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Evangelia G. Drakou[a,*], John Virdin[b], Linwood Pendleton[c,d]

[a] Faculty of Geo-Information Science and Earth Observation (ITC), P.O. Box 6, 7500 AE, Enschede, Netherlands
[b] Nicholas Institute for Environmental Policy Solutions, Duke University, USA
[c] Global Science Leadership Team and Oceans Practice, World Wildlife Fund, 1250 24th Street, NW, Washington, D.C. 20037, United States
[d] Université de Brest, UMR M101, AMURE, CNRS, OSU-IUEM, 12 rue du Kergoat CS 93837, F-29238 Brest Cedex 3, France

A R T I C L E I N F O

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A B S T R A C T

Ecosystem service (ES) maps are instrumental for the assessment and communication of the costs and benefits of human-nature interactions. Yet, despite the increased understanding that we live a globalized tele-coupled world where such interactions extend globally, ES maps are usually place-based and fail to depict the global flows of locally produced ES. We aim to shift the way ES maps are developed by bringing global value chains into ES assessments. We propose and apply a conceptual framework that integrates ES provision principles, with value chain analysis and human well-being assessment methods, while considering the spatial dimension of these components in ES mapping. We apply this framework to the case of seafood provision from purse seine tuna fishery in the Western and Central Pacific Ocean. The ES maps produced demonstrate the flow of a marine ES to a series of global beneficiaries via different trade and mobility pathways. We identify three types of flows – one to one, closed loop and open loop. We emphasize the need to consider a series of intermediate beneficiaries in ES mapping despite the lack of data. We highlight the need for a shift in ES mapping, to better include global commodity flows, across spatial scales.

1. Introduction

We live in the era of globalization, on a planet in which distances and boundaries are increasingly irrelevant, and mobility and trade facilitate connections among different parts of the world. These connections support a growing demand for the flow of goods and services around the globe. Within this global system of flows, a local or regional-scale natural resource can become a global commodity whose benefits are widely distributed (Challies, 2008; Grilly et al., 2015; Nelson et al., 2009). This local to global flow has an impact on the way natural resources are managed by local, national and global decision-makers although the effects of this multiplicity of scales are rarely taken into account.

Oceans are systems in which such local to global flows comprise a dynamic, complex adaptive social-ecological system (Liu et al., 2013), shaped through trade, maritime mobility (Österblom and Folke, 2015; United Nations, 2016) and a series of natural processes (e.g., migration of fish species or carbon sequestration by coastal vegetation). Within such a telecoupled system (Liu et al., 2013) socioeconomic and environmental interactions occur over large distances and across scales. Actions taken by humans locally impact an ecosystem's state and associated human well-being (Drakou et al., 2017a), but also other social-ecological systems that connect with this system either through mobility and trade (in the case of provisioning and cultural ecosystem services (ES)) or through a series of natural processes and biogeochemical cycles (in the case of regulating ES). For instance for cultural ES, the deterioration on water quality of a pristine beach will impact the ecological state of adjacent areas, the quality of life of people living nearby, but also the number of tourists arriving from distant locations to enjoy this beach. For regulating ES, the reduction in mangrove cover in the coastline e.g., of Indonesia, will impact the climate regulation capacity of these in a larger than the country scale, with impacts to the global population.

Seafood provided by marine social-ecological systems is one of the most prominent examples of such flows. Seafood contributes significantly to the global food supply, constituting almost 20% of the average per capita intake of animal protein for more than 3.1 billion people, and representing one of the most-traded segments of the world food sector (Smith et al., 2010). Particularly in Small Island Developing States (SIDS) and coastal states, seafood provides critical societal benefits which help reduce poverty and support the local and regional economy – for example providing 50–90% of animal protein for coastal

* Corresponding author.
E-mail address: e.drakou@utwente.nl (E.G. Drakou).

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communities in many Pacific Island countries and territories (Bell et al., 2018; Merino et al., 2011). For these states, such marine resources are considered a source of economic growth, in some cases in the form of fishing licences paid by foreign fleet operators. A number of efforts (e.g., Erisman et al., 2017) have focused on measuring the size of the economic benefits provided by services such as seafood that are generated from ocean ecosystems, defined here as marine ecosystem services (ES). However the attribution of these benefits, notably between residents of coastal and island states controlling access to the resources and foreign beneficiaries consuming the end products remains under debate (Micheli et al., 2014).

Several management measures have been introduced in recent years to tackle issues arising from these global flows of locally-produced marine ES and particularly on how benefits are shared among local, regional and global beneficiaries. At the global level for example, in October 2014 the United Nations launched the Nagoya Protocol on Access and Benefit Sharing (ABS), to safeguard a fair and equitable access to genetic and natural resources, and attribute ownership rights to societally vulnerable population groups of the developing world (United Nations, 2010). In October 2015, the Sustainable Development Goals (SDGs) for 2030 were adopted by the United Nations General Assembly (United Nations, 2016) focusing on the sustainable use of the oceans and the ES they provide (SDG14), while at the same time raising the need to address the equitable distribution of these services, in order to help end poverty (SDG1) and hunger (SDG2). At a more regional level, the Nauru Agreement concerning the Cooperation in the Management of Fisheries of Common Interest is an example of a cross-country cooperation to manage tuna fisheries. The Agreement was signed in 1982 by eight countries that collectively control access to some 25–30% of the world's tuna supply and approximately 60% of the tuna supplied from the Western and Central Pacific ocean (WCPO). As these examples illustrate, managing marine social-ecological systems and the ES they provide requires a coordination of all these different policy objectives, across multiple spatial scales.

There are a number of emerging ES methods and concepts can be used to address such different policy objectives simultaneously in the shared space of the marine social-ecological systems, across a range of scales (Drakou et al., 2017a). Although to date most marine ES assessments mainly inform rather than influence or shape decision-making (Drakou et al., 2017a; Ruckelshaus et al., 2015), mapping of marine ES has proved to be a powerful tool which facilitates the sharing of scientific evidence to inform policy decision-making (e.g., Liquete et al., 2016). However, most cases of ES mapping focus on aggregate supply or total benefits, and rarely emphasize ES flow and the distribution of benefits across different spatial scales (Drakou et al., 2017b). Proxies and indicators are often used to quantify the total benefits generated by marine ES from a given area, such as total fish landings or total employment in the case of the seafood provision ES (Liquete et al., 2013). Rodríguez-Garcia and Villasante, (2016) are among the few that used Value Chain Analysis (VCA) methods to account for the flow or distribution of benefits from marine ecosystems in addition to the total benefits, but to our knowledge such methods have never been incorporated in ES mapping.

