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The role of non-natural capital in the co-production of marine ecosystem services

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ABSTRACT

A growing concern is arising to recognize that ecosystem services (ES) production often requires the integration of non-natural capital with natural capital in a process known as co-production. Several studies explore co-production in different terrestrial ecosystems, such as agriculture or water delivery, but less attention has been paid to marine ecosystems. Coastal activities such as aquaculture, shellfish harvesting, and small-scale fishing deliver important benefits for seafood provision, but are also inextricably linked to cultural and recreational ES. The degree to which co-production can determine the provision of ES in marine systems has yet not been explored. This paper addresses this key topic with an exploratory analysis of case studies where marine ES are co-produced. We look at five small-scale fisheries that range from intensive semi-aquaculture in Galicia (Spain), to wild harvesting in Northern Portugal, and discuss to what extent co-production influences ES delivery. We find that a direct relationship exists between co-production level and ES delivery in the case of provisioning ES (e.g., fish harvest), but not necessarily in the delivery of other ES. We also find that management practices and property regimes may be affecting trade-offs between co-production and ES.

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1. Introduction

Ecosystem services (ES) have been mainstreamed in science and policy due to various global initiatives that evolved from the Millennium Ecosystem Assessment (MA 2005), the Economics of Ecosystem Services and Biodiversity (The Economics of Ecosystems and Biodiversity 2010), the United Kingdom National Ecosystem Assessment (UK NEA 2011), and the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) framework (Díaz et al. 2015). Each of these initiatives have been increasingly impacting policy and science, and are changing the way we manage natural resources and understand sustainability.

Under this context, scholars have recently raised attention to the interactions between social and ecological factors in the production of ES (e.g., Reyers et al. 2013; Guerry et al. 2015; Partelow 2015; Díaz et al. 2015; Palomo et al. 2016). This claim flows from the incorporation of the Social-Ecological Systems (SES) approach (Ostrom 2009) to the understanding

of ES. Ostrom (2009) defines a SES as a complex system ‘composed of multiple subsystems and internal variables within these subsystems at multiple levels analogous to organisms composed of organs, organs of tissues, tissues of cells, cells of proteins, etc.’. ES and their benefits, on the other hand, are defined as an ecosystems’ contribution to human well-being (MA 2005). Recent studies indicate that when applying a SES framework, we clearly and openly recognize the relationships between human and natural systems and can therefore establish improved policy targets and indicators that better address the complex nature of ES provisioning (Reyers et al. 2013; Leslie et al. 2015). However, standardized methods for operationalizing frameworks for ES provision within SES are not yet universal (Partelow and Winkler 2016) and further applications of scientific evidence into policy advice are needed. Although the underlying mechanisms and interactions between SES for the provision and delivery of ES are still under discussion (Fischer and

Eastwood 2016), there seems to be a widespread consensus that co-production of ES refers to joint processes between humans and ecosystems (e.g., Palomo et al. 2016). The provision of benefits derived from ES depends, therefore, on the joint contribution of nature and anthropogenic assets, as stated in the IPBES conceptual framework (Díaz et al., 2016); as well as the multidimensionality of the different perspectives and values of Nature's Contributions to People (Pascual et al. 2017). These assets include human-engineered components (Guerry et al. 2015), human capabilities and management practices (Reyers et al. 2013), and in a broader sense include the legacies of past and current societies and cultures (Church et al. 2011). In fact, benefits derived from ES can arise from ecosystems of any type, including natural pristine ecosystems to human-altered ecosystems (Polasky et al. 2015).

ES depend on different forms of capital or capital assets (Guerry et al. 2015). Capital assets can take the form of manufactured capital (e.g. buildings and machines), human capital (e.g. knowledge, skills, experience, and health), social capital (e.g. relationships and institutions), and financial capital (e.g. monetary wealth), as well as natural capital (e.g. fish stocks) (Emery and Flora 2006). Multiple forms of capital interact to generate goods and services. For example, shellfish harvesting depends on the availability of shellfish stocks (natural capital), which depend on high-quality habitat (natural capital). But harvesting also depends on fishing vessels and gears (manufactured capital, backed by financial capital), and on the skills and experience of fishers (human capital), and fisheries governance (social capital).

The co-production concept helps us to understand the contributions of different forms of capital, i.e., natural and non-natural, to the supply of ES. It also contributes to a better understanding of the sustainability of ES provisioning. The same ES, say seafood production, can be supplied with different contributions of natural and non-natural capital, constituting a gradient of co-production (Palomo et al. 2016). For example, wild fish caught by small-scale fisheries is mainly provided by natural co-production, as it involves low levels of non-natural capital. On the other side of the spectrum – fish farmed in intensive aquaculture – is the same ES (seafood production) but is mainly provided by human co-production, as the contribution of non-natural capital is much higher. The intensity gradient of co-production and the level of substitution of non-natural capital by natural capital may have implications for the sustainability of SES. In this sense, co-production of ES is a useful concept to assess the sustainability of social and ecological interactions.

