The Ecosystem Services of Marine Aquaculture: Valuing Benefits to People and Nature

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As the world's population continues to grow, the way in which ocean industries interact with ecosystems will be key to supporting the longevity of food and social securities. Aquaculture is crucial to the future supply of seafood, but challenges associated with negative impacts could impede increased production, especially production that is efficient and safe for the environment. Using the typology established by The Economics of Ecosystems and Biodiversity Initiative, we describe how marine aquaculture could be influential in supporting ecosystem services beyond solely the production of goods, through provisioning services, regulating services, habitat or supporting services, and cultural services. The provision of these services will vary, depending on functional traits of culture species, biotic and abiotic characteristics of the surrounding environment, farm design, and operational standards. Increasing recognition, understanding, and accounting of ecosystem service provision by mariculture through innovative policies, financing, and certification schemes may incentivize active delivery of benefits and may enable effects at a greater scale.

Keywords: ecosystem services, aquaculture, mariculture, environmental management, sustainable development

Nature supports humanity through the delivery of ecosystem services, such as the provision of food and raw materials, the maintenance of clean air and water, and the creation of spiritual and cultural connections that foster well-being. Collectively, the ecosystem services provided by marine and coastal habitats (e.g., coral reefs, seagrasses, wetlands) have been valued at $50 trillion per year (Costanza et al. 2014). In terrestrial environments, there is growing recognition that modified, as well as natural, landscapes can provide ecosystem services that extend beyond the provision of food and raw materials (Power 2010). Agroecosystems—agricultural landscapes that both produce and consume ecosystem services—can be actively managed to promote healthy ecosystems, biodiversity, and production alongside socioecological values (Lescourret et al. 2015).

Aquaculture is an increasingly widespread and conspicuous agroecosystem in estuarine, coastal, and marine seascapes. Aquaculture has developed rapidly over the last 50 years and is the fastest growing primary production sector worldwide (Duarte et al. 2009, FAO 2018). but its rapid rise has, at times, been accompanied by significant environmental impacts (Naylor et al. 2000, Diana 2009) and social or economic conflicts (Lester et al. 2013, Brugère et al. 2018), contributing to negative sentiment that potentially limits industry growth (Froelich et al. 2017). Considerable progress has been made over the last several decades toward the development of ecologically sustainable and ecosystem-centric approaches to aquaculture (e.g., Costa-Pierce 2010, FAO 2010, Brugère et al. 2018). However, a pendulum swing toward fully understanding 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 (Brugère et al. 2018), and, potentially, a lack of understanding of the economic value.

Aquaculture typically describes the organized rearing, feeding, propagation, or protection of aquatic resources for commercial, recreational, or public purpose (FAO 2018), and *mariculture* is this same sort of activity in marine (ocean) and non–land-based nearshore environments. In the present article, we use The Economics of Ecosystems and Biodiversity (TEEB) classification system to provide an overview of the ecosystem services associated with mariculture. The TEEB system provides a structured approach to defining the economic values of biodiversity and nature's services in decision-making, aligning ecosystem services with those related to provisioning, regulating, habitat or supporting, and cultural outcomes. Like terrestrial agroecosystems (Power 2010), mariculture not only consumes but also provides ecosystem services far beyond the provision

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of goods. Although a collective effort is needed to continue to address ecosystem disservices from mariculture (Naylor et al. 2000, Diana 2009), recognition of its considerable potential for positive effects should be built in order to enable more accurate accounting of social, economic, and ecological values and the development of an ecologically sustainable industry.

Ecosystem services and mariculture

Ecosystem service accounting and the TEEB initiative were established to provide a finance-based platform for quantifying nature's goods and services, to draw attention to the crucial role biodiversity plays in global economic benefits and to the significance of its loss (Ring et al. 2010). Although human-modified and natural systems differ, ecosystem processes in areas actively used for industry can provide a broad range of services of direct benefit to people (Power 2010). Aquaculture has a long socioecological history. Organized rearing of fish, for example, has been practiced in China for millennia, and in Hawaii, native islanders built extensive integrated agriculture–aquaculture fishponds between the tenth and fourteenth centuries (Kikuchi 1976). These areas were considered an everyday part of the local ecosystems and human activity and continue to be an important source of cultural significance. However, the evolution of more modern, intensive practices has contributed to a delinking of aquaculture from agriculture (Edwards 2015) and divergence from more natural ecohistories (Costa-Pierce 2010). To support sustainable development during a period of industrialization, managers have focused primarily on interventions to address negative environmental impacts, such as reducing reliance on lower trophic level fisheries or nutrient inputs by manufacturing feed (Naylor et al. 2000, Diana 2009).