Our work aims to highlight the need to adopt a global view on the way we map, quantify and assess the benefits generated by marine ES at the local or regional level. To achieve this, we develop and apply a conceptual framework for mapping the size and distribution of benefit flows generated by marine ES, which integrates the principles of VCA and ES mapping. We map the flow of marine ES benefits along a global food commodity chain, using the case of purse seine tuna fishery of the West and Central Pacific Ocean (WCPO) region. The ultimate goal of integrating these two analytical methods is to improve the quality of information given in maps of marine ES, while highlighting the differences in spatial scale and extent among the ES supply, flows and benefits. By quantifying and mapping the size and distribution of marine ES with this method, we aim to emphasize on the difference in the quality of information that can be used for sustainable management of marine ecosystems, enhancing the supply chains they support and their impacts on human well-being.

2. Methodological approach and concepts applied

ES mapping and modeling has been widely used in the last two decades to measure not only the potential and actual size of the benefits provided by ecosystems to society, but also their flow and distribution (Balmford et al., 2008; de Groot et al., 2010; Schirpke et al., 2014). The spatial representation of ES through maps facilitates the way we share information about ES to support planning and decision-making. In many cases, what is represented in traditional ES maps is relatively static and largely focused on mapping ES at the case study level (Egoh et al., 2012), which is not always suitable for marine social-ecological systems. Efforts to date to simultaneously assess and map ES provision, flow and demand, were mostly applied to account for spatial mismatches of ES supply and demand in specific locations (Zhao and Sander, 2015), typically at local or sub-national levels. The ES beneficiaries are usually taken into account for the quantification, modelling and economic valuation of ES, and their role has been explicitly addressed in several studies (Bagstad et al., 2014; Rodríguez-Garcia and Villasante, 2016). However, the different ES dimensions of supply, flow, demand and benefit are usually assessed and mapped separately, and are rarely found in one single map. As a result, many analyses have only provided a partial visualization of the spatial extent of an ES supply chain, and hence the distribution of the benefits.

Efforts to address this gap in understanding the distribution of benefits from ES have accelerated recently. A newly introduced framework was proposed by Drakou et al. (2017b) to improve the way we map ES whose benefits are captured in different locations from the geographic area where they were generated. This framework integrates the basic principles of ES mapping with Value Chain Analysis (VCA) methods. VCA has been widely used in economics, energy and social sciences to capture and analyze the way benefits are distributed along supply chains from the source or point of provision to the point of use or consumption (Mitchell, 2012). Typically a VCA deconstructs the stages that a product follows from the very beginning of its production to its final sale, and even beyond. Some analyses include suppliers or distributers of the product, especially where there are critically important linkages between the various organizations in the chain. The value added in each step of the chain is assessed, from production until final consumption. VCA was initially used to study international trade in the context of a political economy framework, applied to the field of business management as a decision support tool (Porter, 1985). VCA has become increasingly popular and has been applied to various domains from transportation to telecommunications, within the fields of economics, industry, market, information technology (Bolwig et al., 2010; Ketchen et al., 2008; Singer and Donoso, 2008; Swoboda et al., 2008).

The integrated framework proposed by Drakou et al. (2017b) accounts for the spatial distribution of ES flow from the point of harvest to the end beneficiaries. To our knowledge, these two approaches have not been integrated before to add a spatial dimension to value chains, and to show the spatial distribution of the benefits generated through an ES provision chain. The potential of global supply chains based on agricultural food commodities to contribute simultaneously to the objectives of both poverty reduction and food security has been widely studied over the years, and the role of global supply chains based on food commodities generated from marine ecosystems (often located in the jurisdiction of developing countries) has been highlighted as well (Barr and Mourato, 2009).

To better assess nature's contribution to human well-being, Daw et al. (2016) developed a framework that analyzes how this relationship affects ecosystem resilience and elasticity to changes. In that framework the links between ES and well-being are explicitly addressed, and the