This article contributes to the current scientific discussions on social and ecological interactions

associated with the provision of marine ES (Carpenter et al. 2009) by analyzing case studies from marine SES in Northern Portugal and Galicia (Spain), two regions where marine activities are highly relevant for coastal communities (PRESPO 2012; Surís-Regueiro and Santiago 2014). We analyze five marine harvesting systems: two small-scale fisheries in Northern Portugal and three small-scale shellfisheries in Galicia. The latter show an intensity gradient from intensive semi-aquaculture¹ to wild harvesting. Jointly assessing these five case studies may allow us to test whether co-production increases from wild fisheries to semi-aquaculture. One of the main questions regarding co-production is to what extent social–ecological interactions can deliver ES in a sustainable way. In fact, trade-offs among ES can favor one service over the other with a subsequent degradation of the system that can lead to the detriment of other ES (Villasante et al. 2016). Despite the relevance of co-production processes for marine SES, little is known about how various interactions between ecological and social systems determine ES provision. We argue that special care needs to be placed on the concept of co-production so that the sustainability of human interactions with ecosystems can be assessed. This may have important implications for the use of the ES framework and to assess trade-offs between development and conservation (Howe et al. 2014).

Our hypothesis is that co-production of ES is associated with additional ES and ecosystem disservices derived from human interventions. The level of ES and ecosystem disservices depend on the level and means of co-production. Based on five case studies, we aim at understanding differences of co-production levels in marine SES. We give special attention to trade-offs between ES and levels of co-production (i.e., social–ecological interactions). To design our study, we have unfolded the co-production concept focusing on the intensity and the nature of the ES production process. We examine examples of trade-offs in detail in our case studies and explore their relation to the type and co-production intensity, assessing ES and ecosystem disservices at the local and regional scales.

2. Methodology

Our analysis is focused on the marine ES of two neighboring coastal areas on the north-western Iberian Peninsula. These areas were selected based on two criteria: their potentially different levels of co-production, and the existing long-term research experience on fisheries. We conduct a descriptive and qualitative analysis based on our experience in the case studies and the available literature. With the aim of synthesizing the required information on co-production and ES delivery, we follow a sequential

step-wise analysis (Abbott 1995) including three steps: (1) definition of case studies and management practices; (2) design of a matrix to collect information on co-production and ES delivery; and (3) comparison analysis across case studies. What follows is a more detailed explanation of these steps.

2.1. Definition of the case studies and management practices

First, we discussed potential case studies for studying co-production in small-scale fisheries during the ICES Working Group meeting on Resilience and Marine Ecosystem Services (www.ices.dk) held in Porto in 2016. We selected five case studies which have detailed information on property regimes, management practices, actors, and activities. Property regimes are particularly important to understand the output of the ecosystem. They are a type of regulatory regimes for fisheries (Ojea et al. 2016) that can differ on the level of rights allocated to users, from territorial property rights (TURF), to individual user rights such as individual transferable quotas. Our case studies cover a wide range of property regimes which will allow us to explore the co-production of ES under different level of rights allocated to fishers.

2.2. Design of a matrix to collect information on co-production and ES delivery

Second, we develop a matrix for collecting information on shellfish harvesting and small-scale fishing in the case study areas. We begin with information on the target ES and non-natural capital inputs for each of the activities, based on regional fisheries databases and published literature. Afterwards, we analyze the connection between each harvesting activity and the targeted marine ES, their benefits, and other additional ES that may benefit coastal communities in the region. We do this based on the co-authors' experience conducting long-term research and non-participant observation (Cooper et al. 2004) in these areas and the existing evidence from the scientific literature and policy reports. The current and potential ecosystem disservices that these activities may generate are also analyzed. Then we contrast the output and input of these activities in terms of marine ES and their co-production context characteristics, to assess the level of co-production and the potential trade-offs among ES.

2.3. Comparison across case studies

Finally, we provide an exploratory analysis of co-production with the key elements of each activity with an additional nominal scale of co-production level. The case studies were ranked based on the level of co-production, following Palomo et al.

(2016). We also explore the relationship between co-production and ES trade-offs by placing each of the case studies on a two axis scale with both variables, assigning qualitative values within a ranking three order Likert-scale system (low, moderate, and high). In the last step, we compare the co-production level and ES trade-offs with special attention to the property regime.

3.1. Case study areas

Our case studies are from two neighboring regions which share many cultural and geographical features, but are located in different countries: the Southern Galician Ría de Arousa (Spain) and Northern Portugal (Figure 1). These study areas highlight how identifying marine ES, benefits, ecosystem disservices, and trade-offs may help to disentangle the level of co-production to provide new insights for a potential integration into ecosystem-based management approaches.

