Review of the contribution of cultivated bivalve shellfish to ecosystem services

A review of the scientific literature commissioned by Crown Estate Scotland

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Executive summary

The objectives of the study have been to produce conclusions and recommendations regarding the contribution of cultivated bivalve shellfish to ecosystem goods and services, in terms of both the positive and negative impacts of such operations. These are the outcome of an extensive literature search and critical assessment of the most appropriate reports, books and articles on the subject from recognised experts, including efforts to quantify values of such impacts.

Ecosystem services have been assessed from a general or conceptual approach, commencing with definitions and classification of the services (Provisioning services e.g. food, fuel, materials, etc; Regulating services e.g. climate mediation, water quality, etc; and Cultural services e.g. recreational, heritage, spiritual, etc), followed by reviews at increasingly focused levels. The hierarchy followed led from marine and coastal services, to shellfish services, to cultivated bivalves, and finally to farm scale evaluations.

The analytical approach of addressing ecosystem service provision at a site scale has the potential to assist planners, regulators, businesses and the wider community of stakeholders in reaching more balanced and comprehensive decisions relating to proposed developments.

The review of the scientific literature has revealed a variety of views and approaches, with a particular dichotomy in the realm of valuation where researchers are divided by whether ecosystem services can, or indeed should be, valued on a monetary basis or whether a qualitative assessment is required. All are agreed that it is particularly difficult to allocate a monetary value to many of the Regulating Services and virtually the entire portfolio of Cultural Services. The authors have attempted to present the views expressed in the major papers in a balanced manner, while also aiming to achieve some practical and productive conclusions and recommendations.

In order for ***any*** valuation study to be credible and robust, it is essential that the underlying parameters are grounded in accurate research project findings. It is therefore necessary to quantify basic aspects of bivalve culture, such as species filtration rates for nutrients, diatoms, zooplankton and phytoplankton, the overall impact on chlorophyll, the water renewal rate at any given location, planktonic primary production, carbon extraction/sequestration/storage, full cycle carbon 'footprint', the effect of equipment, orientation, current speed, water temperature, bivalve biomass, etc. While contributing to policy- and decision-making is stated as one of the aims of the entire ecosystem approach, there are apparently only a limited number of examples of where this has occurred. One report observed: *"The uptake of valuation results [by policy-makers] is primarily hampered by mistrust [including] a lack of familiarity with valuation procedures, that the techniques do not give rise to 'real' values and a lack of belief in the underlying paradigm."(Gerdes et al. 2014).*

A 'ballpark' assessment of the value of ecosystem services provided by Scottish farmed shellfish operations has been carried out, based on the global valuation exercise of van der Schatte Olivier et al. (2018). This exercise has a number of limitations, specifically the exclusion of the carbon cycle, the valuation of shell solely on the basis of use as aggregate (i.e. not including use as poultry grit, fertiliser, construction material and jewellery material), exclusion of contributions to mediation of flows, benefits from the provision of habitat and all the relevant cultural services (education and research, heritage, culture and spiritual) and non-use values.

Nevertheless, the estimates (2015) for the ecosystem services provided by shellfish aquaculture across Europe include 71,164 tonnes of shell, 3,519 tonnes of Nitrogen remediated, and 287 tonnes of Phosphorus remediated, with an aggregate value of US$163 million. Total shellfish aquaculture production in Europe during 2015 was reported (FAO) at 609K tonnes, giving an ecosystem valuation of $269/tonne.

Scottish shellfish aquaculture production in 2015 totalled some 7.5K tonnes (Munro 2016), which indicates a possible scale of ecosystem services provided of around $2.018 million/£1.313 million (InforEuro exchange rate of GBP 0.65). This equates to 13% of the estimated first sale value of Scottish shellfish in 2015 of £10.1 million (Munro 2016).

Applying the valuation of $269/tonne to the overall Scottish shellfish production ‘for the table’ of 7,212 tonnes in 2018 (Munro 2019, the most recent Annual Survey) results in an aggregate ecosystem services value of $1.940 million/£1.455 (InforEuro rate of GBP 0.75), equivalent to around 15% of the estimated first sale value of Scottish shellfish of £9.5 million (Munro 2019).

Clearly these estimates represent an extremely broad-brush calculation, taking no account of differing mixes of species, variation in chemical composition and recovery rates, and the gaps in valuation noted above. And the impact of relative movements in foreign exchange rates is also not considered.

The carbon ‘footprint’ of shellfish aquaculture is also a positive characteristic for this food source, with inshore cultivation meaning less fuel consumed in comparison to offshore capture fisheries although depuration consumes notable amounts of electricity. Nevertheless, although the ‘footprint’ can be measured at different stages in the process from spat collection to consumption and be calculated on the basis of different assumptions, it appears clear that farmed mussels have one of – if not <u>the</u> - lowest carbon footprints of any food product, particularly in comparison to terrestrial supplies (Meyhoff Fry 2012). One author, having focused on carbon footprint studies, concluded: *“No other option of animal protein currently produced can match mussels in terms of protein quality and associated benefits for the environment”* (Suplicy 2018).

Calculation of ‘embedded energy’ is also technically complex, however again cultivated mussels exhibit a low level (12 MJ/Kg) in comparison to other food products (Hughes 2018).

At a global level, some researchers (Roberts et al 2015, Suplicy 2018, Troell et al 2014) conclude that unless aquaculture growth is encouraged from production systems less dependent on compound feed (whether from capture fisheries or terrestrial crops) and land/water/energy resources, then *“aquaculture is likely to make the global food system less resilient”* (Troell et al 2014). In other words, the main additional contribution to world food supply should preferentially be from non-artificially fed aquaculture species, i.e. shellfish, seaweed and herbivorous fish.

This review endorses the views expressed above regarding the portfolio of benefits from bivalve cultivation, particularly from the standpoint of the provision of ecosystem services. The authors believe that there is a strong case for the inclusion in any shellfish farm proposal of an assessment and valuation of both the ecosystem services *and* disservices resulting from the proposed development. The authors suggest this should come with full disclosure of the parameters used in the calculations of monetary and non-monetary evaluations, alongside an assessment of the ecosystem services impacts on the current level/scale/mix of ecosystem service provision. Such valuations should enable an 'ecosystem cost/benefit analysis', with an overall ecosystem services impact, assisting a more comprehensive and transparent decision-making process.

The positive additional societal benefits generated by the ecosystem services that should be assessed include:

Provisioning Services (additional to the market value of the commercially harvested molluscs), these include:

- Incremental fish population (including crustacea and other marine organisms) around the gear (building on the supporting ecosystem services of habitat provision, creation of sediment and other benthic contribution). The incremental fish population may be less than in a reef restoration, and may not support significant marginal activity (e.g. angling, crab potting) due to restrictions on public access by the farm operator but it does represent a positive ecosystem service provision;
- Potential contributions to expanded finfish production through integrated multi-trophic aquaculture (IMTA), although there are disagreements in the scientific literature on the degree to which finfish sourced nutrients appear in shellfish diets;
- Support of accelerated growth of macroalgae (e.g. kelp), both natural beds and cultivation operations, through nutrient recycling (carbon, nitrogen, phosphorus);
- The production of shell, for use as construction material (aggregate, etc.), fertiliser, poultry grit and artistic/ornamental/ jewellery products;
- Medicinal and genetic resources, an emerging realm of development, reflecting the bioactive peptides, proteins and metabolites sourced from bivalves, which could assist with the development of innovative pharmaceuticals and nutraceutical foods. Mussel powder is a well-established food additive in New Zealand (see: www.enzaq.com for one example).

Regulating services (ecosystem outputs that affect the performance of individuals and communities indirectly), including several 'supporting' services:

- Water purification and waste treatment (including hydrocarbons) – reflecting the principle of extraction and conversion rather than dilution and dispersion as the solution to pollution (Gallardi 2014);
- Improvement of water clarity through filter feeding, contributing to control of excessive phytoplankton blooms (including Harmful Algal Blooms) and also leading to improved benthic flora and fauna production;
- Take up of nitrogen and phosphorus for shell and tissue growth and additional removal of these nutrients through production of biodeposits and increased denitrification and ammonium production thereby supporting primary production;

- Bivalve provision of nutrients to assist in the growth of macroalgae, both natural beds and cultivation operations;
- Carbon sequestration – offset by production of CO_2, so potentially a limited net benefit; and
- Mediation of water flow – reduction of erosion, possible reduction of wave energy.

Cultural services:
- Physical, intellectual and spiritual interaction with seascapes, ecosystems, etc., for both local communities and visitors i.e. promotion of tourism (shellfish farm visits, beachside cafes, etc);
- Scientific and educational interactions, both local interest (e.g. schools) and higher-level research (national and international research projects);
- Heritage and cultural activities, including promotion of and participation in seafood festivals;
- Maintenance of community links with the marine environment, particularly where local fishing activities are under threat; and
- Non-use values, ranging from an economic development at minimal environmental disruption to avoidance of a perceived less attractive usage of the marine resource.

Perceived negative impacts from a farm development that require assessment (and where possible valuation) include several of the same effects noted above, as any impact can be interpreted as being disruptive to the natural ecosystem:
- Modification of the phytoplankton population (total and speciation) and possible modification to zooplankton consumption (although there is limited evidence of molluscan uptake of crustacean larvae – see Sonier et al. (2018); no evidence of consumption of lobster larvae);
- Biological accumulation of pathogens (bacteria, protozoa and viruses harmful to human health) – the risk is usually mitigated by monitoring and regulatory programmes;
- Changes to nitrogen distribution and increased concentrations of ammonium and an overall modification to the nutrient cycle in coastal ecosystems;
- Concentration of heavy metals and other pollutants;
- Modification of habitat and populations;
- Disturbance of marine mammals and seabirds;
- Visual disturbance [very difficult to value, and already regulated in Scotland];
- Competition for seston/feed affecting natural populations of molluscs;
- Production of methane in mussel intestines – although this participation in the biogeochemical cycle of methane production is negligible in relation to the total methane production in the sediment (Fenchel et al. 2017);
- Introduction of non-native species and transfer of established species between countries, with the potential of consequential inadvertent introduction of diseases and pests – this issue certainly represents a risk, but one that is already managed by regulators;
- Potential disruption to the perceived ecosystem bequest/altruist/existence benefits of an unchanged environment.

Despite the difficulty in according monetary values to the Regulating Services and the Cultural Services, which contribute some positive as well as potentially negative non-monetary values, an ecosystem services assessment and valuation exercise would contribute to a more comprehensive and structured appraisal of any proposed bivalve development.

