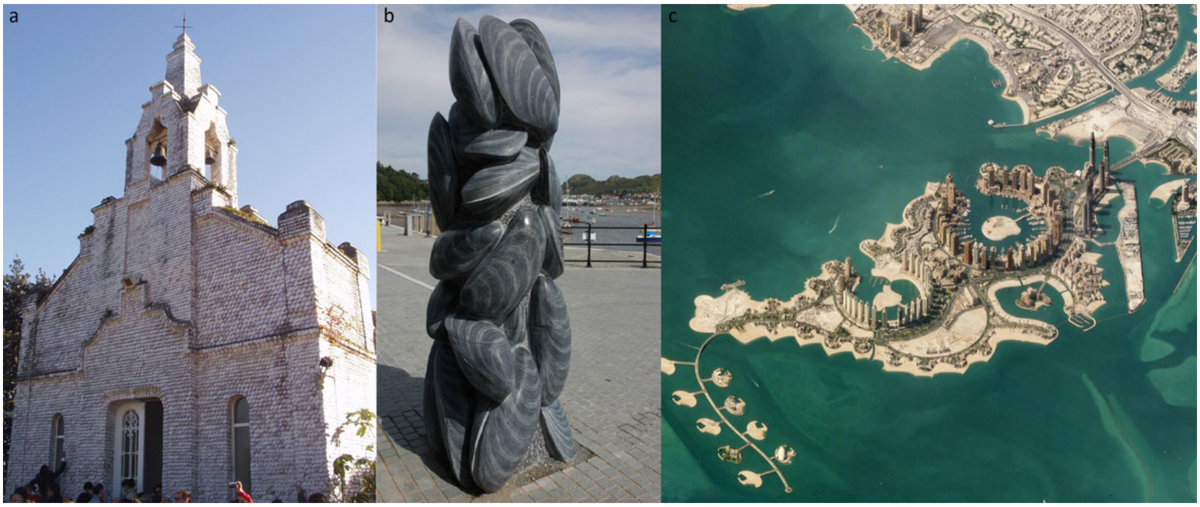

Figure 1 Examples of shellfish used in spiritual, emblematic or cultural contexts. (a) The shell church, covered in scallop shells at La Toja, Spain; (b) Sculpture of mussels in the mussel producing town of Conwy, Wales, UK; (c) Coastal development designed in the shape of an oyster: The Pearl, Qatar.

clay to temper their pottery. Shells were also used as scrapers for removing flesh from hides and scalping defeated enemies (Kuhm 2007).

Cultural (physical and intellectual interactions, heritage)

Seafood is a significant cultural element around the world, involving not just fishers but also distributors and the people who purchase shellfish for consumption. It is a traditional food at Christmas in France (Buestel *et al.* 2009), Italy and Spain. Seafood is commonly eaten in catholic countries on a Friday when red meat is not allowed. Fish and other aquatic animals are known to play an important role in the diet throughout the Asia-Pacific region. The wide range of fishery resources have given rise to a strong tradition of seafood eating in most countries of the region and this is reflected in strong cultural traditions associated with fish (Needham & Funge-Smith 2014). Bivalves have important representation in cultures around the world, with churches, sculptures and whole islands being created to celebrate them (Fig. 1). Bivalves have been mentioned in several songs such as ‘Molly Malone’ and ‘the Oyster Girl’.

Seafood festivals (physical and intellectual interactions, heritage, cultural)

Food has become a recognised component of cultural tourism globally, especially in rural regions (Lee & Arcodia 2011). Local foods or food products contribute to the authenticity of destinations, enhance the sustainability of tourism and strengthen the local economy. High quality food products from a specific region can enhance a region’s overall tourism image and a visitor’s experience (Boyne & Hall 2004). This tourism can provide economic stimulation to a region while also maintaining or regenerating the local identity, especially through its primary production and processing sectors (Telfer & Wall 1996). Academic research is widening from a focus on the financial value and economic implications of food tourism (Bélisle 1983; Telfer & Wall 1996) or its value as a promoting and marketing tool (Boyne & Hall 2004; Tellström *et al.* 2006), to include the cultural and social significance of a place (Hall & Gössling 2016) and regional identity (Du Rand *et al.* 2003; Everett & Aitchison 2008). This change in approach demonstrates the increasing interest and importance of the social and cultural impacts of food tourism (Lee & Arcodia 2011). Food festivals are one tangible manifestation of this interest. ‘Seafood Festivals’ specialise this focus and are usually organised by local businesses with the aim of increasing local benefits to regional communities and businesses.