3.1.1. Ría de Arousa, Galicia (Spain)

A total of 12 fisher's Guilds – 'cofradías' – exist in the Ría de Arousa and one fishing cooperative (Cooperative Society Ría de Arousa). We focus our first case study in the Carril Guild (Figure 1), which is the second most important Guild in shellfish landed volume and third most important in shellfish landed value in Galicia and in Spain (Pescadegalia 2017). Seagrass meadows have river Ulla estuary as a natural distribution area (Cacabelos et al. 2015) providing multiple regulating ES as habitat for fish, shellfish, and other invertebrates. In 2002, the Galician Atlantic Islands Maritime-Terrestrial National Park was established and integrated Cortegada and Malveiras islands (Figure 1). The major protected area is the terrestrial part of the main island, although there are intertidal and subtidal areas which are also protected, causing a major conflicted spatial overlap with shellfish activities, especially in the Malveiras archipelago (Figure 1). The Guild specializes in two types of shellfish – clams and cockles – which represent 99% of the total volume and value (1997–2015) of this Guild (Pescadegalia 2017). In the last 30 years, the Galician administration promoted the professionalization of the shellfish harvesting, particularly with women (Frangoudes et al. 2008). Generally, this has allowed to intensify the production of shellfish in areas where it is physically feasible, i.e., mainly intertidal areas and some shallow subtidal areas. This change coincided with a transformation of the property regime, from a *de facto* open access to a TURF, and a change in the governance regime, from top-down to co-management (Molares and Freire 2003; Macho et al. 2013).

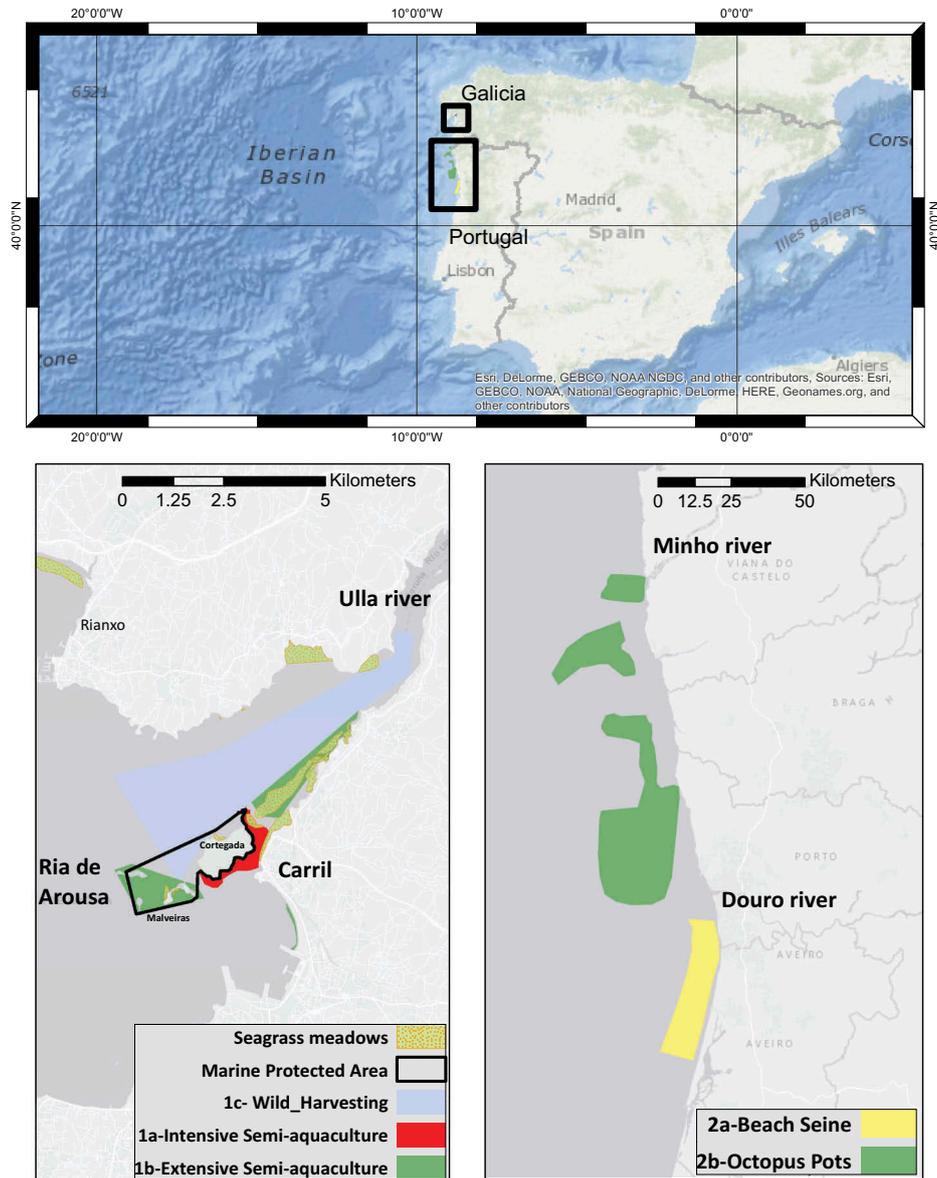


Figure 1. Location of the case studies in Ría de Arousa (Galicia, NW Spain) and Northern Portugal. The figure of Northern Portugal was adapted from PRESPO (2012).

