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Valuation of Ecosystem Services to promote sustainable aquaculture practices

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Abstract

Conceptual frameworks to assess and valuate Ecosystem Services (ES) are rapidly becoming important tools for ecosystem-based management, as they support transdisciplinary approaches to ecological economics and expand current asset boundaries to include natural and social capital. An important area where such ES assessment frameworks could become relevant management tools is aquaculture. Aquaculture activities are an interconnected part of the ecosystem in which they exist and, under certain circumstances, can support many of the same fundamental ES provided by nature. But, in most cases, aquaculture typically increases provisioning services at the expense of the other services (regulation & maintenance and cultural services). To understand the capacity of ES valuation methods to expose existing ES trade-offs in areas under aquaculture development, this study provides a literature review of publications that assessed and valuated ES delivered and/or impacted by aquaculture. In general, it seems that certain types of aquaculture do negatively impact overall ES delivery (e.g. intensive mangrove shrimp farming in Asia), yet certain modes of production (e.g. integrated multi-trophic aquaculture) and cultured species (e.g. algae and certain bivalves) can have a positive impact on ES, not only improving provisioning services but also regulation and maintenance services and, potentially, cultural services. ES valuation methods provide important data that facilitate discussion among stakeholders and policymakers and should be included in marine and coastal management planning processes to foster a more sustainable aquaculture.

Key words: blue growth, economic valuation, ecosystem approach to aquaculture, natural capital, sustainable aquaculture.

Introduction

The concept of Ecosystem Services

In the last 20 years, the Ecosystem Services (ES) concept has gained important visibility in environmental research and policymaking (e.g. Costanza *et al.* 2017). ES has been defined as the "benefits that people obtain from ecosystems" (MEA, 2005) and the "direct and indirect contribution of ecosystems to human well-being" (TEEB, 2010), supporting all domains of human society, from individual survival to the development of the global economy. Despite major advances in developing and operationalizing the concept of ES for ecosystem-based management (EBM), researchers continue to debate and update existing conceptual frameworks for ES assessment, with the intent to create a comprehensive and overarching one. For instance, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) has proposed the concept of 'nature's contributions to people', which builds upon the above definitions of ES and further recognizes the importance of transdisciplinary knowledge (e.g. indigenous and local knowledge) to understanding the links between people and nature (Díaz *et al.* 2015, 2018; Pascual *et al.* 2017). Additionally, the creation of ES classification systems, as proposed in important publications (e.g. Millennium Ecosystem Assessment, The Economics of Ecosystems and Biodiversity and IPBES), is indispensable for measuring and assessing ES. The Common International Classifications for Ecosystem Services (CICES), in particular, aims to become a reference classification that provides a common language for interdisciplinary research, enabling users to move more easily between existing classification systems and avoid double counting when implementing the concept (Haines-Young & Potschin 2017). For this reason, the CICES nomenclature is used in this review.

The importance of coastal ecosystems for human well-being

Marine and coastal ecosystems provide a wealth of benefits that span all three categories of ES identified in the last version (v5.1) of CICES: (i) provisioning, (ii) regulation and maintenance and (iii) cultural services (Haines-Young & Potschin 2017; Lillebø *et al.* 2017). Coastal ES, in particular, are used by over one-third of the human population inhabiting coastal areas and small islands. Remarkably, these areas comprise solely 4% of the world's total land (UNEP 2006). Yet, due to intense human activities, these are exposed to several interconnected drivers of change, which contribute to their degradation and loss (de Groot *et al.* 2012). The main drivers contributing to this scenario include, among others, the development of aquaculture, overfishing, shipping (e.g. introduction of invasive species), land-based activities (e.g. nutrient loading from agriculture and urban development), coastal deforestation, shifting markets, climate change and globalization (Allison *et al.* 2009; Villasante *et al.* 2012; Tröell *et al.* 2014).

Global fish stocks, in particular, are suffering a great deal due to anthropogenic drivers and several stocks are in risk of collapsing (e.g. Pauly & Zeller 2016). Fish provide more than 3.1 billion people with ~20% of their average *per capita* intake of animal protein and, at present, more humans are consuming more fish (FAO 2016). Demand significantly increased during the last five decades, stemming from the rising living standards and prosperity of an ever-growing human population, both in developed and developing countries (Arrow *et al.* 2004; Steffen *et al.* 2011). As a solution to maintain the flow of this important provisioning service without collapsing the capacity of natural fishing stocks to deliver it, humans had to significantly develop aquaculture, which became in itself an important driver of change in marine and coastal systems (Tröell *et al.* 2014).

Ecosystem-based approach to aquaculture management

In the period spanning from 1970 to 2008, aquaculture production increased, on average, 8.3% *per* year and this activity is now the fastest growing food production industry, securing nearly 50% of the seafood supply worldwide (FAO 2016). In light of such a rapid growth, the sustainability of aquaculture has been a source of intense debate among experts. Opposing views point out several concerns such as lower water quality, eutrophication, coastal erosion, chemical accumulation, dependence on fish meal, biodiversity loss and livelihood conflicts (e.g. Primavera 1997; Naylor *et al.* 2005; Olsen 2011; Tröell *et al.* 2014).