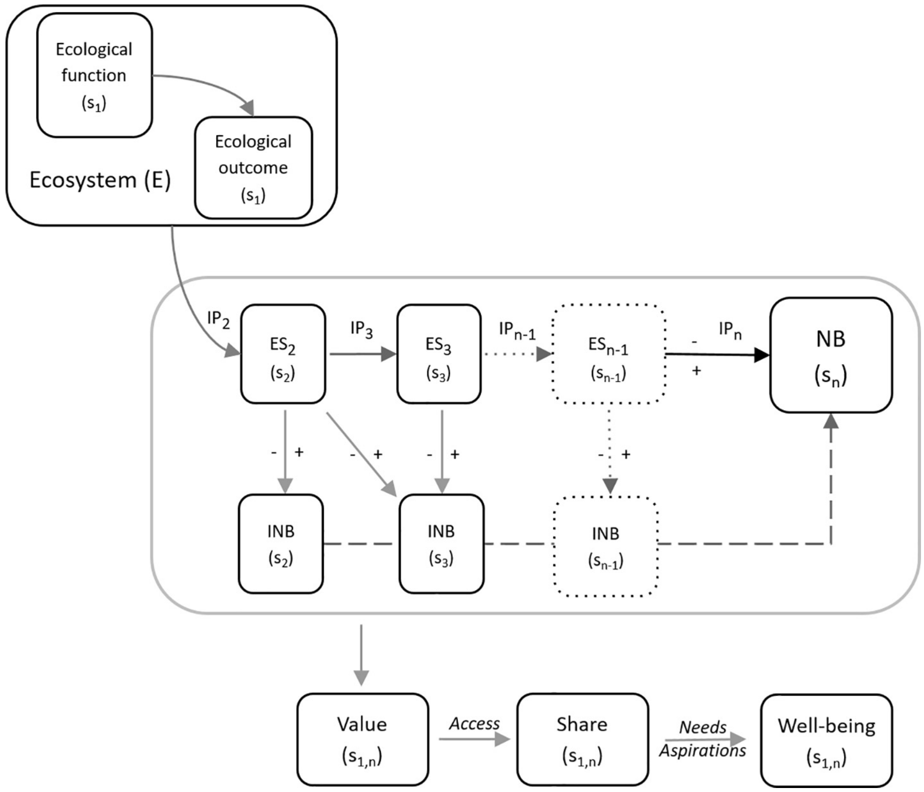

Fig. 1. The integrated framework of ES supply chain, adapted by Daw et al. (2016) and Drakou et al. (2017b). The Ecosystem (E) functions generate ecological outcomes in space s_1. Interim processes (IP) take place in locations s_2, s_3,…,s_{n-1}, and generate ecosystem services (ES), while providing benefits (B), indirectly (IB) or at the end of the process chain (net benefits: NB). Each of those benefits have a societal value, which is shared among different beneficiaries (depending on their access to it) across the different spaces (from s_1 to s_n), and contributes to their well-being in different degrees.

factors that impact these links are analyzed in terms of access to resources, benefit sharing, societal needs and aspirations. Although the objective of this framework is different, we draw inspiration from the (Daw et al. (2016) framework, and use it to give a more complete overview of the system under analysis. Its inclusion gives a different perception of the end-point of the ES supply chain, to include the full range of contributions to human well-being.

We apply an integrated version of the two frameworks to address: (i) the spatial distribution of marine ES benefits, drawing upon the Drakou et al. (2017b) framework for integrating knowledge on ES mapping and VCA methods and (ii) the total contribution of marine ES to human well-being, drawing upon the Daw et al. (2016) framework. The application of these two frameworks allows us to account for the spatial distribution of benefits generated throughout the supply chain from a regionally-generated commodity based on marine ES, which is distributed around the globe. This integrated framework is presented in Fig. 1.

3. The purse seine tuna fisheries of the West and Central Pacific Ocean

We apply the proposed integrated framework to the case of the purse seine tuna fishery in the WCPO region and the benefits of seafood provision as a marine ES generated from this activity (Fig. 2). We chose to use the WCPO purse seine tuna fishery because it provides a vivid illustration of a global food commodity supply chain, which in 2013 generated approximately a third of the world's tuna catch (defined as the catch of the four main commercially-targeted tuna species: albacore – *Thunnus alalunga*, bigeye – *Thunnus obesus*, skipjack – *Katsuwonus pelamis* and yellowfin – *Thunnus albacares*) (Campbell, 2014). Based on the provision of seafood ES from the WCPO, this fishery generates significant economic benefits for a number of Pacific Island states and territories, largely through the sale of fishing access rights to foreign harvesting operations that provides public revenues for investment in social goods, as well as employment and value added from local processing industries in some cases (Campbell, 2014; Allain et al., 2016).

The harvests of the purse seine fishery include multiple species, but consist largely of skipjack tuna and yellowfin tuna (78% and 18% respectively in 2014), captured when an industrial fishing vessel sets a net in a circle around a school of tuna, and cinches a wire through rings around the lower weighted edge of the net to make a 'purse' that can be hauled from the sea (Williams & Terawasi, 2015; West and Central Pacific Fisheries Commission, 2014).

Within the WCPO region, roving purse seine fleets from both inside and outside the region follow the skipjack tuna stocks as they move across national boundaries. After harvest by the fleets, large trading companies buy their catch and guarantee delivery to processors. The purse seine fishery in the WCPO has grown exponentially since the early 1980s (Gillett, 2007), and harvesting takes place largely in the tropical waters of the equatorial band, with the majority in the zone between 5°N and 10°S where the eight Pacific Island states who are Parties to the Nauru Agreement (PNA), as well as Tokelau as an observer, are located (Fig. 2). This distribution of harvesting is expected to change under scenarios that integrate climate change and economic globalization, some of which suggest that several of the regional tuna stocks are likely to be led to depletion (Mullon et al., 2016; Quaas et al., 2016). These considerations can prove to be critical for assessing the distribution of marine ES benefits such as the provision of seafood.

Different types of ES are provided by the social-ecological system created from harvesting WCPO tuna stocks, which contribute benefits to the well-being of a series of beneficiaries around the globe. The provision of seafood ES benefits generated by the WCPO fisheries social-ecological system are most frequently measured in *economic* terms – ranging from direct income, to jobs created – or as contributions to food security through the *nutritional* value of tuna. *Cultural* ES benefits such as the symbolic and spiritual values of fishing practices are also generated from these fisheries at the local level, though they are less studied and measured. Based on the flow of the ES generated through the fishery described above, many of the ES benefits not only accrue to the population of the WCPO region, but also to different countries and population groups spread across the entire globe. The projected future changes in fish stocks will impact the supply and flow of these services,

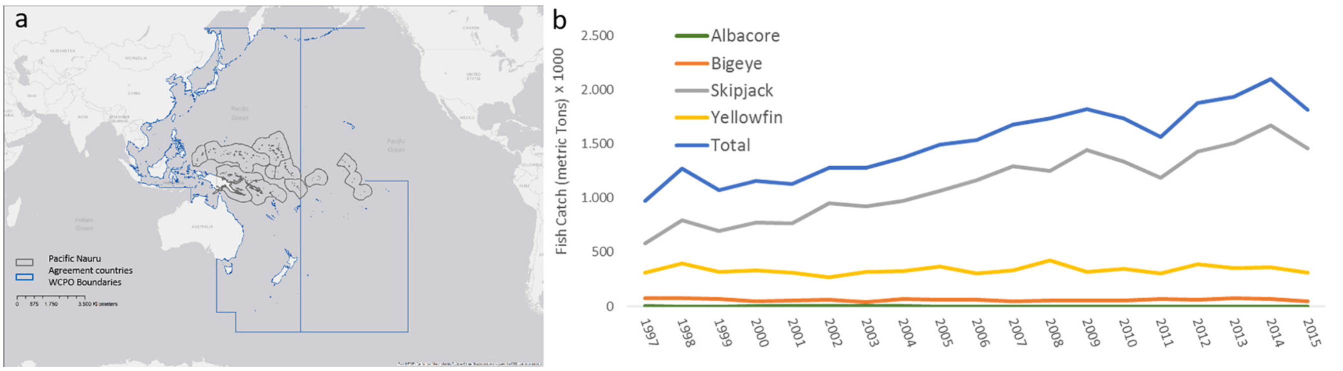

Fig. 2. On the left figure (a), the West and Central Pacific Ocean (WCPO) Region boundaries are delineated. The Exclusive Economic Zones of the Pacific Nauru Agreement countries are indicated to highlight the areas where the highest fishing effort takes place. On the right (b), the evident growth of fish catch per species by purse seine fleet, from 1997 until 2015 (adapted from Williams & Terawasi, 2015).

and impact the well-being of the different beneficiaries involved in the WCPO tuna fisheries across the globe.

