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# Quantifying the ecosystem service benefits that cockles (*Cerastoderma edule*) provide to society

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# 1. INTRODUCTION

The common cockle, *Cerastoderma edule*, provides a wide range of ecosystem services in the Atlantic Area. However, much less is known about the services provided by cockles than for other shellfish species. This report gathers existing data from the literature alongside new data from experiments and field studies to analyse the provisioning, regulating and cultural services provided by cockles and to quantify these services across the Atlantic Area countries of France, Ireland, Portugal, Spain, and the United Kingdom (Wales) involved in the COCKLES project.

## 1.1 Backgound

The most prominent ecosystem service provided by bivalve shellfish is food production, although studies are now quantifying many of the other ecosystem services provided by shellfish (van der Schatte Olivier et al. 2018). These include non-food provisioning services such as use of shell for ornaments, poultry grit and in construction (Kelley, 2009; Morris et al., 2018; van der Schatte Olivier et al., 2018). Regulating services include removal of nutrients from coastal waters, mitigating disease, and increasing seabed roughness. In some areas, the potential for the removal of nitrogen and phosphorus from eutrophic coastal waters has been turned into Payments for Ecosystem Services schemes. In the Baltic Sea, blue mussels (*Mytilus edulis*) have been used to remove nutrients as an alternative nature-based solution to upgrading a tertiary sewage plant (Petersen et al., 2014), while in Chesapeake Bay in the USA, restored Eastern (American) oyster *Crassostrea virginica* reef beds in coastal waters are used to remove nutrients of agricultural origin draining from inland catchments (Rose et al., 2014). There is a potential that cockles could be applied to this.

Cultural services are also provided by shellfish, with many examples of imagery and references to shells in cultures throughout the world (Duncan and Ghys, 2019; van der Schatte Olivier et al., 2018). However, cultural services or ‘non-material benefits’ (Díaz et al. 2015) remain a particular challenge to quantify and assess (Chan et al. 2012), and research on cultural services remains a tiny fraction of that undertaken for the other ecosystem services (Fish et al. 2016; García Rodrígues et al. 2017).

Key to providing these services are the underpinning natural functions performed by shellfish. Shellfish play a vital role as an ecosystem engineer, controlling or influencing processes such as bioturbation and water filtration which underpin marine food webs and biodiversity, and which drive biogeochemical cycling. Shellfish also provide structural habitat which supports a wide range of other species. Although well known in the traditional ecological literature, the role of these supporting functions is rarely assessed within an ecosystem services framework, and so far the majority of the work in this area has been conducted on only a single shellfish species, the Eastern oyster in the USA (Peterson et al. 2003).

Recent studies have assessed (Clements and Comeau, 2019; Coen et al., 2007; Gentry et al., 2019; Grabowski and Peterson, 2007) and valued (van der Schatte Olivier et al., 2018) the benefits of shellfish ecosystem services at a range of scales. They show that some of the non-market values are potentially worth at least 50% in addition to the global production value, and recognise that the true non-market values are likely to be much higher but are not easily quantified. However, these studies have focused almost exclusively on cultured shellfish species for example Pacific oysters *Magallana gigas* (Herbert et al., 2012, UK) and blue mussels (Lindahl et al., 2005, Sweden). The role of wild-harvested species such as the common cockle *Cerastoderma edule* have largely been ignored. The contributions of non-cultured species to ecosystem services are broadly similar to those of cultured species, but differ in some important ways. Cockles are a natural resource that is harvested rather than farmed or cultured from spat (juveniles) (Pronker et al 2013). Thus, the amount of human-derived capital required to access the services (Jones et al. 2016) are typically lower for wild shellfish than for cultured species i.e. the relative contribution of natural capital is higher. In addition, harvesting methods for wild shellfish such as cockles often retain older traditions which have been lost in the more advanced production methods of cultured species, increasing the connections to cockle harvesting among local communities.

The common cockle is one of the main non-cultured bivalve species harvested in western European waters. The species is widely distributed in the Atlantic, extending from northern Europe (Norway, Russia) to the coasts of West Africa (Senegal) (Hayward and Ryland, 1995). Cockles are one of the most abundant mollusc species in European bays and estuaries where population densities of 10,000 per m² have been recorded (Tyler-Walters 2007). Animals mature at 18 months, have a 1-2 year generation time, and live up to 10 years in some habitats but more commonly to 2-6 years (Malham et al 2012).

# 2. MATERIALS AND METHODS

## 2.1 Data collation

The data used for this study was generated through a series of workshops and virtual meetings with participants from the five countries, primary data collection across partners, and synthesise of published data that quantify the supporting, provisioning, regulating and cultural services. Upscaling of services across the partner countries was undertaken using the historical published database collated in WP4 (Mahony et al., 2019) and that collated during the field campaign under Work Package 6.

Numerous examples of cultural ecosystem services were collated, but not valued due to recognised challenges in quantifying these services. The Common International Classification of Ecosystem Services (CICES v5.1) provides the structural basis for the quantification and analysis of final ecosystem services in this study (Haines-Young et al. 2018). We supplement the CICES descriptions with synonymous descriptions to aid understanding where necessary, especially for supporting services which are not featured in CICES.

## 2.2 Valuation

Valuation followed methods in van der Schatte Olivier et al. (2018). Data on meat yield were obtained from the Solway cockle fishery (18%, (Science, 2015)) to give the meat yield. The dry weight of meat was calculated using a drying factor of 8.7 (Ricciardi and Bourget, 1998) and the shell weight calculated using a condition index formula (Brock and Wolowicz, 1994) where shell weight = [meat dry weight x 100]/6.7.

Economic values were estimated for those services that are easily quantified: cockle meat, nutrient (N and P) removal in tissue and shell, and the use of cockle-shell waste as aggregate. All economic values are expressed as US dollars (2017 values). Economic values were adjusted to account for inflation to 2018 and then where necessary converted to USD using purchasing power parities (PPPs) (Hamadeh et al., 2017). The value of cockle meat was calculated by taking values from Marine Management Organisation (2017) for landed cockles, these were converted to US$ and using the meat yield data, calculated the value of cockle meat at an average of $3,583 ($2,827-4,303) per tonne. The value of nitrogen removal was calculated using values from Beseres Pollack et al. (2013) and Newell et al. (2005) and these varied between \$8,996–31,050 $t^{-1}$. The value of phosphorus removal was calculated using values from Molinos-Senante et al. (2011) which varied between \$13,118–58,561 $t^{-1}$ and the value of cockle shell aggregate was calculated from Morris et al. (2018) which varied between \$538-1738 $t^{-1}$.

# 3. RESULTS

## 3.1 Supporting services

We describe here the basic underlying processes and functions performed by cockles as supporting services. These are not final services themselves (Bateman et al. 2011), but underpin the full range of other ecosystem services, including the alteration of energy flows and nutrient cycling at an ecosystem scale. Supporting services described here are water filtration, perturbation and alteration of sediment properties, biogeochemical cycling, habitat creation and biodiversity support.

### *3.1.1 Water filtration*

Cockles are suspension feeding bivalves, consuming minute particulate matter suspended in the water column, which includes both living organisms (e.g. plankton) and non-living material (such as plant debris or suspended soil particles), together known as seston. The filtration power of bivalves has been shown to improve water quality by decreasing turbidity and removing nutrients (van der Schatte Olivier 2018; McLeod et al 2019) Two functions are differentiated: (i) the rate at which water is transported through the gills (pumping or filtration rate), and (ii) the rate at which seston particles are captured (clearance rate).

In general, filtration rate increases with body size (as a result of the associated increase in gill surface area), however rates vary depending on food availability, temperature and physiological (mainly reproductive) conditions (Iglesias et al., 1996 Smaal et al. 1997). The volume of water filtered increases rapidly with increasing proportion of particulate inorganic matter up to a concentration of about 300 mg/L, above which it remains constant as long as the proportion of seston particles is high (Navarro and Widdows 1997). Filtration rates are greatest in the temperature range 8-20°C (Brock and Kofoed 1987), particularly in spring to provide the amount of energy required for the development of gonads (Newell and Bayne 1980), while cockles strongly reduce their filtration activity at low temperature (< 8°C), even when food is available (Smaal et al. 1997). Filtration rate is largely independent of current speed, except below 5 cm/s when clearance rates are lower (Widdows and Navarro 2007). Filtration rates reviewed in Riisgård et al (2001) cite a filtration rate (F) for cockles of $F = 11.60W^{0.70}$, where W is tissue dry weight.

Standardised clearance rates were calculated by Cranford et al. (2011), standardised by body weight (to a 1g animal, and using a standardised *b* coefficient of 0.58) or shell length (to a 60 mm animal, and using a standardised *b* coefficient of 1.8). For *C. edule*, the mean (±2 SE) clearance rate based on body weight was 3.58 (±0.38) Lg$^{-1}$h$^{-1}$. Mean clearance rates standardised by shell length were 6.03 (0.81) Lind$^{-1}$h$^{-1}$. Cranford et al. (2011) stress the importance of quantifying local site-specific rates at relevant times of year to the specific application of the data, noting studies which show that *in-situ* activity rates in mussels range from 42 – 55% of the maximum values observed in laboratory experiments.

The filtration rate cited in Riisgård et al (2001) was applied to individual cockles collected from the field campaign under Work Package 6 (Figure 1). Country averages are provided in Table *1* and incorporate filtration rates for sampled field sites. Analysis revealed no significant different in tissue dry weight, and subsequently filtration rate, between high and low density sites from this field campaign; though sampled cockles from the United Kingdom were significantly (p<0.05) smaller in weight.

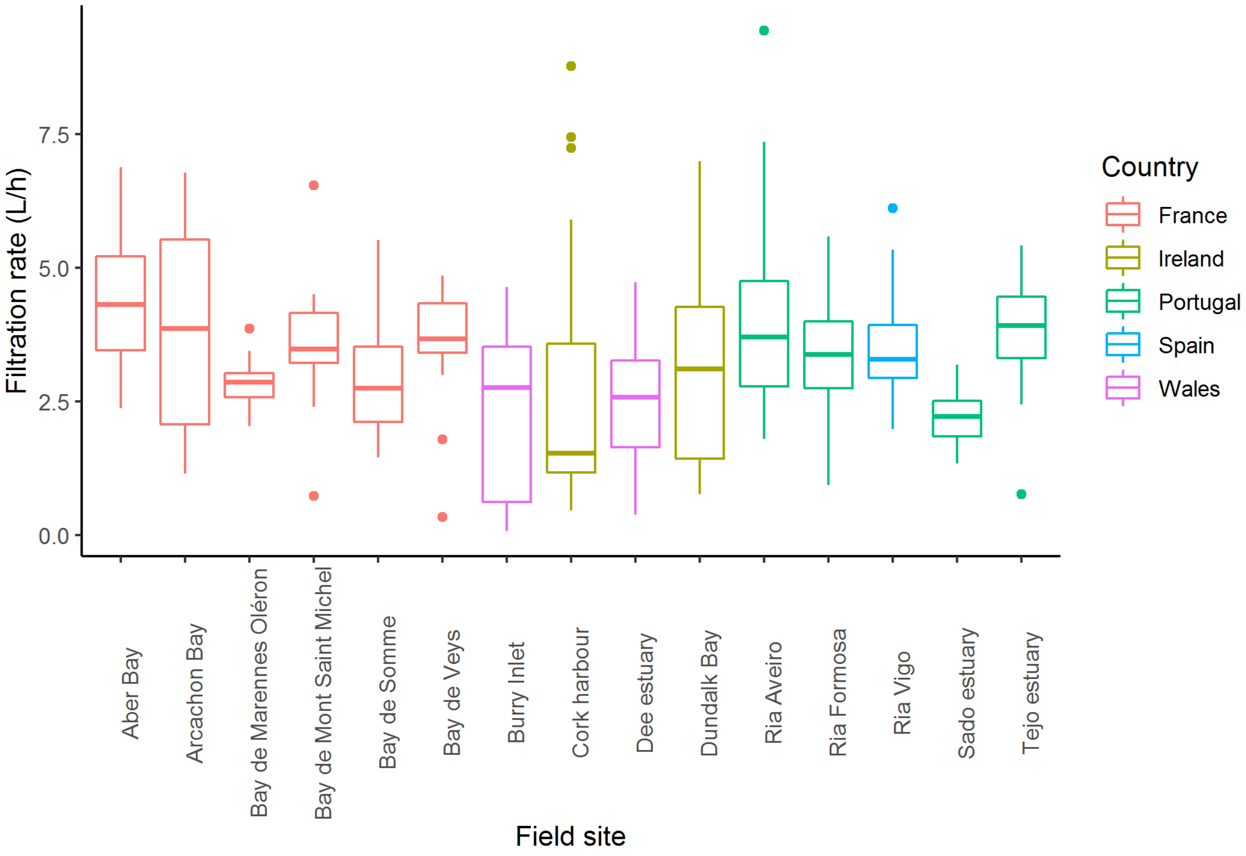

Figure 1. Calculated filtration rates for individual cockles across field sites.

| **Country** | **Average filtration rate** (L $h^{-1}$) |
|---|---|
| France | 3.73 |
| Ireland | 3.04 |
| Portugal | 3.38 |
| Spain | 3.47 |
| United Kingdom (Wales) | 2.32 |

Table 1 Average filtration rates per Atlantic Area partner country.