Conversely, aquaculture advocates refer to it as likely the sole solution that may allow for the recovery of wild fish stocks, while simultaneously satisfying the ever-growing demand for seafood. Thus, aquaculture must be correctly planned and play a central role on EBM and conservation of marine and coastal areas (Tacon *et al.* 2009; Long *et al.* 2015; Froehlich *et al.* 2017; Le Gouvello *et al.* 2017). In order to operationalize an EBM for aquaculture, FAO developed guidelines and defined the Ecosystem Approach to Aquaculture (EAA) as "*a strategy for the integration of the activity within the wider ecosystem such that it promotes sustainable development, equity and resilience of interlinked social-ecological systems*" (FAO, 2010). The EAA has three main objectives: ensure both (i) human and (ii) ecological well-being and (iii) facilitate the achievement of both in the context of other sectors and policies. Mainstreaming EEA in planning processes has raised awareness of the usefulness of holistic and participatory approaches in aquaculture and helped to steer the sector towards greater sustainability, yet the approach has had varying degrees of resonance and uptake with different user groups (Brugère *et al.* 2018).

In the EU context, aquaculture is one of the five maritime economic activities prioritized in the Blue Growth Strategy (European Commission 2012a, 2017) and linking marine/coastal ES with the different blue economy sectors is key to accomplish a sustainable blue growth (Lillebø *et al.* 2017). Furthermore, United Nations Sustainable Development Goals (SDG) for 2030 acknowledges that sustainable aquaculture might contribute to support the sustainable use and conservation of oceans, seas and marine resources (SDG 14 – life below water) and offer ample opportunities to reduce hunger and foster well-being (SDG 2 – zero hunger; SDG 3 – good health and well-being).

As any other human activity, aquaculture evolves within complex environmental, social, economic and cultural contexts, with each one of them having particular effects worth describing explicitly and systematically (Bostock *et al.* 2010). Aquaculture is an interconnected part of the ecosystem in which it occurs and can provide ES far beyond the provision of food (see Table 1) and recognizing the positive effects of certain modes of aquaculture is paramount. Given aquaculture's rapid expansion and intensification worldwide, reframing aquaculture trade-offs analysis through the lens of an ES framework can provide a novel and comprehensive analytical matrix of interactions with its multidimensional context, stimulate science-based EBM and promote sustainable solutions (Bennett *et al.* 2009; Baulcomb 2013; Mach *et al.* 2015).

The present review synthesizes, to our best knowledge for the first time, the results from previous studies on the ES

Table 1 Examples of aquaculture Ecosystem Services

Section	Example of services
Provisioning services	Direct food provision (e.g. aquatic plants and animals)
	Indirect food provision (e.g. boosts fisheries by providing habitat and organic enrichment for wild species)
	Other non-food products (e.g. agar, carrageenan, bivalve shells, ornamental fish)
	Medicinal resources (e.g. extracts from algae and marine invertebrates)
Regulation and maintenance services	Bioremediation and water filtration (e.g. filter-feeders, bottom feeders and algae)
	Wave attenuation/coastal protection (e.g. offshore mussel farms, oyster reefs)
	Carbon sequestration and storage (e.g. bivalves and algae)
	Buffer for ocean acidification (e.g. algae)
	Sediments stabilization (e.g. constructed wetlands)
	Habitat provision (e.g. pseudo-reserves around farms)
Cultural services	Spiritual and physical connection with marine/aquatic environments (e.g. coastal communities, natural reserves)
	Cultural symbols (e.g. Koi carp aquaculture)
	Sense of place (e.g. employment opportunities, gender equity)
	Livelihood (e.g. alternative activity for fishing communities)
	Tourism and recreation (e.g. ecotourism, food tourism, sport fishing)
	Education (e.g. education-oriented activities)
	Research (e.g. pilot-scale experiments)

Note: based on Alleway *et al.* (2018).

produced and/or affected by aquaculture. The evaluation of ES trade-offs between aquaculture development scenarios and conservation efforts are addressed through different valuation methods. It is our conviction that employing conceptual frameworks for the assessment and valuation of ES in the context of an EEA is key to environmental policymaking. This approach can support decision-making processes framed by the preservation of ecosystems, a conscientious regulation of the different components of the ES delivery chain – capacity, flow and demand – and the promotion of positive synergies between stakeholders and the marine/coastal environment. Overall, it can foster an effective implementation of management options supporting the development of sustainable aquaculture practices.

Valuation studies around the globe

A systematic review

The EEA has been increasingly discussed in recent years and the existing literature on the subject is still fragmented but emerging. Nonetheless, the literature survey and selected publications that informed the present study (Fig. 1; see Supplementary Material for more details) provided an important insight into the relevance of the ES framework as a sustainable management tool for EBM in areas displaying high aquaculture potential.