Mapping the flows of ES provided by this system is an efficient way of showing the magnitude of this supply chain, the impact it might have on societal well-being, and can be used to inform decision-making to take action when and where required. However, an ecosystem-based mapping of the benefits generated by the purse seine tuna fishery in the WCPO region will not reflect the spatial magnitude of the contribution of these fisheries to societal well-being. As with many other socio-ecological systems, the WCPO fishery needs to be assessed in terms of the spatial distribution of both the benefits created (in our case we only address the economic benefits), and the different types of beneficiaries that directly or indirectly use the system. The impact of the "extra-local" demand and benefit sharing (Drakou et al., 2017b), should be considered not only to help improved management of the fishery, but also to equally attribute benefits to the different societal groups involved along its production chain. We demonstrate this here, by mapping the global distribution of benefits generated by WCPO tuna fisheries, and highlighting the need to consider this distribution in the way we measure and assess the drivers of change on fish resources.

4. Mapping of the WCPO purse seine tuna fisheries economic benefit distribution

We apply the proposed integrated framework (ES mapping and VCA) to the purse seine tuna fishery of the WCPO region (Fig. 3). The WCPO region (Ecosystem) is a unit of analysis defined operationally for fisheries management, based on the range of movement of what are considered discrete tuna stocks within the larger Pacific Ocean (Hampton et al., 1999). This ecosystem (E) is the point of harvest for the purse seine tuna fishery, where significant economic benefits are generated for the Pacific Island countries and territories (s_1) who have jurisdiction over access to some portion of the stocks, in the form of public revenues from access fees. At the same time extra-local economic benefits are generated for the fishing companies originating from Asia, Europe and the USA (as well as a growing fleet flagged to Pacific Island countries) (Fig. 3: fishing fleet s_2, s_3, s_n). The harvest generates further economic benefits for the economies where the fish are landed, often in the form of employment and local value addition. From the point of first landing the volume of this fish is often sent to subsequent points of loining (the process in which the tuna meat is separated in large pieces from the bones) (s_2, s_3) and canning (s_2), generating economic benefits to the local population, mostly through job provision in Thailand, Japan, China and other Pacific regions. After the canning and processing, the tuna is exported abroad with trans-shipment companies of various origins and is then sent out to the point of final consumption, across different regions worldwide ($s_{4–6}$) (Hamilton et al., 2011). At the point of final consumption nutritional and economic benefits are generated, both contributing to human well-being locally.

For each stage of the proposed framework we generated maps (when sufficient data were available), which we then integrated into a summary map aiming to show 'the big picture' for the global distribution of economic benefits from the WCPO tuna fisheries (Fig. 7). Data on the fish catch (in metric Tons-MT) by local and foreign fleet and by fishing gear within the WCPO region (*Data source [3],* Table 1, Supplementary material), were collected from information published by the Pacific Islands Forum Fisheries Agency (FFA, 2016) (*Data source [4],* Table 1, Supplementary material). Data on the points of canning and loining, as well as final markets, were collected from published market studies (Hamilton et al., 2011; World Bank, 2016). Data on fish harvest is from 2015, while the rest of the data are aggregates over time. The fish harvest data reflects the most recent available and also the most variable, while the other data represent proportional shares of the value chain and are considered as proxies that are less variable. (*Data [4]*, Table 1, Supplementary material). Data on the intermediate economic benefits generated locally and the revenues generated for the trans-shipment companies, as well as the points of canning and loining (*Data [5] & [6]*, Table 1, Supplementary material), were available but not homogeneous. In the cases where we could collect some of these data, it was not possible to attribute values to harvests by specific fleets or fishing gear. Similarly for the final markets, data on the amount of fish biomass entering the markets of different countries were only available per country (World Bank, 2013) (*Data [7], [8], [9]* Table 1, Supplementary material). These data can provide national level estimates of the spatial distribution of the benefits generated by the provision of seafood ES utilized in the WCPO purse seine tuna fishery. To better address societal well-being at a higher resolution i.e., at the sub-national level, data on the types of beneficiaries and associated benefits received by each are required. Although in our analysis we tried to collect this information, it was very scattered, since only a few companies share these data upon request. A detailed overview of all data used and their associated sources is given in the Supplementary material.

4.1. *Tuna catch*

To assess the benefits that flow globally from the point of harvest, we assess the origin of the purse seine fishing fleets operating in the WCPO waters, measuring fish catch (in metric tons) by national fleet (*Data [4],* Table 1, Supplementary material). As shown in Fig. 4, the fleet origin varies and to a large part extends beyond the boundaries of the WCPO region. Around 15% of the fleet comes from USA, 12% from Japan, South Korea and Taiwan, and around 7% comes from Europe (mostly Spain) and China. A very small percentage (~1–2%) of the fleet operating in the WCPO area comes from Vietnam, El Salvador and Ecuador. Hence, some portion of the economic benefits generated by