Mariculture remains an interconnected part of the ecosystem in which it occurs, even where a high degree of intervention is required (e.g., substantial infrastructure, regular feeding, chemical use for infrastructure or stock). But it is now more typically viewed as an industry requiring stringent regulation and active management, as only a consumer of goods and services rather than also as a provider. Resembling agroecosystems, mariculture can, under certain circumstances, support many of the same fundamental goods and services provided by nature (e.g., Dealteris et al. 2004, Humphries et al. 2016). For example, shellfish habitats, such as oyster reefs, provide important high-value functions through filtration, denitrification, stabilization of sediments and shorelines, and the creation of habitat for associated species (Grabowski et al. 2012). But shellfish habitats also represent some of the most degraded marine ecosystems in the world, and traditional restoration efforts can require large sources of public funding, can take decades to achieve, and may, in some instances, be impossible, given the presence of continued stressors. Accordingly, commercial shellfish mariculture could provide a valuable counterpart to the delivery of a wide range of ecosystem services (figure 1).

The relative and unique differences between mariculture and natural systems must always be recognized and valued. But continued ecosystem declines and the reorganization of communities by anthropogenic climate change means mariculture may provide an opportunity to maintain or reinstate lost ecosystem services in the ocean. Drawing on cases from a range of mariculture sectors—but particularly finfish, shellfish, and macroalgae—in the following sections, we explore when, where, and how mariculture might contribute to each ecosystem service described by TEEB. In describing these effects, we acknowledge that ecosystem services and their interpretation can be influenced by a wide range of drivers, including, for mariculture, abiotic and biotic conditions; species of cultivation; operational factors, such as farm size and farming practices; and geographical variation in socioeconomic values (see the discussion below).

Provisioning services. Mariculture generates products of social value. Primarily, these products are food, but the production of medicinal resources for healthcare industries could be an increasing source of goods into the future. In addition, other live products, such as ornamental invertebrates and fish for the aquarium trade, can be produced (Tlutsy 2002), and raw materials from shellfish and algal mariculture have a wide range of current and potential applications (e.g., substrate for restoration, pharmaceuticals, texturizing agents, agar, and biofuel).

Mariculture offers a crucial supply of protein, and although development in regions particularly sensitive to food insecurity and nutritional deficiencies is needed (Golden et al. 2016), the provision of seafood can support nutritionally vulnerable communities (Belton et al. 2018). With high levels of omega-3s, selenium, and other essential nutrients, seafood is of particular value to human health, in some instances protecting against cardiovascular diseases and improving fetal and infant development (Mozaffarian and Rimm 2006). Health risks from consuming seafood cultured in polluted waters can occur, whereby product can become contaminated by heavy metals, dioxins, bacteria, and viruses (Duarte et al. 2009). However, for most adults, the benefits of consuming seafood outweigh the potential risks (Mozaffarian and Rimm 2006) and appropriately locating cultivation sites can reduce contamination, as can depuration, drying, or processing the product prior to sending it to market. Further to direct provision from the operation itself, mariculture facilities have also been shown in some instances to positively affect nearby fisheries species, theoretically by creating additional habitat and organic enrichment, and could perhaps augment local or regional catches (Machias et al. 2006).

A range of taxa, including mollusks, sponges, corals and algae, can be cultivated to produce medicinal resources for use in the healthcare, pharmaceutical, and cosmetic industries. For example, the widespread nutraceutical Lyprinol can be obtained from New Zealand