Out of 19 relevant publications (Table S1), only nine have tried to describe and valuate ES from aquatic ecosystems under aquaculture development using different valuation methods, as summarized in Table 2. The other 10 publications, which include three reviews, a PhD thesis and a BSc thesis, clearly addressed the key role of aquaculture on the flow of ES, through some form of biological/

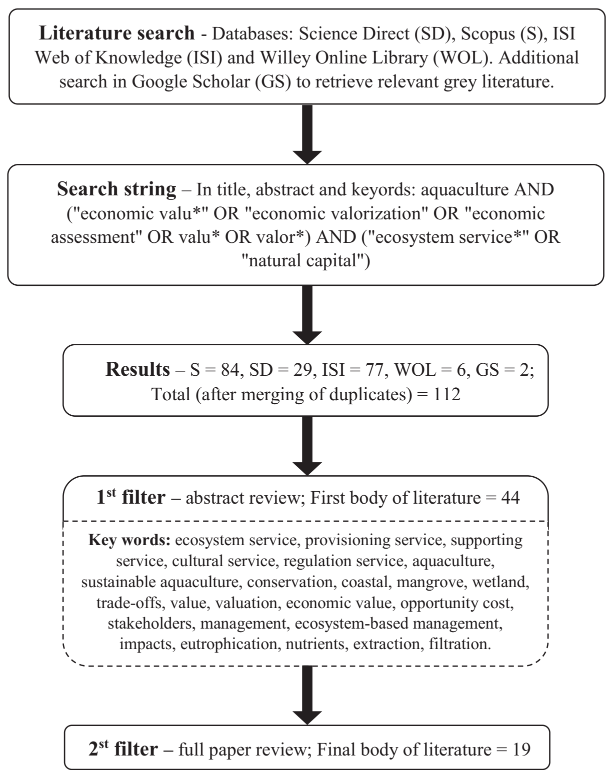

Figure 1 Schematic representation of the process employed for the selection of relevant literature.

Table 2 Empirical studies using ES valuation methods to evaluate trade-offs between aquaculture and the environment

Ecosystem type	Country	Aquaculture type	Species type	Source of evidence	ES assessed†	Valuation method	References
Coastal waters	China	Intensive	Shrimp	Survey and field work	P, R, C	P – Market Price; R – Replacement cost method and contingent valuation; C – other methods.	Liu *et al.* 2010;
	China	Extensive to intensive	–	Survey	R	Contingent valuation method	Zhang *et al.* 2012;
Freshwater ponds	France	Extensive	Fish	Survey	P, R, C	Stated preferences	Blayac *et al.* 2014;
Mangroves	Indonesia	Semi-intensive	Shrimp	Survey and field work	P, R	P – Market price; R – Replacement cost and benefit transfer methods and carbon credits	Malik *et al.* 2015;
	Philippines	Extensive to intensive	Fish	Field work	R	Carbon credits	Thompson *et al.* 2014;
	Philippines	–	–	–	P, R, C	Post-normal science method	Farley *et al.* 2010;
	Thailand	Semi-intensive	Shrimp	Model (based on previous studies)	P, R	P – Market price, Surrogate price R – Production function and Replacement cost method	Barbier *et al.* 2008;
	Thailand	Semi-intensive and intensive	Shrimp	Model and field work	P, R	Bayesian belief networks	Schmitt & Brugere 2013;
	Vietnam	Intensive	Shrimp	Survey	P, R, C	Contingent valuation method	McDonough *et al.* 2014

†P, Provisioning services; R, Regulation and maintenance services; C, Cultural services.

environmental indicators and models, but did not perform any type of valuation. Figure 2 indicates the study locations of these first assessments, with Southeastern Asia concentrating most of them, followed by Europe, China and lastly the USA with a single study so far. It is worth observing that China, the country that most contributes to the global aquaculture production (>60%), is not necessarily using this approach to assess the impacts of aquaculture development (at least according to available publications in English).

Some Southeast Asian and European countries are in the forefront of such approach, even though their combined contribution to global aquaculture production is less than 20% (Fig. 2). Due to the rapid development of shrimp farming in Asia, efforts to bring EBM to mangrove areas have increased in some countries. Growing demand from foreign markets and high economic revenues have been the major driving forces for the blind conversion of mangroves into shrimp farms, at the expense of other ES provided by these ecosystems, which have been evidently overlooked (Polidoro *et al.* 2010; Brander *et al.* 2012). Mangroves are recognized to be important ES providers, including provisioning (e.g. food, timber, fuel wood, charcoal), regulation and maintenance (e.g. floods buffer, storm and erosion protection, prevention of salt water intrusion, spawning and nursery habitat, biodiversity) and cultural services (e.g. recreation, aesthetic, nonuse) (e.g. Brander *et al.* 2012). Unsurprisingly, the first case studies attempting to bring an ES assessment approach to aquaculture management have been done in Asia.

Case studies

The cost benefit of shrimp aquaculture to society is widely debated and there are concerns about its environmental, social and economic costs, including externalities, as shrimp farming expands and intensifies in many countries (Primavera 1997; Knowler *et al.* 2009; Philcox *et al.* 2010; Hossain *et al.* 2013; Hatje *et al.* 2016). Mangrove conservation is likely more beneficial to local communities, providing higher economic value (Primavera 1997). McDonough *et al.* (2014), for example, used a Contingent Valuation