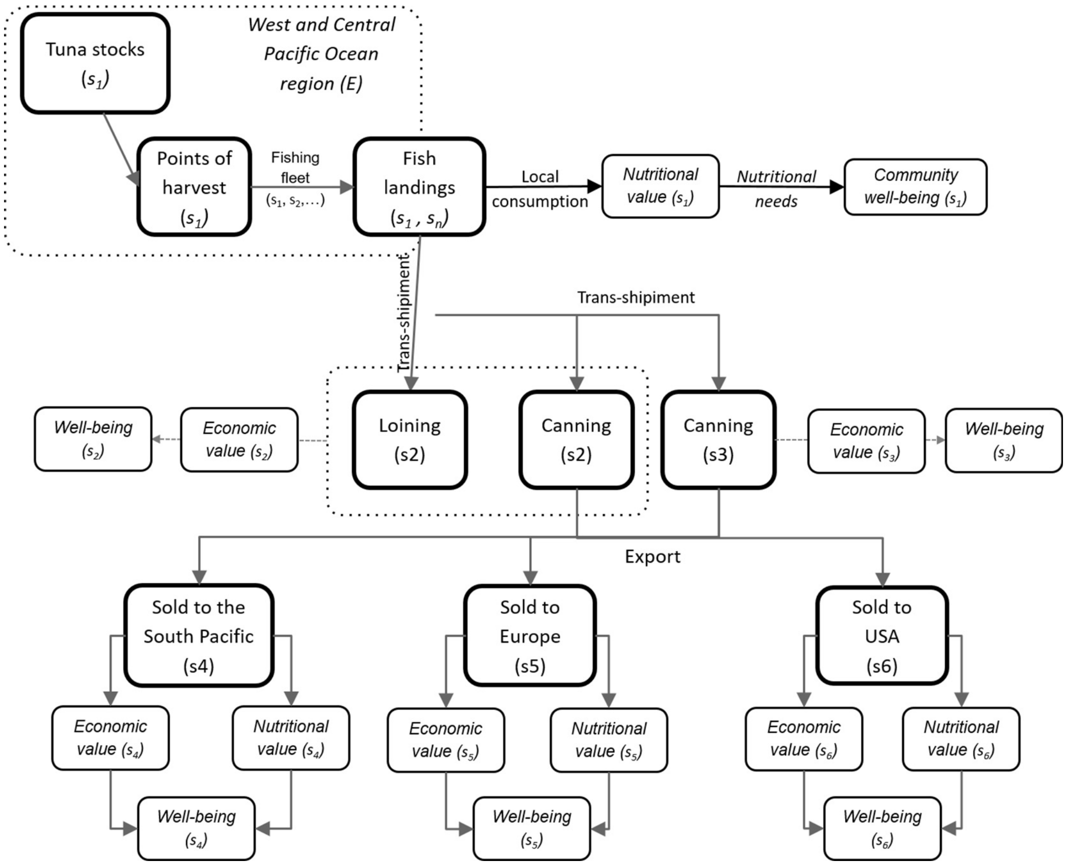

Fig. 3. The WCPO purse seine tuna fishery supply chain, as described in the present study. The different locations-spaces (s_n) where each component of the supply chain takes place, are indicated in each box. For each element of the chain, nutritional and economic values are generated in the same or different locations, which contribute to societal well-being. The cultural values generated throughout the process are excluded from this analysis due to lack of data. Similarly the origin of the trans-shipment companies and export companies, is not known, therefore we could not account for their spatial character in this work. Within each flow (indicated with arrows), besides benefits, several costs are generated, which are acknowledged but could not be quantified.

Fig. 4. Distribution of the origin of purse seine fishing fleet operating in the WCPO region in 2013, by flag. Different colors represent the percentage of fish catch (compared to the total catch) per flag state of the fleet.

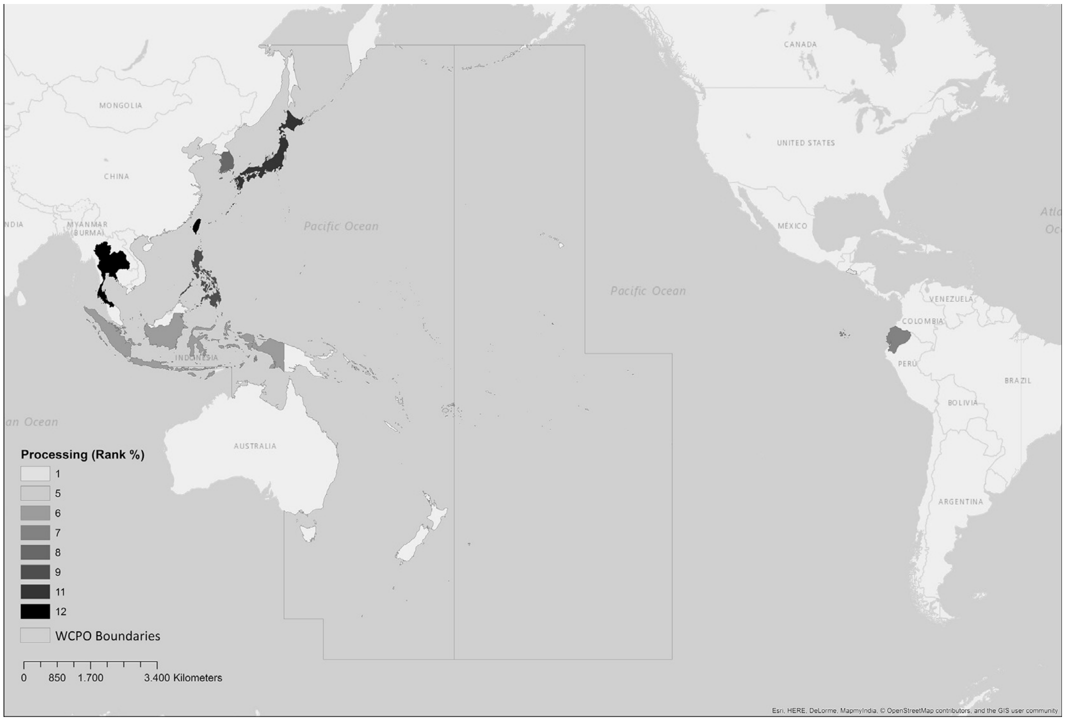

Fig. 5. Distribution of the canning and loining points of the tuna caught in the purse seine fishery in the WCPO region. Different colors represent the percentage of fish processed (compared to the total catch) per country.

WCPO tuna flow directly to these countries, contributing to the economic well-being of their societies.