The reasons why people attend seafood festivals have not been fully investigated. An evaluation of the Menai Seafood Festival, in North Wales, UK, (Lane & Jones 2016) found that 90% of respondents expressed their interest in purchasing local produce in the future, and the respondents were also encouraged by what they saw and experienced at the festival. Stallholder motivations for attending were mainly focused around the direct advantages for their businesses, such as promoting their products. Stallholders receive benefits in terms of high sales but also enjoy participating in the local event and supporting the surrounding community (Lane & Jones 2016). Estimates of economic value can be considerable. In the USA, the Louisiana seafood festival in 2015 attracted approximately 56,000 attendees and generated a total economic impact of $1.75 million (Ortiz 2015). To provide some examples from around the world, seafood festivals in selected countries were identified using Google, Australia.com, everfest.com and foodfestivalfinder.co.uk. 120 were identified and contacted to find the number of visitors attending. Forty-nine responses were received from countries such as Australia, Jamaica, the Republic of Ireland, the United Kingdom and the USA, with an approximate attendance of ~1.4 million visitors (Appendix IV).

Spiritual significance and emblematic (spiritual, symbolic and other interactions with biota)

There is a long historic spiritual significance of bivalves. In Roman times, it was believed that Venus, the goddess of love was born in the sea and emerged on a scallop shell towed by sea creatures. The Romans revered her and erected shines in their gardens, praying to her to provide water and verdant growth (Hoena 2003). Following the depiction of fertility and growth associated with the goddess of Venus, the scallop and other bivalve shells have come to be used as a symbol in architecture, furniture, fabric design (Fontana 1993), for example, within the logo of the Royal Dutch Shell (the global oil and gas company). Scallops, whelks and other shells also feature as symbols in heraldry and coats-of-arms. The scallop is the symbol of St James and is called *Coquille Saint-Jacques* in French and it is an emblem carried by pilgrims on their way to the shrine of Santiago de Compostela in Galicia. Pilgrims that completed the pilgrimage were often buried with a scallop shell or had it carved on their tombs (Fulcanelli 1984). Scallop shells feature as a symbol in many churches in this region (e.g. Fig. 1).

Non-use (existence and bequest) values (other cultural outputs)

Bequest value is the value of satisfaction from preserving a natural environment or a historic environment for future generations (Turner & Schaafsma 2015). Shellfisheries are often important local centres of economic activity by