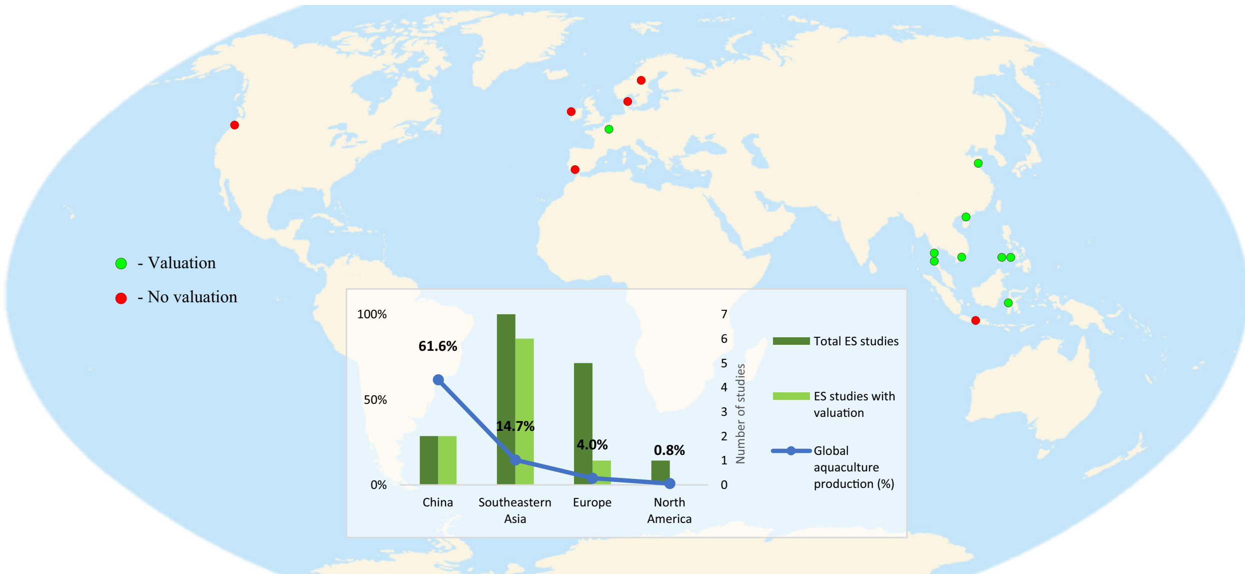

Figure 2 Global distribution of reviewed empirical studies. Review studies (4) have not been included as they are not location specific. The center chart shows each region contribution to global aquaculture production in 2014 (FAO 2016) in relation to the number of aquaculture ES studies performed in those regions.

Method (CVM) to assess stakeholder's stated preferences regarding mangrove ES in different aquaculture development scenarios. Participants demonstrated a preference for ES maintained at natural state (56–74%), followed by present state (21–35%) and only 6–9% of them chose the scenario for intense aquaculture development.

In Indonesia, Total Economic Value (TEV) of mangroves in South Sulawesi was determined, to understand the impacts of their conversion into shrimp-farms in terms of ES (Malik *et al.* 2015). The TEV is the sum of direct-use, indirect-use and option values,[1] and different monetary valuation methods (market and non-market based) exist to assess each component. For instance, direct-use value (e.g. fishery and forestry products) was estimated through the 'market price method', suitable for products traded in real markets. Indirect-use value, namely coastal protection, seawater intrusion, nursery ground and carbon sequestration, was assessed through 'replacement cost' and 'benefit transfer' methods, estimating people's willingness-to-pay (WTP) and/or cost of measures to avoid adverse effects stemming from lost services. The study concluded that TEV of intact mangroves (4000–8000 USD per ha) exceeded that of commercial aquaculture (3000 USD per ha), with indirect-use value accounting for most of the benefits.

In China, Zhang *et al.* (2012) assessed the ES of coastal aquaculture in the Shandong province, based on a CVM. Main factors influencing both WTP and willingness-to-accept (WTA)[2] were 'age', 'annual income' and 'education', demonstrating the importance of demographics and socioeconomic variables on ES valuation. Average WTP for marine protection was 561.8 CNY (90.2 USD – 31/12/12 exchange rate) and WTA compensation for marine pollution was 5175.5 CNY (830.6 USD). The 'free rider' effect was evident, as WTA is ~10 times higher than WTP. Such gap is a consistently observed phenomenon regarding public goods and is explained by several cognitive biases inherent to human behaviour which have been widely discussed (Horowitz & McConnell 2002; Morewedge & Giblin 2015). In Guangdong province, also in China, Liu *et al.* (2010) used several valuation methods (e.g. market price, replacement cost, contingent valuation) to expose the multiple costs and benefits of shrimp aquaculture within the mangrove ecosystem.

Furthermore, transdisciplinary approaches, that is, combining science-based knowledge with stakeholders/users' common knowledge, to ES valuation are being used, such as 'Bayesian belief networks' (Schmitt & Brugere 2013) and the 'post-normal science' (PNS) methodology (Farley *et al.* 2010), with practical application in local mangrove aquaculture management decisions. Interestingly, the PNS method moves beyond the boundaries of conventional science-based knowledge to include alternative knowledge systems (e.g. folk knowledge, investigative journalism), a

[1]For a detailed discussion about the meaningfulness of the option value in the literature, see Perman *et al.* (2011).

[2]A discussion about the factors influencing the WTP and willingness-to-accept (WTA) can be consulted in Hanley *et al.* (1997).

consideration that is being taken seriously by some recent conceptual frameworks on ES assessment (e.g. IPBES Conceptual Framework; Pascual *et al.* 2017; Díaz *et al.* 2018). PNS rationale lays in the need for urgent informed decisions with limited data, prioritizing open debates among stakeholders to peer-reviewed data and analytical rigor (Turnpenny *et al.* 2011). So far, a general consensus stems from these studies on mangrove aquaculture development in Asia: intact mangroves score highest for all ES except food provision, which is usually higher in mangroves converted to shrimp farming. Nonetheless, conversion consistently goes together with lower delivery of all other ES. Decision makers are advised to include mangrove ES assessments in their coastal EBM (van Oudenhoven *et al.* 2015).