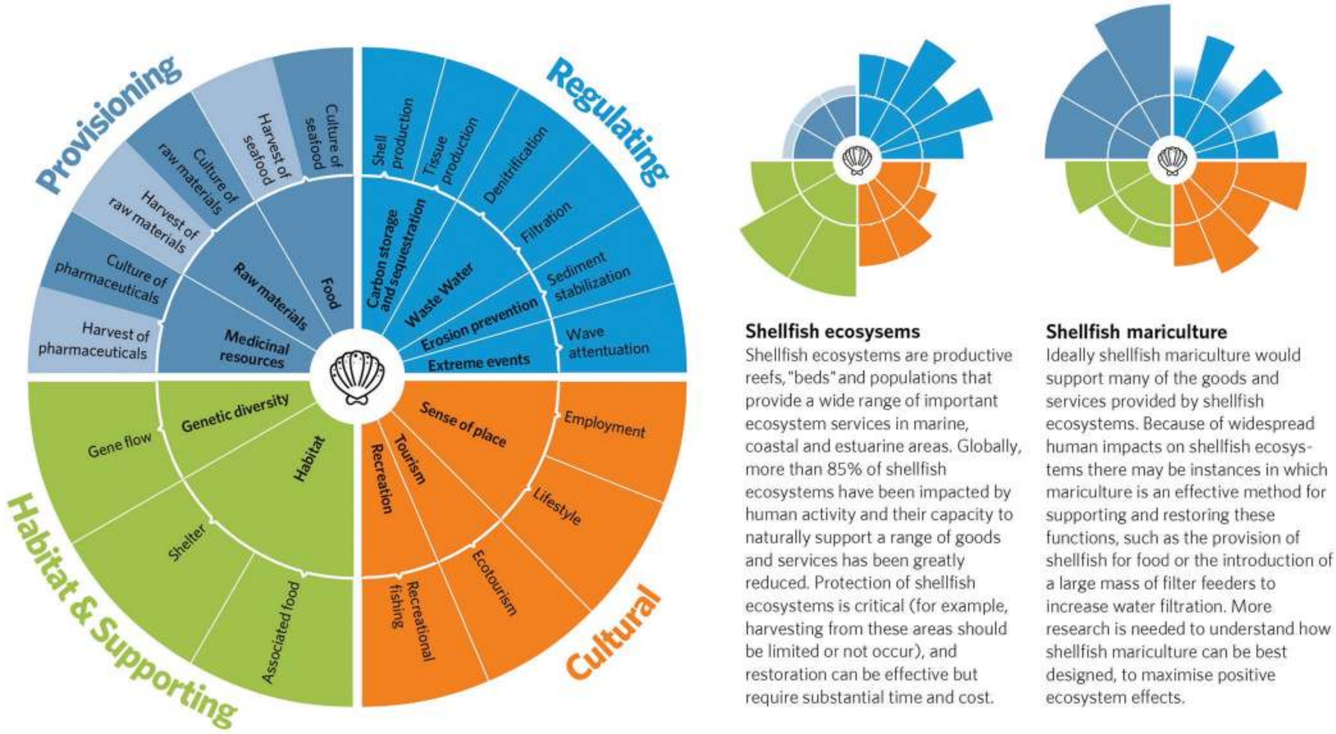

Figure 1. Shellfish ecosystems and shellfish mariculture can provide similar—although notably different—goods and services. Because widespread impacts on shellfish ecosystems present challenges to restoration, mariculture may now be disproportionately valuable in delivering a range of goods and services. (The proportions of different values are based on theoretical measures for the illustration.)

green-lipped mussels, now widely produced through mariculture (Benkendorff 2009). Marine sponges and corals can be rich in bioactive compounds and may be able to be successfully cultured to assist discovery and development and to provide a sustainable source for production (Munro et al. 1999, Leal et al. 2013).

The production of widely used natural products, such as agar or carrageenan from algae (Nayar and Bott 2014) or bivalve shell, is another provisioning service achieved by mariculture. Although now typically considered waste, oyster shells were historically used as lime in cement, and more recently, they have been adapted as a substrate for shellfish reef restoration (Brumbaugh and Coen 2009). Mariculture currently contributes a nominal amount of shell for such efforts, but in the United Sates, this resource is increasingly traded across municipal boundaries to support works, such as its use as substrate for reseeding and release of live shellfish, and in a growing number of locations, shells are recycled from restaurants.

The capacity of mariculture to not only sustain but also increase its contribution to provisioning services in many regions is substantial. Gentry and colleagues (2017a) estimated that 15 billion metric tons of finfish per annum could be produced through open ocean aquaculture, a quantity more than 100 times the current global seafood consumption. In contrast with land-based primary industries, many of which are projected to be negatively affected by climate change (Godfray et al. 2010), even under future climatic variability, total mariculture production is projected to grow (Klinger et al. 2017).

Regulating services. A wide range of regulating services can be associated with mariculture, such as nutrient cycling, assimilation, and removal; water filtration; and the attenuation and stabilization of wave energy. Filter-feeding organisms particularly but also grazing animals and algae cycle and take up nutrients (e.g., nitrogen, phosphate, carbon) and can remove these elements, organic matter, and other particulates from the water. The assimilation and storage of nutrients, including through secondary microbial activity, can transform nutrients from one state to another, making these accessible to other biota or reducing excess loads (Neori et al. 2004, Humphries et al. 2016). By reducing excess anthropogenic nutrients, the mariculture of shellfish and algae can combat eutrophication (Petersen et al. 2016). In influencing carbon cycling, the cultivation of algae and bivalves may also play an important role in carbon sequestration and storage (see box 1), and algal culture can have a locally protective effect on ocean acidification (Mongin et al. 2016). Although more research is needed to understand the dynamics of algal culture in buffering ocean acidification, the application might provide an important opportunity for the industry to

Box 1. Can seaweed mariculture contribute to carbon sequestration?

Marine macroalgae (kelps and seaweeds) play an important role in coastal carbon cycling and have been identified as significant carbon sinks. Recent estimates suggest globally macroalgae could sequester 173 teragrams of carbon per year, with approximately 90% of this sequestration achieved through the export of both dissolved and particulate organic matter to the deep sea, the remainder achieved through burial of organic matter in coastal sediments (Krause-Jensen and Duarte 2016). During mariculture of macroalgae, the biomass is primarily harvested, so a smaller proportion becomes detritus (dead organic material) and therefore available for potential sequestration in the sediment (Duarte et al. 2017). However, up to 60% of the carbon fixed by macroalgae is released into the water column as dissolved organic carbon, a portion of which remains resistant to remineralization and enters the refractory pool, where it can be sequestered for hundreds to thousands of years (Hughes et al. 2012).