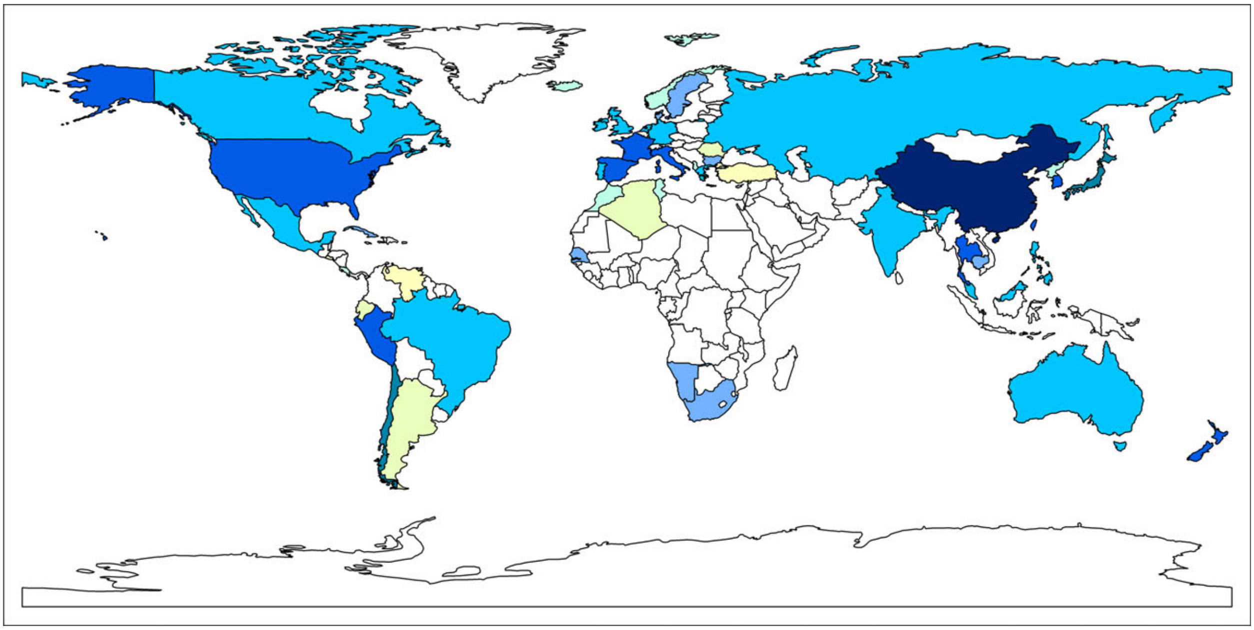

Figure 2 World map showing the potential combined value of carbon sequestration, nitrogen and phosphorus remediation and the use of oyster shells for aggregate ($). (□) No FAO data; (🟨) ≤ 10,000; (🟨) 10,001 – 100,000; (🟦) 100,001 – 1,000,000; (🟦) 1,000,001 – 10,000,000; (🟦) 10,000,001 – 100,000,000; (🟦) 100,000,001 – 1,000,000,000; (🟦) 1000,000,001 – 10,000,000,000; (🟦) 10,000,000,001 – 25, 000,000,000.

fishers, local points of sale and wider distribution, nationally and internationally. A significant number of individuals may rely on the industry and a significant proportion of income in some coastal communities may rely on functioning shellfisheries. Often families are involved in this industry from generation to generation and therefore safeguarding shellfish waters from pollution can preserve these traditions (ECOTEC 2000). Hicks *et al.* (2004) suggested that people may benefit from oyster reefs in Chesapeake Bay even if they do not directly use the environmental asset. They achieve this by either deriving value from knowing that oyster reefs exist and provide ecosystem services or from knowing that improved environmental conditions might make future use of the bay more enjoyable should they choose to use the bay directly (Northern Economics 2009).

Global estimate of the potential value of non-market ecosystem services from bivalves

While the value of food from bivalve aquaculture is well reported (FAO 2016), the non-food ecosystem services are not. Therefore, using information collated in this study, we estimated global tonnages (Table 9) and their value (Table 10; Fig. 2). The services we were able to quantify and provide values for included nutrient (N and P) removal, and the use of oyster-shell waste as aggregate. Services we could not adequately quantify or value included: nursery grounds, bivalve use as fertilisers, pearls and nacre, biological accumulation of *E. coli* and other pathogens, shoreline defence, wildlife watching, use in education and research and the value of seafood festivals. We have estimated ecosystem services provided by

Table 9 Estimate of potential tonnages of constituents within shellfish aquaculture production in 2015

Region	Tonnage of oyster-shell waste (t)	Nitrogen remediated (t)	Phosphorus remediated (t)	Total Tonnage (t)	Tonnage of meat (t)
Africa	1,263	16	2	3,410	584
Americas	124,387	2,253	215	463,419	81,856
Asia	4,316,550	42,852	5,337	13,478,692	1,998,196
Europe	71,164	3,519	287	608,957	122,819
Oceania	12,513	549	46	95,054	19,306
World	4,525,876	49,210	5,886	14,649,532	2,222,762

Table 10 Estimate of potential value of shellfish ecosystem services for shellfish aquaculture production in 2015 (US$ 000)

Region	Value of food ecosystem services	Value of using shell	Value of nitrogen remediation	Value of phosphorus remediation	Total value of non-food ecosystem services	Total value of ecosystem services
Africa	8,703	$1,474 ($680–2,268)	$326 ($147–506)	$58 ($21 95)	$1,859 ($848–2,869)	$10,562 ($9,551–11,572)
Americas	2,300,791	$144,973 ($66,920–223,026)	$45,110 ($20,267–69,953)	$7,690 ($2,815–12,565)	$197,773 ($90,002–305,544)	2,498,564 (2,390,793–2,606,335)
Asia	19,983,869	$5,030,939 ($2,322,303–7,739,574)	$858,033 ($385,500–1,330,566)	$191,280 ($70,017–312,543)	6,080,252 ($2,777,821–9,382,683)	26,064,121 (22,761,690–29,366,552)
Europe	1,103,576	$82,942 ($38,286–127,597)	$70,459 ($31,656–109,262)	$10,286 ($3,765–16,807)	$163,686 ($73,707–253,665)	1,267,262 (1,177,283–1,357,241)
Oceania	522,254	$14,583 ($6,732–22,435)	$11,407 ($5,125–17,690)	$1,655 ($606–2,705)	$27,646 ($12,463–42,830)	549,900 (534,717–565,084)
World	23,919,193	$5,274,912 ($2,434,923–8,114,901)	$985,336 ($442,695–1,527,977)	$210,969 ($77,224–344,715)	$6,471,217 ($2,954,842–9,987,592)	30,390,410 (26,874,035–33,906,785)