On the single valuation study performed in Europe, which was applied to inland aquaculture in north-eastern France, Blayac *et al.* (2014) conducted a survey on stakeholder's perception of ES delivered by an extensive freshwater fish polyculture in the Lorraine region. Participants included fish farmers, industry operators, institutions, service users and residents. Results suggested that the demographic characteristics that most influence the perception of services are 'age' and 'education'. 'Age' has a positive effect on the preference for provisioning services and 'education' has a positive correlation with preference for regulation and maintenance services over provisioning. These results demonstrate again the relevance of the sociocultural context for ES valuation (Perrings *et al.* 2011; Bennett *et al.* 2015; Díaz *et al.* 2018).

By comparing the value of ES in different scenarios of conservation versus conversion to aquaculture, we can provide decision makers with better data for EBM planning processes that entail an EAA. Decisions can fall either into total conservation, total conversion or integration. According to Barbier *et al.* (2008), ES delivered by coastal ecosystems should vary non-linearly with habitat variables such as area, as suggested by ecological theory (e.g. Petersen *et al.* 2003) Indeed, the socioecology of marine ES over space and time may be linear or non-linear, and may contain unexpected, even abrupt, ecological thresholds (Hughes *et al.* 2013) and social tipping points (Villasante *et al.* 2017; Milkoreit *et al.* 2018). Therefore, an optimal management solution will most likely be the integration of development and conservation measures (e.g. Knowler & Barbier 2005). For example, a modelling case study of coastal protection service by coastal systems in Thailand established a relationship between mangrove area and measurements of wave attenuation (Barbier *et al.* 2008). Data suggested that a non-linear ecological function was a better fit and, thus, the aggregate value of shrimp farming and preserved habitat would find its highest value at a partial conversion state. Such outcomes can produce a more equitable distribution of value across stakeholders (e.g. investors, farmers, local communities and ecologists).

Aquaculture can deliver key Ecosystem Services

Sustainable modes of aquaculture production

Some types of aquaculture are potentially more impactful on the supply of ES than others due to their high energy needs and ecological risk. Both fish- and shrimp farming are usually on top of the list, as they are typically fed with artificial feeds, which promote externalities (e.g. sourcing fish meal from fisheries) and nutrient pollution, and pose greater a threat to local biodiversity due to, for example, escapees, disease and chemical inputs. For instance, a global review on the impacts of tilapia production on the supply of ES suggested real ecological changes due to tilapia introduction in many countries, although social and economic benefits have also been reported (Deines *et al.* 2017). On the other side, certain modes of aquaculture production and cultured species can actually increase the local capacity and flow of several ES while simultaneously satisfying demand for seafood, the primary objective of aquaculture.

Regarding production systems design, Integrated Multi-Trophic Aquaculture (IMTA) has been endorsed by scientists as a more sustainable mode of aquaculture than intensive monocultures, as that practice is capable of enhancing multiple ES (Chopin *et al.* 2012; Granada *et al.* 2016; Marques *et al.* 2017; Buck *et al.* 2018). In IMTA, nutrients wasted on artificially fed cultures (e.g. fish, shrimp), in both particulate and dissolved forms, are redirected to downstream trophic levels to nourish extractive species. Bottom feeders (e.g. sea cucumber, polychaeta) and filter-feeders (e.g. bivalves) feed on the wasted particulate fraction and other extractive species, such as seaweeds and macrophytes, utilize the dissolved nutrients for growth (Chopin *et al.* 2012). Such system mimics natural trophic interactions, benefiting from ES supported by certain aquatic species to create a more sustainable and productive environment. Walton *et al.* (2015) assessed the potential ES delivered by sustainable aquaculture systems in wetlands from Doñana National Park, Spain, and concluded that properly designed dual-purpose farms could provide a suitable environment for ecological synergies to develop. Moreover, a review on the status of semi-intensive and extensive aquaculture in Southern European countries suggested that developing IMTA in degraded wetlands would potentially benefit stakeholders and improve ES in those areas (Anras *et al.* 2010). The European Commission has provided guidance on the integration of aquaculture activities within Natura 2000 sites, so they can also provide habitats for local species and boost biodiversity (European Commission 2012b). Examples of successful coexistence exist in the Natural Park of La Brenne in France, the Sado

Estuary in Portugal, the Bahía de Cadiz Natural Park in Spain, the Nesyt lake in Czech Republic and several fishponds in Slovakia (European Commission 2012b). It is also advised that prospection of new suitable locations for aquaculture expansion should take into consideration the mapping of ES. Such *a priori* mapping will provide knowledge on the actual values delivered by the ecosystem into which an aquaculture activity would be established and identify major trade-offs between aquaculture and existing ES (Marcianò 2015).

Seaweeds and rooted macrophytes

Seaweed farming represents approximately 27% of global aquaculture production, generating around 27.5 million tons, which in 2014 alone were valued in 5.6 billion USD (FAO 2016). Researchers working on seaweed aquaculture have been advocating in favour of its intensification due to important additional ES they support beyond the supply of biomass for nutrition, materials and energy. Important regulation and maintenance ES include the extraction of dissolved inorganic nutrients and carbon, which decrease aquatic eutrophication and acidification of coastal waters (Chopin *et al.* 2012; Radulovich *et al.* 2015). Moreover, seaweed farms also provide habitat to many aquatic organisms, boosting biodiversity onsite and near the farm (Walls 2017).