Our analysis focuses on shellfish harvesting, in the context of three different harvesting systems. Harvesters target mainly three species of clam, namely pullet carpet shell (*Venerupis pullastra*), grooved carpet shell (*Ruditapes decussatus*), and Japanese carpet shell (*Ruditapes philipirarum*), and two species of cockles (*Cerastoderma edule* and *Cerastoderma glaucum*), by either men or women by foot, or only by men aboard small boats (<6 m length). Boats operating in this fishery use rakes with a long pole, whereas individuals on foot use a shorter pole and sometimes diverse types of rakes.

3.1.1.1. Intensive semi-aquaculture (1a). In the intensive intertidal semi-aquaculture, harvesting is conducted in 2017 by 656 owners inside 1168 intertidal plots (AGPPCC 2017), which are awarded for

50 years at a time to harvest clams and cockles. These concessions are awarded by the Regional Government, Xunta de Galicia, and are *de facto* private property during the time of the concession, where the owner is fully able to take decisions regarding the production, harvesting, and management of the plots. Sizes of plots range substantially from less than 30 m² up to 5000 m². The total area managed under intensive semi-aquaculture is approximately 1 km². This harvesting system has evolved substantially since the first official awarding in 1950s. The whole area is an intertidal ecosystem, and occupies a natural soft-sediment bed which is within the natural distribution range of seagrass *Zostera sp.* between the continent and the island of Cortegada (Figure 1).

With the economic development plans that followed the Spanish civil war in 1939, local people

proposed to fill the seabed progressively with sand to have larger areas to cultivate clams and cockles, in addition to blue mussels and oysters which had already being harvested extensively with artificial rocky gardening methods (Graells 1870). The results were positive and the activity generated economic benefits over time, which allowed them to invest in more boats to fill deeper areas in the following decades. Consequently, the removal of seagrass meadows was a needed task to facilitate harvesting but also to maximize yields. As the area became shallow, specialization on shellfish species was taking over, and in the 1970s, harvesting species other than clams was residual. Currently, these beds may be labeled as anthropogenic beds, as they are no longer part of the fluvial erosion-accretion natural process. Harvesters need to fill at a recurrent interval to maintain optimal conditions for their cultured species.

3.1.1.2. Extensive semi-aquaculture (1b). In the extensive semi-aquaculture, harvesting occurs in intertidal and subtidal areas and is undertaken by 80 individuals on foot and 27 boats on floating with 47 individuals (Consellería do Mar 2017). The property regime is substantially different from intensive semi-aquaculture as it is managed based on a limited access rights, co-managed by the local Guild and the Regional Government, Xunta de Galicia. The number of permits to develop the shellfishery fluctuates depending on annual demand of permits to enter the fishery; however, a maximum number of permits is allowed based on the maximum production yield defined each year. Shellfish harvest is regulated annually by a total number of kilograms per person per day. This quantity may be modified depending on natural mortality and abundance, which the shellfishers face. This is an interactive process of decision-making, first with the technical assistant of the Guild (namely, a biologist by training), and then with the regional administration which is the final entity that approves the management plan (Macho et al. 2013). The total area available for harvesting in the extensive system 2 is around 1.5 km². The area occupied (Figure 1) overlaps with a natural soft-sediment bed with patches of seagrass meadows especially important in the intertidal areas. The subtidal harvesting area overlaps entirely with the Marine Protected Area of the National Park, and semi-aquaculture activities have a larger recurrent interval than in the case of intertidal.

3.1.1.3. Wild harvesting (1c). In the wild harvesting system, the area is located entirely in subtidal banks (Figure 1), with depths below 2 m. This area occupies the main river sediment arms where the largest currents occur, and thus no-spatial overlap with seagrass is observed (Figure 1). The number of shellfishers

fluctuates substantial seasonally and inter-annually, from a maximum of 600 individuals to a minimum of 200 individuals (Parada et al. 2006) coming from all the Guilds of Ria de Arousa. As subtidal harvesting, it requires the use of a boat, where rakes are deployed with a long pole. In this system, the Regional Government, Xunta de Galicia, consults the head of the fishing Guilds for managing the resources. The management regime is operated through an Extraction permit (in Galician 'Permex') and a system of daily individual quotas that also limits working hours per day. The area available for this management is nearly 6 km². This subtidal habitat is a natural seabed, and despite pressures from Guilds for artificial regeneration with dredges, the habitat is still unmodified by humans. Management activities here are stock assessments, control, and surveillance to establish a quota.

3.1.2. Northern Portugal

With one of the largest Exclusive Economic Zone of the European Union Member States, 1,700,000 km², and a mainland coastline 942 km long, the fishing industry is of particular importance to Portugal. The country has always relied on fishing as a major means of subsistence, mainly for the coastal communities that depend almost exclusively on fisheries and related activities (OECD 2017).

Beach seine and octopus pots fisheries are developed in coastal waters of Northern Portuguese coast, south and north of Porto, respectively (see Figure 1). These fisheries are managed by a quota-based system with collective decision-making, and regulated by the Portuguese Ministry of the Sea (Table 1). These fisheries mainly differ on the historical tradition (Cabral 2000), and in their specialization due to gear selectivity.