Table 11 Estimate of potential of bivalve nutrient remediation (t) between species for production in 2015

Species	Tonnage of species produced through aquaculture (t)	Potential nitrogen remediation (t)	Tonnes of nitrogen removed tonne^{-1} of shellfish harvested	Potential phosphorus remediation (t)	Tonnes of phosphorus removed tonne^{-1} of shellfish harvested
Clams, cockles, arkshells	5,395,188	15,759	2.92×10^{-3}	1,567	2.90×10^{-4}
Mussels	1,856,300	12,370	6.66×10^{-3}	913	4.92×10^{-4}
Oysters	5,316,345	12,399	2.33×10^{-3}	2,408	4.53×10^{-4}
Scallops, pectens	2,081,699	8,682	4.17×10^{-3}	998	4.79×10^{-4}

bivalves based on the biomass removed at harvest (Table 9). While shellfish farms will have a larger standing stock, which will cycle nutrients during feeding and excretion, it is the harvested biomass that gives the most certain measure of nutrients removed from the marine system.

Global ecosystem services provided by bivalve aquaculture total $30.39 billion (Table 10). Of these provisioning services (food) make up $23.92 billion. Nutrient remediation has the potential to increase the value of the bivalve industry by approximately $1.20 billion. Oyster shell has the greatest potential value of ecosystem services globally. Annually 4.5 million tonnes of oyster shell is produced which has the potential to be used as aggregate, worth $5.27 billion ($2.43 billion–8.11 billion).

Bivalve production in Asia has by far the greatest potential ecosystem service value at $26 billion, making up the majority (86%) of the global projection. Comparing between the various species produced globally (Table 11) it is clams, cockles and arkshells that are removing the most nitrogen (15,759 tonnes), and oysters removing the most phosphorus (2,408 tonnes). Mussels have the greatest potential for bioremediation as they remove the most nitrogen and phosphorus per tonne of shellfish produced.

Knowledge gaps

The biological functions performed by bivalves are generally well-understood. However, there still remain knowledge gaps. For example, filtration rates of many species are not clearly reported, and the supporting ecological functions and trophic interactions supported by bivalves have only been studied extensively in the USA for one species: oysters. Therefore, for the supporting services, more basic quantification of processes is required to allow upscaling for other species and in other contexts. Although the value of oyster reefs acting as nursery grounds has been valued in the southeast United States (Peterson *et al.* 2003; Grabowski & Peterson 2007), these values are unsuitable for use in other parts of the world due to the difference in species and habitats. With a wider range of sites and species around the world assessed, it would be possible to better quantify the importance of this supporting service.

The attempt to value provisioning services relies heavily on official statistics, which may under-record what is being landed due to the contribution of small-scale and subsistence aquaculture (FAO 2016). There is no comprehensive data on use of shell in poultry grit, in aggregate, or of bivalve waste as a fertiliser, making it difficult to upscale on a regional or global basis. Due to the uncertainty in pearl value and the lack of valuation on nacre, these also have not been included in the global valuation.

Much of the information in bivalve regulating services is based on oysters in the USA and mussels in the Baltic, and their ability to remove nitrogen and phosphorus. The USA is also the only country with published estimates of their role in coastal protection. There is little data from other regions in the world and for other species and it is uncertain whether nitrogen and phosphorus removal rates differ regionally/globally. There is one study in the UK (Herbert *et al.* 2012) but this lacks in depth analysis on regulating services. More importantly, whilst we found some data on regulating services from Asia, there is relatively little data considering they are the largest producers of bivalves in the world. With regards to carbon sequestration, there remains disagreement in the literature on the net carbon storage attributable to carbonate in bivalve shells. Many of the values within this study refer to remediation or sequestration potential per hectare, however, the lack of information on the area of shellfish beds and their stocking densities makes it difficult to upscale to national or global potential from these studies.

Cultural services are among the most difficult to classify and value. Previously the cultural services of bivalve aquaculture have been largely ignored. To date there has been no published work into the cultural or economic importance of bivalve aquaculture, but with the growing interest in seafood festivals around the world, there is scope for the scale and value of some aspects of cultural services to be investigated. While it is difficult to value the existence and bequest value of bivalve aquaculture, it is an important aspect for both people involved in the industry and the wider population.