Resembling blue carbon strategies for marine and coastal vegetation, well-designed macroalgal mariculture could potentially be purposefully developed as a climate change mitigation strategy. Duarte and colleagues (2017) provided an upper estimate of current carbon dioxide capture by macroalgal mariculture of 2.48 million tons per year. Although this is significant, it represents only 0.4% of the total carbon capture by macroalgae; wild beds currently dwarf the contribution of mariculture. However, because macroalgal mariculture only covers a tiny fraction (approximately 0.04%; Duarte et al. 2017) of the area covered by wild macroalgae, the global potential for increased aquaculture activity (Gentry et al. 2017a) speaks to the positive influence on carbon sequestration and storage that could be achieved by this sector.

influence this emerging issue by providing local protection for significant marine habitats or species.

Regulating services can be achieved through passive action, in which mariculture centers on commercial production but incidentally returns a positive effect, and via more active modes of delivery, such as bioremediation (e.g., the growth and removal of algal biomass to reduce dissolved nutrients; Neori et al. 2004). Nutrients and byproducts generated by finfish mariculture can be used as the basis for developing polyculture or integrated multitrophic aquaculture systems, in which species from a range of trophic levels are used to exploit and extract inorganic and organic matter resulting from farming. Done on a broad scale and in locations in which regulating effects can have influence, it may be possible for mariculture to be a significant contributor to broader ecosystem processes. For example, modeling suggests that it might be possible to remove the full nitrogen load in the Potomac River, which flows into the Chesapeake Bay on the East Coast of the United States, if 40% of the river area were used for oyster culture (Bricker et al. 2014).

Biogenic habitats play an important role in moderating extreme events and controlling erosion by dissipating wave energy and stabilizing sediment along shorelines (Grabowski et al. 2012). Under certain circumstances, mariculture may return similar benefits. For example, at a site scale, offshore mussel farms in New Zealand dampened wave energy by up to 17% (Plew et al. 2005), and along the North Atlantic French coastline, mussel bouchots did so by up to 50%, which also stabilized local sediments and increased sedimentation (Nikodic 1981).

Habitat or supporting services. Habitat or supporting services include the provision of habitat for species and the maintenance of genetic diversity. Mariculture infrastructure can support a diversity of wild (i.e., not cultivated) marine life (Costa-Pierce and Bridger 2002). The hard substrate provided by mariculture that enhances habitat for wild species might provide stepping stones that enable fouling organisms to migrate across sedimentary landscapes in a changing climate (e.g., Bishop et al. 2017). Aggregations of transient and resident fish are often observed around sea cages (Machias et al. 2006, Dempster et al. 2009), because of the structural habitat, facilitation of prey organisms (e.g., within biofouling), and organic enrichment through food and animal waste they provide (Costa-Pierce and Bridger 2002). Whether this interaction enhances fish populations is dependent on the extent to which aggregations are redistributed from other sites and on the harvest pressure permitted. Mariculture may lower fish biomass if infrastructure serves as an ecological trap, attracting fish and making them more vulnerable to capture by humans or natural predators (e.g., seals). However, mariculture facilities can also resemble small-scale protected areas, or *pseudoreserves*, because they can be licensed, permitted, or managed to exclude or restrict activities, including fishing, ensuring that the potential benefits of operations in enhancing production are not offset by other effects, such as overexploitation (Özgül and Angel 2013).

The escape of stock or viable gametes from mariculture is often considered a negative environmental impact (Naylor et al. 2001), but in areas in which a species survival is otherwise marginal or in which restoration is warranted because of historical declines, spillover of stock from mariculture sites could support the maintenance of wild populations. For example, along the east coast of Australia, where wild oyster reefs are functionally extinct, a significant mariculture industry for Sydney rock oysters contributes spawning stock biomass that could be used to naturally supply adjacent restoration projects with larvae. The introgression of mariculture genotypes into wild populations may enhance genetic diversity, particularly where wild populations are severely genetically bottlenecked (Thompson et al. 2017). However, the positive effects of this service will depend on the status of the cultivated species as native and the genetic composition of the population that spills over (e.g., the relationship

Box 2. The role of ecosystem services in supporting gender equity.