Overall, this review of the scientific literature concludes that the positive effects resulting from bivalve cultivation – ranging from reduction of eutrophication, contributions to the carbon cycle (degree of +/- to be determined), nitrogen and phosphorus recycling, improving water clarity, improvement of seagrass and macroalgae growth, harvesting of phytoplankton and reduction in algal blooms, denitrification, enhancement of habitat availability and marine organism populations, plus the provision of positive cultural services of promotion of tourism, scientific and educational interactions, cultural activities and maintenance of community links with the marine environment – appear likely to significantly outweigh the negative impacts of disruption to water flow, impact on phytoplankton populations and mix, depositional and benthic concerns and possible disruption to some Cultural Services (recreational, aesthetic and spiritual interactions).

This report recommends an initiative to support farm-scale analysis and a combination of monetary/non-monetary valuation of ecosystem service provision. The 'Florida Clam Farm Environmental Benefits Calculator' approach could well provide an initial platform or model for the analysis and valuation of societal environmental benefits over and above the provision of food from shellfish aquaculture operations.

In addition, in order to fully assess the role of shellfish in carbon sequestration/CO2 production, further research should be supported – the alternative, of continuing to exclude the contribution from the carbon sinks of tissue and shell, is clearly not desirable.

The impact on both the immediate local ecosystem and possibly the wider tidal excursion area, should also be assessed, covering as many of the services listed above as possible (including the difficult to value 'cultural' services).

In addition to these ecosystem services provided by the shellfish farm, the production of high quality marine protein, contributing to food supply in a manner which is more efficient than natural supply (and less of an environmental impact than dredging used for the wild capture fishery) in a hungry world characterised by rising populations must be seen as a positive.

Contents

Introduction

The objectives of the study are to come to conclusions and provide recommendations regarding the contribution of cultivated bivalve shellfish to ecosystem goods and services, in terms of both the positive provisions and negative impacts of such operations. This will be the outcome of an extensive literature search, review and assessment of the leading and most appropriate reports, books and articles on the subject, including efforts to quantify values of such provisions and impacts.

The location characteristics (as ecosystem services vary according to the aquatic environment) for the study have been identified as 'typical west coast and islands of Scotland', extending 2 – 3 nautical miles. Further locational parameters have been clarified, including the presence of current bivalve cultivation plus the opportunity for expansion to sites further offshore while the main species of interest has been identified as mussels, followed by oysters.

The current scale of interest by economic and ecology/sustainability researchers in ecosystem services is generally agreed to date from 1996, with a Workshop of 13 participants in Santa Barbara, CA, USA, entitled 'The Total Value of the World's Ecosystem Services and Natural Capital' and the publication of the proceedings in *Nature* (Costanza et al. 1997). Around the same time an edited book (30 authors) had been proposed and was published under the title 'Nature's Services: societal dependence on natural ecosystems' (Daily 1997). These in combination "kicked off an explosion of research, policy and applications of the idea" (Costanza et al. 2017) of valuation of ecosystem service provision.

This review has assessed publications within this period of just over 20 years, with a particular focus on the most recent peer reviewed publications, as these generally build on the outcomes of previous research.

The number of 'ecosystem services' papers and articles runs into the multiple thousands – the Costanza et al. (1997) paper alone has over 20,000 citations (Source: Google Scholar), which implies that the aggregate of relevant publications on a global basis is likely to be significantly higher. A search using SCOPUS (April 2017) showed a total of over 17,000 papers published with the terms 'ecosystem services' in the title, abstract or keywords (Costanza et al. 2017), while the work of Constanza – 600 scientific papers and 27 books – has been cited in SCOPUS 34,000 times and in Google Scholar 92,000 times (Robert Costanza profile, Australian National University website).

This report provides a general introduction to the concept of ecosystem service provision, a wider perspective than that of the specific title of the report – the authors hope that this background will prove helpful in explaining the emergence of themes and issues relating to the overall concept and the issues of practical implementation into regulatory decision-making.

Assessment of coastal and marine ecosystem services is a major research area, covering capture fishing, littoral environments, ocean services, etc. Clearly this is a significant area of research for scientists, institutes, regulators and governments, with the impact of pollution (chronic and catastrophic) having well publicised impacts on the environment and ecosystem services. Globally, and in particular in North America, restoration and enhancement projects and their effects have dominated the 'shellfish' literature since the '90's. However, 'aquaculture' as an aspect of ecosystem research papers has only really emerged in recent years (Figure 1), although the scientific approach has frequently focused on the impact of developments on the ecosystem rather than any augmentation of services as a result of incremental cultivation operations.

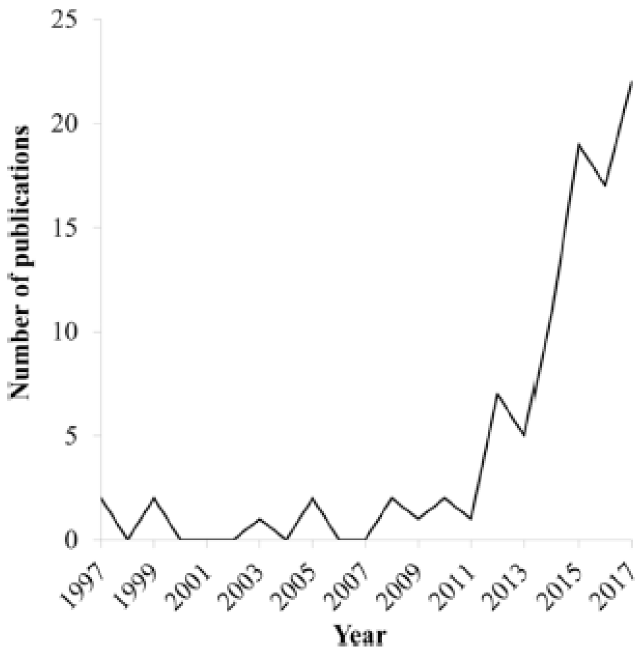

Figure 1. The number of publications within the scientific literature per year of publication (N= 94) referring to ecosystem services and aquaculture. Source: Weitzman (2019).

Despite the Weitzman (2019) paper having limited its search (using SCOPUS, December 2017) to academic journals and excluding other publications it still specifically identified 94 relevant publications.

This review commenced with the determination of search terms for the literature search (see 'Review Methodology' for details) and a search using the Google Scholar and PubMed search engines. In addition, secondary sources, literature reviews and macro-studies have been reviewed to assist in identifying primary empirical studies, reports, books, unpublished papers and conference proceedings.

This database of retrieved items (see Annex A for a listing of the major papers reviewed) has then been assessed and common issues - along with areas of disagreement between researchers - have been identified. The items have been reviewed in a hierarchy, from overall ecosystem concepts (definitions, groupings, etc), through general marine and bivalve shellfish, to specific aquaculture mussel and oyster issues. The final effort of the review has focussed on valuation of the impacts of bivalve cultivation on the provision of ecosystem services, with consideration of how such quantitative outcomes can form an element in assessment of development projects (planners, businesses, societal concerns).

This approach has been developed so that the study outcomes will hopefully be of practical assistance to Crown Estate Scotland in future evaluations of the ecosystem contribution (the net ecosystem impact) of proposed shellfish cultivation operations.
Such analysis can assist in decision making processes and more importantly provide helpful in-depth information for the wider community of stakeholders, including the general public.

Review methodology

Literature searches were undertaken to collate information on ecosystem services provision by bivalve molluscan shellfish, particularly mussels and oysters.

Literature searches began with a structured electronic search using the Google Scholar and PubMed search engines. Electronic literature searches commenced with the following key words:

- Ecosystem services AND marine
- Ecosystem services AND bivalve (OR shellfish OR mussels OR oysters)
- Ecosystem services AND aquaculture

Searches were limited to keywords appearing in the title and abstracts of publications. Table 1 shows the number of publications identified using this approach.

Table 1. Number of publications identified by Google Scholar and PubMed for the Ecosystem Services review.

Keywords	PubMed	Google Scholar
Ecosystem service AND marine	49	177
Ecosystem service AND bivalve	2	3
Ecosystem service AND shellfish	3	1
Ecosystem service AND mussels	3	4
Ecosystem service AND oysters	6	11
Ecosystem service AND aquaculture	10	13

The titles and/or abstracts of all citations identified using this approach were reviewed for relevance. Additional papers were accessed using the reference list of reviewed publications and through internet trawling. Only English language papers were reviewed. Critical appraisal of the items ‘discovered’ by the searches forms the basis of the next sections of this Report.

Definitions

Ecosystem services

An overall definition of 'ecosystem services' appears a logical place to commence this review. The definition from Costanza et al. (1997), a paper recognised as the second most highly cited analytical paper in the history of environmental studies (20,360 citations reported – Google Scholar), remains a simple and seemingly straightforward form of words: *"Ecosystem services are the ecological characteristics, functions or processes that directly or indirectly contribute to human wellbeing; that is the benefits that people derive from functioning ecosystems."*

Costanza et al. (2017) describes how: *"the ecosystems that provide these services are sometimes referred to as 'natural capital', using the general definition of 'capital' as a stock that yields a flow of services over time. Here the term 'capital' is useful to reconnect the human economy with its ecological dimension. In order for these benefits to be realised, natural capital must interact with other forms of capital that do require human agency to build and maintain. These include: (1) built/manufactured capital; (2) human capital; and (3) social or cultural capital."*

The four types of capital are all required in complex combinations to produce human benefits (Figure 2).

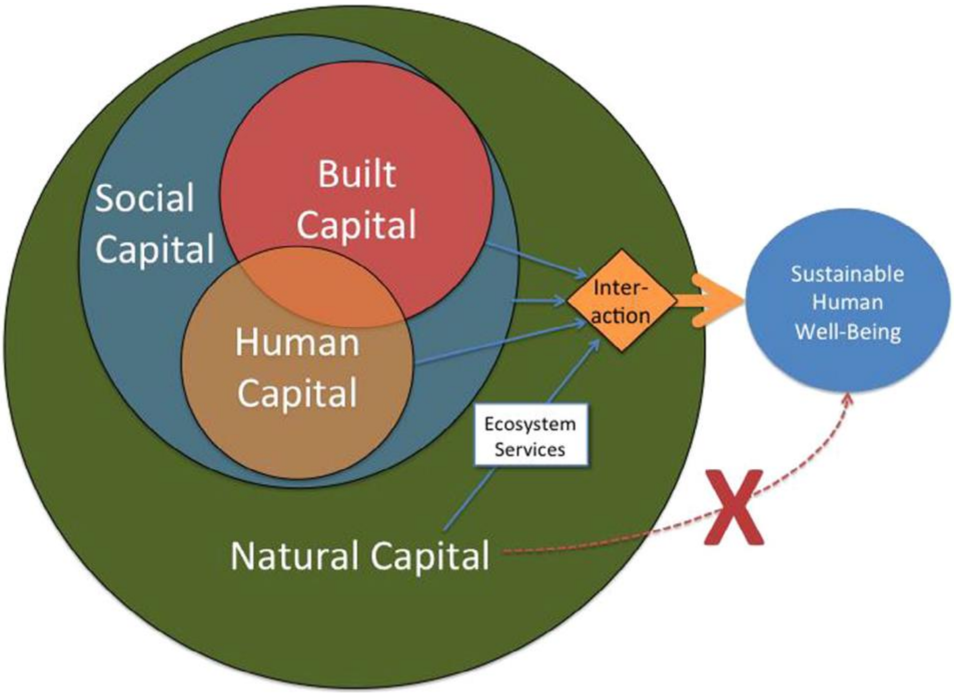

Figure 2. Interaction between Built, Social, Human and Natural Capital. Source: Costanza et al. (2017)

Although academic discussions have ebbed and flowed around definitions, the 1997 version remains an excellent summary of the relatively straightforward concept. However, an alternative wording from the University of Florida (Baker et al. 2015) is a slightly different description of ecosystem services: *"The transformation of a set of natural resources supplied by ecosystems into beneficial goods and functions that humans value. An ecosystem is a complex system of plant, animal, fungal and microorganism communities and their associated non-living environment interacting as an ecological unit. While ecosystem services are often* *associated with natural systems, agricultural and aquaculture systems can also provide ecosystem services".* The last sentence is of particular interest in the context of this review.