### *3.1.2 Perturbation and alteration of sediment properties*

From a functional point of view, cockles are classified as surficial biodiffusers, inducing diffusive-like sediment reworking and bioirrigation processes within the uppermost few centimeters of the sediment column (Norkko and Shumway 2011, Kristensen et al. 2012). The burrowing and locomotion activities of cockles induce a continuous mixing of particulate material, whilst their filtration and valve movements enhance porewater displacement and solute exchanges across the sediment-water interface (Mermillod-Blondin et al. 2005). However, the activity of cockles on sediment bed properties is complex and can either increase (e.g. Andersen et al. 2010) or decrease (e.g. Ciutat et al. 2006, 2007) sediment stability.

On one hand, cockles act through their bioturbation activity, as sediment destabilizers. By mechanically altering the physical properties of the sediment matrix (i.e. decreasing compaction and cohesiveness while increasing bed roughness), cockles can drastically lower erosion thresholds and increase erodibility (Ciutat 2006, 2007, Neumeier et al. 2006, Liu & Su 2017). On the other hand, by improving microbially-mediated nutrient regeneration and facilitating the development of microphytobenthic diatoms, cockles indirectly stimulate the secretion of exopolymeric substances (EPS) that creates bonds between particles and thus reinforces their cohesion, contributing to sediment stability (Tolhurst 2010, Meadows et al. 2012).

The effect on sediment stability is substrate dependent. In fine sediments, cockle movement can disrupt cohesive sediments, especially when the mud fraction is high (>30%). By contrast, in coarse sandy sediments the biodeposit production, integration of pseudofaeces in the sand matrix and microphotobenthic (MPB) biofilm produced by a range of benthic organisms can considerably enrich the fine fraction, thereby stabilizing the non-cohesive sandy areas. Cockles thus engineer the habitat to be more suitable to their requirements, and this has implications for the ecosystem services they provide.

### *3.1.3 Biogeochemical cycling*

Cockles contribute to nutrient transformation and fluxes across the sediment-water interface through respiration and direct excretion of metabolic wastes (Swanberg 1991). However, their primary influence on the biogeochemical dynamics of intertidal sediments comes through their biodeposition and bioturbation activities (Mermillod-Blondin 2004, Rakotomalala et al. 2015). Cockles capture seston particles in the water column and eject substantial amounts of faeces and pseudofaeces on the sediment surface, thereby increasing the vertical downward flux of organic matter. Tightly bound in mucus, biodeposits are not easily resuspended by turbulence and thus accumulate within the surficial sediment (Widdows & Navarro 2007). The biogenic sediment reworking induced by cockles and associated macrofaunal communities quickly incorporates this freshly sedimented organic material into deeper sediment layers, thereby fuelling the benthic microbial food web. Microbial remineralisation activities are further stimulated by bioirrigation, which increases the depth of oxygen penetration and modifies the vertical sequence of redox reactions (Aller 1982).

Collectively, biodeposition and bioturbation processes increase the pore water concentrations of inorganic nutrients, some of which is re-released to overlying water (Karlson et al., 2007). In doing so, they increase ammonium concentrations which is the most important resource for microphytobenthic communities (Brito et al., 2010). As benthic microalgae can represent a large part of the diet of cockles (Kang et al. 1999), the stimulation of MPB production represents an indirect way of supporting their own food sources (Andersen et al., 2010; Donadi et al., 2013).

### *3.1.4 Habitat creation and biodiversity support*

Cockles directly and indirectly support complex food webs ranging from primary producers right up to avian and other predators. The direct effects (valve movements) of cockles on microphytobenthic biofilm productivity (Swanberg et al. 1991) and the indirect effects of increasing the resuspension rates of organic material towards the water column (Rakotomalala et al. 2015), help sustain pelagic food webs. In estuaries where blue mussels and Pacific oysters are cultivated, the dominance of cockles in adjacent areas can contribute to increased food availability for these farmed species through resuspended microphytobenthos (Ubertini et al. 2012). The positive influence of cockles on microphytobenthos also supports populations of the tellinid *Macoma balthica*.

Cockles are a major food source for crustaceans, fishes and wading birds, with species-specific predation varying according to cockle size. At very early stages, bivalve larvae can be inhaled by filtering bivalve feeders, including adult cockles (André and Rosenberg, 1991). Post-larvae cockles (newly settled spat) are particular vulnerable from predation by brown shrimp (*Crangon crangon*) and juvenile shore crabs (*Carcinus maenas*; van der Veer, 1998; Beukema and Dekker, 2005). At sizes of 5-10 mm cockles become prey for fish, particularly European plaice (*Pleuronectes platessa*) and flounder (*Platichtys flesus*), (Möller and Rosenberg, 1983; Pihl, 1985). Larger cockles are predated by shore crabs, a range of gastropod predators and fishes (Mascaró and Seed, 2000; Morton et al., 2007) and wading birds. In Europe, the cockle is the main food supply for overwintering oystercatchers (*Haematopus ostralegus;* Bryant, 1979; Ens et al., 2004). In the absence of mussel beds (their main alternative food source), oystercatchers require an estimated 105-232 kg cockle flesh (wet weight) per bird per winter (Ens et al., 2004). Other birds such as eider (*Somateria mollissima*), knot (*Calidris canutus*), shelduck (*Tadorna tadorna*), curlew (*Numenius arquata*), redshank (*Tringa tetanus*), dunlin (*Caladris alpine*), sanderling (*Caladris alba*) and common gull (*Larus canus*) also eat cockles as part of a broader diet of bivalves and worms (Cadée, 1979; Bryant, 1979). Cockle availability is a key resource supporting many overwintering wader populations and the responses of oystercatchers and other species to insufficient food supplies during the overwinter period are well documented and include reduced individual body condition, increased mortality and reduced population sizes (Verhulst et al., 2004). In turn, the birds that cockles support provide ecosystems services of their own, most often explored as cultural services.

## 3.2 Provisioning services

The CICES provisioning services includes the Division ‘Biomass’, which includes the Group ‘Reared aquatic animals for nutrition, materials or energy’, further divided into Classes used for nutritional purposes (CICES code 1.1.6.1) or for other uses (1.1.6.2). In the following text we categorise these as use of the shellfish meat for consumption and multiple uses of shells: shell by-products, poultry grit, and use in construction.

### *3.2.1 Shellfish meat*

Cockles are consumed for their taste and nutritional benefits and harvesting cockles is embedded deep within the history and culture of European countries. Humans have gathered cockles for consumption since at least Neolithic times (Montgomery et al., 2013). The historical importance of cockles as a food source for people is highlighted by their presence in many middens across Europe (e.g. Murray, 2011; Duarte et al., 2017). Today a multinational industry has grown around the processing and supply of cockles to markets in continental Europe, the UK and Ireland, and beyond.

Shellfish meat is a good source of many vitamins and minerals and is low in saturated fat and high in the omega-3s DHA and EPA (Heid, 2018). Using literature data collated in WP4, cockle bed regions across partner countries with ten or more years of recorded tonnage data between 2000 and 2017 were identified, and an annual average amount of cockle meat (dry weight) harvested has been calculated (Figure 2). It is unknown whether gaps within the data record for these regions are a result of failed/no harvesting or missing/un-recorded data.

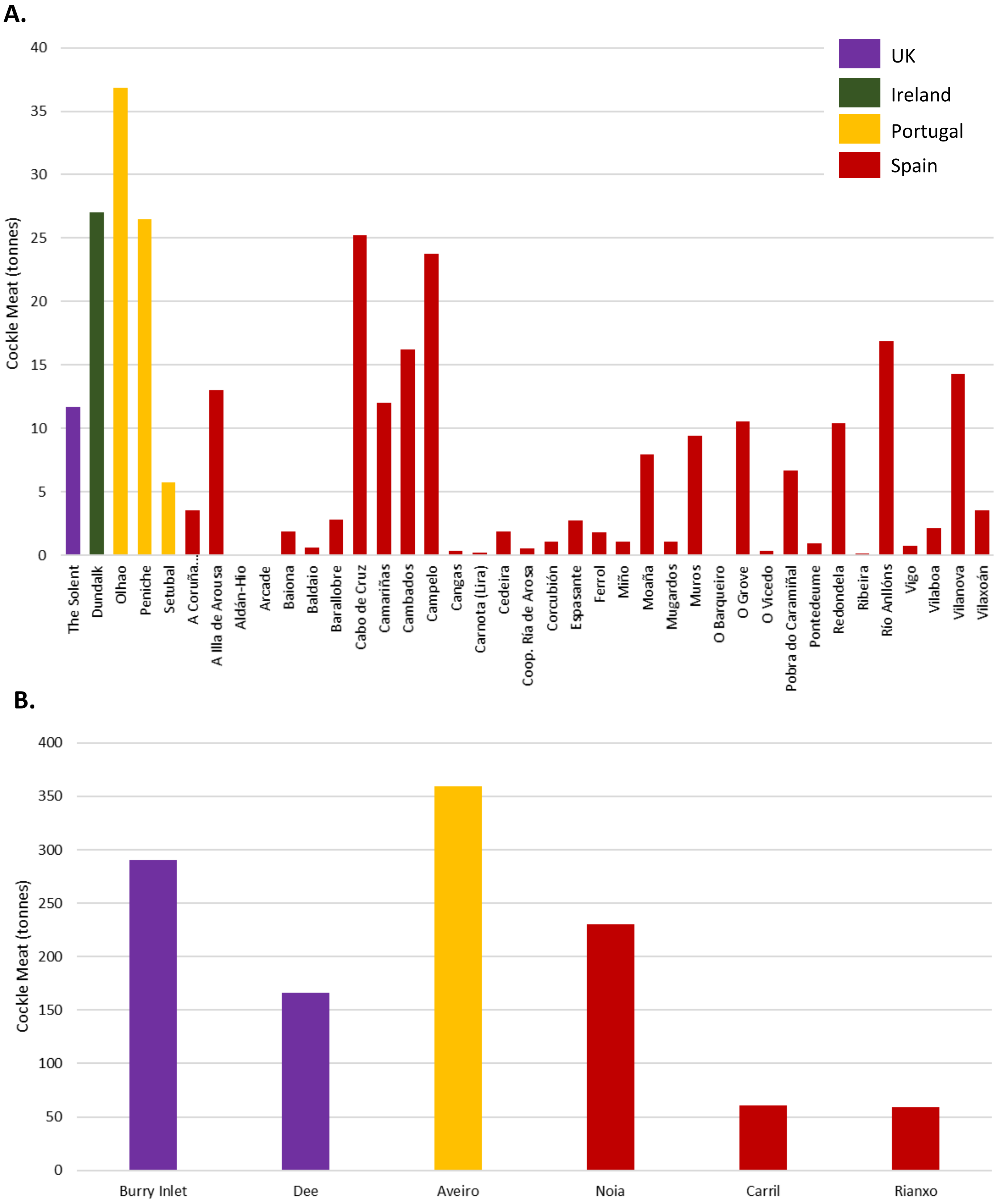

Figure 2 Average annual amount of cockle meat harvested from 2000 and 2017 across selected sites in partner countries of a) low yield regions and b) high yield regions.

For partner countries there is a consistent record of tonnage by the FAO between 2000 and 2017, and average annual amount of cockle meat harvested per country is listed in Table 2.

| **Country** | **Average annual amount of cockle meat (tonnes)** |
|---|---|
| France | 309 |
| Ireland | 31 |
| Portugal | 445 |
| Spain | 501 |
| United Kingdom (Wales) | 2118 |

Table 2 Average Annual Amount of cockle meat (dry weight) harvested between 2000 and 2017 per Atlantic Area partner country, using FAO reported tonnages.