Conclusion

For the first time we have valued on a global scale the ecosystem services provided by bivalve aquaculture. While the knowledge gaps summarised above currently hinder a comprehensive valuation, by using the values collated in this paper it is possible to make a partial estimate of the value of ecosystem services, including values for nutrient remediation and the use of oyster shell as aggregate. Worldwide these non-food services are worth $6.47 billion (representing 27% of the current value for bivalve meat (FAO, 2016)). This shows that even without including the other services described in this synthesis, bivalve production areas have the potential to increase the overall value of the bivalve aquaculture industry globally, while simultaneously providing environmental benefits. Studies focused around the large estuaries of the USA and the eutrophic Baltic Sea show how significant bivalve aquaculture can be in terms of nutrient remediation, and nutrient offset schemes are being used in Denmark and Sweden (Petersen *et al.* 2014). Already there is a growing trend to use shellfish in integrated multi-trophic aquaculture due to their ability to remove nutrients and waste products from fed aquaculture. The benefit this could present to the farmer, could be through direct payment for nutrient removal through a nutrient trading scheme, similar to the carbon trading schemes already in existence. While the carbon trapped in shell is considerable (1.06 M t yr^{-1}), it cannot be considered as a form of sequestration due to the CO_2 released during calcification and respiration. Much of the extra value to non-food based ecosystem services, however, is in the use of shell as aggregate. Providing a market for the waste products of the industry. There remain gaps in this analysis due to lack of sufficient data, but we expect these to further increase the overall value for ecosystem services provided by bivalve aquaculture. These include the prevention of shoreline erosion, increased biodiversity and the uses of bivalve waste, which have not been included in this valuation. Furthermore, while some estimates of non-use values, including existence, bequest and cultural values, are available for localised studies, there is insufficient data as yet to scale these into a global valuation. The analysis presented here can be used to indicate the likely scale of payments for ecosystem services provided by bivalve aquaculture, prior to more detailed assessments.

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Appendix I

Major crop nutrients in fisheries and aquaculture wastes compared with traditional organic manures (kg per tonne of fresh weight; ND represents no data) taken from ADAS UK Ltd (2006)

	Total Nitrogen (N)	NH_4-N	Phosphate P_2O_5	Potash (K_2O)	Sulphur (as SO_3^-)	Magnesium (as MgO)
Whelk waste	22.6	0.51	2.6	2.7	10.3	1.0
Nephrop waste	14.9	0.89	7.0	2.0	2.8	2.1
Crab waste	18.7	0.49	7.2	1.1	3.	6.8
Scallops waste	16.8	1.18	1.8	1.6	4.4	1.1
Cattle manure	6.0	1.1	3.5	8.0	1.8	0.7
Sewage sludge cake	7.5	1.0	930	Trace	6.0	1.3
Green waste compost	7.0	0.2	2.8	5.3	3.5	3.8
Shellfish-based compost	10.0	0.5	4.1	4.2	ND	ND

Appendix II

Shellfish pumping rates from literature of laboratory-based experiments

Species	Size of organisms (mm)	Pumping rates per individual bivalve (l h^{-1})	Source
Mytilus edulis	30–40	0.75–1.20	Jones *et al.* (1992)
Mytilus edulis	25.5	0.80	Quraishi (1964)
Mytilus edulis	48	1.06	Willemsen & Willemson (1954)
Crassostrea virginica	100	34.00	Loosanoff & Nomejko (1946)
Crassostrea virginica	100	26.00	Nelson (1935)
Mya arenaria	70	0.95	Allen (1962)
Venus mercenaria	40	2.07	Coughlan & Ansell (1964)
Venus striatula	20	0.12	Allen (1962)
Cardium edule	30–40	0.50	Willemsen & Willemson (1954)

Appendix III

Chlorophyll α removal by bivalves

Species	Location	Density (individuals m^{-2})	Summary of findings	Source
Crassostrea virginica	South Carolina estuaries, USA	217–2,831	Removed 28% of chlorophyll α in situ (40.7% in laboratory experiment)	Grizzle *et al.* (2008)
Crassostrea gigas	Thau Lagoon, France	40	Removed 56 to 86% of chlorophyll α	Souchu *et al.* (2001)
Crassostrea gigas	Moreton Bay, Australia	33–100	Removed 92% of chlorophyll α	Jones & Preston (1999)
Mytilus edulis	Menai strait, Wales	–	Removed 69% of chlorophyll α	Morioka *et al.* (2017)
Corbicula japonica	Lake Shinji, Japan	0–1,000	Removed 60% of chlorophyll α	Nakamura & Kerciku (2000)
Corbicula fluminea	Potomac River, USA	1.2–1,467	Removed 30% of chlorophyll α	Cohen *et al.* (1984)