4.2. Processing: loining and canning

Most of the tuna caught in the WCPO by the different purse seine fleets are then transferred for processing (canning and loining) to Thailand, and to a much lesser extent Japan, South Korea, Papua New Guinea and the Philippines (Fig. 5) (*Data [5] & [6],* Table 1, Supplementary material). Thailand is by far the most prominent processor of canned tuna globally (processing 700 000 MT of tuna from the WCPO in 2010), due to both a well-established industry and the country's strategic location. The canned tuna processing industry of Japan is the second largest by volume, targeting almost exclusively (~95%) the domestic markets of this countries as a final consumption point. The Philippines and South Korea are the next largest processors, with a recorded processing capacity in 2010 of 220 000 MT and 110 000–130 000 MT respectively. South Korea, similar to Japan, exclusively targets its domestic market, while most exports from the Philippines are destined for Europe (~60%) and the USA (~10%). Among the Pacific Island countries, Papua New Guinea processed around 100 000 MT in 2010, while the Solomon Islands, Fiji, Marshall Islands and Kiribati are the next largest processors respectively, with smaller but still significant production levels (World Bank, 2016). Additional canning and loining industry is based in Ecuador (70 000 MT in 2010), Vietnam (35 000 MT in 2010) and Indonesia. Of these countries, processing plants in Ecuador, Vietnam and Indonesia mostly target the EU and to a lesser extent USA markets, while Indonesia also exports to the Middle East. The exact amount of tuna harvested by purse seine vessels from the WCPO and processed in the different countries' plants is not homogeneous in space and time. We therefore used a qualitative way to rank the countries' production based on the best available data used by the World Bank (2016) and FAO (2015).

We were able to acquire information on the number of jobs created by this industry in the Pacific Island countries, with a total of 12 867 employees in 2010 and another 18 200 predicted to be added in Papua New Guinea (*Data [10]*, Table 1, Supplementary material). For the rest of the countries it was not possible to directly attribute the jobs created or the economic benefits from the WCPO purse seine tuna fishery. Due to the highly heterogeneous data (in terms of completeness) for this stage of the tuna supply chain, we approached this step of the VCA in a purely qualitative way.

4.3. Final markets

After the tuna is processed, the product is transferred to the points of sale, either by companies originating from the countries of final consumption or from trans-shipment companies. While data and information on the distribution of benefits across importing companies were not available, we could acquire published information on the final points of sale, as well as the percentage of the fish products (canned, loins or fresh-frozen) sold in the different end points of the supply chain (*Data [7], [8], [9],* Table 1, Supplementary material). The largest (30%) final market was Europe (~950 000 MT/year), followed by the USA (19% or ~600 000 MT/year), Asia (15%), Latin America (13%), the Middle East (6%), Australia and New Zealand (3%), some countries in Africa (2.7%) and Eastern Europe (1.6%). The remaining 7.5% is consumed by all other countries. The total weight of tuna exported in these countries in the form of cans, loins or fresh-frozen products is 3 137 500 MT. These end points in the value chain are represented in the map of Fig. 6. These data change every year, and although there has been no recent global assessment of these estimates, the overall volumes are considered as representative of the current situation (Hamilton et al., 2011).

In terms of the trans-shipment companies, three major companies are involved, named also as *the big three*: Trimarine, Itochu and FCF Fishery Co. Ltd. These companies shipped some 900 000 MT of tuna sourced from fishing vessels operating in the WCPO, with the major volume traded by FCF Fishery Co. Ltd. (around 650 000 MT). Beyond basic information on these companies, it was not possible to acquire quantitative information in terms of associated jobs, and economic revenues.

Fig. 6. Distribution of the major final markets of the canned tuna originating from the purse seine fishery in the WCPO region in 2013.

5. The big picture

Looking at the big picture of the WCPO tuna supply chain, a very broad range of costs and benefits is generated and a series of different levels of economic beneficiaries is involved in the various steps of the chain, making mapping extremely complex. We can identify three types of ES spatial flows within the WCPO purse seine tuna fishery social-ecological system: (i) one-to-one flows; (ii) closed loop flows; and (iii) open loop flows. All are represented within the map shown in Fig. 7. It is important to note that for some countries data were incomplete, so we could not accurately account for all spatial flows emerging from the fishery.

These countries are only indicated in the final map, since they are part of the system, but benefit flows are not directly indicated. The observed flows are explained below.

(i) *One-to-one flows* occur when cost and benefit trade-offs are observed among ES supply and demand areas. In particular a place, a country in our case, receives economic benefits as a result of its government selling access rights to a company to utilize the ES supplied in the area under its jurisdiction. The company that buys access rights to a specific ES bears the financial cost on the one hand, but receives a series of economic (and nutritional) benefits on the other. No intermediate agents are observed in these spatial flows. A typical example of this is the companies whose fishing vessels are registered to South Korea, who buy access rights to fish with their purse seine fleets in the WCPO region. The harvest is then transferred for processing back to South Korea, where it is locally consumed. Japan shares a very similar structure, with a number of registered vessels fishing in the WCPO region, while processing takes place domestically and 95% of the final product is distributed and consumed by Japanese markets. Only 5% of the Japanese production is processed in Thailand, due to capacity restrictions, and then returned to the country (One to one, Fig. 7).

(ii) *Closed loop flows* refer to cases in which the ES is demanded in one location, triggers a flow to different locations, with different types of agents bearing the costs and benefits in between (in our case, other countries and industries), and the final benefit received in the place of initial demand. Such closed loops involve a multiplicity of intermediate agents, with costs and benefits for each. Such an example is the USA, with a large fleet operating in the WCPO region (harvesting 3774 metric tons in 2015), most of which is then processed in Thailand (and some in other locations) and then exported back to the USA (Closed loops, Fig. 7).

(iii) *Open loop flows* are the most socially fragmented type of flow. Here the points of supply and demand generate multiple ES flows from a multiplicity of locations, with different types of agents (in our case, other countries and industries) bearing the costs and benefits throughout each step of the ES supply chain. In open loop flows, the ES flows generated are a result of multiple types of demand occurring in different locations. In this case the downstream and upstream parts of the supply chain, as well as the intermediate steps, spatially differ. For example, the Spanish fleet buys access rights to the waters of a number of Pacific Island countries and territories throughout the WCPO region, using tuna processing facilities of several Pacific countries and Thailand. The final product is then exported by trans-shipment companies to Europe. For the rest of the countries, we had very heterogeneous information on the flow of benefits across the three major steps of the value chain (harvesting, processing and final markets). In many cases we could not clearly identify the exact flow, mostly due to the level of details in the data obtained (Open loop, Fig. 7).