Ecosystem services (totalling 17) were listed in the 1997 publication, without grouping; however, since that time the individual services have been categorised in a number of ways, but the most widely adopted classification has been 'Functional', into four – and later three - groups.

The main categories are: Provisioning, Regulating and Cultural. 'Supporting' services were initially defined as a separate category, but the latest common classification (The Common International Classification of Ecosystem Services – CICES[1]) treats 'supporting' services as part of the underlying functions that characterise ecosystems and are only consumed or used indirectly and may simultaneously facilitate many final outputs in the other categories. This approach appears to be generally accepted by the majority of researchers.

A simplified view of linkages between ecosystem services is summarised in Figure 3 below.
To further 'populate' the different categories:

- **Provisioning services** – ecosystem services which combine with built, human and social capital to produce food, biomass for construction, energy, etc. Example: fish delivered to people as food requires fishing boats and equipment (built capital), fishermen/women (human capital) and communities (social capital);
- **Regulating services** – combination with the other 3 capitals (built, human and social) to provide flood control, water regulation, air quality, climate control, etc.;
- **Cultural services** – including recreational, aesthetic, scientific, 'identity' benefits that are valued by humans.

The Royal Society of New Zealand notes (Anon 2011): *"the natural world provides numerous contributions to human well-being; however, few of these services are widely recognised and fewer are valued. Recognising these contributions allows the inclusion of a wider range of ecological, social and economic factors into the trade-offs that are an integral part of natural resource management decisions."*

The Millennium Ecosystem Assessment (Anon 2005) defined ecosystem services similarly:
"The direct and indirect contributions of ecosystems to human wellbeing … categorised as provisioning services, such as food, water, timber and fibre; regulating services that affect climate, floods, pests, disease, wastes and water quality; cultural services that provide recreational, aesthetic and spiritual benefits; with supporting services such as soil formation, photosynthesis and nutrient cycling behind all others."

[1] Common International Classification of Ecosystem Services; https://cices.eu/cices-structure; 2019

Figure 3. Ecosystem service grouping and linkages. Based on a schematic in Molnar et al. (2009).

A number of researchers, in particular Potschin and Haines-Young (2016), have argued that there is a 'cascade', from ecosystem functions, to ecosystem services, to benefits, to values. However, there has been limited endorsement of this conceptual approach from within the research community, as connections between ecosystems and humans are complex and dynamic whereas the 'cascade' view is essentially linear.

Development disservices

Whilst noting that the distinction between positive ecosystem services and disservices/ negative impacts could be dependent on context and the perceptions of actors involved, the UK Joint Nature Conservation Committee (JNCC – the statutory adviser to UK government and devolved administrations) highlighted the following potential disservices from developments:

increased prevalence of allergens, promoting invasive species, hosting pathogens or pests, inhibiting human mobility or safety, bringing about negative cultural and psychological effects or increasing the necessity for using natural resources (e.g. water) or chemicals (e.g. pesticides).

"JNCC's goal is to embed the ecosystem services framework in decision making"[2] – to this end an on-going project 'Spatial framework for assessing evidence needs for operational ecosystem approaches' (Medcalf et al. 2012) has been assessing the method on a number of case studies (mostly terrestrial, one marine - Dogger Bank) and developing training courses ('Incorporating natural capital and ecosystem services into environmental assessments').

The NRC (2010) noted that, for bivalve shellfish aquaculture there could be a number of negative impacts, including:

- Promotion of colonisation and spread of introduced/non-native species by the additional hard substrate;
- Disturbance of benthic flora (both aggregate supply and species balance) and marine animals;
- Competition for resources with 'natural' populations;
- Alteration of the water flow;
- Composition and rate of sedimentation; and
- Litter.
-

Nevertheless, the literature is heavily skewed towards the positive ecosystem services provided, and the loss thereof as a result of human activity. Indeed, the concept of negative impacts is solely restricted to the impact from 'developments'.

Valuation

Economic/monetary valuation of ecosystem services is complicated by the fact that some are part of the market economy (particularly provisioning services) with established values for both direct or indirect use, while others are non-marketed but still have value – the complication here is how to value these services. Researchers disagree over the accuracy of the various methods, including the evaluation of ecosystem services provided by bivalve shellfish, both wild and cultivated.

In contrast, Non-Monetary Valuation (NMV) has a long tradition in some fields of environmental policy making (Kukkala and Moilanen 2013). NMV approaches rely on structured inquiries into people's perceptions (questionnaires and interviews) along with participatory approaches such as focus groups and 'citizen juries'. The outcomes from these approaches are qualitative, although in some instances there have been efforts to translate these into monetary values.

In the EU-funded OpenNESS Project, a variety of NMV techniques were addressed, however it was concluded that this field (sociocultural valuation is proposed as an umbrella term) requires more research into terminology, methods and case studies (Kelemen et al. 2014).

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[2] www.jncc.defra.gov.uk/default.aspx?page=6382

While the overwhelming majority of valuation studies highlight the value of their results for policy-makers, evidence of successful uptake for resource management has been limited. Indeed, Marre et al. (2016) concludes that *"ecosystem valuation is globally perceived as useful by decision-makers but is rarely used".*

The 2011 UK National Ecosystem Assessment[3] (NEA) comprehensively included ecosystem services in its review, although from this review's standpoint the emphasis was skewed towards the terrestrial ecosystem.

The 2014 NEA Follow-on Phase[3] (NEAFO) endorsed and expanded upon the significance of ecosystem services, noting that embedding knowledge of the services, *"rarely considered explicitly in government impact appraisals before 2013, is critical for decision making".* The NEAFO included methodologies and tools *"to guide inclusion of ecosystem services in policy- and decision-making".*

The successful implementation of this approach is not yet clear – a review of public sector decisions, highlighting their consideration of ecosystem services and their value, would be a useful document. Such a study could, for example, clarify the extent to which the official UK 'price' for carbon (established at £52/tonCO2e in 2010, scheduled to rise to £200/tonCo2e in 2050), intended to be factored in to public sector appraisals, has been used in recent years (NB this is separate from the carbon value used in the EU Emissions Trading System and the UK carbon price for power generators).

Scotland's National Marine Plan (published March 2015) includes 77 objectives and policies (of the total 187) which reference ecosystem services (Sangiuliano 2019), an indication of the significance they are afforded by the Scottish Government. On the other hand, a review of the 'Aquaculture' section of the Plan does not reveal any mention of the words 'ecosystem services'.

In addition, an EU funded project on valuation in overseas possessions (Gerdes et al. 2014), includes a list of 9 examples where ecosystem service valuations have contributed to decision making, with three detailed Case Studies of ecosystem valuations and their contributions to policy decisions. The Case Studies are specific to tropical and sub-tropical environmental valuations and while interesting exemplars of method, have few overlaps with bivalve cultivation in Scottish waters for ecosystem services (see details in the 'Ecosystem Service Valuation' section below).

In conclusion, measuring 'value' in monetary terms provides – literally – a common currency for decision-making, including comparison of benefits with costs, which can allow the development of a logical and transparent tool for planners and policy-makers.

[3] http://uknea.unep-wcmc.org/

Estuarine, coastal and marine ecosystem services

Estuarine and coastal ecosystems are both part of the wider marine ecosystem, which includes the deep oceans, and form two areas of particular interest for this review. Estuarine is defined as a location where fresh and saline waters mix (brackish water) while coastal ecosystems are areas where sea/ocean waters meet the land.

Estuarine and coastal ecosystems represent some of the most heavily exploited ecosystems in the world, with an estimated one third of the global population in 4% of the total land area and 11% of the planet's seas and oceans (Barbier 2017).

High amongst the losses in ecosystem suffered over the years has been shellfish beds – "shellfish habitats also represent some of the most degraded marine ecosystems in the world"(Alleway et al. 2018). Indeed, one estimate claims 89% of oyster reefs may have been lost globally, which has led to increasing interest in restoration projects and commercial cultivation operations (Barbier 2017).

One specific example of the decline in shellfish ecosystem services is Australia, where only one out of 118 historical locations containing native oyster ecosystems still retains oysters (Gillies et al. 2018).

Alexander et al. (2016) explores the influences affecting example services, one from each classification (provisioning [kelp production], regulating [bioremediation of hydrocarbons] and cultural [good diving experiences]) and generated maps which could be "useful in informing future marine planning, management options or impact assessment decisions".
Following the review of the literature, a summary of marine ecosystem services have been identified:

- **Provisioning services** from estuarine and coastal environments include: wild and cultured seafood (fin fish, shellfish, seaweed), raw materials for manufacturing, building materials, production of renewable energy, water, biochemical resources (used in medicines, pharmaceuticals, cosmetics, etc) and genetic (used for animal and plant breeding, omega 3 oils, etc) resources.
- **Regulating services** include: climate regulation (retention of CO_2 and other greenhouse gases, absorption and redistribution of heat), waste and disease regulation (dilution/detoxification/dispersion through transportation across ecosystems, storage and recycling of pollutants, reduction of the effects of eutrophication, the break-down of hydrocarbons into their basic components) and acting as a buffer zone against natural hazards and environmental disturbances.
- **Cultural services** relate to recreational activities such as sea sports (fishing, surfing, kayaking, etc), aesthetic (inspiration for art and music), cognitive and spiritual activities as well as scientific and educational dimensions.
- **Indirect Supporting services** include nutrient cycling (carbon, nitrogen and phosphorus) through absorption into the marine food web and recycled via the transfer between life cycles of different organisms as well as the supply of habitat by marine structures (living and man-made) for other organisms. Coastal waters provide critical ecosystem services by assimilating run-off of dissolved inorganic nutrients, organic matter and sediment from the land. In addition, the marine ecosystem is also responsible for the production of organic matter through processes such as

photosynthesis and chemosynthesis (‘primary production’) which forms the basis of all food webs, along with oxygen which is an extremely important element for sustaining much of the planet’s living animals.