As well as harvesting for commercial purposes, there is often a commonly accepted 'public right' to collect shellfish along the foreshore (Meadowcroft and Blundell, 2004) although in certain countries the amount is limited per person per day when the fishery is open. In Ireland, historically cockles were collected by the poorer in society (West et al., 1979). Cockle meat is also used by recreational anglers as an effective bait for a wide variety of sea fishes, including cod (*Gadus morhua*), flounder (*Platichthys flesus*), dab (*Limanda limanda*) (SeaAngler, 2009).

### *3.2.2 Shell by-products*

Cockle shells are used for a variety of purposes, including chicken grit, aggregate and for ornamental uses. Shells for these purposes are sourced from shellfish processing centres. Traditionally, after the meat was removed the shells were left to dry for several months before being heat treated and then crushed to the appropriate size. Modern approaches involve some pre-treatment of the shells, and the development of value-added products for construction, including mortar, aggregate, and fillers.

Average annual amount of cockle shell harvested across cockle regions as per section 3.2.1 is shown in *Figure 3,* with country averages reported in Table 3.

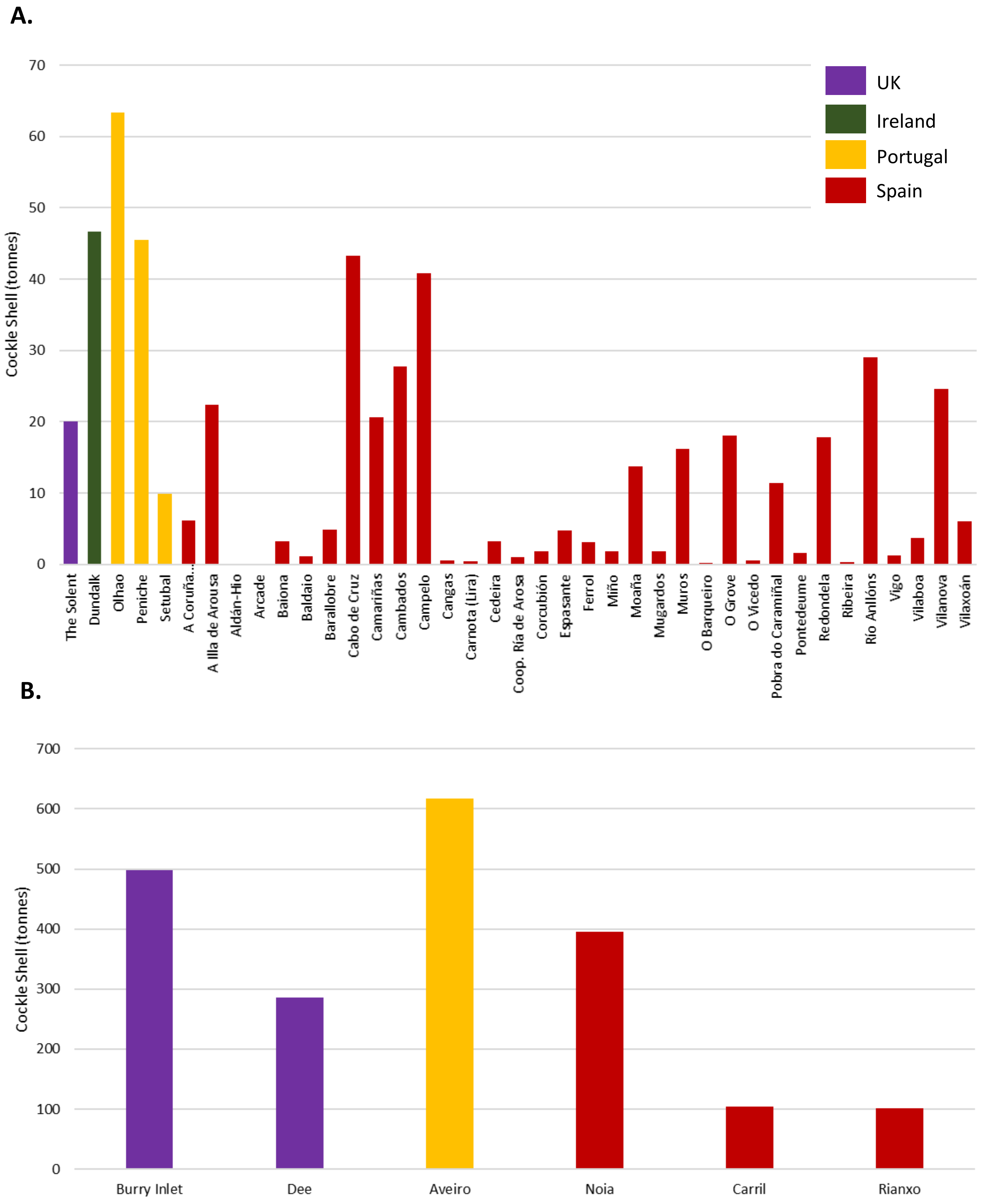

Figure 3 Average annual amount of cockle shell by-product from 2000 and 2017 across selected sites in partner countries for a) low yield regions and b) high yield regions.

| Country | Average annual amount of cockle shell (tonnes) |
|---|---|
| France | 530 |
| Ireland | 53 |
| Portugal | 765 |
| Spain | 860 |
| United Kingdom (Wales) | 3630 |

Table 3 Average Annual Amount of cockle shell by-product between 2000 and 2017 per Atlantic Area partner country, using FAO reported tonnages

#### *3.2.2.1 Poultry grit*

Global poultry production has been estimated at 21 billion birds per year, producing 1.1 trillion eggs and approximately 90 million tonnes of meat annually (Blake and Tomley, 2014). Cockle shells are one of the two main shell types used in poultry grits (ground-up shell is mixed with ground granite and fed to poultry to help digestion and to provide calcium for egg shells) as their shells do not break down into sharp shards: unlike mussel and scallop shells (van der Schatte Olivier et al., 2018).

#### *3.2.2.2 Construction and other uses*

Shell aggregate can be worth between \$240 and \$2,400 $t^{-1}$ (Morris et al. 2018) and one of the most common uses for cockle shells is for pathways (Figure 1). Studies have investigated the potential of cockle shell ash as a material for partial cement replacement or a filler material. Incorporation of ground seashells resulted in reduced water demand and extended setting times of mortar, which is advantageous for rendering and plastering in hot climates. Mortar containing ground seashells also showed less shrinkage with drying and lower thermal conductivity compared to conventional cement, thereby improving the workability of rendering and plastering mortar (Hazurina Othman et al., 2013; Lertwattanaruk et al., 2012). Concrete made with shell fragments as a major component of the aggregate (up to 40 %), is a suitable substrate for artificial reefs, which provide effective refuge areas for marine biodiversity (Olivia et al., 2017) (Carr and Hixon, 2004).

### 3.3 Regulating services

The CICES regulating services that cockles provide include the Division ‘Regulation of physical, chemical, biological conditions’, further broken down into the following Groups: ‘Atmospheric composition and conditions (2.2.6.1)’ ≈ carbon sequestration, ‘Water conditions (2.2.5.2) ≈ Salt water quality through filtration, ‘Regulation of baseline flows and extreme events’ (2.2.1.1) - erosion control, ‘Pest and disease control’ (2.2.3.2) ≈ disease control. They also include the Division ‘Transformation of biochemical or physical inputs to ecosystems’, which contains the group ‘Mediation of wastes or toxic substances of anthropogenic origin by living processes’ (2.1.1) ≈ pathogen and toxin removal.

#### *3.3.1 Carbon sequestration in shell and sediment*

Bivalve aquaculture is gaining widespread attention because of its role in the carbon cycle in relation to mitigating climate change. Bivalves sequester carbon in the form of calcium carbonate via shell production (Peterson & Lipcius 2003; Hickey 2009). The average carbon in bivalve shell is 11.7%, although this varies between species. Currently there are no published figures for shell %C content of *C. edule* (van der Schatte Olivier et al., 2018). However, although shell formation fixes carbon, the biogeochemical processes involved also lead to the release of $CO_2$ into the atmosphere via the water column. Therefore, there is ongoing debate on whether there is a net sequestration of carbon as a result of shell formation, and whether it can be counted as an ecosystem service.

#### *3.3.2 Nutrient removal*

Shellfish remove both nitrogen and phosphorous in a variety of ways (Carmichael et al. 2012). Nitrogen and phosphorus are taken up and used for both shell and tissue growth, and will be removed from the ecosystem when animals are harvested (van der Schatte Olivier et al., 2018). Cockles also remove nutrients from the water column through the production of biodeposits in the form of faeces and psuedofaeces. The biodeposits increase the denitrification potential by providing anoxic environments for denitrifying bacteria (Newell et al. 2005). This microbial-facilitated process releases nitrogen gas ($N_2$) from the aquatic system to the atmosphere. To our knowledge, there is no published quantification of %N and %P content of cockle shell and tissue. Analysis within this work package will present the first analysis of this kind, meanwhile the average annual physical quantities of nitrogen and phosphorus remediated between 2000 and 2017 has been calculated using methods in van der Schatte Olivier et al. (2018). Country totals are provided in Table *1*Table 4, with values for cockle regions (as per section 3.2.1) shown in Figure 4 and Figure 5.

| **Country** | **Average annual amount of nitrogen remediated (tonnes)** | **Average annual amount of phosphorus remediated (tonnes)** |
|---|---|---|
| France | 5 | 1 |
| Ireland | 1 | 0 |
| Portugal | 8 | 1 |
| Spain | 8 | 1 |
| United Kingdom (Wales) | 35 | 2 |

Table 4 Average Annual Amount of nitrogen and phosphorus remediated between 2000 and 2017 per Atlantic Area partner country, using FAO reported tonnages

### *3.3.3 Erosion protection*

While cockles do not form large reefs in the same way most oyster and mussel species do, their activity can lead to increased bed stability and reduced erosion risk in sandy substrates, but see section 3.1.2 for a description of processes which have the opposite effect in fine silty sediment. The biodeposition of fine-grained material, the production of mucus and the formation of a structural layer of shells within the sediment layer are all factors which increase surficial stability, hence reducing erosional processes caused by hydrodynamic forces (Andersen et al. 2010, Eriksson et al. 2017) (see more detailed description of the processes in section 3.1.2).