For the countries outside the WCPO region, the major costs are economic and can be measured in terms of access fees for fishing in the waters under the jurisdiction of Pacific Island countries and territories, and transportation costs. The latter are true also within the WCPO region, since most of the fishing grounds are under the jurisdiction of the Nauru Agreement countries. The trade-off the Pacific Island countries and territories typically make in that socio-ecological system is that

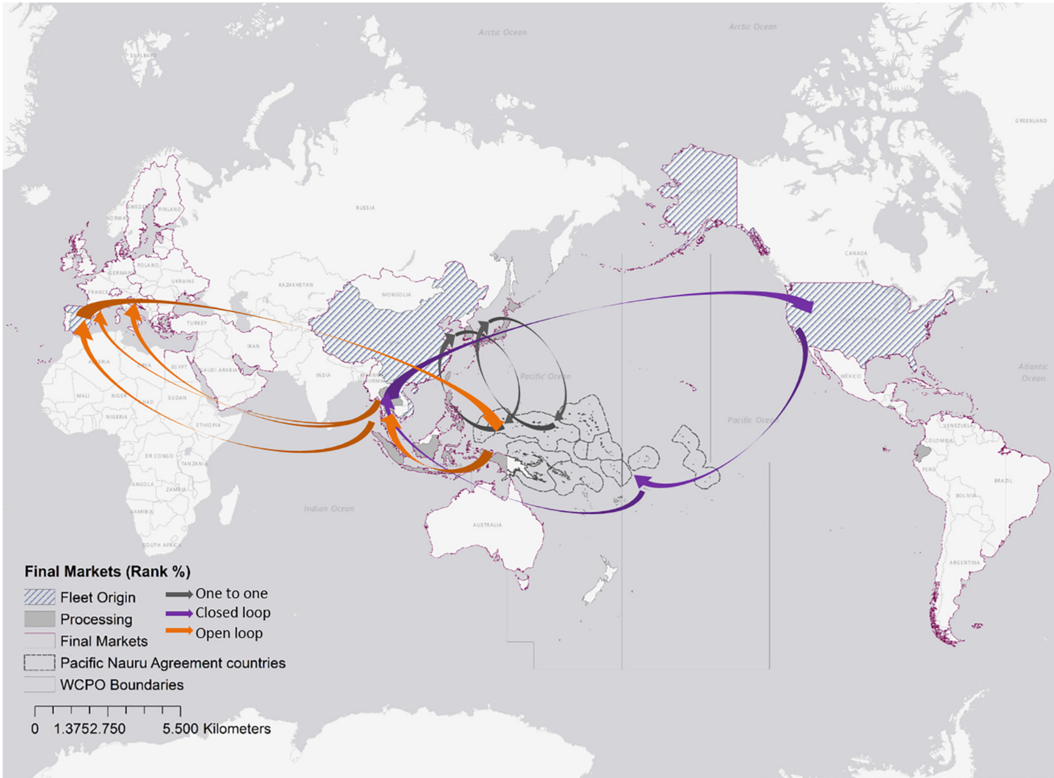

Fig. 7. The global distribution and flow of economic costs and benefits generated by the purse seine tuna fishery in the WCPO region. The different colors in arrows represent the three different types of flows observed.

they exchange access to foreign companies for benefits in the form of public revenues and the jobs generated from this system.

From the final integrated map, we can see that the economic benefits generated from the ES utilized by this fishery are spatially distributed in very different regions across the globe. This indicates the amount, variety and geographic heterogeneity of beneficiaries, but also the amount of externalities and cost types generated across the chain. The major objective of this map, despite the data gaps we have for a significant amount of flows, is to indicate the spatial dimension of economic benefits generated by specific marine ES at a global level, and the implications of using value chain analysis to illustrate the distribution of economic benefits from an ecosystem service. Fig. 7 provides a crude attempt to depict the flow of benefits and distribution, across more than 20 countries and 5 continents around the world.

6. Reflection points

In this manuscript we propose an integrated way of assessing and mapping global flows of marine ES. Our objective is to highlight the need to re-consider marine ES maps, especially when referring to socio-economic benefits accruing to beneficiaries globally. Of course this also applies to terrestrial systems, but further applications would be required to validate the method. The proposed approach revealed: (i) the different messages conveyed in mapping outputs when using the integrated framework, compared to the most commonly used ecosystem-based mapping approaches; and (ii) the significance of mapping and considering the spatial distribution of benefits and beneficiaries in marine ES flows (notably intermediate benefits and beneficiaries). Most ES mapping approaches (terrestrial or marine) generate ecosystem-based spatial information, highlighting mostly the supply side of ES (Egoh et al., 2012; Willemen et al., 2008). However when dealing with global commodities provided by ES such as the case of the WCPO tuna fishery, it is essential to account for the spatial dimension of the flow and distribution of the globally generated benefits. Particularly when ES maps are used to inform ecosystem management or to address policy objectives, considering the global dimension of the ES provided could change the way management decisions are made. In our case, using the map of Fig. 7 to illustrate the global reach of the ES generated by the WCPO fisheries suggests that decision-makers need to consider a series of different ecosystems, social groups and beneficiaries. Similarly, using a map of regional extent i.e., the map of ES supplied by the WCPO region (Fig. 2) is relevant for regional level decision-making. We do not claim that one type of mapping should be preferred over the other, but rather that both types of ES mapping approaches are required for a more informed, inclusive and robust decision-making process over the use of marine natural resources.

A major point addressed by integrating VCA into marine ES mapping is the importance of intermediate steps (and associated benefits and beneficiaries) emerging in the ES supply chain. Each of these intermediate steps is a social-ecological system in which a series of costs and benefits emerge. In our case a series of intermediate agents emerge within the ES flow chain. Such agents either contribute to the final ES benefit in a positive way (generating added benefits) or negatively (by generating costs), or receive benefits in their specific location, without affecting the final benefit received (neutral). Such agents are for instance, trans-shipment companies that receive a financial benefit from this ES flow (e.g., through jobs created) and generate the environmental costs of pollution through shipping. Such ES flow structures are evident in the *closed loop* and *open loop* flows identified in our analysis. In ES such as those related to seafood supply, intermediate beneficiaries such as the trans-shipment companies have a very strong role in driving the economies of WCPO countries, through their agreements with the countries generating the demand for seafood provision (Schurman, 1998). In our analysis, access to this information was very limited and scattered. In some cases the names of the intermediate beneficiaries were known, but further access to their costs and benefits was not possible. Due to the role that such intermediate beneficiaries play in shaping marine ES flows, we consider this paper as a first call for more transparent, shared and open access data on intermediate costs, benefits and beneficiaries.