Mapping and assessment of coastal ecosystem services in complex regions (such as many European areas) is challenging, even when using the CICES services identification system and GIS mapping approach. It is generally accepted that ecosystems vary in their capacity or ability to provide services, therefore a detailed and specific assessment is required to accurately carry out a quantitative valuation process (Martínez-López et al. 2019).

These exercises are necessary in order that assessment of ecosystems can accurately contribute to the efficient management of marine resources. One example of a formalised process is the ‘Ecosystem Principles Approach’ which was developed by the New Zealand ‘National Institute of Water and Atmospherics Research’ (NIWA) in conjunction with Auckland Council, to help decision making for the management of coastal resources. This particular approach has also reportedly been used elsewhere in New Zealand and in Spain.

The limited effort to date in identifying ‘disservices’ or negative impacts from mariculture was noted by Alleway et al. (2018), albeit in passing, as the paper identified the sector’s significant “potential for positive effects”.

Bivalve shellfish

Bivalve shellfish cultivation in Scotland

The shellfish species currently cultivated in Scottish waters are Mussels, Pacific Oysters, Native Oysters, King Scallops and Queen Scallops, on sites mainly across the west coast and western and northern island groups plus a small number on the Moray Firth and Northeast coast.

The data presented in the latest Marine Scotland annual 'Scottish Shellfish Farm Production Survey 2018' reported a total production of 7,212 tonnes, valued at £9.5 million, with Mussels output of 6,874 tonnes dominating at 95% of volume (82% of value) followed by Pacific Oysters at 322 tonnes (4.5% of volume, 16% of value), Native Oysters at 11 tonnes and Scallops at 5 tonnes (Munro 2019). Production trends over the last 10 years are shown in Figure 4.

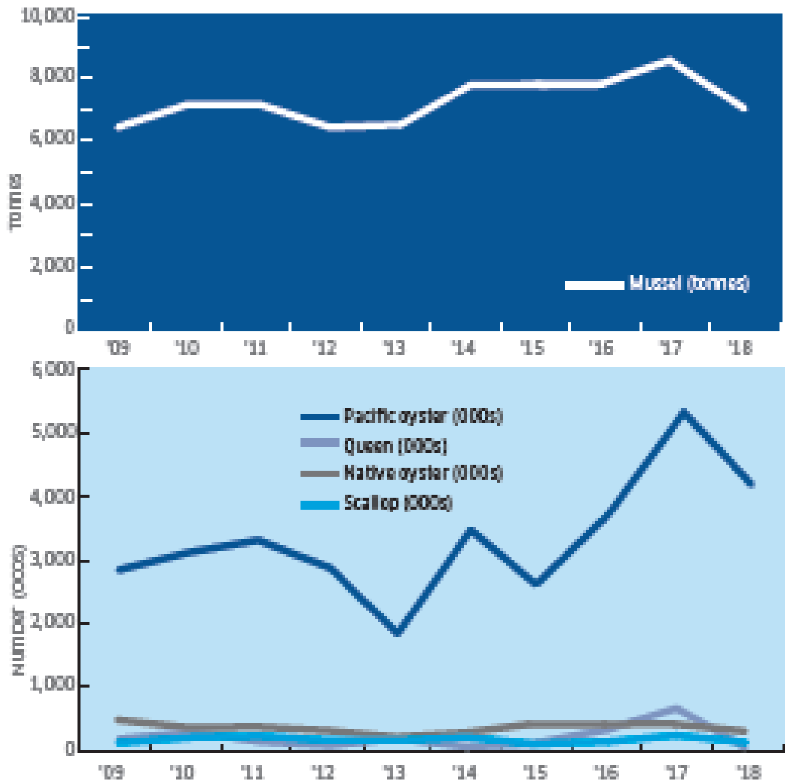

Figure 4. Production by shellfish species in Scotland (Munro 2019).

These volumes indicate a broad decline in production volumes from 2017 across all species, with reductions of 16% for Mussels, 20% for Pacific Oysters, 29% for Native Oysters and 85% for King and Queen Scallops. It is not clear whether these declines reflected specific conditions such as environmental (e.g. algal blooms), regulatory (e.g. e-coli levels) or company decisions or a more fundamental secular trend in sectoral development.

It must be a concern that the dominant species, the mussel sector, has essentially fallen back to the volumes produced ten years previously (6,874 tonnes in 2018 compared to 6,756 in

2009), with the year on year decline largely driven by the reduction in Shetland volumes (5,160 tonnes in 2018 compared to 6,647 tonnes in 2017, i.e. a fall of 22%). Nevertheless, Shetland continues to represent the largest regional producer of mussels, having risen from 55% of national output in 2009 to 80% in 2017 before declining to 75% in 2018.

Mussel production in the Western Isles increased to 555 tonnes in 2018, +40% compared to 2017, but even so this level was only 44% of the output of 1,264 tonnes in the previous peak year of 2010 and only 77% of the 10-year average volume.

Production of mussels in other regions of Scotland (the West Coast, Moray Firth and North Coast) over the past decade has exhibited a decline from over 2,000 tonnes/year to a stable average in recent years of around 1,000 tonnes/year.

Turning to Pacific Oysters, total production expanded from around 3 million shells to a peak level of some 5 million shells in 2017, before declining to 4 million shells in 2018. The combined production from the West Highlands and North Coast has risen significantly since 2009, from 300K shells to 1.8 million shells, while volumes from Argyll, the traditionally major producing region, have declined from 2.2 million shells to around 1.7 million shells.

Native oyster production has declined steadily over the decade, from 490K shells in 2009 to 142K shells in 2018, while scallop production has been relatively static for King Scallops and erratic for Queen Scallops – from a low of 10K shells in 2012 to a peak of 273K shells in 2017, followed by a decline of over 90% to 18K shells in 2018.

The number of active businesses involved in shellfish farming has declined consistently over the past decade, from 168 to 130, reflecting both company closures and consolidation within the industry. The number of active sites rose from 319 to a peak of 335 in 2015 followed by a decline to 329 in 2018 while the number of producing sites rose from 150 to a peak of 180 in 2016 followed by a decline to 160 in 2018.

Total employment in the sector has been generally stable around the mid-300 employees for the period 2009 – 2017 (average of 346), however there was a contraction to 298 in 2018, another sign of an ongoing restructuring process in the industry.

Overall, although there has been a reduction in volumes, sites and number of businesses in 2018 compared to 2017 and previous years, this is not expected to be more than a temporary setback in the long term development of the industry, in light of the robust demand for the products, the quality of the growing waters and the positive contribution of ecosystem services from shellfish cultivation activities.

Bivalve shellfish ecosystem services

The starting point for assessing ecosystem concepts for bivalve shellfish is accepting that enhancement and cultivation operations both ***depend upon*** and ***affect*** the current 'natural' ecosystem and the provision of ecosystem services.

A second recognition of the effect of bivalve operations is to note that these can have both ***positive*** and ***negative*** impacts on the marine environment.

- ***'Natural' bivalve ecosystems***

There are numerous studies (see Annex A) which have reviewed and evaluated shellfish ecosystem services from natural reefs and beds, and, as noted by Alleway et al. (2018), generally identify the positive impacts rather than any perceived negative impacts.

Reflecting the genesis of the ecosystem goods and services approach in the ecology and environmental science realm, the majority of assessments until recently have been focused on these natural beds and reefs of bivalve shellfish, with a particular interest in the identification and 'valuing' of the restoration and enhancement of degraded environment. The development of a systematic, albeit qualitative approach, to the ecosystem services provided by enhanced shellfish resources has provided justification and support for significant academic research efforts, particularly in the USA.

The environmental benefits from natural shellfish beds – and by extension, from restoration of degraded ecosystems – include some ecosystem services that are not likely to result from commercial development of cultivation operations, in particular the environmental positives of coastal protection and the creation of extensive habitat for crustaceans and fin fish. However, as noted above, the assessments of enhancement and restoration ecosystem services have tended to be qualitative rather than quantitative monetary values.

Alleway et al. (2018) illustrated the relationships of ecosystems services (Figure 5).

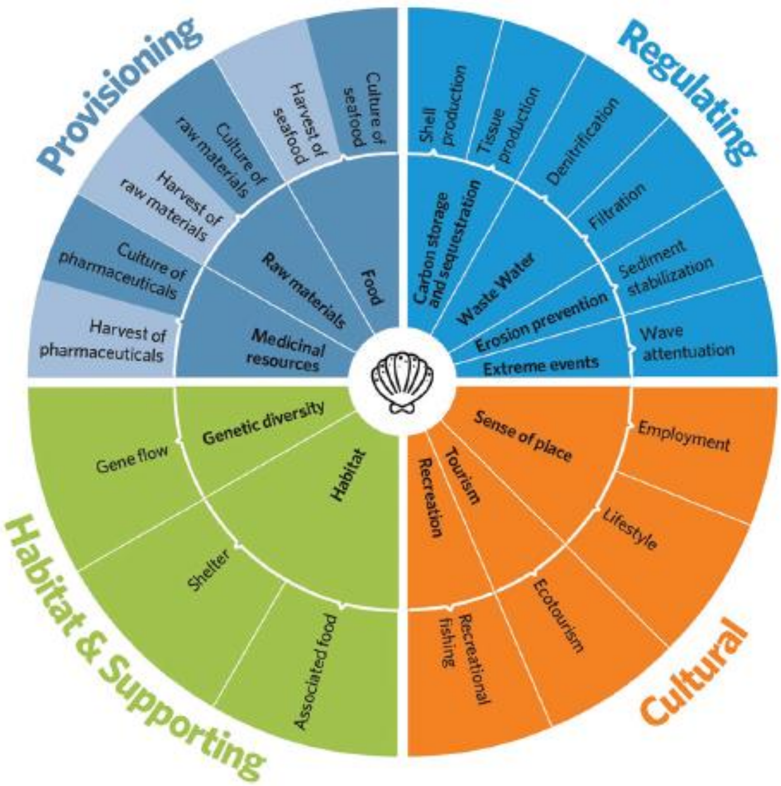

Figure 5: Shellfish ecosystem classifications and services. Source: Alleway et al. (2018).

The positives include:

- Enhanced production in seagrass/macroalgae beds by increasing water clarity/reducing turbidity through filtration;
- Reduction of algal blooms;
- Fertilisation of the benthos through biodeposition;
- Increasing the availability of hard substrate and habitat which supports higher densities of finfish and invertebrates.