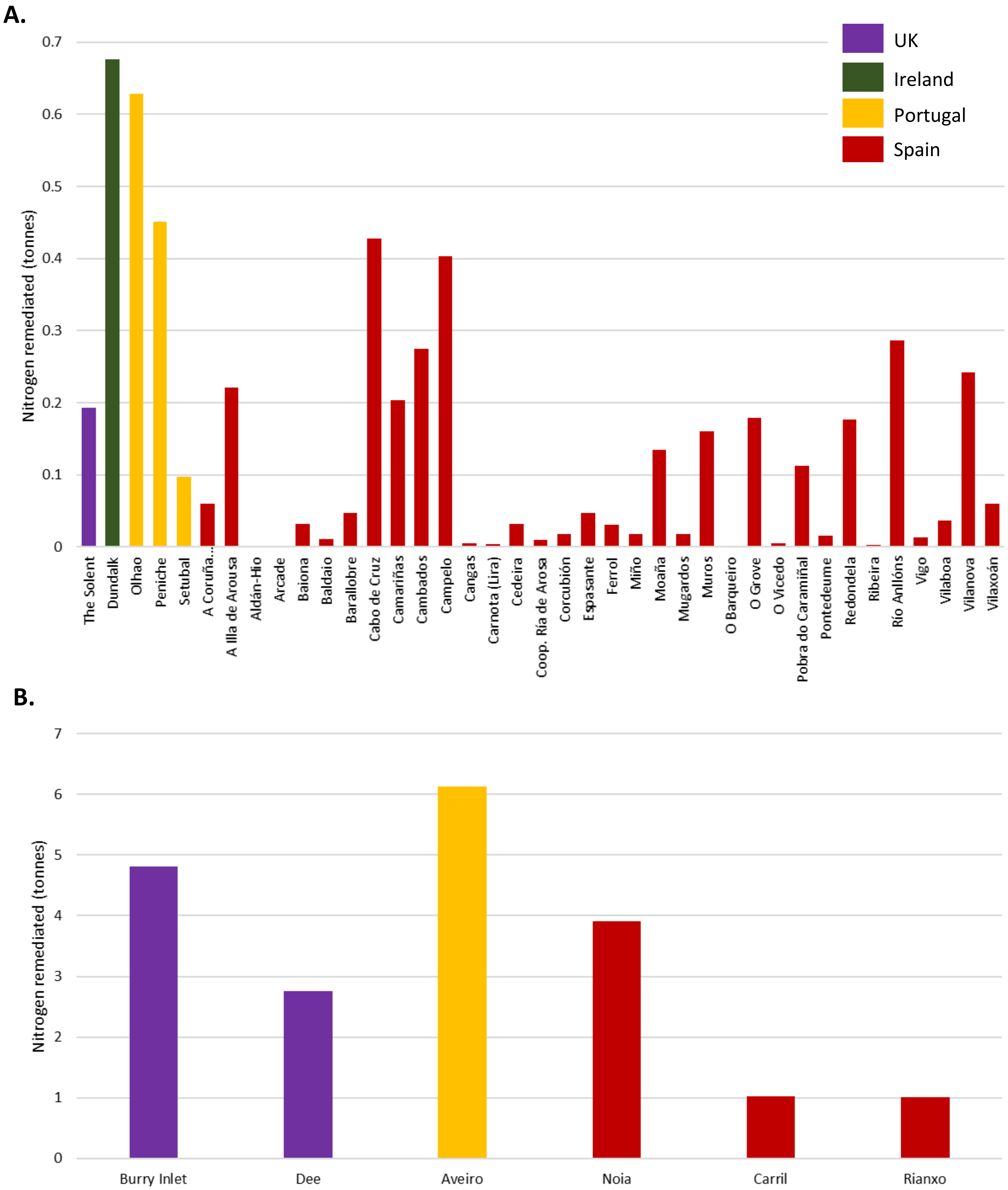

Figure 4 Average annual amount of nitrogen remediated as a result of cockle harvesting from 2000 and 2017 across selected sites in partner countries for a) low yield regions and b) high yield regions.

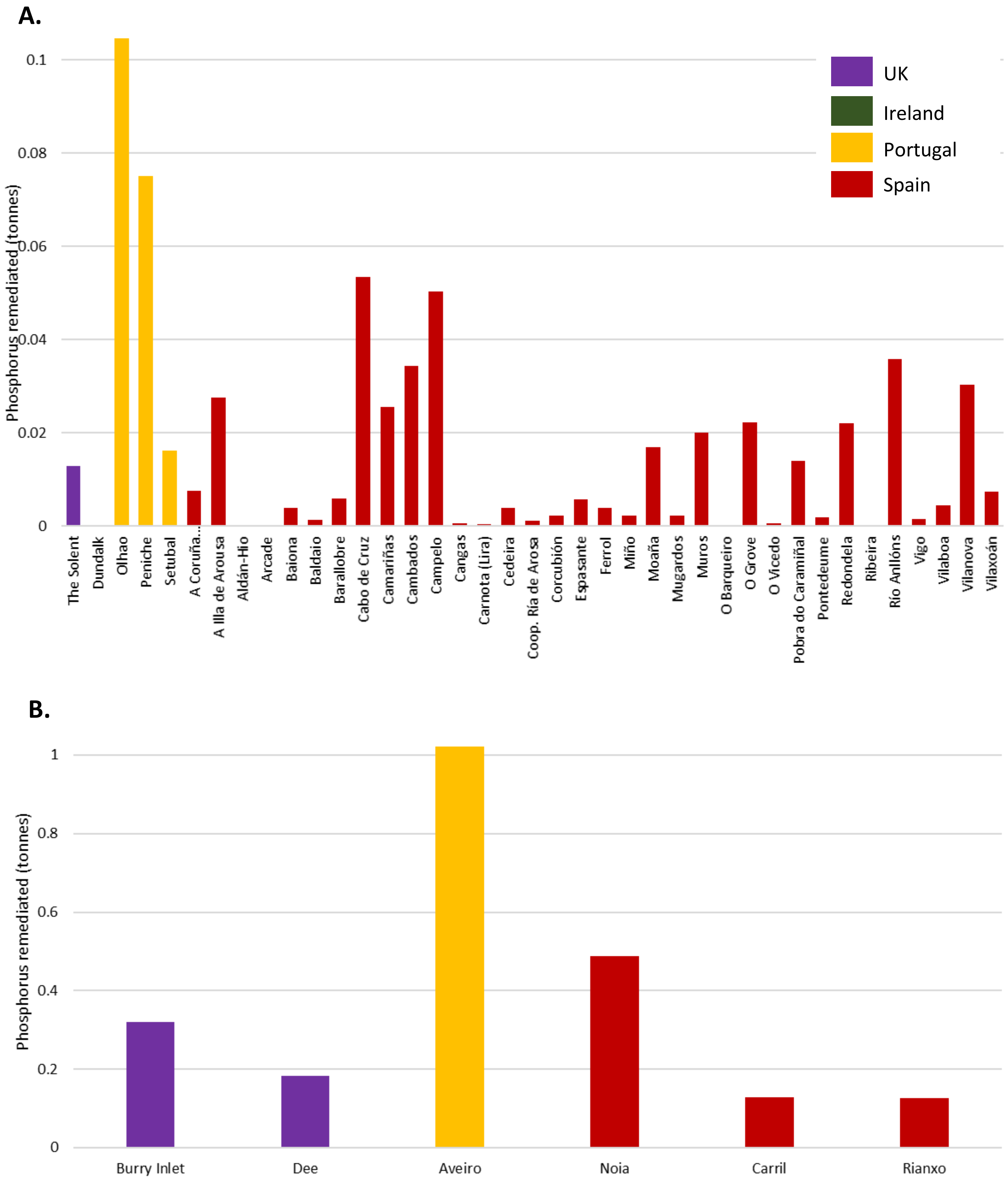

Figure 5 Average annual amount of phosphorous remediated as a result of cockle harvesting from 2000 and 2017 across selected sites in partner countries for a) low yield regions and b) high yield regions.

### 3.3.4 Disease regulation

Cockles are hosts to a wide variety of parasites and diseases (Longshaw and Malham 2013). As with other filter and deposit feeding organisms, cockles can accumulate agents that are potentially 'pathogenic' (Zannella et al 2017). This can both positive and negative effects, either accumulation in the cockles thus reducing general pathogen load, or alternatively acting as a reservoir for subsequent infection of other species. The high levels of MPB biofilms associated with cockles beds may increase the persistence of infectious agents in the sediment. Further research is required to better estimate the positive and negative influence of bivalves on pathogen levels in the coastal environment (Zannella et al 2017).

### *3.3.5 Pathogen and toxin removal*

Harmful algal blooms in the coastal zone are regarded with some concern, as they can have direct impacts on human health, as well as the environment (Berdalet et al., 2016). Most algal toxins are relatively harmless for bivalves but they accumulate and concentrate toxic compounds that can be lethal to humans or other consumers (Anderson 2009). The toxins do not remain indefinitely, but are eliminated at rates dependent on the physiological mechanisms of the bivalve and the type of toxin (Blanco, 2018). Modelling studies suggest that removal of harmful algae cells and cysts by shellfish can occur, but is dependent on the bivalve species and their filtering capacity (Yñiguez et al 2018). Cockles remove significant amounts of phytoplankton biomass through filter feeding, however few studies have focused on the potential to reduce quantities of harmful algae. Furthermore, while they may provide a service in reducing the incidence or severity of algal blooms, there can be trade-offs with cockle harvest for human consumption.

## 3.4 Cultural services

The classification of cultural ecosystem services in CICES is wordy, but broadly encompasses Divisions describing direct (*in situ*) or indirect (remote) interactions with living or abiotic systems. These are further categorised into Groups which include: 'Physical and Experiential (3.1.1)', 'Intellectual and Representative (3.1.2)', 'Spiritual or Symbolic (3.2.1)' and other 'non-use (3.2.2)' interactions.

A suite of cultural services for cockles with 'value' to individuals and society emerged clearly during the workshops and subsequent meetings with the participants from all five countries. These included evidence of interactions with the physical landscape passing from generation to generation, and also of intangible aspects of cultural behaviour (cf. Tenberg et al. 2012). They are described under the CICES group-headings below.

### *3.4.1 Physical and experiential*

Perhaps the most common manifestation of this was the ubiquitous value attached to family-focused activities, where cockles formed part of a wider evocation of 'place' (Fish et al. 2016):

- Family holidays or day trips to the seaside
- Memories of childhood, often recreated by adults now with their own children – very often spanning several generations
- Space to play: sandy/muddy shores – shallow water, relatively safe environments, easy access
- Wide vistas of sea and sky – high visual amenity
- Collecting, cooking and eating cockles as a family/summer activity

Alongside non-commercial ('family') harvesting conducted as part of a social activity, there was also evidence for strongly traditional cultural activities in relation to small-scale commercial harvesting of cockles (often referred to as 'gathering'). These traditional practices were widespread, for example cockles have been gathered in Wales (Jenkins 1984) and Galicia (Villalba et al., 2014) for centuries - providing much-needed employment (very often for women) and cheap food. In Galicia, there is a growing movement working for cockle gathering to be granted a protected 'cultural landscape' status in the Ría de Noia.

### *3.4.2 Intellectual and representative*

The largest body of evidence fell under this category, encompassing art, architecture, and advertising. Cockles and cockle harvesting are represented in both historical and contemporary art. One of the earliest records of cockles in European human culture relates to *Cardium* pottery. This is a Neolithic (6400 BC - 5500 BC) decorative style of pottery derived from imprinting clay with the shells of cockles (formerly named *Cardium edule*). This pottery style gives its name to the main Mediterranean Neolithic culture – 'Cardial' culture – which extended from the Adriatic Sea to the Atlantic coasts of France, the Iberian Peninsula and Morocco (see for example, Spataro 2009).

Modern examples of art include a sculpture in Aveiro, Portugal, by the artist Albano Martins. The sculpture embodies a giant cockle shell (Figure 1) as a homage to Ovos Moles de Aveiro ("soft eggs from Aveiro") a local sweet delicacy made from egg yolks and sugar, frequently put inside small rice paper casings in sea-themed shapes such as shells. The artist Raphael Bordallo Pinheiro (1846-1905) was one of the most influential people in nineteenth century Portuguese culture, associated with caricature and artistic ceramics. He was responsible for an internationally recognised cockle-shaped piece produced by the ceramics company Bordallo for advertising purposes. In Spain there is a rich tradition of cockles and other shellfish being represented in fine art during the 20th Century, particularly in relation to harvesters (often women) and specific estuarine habitats with shifting land- and seascapes. A number of Spanish sculptors have depicted cockle fishers, either as monuments to them and their activities or in the form of individuals representing 'place' in terms of their clothing and harvesting tools, 'status' in terms of their means of livelihood, and 'freedom' in terms of their activity and relation to nature. Evoking coastal landscapes and activities, cockle fishing is also represented in French, Irish and British art works, including in Ireland a recent (2018) sculpture called '*The Cocklepickers*' celebrated the historic culture of local cockle picking (Figure 1). Possessing or viewing such art works feeds into, and is deeply interwoven with, notions and memories of family-focused activities with cockles evoking a strong sense of 'place' (Fish et al. 2016).

As well as the examples described above, the workshop also produced other examples of cultural services provided by cockles. For example, their shells are an element of tourist trinkets and souvenirs in many coastal towns and villages (Figure 6). Collecting seashore shells is a worldwide leisure activity, and is the basis of the scientific discipline of malacology. They are used as examples of anatomy and invertebrate structure in zoological textbooks; the presence of shells in the fossil record informs evolutionary studies; and their mineral content can reveal past climatological events and act as long-term archives.

Figure 6. **Clockwise from the left:** a) Oves Molles © Laurence Jones; b) cockle shells as an element of a tourist trinket/souvenir © David Carss ; c) ‘*The Cocklepickers*’ by Michéal McKeown in Blackrock, Co. Louth, Ireland. The sculpture overlooks Dundalk Bay, an area of importance for cockles historically and currently © Kate Mahony ; d) cockle shells used on footpath on Ynys Llanddwyn, Wales © Andrew van der Schatte Olivier ; e) Molly Malone statue by Jeanne Rynhart in Dublin (Nol Aders, Wikimedia Commons [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)]e,)].