3.1.2.1. Octopus pot 'alcatruz' (2a). The common octopus (*Octopus vulgaris*) fishery is of substantial importance in southern Europe. In Portugal, the octopus fishery has considerable social and economic value, with small-scale fishing being increasingly economically dependent on this resource. Since this type of fishery in the European Union is excluded from quota regulations under the Common Fisheries Policy, Portugal is responsible for managing its own fishery (Pita et al. 2015).

The octopus pot ('alcatruz') fishery is prosecuted throughout Portugal (Figure 1) and mainly targets common octopus. It has been used commercially since at least the fifteenth century (Godinho 1963) and uses sets of clay or plastic pots that are mechanically hauled from the water. The costs associated with this fishery are low compared with other gears commonly used to catch octopus, which results in a popular fishing gear among Portuguese octopus

Table 1. Management, property regime, and social-ecological characteristics of the Galician and Northern Portugal case studies. In the Portuguese case studies, the row 'No. of fishing units' refers to the number of vessels participating in the fishery, whereas for the Galician case study the data refer to number of individuals participating in the fishery (Data from Centro de Investigacións Mariñas, Xunta de Galicia).

Case study	Galicia			Northern Portugal	
	1a. Intensive semi-aqua. ('Parques cultivo')	1b. Extensive semi-aqua. ('Autorizacións-Plans específicos')	1c. Wild harvesting ('Libre marisqueo')	2a. Octopus pots ('Alcatruz')	2b. Beach Seine ('Xávega')
Ecosystem type	Intertidal/estuary	Intertidal and subtidal/estuary	Subtidal estuary	Coastal/marine	Coastal/marine
Property regime	Concession to individuals/private	User rights with quota	Common quota based	Common property rights/quotabased	Common property rights/quotabased
Management	Individual decision-making/market driven	Collective decision-making with technical support	Scientific-based decision-making	Collective decision-making	Collective decision-making
Management actors	Owners	Shellfishers, Guild biologist, regional government	Guilds and regional government	Ministry of the Sea; Directorate-General of Natural Resources, Maritime Services and Safety; Research institutions; Fishers' Associations	Ministry of the Sea; Directorate-General of Natural Resources, Maritime Services and Safety; Research institutions; Fishers' Associations
Management activities	Surveillance	Monitoring, control, and surveillance	Monitoring, control, and surveillance	Monitoring, control, and surveillance	Monitoring, control, and surveillance
Gears	Rakes and hoes	Hoes and rakes with short pole	Rakes with long pole	Pots	Seine nets
Total area (km ²)	1	1.5	6	n/a	n/a
No. of fishing units	656	134	300	50	53
Gender	Male and female	Mainly females	Only males	Mainly males	Mainly males

fishers. Octopus catches have been increasing quickly over recent decades and are currently the most important commercial species in value in Portugal (Pita et al. 2015), thus sustaining and providing for many fishing communities.

3.1.2.2. Beach seine 'xávega' (2b). The beach seine ('xávega') fishery is operated out of small fishing communities mainly located in north-center Portugal (Figure 1). It is an old commercial fishery, which has been reported since the fifteenth century (Franca and Costa 1979; Martins et al. 2000), although some authors date back the use of similar nets in the Mediterranean as far back as 3000 B.C. (Cabral 2000). This fishery uses nets that are approximately 170 m long, with a central bag about 30 m long. The nets are rowed out into the surf on small vessels (3–8 m long), leaving the end of the trailing rope on the shore. The net then encircles a targeted coastal shallow sandy area, and the leading rope is brought back to shore, where the net is then hauled by tractors and people. The main targeted species are small pelagic fish, such as sardine (*Sardina pilchardus*), horse mackerel (*Trachurus trachurus*), mackerel (*Scomber japonicus*), anchovy (*Engraulis encrasicolus*), and sea bream (*Diplodus spp.*). Due to the low selectivity of the fishing gear, this fishery can have high bycatch rates and result in a large quantity of discards (Cabral et al. 2003).

The beach seine ('xávega') fishery is run by a specific type of fishers' associations called 'companhas' which are run according to agreed norms and rules to manage income, tasks, and fishing resources. According to the General Directorate of Natural Resources, Safety and Maritime Services follow-up report on Fishing with 'xávega' gear in Portugal, in 2013 there were 53 vessels using this gear, mostly in the north and central regions (Santos 2015).

4. Results

To compare and analyze the case studies, we present Figure 2 that illustrates the position of each of them according to the expected level of co-production, in a gradient of natural and non-natural capital inputs, following Palomo et al. (2016). The harvesting system with the largest use of non-natural capital is the intensive intertidal semi-aquaculture, as it uses all the forms of non-natural capital, i.e., human, social, manufactured capital. The second most important activity using non-natural capital is the extensive semi-aquaculture, which needs almost the same practices as intensive semi-aquaculture but at a lower intensity level, using all the forms of non-natural capital, except financial capital. The small-scale fishing systems present a decreasing level of reliance on non-natural capital but still using human, social, and manufactured capital. Wild harvesting is mostly reliant on natural