Appendix IV

Examples of seafood festivals in five countries, and the number of visitors reported at each festival

Seafood Festival	Location	Number of visitors
USA		
Asbury park Oysterfest	Asbury Park, New Jersey	~10,000
Austin oyster festival	Austin, Texas	~2,000
Ballard Seafood Fest	Seattle, Washington, USA	~75,000
Bodega seafood festival	Bodega, California	~10,000
Boston Seafood Festival	Boston, Massachusetts	~7,500
Chesapeake Bay crab and beer Festival – Baltimore	Baltimore, Maryland	~4,000
Chesapeake Bay crab and beer Festival – Washington DC	Washington DC	~7,000
Chesapeake Bay maritime museum Oyster festival	St. Michaels, Maryland	~4,500
Chesapeake Bay maritime museum Watermen’s Appreciation Day	St. Michaels, Maryland	~3,500
Good Catch Oysterfest	Charleston, South Carolina	~400
Louisiana seafood Festival	New Orleans, Louisiana	~55,000
Lowcountry Oyster Festival	Mount Pleasant, South Carolina	~10,000
Milford Oyster Festival	Milford, Connecticut	~50,000
Mount Dora Seafood Festival	Mount Dora, Florida	~50,000
North Carolina seafood festival	Morehead City, North Carolina	~200,000
Ocean State Oyster Festival	Rhode Island	~1,500
Poquoson seafood festival	Poquoson, Virginia	~50,000
Port Fish Day Festival	Port Washington, WI	~50,000
Potomac Jazz and Seafood Festival	Coltons Point, Maryland	~1,000
Riverwalk Stone Crab & Seafood Festival	Fort Lauderdale, Florida	~7,000
Rockport-Fulton Sea Fair	Rockport, Texas	~15,000
Roscoe village Oyster Festival	Chicago, Illinois	~8,000
Salmonfest Alaska Festival	Ninilchik, Alaska	~8,000
India Point Seafood Festival	India Point, Rhode Island	~5,000
Sensible Seafood Fest	Virginia Beach, Virginia	~600
Washington Oyster festival	Shelton, Washington	~15,000
Wellfleet Oyster festival	Wellfleet, Massachusetts	~25,000
Yarmouth Clam Festival	Yarmouth, Maine	~100,000
	Subtotal	~775,000
Australia		
Ballina Prawn Festival	Ballina, New South Wales	~10,000
Mandurah Crab Fest	Mandurah, Western Australia	~120,000
Narooma Oyster Festival	New South Wales, Australia	~4,000
Taste of Tasmania	Hobart, Tasmania	~115,000
Tin Can Bay Seafood Festival	Tin Can Bay, Queensland	~10,000
	Subtotal	~259,000
Republic of Ireland		
Seafest Festival	Galway, Ireland	~101,000
	Subtotal	~101,000
Jamaica		
Little Ochi Seafood Festival	Jamaica	~650
	Subtotal	~650
United Kingdom		
Clovelly Lobster and Crab Feast	Clovelly, Devon	~1,500
Crabstock	Chippenham	~4,000
Cromer and Sheringham Crab and Lobster Festivals	Cromer, Norfolk	~20,000
Fishstock	Brixham, Devon	~5,000
Isle of Man Queenie Festival	Isle of Man	~4000
Menai Seafood Festival	Menai Bridge, Wales	~12,000
Newlyn Fish Festival	Newlyn, Cornwall	~15,000
Newquay Fish Fest	Newquay, Cornwall	~10,000
Paignton Harbour day	Paignton, Devon	~5,000

Table (continued)

Seafood Festival	Location	Number of visitors
Pembrokeshire Fish Week	Pembrokeshire, Wales	~30,000
Plymouth Seafood Festival	Plymouth, Devon	~12,000
Pommery Dorset Seafood Festival	Weymouth, Dorset	~50,000
Rock Oyster Festival	Rock, Cornwall	~3,000
Whitstable Oyster Festival	Whitstable, Kent	~80,000
	Subtotal	~251,500
Total		~1,387,150