Recently, Kim *et al.* (2017) estimated that the total nitrogen (N) and carbon (C) extracted by the five most heavily cultured seaweed groups (*Eucheuma*, kelp, *Gracilaria*, *Porphyra* and *Sargassum*) added up to 65,000 tons of N year^{-1} and 760,000 tons of C year^{-1}. Yet, there still is a gap in the literature on the economic valuation of ES provided by seaweeds (Barbier 2013; Costanza *et al.* 2014). Analogously, rooted macrophytes can also play a significant role on improving ES delivered by aquaculture, in both freshwater and saltwater settings, through the phytoremediation of wasted dissolved nutrients and production of valuable biomass with several application (Goddek *et al.* 2015; Custódio *et al.* 2017).

Filter-feeders and bottom feeders

Bivalves feed on suspended particulate organic matter in the water column, potentially enhancing regulation and maintenance ES by improving water quality, reducing eutrophication and also providing habitat for microbenthic species. Recent models of shellfish production that integrate environmental interactions have been proven useful for EBM of coastal aquaculture and several studies have shown their capacity to mitigate the leaching of nutrients from coastal fish farms (Nobre *et al.* 2010; Ferreira *et al.* 2012).

Following a model by Saurel *et al.* (2014), individual Manila clams are capable of a net removal of 0.28 g N year^{-1}, with a follow-up modelling study having estimated that 700,000 metric tons of bivalves could remove 46,800 tons N year^{-1} (Ferreira & Bricker 2016). In the fjords of Denmark, farmed mussels significantly improved regulation services by filtering phytoplankton (Nielsen *et al.* 2016). Authors suggested that filtration rate could be increased by 80–120% without affecting growth. Previous studies in Chesapeake Bay (USA) have also demonstrated that oyster reefs and oyster farming enhance denitrification (Higgins *et al.* 2011; Kellogg *et al.* 2013). Nitrogen removal by shellfish is potentially more cost-effective than wastewater treatment plants (Rose *et al.* 2015). Nonetheless, it is important to analyze trade-offs between shellfish remediation and organic deposition below grow-out structures (e.g. cages and tables), as this affects benthic biodiversity and substrate chemistry (Quintino *et al.* 2012).

Bottom feeder organisms, such as polychaeta and sea cucumbers, have also been cultivated under aquaculture conditions due to their economic value and their integration in IMTA systems has been explored. Besides the valuable biomass, these organisms are capable of delivering regulation and maintenance ES on a similar fashion as filter-feeders, through bioremediation of sediments and nutrient recycling (Purcell *et al.* 2016; Marques *et al.* 2017). Polychaeta species (e.g. *Hediste diversicolor*) and sea cucumbers (e.g. *Holothuria tubulosa*) can be integrated into aquaculture sand filters or placed below offshore fish-cages, feeding on the organic matter that is retained in the sediment (Marques *et al.* 2017; Neofitou *et al.* 2019). Moreover, they can incorporate the valuable nutraceutical compounds from wasted aquafeeds, such as EPA and DHA fatty acids, adding value to the production (Marques *et al.* 2018).

A framework for better decision-making

Transdisciplinary communication is at the core of every ES assessment for any particular ecosystem, principally in those affected by intense human activity. Marine and coastal systems, in particular, are exposed to multiple anthropogenic stressors, mainly driven by human economic activities, which destabilize ecological homoeostasis by pushing ecosystem properties away from equilibrium (Halpern *et al.* 2007; Durrieu de Madron *et al.* 2011).

Southeastern Asian countries have experienced an intensification of shrimp farming, a highly profitable activity for investors and a source of employment for local people. Yet, externalities emerging from aquaculture added to the loss of mangroves have proven disastrous in many fronts, with loss of biodiversity and ES, with consequent grave economic costs to local communities and to society (Polidoro *et al.* 2010; Brander *et al.* 2012). The published studies discussed in this review consistently revealed substantially higher ES value for intact mangroves, advising decision makers about which development scenarios to pursue (van Oudenhoven *et al.* 2015). Nonetheless, ideal trade-offs might be achieved at partial conversion states, without affecting the optimal flow of ES. Thus, evaluating integrative scenarios is key to promote constructive dialogue and improve relations among stakeholders.

As seen above, certain types of aquaculture can have a positive impact in the capacity of ecosystems to deliver ES. Seaweeds, rooted macrophytes and bivalves, besides being important food providers and sources of compounds with many applications, are also important at remediating eutrophied water bodies and at promoting the increase in biodiversity. Thus, culturing such species can actually enhance provisioning services along with regulation & maintenance ES of marine and coastal ecosystems, which could be achieved through the adoption of, for example, IMTA-based solutions.

The ES framework approach exposes trade-offs associated with management alternatives using a common transdisciplinary language and valuation measures on which to base negotiations, ultimately improving communication among groups with competing interests and differing worldviews (Peterson *et al.* 2018). Several valuation methods exist, from direct monetary valuation techniques to assess direct use services, to deliberative approaches for less tangible services, to help provide a more complete picture of ES capacity, flow and demand. The choice of valuation methods is paramount and will ultimately dictate the reliability of the assessment, since some methods elicit better value estimates than others depending on the type of service being valued. For instance, use-values are usually elicited quantitatively using 'revealed preference methods' (e.g. market price, replacement cost, benefit transfer) for consumptive products traded in markets and are the most used valuation methods (Vo *et al.* 2012; Himes-Cornell *et al.* 2018). But non-marketed use-values and nonuse values are more difficult to assess using those same market-based methods and 'stated preference methods' (e.g. contingent valuation), which rely on participatory processes (e.g. surveys, workshops), are more reliable and informative (Gómez-Baggethun *et al.* 2014).