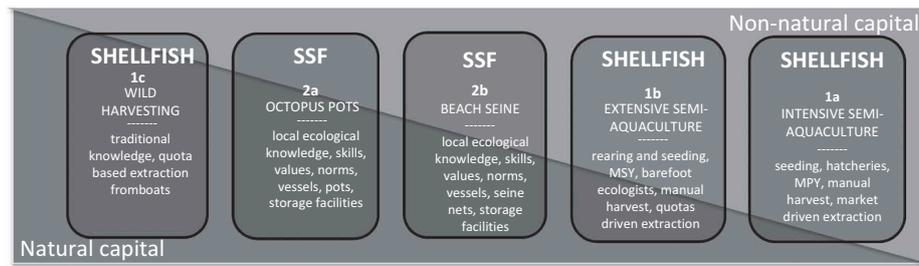


Figure 2. Gradient of marine ecosystem service co-production based on inputs of natural and non-natural capital in the Galician and Northern Portugal shellfish fisheries and small-scale fisheries (SSF) (based on Palomo et al. 2016).

capital with the lowest level of co-production using mainly human and some sort of manufactured capital with small boats and power engines.

4.1. Shellfisheries in Galicia (Spain)

The three Galician shellfish harvesting systems target the same marine ES, i.e., seafood provisioning, as they are providing seafood as a benefit that is directly consumed through commercial transaction. More importantly, in all three harvesting systems, shellfish is marketed and generates revenues for shellfishers by contributing to their livelihoods. The three systems also generate cultural ES, such as cultural identity, community identity, sense of place, and tourism. These cultural ES are understood as the relationships and sense of belonging to a specific activity that facilitates a differentiated way of life (Klain and Chan 2012). Shellfish harvesting yields high valued fresh seafood (Molares and Freire 2003) for consumers that generates a rich and diverse gastronomic culture, which attracts national and international tourists to the region.

There are also differences in co-production between the harvesting systems (Table 2). A portion of its total production of the intensive intertidal semi-aquaculture depends on artificial seeding. It uses intensive seeding from hatcheries of three species of clams: Pullet carpet shell (*V. pullastra*), Grooved carpet shell (*R. decussatus*), and Japanese carpet shell (*R. philipinarum*). The latter is allochthonous and was introduced in the early 1990s from hatcheries imported from Italy and France. *R. philipinarum* is more resistant than other species to environmental shocks produced by anthropogenic pressures (e.g., dams, floodings, heatwaves, etc.) (e.g., Dominguez et al., 2016; Macho et al. 2016), and weight per individual is higher than others. Cockle (*C. edule* and *C. glaucum*) production here depends exclusively on natural seeding and recruitment.

The co-production process relies on a both manufactured and human capital. Due to technology and scientific advances, harvesters can massively

reproduce this species to later exploit it in plots, depending on how much seed plot owners decided to purchase. Each year, owners of the concession plots buy a quantity of seed, in theory equivalent to their allotted production area. However, sometimes maximum seeding densities is surpassed. Although natural spawning is also occurring, owners who have been harvesting shellfish for the last couple of decades have abandoned the idea of solely relying on natural factors for the production process. The relative proportion of manufactured versus naturally produced seed varies among owners and depends on the intensity of the production. However, between 30 and 75% of the final production of a plot each year can be linked to this co-production (AGPPCC 2017; Fisher pers. Comm.). The production not only depends on artificial seedlings, but also relies on plowing the seabed, cleaning with rakes the algae in summer, and removing the natural sprouting of seagrass which finds here its natural environment.

Intensive semi-aquaculture plots are in an intertidal area located in the right arm bank of the Ulla river, a natural area that was historically occupied by seagrass meadows (Figure 1). Since the start of the intensive production in 1940s, seagrass meadows have been removed systematically by plot owners due to the difficulty of collecting clams covered with seagrass and silt, which normally is accumulated in seagrass meadows. Moreover, the plot owners claim that seagrass meadows are low production areas that prevent target species to develop at the same rate as in the 'clean' sandy areas. This co-production activity implies a different causality of trade-offs and risk of ecosystem disservices.

In terms of trade-offs, the removal of seagrass involves the loss of habitat for fish and cephalopod species (i.e., *Sepia officinalis*), which uses seagrass meadows as spawning areas (Bas et al. 2015). Also, the removal causes a potential loss on regulating ES, such as water flow, nutrient cycling, and food web structure (Orth et al. 2006) with a potential cascade effect on eutrophication process in estuaries (Patricio and Marques, 2006). Other trade-offs involve the

Table 2. Disaggregated non-natural capital use and co-production of marine ecosystem services and ecosystem disservices in the Galician and Northern Portugal case studies.