These impacts are additional to other ecosystem services provided to society, such as:

- Provisioning services of food, building and infrastructure material (e.g. shell) and source material for medicinal products;
- Regulating services in the form of attenuation of wave energy, nutrient recycling, combating of eutrophication and possibly carbon sequestration (see discussion below), etc.;
- Cultural services, such as the preservation of 'connection' with the marine environment, participation in eco/food tourism and seafood 'festivals'.

Reports of the perceived positive impacts are included in many of the reports cited in attached Annex A.

Several legislative instruments in the USA, from the National Aquaculture Act of 1980 through to the NOAA National Ocean Policy of 2016, have the broadly similar objectives of increasing shellfish cultivation and improving ecosystem health (Ferreira et al. 2018). This indicates a long term and broad recognition that shellfish are a positive element of marine and coastal ecology.

- ***Cultivated bivalve ecosystems***

Publications which have identified positives for cultivated bivalve ecosystems include the US National Research Council assessment (NRC 2010), which noted enhanced production in seagrass beds as a result of increased water clarity (filtration) and fertilisation by biodeposition, higher densities of fish and other organisms that associate with structured habitat.

The positives have been similarly highlighted in other books, including 'Shellfish aquaculture and the environment', specifically the section on the impact on eutrophication (Burkholder and Shumway 2011), and the more recent compendium 'Goods and Services of marine bivalves' (Smaal 2018), particularly the chapters on regulating services.

An extensive study (Burkholder and Shumway 2011) that assessed the significance of bivalve shellfish aquaculture in the eutrophication of coastal waters found that *"of the 62 ecosystems reviewed, only 4 ecosystems (around 7%) sustained system-level adverse effects from large, intensive bivalve culture operations [mostly in poorly flushed lagoons with high density shellfish culture]. The other 93% sustained either negligible or only localised significant adverse effects contributing to eutrophication from bivalve shellfish aquaculture".*

The authors also pointed out that the 4 exceptions *"underscore the need to consider the ecosystem's carrying capacity, rather than only the carrying capacity for maximal shellfish production".*

A comprehensive and, where considered possible, quantified version of the ecosystem services provided by shellfish aquaculture is given in van der Schatte Olivier et al. (2018). This report helpfully details the calculations for each service identified, albeit using global 'average' criteria/values, including biochemical and biological accumulation, carbon sequestration and nutrient removal, from species specific pumping rates to valuation of shell material, indicating average total global non-food ecosystem services at a value of $6.5 billion/year. In addition, there are examples quoted of shellfish farms established solely to 'clean up' marine environments (Sweden, Denmark), where the cost of the 'farm' is less than the alternative water treatment plant.

The US National Research Council report, 'Ecosystem concepts for sustainable bivalve mariculture' (NRC 2010), acknowledged possible "negative ecological impacts on the marine environment" from bivalve mariculture, including altered water flow due to husbandry operations and associated gear, composition of the sediment and rate of sedimentation, and in some cases disturbance to the benthic flora, while the increased availability of hard substrate can promote the spread of non-native and competing species. The report also noted that removal of phytoplankton from the water column could be included as both a positive and negative impact.

A paper by Diana (2009) identified a number of "negative impacts" from aquaculture, including (relative to shellfish) non-native species escapees, effluents causing eutrophication, and disease transfer. These and other 'certification issues' are summarised in Table 2 below.

Table 2: An example of 'certification' issues for various species in global aquaculture and the level of concern expressed about them (Diana 2009).

	Species or species group										
Issue	**Tuna**	**Shrimp**	**Salmon**	**Trout**	**Catfish**	**Tilapia**	**Abalone**	**Scallops**	**Oysters**	**Clams**	**Mussels**
Antibiotic use	M	H	H	H	M	M	M	–	–	–	–
Benthic biodiversity	H	M	M	M	–	M	–	M	M	M	M
Chemical use	M	H	M	H	H	–	M	–	M	M	–
Disease transfer	H	H	H	–	–	–	M	–	H	–	–
Escapees/invasive	H	M	H	–	–	H	M	–	H	–	–
Genetic alteration	–	–	H	H	H	H	–	M	H	–	M
Land and water use	–	H	–	H	H	H	M	M	M	M	M
Removal of dead fish	–	–	M	M	H	H	–	–	–	–	–
Fish meal/oil use	H	H	H	H	M	M	M	–	–	–	–
Water pollution	H	H	M	H	M	H	–	–	–	–	–
Predator control	–	M	M	H	H	H	H	H	H	H	H
User conflicts	M	H	M	–	–	M	–	M	M	M	M

H, high level of concern; M, medium level of concern.
Note: The level of concern was derived from focus group and published evaluations (from Boyd et al. 2005).

This summary of evaluations of the perceived impacts of an extensive portfolio of cultured species (although several are not relevant to the Scottish environment) clearly shows that bivalve shellfish are generally viewed as having significantly lower impact on ecosystems, with mussels as one of the species attracting lowest concerns.

An earlier study by Naylor et al. (2000) identified relevant potential bivalve disservices of "habitat modification, wild seed collection and other ecological impacts".

Ecosystem service valuation

In essence, there are 2 types of valuation for ecosystem goods and services, those that are market based (e.g. production of food, etc.) and those that are non-market (i.e. the benefits accrue directly to people without passing through the market economy). No single method can capture the total value of the many and disparate services provided by a natural asset such as a shellfish reef (Johnston et al. 2002). Indeed, there are many approaches to both market and non-market valuation, with varying degrees of appropriateness and clarity.

Typical valuation methods and value types are summarised in Table 3 (Pascual et al. 2010).

Table 3: Valuation methods and value types. Reproduced from Pascual et al. (2010).

<table>
<tr><th colspan="2">Approach</th><th>Method</th><th>Value</th></tr>
<tr><td rowspan="6">Market valuation</td><td>Price based</td><td>Market prices</td><td>Direct and indirect use</td></tr>
<tr><td rowspan="3">Cost based</td><td>Avoided cost</td><td>Direct and indirect use</td></tr>
<tr><td>Replacement cost</td><td>Direct and indirect use</td></tr>
<tr><td>Mitigation/Restoration cost</td><td>Direct and indirect use</td></tr>
<tr><td rowspan="2">Production based</td><td>Production function approach</td><td>Indirect use</td></tr>
<tr><td>Factor Income</td><td>Indirect use</td></tr>
<tr><td colspan="2" rowspan="2">Revealed preference</td><td>Travel cost method</td><td>Direct (indirect) use</td></tr>
<tr><td>Hedonic pricing</td><td>Direct and indirect use</td></tr>
<tr><td colspan="2" rowspan="4">Stated preference</td><td>Contingent Valuation</td><td>Use and non-use</td></tr>
<tr><td>Choice modelling/conjoint analysis</td><td>Use and non-use</td></tr>
<tr><td>Contingent ranking</td><td>Use and non-use</td></tr>
<tr><td>Deliberative group validation</td><td>Use and non-use</td></tr>
</table>

The 'Total Economic Value' concept combines the values of the various services, as illustrated in Figure 6.

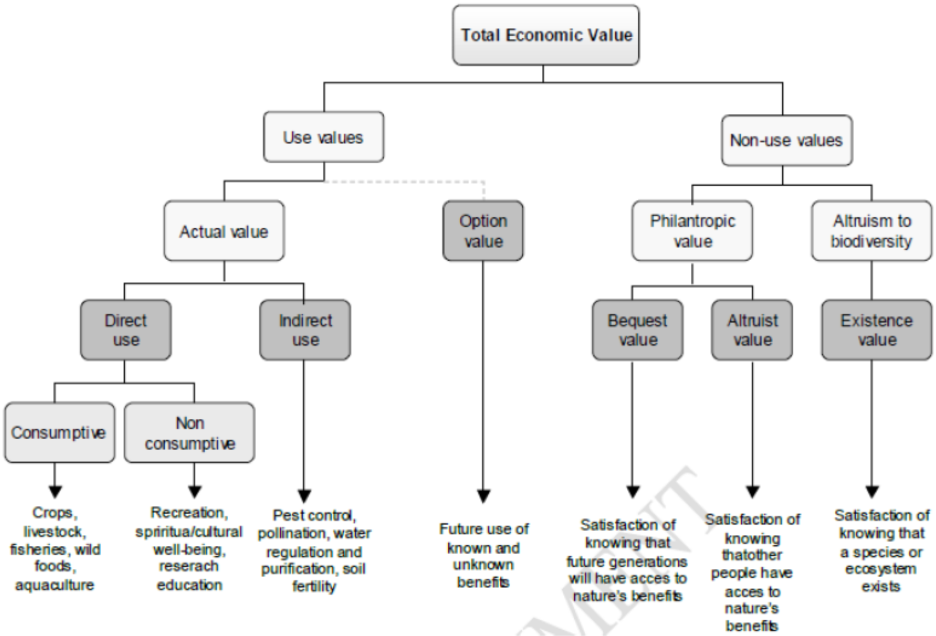

Figure 6. Value types within the TEV approach (Pascual et al. 2010).

This approach distinguishes between values that individuals derive from using the environmental resources (use values) and values that are derived even if they do not themselves use them (non-use values); use values can be either direct (e.g. provisioning services) or indirect (e.g. regulating services), while non-use values are typically assigned to cultural services.

The NetBiome report (Gerdes et al. 2014) includes three detailed case studies on valuations and their impact on economic development planning decisions.

One of the case studies is 'The economic value of Bonaire's ecosystems and National Marine Park'. The reef which surrounds the island supports the main economic driver of tourism, however it has been impacted by a number of concerns, including over heavy recreational use, nutrient enrichment, conversion of land use, sedimentation, terrestrial run-off (leading to increased eutrophication) and illegal sand mining. There have also been climatic impacts - unusually warm sea temperatures killed significant amounts of coral in 2010, while a decline in herbivorous fish since 2003 has led to an increase in reef damaging seaweeds.

The government proposed to eliminate the protection from commercial construction in the National Marine Park waters, however this was perceived as potentially harming tourism based on the reef, so a valuation project of the ecosystem services was commissioned by the Dutch government (2012). This study estimated that the aggregate value of the 10 ecosystem services considered was more than US$100 million/year, including recreational/cultural and non-use values, and the project concluded that it would be more efficient to prevent future extensive environmental damage (including abatement of invasive species) than attempting to revitalise the impacted environment.

Diver willingness to pay higher access fees was assessed by survey, and the valuation study led to an increase from $10 to $25 for the annual dive tag, despite some initial stakeholder concerns that this would lead to a decline in diver numbers, particularly from the USA. This increase generated more than the entire budget required to operate the National Marine Park and financed the introduction of protective measures and made the Bonaire Marine Park one of the few self-financed parks in the entire Caribbean.

The valuation study also raised awareness of the value of the coral reef and led to a decision to construct a water purification plant to reduce the negative impacts of waste water discharges on the coral.