Although economic growth and social well-being can be correlated with gender equity (Hausmann et al. 2007), inequality can occur throughout a range of variables, such as food, nutrition and health, education, and influence. In seafood industries, there can be differences in the contributions and status of men and women and in the remuneration they receive for their work (Weeratunge et al. 2010, Kruijssen et al. 2018), which can sometimes see women relegated to levels of poverty. Inequalities in seafood value chains are, however, not always biased against women, and in a number of countries, women's participation in aquaculture activities is higher than in capture fisheries (see Kruijssen et al. 2018's table 1 for information and sources on gender division in different countries). Women conduct the vast majority of pre- and postharvest activities for the Indonesian macroalgal industry, with much of this activity occurring in remote areas, thereby serving as a source of empowerment where historically few employment opportunities for women have existed (Fitriana 2017).

The role of ecosystems in supporting gender equity is not typically considered an ecosystem service. But links between the environment and mental and physical health are known, particularly in relation to the personal use of environments, opportunities for participation in economically valuable activities, and an individual's sense of purpose. Opportunities for equitable, nongendered generation of self-worth from marine environments and resources, including those achieved through mariculture, may be an important consideration for nature's services, alongside cultural services, such as recreation for mental and physical health or spiritual experiences and a sense of place.

with the local genetic population, wild adaptive capacity). In addition, positive effects may depend on how traits desirable for mariculture (e.g., fast growth, disease resistance) trade off with those that confer environmental resilience to a range of stressors (McAfee et al. 2017).

Stock bred and used for mariculture can also be an important resource for deliberate introductions through restocking and restoration programs, including those explicitly focused on supporting biodiversity (Froelich et al. 2017). For example, hatchery-produced stock selectively bred for disease resistance can be used to seed oyster reef restoration projects in disease-afflicted estuaries (Brumbaugh et al. 2000).

Cultural services. Mariculture has played an important role in early and more modern cultural histories and can support the continued preservation of individual and collective spiritual and physical connections with the marine environment and marine resources. Reis and Hibbeln (2006) highlight cultural labeling of fish as symbols of emotional well-being and social healing in religious and medical practices among independent cultures for at least six millennia. Mariculture could be used to support continued associations such as these and to provide a means for traditional and indigenous communities to maintain and preserve customary access or ways of life. For instance, Australian Aboriginal peoples used temperate seaweed species for a wide range of purposes, a spiritual and physical connection that could be aligned with mariculture development for the benefit of traditional custodians (Thurstan et al. 2018).

An important service of mariculture is the employment opportunities it provides, which can build a sense of place, including in regional, isolated areas and disadvantaged or impoverished communities. Employment is not, however, a default outcome of development, and the effective application of socially relevant policies is needed to ensure that employment is accessible, particularly in developing countries (Allison 2011). An important contribution of mariculture in relation to economic and work-related opportunities may be the provision of gendered opportunities, in support of gender equity (see box 2). For coastal communities that have experienced a decline in fisheries-related employment, mariculture can provide an alternative but similarly skill-focused livelihood (McCausland et al. 2006).

Food tourism is a rising industry that can be important in sustaining and building regional community identity (Everett and Aitchison 2008). Individual mariculture operators may be able to provide farmgate experiences to interact with their business, and regional hubs or collectives of tourism or education-oriented activities can showcase operations across the value chain (e.g., farming, harvesting, processing, marketing, transport, and sales). Ecotourism can also be associated with mariculture. For example, in Indonesia, macroalgal farms have become common stops on ecotours (Long and Wall 1996).

Notably, mariculture operators who develop value-added activities as a part of their business and link production to other ecosystem services adopt broader socioecological principles resembling an ecosystem-centric approach to aquaculture (Costa-Pierce 2010, Brugère et al. 2018). For instance, the use of artificial structures to grow out hatchery-bred juvenile greenlip abalone in a marine park in southwestern Australia avoids additional pressure being placed on wild abalone stocks and incidentally provides habitat for a large-bodied fish (dhufish, a pearl perch) important to recreational and commercial fisheries (Lewis 2015). This activity is being coupled with food, processing, and educational experiences, thereby supporting provisioning, habitat, and cultural services (figure 2).

Factors affecting ecosystem service delivery

Inherent in many of the ecosystem services provided by mariculture can be variability arising from the nature of the activity and the context in which it occurs. Consequently,

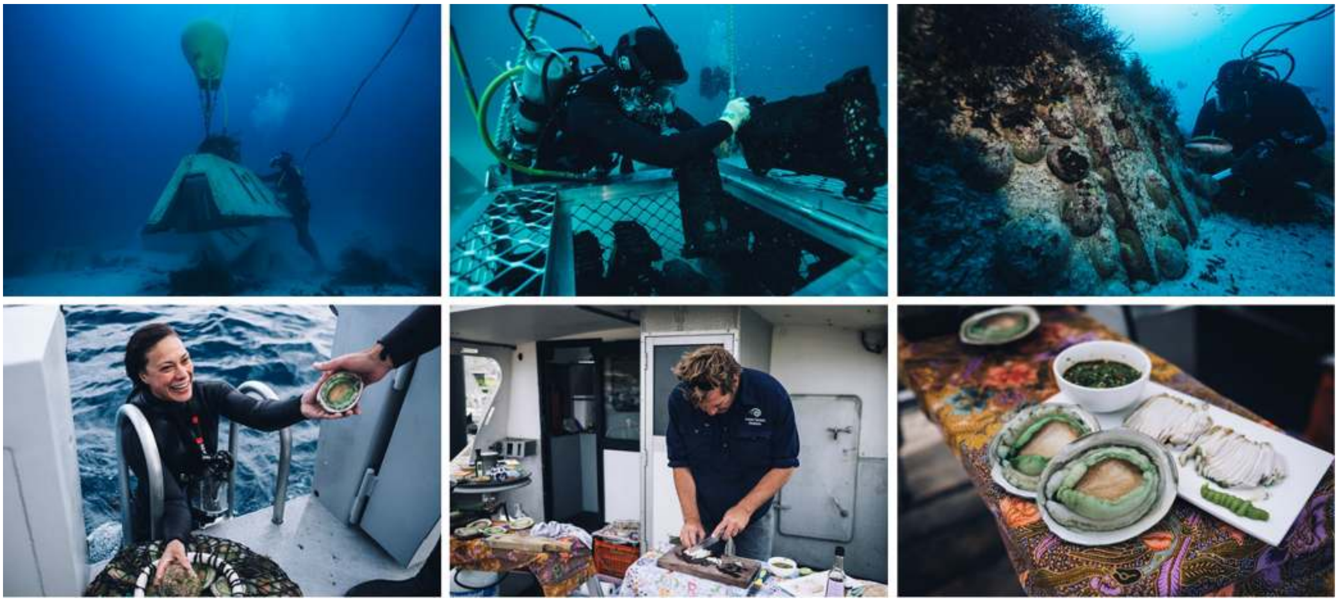

Figure 2. Ocean Grown Abalone Pty Ltd, located in Augusta, Western Australia, operates ocean ranching of greenlip abalone in Ngari Capes Marine Park and combines in-sea production with unique cultural outcomes. Through an integrated approach, this business provides a wide range of ecosystem benefits, spanning provisioning, habitat, and cultural services. Photographs: Russell Ord.

to fully understand the value of mariculture in supporting ecosystem services, across all sectors and at successive scales, there is a need to evaluate cause and effect relationships and to generate primary data on interactions between fundamental factors, such as biogeochemical cycles, species, and surrounding habitats. For instance, farm design (e.g., fixed versus moving shellfish baskets, the proximity of sea cages to one another) and sector-wide operational standards (e.g., stocking densities, stock and infrastructure rotation, and the controls and maintenance standards adopted to reduce biosecurity or aquatic animal health issues) will influence the ecosystem services provided and the extent to which the negative impacts might undermine the benefits.

The functional traits of culture species will largely underpin the types of ecosystem services that can be delivered and the degree to which these can be achieved. For example, shellfish and algae can exact a fundamental influence on water filtration and nutrient assimilation. Whereas finfish mariculture may not have a direct positive effect on water filtration, modest nutrient enhancement in nutrient-limited environments could enhance productivity in the surrounding environment, including filter feeders, to support an indirect effect on this same service (Costa-Pierce and Bridger 2002).

Beyond functional traits, abiotic (e.g., wave energy, current speed) and biotic (e.g., benthic habitat, ecosystem trophic structure) factors, which can vary at multiple spatial and ecosystem scales, will influence the direction (positive or negative) and magnitude of ecosystem services attained. For example, nutrient addition from mariculture in naturally eutrophic waters may result in excessively high loads and induce anoxia, but in naturally oligotrophic waters, nutrient enrichment might stimulate productivity. Also, nearshore operations in wave-swept environments will likely have greater benefits for shoreline stabilization than those in sheltered environments or offshore. Accordingly, our understanding of ecosystem services associated with mariculture must include the effects of ecosystem and operational scale (table 1). Spatial planning and farm siting that is intentionally oriented toward successive scales of ecosystem service delivery could assist in identifying locations in which mariculture could have the greatest positive effect (see box 3).

The health of the surrounding ecosystem will also have consequences for mariculture's role in supporting ecosystem services. Degraded ecosystems might represent opportunities for mariculture to have a greater effect (e.g., habitat for species in which hard or complex substrate has been lost or in which areas have high levels of anthropogenic eutrophication). But degraded species and habitats can also be the subject of conservation covenants (e.g., marine protected areas), which might actively exclude mariculture to protect the object of interest. In such instances, explicit understanding of the trade-offs of developing mariculture will be needed (Lester et al. 2013). Also, coastlines in some areas have already undergone considerable change to facilitate mariculture development, such as clearing and conversion of mangrove forests to make way for shrimp farms (Paez-Osuna 2001). In such instances, consideration of whether mariculture provides a net positive or negative effect on ecosystem services should include services previously provided by natural habitats that have been displaced or degraded. Like accounting for abiotic and biotic factors,

Table 1. Examples of abiotic and biotic factors and processes, across successive ecosystem scales, that might influence the capacity of different types of mariculture to deliver ecosystem services.