This assessment is a first step towards a spatial understanding of the flows of regionally-produced commodities from marine ES that benefit societies throughout the globe. Our approach clearly indicates the existence of a *system of systems*, in which three types of ES flow systems emerge from one marine social-ecological system (in our case the fisheries of the WCPO region), forming a global supply flow system. This has a direct impact on societal well-being, in economic, nutritional or cultural terms. The complexity of the system and the varying smaller scale ES flows inherent in such multi-flow systems should be considered when designing long-term management strategies, notably within the countries that have jurisdiction over the use of the ecosystems supplying the services.

By adopting the proposed approach for mapping, ES research outputs can be used to inform multiple management objectives, from poverty alleviation (Suich et al., 2015) to equitable sharing of benefits and the sustainable contribution of nature to human well-being (Díaz et al., 2015). Especially in developing countries whose economies are more reliant on natural resources, there is a pressing need to understand the social-ecological implications of such ES flows to safeguard equity among external beneficiaries and the local population (Adams and Moon, 2013; Klain et al., 2014). Understanding the links with well-being is not easy and several frameworks have been proposed toward this objective (Daw et al., 2016; Fisher et al., 2014). Yet, we argue that integrative approaches such as the one proposed in this paper can help stimulate future research and are powerful communication tools that can inform both society and decision-makers.

In our application it became evident that we have better knowledge in terms of data and methods to assess ES supply and flow from the ecosystem to the first-level beneficiaries. Data gaps were found in the flows among the intermediate steps of the supply chain, as well as the actual economic and nutritional benefits generated (detailed information on the data required and their availability is given in the Supplementary material). We see such data limitations as a call for greater transparency in the way food systems (in our case) are managed and monitored. Already food traceability is an effective instrument that is expected to grow in use (Smith et al., 2010). Although complete data are not yet available, several initiatives have been launched recently to fill in such data gaps e.g., THIS FISH (http://thisfish.info/), allowing society to know the origin of specific seafood products. These initiatives combine crowdsourcing information with food traceability to allow seafood suppliers, restaurants, retailers and consumers to trace products through the supply chain and connect consumers to the fish harvesters who caught their seafood. There is already a broad range of FishChoice Supplier Members using THISFISH traceability (e.g., Albion Fisheries, Ltd., Allseas Fisheries Corp., Off the Hook Community Supported Fishery, Organic Ocean Seafood Inc.).

To further develop and ensure usability of the proposed integrated framework, we identified three major needs for future research:

(i) An in-depth application of the proposed framework to *regulating and cultural* marine ES. Replication to other ES is required in order to increase the robustness of the framework proposed here. Examples of such applications have been presented in the conceptual paper developed by Drakou et al. (2017b) e.g., for the ES of climate regulation through carbon sequestration by mangrove forests. Applying this for other regulating ES would require a deep understanding of the way ES flow to beneficiaries. For the cases of climate and weather regulation, air quality regulation the approach would need to go across scales, since an ES might be supplied by one ecosystem at a local level, but its associated benefits may reach beneficiaries around the globe. The framework has not yet been applied for cultural ES, which would be a proposed next step. Potential applications of this would be related to ES of recreation and tourism or cognitive effects, for which the beneficiaries in many cases are located far from the area that supplies the ES. That would require a better understanding of the demand for these ES at international and global level, which is now partly addressed through a series of crowdsourcing data collection methods from social media (Willemen et al., 2015).

(ii) A revised definition of *ES bundles* for marine ecosystems. ES bundles describe the multiplicity of ES provided by specific parts of ecosystems and are assessed for the integrated ecosystem management (Raudsepp-Hearne et al., 2010). Although societal preferences and demand for ES are considered when assessing ES bundles (Martín-López et al., 2012), they are only mapped at the ES supply side (Van der Biest et al., 2014). Although this works well for the management of terrestrial ecosystems and associated services, it is less representative of marine ES (Howe et al., 2014). Marine seascapes are dynamic systems, but the current mapping practices focused on the ES supply side are very static. Marine social-ecological systems are also shaped by multiple types of societal demand (e.g., with different access rights for fisheries). Applying our framework for marine ES bundles can help us reconsider the notion of these bundles, as well as the way they are mapped. That would require considering the way multiple benefits flow to different societal groups like we did in our case (e.g., through closed, open loops) as well as collecting information on series of all those indirect beneficiaries that emerge throughout the process. Our case of the WCPO fishery attempted to illustrate these aspects, by looking at the flow of nutritional and economic benefits. However, data limitations did not allow for an in-depth analysis of the bundles of ES flow.

(iii) An *integration* of different types and levels of beneficiaries to better assess the input of ES to *human well-being*. Aspects of human well-being were explored in our analysis, yet the level of detail could only be quantified in a partial and fragmented way. Although the framework allows for the identification of different benefits and beneficiaries (Fig. 3), a more in-depth understanding of the contribution of marine ES to human well-being was not possible. To do so would require access to financially sensitive information or further exploration via surveys. Alternatively, a series of data retrieval methods utilizing social media (using APIs), such as Twitter and Instagram, could be used as proxies to reveal tuna consumption patterns (in our case) and ES impact to human well-being.

This work was indeed a first approach towards better assessing and mapping marine ES, with methods that go beyond the standard land-based adaptations. We hope that this work will trigger further projects that map the flow of marine ES and consider benefit/demand aspects. The proposed framework was developed for, but is not restricted to marine systems. It can be also adapted and applied in terrestrial systems, especially when trying to understand the environmental and societal impacts of traded commodities (Wiedmann and Lenzen, 2018). We expect new maps and visualization methods to emerge that can account for the dynamic interactions emerging in marine social-ecological systems. Such maps could increase trust in the scientific outputs of marine ES analysis, and better inform decision-making. There is a pressing need for such approaches, especially in this coming decade declared by the United Nations as the Decade of Ocean Science for Sustainable Development (2021–2030).

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecoser.2018.05.008.

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