The other case studies similarly detail the valuation of ecosystems and the services provided and their recognition as providing valid arguments for policy decisions by governments and other agencies (planners, development agencies and courts - in one case of fining the owner of a ship which grounded on a reef).

‘Natural’ bivalve ecosystem services valuation

Schug (2012) provides a comprehensive assessment of numerous studies that have attempted to value the services provided by shellfish enhancement projects. These range from provisioning services (commercial fisheries), regulating services (water quality improvements, reduction of nutrient loads, shoreline protection) as well as cultural and supporting services, with a selection of these efforts summarised in Table 4 below.

Table 4: Examples of Ecosystem Valuations. Source: Schug (2012)

Commercial fisheries and aquaculture	Lipton (2008a) projected that the net returns to harvesting oysters in Maryland and Virginia over a 10-year time horizon were $12.8 million.
	Lipton (2008b) estimated the annual gain in consumer surplus from an increase in Chesapeake Bay harvest of 2.57 million bushels of oysters to be $11.6 million.
Recreational fisheries	English (2008) reported an average per-trip value of $21.40 for recreational shell fishing in south-eastern Massachusetts.
Water quality maintenance	Hicks et al. (2004) determined that the water quality improvements resulting from restoring 1,890 acres at 73 reef sites in Chesapeake Bay would annually generate $640 thousand in benefits for recreational anglers.
	Newell et al. (2005) derived an annual replacement value of nitrogen removal by oyster reefs in the Choptank River, Maryland of $314,836, or $181 per hectare.
Cycling of nutrients and creation of habitat	Grabowski and Peterson (2007) estimated the value of enhanced commercial fish production by oyster reefs in the southeast United States to be $3,700 per hectare per year.
	Isaacs et al. (2004) found that the average annual net willingness to pay among resident saltwater recreational fishermen to maintain access to fishing over Louisiana’s oyster reefs was $13.21.

An exercise in the valuation of provisioning services from natural shellfish beds in the Solent, UK (Williams and Davies 2018), found that the direct and indirect Gross Value Added for a series of scenarios of shellfish enhancement increased as a result of expanded shellfish harvest, an unsurprising result. Unfortunately, the regulating and cultural ecosystem services were not valued.

However, *"the conclusion* [from the project] *is clear and shellfish bed restoration should be seen as a major consideration for estuarine management in the Solent. A restored shellfish bed system would boost the respective shellfish populations, improve water clarity by filtering phytoplankton and sediment, provide valuable habitat for crabs, fish and other organisms, while also providing direct and indirect income for families and communities".*

It is important to note, that as no costs for the interventions were provided, the study did not present any conclusions as to an overall cost-benefit ratio.

Many other studies, particularly in the USA, have come up with similar conclusions and are similarly light on quantified cost-benefit results.

'Cultivated' bivalve ecosystem services valuation

In recent years, there has been a growing level of interest within the research community to examine the contributions from commercial bivalve shellfish cultivation (see Figure 1, in the Introduction section), with a number of studies which have included both qualitative and quantitative assessments and valuations of ecosystem goods and services provided by cultivated shellfish operations.

In comparison to 'natural' shellfish reefs and beds, cultivation is generally considered to contribute a greater amount/value of provisioning services (primarily food) but fewer regulating and habitat services.

The US National Research Council report, 'Ecosystem concepts for sustainable bivalve mariculture' (NRC 2010) noted that *"there is no free lunch – every additional animal has an incremental effect arising from food extraction and waste excretion. The scope of impacts of cultured bivalves is a function of the scale and location of mariculture operations. Some effects may be beneficial to the ecosystem, while others may be detrimental, depending on the scale and location of the bivalve farm".*

This review then went on to denote 'Best Management Practices' and/or 'Performance Standards' as approaches *"to protecting against undesirable consequences of mariculture, with pros and cons for both. To achieve a better understanding of how the scale and intensity of bivalve mariculture influence the natural ecosystem structure and processes, methods for accurate estimation of carrying capacity will be vital".*

Interestingly, the report noted that the impact of harvesting wild bivalves (dredging in particular) was greater on benthic communities than suspended mariculture – not a particularly surprising conclusion but an observation frequently not acknowledged.

Modelling of oyster 'bioextraction' of land-based nutrient discharges into Long Island Sound found that 1.3% of incoming nutrients could be removed by the current oyster population, rising to 2.68% with expanded production (Bricker et al. 2017): *"The value of nitrogen removed was estimated using alternative management costs (e.g. wastewater treatment) as representative, showing ecosystem service values of $8.5 and $470 million/year for current and maximum expanded production, respectively",* but not including contributions from other shellfish species or denitrification benefits.

A recent study by van der Schatte Olivier et al. (2018), has reviewed the scientific literature on bivalve aquaculture ecosystem services, noting that *"there remain substantial gaps on non-market benefits, and some services remain largely unquantified".* Referring to previously published reviews, the authors note that "there is a distinct lack of quantification of the services and their economic value", a view which this review would endorse.

The paper conducts a global assessment of the potential value of ecosystem services from farmed bivalve shellfish (oyster and mussels), establishing species parameters (pumping rates, meat yields, shell weights, nitrogen and phosphorous removal and denitrification rates, etc.) and authoritative (FAO) production statistics.

However, and significantly, *"Due to a lack of consensus on whether calcification represents a sink or a source of CO2, the potential value of sequestration was not used in the valuation"* (van der Schatte Olivier et al. 2018).
Global ecosystem provision (regulating services and non-food provisioning services) for 2015 has been calculated at $6.47 billion.

In addition, the study notes that *"mussels have the greatest potential for bio-remediation as they remove the most nitrogen and phosphorus per tonne of shellfish produced".* There are also comments about the lack of comprehensive data in the literature for non-food provisioning services, non-USA regulating services and the quantification of cultural services, which limits the global comprehensiveness and accuracy of the valuation exercise.

However, the development of nutrient offset and carbon trading schemes in the USA must be acknowledged as indicators of economic/market valuation of non-market ecosystem goods and services, with a possible development of similar schemes for nutrients.

In addition, the EU Emissions Trading System (ETS), established in 2005, is the world's biggest emissions trading market (6.7 million tonnes in 2015), accounting for over 75% of international carbon trading (source: European Commission – https://ec.europa.eu/clima/policies/ets_en). The ETS generates a market value for carbon, which reflects demand and supply for allowances from power generators, other large industrial CO2 producers and the aviation industry, which reached a 10 year high of €26.89/tonne on 10th April 2019, with analysts forecasting a rise to €65/tonne by 2020 (source: Berenberg, London – https://www.ctrmcenter.com/news/energy/corrected-update-2-eu-carbon-price-hits-over-10-year-high-on-brexit-extension-hopes/)

An area of recent expanding interest is the inclusion in bivalve shellfish valuation exercises of biotechnology and medical resources/pharmaceuticals as one of the provisioning services.

Bivalves produce a variety of bioactive peptides, proteins and metabolites, which could assist with the development of innovative pharmaceuticals and nutraceutical foods. Quantitative valuation of these services is clearly problematic at this point in time; however, this will doubtless be eased in the future as examples of successful medical developments become more common.

One well established and successful example of the use of shellfish as an innovative food product is 'mussel powder', developed in New Zealand using green shell mussels, and marketed as an anti-inflammatory, high nutrient content food additive is 'mussel powder'. Further information is available on commercial websites, such as www.enzaq.com, www.noted.co.nz/health/nutrition/mussel-power-how-the-green-lipped-mussel-became-nzs-first-superfood/ , http://aromanz.nz/ .

Farm scale ecosystem services and valuations:

Moving from the wider concepts and valuations of cultivated bivalve shellfish to a focus on farm level ecosystem services, the literature becomes even sparser. Farm models have usually been developed to predict individual growth and farm yield through hydrodynamic forcing, bivalve growth drivers and bioenergetic growth models. New approaches, using remote sensing (satellites) and links between the farm model and ecosystem models, are expected to improve the utility of farm-scale models for the estimation of specific bivalve ecosystem goods and services.

A study in New Zealand (Pinkerton et al. 2018), assessed the effects of a large coastal mussel farm on water quality over a 15-year period, using satellite observations to estimate the concentration of chlorophyll a (as a proxy for phytoplankton), turbidity and sea surface temperature.

The conclusions included:

- The farm had a significant effect on chlorophyll a (a reduction of 1.6% over an area 1.5 times the area of the farm (1,400 ha));
- The farm caused a seasonal pattern of winter warming (+0.03C) and summer cooling (-0.11C).
- No significant effect on turbidity was detected.
-

Long term observations like these could prove extremely useful in evaluating the impact of large-scale bivalve developments. However, there was no attempt to estimate a monetary value to these impacts in this study.

"Models are becoming increasingly more realistic" (Ferreira et al. 2011), and this can allow assessment and calculation of 'trade offs' between farm development and the provision of services. The FARM (Farm Aquaculture Resource Management) model appears to offer a decision support tool (regulators and industry) by combining species/production criteria with wider hydrodynamics input and environmental impact.

However, the model has been described as *"being limited to testing scenarios with relatively moderate changes to present day conditions"* in a review of model results in a single location of Killary Harbour, Ireland (Nunes et al. 2011). As with many other studies and modelling exercises of this vintage, the target objective has been the impact of bivalve aquaculture on the ecosystem, not the valuation of the ecosystem services provided by the incremental production from the bivalve farm.

Deliberate use of mussel farms for removal of excess nutrients from eutrophic marine areas has been studied and practiced in Scandinavia. For example, in Denmark, a farm in the eutrophic Skive Fjord has been assessed as a pilot study for nutrient removal (Nielsen et al. 2016, Petersen et al. 2014). The results show significant promise, with high levels of nitrogen and phosphorus capture and costs of nitrogen removal calculated at €14.8/Kg.

A modelled production expansion, with a target phytoplankton biomass threshold of 1 mg chl a m^{-3}, led to a doubling of the farm's standing stock of mussels whilst remaining within the area's carrying capacity. The researchers concluded that this made *"mitigation mussel production a cost-efficient measure compared to the most expensive land-based measures"* (Petersen et al. 2014) and that "*nutrient extraction mussel farms represent an effective bioengineering approach for the provision of positive coastal ecosystem services and economic benefits" (*Nielsen et al 2016). In addition, a number of other positive ecosystem service provisions were noted, although not quantified.

A University of Florida/SeaGrant Florida study (Baker et al. 2015) has evaluated the non-food monetary contribution of the hard clam cultivation industry to the State, although limiting the 'economic' contribution to nitrogen removal and carbon sequestration. This assessment calculated the creation of a 'public good' value of $100K/year, around 1% of the farmgate sales value of clams.