Case studies	Galicia			Northern Portugal	
	1a. Intensive semi-aquaculture ('parques cultivor')	1b. Extensive semi-aquaculture ('autorizaciones-plans específicos')	1c. Wild harvesting ('libre marisqueo')	2a. Octopus pots ('alcatruz')	2b. Beach seine ('xávega')
Property regime	Concession to individuals	Territorial use rights	Common pool resource	Common pool resource	Common pool resource
Target species	Bivalves (mainly clams and cockles)	Bivalves (mainly clams and cockles)	Bivalves (mainly clams and cockles)	Common octopus (<i>O. vulgaris</i>)	Pelagic fish
Benefits	Food, employment, identity, tourism	Food, employment, identity, tourism	Food, employment, identity, tourism	Food, employment, income, identity, social relations	Food, employment, income, identity, social relations, religious
Human capital input	LEK (local ecological knowledge) and skills, high intensity rearing, plowing, predators and algae removal, manual and mechanical harvest	LEK and skills, low-medium intensity rearing, plowing, predators and algae removal, manual harvest	LEK and skills	LEK and skills	LEK and skills
Social capital	Collective surveillance, minimum size	Gear restriction, minimum size, quota based, collective surveillance	Gear restriction, minimum size, quota based, collective surveillance	Gear restriction, minimum size	Gear restriction, minimum size
Manufactured capital	Boats and rakes	For subtidal boats and long pole rakes	Boats and rakes	Vessels, pots	Vessels, seine nets
Financial capital	Lease of plots, buy seed hatcheries, machinery	For buying seed and surveillance might be needed. For subtidal, may apply to buy the boat	May apply to buy the boat and might apply for surveillance	May apply to buy the boat	May apply to buy the boat
Level of Co-production	High-intensive	Medium-extensive	Low	Medium	Medium-high
Co-production details	Year round owners might be rearing the intertidal areas of their ownership to maximize the production of certain clam species. Seeding activities might be year round, and the owner decides the amount of seed and species based on experience. Period and amount of extraction are subjected to individual decision and might be year round, mainly regulated by market demand.	The ratio of area/shellfishers is lower than in the intensive. Rearing and seeding are subjected to specific plans where a local biologist jointly with management authorities and shellfishers decide the amount and intensity of these human disturbances based on past experiences and technical advice. Quantity and period of extraction are subjected to quotas and specific plans which look after the economic and equity among all stakeholders.	Skills and knowledge of shellfishers are the most important human traits to develop the service and obtain the benefit. Quantity and period of extraction are subjected to quotas and specific plans which look after the economic and equity among all stakeholders.	Specific knowledge and skills are needed to operate vessels and gears, and to know suitable areas to deploy nets. Logistics on land to pull the nets require a high number of workers and tractors. Fishers' societies are run according to agreed norms and rules to manage income, tasks, and fishing resources. Fishers have a strong sense of belonging to their community, and attribute symbolic meanings and religious rituals to fishing activities.	Specific knowledge and skills are needed to operate vessels and gears, and to know suitable areas to deploy nets. Logistics on land to pull the nets require a high number of workers and tractors. Fishers' societies are run according to agreed norms and rules to manage income, tasks, and fishing resources. Fishers have a strong sense of belonging to their community, and attribute symbolic meanings and religious rituals to fishing activities.
Ecosystem disservices	Regulating, risk of pests	Regulating, risk of pests	Unknown	Adverse climate/sea conditions; predation of octopus by other spp.; unsuitable water temperature and salinity for octopus recruitment	Adverse climate/sea conditions; predation of forage fish by other spp.; unsuitable water temperature and salinity for fish recruitment

availability of large quantities of dead seagrass stems, which float on the surface and cause physical disturbance creating a barrier for sports/recreational users, such as recreation fishers or water sports.

Regarding ecosystem disservices, regulating ES might be affected by the risk of invasive species when bringing seeds from hatcheries in other ecosystems, which can come along with resistance viruses, bacteria, or allochthonous undesired species. This is especially relevant given a recent infestation in 2012–2014 in the cockle (*C. edule*) by the protozoan *Marteilia cochillia* with Marteiliosis (Villalba et al. 2014). The protozoan devastated *C. edule* production, negatively affecting 1500 families who directly depend on this resource. The exact entrance pathway of this parasite is still unknown, but one of the most plausible hypotheses is that the species was brought from hatcheries which are dedicated to supply producers. Similar trade-offs were found for crop systems between increasing provision ES in the short term and reducing the ability to cope with pest at the long run (Bonmarco et al., 2013). The pest episode has direct links to the resilience of SES with trade-offs between provisioning and regulating ES that are compromising the ability of the system to cope economically with the pest outbreak. Moreover, it also opens the discussion toward the inter-personal trade-offs which may be caused using seed from unknown origin in semi-aquaculture, and the impacts received on the wild harvesting fishers which could not harvest in this area for two campaigns in 2013 and 2014 due to the lack of shellfish (LVG 2017). This episode triggered an increased artificial seeding rate on the semi-aquaculture areas in order to cope with the lack of cockles, but no alternative other than closing was found for the wild harvesting areas.

Despite being initially conceived with the aim of wild harvesting with no artificial seeding, extensive intertidal and subtidal semi-aquaculture has evolved progressively in some practices toward intensive semi-aquaculture. The main difference between

extensive semi-aquaculture and other semi-aquaculture types is in the intensity of the seeding rate, and the type and origin of the species.