	Local (farm) scale[a]	Regional (landscape) scale[b]	Biogeographical scale[c]
Abiotic factors	• Cultivation method, infrastructure and gear used, and farming inputs (e.g., feed, fertilizer) • Local hydrodynamics (e.g., current strength and direction, tidal movement, waves and exposure to wave energy) • Depth or elevation of cultivation • Benthic sediment type—sediment stability and nutrient absorption capacity • Water quality and chemistry parameters and ranges (e.g., pH; dissolved oxygen, nitrogen, phosphorus, and carbon dioxide; and turbidity) • Benthic habitat type (e.g., baskets, bags or rack oyster culture)	• Regional hydrodynamics • Water temperature and salinity ranges • Weather patterns (e.g., rainfall, prevailing wind direction) • Distance between and density of aquaculture operations • Distance from and discharge magnitude of nutrient and pollutant sources • Water quality and chemistry parameters and ranges (e.g., pH; dissolved oxygen, nitrogen, and phosphorus; turbidity) • Solar irradiance (particularly seaweeds)	• Nutrient status of ecosystem (e.g., oligotrophic, eutrophic) • Additional anthropogenic inputs (e.g., land-based runoff, estuarine or delta inputs) • Water temperature and salinity ranges • Weather patterns (e.g., rainfall, prevailing wind direction) • Vulnerability to climate-related disturbances, such as ocean acidification • Solar irradiance (particularly seaweeds)
Biotic factors	• Stocking density of species • Coculture and interaction with multiple species • Benthic habitat type • Benthic community structure and biodiversity • Pathogen dissemination pathways • Marine pest presence and dissemination pathways • Phytoplankton availability (bivalves)	• Prevalence of disease and parasites • Reproductive status of stock (nonreproductive or spawning potential) • Distance to natural habitats • Distance from critical or sensitive habitats, key biodiversity areas, or protected areas • Regional species pool of available colonists • Regional biodiversity and use of hard substrate	• Culture of endemic or naturalized species • Population status of existing wild harvest resources • Conservation status of existing coastal habitat and biodiversity

Note: Factors can occur at multiple scales but at each might generate a different strength of effect. [a]Less than 1 kilometer. [b]Between 2 and 20 kilometers. [c]More than 20 kilometers.

spatial planning could assist in maximizing the benefits that could be realized while accommodating a range of management objectives (Gentry et al. 2017b), including those that might ordinarily seem conflicted.

Emerging opportunities to incentivize ecosystem services from mariculture

Innovative policies and management approaches in which the ecosystem services provided by mariculture are valued and monetized and their delivery incentivized present an opportunity to build numerous and influential positive environmental impacts. For example, policies that enable nutrient trading schemes are being trialed at regional and global levels to address water and air pollution. Emissions trading of sulfur dioxide and nitrogen oxides occurs on a limited scale in the United States (Nishizawa 2003, DePiper and Lipton 2016). It might be possible to value oyster growth and harvest within such schemes, to explicitly recognize and ultimately compensate farmers for the ecosystem services they are providing (DePiper and Lipton 2016, Ferreira and Bricker 2016). Such efforts are currently being explored for oyster aquaculture in the Chesapeake Bay and in Massachusetts.

Ecosystem service provision from mariculture might also be enabled through new possibilities in green financing. Despite a rapid increase in impact investment in agriculture (impact investors target opportunities that generate environmental and social return, as well as profit) aquaculture has not traditionally been targeted, perhaps because of negative perceptions of environmental harm. The recognition of ecosystem service provision, along with frameworks that enable accounting and documentation of the accrual of positive benefits, might mobilize significant investment into mariculture, reinforcing further delivery of ecosystem services, thus enabling positive effects at scale.

There may also be opportunities to align the valuation of ecosystem services from mariculture with global goals and policies that are intended to support smart, equitable, and well-informed development, such as the United Nation's Sustainable Development Goals, which provide a blueprint for human prosperity and environmental sustainability, or the European Commission's Blue Growth strategy. Furthermore, incorporating valuations into existing seafood certification schemes (e.g., Best Aquaculture Practices, the Aquaculture Stewardship Council, Global GAAP, the Monterey Bay Seafood Watch program) might facilitate greater market recognition of these services. Certification schemes are currently focused on identifying the producers, systems, and species of least environmental impact, and although a number of these schemes acknowledge some of the unique attributes of operations that provide benefits to the surrounding environment, rarely do they incorporate scoring systems to evaluate ecosystem service delivery. Linking ecosystem services to reputable certification schemes, in conjunction with the development of jurisdictional management and regulatory frameworks, could create a pathway to the intentional delivery of benefits by operators while deterring the occurrence of unaddressed negative impacts.

Further, to the development of policy and accounting approaches, advancing progressive, codesigned initiatives could support development across a multitude of sectors

Box 3. Spatial planning for mariculture could unlock ecosystem services potential.

The location of mariculture operations may be a key determinant of overall or cumulative effects (including benefits and costs or risks) on ecosystem service delivery. Spatial planning approaches in which biotic, abiotic, and socioeconomic factors are considered could be used to identify where the positive effects of mariculture could be maximized. For example, current velocity can influence nutrient transport and mixing and can therefore affect availability and absorption in macroalgae and shellfish. Oysters rely on flow to access sufficient feed from the surrounding water. Low and high current speeds can reduce oyster filtration and growth rates (see figure 3 below) because of a lack of feed availability, delivery, or capacity to sort feed and nonfeed particles and because of differences in settling rates of feed to the benthos, including increased deposition contributing to low levels of dissolved oxygen (Lenihan et al. 1996, Puckett et al. 2018). Moderate current speeds, however, can result in ideal food delivery and the dispersion of waste products across a broader benthic area and, therefore, optimal growth rates for oysters.

Because of this natural variability and differing scales of influence, the opportunity to maximize ecosystem service outcomes from mariculture might therefore be achieved at an intersection of considerations (e.g., current velocities, phytoplankton availability, environmental characteristics). To operationalize recommendations on the use of oyster mariculture for removing excess nitrogen and phosphorus from the Chesapeake Bay region, the Maryland Department of Natural Resources developed marine spatial planning products (i.e., web-accessible, dynamic maps of priority areas for various forms of oyster mariculture) by identifying priority areas in which the establishment of leases would most likely yield optimal oyster growth, alongside regulating services of water filtration, and while minimizing the likelihood of spatial use conflicts (Carlozo 2014).

Spatial planning for mariculture can be effectively administered through a range of management frameworks, including legislation or statutory policies (e.g., Lauer et al. 2015). Such approaches could be combined with spatial identification of marine ecoregions in which coastal nutrient pollution, habitat degradation, and other ecosystem stressors are most pronounced in order to determine where their ecosystem services benefits might best be realized. Extending regulatory mechanisms to incorporate spatial planning of the ecosystem services provided by mariculture would provide an effective opportunity to drive ecologically sustainable development.

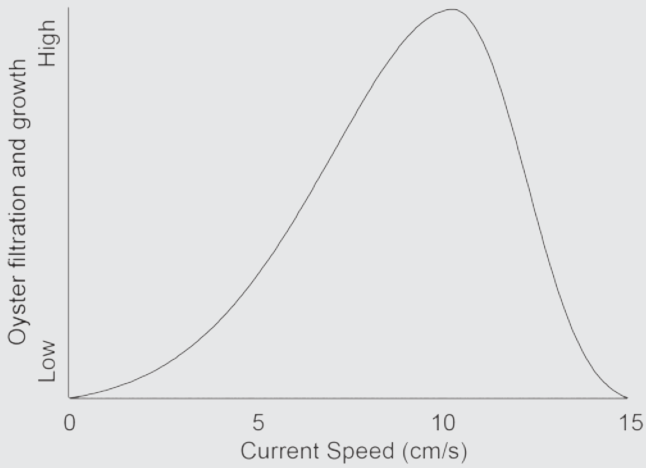

Figure 3. Demonstrated distribution of oyster filtration rates and growth at varying current speeds, based on feed availability and delivery.

(e.g., energy, transport, communication; Dafforn et al. 2015), to coproduce ecosystem services to support multiple stakeholder needs and interests (Outeiro et al. 2017). For example, offshore wind farms could provide a platform to which mariculture facilities could be attached, the operational costs of which might otherwise be prohibitive or the space and location required contested (Buck et al. 2018). To maximize the cobenefits of mariculture it will be imperative to understand how ecosystem services scale with operations, interact with adjacent infrastructure and associated processes, and might be influenced by implicit or explicit trade-offs between stakeholder values or other users.

Conclusions

The delivery of ecosystem services through industry activity is not a panacea for securing the future of nature's goods and services. But at no time in history has the world been required to provide life-sustaining services for such a large population, and so we must look to our ability to advance industries with greater positive environmental and social influence. Reinforcing the inherent link between aquaculture and the surrounding environment, and building integrated, ecosystem-centric management across marine, coastal, terrestrial, and atmospheric spheres could support the continued reduction of negative impacts. Actively accounting for the positive effects of aquaculture on ecosystem services, however, could provide a broader and more accurate valuation of the full range of effects the industry might have at successive scales of influence (local, regional and global), and emphasize its link to healthy ecosystems. It could also, we believe, drive increased appreciation and continual improvement in seeking ecological benefits, alongside economic and social outcomes.

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