The project also developed a 'Clam Farm Benefit Calculator', which enables individual farmers to estimate the environmental benefits/ecosystem services at a farm level. For further details see Annex B of this report for an excerpt from the website – it is a bit of a 'black box', but a useful initiative, nonetheless. This is an interesting development which could possibly be adapted for assessment of the 'public good' provided by mussel farm development in Scotland.

Overall, there is a clear paucity of farm scale valuations of ecosystem services provision, despite the generalist claims in the scientific literature that bivalve aquaculture provides positive services estimated to exceed the negative impacts of such developments.

A farm-based study to provide planners and regulators with 'best estimate' monetary values of positive and negative impacts, to add to the qualitative community/societal values, would be a helpful step forward in improving transparency in decision making and reducing fractious confrontation when discussing such proposals.

Uncertainties and Information Gaps

Carbon – sink or source?

There is a major debate in the literature over the role of bivalve shellfish in the carbon cycle – whether molluscs represent a sink for carbon (calcium carbonate in shells) or are net producers of carbon (in the form of CO_2).

The carbon content of mussel shells (*Mytilus edulis*) is around 12.7% dry weight (Zhou et al 2002) in the form of calcium carbonate. However, with CO_2 being produced during the calcification process: *"so potentially leading to an increase in pCO_2 in surface waters and [release] of CO_2 to the atmosphere [when the water pCO_2 is higher than that of the atmosphere] – especially in shallow well-mixed coastal waters where shellfish are typically farmed …. However, the long-term net effect on carbon storage is still unclear, and further work is required to look at the true potential of shellfish as a store of CO_2. [As a result,] Due to a lack of consensus on whether calcification represents a sink [for carbon] or a source of CO_2, the potential value of sequestration was not used in the valuation"* (van der Schatte Olivier et al. 2018).

Exclusion of the generally perceived carbon sequestration value in the assessment of ecosystem services from bivalves is clearly an issue that requires some additional in-depth research, including site specific parameters.

Nitrogen and phosphorus uptake

The range of results from assessment of nitrogen and phosphorus uptake also makes an average/mean/median estimate difficult, with rates varying by species, growth rates, food concentration and supply, temperature, salinity and stock density. However, a mean nitrogen removal across 7 species and 14 locations was calculated at 0.6 t ha^{-1} $year^{-1}$ (ranging from 0.1 – 0.7 t ha^{-1} yr^{-1}) based on the FARM model (Rose et al. 2015).

On the other hand, a study of a mussel farm in the eutrophic Skive Fjord, Denmark calculated that, at the optimal production level of the site, determined by a target phytoplankton biomass threshold of 1 mg chlorophyll a m^{-3}, nitrogen removal would be 1.8 t ha^{-1} yr^{-1} (Nielsen et al. 2016).

Nitrogen uptake is clearly a variable that is extremely site and species specific. Research would be required for any evaluation of a proposed farm development.

Dietary uptake for mussels in Integrated Multi-Trophic Aquaculture (IMTA)

Although the use of mussels in IMTA is possible, with numerous pilot projects around the world, the results provided in the literature regarding the shellfish dietary uptake vary widely:

- Mazzola and Sarà (2001): The mixed diet for mussels and clams was composed of phytoplankton, waste material from the bivalves and surplus uneaten pelleted feed, with phytoplankton more important for mussels;
- Deudero et al (2011): Pellet food was the main food for mussels (*M. galloprovincialis*), with a mean contribution of 57.95%, with phytoplankton contributing only 3.83%;

- Sanz-Lazaro and Sanchez-Jerez (2017): This study (6 fish farms) concluded that fish farm wastes did not form a major component of mussel diet, however the authors propose a move to a more general approach to IMTA of assessing regional nutrient budgets.

There is clearly a need for species- and site-specific assessments of mussel diets in order to gain site specific values of nitrogen, phosphorus and any IMTA components when assessing a proposed farm development.

Valuation of cultural services

Valuation of Cultural Services is similarly lacking in consensus, either for methodology or actual quantification – all agree that these services have value, but it is widely valued more at a personal and quality of life level and thus difficult to aggregate. Even the proponents of Non-Monetary Valuation accept that there are challenges in reaching consensus values for these ecosystem services. Despite the use of extensive surveys of opinion, 'citizen courts' and focus groups it is likely that there will always be divergencies in individual valuations of cultural (recreational, aesthetic, etc) services from ecosystems/coastal environments.

Therefore, it would be ambitious to attempt to include either contribution to or impact on cultural ecosystem service values in an assessment of a specific farm proposal, beyond qualitative statements of likely effects.

Farm level evaluations

In terms of information gaps, as noted there is a notable absence of research publications which focus on farm level operations and their contributions to ecosystem services and disservices. For any such analyses to be useful in a decision-making process, any data inputs should be innovative and site specific.

Conclusions and Recommendations

The review of the scientific literature regarding ecosystem services clearly indicates a consensus across the relevant environmental research community that bivalve shellfish are significant providers, particularly in the inshore coastal zones, of a range of positive ecosystem services, both from 'natural' reefs and beds and aquaculture operations.

There is also widespread recognition of a number of potential negative impacts resulting from intensive bivalve farming operations.

Ecosystem services parameters

Species and site specific parameters and practical criteria play a part in assessing the scale of positive and negative impacts, and it would appear that after some 20+ years of ever increasing research projects (measured by the number of scientific papers published) there is a reasonably substantial database of at least some of the biological and environmental flows, fluxes and relationships, which can enable quantifiable assessments and valuations of bivalve shellfish aquaculture operations. In addition, a degree of clarity has emerged over 'what is missing' in order to contribute to policy- and decision-making.

The advance from ***assessment*** of services to ***valuation*** (whether monetary or non-monetary) of the full portfolio of services remains somewhat problematic. However, this step is essential in order to contribute to a more transparent balance of overall costs and benefits resulting from individual projects for the benefit of planners, regulators and communities.

Some of the ecosystem services provided by shellfish aquaculture can be and have been valued, albeit only partially and usually at a system level, with farm scale assessments proving more elusive. This may reflect the research community's focus on national/ecosystem/ international scale operations rather than individual commercial scale activities.

However, In order for ***any*** valuation study to be credible and robust, it is essential that the underlying parameters are grounded in accurate research project findings – it is necessary to quantify basic aspects of bivalve culture, such as species filtration rates for nutrients, diatoms, zooplankton and phytoplankton, the overall impact on chlorophyll, the water renewal rate at any given location, planktonic primary production, carbon extraction/sequestration/storage, full cycle carbon 'footprint', the effect of equipment, orientation, current speed, water temperature, bivalve biomass, etc. and so on, with many of the parameters being extremely site specific.

The carbon sequestration issue is not as simple as it might appear – the process of extraction of carbon from seawater to form shell also results in the production of carbon dioxide which is a 'Greenhouse' gas, so there are both positive and negative aspects to this issue, the value of which researchers disagree. However, in the view of the authors, there is little doubt that the carbon that is sequestered into shell provides a long-term store or sink of atmospheric carbon, probably generating a net positive impact for the overall process although a detailed review of the scientific literature and/or a research project is probably necessary.

Valuation of ecosystem services

There are some researchers who criticise the entire concept of ecosystem services monetary valuation for the lack of methodological solidity, the variety of methods and lack of consensus over the appropriate approach. These experts support the application of techniques of Non-Monetary Valuation (NMV), some of which have a long tradition, for example, in the delineation of protected areas, such as National Parks.

However, NMV of ecosystem services has been equally criticised as *"not yet constituting a formalised methodological field and on the basis of coarse and arbitrary indicators produces results whose accuracy and reliability are hard to judge"* (Kelemen et al. 2014).

Despite the criticisms from proponents of NMV, there is clearly global interest in valuing the provision of ecosystem services and there is a basic logic in using monetary values in the attempt to value the contribution of the services, in the widest sense, provided by natural capital and, in the case of this review, particularly the marine ecosystem – and using a common monetary unit would appear to be an appropriate approach.

Implementation

A 2018 paper which describes the ecosystem services derived from mariculture, notes that a full *"understanding of when and how aquaculture can return positive ecosystem effects has not occurred, and the uptake of ecosystem-centric approaches has been limited by regulatory impediments, management constraints, ambiguity in their value and, potentially, a lack of understanding of the economic value"* (Alleway et al. 2018).

Another author has noted that *"for a policy-maker, it is important that the results of a commissioned valuation study are not vulnerable to criticism and dismissal. The lack of established and consensual methodologies makes valuation studies prone to such criticism and consequent dismissal. The uptake of valuation results [by policy-makers] is primarily hampered by mistrust [including] a lack of familiarity with valuation procedures, that the techniques do not give rise to 'real' values and a lack of belief in the underlying paradigm"* (Gerdes et al. 2014).

The development of nutrient offset (USA) and carbon trading (EU and USA) schemes should be acknowledged as the emergence of real world/market indicators of economic valuation of non-market ecosystem services. Furthermore, the UK government established a single carbon valuation (Department of Energy and Climate Change) in 2009 that was to be factored in to future public sector appraisals, with the price rising from £52/ton CO_2e in 2010 to £200/ton CO_2e by 2050.

There is a current lack of detailed and practical assessment and/or valuation of farm level provision of ecosystem services (as mentioned above), to some extent a reflection of the paucity of farm-scale studies. This dearth also reflects the site- and species-specific nature of any such assessment, along with limited data available for such calculations.

A value of the total ecosystem services provided by the Scottish bivalve shellfish cultivation industry has been estimated, based on the global valuation exercise of van der Schatte Olivier et al. (2018). This exercise has a number of limitations, specifically the exclusion of the carbon cycle, the valuation of shell solely on the basis of use as aggregate (i.e. not including use as poultry grit, fertiliser, construction materials and jewellery material), the exclusion of contributions to mediation of flows, benefits from the provision of habitat and all the relevant cultural services (education and research, heritage, culture and spiritual) and non-use values.

The estimates (2015) for the ecosystem services provided by shellfish aquaculture across Europe include 71,164 tonnes of shell, 3,519 tonnes of Nitrogen remediated, and 287 tonnes of Phosphorus remediated, with an aggregate value of US$163 million. Total shellfish aquaculture production in Europe during 2015 was reported (FAO – http://www.fao.org/fishery/statistics/global-aquaculture-production/query/en) at 609K tonnes, giving an ecosystem valuation of $269/tonne.

Scottish shellfish aquaculture production in 2015 totalled some 7.5K tonnes (Munro 2016), which indicates a possible scale of ecosystem services provided of around $2.018 million/£1.313 million (InforEuro rate of GBP 0.65). This equates to 13% of the estimated first sale value of Scottish shellfish in 2015 of £10.1 million (Munro 2016).

Applying the valuation of $269/tonne to the overall Scottish shellfish production 'for the table' of 7,212 tonnes in 2018 (Munro 2019) results in an aggregate ecosystem services value of $1.940 million/£1.455 (InforEuro rate of GBP0.75), equivalent to around 15% of the estimated first sale value of Scottish shellfish of £9.5 million (Munro 2019).

