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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 2006; 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 synthesize 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) \(((WMW/(LW – SW))) \times 100\) reported in both Okumuş and Stirling (1998) and Muniz et al. (1986) to calculate the shell weight for mussels and oysters.
For clams we used the condition index \((\text{CI} = (\text{Meat dry weight/Shell dry weight}) \times 1,000)\) 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 ($8,996–31,050 \text{ t}^{-1}$ 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 ($13,118–58,561 \text{ t}^{-1}$ Molinos-Senante et al. 2011)). Due to a lack of consensus on whether calcification represents a source or a sink of \(\text{CO}_2\), 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.

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

| Service                  | 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     | 66.1                       | Orban et al. (2006a, 2006b)                      |
| Condition index Mussel   | 45.9                       | Okumus and Stirling (1998)                       |
| Condition index Oyster   | 72.3                       | Muniz et al. (1986)                              |
| Clam (Shell/Tissue)      | C: 11.41/43.70, N: 0.25/10.28, P: 0.04/0.79 | Ricciardi and Bourget (1998)                     |
| Mussel (Shell/Tissue)    | C: 12.68/45.98, N: 0.84/9.08, P: 0.05/0.92 |                                                    |
| Oyster (Shell/Tissue)    | C: 11.85/44.81, N: 0.16/7.85, P: 0.04/0.91 |                                                    |
| Scallop (Shell/Tissue)   | C: 11.72/44.86, N: 0.32/9.28, P: 0.04/0.88 |                                                    |
| Shell free wet weight to dry weight conversion | 8.7 |                                                    |
| Value of N removal       | $8,996–31,050 \text{ t}^{-1}$ | Beseres Pollack et al. (2013); Newell et al. (2005) |
| Value of P removal       | $13,118–58,561 \text{ t}^{-1}$ | Molinos-Senante et al. (2011)                    |
| Value of shell aggregate | $538–1,783 \text{ t}^{-1}$ | Morris et al. (2018)                            |
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 & Commoto 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 nemertean (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 |
|          |       | Fibres and other materials from plants, algae and animals for direct use or processing | Using the ground flesh or associated nutrient rich mud’s as sources of fertiliser. Crushed shell as a source of lime |
|          |       | | Shells used as construction materials (aggregate and lime) |
|          |       | | Pearls/mother of pearl |
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, actinomycetes 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 year 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 1999. 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 pseudofaeces. 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 |
|                                              |                                             | Filtration/sequestration/storage/accumulation by microorganisms, algae, plants and animals | Biological accumulation e.g. E. coli into shellfish, pathogen deposition into sediments          |
| Mediation of flows                           | Liquid flows                                | Hydrological cycle and water flow maintenance  | Carbon sequestration in the form of calcium carbonate in shells, removing CO₂ from the system, Carbon deposition |
| Mass flows                                   |                                            | Mass stabilisation and control of erosion rates | Reduced rates of shoreline and bed erosion                                                        |

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 (Cerce & 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 N₂ or N₂O which has been identified as an important removal mechanism for nitrogen in coastal waters (Pielhler & 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.
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 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

| Nutrient Removal | Location | Density (m⁻²) | Summary of findings | Source |
|------------------|----------|---------------|---------------------|--------|
| 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 × 10⁻⁶ 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) |
around 1.5 grams of phosphorus per day into sewage, so
with the current population of 7.5 billion an annual excre-
tion 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 sha-
dow price of phosphorus, estimating it to be worth between
$13,118–58,561 \text{t}^{-1} \text{C}0 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

| 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         | Zhou et al. (2002) |
| Crassostrea gigas       | –      | 7.4    | –             | Linehan et al. (1999) |
| Crassostrea virginica   | 44.72  | 7.72   | 0.83          | 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         | Zhou et al. (2002) |
| Mytilus edulis          | –      | 10.6   | 0.80          | 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          | 12.68          | 0.84 ± 0.29 | 0.05 |
| Other spp.              |        |        |               |
| Arctica islandica       | –      | –      | –             | Westermark et al. (1996) |
| Chlamys farreri         | 43.87  | 12.36  | 0.839         | Zhou et al. (2002) |
| Corbicula japonica      | –      | 9.81   | –             | Nakamura et al. (1988) |
| Macrha chinensis        | 42.21  | 10.57  | –             | Zhou et al. (2002) |
| Macrha verriformis      | –      | 9.67   | –             | Hivatari et al. (2002) |
| Macoma baltica          | –      | –      | –             | Seire et al. (1996) |
| Arcuatula senhousia     | –      | –      | –             | Yamamuro et al. (2000) |
| Pinctada imbricata      | –      | 9.82   | 0.74          | Gifford et al. (2005) |
| Pinctada imbricata      | –      | 10.5   | –             | Seki (1972) |
| Ruditapes              | 42.84  | 10.76  | 11.40         | Zhou et al. (2002) |
| philippinarum           | –      | –      | –             | – |
| Anadara                 | 45.86  | 8.71   | 11.29         | 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 |
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 on the aq phase balanced: \( \text{Ca}^2+ + 2\text{HCO}_3^- \text{aq} \rightleftharpoons \text{CaCO}_3 + \text{H}_2\text{O} + \text{CO}_2 \), so potentially leading to an increase in \( p\text{CO}_2 \) in surface waters and evasion of \( \text{CO}_2 \) 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 \( \text{CO}_2 \) (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 ha\(^{-1}\) 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 ha\(^{-1}\) 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 \( \text{CO}_2 \).

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...
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.

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, Heritage, cultural, aesthetic | Subject matter for research and education both on location and via other media. 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 Other cultural outputs | Symbolic Existence Bequest | Emblematic animals Enjoyment provided by wild species, wilderness, ecosystems Willingness to preserve plants, animals, ecosystems for the experience and use of future generations; moral/ethical perspective or belief |

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 (Béisle 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 shrines 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
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           |

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; ( ) 0 – 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; ( ) 1,000,000,001 – 10,000,000,000; ( ) 10,000,000,001 – 25,000,000,000.
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.

### Table 10
| Region | Value of food ecosystem services (t) | Value of using shell remediation (t) | Value of nitrogen remediation (t) | Value of phosphorus remediation (t) | Total value of non-food ecosystem services (US$ 000) | Total value of ecosystem services (US$ 000) |
|--------|-------------------------------------|-------------------------------------|----------------------------------|----------------------------------|-----------------------------------------------|------------------------------------------|
| 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)        | $27,646 ($12,463–42,830)         | 549,900 ($334,717–565,084)                   | 30,390,410 ($26,874,035–33,906,785)   |
| World  | 23,919,193                     | $5,274,912 ($2,434,923–8,114,901) | $985,336 ($442,695–1,527,977) |

Table 11
| 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                                           | 8,862                             | 4.17 × 10⁻³                                               | 998                                 | 4.79 × 10⁻⁴                                               |

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 CO₂ 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) | NH₄-N | Phosphate P₂O₅ | Potash (K₂O) | Sulphur (as SO₃⁻) | 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          | 3.4               | 6.8               |
| Scallops waste        | 16.8               | 1.18   | 1.8            | 1.6          | 4.8               | 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                    | 34.0                                         | Loosanoff & Nomejko (1946)   |
| Crassostrea virginica    | 100                    | 26.0                                         | 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 a 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 a in situ (40.7% in laboratory experiment)              | Grizzle et al. (2008)        |
| Crassostrea gigas        | Thau Lagoon, France | 40                       | Removed 56 to 86% of chlorophyll a                                                | Souchu et al. (2001)        |
| Crassostrea gigas        | Moreton Bay, Australia | 33–100                  | Removed 92% of chlorophyll a                                                     | Jones & Preston (1999)      |
| Mytilus edulis           | Menai strait, Wales | –                        | Removed 69% of chlorophyll a                                                     | Morioka et al. (2017)       |
| Corbicula japonica       | Lake Shinji, Japan  | 0–1,000                  | Removed 60% of chlorophyll a                                                     | Nakamura & Kerciku (2000)   |
| Corbicula fluminea       | Potomac River, USA  | 1.2–1,467                | Removed 30% of chlorophyll a                                                     | 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                                           | Chippingham                       | ~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, Cromwell                  | ~15,000            |
| Newquay Fish Fest                                   | Newquay, Cromwell                 | ~10,000            |
| Paignton Harbour day                                | Paignton, Devon                   | ~5,000             |

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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         |