### *3.4.3 Spiritual and symbolic*

Cockles in folklore are difficult to classify, forming part of both inspirational but also symbolic values. Here we chose to group them under the latter, due to their role in defining national identity. Perhaps the most widely known example is that presented in the Irish (but also claimed as originally Scottish) folk song (ca. 1870s-1880s) celebrating the life of Molly Malone (see Murphy 1992). The song (variously titled: “Molly Malone”, “Cockles and Mussels” or “Dublin’s Fair City”) tells of a fishmonger who plied her trade on the streets. The persona of Molly Malone and her cry of “Cockles and mussels, alive, alive oh!” have become world famous. Set in Dublin, the song has become the unofficial anthem of Ireland sung regularly by crowds at international sporting events. Other human-associated links with cockles are seen in structures such as tombs (O’Nualláin, 1989), ringforts and monasteries (Murray, 2011).

### *3.4.4 Other non-use values*

One service rarely discussed is the role of biotic/abiotic inspiration in language. Cockles provide some interesting examples, with some unusual alternative meanings in slang and vernacular language in several countries. In Cornwall, south west England, cockle gathering or 'raking' occurs each spring as part of the Christian Easter celebrations and is called "trigging" in the local dialect. This word is also slang for female masturbation (see lyrics for OutKast song 'Caroline'). In Portugal, *berbigão* - the word for cockle - is used as a synonym for the clitoris in vernacular language, presumably as a result of similarities in appearance between the shucked bivalve and the human female sex organ.

Besides cockles, but ecologically dependent on them (see section 2.5), shorebirds are also observed and used as artistic and spiritual inspiration by millions of people around the globe (Whelan et al. 2015) and the large flocks of oystercatchers, red knot and other cockle-feeding birds are an integral part of the cultural experience of a visit to the coast. The indirect value of cockles to the bird watching economy is difficult to quantify but undoubtedly contributes to visitor numbers in coastal areas.

## 3.5 Preliminary valuation of ecosystem services from cockles in Europe

The value of harvested cockles is mainly in the market value of their meat, and though nutrient remediation is a valuable service, the largest non-food value is ascribed to shell waste. Average annual potential economic value of these services per partner country is listed in Table 5, with potential values for cockle regions across the Atlantic area displayed in Figure 7 and Figure 8.

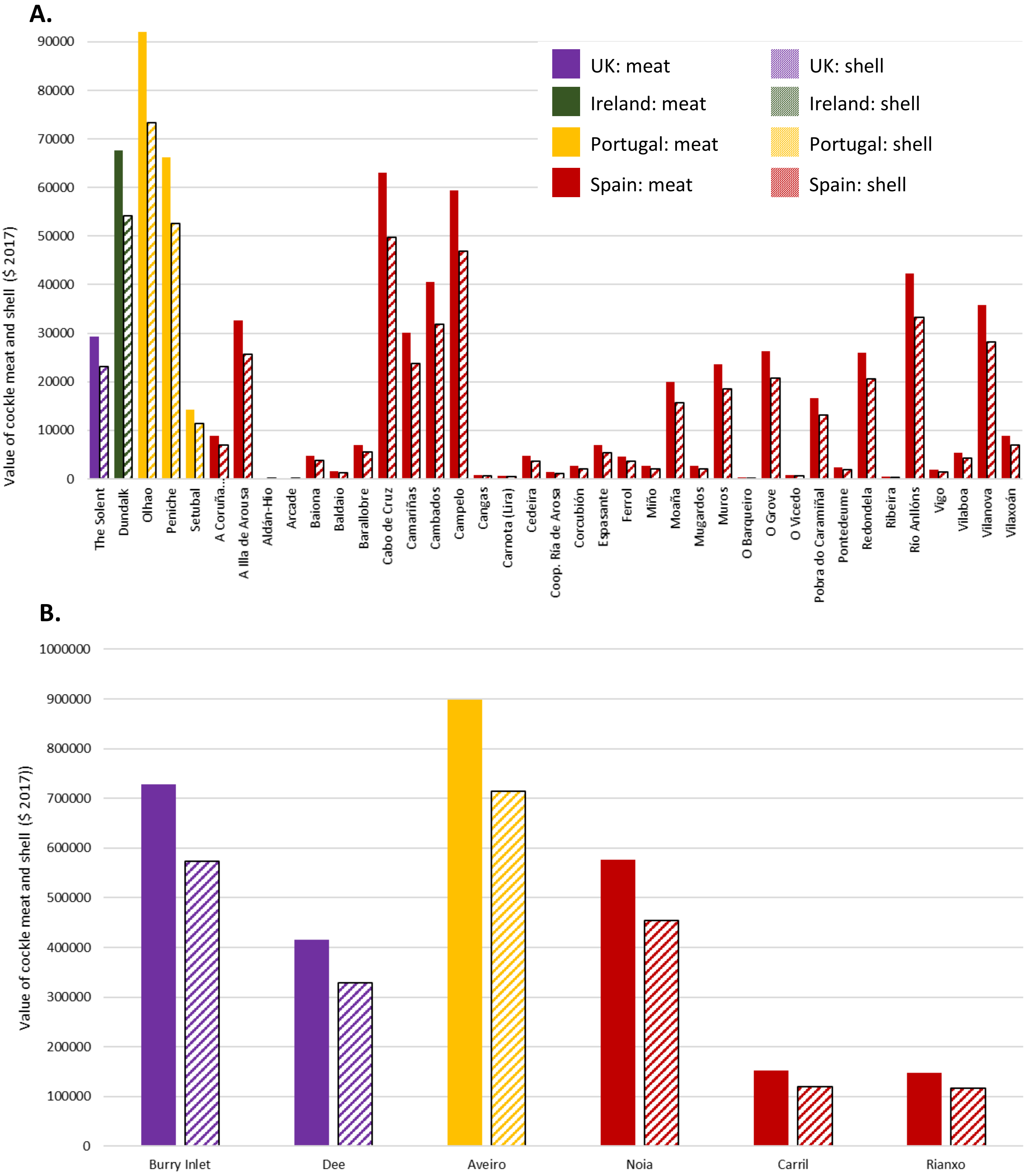

Figure 7: Average annual value of cockle meat and shell from 2000 and 2017 across selected sites in partner countries for a) low yield regions and b) high yield regions.

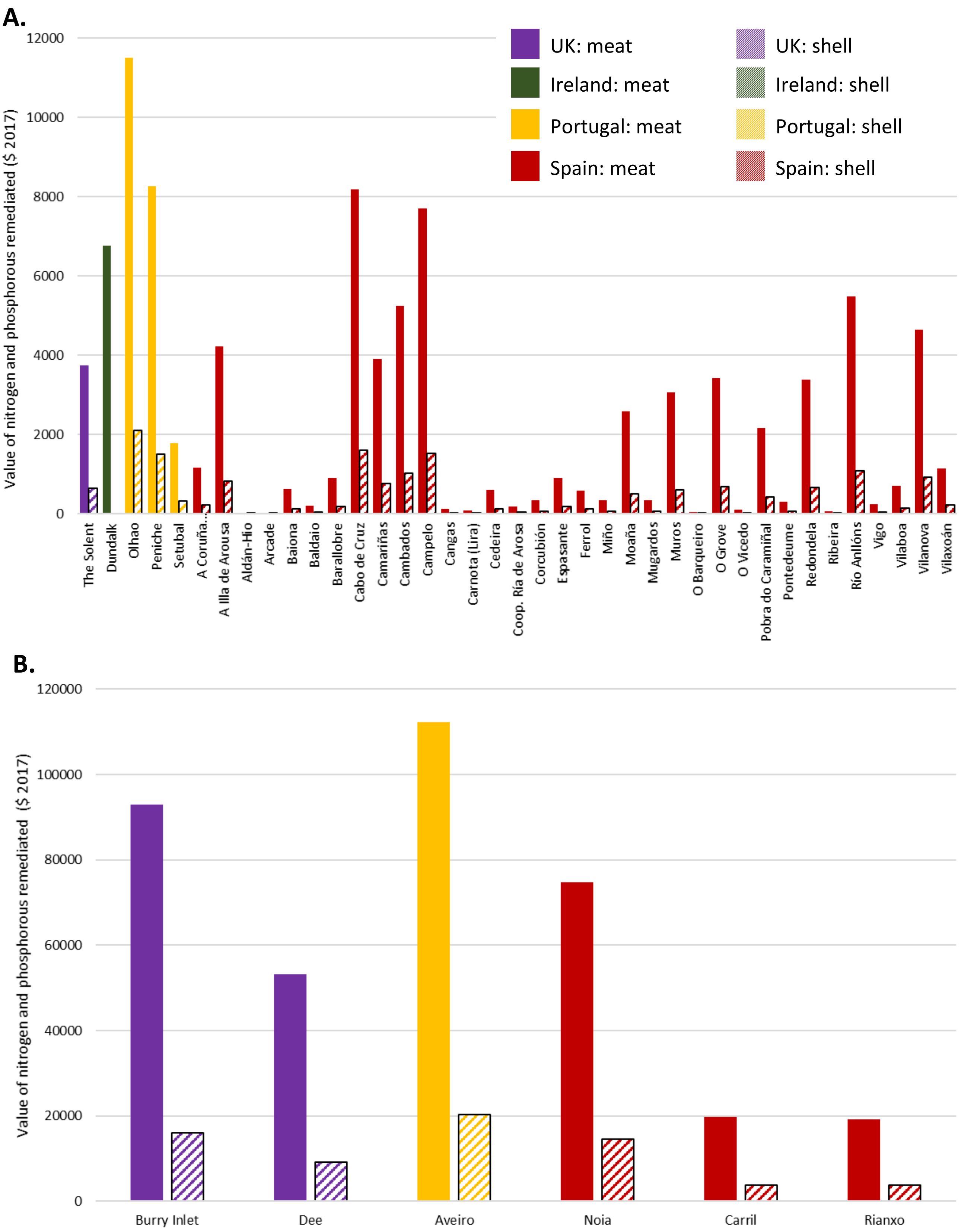

Figure 8 Average annual value of nitrogen phosphorous remediated as a result of cockle harvesting from 2000 and 2017 across selected sites in partner countries for a) low yield regions and b) high yield regions.

| Country | Meat | Shell | Nitrogen remediated | Phosphorous remediated |
|---|---|---|---|---|
| **France** | $779,435 | $616,297 | $99,695 | $18,126 |
| **Ireland** | $76,769 | $61,415 | $7,677 | $1,535 |
| **Portugal** | $1,113,443 | $885,694 | $139,180 | $25,306 |
| **Spain** | $1,252,931 | $987,480 | $162,456 | $31,854 |
| **United Kingdom (Wales)** | $52,996,210 | $4,178,996 | $677,044 | $116,732 |

Table 5: Average annual value between 2000 and 2017 of cockle meat (dry weight), shell, remediated nitrogen and remediated phosphorous per Atlantic Area partner country.

# 4. CONCLUDING REMARKS

The cockle is an important commercial and cultural species in those habitats/land-sea-scapes where it is common. This study suggests that cockles are likely often overlooked, compared to other commercial bivalve species, in relation to their position and value within ecosystems. Whilst often considered the 'poor relation' of mussels and oysters, cockles clearly contribute significantly to the coastal systems where they occur. Indeed, many innovations involving cockles could be derived for estuarine ecosystem management plans. As an ecosystem engineer, the species is very effective at making sedimentary habitats productive whilst also playing a positive role in intertidal mud accretion. Cockles could thus play an important role in coastal defence against the effects of erosion in areas with sandy sediments, which is expected to increase in the current context of global change. Moreover, the species also helps ensure a certain resilience to estuarine ecosystems, and indeed is a keystone species, in terms of supporting diversity and productivity of other species, and the associated ecosystem services the cockles provide such as water purification, eutrophication control, nursery, and refuge areas for migratory species.

A second point to note is the wider societal value of cockles and the positive implication for their sustainable management through acknowledgement of the diverse cultural ecosystem services associated with them. There is a clear link between cockle harvesting and the historically less affluent coastal communities (acknowledged in popular songs and poems of oral tradition for example), and this was a common feature of the cultural footprint of cockles in all areas covered by the present work. Such clear cultural associations also suggest that the cockle may be a useful species to include in future exploration of cultural ecosystem services in coastal areas. Despite difficulties in quantitatively assessing cultural ecosystem services, they are often more directly and intuitively recognised by local stakeholders. Some studies suggest that the perception of value and the willingness to pay for environmental protection and greater management costs is normally higher in coastal indigenous communities than inland, when compared with other trade-offs (Kirsten et al. 2015). Therefore, the work around cultural ecosystem services in cockles could facilitate the adoption of measures for a more sustainable approach to the management of this important coastal resource.