The other operations involved (e.g., rearing, plowing, and cleaning) are substantially less intensive in time and space compared with intensive semi-aquaculture. Therefore, this activity might trigger or contribute to similar trade-offs and ecosystem disservices as explained above, but with lower intensity. In fact, people are harvesting a larger area, and the management actors are jointly involved with decision-makers. In extensive semi-aquaculture, production is determined by setting a maximum sustainable yield, and decided with collective harvesting quotas determined through collaboration between existing social capital with input of local ecological knowledge of fishers. Despite these trade-offs between provisioning and regulating ES, extensive semi-aquaculture individuals have recently created initiatives to diversify their income through aquaculture tourism, which allows tourists to live the experience of being harvesters for one day (LVG 2009).

Wild harvesting is perhaps the oldest activity performed in this area. Before the co-management regime adopted by the Galician Government in the 1990s, these areas were subjected to a *de facto* open-access with no quotas or permits, where all interested individuals could develop extraction activities. Today, these areas are the only areas managed mainly by the Galician administration which elaborates annually a stock assessment to set quotas and regulate effort (Parada et al. 2006). The co-production process involves less manufactured capital than the other two harvesting systems given that artificial seeding is negligible. Therefore, this case does not involve the risk of ecosystem disservices and trade-offs as shown in other two previous harvesting systems case studies (Table 3). This is also because the activities of plowing, cleaning, and rearing are not yet implemented despite the claims by Guilds. The level of co-production is relatively lower compared to the other two

Table 3. Ecosystem service trade-offs disaggregated per category and type for each of the co-production study case in Galicia and Northern Portugal.

ES type	ES categories	1a. Intensive semi-aqua.	1b. Extensive semi-aqua.	1c. Wild harvesting	2a. Octopus pots	2b. Beach Seine
Provisioning	Shellfish	V	V	V	–	–
	Fish	X	X	–	V	V
Cultural	Heritage and identity	V	V	V	V	V
	Social capital	–	V	V	–	–
	Social relations	–	–	–	V	V
	Tourism	V	V	–	–	X
	Recreation activities	X	X	–	X	X
	Sense of place	–	–	–	–	V
	Symbolic, spiritual, religious	–	–	–	–	V
Regulation	Climate regulation	X	X	–	–	X
	Water regulation	X	X	–	–	X
	Genetic resources	X	X	–	–	–
Supporting	Primary production	X	X	–	–	–

V: Ecosystem services co-produced; X: ES trade-offs; – : No detected effect.

harvesting systems. It is the closest harvesting system where the human intervention is negligible, co-production is low, and synergies are more common than trade-offs (Table 3).

As shown in other study cases in the agricultural context (Omer et al. 2010), the volume of production of the targeted ES, here clams and cockles, is also dependent on the co-production gradient found in these three harvesting systems. From the 1141 tons of shellfish officially landed in 2016, around 61% were landed by the intensive semi-aquaculture, 25% were landed by the extensive semi-aquaculture, and almost a 13% were landed from the wild harvesting area (Figure 3). This different order of magnitude in the production of these three systems has been a claim by fishers (Parada et al. 2006). They use the intensive semi-aquaculture as an example of production efficiency using only 1 km² to obtain 61% of the total production of the Guild. Furthermore, shellfisheries from extensive semi-aquaculture had claimed over the last decade for progressively transforming wild harvesting areas toward an extensive semi-aquaculture where more shellfishers could eventually join and sustain their livelihoods (LVG 2014). In terms of social equity, semi-aquaculture systems provide an example of differentiated co-production and social equity especially due to the property regime. Intensive semi-aquaculture systems are individual property plots which can be transacted economically between individuals or inherited from relatives. Despite that, before the 1990s, the plots were evenly distributed among the local families providing their livelihoods. Today, the concentration of large areas in the hands of a small number of producers is happening slowly with the consequent income distributional effect. In contrary, extensive semi-aquaculture has its property regime in public hands, and everyone may apply for a right of harvest. However, the selection criteria for ultimately awarding harvest rights favors long term unemployed applicants and victims of gender violence.

4.2. Beach seine and octopus pot fisheries (Northern Portugal)

Fishers of the Northern Portuguese beach seine and octopus pot fisheries are involved in the co-production of seafood provisioning, targeting benefits such as nutrition, income, and employment (Table 2). Yet cultural ES such as cultural heritage and identity, opportunities for social relations, symbolic services, spiritual, sacred and/or religious experiences, sense of place, and tourism are fundamental for the fishing communities that engage in these fisheries (Oliveira et al. 2010; Santos 2015). For example, each of the beach seine ‘companhas,’ or fishers’ associations, has its own symbolic and religious devotions (Santos 2015), which contribute to the co-production of cultural ES generated by the marine environment (Garcia Rodrigues et al. 2017). These associations also foster the strengthening of sense of place, belonging and social relations within the fishing community.

In addition to natural capital, these fisheries strongly depend on non-natural capital, such as human, social, and manufactured capital to extract food from the sea (Pereira 1999; Antunes 2007; Santos 2015). Human capital, such as local ecological knowledge about the seasonal variability of fish/octopus stock abundance, location of fishing grounds, and skills to operate forms of manufactured capital, such as fishing vessels and gears, are all pre-requisites for a successful catch (Berkes et al. 2000). