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Exploring the potential for marine aquaculture to contribute to ecosystem services

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Abstract

Marine aquaculture is growing quickly and has substantial effects on people and the environment. Existing research has demonstrated that marine aquaculture can contribute to ecosystem service provisioning that extends beyond production of a resource; however, the extent and significance of these goods and services are not well understood. Here we review existing knowledge of ecosystem service provision by marine aquaculture by systematically examining 129 peer reviewed papers that describe the provision of nine distinct ecosystem services by operational or experimental marine aquaculture farms. We quantify service provision and classify services by type and by farm characteristics. We show that while certain services, such as nutrient absorption by kelp aquaculture, are well understood and have been documented across multiple species, scales and environments, the evidence for other services, such as the cultural service of tourism, is currently minimal. Importantly, we identify ecosystem services associated with a diversity of farm types (including fish, bivalve, algae and polyculture farms) but find that certain services were most often delivered by specific farm types (e.g. habitat services were most often associated with fish farms). Incorporating acknowledgement of ecosystem services into farm design and planning has the potential to improve environmental performance and sustainable management of aquaculture. However, outstanding questions, including how spatial expansion of marine aquaculture will affect the provisioning of these services, are important challenges facing sustainable development.

Key words: aquaculture, ecologically sustainable development, ecosystem services, mariculture, restorative aquaculture.

Introduction

Marine aquaculture's growth across the globe has important effects on humans and the environment, both positive and negative (Smith *et al.* 2010; Klinger & Naylor 2012). However, it is the potential negative impacts of this growth that have received the most attention, in both the scientific and popular press (e.g. Naylor & Burke 2005; Froehlich *et al.* 2017b). Marine aquaculture (henceforth referred to as 'mariculture' and defined here as aquaculture activities taking place in marine and coastal environments) can have significant and far reaching negative effects on both people and the environment, such as diminishing water quality (e.g. Islam 2005), damaging coastal habitat (e.g. Dewalt *et al.* 1996), decreasing the fitness of wild conspecifics through disease and genetic pollution (e.g. Hindar *et al.* 1991; Johansen *et al.* 2011), and creating conflicts within coastal communities (e.g. Barton & Fløysand 2010). Recently, however, increased attention has been placed on examining mariculture as part of the wider ecosystem, minimising conflicts with other users, and creating synergies with wider management goals (Aguilar-Manjarrez *et al.* 2010; Outeiro & Villasante 2013; Lester *et al.* 2018). Furthermore, the idea that mariculture can be managed in such a way that it provides environmental and social benefits beyond the production of food or other material resources is gaining momentum (Froehlich, *et al.* 2017a; van der Schatte Olivier *et al.* 2018; Alleway *et al.* 2019).

Measuring ecosystem services, or the intrinsic ability for the natural environment to provide goods and services that are beneficial to humans (TEEB, 2010), is a largely novel method for investigating the potential ecosystem-enhancing aspects of mariculture. Ecosystem services are usually applied to natural environments and, by quantifying the value of nature, can create a strong incentive for conservation. Oceans and marine habitats support coastal communities by providing food, jobs, recreation, clean environments and protection from storms (Costanza *et al.* 1998; Barbier *et al.* 2011). In addition, the coastal environment has a strong effect on global processes, such as by sequestering carbon and promoting biodiversity (Seidel & Lal 2010; Halpern *et al.* 2012). However, much of our ocean environment has been degraded by human impact, including habitat conversion, overfishing, pollution and unsustainable development, thus limiting the ability of the natural environment to provide these important services (Halpern *et al.* 2008). While conservation of wild species and habitats has the potential to preserve and restore these services, it is important to understand if and when human modified systems and infrastructure, such as those presented by mariculture, can provide the same or similar services as the natural ecosystem.

The achievement of sustainable mariculture development requires management that considers the effects of mariculture on ecosystem services. Part of this process is to manage mariculture so that it maximises the provisioning of beneficial goods and services and minimises detrimental effects (Alleway *et al.* 2019). Modified ecosystems can be both consumers and producers of ecosystem services (Power 2010). Although the negative ecosystem impacts of mariculture have been extensively studied and reviewed (e.g. Cranford *et al.* 2003; Newell 2004; Islam 2005; Price & Morris 2013), positive effects of mariculture on ecosystem services have not received the same attention. A critical need exists to survey the potential upside of ecosystem service provisioning and to understand the scope of these services. Understanding ecosystem service benefits can also support industry and farm threat and risk assessments, by developing a more comprehensive understanding of the impact of threats and through the identification of potential new risk mitigation activities. Most studies on the ecosystem services provided by mariculture are focused on only one type of mariculture and/or a single location (e.g. Higgins *et al.* 2011; van der Schatte Olivier *et al.* 2018), making it difficult to ascertain more broadly the types of farms and environments where maximised service provisions could occur. Broadly integrated assessment of ecosystem service potential is vital given that both positive and the negative effects of mariculture often vary spatially and temporally according to environmental context, cultivated species and farming practices (Gentry *et al.* 2016).

Here, we synthesise existing literature on positive ecosystem services benefits provided by mariculture, across nine distinct categories of goods and services. We examine what is known about each of these goods or services and identify for which farmed species, and in which geographic areas each has been identified. Where enough data exists, we identify the specific contexts or species where the provision of each good or service is greatest. Finally, we evaluate the current known significance and scale of benefits provided by each, including the spatial scale of the service provisioning. In doing so, we provide a basis for understanding what it might be possible to achieve with mariculture when planned and managed in a way that encourages service provisioning. Importantly, we identify where research is lacking, and therefore provide guidance about future research priorities and insight regarding the current uncertainties related to mariculture and its ecosystem service provisioning.

Methods

We used The Economics of Ecosystems and Biodiversity (TEEB) framework (TEEB, 2010) for considering the suite of ecosystem services provided by mariculture. While there are several different approaches for defining and classifying ecosystem services (Haines-Young & Potschin 2010), the TEEB framework is widely employed and provides a clear framework for evaluation. It defines four broad categories for classifying ecosystem services: provisioning, meaning the production of food, water or other goods; regulating, which encompasses services that regulate the environment such as improving water quality, moderating storms and sequestering carbon; habitat and supporting, which includes providing habitat and maintaining diversity; and cultural, which includes benefits related to tourism, recreation and culture. Within these four major categories, we then divided services into the sub-categories (see Table 1) identified by Alleway *et al.* (2019) as being addressed by the primary research literature. For example, ‘augmentation of wild fisheries catch’ was considered a sub-category of ‘food’ and ‘livelihoods’ was established as a sub-category of ‘cultural’ services described by TEEB (Alleway *et al.* 2019). Some of the services provided by mariculture farms provide a direct service to people such as by increasing productivity of commercially important products or directly

Table 1 Ecosystem services pertaining to mariculture that were included in this analysis

Service category	Service	Potential species providing service
Provisioning	Augment wild fisheries catches	Bivalves, Fish, Algae
Regulating	Carbon sequestration	Bivalves, Algae
	Acidification regulation	Algae
	Coastal protection	Bivalves, Fish, Algae
	Nutrient removal	Bivalves, Algae
	Improve water clarity	Bivalves, Algae
Habitat and supporting	Provision of artificial habitat	Bivalves, Fish, Algae
Cultural	Livelihoods	Bivalves, Fish, Algae, Crustacea
	Tourism	Bivalves, Fish, Algae, Crustacea

improving livelihoods; but in other cases the benefits to people are more indirect, such as by providing habitat to non-commercially important species. In this review we followed the TEEB approach, including services that directly benefit people or indirectly benefit people by increasing diversity or productivity of the ecosystem (TEEB, 2010). We did not include the service that was the principle commercial objective of a mariculture operation (e.g. food production, pharmaceutical production) in our analysis as our interest here was to identify services that are occurring in conjunction with the production of a commercially valuable output and to document the broader benefits and ecosystem interactions that can occur as a result of mariculture. Hence, categories such as 'food provisioning' were not included as service categories in this analysis.

For each ecosystem service, we used Web of Science (www.webofscience.com) to identify research articles demonstrating mariculture's provisioning of these ecosystem services. Searches were conducted separately for each ecosystem service category, using a topic search and specific key words describing the farming activity (e.g. 'mariculture' or 'aquaculture'), environment (e.g. 'marine' or 'coastal') and the service (e.g. 'artificial habitat' or 'acidification') (see Appendix S1). For certain services, such as acidification regulation, specific species groups were targeted in the search ('algae' 'kelp' and 'seaweed' in this instance) in order to narrow the total number of results to include only species that have been implicated in providing the service. Results were narrowed to the Web of Science Core Collection (which includes over 69 million articles from 20,000 peer-reviewed scholarly journals) and limited to include only 'articles' (which excluded books, reviews and conference proceedings). Dates were not specified in the searches; the earliest articles included in the Web of Science Core Collection date back to 1900. All searches took place in February and March 2018.

Seven hundred and thirty-nine articles were identified in the initial search. All of these articles were individually assessed to determine if they were on topic and met the following criteria required for further analysis: (i) the focus was on the provision of ecosystem services, not on negative impacts of mariculture on ecosystems (the latter of which has been extensively reviewed elsewhere, e.g. Cranford *et al.* 2003; Newell 2004; Islam 2005; Price & Morris 2013); (ii) evidence for the ecosystem service was based on primary data collected through field, laboratory, survey or modelled results; (iii) the focus of the research was on mariculture (i.e. papers focused on analogous or related systems that can be extrapolated to hypothesise mariculture's provision of ecosystem services were not included); (iv) the provision of the service was not the primary goal of the mariculture (e.g. mariculture that is developed exclusively for habitat restoration would not be included as providing habitat-related ecosystem services); (v) the aquaculture system was marine or brackish (land-based operations or experiments cultivating marine or brackish species were included); and (vi) the article was written in English and published in a peer-reviewed scientific journal. Once these criteria were applied, a total of 129 studies were included in the analysis (see Appendix S1). If a paper described more than one service, it was included in multiple categories and therefore counted twice. We acknowledge that some relevant papers were not found by our search terms and therefore our analysis does not include an exhaustive collection of every available paper that meet our criteria. However, by explicitly defining our parameters by key words and the above criteria, we were able to limit bias that would be introduced by the authors' familiarity or perspective of each service category.

Data on the service provided, the species involved in provision of the service, the type of farm (fish, algae, bivalve, polyculture or other), whether the aquaculture was experimental, the location of the farm, the type of research (lab, field, model or survey based), and the environmental setting (open ocean, inlet or bay, intertidal, pond or other), were extracted from each paper, compiled and summarised. When available, information about the scope and scale of the service provisioning were also extracted and summarised.

Results

Overview

Our analysis indicates a sharp increase in published data on ecosystem service provision by mariculture over time. Between 1995, the publication date of the earliest paper included in our analysis and 2000, only two papers were published - both on nutrient removal. By contrast, nearly 60% of the data we included was published after 2014 and nearly 20% in 2017 alone. Research published in 2017 covered all four ecosystem service categories and nearly all of the nine specific goods and services.

We found a very uneven distribution of research across services (Fig. 1). Of the 129 documented examples of services included in the analysis, over 50% were regulating services, with 75% of these focused on nutrient removal. The second most studied service was livelihoods, accounting for 22% of studies. In contrast, water clarity, coastal protection and tourism were each covered by 3% or fewer of the studies included.

The location of research displayed geographic bias (Fig. 2). Although 39 countries had at least one study demonstrating ecosystem service provision by mariculture (Fig. 2), China accounted for almost 20% of all studies (25 of the 129). The United States and Spain followed China with 21 and 17 of the 129 studies, respectively. Notably, there was minimal research from Africa or from South America. Documentation of particular ecosystem services also varied geographically. In China, over 90% of research was on regulating services, and in the US, this figure was 75%. By contrast, over 50% of the Spanish research focused on habitat services. Notably, research on cultural services tended to be concentrated in the developing world, while the provisioning, regulating and habitat service categories were studied primarily in the developed world and China. Five of the six examples of mariculture augmenting wild fish catches were based in the Mediterranean Sea. While some countries, such as China, that have high mariculture production are also significant contributors of ecosystem service research, other top producers, such as Chile and Norway have generated minimal ecosystem services research (Fig. 2). Other high producing countries such as Indonesia, have significant research, but only in one service category (for Indonesia, all of the research is cultural). Spain and the USA are both notable for their high ecosystem services research output despite moderate mariculture production.

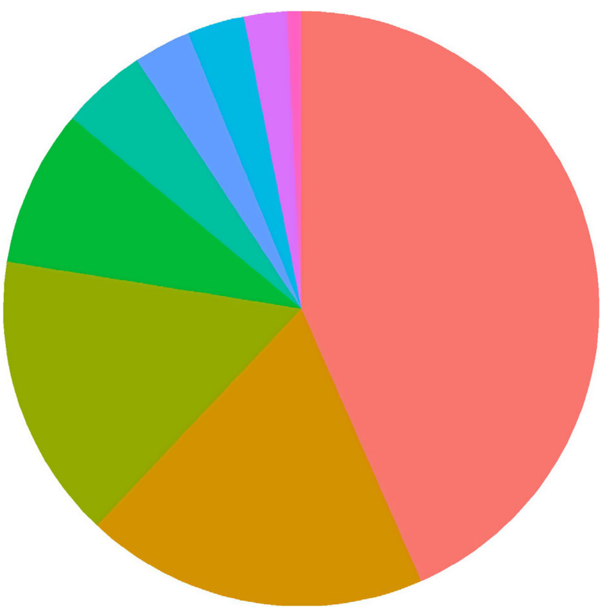


Figure 1 Proportion of studies documenting positive effects of mariculture on each type of ecosystem service. The numbers in parentheses refer to the number of research papers included in the analysis that pertain to each ecosystem service. ■ Nutrient Removal (56); ■ Livlihoods (24); ■ Habitat Provision (20); ■ Carbon Sequestration (11); ■ Augment Wild Fisheries (6); ■ Tourism (4); ■ Water Clarity (4); ■ Acidification Regulation (3); ■ Coastal Protection (1).

Ecosystem service provision was documented across a variety of species, with bivalve, algae, crustacean and polyculture farms each being the focus of more than 10 studies each (Fig. 3). Among taxa, algal cultivation was the most researched, accounting for 25% of all ecosystem services and contributing to many polyculture studies. All but one of the polyculture studies examined the potential for regulating services, as did the majority of bivalve and algae focused research. Habitat provisioning and augmentation of wild fisheries was dominated by studies of fish farms, whereas documentation of cultural services was relatively evenly distributed among farm types.

The research approach also varied between service categories, with survey and interview methods being used exclusively for studies documenting cultural services. All but four of the 28 studies documenting livelihood services included survey or interview data. Studies on regulating services were diverse in method; this was the only category that used significant amounts of lab and modelled data.

Studies of cultural services also stood out for the predominant focus on small-scale artisanal mariculture (19 of the 28 studies). Research on other services generally took place on either larger commercial farms, experimental farms or in the lab.

The following paragraphs provide brief summaries of the research for each ecosystem service category.

Provisioning services

Augmenting wild fisheries catches

There are limited studies documenting positive effects of mariculture on wild fisheries catches, however, evidence exists that in certain circumstances, establishment of a mariculture farm can have positive effects on fisheries landings – both in the immediate vicinity of the farm (Bacher & Gordoa 2016) and at a regional scale (Machias *et al.* 2006). The source of increased productivity was due to export of food and nutrients from the farm (e.g. Arechavala-Lopez *et al.* 2011), escapees from

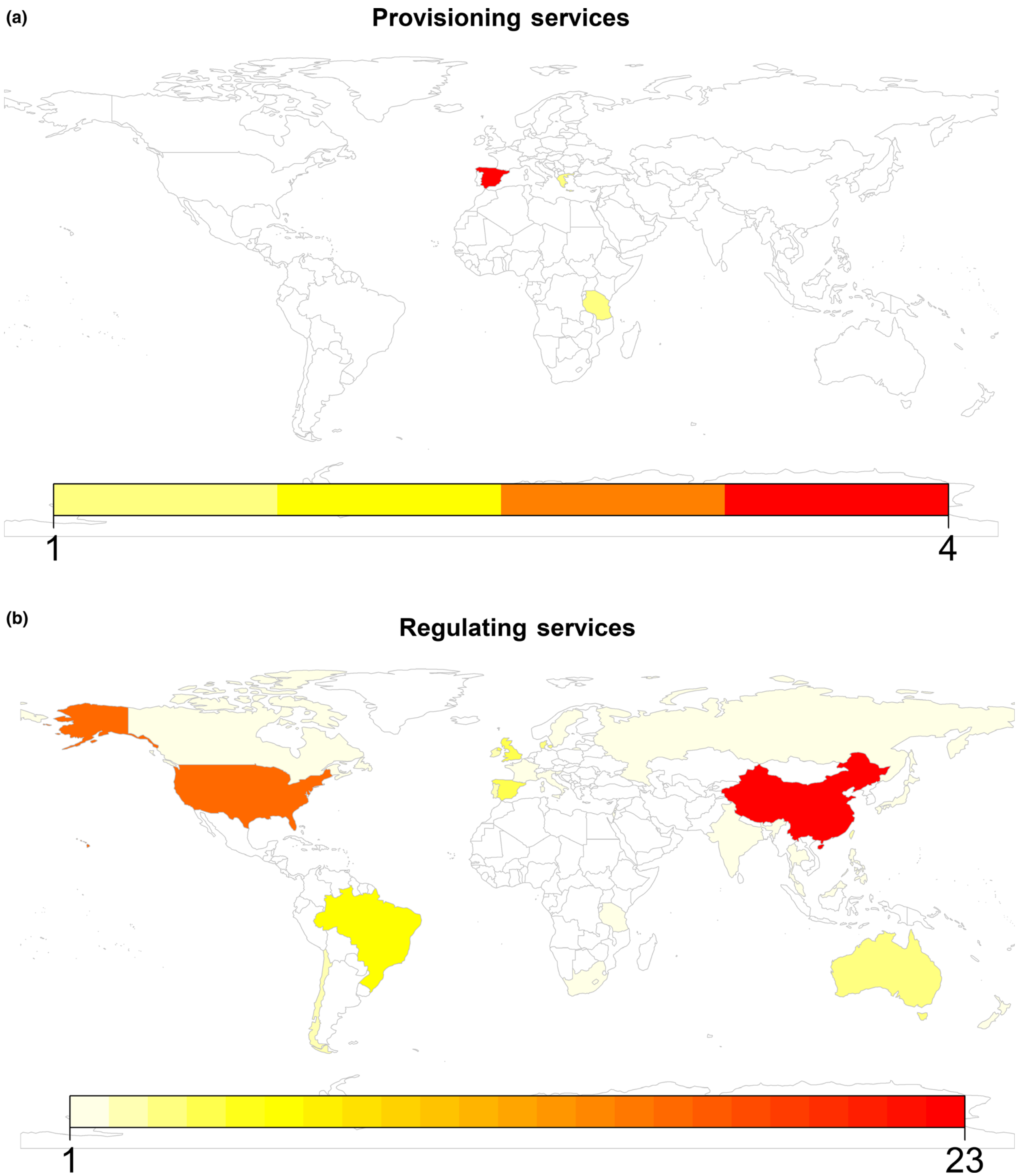
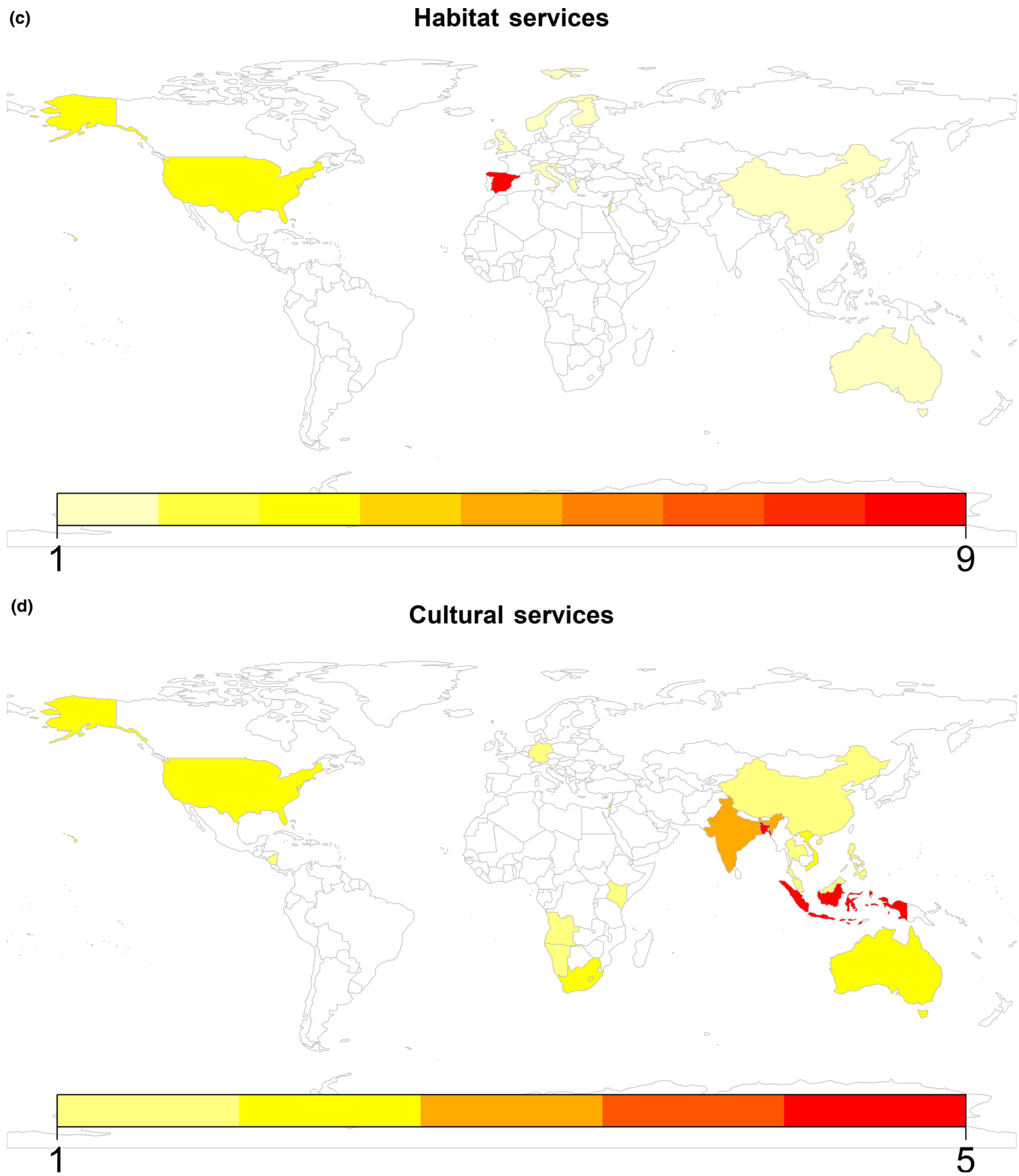


Figure 2 Global documentation of ecosystem services. The amount of research in each country documenting positive effects of mariculture on (a) provisioning services, (b) regulating services, (c) habitat services and (d) cultural services. The legend in each map is scaled to the number of total studies for each service category. Note that the scarce amount of research pertaining to Provisioning Services is impacted by our exclusion of aquaculture product provisioning from the analysis. For reference, panel (e) shows current mariculture production in each country (production is log transformed for ease of viewing) (FAO, 2018).



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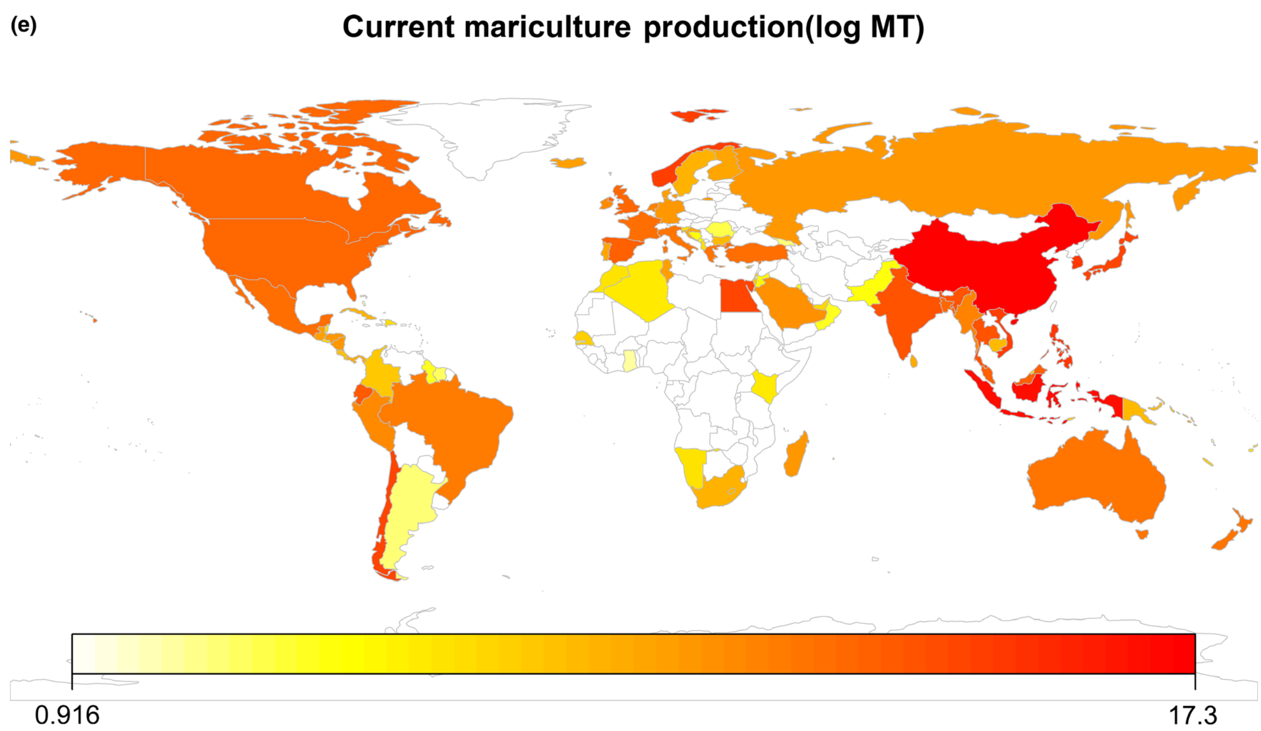
farms being caught by fishers (e.g. Arechavala-Lopez *et al.* 2015; Izquierdo-Gomez *et al.* 2017), and added structure or vegetation within the farms (e.g. Eklöf *et al.* 2006). Even when an effect on fisheries catches was identified, the spatial extent and significance of this effect varied.

Fish farming, particularly seabass and seabream farms on the Mediterranean coast of Spain, provided the majority of



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the evidence for a positive effect on fisheries landings. However, there was evidence from one study in Zanzibar, Tanzania (Eklöf *et al.* 2006) of a positive effect from a seaweed farm.

Increases in catches of wild fish is directly related to increases in fish abundance; research examining the effects of mariculture on fish abundance in the vicinity of farms (but not directly the effects of this increased abundance on fisheries) is discussed separately as the provisioning of a habitat service. Examining these two services together provides a more complete picture of the existing knowledge related to how mariculture farms affect wild fish and the humans that depend on these fish for their livelihoods.

Regulating services

Carbon sequestration

Multiple studies demonstrate that both kelp and bivalves contain significant amounts of carbon which, when harvested, is removed from the coastal environment. The scope for carbon removed via mariculture harvest is significant—for example Tang *et al.* (2011) estimated that seaweed and bivalve culture in China alone removed 1.2 million tonnes of carbon from the coastal seas annually. However, whether this carbon is actually sequestered or released back into the environment depends on the fate of the harvested product (Augyte *et al.* 2017).

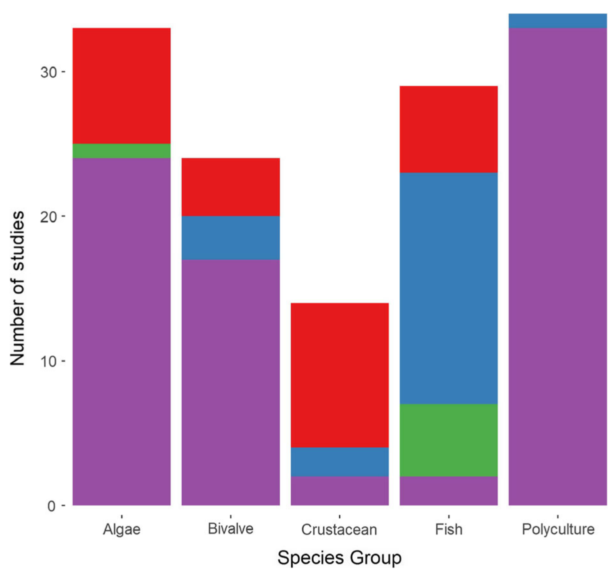

Figure 3 Amount of research demonstrating provision of ecosystem services by species group: bivalve, fish, algae, crustacean and polyculture. ■ Cultural; ■ Habitat; ■ Provisioning; ■ Regulating.

In addition to the carbon removed through harvest, some of the carbon fixed by algal mariculture remains in the ocean (as both dissolved and particulate carbon). A portion of this carbon is buried in sediments or transported to the deep sea, where it is essentially sequestered for hundreds to thousands of years (Sondak *et al.* 2017). This is the most permanent type of sequestration discussed. Sondak *et al.* (2017) calculated that sequestration of carbon from seaweed culture in Asia-Pacific could be valued at approximately US$29 million dollars per year.

Bivalves have also been noted for their ability to sequester carbon in the calcium carbonate of their shells although the processes of calcification and respiration release carbon dioxide (Han 2017). The dynamics of how these processes interact in terms of the net effect on coastal carbon cycling are not fully understood, but are important for understanding climate change related impacts of mariculture (Tang *et al.* 2011).

Acidification regulation

We found limited studies on the effects of mariculture on ocean acidification that met the criteria to be included in our analysis. Several studies demonstrate the ability of kelp to absorb carbon dioxide in polyculture systems, which has clear implications for both carbon sequestration and acidification regulation, but most of this research did not measure the direct effects of mariculture on aragonite saturation states (e.g. Han *et al.* 2013). An exception is Mongin *et al.* (2016), which demonstrated that seaweed mariculture could mitigate the effects of increased acidification at a local level, by increasing the aragonite saturation state. The authors estimate that an optimally located and managed 1.9 km^2 farm could protect over 24 km^2 of coral reef for 7–10 years and a smaller section of reef closer to the farm for up to 40 years given the current predictions for future carbon dioxide levels.

Nutrient removal

A wide variety of species were studied for their capacity to remove nutrients, constituting the most studied ecosystem service according to our analysis. This category included both research that assessed the effect of mariculture on nutrient concentrations in the surrounding water and studies that calculated the amount of nutrients removed via mariculture harvest (such as by measuring the nutrients in the harvested products). Collectively, the research provided strong evidence that both algae and bivalve mariculture can remove nutrients from the water, with smaller numbers of studies documenting that cultured polychaetes, seabass and sea cucumbers can also perform this service. Algae were featured in 44 of the 56 studies documenting nutrient removal, with *Gracilaria* spp. the subject of 17 studies. Research on *Ulva* spp. was also common, with a total of 10 studies covering seven different species of this genus. For bivalves, oysters were the most intensively investigated, with six studies demonstrating their potential to remove nutrients; mussels and clams were also demonstrated to provide this service. Many of the studies in this category were in polyculture systems, specifically examining to what extent nutrient-laden effluent from fed mariculture could be mitigated by co-culture with algae and other species.

The studies in this category used a variety of different methods to quantify nutrient removal, and varied in the stocking density they investigated and the time-scale of assessment. This made direct comparison between the studies challenging. One commonly measured parameter was the percentage of nitrogen removed from wastewater by different mariculture species. For example, ammonium removal ranged from a low of 29.8% by *Gracilaria caudata* and the microcrustacean, *Artemia,* from shrimp farm effluent in Brazil (Marinho-Soriano *et al.* 2011) to a high of 95% (seasonally) by *Gracilaria chilensis* from land-based salmon farms in Chile (Troell *et al.* 1999). Bivalve studies more commonly measured the amount of nutrients removed by harvest. Averaged over five studies, we found that each year, a hectare of bivalve mariculture removed approximately 170 kg of nitrogen, with estimates ranging from 50.5 kg (Bricker *et al.* 2018) to 378 kg (Higgins *et al.* 2011).

Unlike other categories, much of the research for this service involved laboratory experiments (48%). In many of these experiments, different species were grown in relatively small tanks, with growth of target species and effects on water quality measured (e.g. Kumar *et al.* 2015). The use of controlled environments allowed for precise measurement of nutrient changes, but typically did not enable evaluation of the ecological relevance of the service in field settings. Less than 40% of nutrient studies included field data, and many of these examined the nutrient composition of the harvested product (e.g. Wu *et al.* 2017), rather than measuring changes to the ecosystem specifically. Notably, one of the studies found that for the first year of growth, mussels farmed in a Danish Fjord were a sink of nitrogen, but after a year they became a net source of nitrogen due to nutrient excretion from the mussels and sediments (Holmer *et al.* 2015).

Although the studies reported positive results for nutrient extraction capability, the scale of mariculture that would be necessary to mitigate pollution was found to be large and, in some instances, unrealistic (e.g. Gifford *et al.* 2005). For example, Xiao *et al.* (2017) found that China would need to increase its seaweed production area by 17 times to remove all of the nitrogen coming into the system. China is the largest producer of cultured seaweed, cultivating nearly 15 million metric tonnes per year (FAO, 2018), so an increase in this magnitude would be ambitious. Many of the studies suggest that mariculture may be most effective in mitigating nutrient inputs if combined with other strategies such as wetland restoration and upstream management (Kim *et al.* 2014; Bricker *et al.* 2018).

Water clarity

We found several studies documenting the effects of bivalve and algal farms on the clarity of water in and around the farm. These studies focused on assessing clarity, such as through the use of a secchi disk, rather than laboratory measurements of water quality. The effects on water clarity were significant, and in at least one instance extended beyond the farm boundary (Schröder *et al.*, 2014). Mussel farms were the most commonly assessed for water quality effects, but the sample size of studies was small (four).

Coastal protection

We found only one article in this category that met the guidelines for this study. Plew *et al.* (2005) demonstrated that a greenshell mussel farm off the coast of New Zealand resulted in wave attenuation. To what extent this effect protected the coast from erosion or extreme events was not studied.

Habitat and supporting services

Habitat provisioning

There is substantial evidence that a wide variety of fauna live or gather in and around mariculture farms. The most commonly documented in our analysis were fish living within or aggregating around fish farms (12 out of 20 studies), but there was also evidence that bivalve farms and a polyculture operation provide habitat and/or foraging opportunities for invertebrates, birds and marine mammals (e.g. Fernandez-Gonzalez *et al.* 2014; Díaz López 2017). Most of the species utilising mariculture farms were wild species, with increases in both their biomass and diversity reported. The size of fish aggregations documented around a single farm ranged from negligible up to 38.5 tonnes (Dempster *et al.* 2004).

For many of the studies, especially those focused on mobile species, it was unclear if the farms were actually increasing productivity or just attracting species away from other natural habitats (e.g. Bacher *et al.* 2012). However, several studies used techniques such as mark recapture to demonstrate enhanced production (e.g. Tallman & Forrester 2007). This increased production can lead to mariculture farms supporting different species than adjacent natural habitats (Oakes & Pondella 2009). In some instances, habitat provisioning by farms resulted in regional level effects on ecosystem structure and function, such as by increasing spawning biomass (Fernandez-Jover *et al.* 2007) and shifting predator behaviour (e.g. Arechavala-Lopez *et al.* 2015).

Cultural services

Tourism

There were limited studies examining the tourism benefits of mariculture operations, and those included in the analysis typically demonstrated synergies between a number of services, such as through provisioning of fresh fish products (e.g. van Putten *et al.* 2016) rather than measuring a direct benefit to tourism per se. The exception is Su *et al.* (2016) which documented the benefits of mariculture and fishing-based tourism on rural communities. They found that although tourism did bring income into the community, there were potential problems with inequality as poor mariculturists attracted little of this benefit.

Livelihoods

There is a diverse literature demonstrating the potential for mariculture to provide livelihood benefits to mariculturalists and communities. These benefits included income (e.g. Benessaiah & Sengupta 2014), employment (e.g. Malik *et al.* 2017), and food (e.g. Karim *et al.* 2014). In some instances, the addition of mariculture as an additional source of livelihood provided security to fishing communities (e.g. Hoque *et al.* 2017). The included studies focused almost entirely on small-scale farming (75% of livelihood studies) in the developing world (91% of livelihood studies). Evidence for this service spanned multiple farm types, with examples from fish, algae and bivalves.

However, despite the potential to provide livelihood benefits, mariculture also caused problems in some communities. Several studies demonstrated that development of mariculture increased inequality, as those that have access to farming become significantly better off than those that do not (e.g. Huong & Berkes 2011; Abdullah *et al.* 2017). In other studies it was also shown that mariculture can be low paying and create poverty traps, especially for small scale farmers and waged workers (e.g. Mirera *et al.* 2014). In addition, unsustainable farming practices (particularly for brackish water pond-based mariculture) have damaged the environment, resulting in a reduction in other ecosystem services and economic opportunities, for example by degrading fertile soil and destroying habitat for commercially important fisheries species (Malik *et al.* 2017). In some communities, especially those that embraced unsustainable practices, the problems of mariculture appeared to outweigh its livelihood benefits (e.g. Belton 2016).

Discussion

Our analysis uncovered substantial evidence for positive contributions of mariculture to a wide range of ecosystem goods and services beyond their key commercial goal. The analysis also pointed to considerable variability in documented benefits of these ecosystem services, among locations (e.g. countries, ecoregions and operating areas), and farm types. Overall, once key commercial benefits (i.e. food production) were excluded, nutrient removal was the most documented and coastal protection was the least documented service provided by mariculture. The uneven distribution of research effort across services may reflect variability in the importance or ability of mariculture to contribute to certain services more than others. Alternatively, it could be a result of research biases, associated with national, regional or local institutional agendas, the ease of studying particular services, or the productivity of key contributing research groups. Even more simply, studying some of these services may not receive as much attention due to the tradition of focusing research on understanding or solving problems rather than identifying solutions.

Another reason for the apparent lack of information about mariculture effects on certain services, such as tourism and other cultural services, may be due to the considerable amount of knowledge captured in formats not considered by our analysis. This includes white papers, technical reports, theses and non-English analyses. In addition, information acquired from study of natural systems may be applicable to mariculture. For example, there is significant information about the potential for wild seaweed to sequester carbon (Krause-Jensen & Duarte 2016), much of which could be translated to mariculture, to scope new opportunities for industry growth, development and value. Looking at modified agro-ecosystems, such as mariculture, through the lens of natural ecosystems will provide important insight into the way that human modified systems can support the functioning and regulating aspects of the natural world. If mariculture continues to expand, the relative service contributions of these agro-ecosystems will become increasingly important in the oceans.

Even though mariculture may be capable of supporting an ecosystem service, there may be considerable spatial and temporal variation in realisation of service provision, including 'legacy effects' (e.g. prior habitat removal to install mariculture infrastructure) that extend well beyond the current mariculture activity. Indeed, two different mariculture farms can have opposite ecosystem service outcomes, such that mariculture activity can deliver a service in one instance and damage it in another. Variation in outcomes may reflect differences in the species farmed, management strategy, or surrounding environment. For example, while our literature search uncovered 20 studies documenting creation of habitat by mariculture, it also found nine articles (not reviewed here) that describe mariculture destroying or degrading habitat. Furthermore, the effects of cultivated bivalves on coastal carbon has recently been found to vary significantly across locations (Morris & Humphreys 2019). Further research to clearly identify when and under what social, economic and ecological circumstances mariculture provides for versus damages an ecosystem service is a striking priority that will need to be addressed in order to inform and guide effective management.

Even when a mariculture farm is clearly providing a valuable service, this positive effect can have related negative consequences. A comprehensive evaluation of the trade-offs between positive and negative effects of mariculture was not the aim of this study, but we did note that many of the studies we identified also documented or discussed some of

Table 2 A selection of suggested research opportunities related to ecosystem service provisioning by mariculture, organised by theme. These topics build on the analysis of existing information presented here and perceived gaps in knowledge

Geographic variability

- Build understanding as to the extent to which the provisioning of a range of ecosystem services vary across geographies and mariculture types
- Invest in more ecosystem service research across a range of geographies, especially in high mariculture producing nations, such as Indonesia, that are under-represented by current research
- Investigate the effects of climate change on existing mariculture activities and mariculture on local climate change symptoms, and design resilient systems of future benefit to communities and ecosystems
- Investigate profitability of diversified models of operation (e.g. integrated multi-trophic aquaculture, education and training) across locations
- Measure the effects of finfish nutrient enrichment on local productivity and biodiversity across a wider spectrum of geographies, including in both eutrophic and oligotrophic oceans

Social and economic interactions

- Evaluate economic effects of mariculture-associated tourism activities (e.g. mariculture facilities or practices hosting paying tourists)
- Resolve economic values (costs) for a range of nutrients and the efficacy of nutrient trading mechanisms in supporting ecosystem outcomes
- Evaluate effectiveness of mariculture in providing unbiased access to livelihood opportunities in both developed and developing countries
- Investigate if and how local communities derive social values from mariculture, such as spiritual wellbeing, a sense of place or recreation (including recreational fishing)

Environmental setting and scalability

- Determine the influence on carbon sequestration and storage, and ocean acidification, of abiotic and biotic factors, across a range of mariculture sectors and scales
- Measure fish aggregation versus local fish production across a variety of different mariculture types and environments
- Resolve the effectiveness of a range of mariculture practices, including both near shore and offshore operations, to stabilise sediments and reduce coastal erosion
- Investigate the influence of mariculture on biodiversity (e.g. local community assemblages, species diversity and richness), and the opportunity to engineer biodiversity benefits
- Measure top-down control by a range of mariculture species, including reduction of phytoplankton and plankton booms and influences of mariculture species on trophic cycling, particularly as it relates to scale of production

the negative effects associated with the provision of a positive service. For example, in delivering jobs and income benefits, mariculture can also exacerbate inequalities and lead to poverty traps (Marschke & Betcherman 2016). Additionally, although mariculture can provide habitat, it may alter ecosystem dynamics when it supports different species to natural ecosystems (Dempster *et al.* 2002). This is particularly problematic when farms facilitate invasive species, such as the vase tunicate in Canada (Daigle & Herbinger 2009). Also, where provision of habitat brings wild and farmed species into close proximity, negative interactions may result, such as from predation or disease (Arechavala-Lopez *et al.* 2014; Díaz López 2017).

Given the importance of seafood to global diets and livelihoods (Smith *et al.* 2010), projected increases in the human population and its demand for protein (Tilman & Clark 2014), and significant opportunity for mariculture expansion (Gentry *et al.* 2017), there appears to be momentum towards continued growth of the sector. As mariculture production expands, understanding trade-offs and synergies between provision of different ecosystem services, and how these vary with scale and environmental context, needs to be a priority for future research. While it is clear that benefits of mariculture can vary in time and space, it is unclear what the thresholds are at which net effects on services can flip from positive to negative. For example, whereas at low-medium densities, and farm sizes, positive effects of bivalve molluscs on water clarity and nutrient removal may increase with animal density, at high densities or farm sizes, the relationship may conceivably become negative as waste production becomes a more significant issue. In order for such trade-offs and context dependency to be assessed it is critical that future work clearly articulates the environmental conditions, stocking densities and farming practices at study sites. Furthermore, studies need to move beyond site-by-site assessments of single ecosystem services, to assess a range of goods and services and their interaction. Ideally these studies should span multiple time and spatial scales, as benefits and impacts may vary depending on environmental factors, length of operation or according to life-histories of species that use mariculture farms as food and habitat. Furthermore, a wider range of research, both geographically and topically would help with understanding the variability in service provisioning and provide deeper understanding for ecosystem services, such as coastal protection and acidification regulation that may be provided, but are poorly understood. Studies with a wider, system-level scope would also help contextualise mariculture within the human-modified ecosystem in which it operates and provide insight into mariculture's role in sustainable development. We provide examples of some of the most important research gaps we identified across the various services (Table 2). The growing interest in this research topic, as reflected in the strong increase in research volume in recent years, provides optimism that some of the gaps in our knowledge will soon be filled.

Understanding how and when mariculture can contribute to ecosystem service provisioning has significant implication to improve sustainable development outcomes. For the aquaculture industry, this includes the potential for higher profits (due to increased yields and the commodification of services such as carbon sequestration), a better environmental image and increased social licence to operate. Managers can seize this information to improve spatial planning and improve risk assessments, and allow for more efficient and effective mitigation of environmental impacts. Better understanding of potential benefits can also lead to new opportunities such as co-siting mariculture with restoration and building mariculture into marine protection plans that could increase value and productivity of the ocean environment while simultaneously providing for better environmental and social outcomes.

Deciding whether the provision of certain services is important enough or outweighs associated negative effects is as much a question of values as it is of science and the desired outcomes may vary across locations according to socio-economic factors. Particular ecological and development goals may be of higher importance in some regions and communities than in others. By identifying what is known about when and how ecosystem service provision can be associated with mariculture, we aspire to guide research and management towards simultaneously achieving both economic development and conservation within our ocean ecosystems. We suggest that increased opportunities for green capital and impact investment may grow if the ecosystem service potential of mariculture is more clearly considered in mariculture management and promoted by industry. Ultimately, successfully designing mariculture systems that produce important ecosystem services while minimising negative impacts could help steer mariculture towards not only a more sustainable future, but an environmentally influential one.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Appendix S1: Literature review method details.