Against a background where little attention is usually given to cultural ecosystem services, there are calls to fill these knowledge gaps by linking ecosystem services research with cultural landscape research, through the common interest in the demands that people place on, and the benefits derived from, landscapes and ecosystems (Schaich et al 2010). Landscapes – or seascapes – have been shown to provide a useful conceptual bridge between ecosystem functions and cultural values in the ecosystem (e.g. Gee and Burkhard 2010) as clear relationships between them are inherently difficult to establish (Verje et al. 2010). The physical landscape is a foundation but intangible value is assigned by adding cognitive and imaginative overlays to this environment (Brady, 2003; see also Fischer & Hasse, 2001), the nature of which depends on prior experience, knowledge, imagination, expectations and tradition. In this context, so-called cultural heritage values (Millennium Ecosystem Assessment, MEA 2005) are important to consider in relation to ecosystem management because societies tend to place high value on the maintenance of historically important landscapes (cultural landscapes) or culturally significant species (Tenberg et al 2012). Cockles are strongly associated with physical landscapes - the intertidal reaches of muddy and sandy shores, often in estuarine areas - and are usually the culturally significant species there.

The 'humble' cockle thus has the potential to become not only an important focus of conservation and for improved sustainable management practices in relatively economically-deprived coastal areas and communities, but also a model study species for the better integration of cultural ecosystem services within the broader paradigm and application of 'ecosystem services' as a way of conceptualising the environment.

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## REFERENCES

Aller, R.C. (1982). The effects of macrobenthos on chemical properties of marine sediment and overlying water. In: McCall Pl, Tevesz MJS (eds)  Animal-sediment relations-the biogenic alteration of sediments. Topics in Geobiology Plenum Press, New York, Plenum Press, New York.

Anderson, DM. 2009. Approaches to monitoring, control and management of harmful algal blooms (HABs). Ocean & Coastal Management. 52: 342-347.

Andersen, T.J., Lanuru, M., van Bernem, C., Pejrup, M., Rirthmueller, R., 2010. In situ erosion measurements on fine-grained sediments from the Bay of Fundy. Mar. Geol., 108:175-196.

André, C. and Rosenberg, R. (1991) Adult–larval interactions in the suspension-feeding bivalves *Cerastoderma edule* and *Mya arenaria*. Marine Ecology Progress Series 71, 227–234.

Barbier, E.B., Hacker, S.D., Kennedy, K., Koch, E.W., Stier, A.C. & B.R. Silliman, 2011. The value of estuarine and coastal ecosystem servivces. Ecological Monographs, 81(2): 169-193.

Bateman IJ, Mace GM, Fezzi C, Atkinson G, Turner K (2011) Economic analysis for ecosystem service assessments. Environmental and Resource Economics 48: 177–218.

Beaumont N.J., Jones, L., Garbutt, A., Hansom, J.D., Toberman, M. (2014). The value of carbon sequestration and storage in UK coastal habitats. Estuarine, Coastal and Shelf Science 137, 32-40. http://dx.doi.org/10.1016/j.ecss.2013.11.022

Berdalet, E., Fleming, L.E., Gowen, R., Davidson, K., Hess, P., Backer, L.C., Moore, S., Hoagland, P., Enevoldsen, H., 2016. Marine harmful algal blooms, human health and wellbeing: challenges and opportunities in the 21st century. J Mar Biol Assoc UK, 96:61-91.

Beukema J.J. and Dekker R. (2005) Decline of recruitment success in cockles and other bivalves in the Wadden Sea: possible role of climate change, predation on postlarvae and fisheries. Marine Ecology Progress Series 287, 149–167.

Blake, D.P. & Tomley, F.M., 2014. Securing poultry production from the ever-present Eimeria challenge. Trends in Parasitology 30 (1) : 12-19. https://doi.org/10.1016/j.pt.2013.10.003.

Blanco, J., 2018. Accumulation of Dinophysis Toxins in Bivalve Molluscs. Toxins, 10: 453.

Brito, A.C., Newton, A., Tett, P. & Fernandes, T.F., 2010. Sediment and water nutrients and microalgae in a coastal shallow lagoon, Ria Formosa (Portugal): Implications for the Water Framwork Directive. J. Environ. Monit., 12 :318-328.

Brady, E., 2003. Aesthetics of the Natural Environment. Edinburgh University Press, Edinburgh.

Brock, V. & Kofoed, L.H. 1987, Species specific irrigatory efficiency in *Cardium* (Cerastoderma) *edule* (L.) and *C. lamarcki* (Reeve) responding to different environmental temperatures. Biological Oceanography 4 (3): 211-226. (https://doi.org/10.1080/01965581.1987.10749491)

Bryant D.M. (1979) Effects of prey density and site character on estuary usage by overwintering waders (Charadrii). Estuarine, Coastal and Marine Science 9, 369–384

Cadée G.C. (1994) Eider, shelduck, and other predators, the main producers of shell fragments in the Wadden Sea: palaeoecological implications. Palaeontology 37, 181–202.

Carmichael RH, Walton W, Clark H (2012) Bivalve-enhanced nitrogen removal from coastal estuaries. Canadian Journal of Fisheries and Aquatic Sciences 69:1131–1149

Carr, M.H., Hixon, M.A., 2004. Artificial Reefs: The Importance of Comparisons with Natural Reefs. Fisheries 22, 28–33. doi:10.1577/1548-8446(1997)022<0028:artioc>2.0.co;2

Chan, K.M.A., Satterfield, T. & Goldstein J. (2012) Rethinking ecosystem services to better address and navigate cultural values. Ecological Economics, 74:8–18. https ://doi.org/10.1016/j.ecolecon.2011.11.011

Ciutat, A., Widdows, J. & Pope, N.D. (2007). Effect of *Cerastoderma edule* density on near-bed hydrodynamics and stability of cohesive muddy sediments. Journal of Experimental Marine Biology and Ecology, 346, 114-126.

Ciutat, A., Widdows, J. & Readman, J.W. (2006). Influence of cockle *Cerastoderma edule* bioturbation and tidal-current cycles on resuspension of sediment and polycyclic aromatic hydrocarbons. Marine Ecology Progress Series, 328, 51-64.

Clements, J.C., Comeau, L.A. 2019. Nitrogen removal potential of shellfish aquaculture harvests in eastern Canada: A comparison of culture methods. Aquac. Reports 13, 100183. https://doi.org/10.1016/j.aqrep.2019.100183

Coen, L.D., Brumbaugh, R.D., Bushek, D., Grizzle, R., Luckenbach, M.W., Posey, M.H., Powers, S.P., Tolley, S.G., 2007. Ecosystem services related to oyster restoration. Mar. Ecol. Prog. Ser. 341, 303–307. https://doi.org/10.3354/meps341299

Cranford, P J., Ward, J E, Shumway S E. 2011. Bivalve filter feeding: variability and limits of the aquaculture biofilter. Chapter 4 in: Shumway SE (ed) Shellfish Aquaculture and the Environment. Wiley-Blackwell, Hoboken.

Díaz S, Demissew S, Carabias J et al (2015) The IPBES conceptual framework—connecting nature and people. Current Opinion in Environmental Sustainability, 14:1–16. https://doi.org/10.1016/j.cosus t.2014.11.002

Donadi, S., Westra, J., Weerman, E.J., van der Heide, T., van der Zee, E., van de Koppel, J., Olff, H., Piersma, T., van der Veer, H.W., Eriksson, B.K., 2013. Non-trophic interactions control benthic producers on intertidal flats. Ecosystems, 16:1325-1335.

Duarte, C., Iriarte, E., Diniz, M., Arias, P., 2017. The microstratigraphic record of human activities and formation processes at the Mesolithic shell midden of Poças de São Bento (Sado Valley, Portugal). Archaeological and Anthropological Sciences, 11(2), 483-509.

Duncan, P.F., Ghys, A., 2019. Shells as Collector's Items, in: Smaal, A.C., Ferreira, J.G., Grant, J., Petersen, J.K., Strand, Ø. (Eds.), Goods and Services of Marine Bivalves. Springer International Publishing, Cham, pp. 381–411. https://doi.org/10.1007/978-3-319-96776-9_20

Elliott, M., Burdon, D., Callaway, R., Franco, A., Hutchinson, T., Longshaw, M., Malham, S., Mazik, K., Otto, Z., Palmer, D., Firmin, C., Smith, T., Wither, A., 2012. Burry Inlet Cockle Mortalities Investigation 2009-2011. Technical Report to Environment Agency Wales, 337p.

Ens BJ, Smaal AC, De Vlas J (2004) The effects of shellfish fishery on the ecosystems of the Dutch Wadden Sea and Oosterschelde. Final report on the second phase of the scientific evaluation of the Dutch shellfish fishery policy (EVA II). Alterra Rapport 1011, RIVO rapport C056/04, RIKZ-rapport RKZ/2004.031, Alterra, Wageningen

Ens, B.J., Kats, R., Camhuysen, K. (C. J.) (2006) Why was there no mass starvation of Eiders *Somateria mollissima* in the Netherlands in winter 2005/06? Waarom zijn Eiders niet massaal gestorven in de winter van 2005/2006? Limosa 79:95-106.

Fernandes, S., Sobral P., Van Duren L., 2007. Clearance rates of *Cerastoderma edule* under increasing current velocity? Continental Shelf Research, 27: 1004-1115.

Fish, R., Church, A. & Winter, M., 2016. Conceptualising cultural ecosystem services: a novel framework for research and critical engagement. Ecosystem services, 21: 208-217. https://doi.org/10.1016/j.ecoser.2016.09.002

Fischer, L. & Hasse, J., 2001. Historical and current perceptions of the landscapes in the Wadden Sea Region. In: Vollmer, M., Guldberg, M., Maluck, M., van Marrewijk, D., Schlicksbier, G. (Eds.), Landscape and Cultural Heritage in the Wadden Sea Region—Project Report. Wadden Sea Ecosystem No. 12. Common Wadden Sea Secretariat, Wilhelmshaven, Germany, pp. 72–97.

Floor, J.R., van Koppen, C.S.A. (Dris)., Lindeboom, H.J. 2013. A review of science-policy interactions in the Dutch Wadden Sea – The cockle fishery and gas exploitation controversies. Journal of Sea Research. 82: 165-175

Fodrie, F.J., Rodriguez, A.B., Gittman, R.K., Grabowski, J.H., Lindquist, N.L., Peterson, C.H., Piehler, M.F., Ridge, J.T., 2017. Oyster reefs as carbon sources and sinks. Proc. R. Soc. 284. doi:10.6084/m9

Garcia Rodrigues, J., Conides, A., Rivero Rodriguez, S., Raicevich, S., Pita, P., Kleisner, K., Pita, C., Lopes, P., Alonso Roldán, V., Ramos, S., Klaoudatos, D., Outeiro, L., Armstrong, C., Teneva, L., Stefanski, S., Böhnke-Henrichs, A., Kruse, M., Lillebø, A., Bennett, E., Belgrano, A.,, Murillas A., Sousa Pinto, I., Burkhard, B., Villasante, S. 2017. Marine and Coastal Cultural Ecosystem Services: knowledge gaps and research priorities. One Ecosystem 2: e12290. https://doi.org/10.3897/oneeco.2.e12290

Gee, K. & Burkhard, B. 2010. Cultural ecosystem services in the context of offshore wind farming: a case study from the west coast of Schleswig-Holstein. Ecological Complexity 7: 349-358.

Gentry, R.R., Alleway, H.K., Bishop, M.J., Gillies, C.L., Waters, T., Jones, R., 2019. Exploring the potential for marine aquaculture to contribute to ecosystem services. Rev. Aquac. 1–14. https://doi.org/10.1111/raq.12328

Grabowski, J.H., Peterson, C.H., 2007. Restoring oyster reefs to recover ecosystem services. Theor. Ecol. Ser. 4, 281–298. https://doi.org/10.1016/S1875-306X(07)80017-7

Haines-Young, R. and M.B. Potschin (2018): Common International Classification of Ecosystem Services (CICES) V5.1 and Guidance on the Application of the Revised Structure.