Clearly these estimates represent an extremely broad-brush calculation, taking no account of differing mixes of species, variation in chemical composition and recovery rates, and the gaps in valuation noted above. In addition, the impact of relative movements in foreign exchange rates has also not been considered. However, it does indicate that there is a significant yet currently unacknowledged value flowing from shellfish cultivation operations.

Recommendations

There is a strong case that any shellfish farm development proposal should include:

- An assessment and valuation of the provision of ecosystem services and disservices flowing from the proposed operation – the specific parameters of the calculations and the assumptions/ assessments, for both the quantitative and the more qualitative services, should be detailed; this would contribute to a more transparent debate between proposers and opponents;
- An assessment of the impact of the development on the current level/scale/mix of localised ecosystem service provision (i.e. the status quo).

Such analyses would enable an environmental cost/benefit assessment, contributing an overall ecosystem services impact evaluation to the process of achieving a more comprehensive decision by resource managers (and the development proposers and wider stakeholders).

The 'Florida Clam farm environmental benefits calculator' (mentioned in the 'Farm scale ecosystem services and valuations' section above; see Annex B for details) could be the basis for an initial equivalent 'Scottish bivalve shellfish farm ecosystem services calculator', using species- and site-specific parameters wherever possible.

There is certainly an opportunity for an innovative quantification and valuation exercise to assess the provision of ecosystem services for a proposed mussel cultivation operation in Scottish inshore waters, both on an initiation and an incremental basis (the latter could include an evaluation of the impact on a wider spatial basis, i.e. an expansion from an established operation).

The positive additional societal ecosystem services that should be assessed and where possible valued in such an exercise for a Scottish west coast and island site are summarised below:

Provisioning Services (additional to the market value of the commercially harvested molluscs):

- Incremental fish population (including crustacea and other marine organisms) around the gear (building on the supporting ecosystem services of habitat provision, creation of sediment and other benthic contribution). Although the incremental fish population may be less than in a reef restoration, and may not support significant marginal activity (e.g. angling, crab potting) due to restrictions on public access by the farm operator, it does represent a positive ecosystem service provision;
- Potentially (although there are disagreements in the scientific literature) contributing to expanded finfish production through IMTA (integrated multi-trophic aquaculture);
- Support of accelerated growth of macroalgae (e.g. kelp), both natural beds and cultivation operations, through the support services of nutrient recycling (carbon, nitrogen, phosphorus);
- Shell, for use as construction material (aggregate, etc.), fertiliser, poultry grit and artistic/ornamental/ jewellery products; and
- Medicinal and genetic resources, an emerging realm of development, reflecting the bioactive peptides, proteins and metabolites sourced from bivalves, which could assist with the development of innovative pharmaceuticals and nutraceutical foods.

Regulating services (ecosystem outputs that affect the performance of individuals and communities indirectly), including several 'supporting' services:

- Water purification and waste treatment (including hydrocarbons) – the principle of extraction and conversion rather than dilution and dispersion as the solution to pollution (Gallardi 2014);
- Improvement of water clarity through filter feeding, contributing to control of excessive phytoplankton blooms (including Harmful Algal Blooms) and also leading to improved benthic flora and fauna production;
- Take up of nitrogen and phosphorus for shell and tissue growth and additional removal of these nutrients through production of biodeposits and increased denitrification and ammonium production supporting primary production;
- Bivalve provision of nutrients to assist in the growth of macroalgae;
- Carbon sequestration – offset by production of CO_2, so potentially a limited net benefit (more research/analysis is needed); and
- Mediation of water flow – reduction of erosion, possible reduction of wave energy.

Cultural services, including:

- Physical, intellectual and spiritual interaction with seascapes, ecosystems, etc., for both local communities and visitors (i.e. promotion of tourism [shellfish farm visits, beachside cafes, etc] and the economic multiplier for coastal communities);
- Scientific and educational interactions, both local interest (e.g. schools) and higher-level research (national and international research projects);
- Heritage and cultural activities, including promotion of and participation in seafood festivals;
- Maintenance of community links with the marine environment, particularly where local fishing activities are under threat; and
- Non-use values, ranging from an economic development at minimal environmental disruption to avoidance of a perceived less attractive usage of the marine resource.

Perceived negative impacts from a farm development that require assessment and where possible valuation include several of the same effects noted above, as any impact can be interpreted as an impact on the natural ecosystem:

- Modification of the phytoplankton population (total and speciation) and possible modification to zooplankton consumption;
- Biological accumulation of pathogens (bacteria, protozoa and viruses harmful to human health) – usually mediated by monitoring and regulatory programmes;
- Changes to the nitrogen distribution and increased contribution of ammonium (NH4+) and an overall modification to the nutrient cycle in coastal ecosystems;
- Concentration of heavy metals and other pollutants;
- Modification of habitat and populations;
- Disturbance of mammals and seabirds;
- Visual disturbance [very difficult to value, and already highly regulated];
- Competition for seston/feed affecting natural populations of molluscs;
- Production of methane in mussel intestines - this production is negligible in relation to the total methane production in the sediment (Fenchel et al. 2017);
- Introduction of non-native species and transfer of established species between countries, with the potential of consequential inadvertent introduction of diseases and pests – this issue represents a risk, which is already managed by regulators; and
- Potential disruption to the perceived ecosystem bequest/altruist/existence benefits of an unchanged environment.

The negative impacts of bivalve cultivation developments appear to be largely qualitative and difficult to quantify, particularly in monetary terms – this does not imply that they should be ignored, indeed there are a number of established methodologies, including surveys/ questionnaires/focus groups that should be able to elicit ‘values’ to such elements.

Despite the difficulty in according monetary values to these Regulating services and the Cultural services, which as noted contribute some positive as well as potentially some negative non-monetary values, this exercise would enable a more comprehensive and structured assessment of any proposed development.

However, this review of the scientific literature concludes that the positive effects resulting from bivalve cultivation – ranging from reduction of eutrophication, contributions to the carbon cycle (degree of +/- to be determined), nitrogen and phosphorus recycling, improving water clarity, improvement of seagrass growth, harvesting of phytoplankton and reduction in algal blooms, denitrification, enhancement of habitat availability and marine organism populations, plus the provision of positive cultural services of promotion of tourism, scientific and educational interactions, cultural activities and maintenance of community links with the marine environment - appear likely to significantly outweigh the negative impacts of disruption to water flow, impact on phytoplankton populations and mix, depositional and benthic concerns and possible disruption to some Cultural Services (aesthetic and spiritual interactions) etc.

This report recommends an initiative to support farm-scale analysis and monetary valuation of ecosystem service provision on both the immediate local ecosystem and possibly the wider tidal excursion area, covering as many of the services as possible (including the difficult to value 'cultural' services). The 'Florida Clam Farm Environmental Benefits Calculator' approach could well provide an initial platform or model for such analysis and valuation (see Annex B).

In addition, in order to fully assess the role of shellfish in carbon sequestration/CO2 production, further research should be supported – the alternative, of continuing to exclude the contribution from the carbon sinks of tissue and shell, is clearly not desirable.

The contribution to decision-making by regulators and planners from the additional analysis would be positive, despite a need to combine quantification valuation of some services with a qualitative 'plus/minus' evaluation of other ecosystem services.

The publication of such farm-scale analyses of monetary and non-monetary valuations would also make a potentially positive contribution to reassuring the general public and local communities of the inclusive nature of the process of reaching decisions regarding specific bivalve shellfish development projects, elucidating the comprehensive assessment of concerns raised by the full spectrum of stakeholders.

A communication strategy to disseminate the concept of ecosystem benefits to wider stakeholder groups and local communities where developments are under consideration should be a primary objective for CES as a resource manager.

Annex A: References

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Annex B – Florida Clam Farm Environmental Benefits Calculator

Link: http://shellfish.ifas.ufl.edu/farm-benefits-calculator/

Florida Clam Farm Environmental Benefits Calculator

Enter county where your clam farm is located:

Enter your **annual** clam farm production:

Number of littleneck (1" or greater) clams harvested

Number of buttons (7/8") clams harvested

Pounds of pasta (5/8") clams harvested (calculator will convert to numbers)

Understanding this tool:

The Clam Farm Benefit Calculator allows Florida growers to make a simple estimation of the environmental benefits their farms provide to the coastal waters in which their clams are grown. These benefits include nitrogen removal and carbon sequestration (storage). With inputs of farm location and the

	number of clams harvested per year by grade size, this tool will provide an estimate of the economic value of the benefits that a clam grower's crop provides on an annual basis. The Clam Farm Benefit Calculator is intended to be simple and accessible. As such, this tool should be considered as a starting point for understanding the value of molluscan shellfish in the environment, rather than a scientific accounting of precise values.

	An annual harvest of **295,000 clams** provides overall environmental benefits of **$169**. While some environmental benefits of clams can be easily documented, such as nutrient (for example, nitrogen) extraction associated with removing the product at harvest;	$ Value

	others, such as denitrification, are not. The benefits in this calculator are based only on the clams harvested in a year, not on the entire standing crop of the farm (for example, seed, juveniles). This makes precise calculations of the economic value of these benefits difficult. The results presented here should be considered approximations of the benefits produced by clams. These benefits do not account for sales value of the clams harvested or costs (seed, gear, labor) associated with growing them.	 Nitrogen: $147 Carbon: $22 Total: $169

The Florida Clam Farm Benefit Calculator allows clam growers to estimate the economic values associated with environmental benefits their farms provide to the coastal environment. The value of environmental services provided by clams is determined by considering how much it would cost to replace these services with human activities.

Value of Nitrogen Removal - Nitrogen removal could be provided through a wastewater treatment plant. For the Cedar Key area (Levy County), this would cost about $16.71 per pound of nitrogen removed (Burke 2009). This implies that each pound of nitrogen removed by clams saves $16.71 relative to obtaining the same water quality improvement through alternative means. Costs of providing the water treatment include land and labor costs, which vary by county in Florida. Consequently, the value of nitrogen removal will vary depending on where it is provided. Values are determined for 11 coastal counties where clam farming is occurring in Florida.

Value of Carbon Sequestration - Similarly, the carbon sequestration provided by clams could also be provided by converting existing pasture or agricultural land to forest. In the Cedar Key area, these activities would cost about $20.47 per ton (short) of carbon sequestered (Nielsen et al. 2014). This value includes the cost of planting forest as well as potential revenues lost from changing land uses. In areas with highly valued agricultural land uses, the cost of converting that land to forest will be higher. Consequently, in these areas, the value of sequestering carbon through clam production instead of alternative means will be greater. Of the clam producing counties in Florida, the highest replacement costs ($144.33 per ton) occur in Collier County, while the lowest ($0.86 per ton) occur in Franklin County, driven by county land values.