Stakeholder's involvement through participatory processes is a central part of an ES assessment, especially in coastal areas, where many groups, institutions and industries coexist and interact. In this particular context, stakeholders are usually fish farmers, fishermen, watershed recreational users, local community, research institutions, managers, maritime authorities, government representatives and NGOs, depending on the location and scale of the assessment.

The Integrated Coastal Zone Management (ICZM) is an important policy instrument that aims to coordinate the different strategies affecting the coastal zone and associated with activities such as fisheries, aquaculture, agriculture, renewable energy, shipping, tourism, conservation and coastal protection infrastructures (European Commission 2007). Its approach takes into consideration the state of natural resources and ecosystem boundaries to which the ES framework would be an important assessment tool. Due to the overlapping of human activities at the sea-land interface, EU recommendation on the implementation of ICZM (Recommendation 2002/413/EC) is to be implemented in coherence with existing EU Coastal and Marine Policy.

Relevant examples are the Maritime Spatial Planning (MSP), concerned with the sustainable use of the maritime space (Directive 2014/89/EU); the Marine Strategy Framework Directive (MSFD), which aims at good environmental status in marine waters, following an ecosystem-based approach (Directive 2008/56/EC), the Water Framework Directive (WFD), addressing community actions in the field of water policy, including transitional and coastal waters (Directive 2000/60/EC), the Common Fisheries Policy (CFP), which aims to achieve sustainable use of fishery resources (Regulation EU 1380/2013). This implementation has the potential to improve planning and management in both the environmental and socio-economic dimensions such as, for instance, to minimize the effects of maritime infrastructures (e.g. coastlines protections, oil platforms) on coastal activities (e.g. aquaculture and fisheries) and on protected areas. Most importantly, the principles of EEA should become fully operational in ICZM, MSP and aforementioned EU directives in order to preserve marine and coastal ES capacity and flow to meet human populations demand (Katsanevakis *et al.* 2011; Ansong *et al.* 2017).

The step-forward: pluralistic valuation

Monetary valuation measures the contributions of nature to human well-being from a utilitarian perspective using monetary metrics and is suitable for assessing certain types of ES, mostly within the provisioning and regulation and maintenance sections. However, it often fails to capture the importance of nature beyond economic values (Jacobs *et al.* 2018). In order to elicit the diversity of values associated with nature, non-monetary approaches are essential methods to examine the relevance of preferences, values and demands of people towards nature and provide a holistic assessment through integrated valuation (Norgaard 1989; Chan *et al.* 2012; Jacobs *et al.* 2018). These approaches aim to demonstrate the pluralistic value of nature and its importance within the ES framework (Fig. 3), where monetary value is only one type of value among others, including