Hayward, P.J. & Ryland, J.S. 1995. Handbook of the Marine Fauna of North-West Europe. Oxford University Press, Oxford, pp 812.

Hazurina Othman, N., Hisham Abu Bakar, B., Mat Don, M., Azmi Megat Johari, M. 2013. Cockle shell ash replacement forcement and filler in concrete. Malaysian J. Civ. Eng. 25, 201–211. https://doi.org/10.11113/MJCE.V25N2.303

Heid, M. 2018. Is Shellfish Healthy? Here's What the Experts Say. *Time*. [online] Available at: http://time.com/5341293/is-shellfish-healthy/ [Accessed 21 Feb. 2019].

Herbert, R.J.., Roberts, C., Humphreys, J., Fletcher, S., 2012. The Pacific Oyster (*Crassostrea gigas*) in the UK: Economic, Legal and Environmental Issues Associated with its Cultivation, Wild Establishment and Exploitation. Report to Shellfish Association of Great Britain.

Hickey, J.P. 2009. Carbon sequestration potential aof shellfish. Available from URL; www.thefishsite.com/articles/615/carbon-sequestationpotential-of-shellfish. (accessed 09 August 2019).

Iglesias, J.I.P., Urrutia, M.B., Navarro, E., Alvarez-Jorna, P., Larretxea, X., Bougrier, S. and Heral, M., 1996. Variability of feeding processes in the cockle *Cerastoderma edule* (L.) in response to changes in seston concentration and composition. Journal of Experimental Marine Biology and Ecology, 197(1), pp.121-143.

Jenkins. J.G. 1984. Cockles and Mussels: aspects of shellfish-gathering in Wales. National Museum of Wales (Welsh Folk Museum), pp32, Cardiff.

Jones M.L.M., Angus S., Cooper A., Doody P., Everard M., Garbutt A., Gilchrist P., Hansom G., Nicholls R., Pye K., Ravenscroft N., Rees S., Rhind P. & Whitehouse A. (2011) Coastal margins [chapter 11]. In: UK National Ecosystem Assessment. Understanding nature's value to society. Technical Report. Cambridge, UNEP-WCMC, 411-457.

Jones, L., Norton, L., Austin, Z., Browne, A.L., Donovan, D., Emmett, B.A., Grabowski, Z.J., Howard, D.C., Jones, J.P.G., Kenter, J.O. and Manley, W., 2016. Stocks and flows of natural and human-derived capital in ecosystem services. Land Use Policy, 52, pp.151-162.

Kamermans, P. & Smaal, A.C. 2002. Mussel culture and cockle fisheries in The Netherlands: finding a balance between economy and ecology. J. Shellfish Research, 21: 509–517.

Karlson, K., Bonsdorff, E., Rosenber, R., 2007. The impact of Benthic Macrofauna for Nutrient Fluxes from Baltic Sea Sediments. Ambio, 36:161-167.

Kelley, K.N. 2009. Use of Recycled Oyster Shells as Aggregate for Previous Concrete. MSC Thesis, pp.64. University of Florida, Gainesville, FLA. 64.

Kirsten L.L., Oleson, M.B., Brander, L.M, Oliver, T.A., van Beek, I., Zafindrasilivonona, B. & van Beukering, P. 2015. Cultural bequest values for ecosystem service flows among indigenous fishers: A discrete choice experiment validated with mixed methods. Ecological Economics 114: 104-116, https://doi.org/10.1016/j.ecolecon.2015.02.028.

Kristensen, E., Penha-Lopes, G., Delefosse, M., Valdemarsen, T., Quintana, C.O. & Banta, G.T. 2012. What is bioturbation? the need for a precise definition for fauna in aquatic sciences. Marine Ecology Progress Series, 446, 285-302.

Lertwattanaruk, P., Makul, N., Siripattarapravat, C. 2012. Utilization of ground waste seashells in cement mortars for masonry and plastering. J. Environ. Manage. 111, 133–141. https://doi.org/10.1016/j.jenvman.2012.06.032

Lindahl, O., Hart, R., Hernroth, B., Kollberg, S., Loo, L.O., Olrog, L., Rehnstam-Holm, A.S., Svensson, J., Svensson, S., Syversen, U., 2005. Improving marine water quality by mussel farming: A profitable solution for Swedish society. AMBIO 34(2): 131–138. https://doi.org/10.1639/0044-7447(2005)034[0131:imwqbm]2.0.co;2

Liu H. & Su, J. 2017. Vulnerability of China’s nearshore ecosystems under intensive mariculture development. Environmental Science and Pollution Research 24: 8957-8966.

Longshaw, M., Malham, SK. 2013. A review of the infectious agents, parasites, pathogens and commensals of European cockles (*Cerastoderma edule* and *C. glaucum*). Journal of the Marine Biological Association of the UK. 93: 227-247

Malham, SK., Hutchinson, TH., Longshaw, M. 2012. A review of the biology of European cockles (*Cerastoderma* spp.). Journal of the Marine Biological Associaton of the UK. 92: 1563-1577

Mahony, K., Egerton, S., Lynch, S.A., and Culloty, S. 2019. Baseline historical survey of common cockles (*Cerastoderma edule*) populations in the Atlantic area. COCKLES WP4 deliverable.

Marine Management Organisation, 2012. UK Seas Fisheries Statistics 2012. A National Statistics Publication.

Marine Management Organisation, 2017. UK Seas Fisheries Statistics 2017. A National Statistics Publication.

Mascaró M. and Seed R. (2000) Foraging behavior of *Carcinus maenas* (L.): comparisons of size-selective predation on four species of bivalve prey. Journal of Shellfish Research 19, 283–291.

McLeod, I.M., zu Ermgassen, P.S.E., Gillies, C.L., Hancock, B., Humphries, A. 2019. Chapter 25 – Can Bivalve Habitat Restoration Improve Degraded Estuaries? Coasts and Estuaries The Future. 427-442

Meadowcroft, J., Blundell, J. 2004. The Morecambe Bay cockle pickers: Market failure or government disaster? Econ. Aff. 24, 69–71. https://doi.org/10.1111/j.1468-0270.2004.t01-1-00495.x

Mermillod-Blondin, F., Rosenberg, R., Francois-Carcaillet, F., Norling, K. & Mauclaire, L. (2004). Influence of bioturbation by three benthic infaunal species on microbial communities and biogeochemical processes in marine sediment. Aquatic Microbial Ecology [Aquat. Microb. Ecol.]. Vol. 36, no. 3.

Mermillod-Blondin, F., Francois-Carcaillet, F. & Rosenberg, R. (2005). Biodiversity of benthic invertebrates and organic matter processing in shallow marine sediments: an experimental study. Journal of Experimental Marine Biology and Ecology, 315, 187-209.

Beseres Pollack, J., Yoskowitz, D., Kim, H.C., Montagna, P.A., 2013. Role and Value of Nitrogen Regulation Provided by Oysters (Crassostrea virginica) in the Mission-Aransas Estuary, Texas, USA. PLoS One 8. doi:10.1371/journal.pone.0065314

Blake, D.P., Tomley, F.M., 2014. Securing poultry production from the ever-present Eimeria challenge. Trends Parasitol. doi:10.1016/j.pt.2013.10.003

Brock, V., Wolowicz, M., 1994. Compositions of European population of the cerastoderma complex based on reproductive physiology and biochemistry. Oceanol. ACTA 17, 97–103.

Carr, M.H., Hixon, M.A., 2004. Artificial Reefs: The Importance of Comparisons with Natural Reefs. Fisheries 22, 28–33. doi:10.1577/1548-8446(1997)022<0028:artioc>2.0.co;2

Clements, J.C., Comeau, L.A., 2019. Nitrogen removal potential of shellfish aquaculture harvests in eastern Canada: A comparison of culture methods. Aquac. Reports 13, 100183. doi:10.1016/j.aqrep.2019.100183

Coen, L.D., Brumbaugh, R.D., Bushek, D., Grizzle, R., Luckenbach, M.W., Posey, M.H., Powers, S.P., Tolley, S.G., 2007. Ecosystem services related to oyster restoration. Mar. Ecol. Prog. Ser. 341, 303–307. doi:10.3354/meps341299

Duncan, P.F., Ghys, A., 2019. Shells as Collector's Items, in: Smaal, A.C., Ferreira, J.G., Grant, J., Petersen, J.K., Strand, Ø. (Eds.), Goods and Services of Marine Bivalves. Springer International Publishing, Cham, pp. 381–411. doi:10.1007/978-3-319-96776-9_20

Gentry, R.R., Alleway, H.K., Bishop, M.J., Gillies, C.L., Waters, T., Jones, R., 2019. Exploring the potential for marine aquaculture to contribute to ecosystem services. Rev. Aquac. 1–14. doi:10.1111/raq.12328

Grabowski, J.H., Peterson, C.H., 2007. Restoring oyster reefs to recover ecosystem services. Theor. Ecol. Ser. 4, 281–298. doi:10.1016/S1875-306X(07)80017-7

Hamadeh, N., Mouyelo-Katoula, M., Konijn, P., Koechlin, F., 2017. Purchasing Power Parities of Currencies and Real Expenditures from the International Comparison Program: Recent Results and Uses. Soc. Indic. Res. 131, 23–42. doi:10.1007/s11205-015-1215-z

Hayward, P.J. (Peter J.., Ryland, J.S. (John S., 1995. Handbook of the marine fauna of north-west Europe.

Hazurina Othman, N., Hisham Abu Bakar, B., Mat Don, M., Azmi Megat Johari, M., 2013. COCKLE SHELL ASH REPLACEMENT FORCEMENT AND FILLER IN CONCRETE. Malaysian J. Civ. Eng. 25, 201–211. doi:10.11113/MJCE.V25N2.303

Herbert, R.J.., Roberts, C., Humphreys, J., Fletcher, S., 2012. The Pacific Oyster ( Crassostrea gigas ) in the UK : Economic , Legal and Environmental Issues Associated with its Cultivation , Wild Establishment and Exploitation. Rep. Shellfish Assoc. Gt. Britain.

Kelley, K.N., 2009. Use of Recycled Oyster Shells as Aggregate for Previous Concrete 64.

Lertwattanaruk, P., Makul, N., Siripattarapravat, C., 2012. Utilization of ground waste seashells in cement mortars for masonry and plastering. J. Environ. Manage. 111, 133–141. doi:10.1016/j.jenvman.2012.06.032

Lindahl, O., Hart, R., Hernroth, B., Kollberg, S., Loo, L.O., Olrog, L., Rehnstam-Holm, A.S., Svensson, J., Svensson, S., Syversen, U., 2005. Improving marine water quality by mussel farming: A profitable solution for Swedish society. AMBIO A J. Hum. Environ. 34, 131–138. doi:10.1639/0044-7447(2005)034[0131:imwqbm]2.0.co;2

Marine Management Organisation, 2017. UK Sea Fisheries Statistics 2017 1–20. doi:10.3389/fmicb.2018.02112

Meadowcroft, J., Blundell, J., 2004. The Morecambe Bay cockle pickers: Market failure or government disaster? Econ. Aff. 24, 69–71. doi:10.1111/j.1468-0270.2004.t01-1-00495.x

Mermillod-Blondin, F., 2011. The functional significance of bioturbation and biodeposition on biogeochemical processes at the water–sediment interface in freshwater and marine ecosystems. J. North Am. Benthol. Soc. 30, 770–778. doi:10.1899/10-121.1

Molinos-Senante, M., Hernández-Sancho, F., Sala-Garrido, R., Garrido-Baserba, M., 2011. Economic Feasibility Study for Phosphorus Recovery Processes. Ambio 40, 408–416. doi:10.1007/s13280-010-0101-9

Morris, J.P., Backeljau, T., Chapelle, G., 2018. Shells from aquaculture: A valuable biomaterial, not a nuisance waste product. Rev. Aquac. 1–16. doi:10.1111/raq.12225

Newell, R., Fisher, T., Holyoke, R., Cornwell, J., 2005. Influence of eastern oysters on nitrogen and phosphorus regeneration in Chesapeake bay, USA 47.

Olivia, M., Oktaviani, R., Ismeddiyanto, 2017. Properties of Concrete Containing Ground Waste Cockle and Clam Seashells, in: Procedia Engineering. pp. 658–663. doi:10.1016/j.proeng.2017.01.404

Petersen, J.K., Hasler, B., Timmermann, K., Nielsen, P., Tørring, D.B., Larsen, M.M., Holmer, M., 2014. Mussels as a tool for mitigation of nutrients in the marine environment. Mar. Pollut. Bull. 82, 137–143. doi:10.1016/j.marpolbul.2014.03.006

Ricciardi, A., Bourget, E., 1998. Weight-to-weight conversion factors for marine benthic macroinvertebrates. Mar. Ecol. Prog. Ser. 163, 245–251. doi:10.3354/Meps163245

Rose, J.M., Bricker, S.B., Tedesco, M.A., Wikfors, G.H., 2014. A role for shellfish aquaculture in coastal nitrogen management. Environ. Sci. Technol. 48, 2519–2525. doi:10.1021/es4041336

Science, M.S., 2015. Marine Scotland Science - Solway Cockle Fishery Management Study.

Smaal, A.C., Ferreira, J.G., Grant, J., 2019. Goods and Services of Marine Bivalves. Springer. doi:10.1007/978-3-319-96776-9

van der Schatte Olivier, A., Jones, L., Vay, L. Le, Christie, M., Wilson, J., Malham, S.K., 2018. A global review of the ecosystem services provided by bivalve aquaculture. Rev. Aquac. doi:10.1111/raq.12301

Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Synthesis.
Island Press, pp 155, Washington, DC.

Möller, P and Rosenberg, R (1983) Recruitment, abundance and production of *Mya arenaria* and *Cardium edule* in marine shallow waters, western Sweden. Ophelia 22: 33-35.

Montgomery, J., Beaumont, J., Jay, M., Keefe, K., Gledhill, A.R., Cook, G.T., Dockrill, S.J., Melton, N.D., 2013. Strategic and sporadic marine consumption at the onset of the Neolithic: Increasing temporal resolution in the isotope evidence. Antiquity 87, 1060–1072. https://doi.org/10.1017/S0003598X00049863

Montserrat, F., Van Colen, C., Provoost, P., Milla, M., Ponti, M., Van den Meersche, K. et al. (2009). Sediment segregation by biodiffusing bivalves. Estuarine Coastal and Shelf Science, 83, 379-391.

Morris, J.P., Backeljau, T., Chapelle, G., 2018. Shells from aquaculture: A valuable biomaterial, not a nuisance waste product. Rev. Aquac. 1–16. https://doi.org/10.1111/raq.12225

Morton B., Peharda M. and Harper E.M. (2007) Drilling and chipping patterns of bivalve prey shell penetration by Hexaplex trunculus (Mollusca: Gastropoda: Muricidae). Journal of the Marine Biological Association of the United Kingdom 87, 933–940.

Murphy, S. 1992. Mystery of Molly Malone. Divelina Publications, Dublin, pp24.

Murray, E., 2011. A late Mesolithic shell midden at Kilnatierny near Greyabbey, Co. Down. The Journal of Irish Archaeology, 20, 1-18.

Murray, F., Tarrant, P., 2015. A social and economic impact assessment of cockle mortality in the Burry Inlet and Three Rivers cockle fisheries, South Wales UK. Final Report.

Navarro J.M. & Widdows J. 1997. Feeding physiology of *Cerastoderma edule* in response to a wide range of seston concentrations. Mar. Ecol.

Neumeier, U., Lucas, C.H. & Collins, M. (2006). Erodibility and erosion patterns of mudflat sediments investigated using an annular flume. Aquatic Ecology, 40, 543-554.

Newell, R.I.E., and Bayne, B.L. 1980. Seasonal changes in the physiology, reproductive condition and carbohydrate content of the cockle *Cardium (=Cerastoderma) edule* (Bivalvia: Cardiidae). Marine Biology 56:11–19.

Newell R, Fisher T, Holyoke R, Cornwell J (2005) Influence of Eastern Oysters on Nitrogen and Phosphorus Regeneration in Chesapeake Bay, USA. Springer, Dordrecht.

*Norkko*, J. & *Shumway*, S. 2011. *Bivalves as bioturbators* and bioirrigators. In S. *Shumway* (Ed.), Shellfish Aquaculture and the Environment, pp. 297-317.

Northern Economics (2009) Valuation of ecosystem services from shellfish restoration, enhancement and management: a review of the literature. Report for Pacific Shellfish Institute.

Olivia, M., Oktaviani, R., Ismeddiyanto, 2017. Properties of Concrete Containing Ground Waste Cockle and Clam Seashells, in: Procedia Engineering. pp. 658–663. doi:10.1016/j.proeng.2017.01.404

Ó Nualláin, S, 1989. Survey of the Megalithic Tombs of Ireland. The Stationery Office, Dublin.

Pernet, F., Barret, J., Le Gall, P., Corporeau, C., Dégremont, L., Lagarde, F., Pépin, J., and Keck, N. 2012. Mass mortalities of Pacific oysters *Crassostrea gigas* reflect infectious diseases and vary with farming practices in the Mediterranean Thau lagoon, France. Aquac. Environ. Interact. 2, 215–237.

Petersen, J.K., Hasler, B., Timmermann, K., Nielsen, P., Tørring, D.B., Larsen, M.M., Holmer, M., 2014. Mussels as a tool for mitigation of nutrients in the marine environment. Mar. Pollut. Bull. 82, 137–143. https://doi.org/10.1016/j.marpolbul.2014.03.006

Peterson, C.H. & Lipcius, R.N. 2003. Conceptual progress towards prediciting quantitative ecosystem benefits of ecological restorations. Marine Ecology Progress Series 264: 297-307.

Peterson, C.H., Grabowski, J.H. and Powers, S.P., 2003. Estimated enhancement of fish production resulting from restoring oyster reef habitat: quantitative valuation. Marine Ecology Progress Series, 264, pp.249-264.

Pihl, L. (1985) Food selection and consumption of mobile epibenthic fauna in shallow marine areas. Marine Ecology Progress Series 22: 169-179.

Pronker, AE., Peene, F., Donner, S., Wijnhoven, S., Geijsen, P., Bossier, P., Nevejan, MN. 2013. Hatchery cultivation of the common cockle (Cerastoderma edule L.): from conditioning to grow-out. Aquaculture Research. https://doi.org/10.1111/are.12178

Rakotomalala, C., Grangeré, K., Ubertini, M., Forêt, M., Orvain, F., 2015. Modelling the effect of *Cerastoderma edule* bioturbation on microphytobenthos resuspension towards the planktonic food web of estuarine ecosystem. Ecological Modelling, 316: 155–167.

Riisgård, H.U. 2001. On measurement of filtration rates in bivalves - the stony road to reliable data: review and interpretation. Mar. Ecol. Prog. Ser. 211: 275–291

Rose, J.M., Bricker, S.B., Tedesco, M.A., Wikfors, G.H., 2014. A role for shellfish aquaculture in coastal nitrogen management. Environ. Sci. Technol. 48, 2519–2525. https://doi.org/10.1021/es4041336

Schaich, H., Bieling, C. & Plieninger, T. 2010. Linking ecosystem services with cultural landscape research. Gaia 19: 269-277.

Scottish Government, 2017. Scottish Sea Fisheries Statistics. APS Group Scotland, Edinburgh.

SeaAngler (2009). SEA FISHING WITH COCKLES. [online] Available at: https://www.seaangler.co.uk/fishing-tips/baits/articles/sea-fishing-with-cockles [Accessed 21 Feb. 2019].

Smaal, A.C., Ferreira, J.G., Grant, J., 2019. Goods and Services of Marine Bivalves. Springer. https://doi.org/10.1007/978-3-319-96776-9

Smaal, A.C., Vonck, A.P.M.A., and Bakker, M. 1997. Seasonal variation in physiological energetics of *Mytilus edulis* and *Cerastoderma edule* of different size classes. Journal of the Marine Biological Association of the United Kingdom 77:817–838.

Spataro, M. 2009. Cultural diversities; the early Neolithic in the Adriatic region and the central Balkans: a pottery perspective. In: Gheorghiu, D. (ed.) early Farmers, Late Foragers, and Ceramic Traditions; on the beginning of pottery in the Near East and Europe, pp. 63-86. Cambridge Scholars Publishing, Cambridge.

Swanberg, L.I. 1991. The influence of the filter-feeding bivalve *Cerastoderma edule* L. on microphytobenthos: a laboratory study. J. Exp. Mar. Biol. Ecol., 151 : 93–111.

Tenberg, A., Fredholm, S. Eliasson, I., Knez, I., Saltzman, K. & Wetterberg, O. 2012. Cultural ecosystem services provided by landscapes : assessment of heritage values and identity. Ecosystem Services 2 : 14-26. https://doi.org/10.1016/j.ecoser.2012.07.006.

Thomas, S., David, P., Marie, 2014. Inshore fishing and governance (France). The case of professional shore-gathering fishermen in the Bay of Somme. Study report. Les publications du Pôle halieutique AGROCAMPUS OUEST 24, pp. 44.

Tolhurst, T.J., Gust, G. & Paterson, D.M. (2002). The influence of an extracellular polymeric substance (EPS) on cohesive sediment stability.

Tyler-Walters, H., 2007. *Cerastoderma edule* Common cockle. In Tyler-Walters H. and Hiscock K. (eds) Marine Life Information Network: Biology and Sensitivity Key Information Reviews, [on-line]. Plymouth: Marine Biological Association of the United Kingdom. [cited 15-03-2019]. Available from: https://www.marlin.ac.uk/species/detail/1384

Ubertini, M., Lefebvre, S., Gangnery, A., Grangeré, K., Le Gendre, R., Orvain, F., 2012. Spatial variability of benthic-pelagic coupling in an estuary ecosystem: consequences for microphytobenthos resuspension phenomenon. PLoS One 7, e44155.

van der Schatte Olivier, A., Jones, L., Vay, L. Le, Christie, M., Wilson, J., Malham, S.K., 2018. A global review of the ecosystem services provided by bivalve aquaculture. Rev. Aquac. https://doi.org/10.1111/raq.12301

van der Veer, H. W., Feller, R. J., Weber, A., Witte, J. I. J. (1998) Importance of predation by crustaceans upon bivalve spat in the intertidal zone of the Dutch Wadden Sea as revealed by immunological assays of gut contents. Journal of Experimental Marine Biology and Ecology 231: 139-157.

Vejre, H., Søndergaard Jensen, F., Jellesmark Thorsen, B., 2010. Demonstrating the importance of intangible ecosystem services from peri-urban landscapes. Ecological Complexity 7 (3), 338–348.

Verhulst, S., Oosterbeek, K., Rutten, A. L., Ens, B. J. (2004) Shellfish fishery severely reduces condition and survival of oystercatchers despite creation of large marine protected areas. Ecology and Society 9:17

Villalba, A., Iglesias, D., Ramilo, A., Darriba, S., Parada, J.M., No, E., Abollo, E., Molares, J., Carballal, M.J., 2014. Cockle *cerastoderma edule* fishery collapse in the Ría de Arousa (Galicia, NW Spain) associated with the protistan parasite *Marteilia cochilli*. Dis. Aquat. Organ. 109, 55–80.

https://doi.org/10.3354/dao02723

West, A., Partridge, J., Lovitt, A., 1979. The Cockle *Cerastoderma edule* (L.) on the South Bull, Dublin Bay: Population Parameters and Fishery Potential. Irish Fisheries Investigations B (Marine), 20, 19pp.

Whelan, C.J., Sekercioglu C.H. and Wenny D.G. 2015. Why birds matter: from economic ornithology to ecosystem services Journal of Ornithology 156:S227–S238

Widdows, J. & Navarro, J.M. 2007. Influence of current speed on clearance rate, algal cell depletion in the water column and resuspension of biodeposits of cockles (*Cerastoderma edule*). Journal of Experimental Marine Biology and Ecology, 343: 44-51.

Yñiguez, AT., Maister, J., Villanoy, CL., Deauna, JD., Peñaflor, E., Almo, A., David, LT., Benico, GA., Hibay, E., Mora, I., Arcamo, S., Relox, J., Azanza, RV. 2018. Insights into the harmful algal blooms in a tropical estuary through an integrated hydrodynamic-*Pyrodinium*-shellfish model. Harmful Algae. 80: 1-14.

Zannella, C., Mosca, F., Mariani, F., Franci, G., Folliero, V., Galdiero, M., Tiscar, PG., Galdiero, M. 2017. Microbial Diseases of Bivalve Mollusks: Infections, Immunology and Antimicrobial Defense. Marine Drugs. 15: doi:10.3390/md15060182