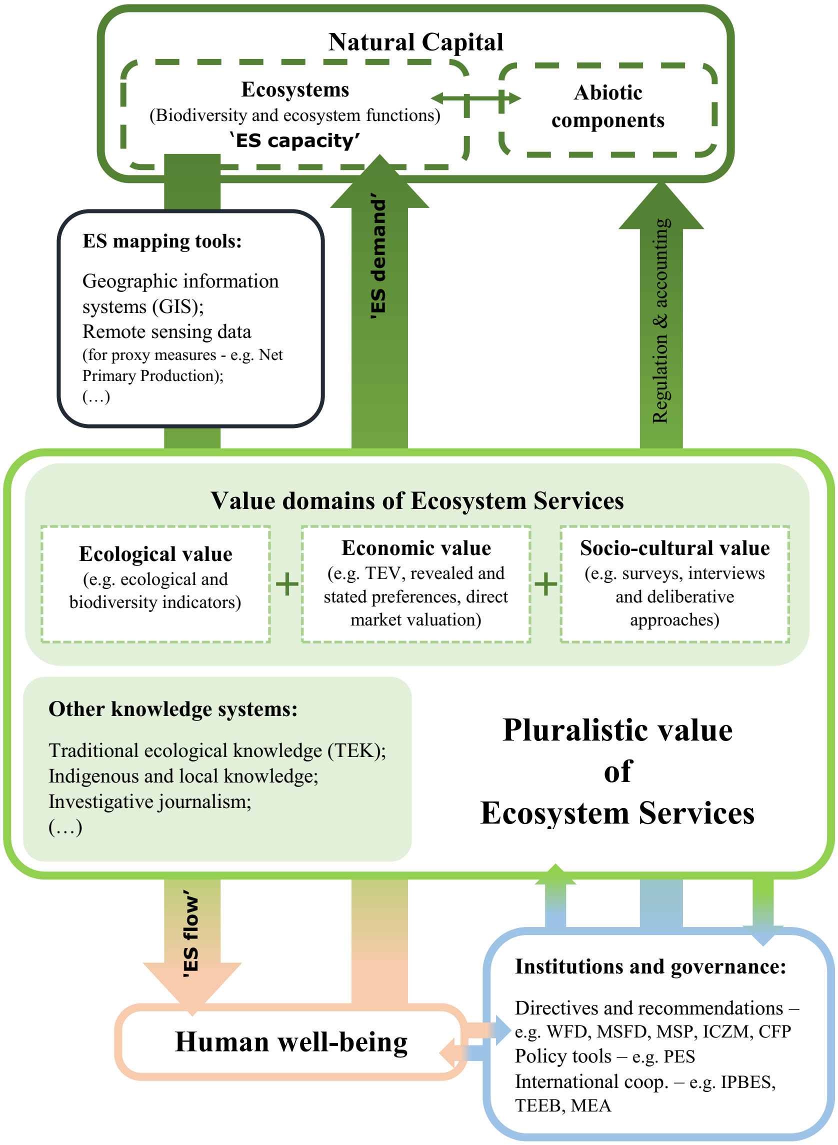

Figure 3 Conceptual framework for the pluralistic valuation of ES.

cultural, spiritual and symbolic values (Garcia-Rodrigues *et al.* 2017; Pascual *et al.* 2017; Díaz *et al.* 2018).

In that sense, ES should be considered under three value domains: economic, ecological and sociocultural (Braat & de Groot 2012). Ecological value is obtained using ecological indicators (e.g. diversity and integrity) to assess flow of services from the supply side, the ecosystem. Sociocultural value involves non-tangible services, such as cultural and spiritual identity, and is usually estimated through surveys and deliberative approaches (e.g. Q-methodology) which assess stakeholders' perceptions and preferences. Economic value is typically obtained using the Total Economic Value framework, through methods that allow for monetary-based assessments (Science for Environmental Policy 2015). Developments on this domain have led to the creation of a novel environmental policy tool designated as Payment for Ecosystem Services (PES). It aims to internalize the positive externalities generated by ecosystems, producing incentives for landowner behavior that creates and ensures the delivery of ES that belong to the realm of public goods (Salzman *et al.* 2018). Nonetheless, PES captures only a fraction of the value, as existence and option values and other benefits are not usually captured by this mechanism.

Furthermore, modern information technology tools such as 'remote sensing' and 'geographic information systems' are being used to map ES and can be integrated with valuation data to better understand ES state and dynamics within EBM (de Araujo Barbosa *et al.* 2015; Schägner *et al.* 2013; Science for Environmental Policy 2015). Integrated ES valuation should also feed on other knowledge systems, such as folk knowledge and traditional ecological knowledge, most importantly in locations where scientific data are still scarce or even inexistent (Tengö *et al.* 2014; Díaz *et al.* 2018). As an example, IPBES, through its 'nature's contribution to people' approach, already acknowledges such alternative worldviews, defined as 'local and indigenous knowledge', and incorporates them within its framework (Díaz *et al.* 2018).

Undoubtedly, the most important next step in ES valuation is to operationalize an integrated valuation framework that endorses 'value pluralism' to better support global policy initiatives in EBM of marine and coastal ecosystems, where aquaculture is increasingly becoming an important driver of change. In this way, a greater portion of society will be involved in assessing the value of ES and both 'natural capital' and 'social capital' will be further integrated within national and global accounts of economic development (Drakou *et al.* 2018; Garcia-Rodrigues *et al.* 2018).

Conclusion

By identifying the ES delivered by marine and coastal ecosystems and aquaculture and by using pluralistic valuation approaches to reveal ES trade-offs between different scenarios, researchers are able to provide a more accurate forecast of the environmental and socio-economic impacts of aquaculture development. Aquaculture not only consumes but also provides ES beyond the provision of goods and the recognition of the positive effects of certain modes of aquaculture will enable more accurate accounting of economic, ecological and social values. This approach can ultimately improve decision-making, improve the effective implementation of EBM options and allow policymakers to use knowledge-based solutions that foster sustainable aquaculture development scenarios. From the present review, it became evident that many more valuation studies are necessary to assess ES trade-offs between aquaculture and the environment in which it occurs, to demonstrate the validity of ES conceptual frameworks to effectively support an EEA. The strengths and limitations of the different valuation methods must be pondered and a combination of them should make the valuation process more reliable. Practical reasons (e.g. available data and resources, expertise), stakeholder-oriented reasons (e.g. stakeholder participation, inclusion of local knowledge, ease of communication) and decision-oriented reasons (e.g. purpose of the assessment, Ecosystem Services at stake) should be key considerations in selecting those methods.

Even though the literature on marine and coastal EBM is already diverse, its practical application has been generally impaired by the diversity of perspectives among management players on how to operationalize it. Moreover, outputs from previous marine and coastal ES assessments performed with the intention to inform decision-makers did not translate into the decision-making process. Thus, the application of the ES framework to foster a sustainable development of aquaculture will depend on the research efforts carried out in the future, the valuation methodologies chosen to correctly elicit value, the successful communication of results to key players and the actual application of conforming measures into decision-making. Additionally, government incentives towards the mapping of ES in marine and coastal areas most likely to be selected for and impacted by the development of aquaculture are also paramount. Only by shifting towards this approach will it be possible, in the future, to sort through different development scenarios and conscientiously support projects that sustain ES capacity and maintain or enhance ES flow to local communities and human societies.

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Supporting Information

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

Table S1. Relevant peer-reviewed articles on aquaculture ecosystem services.

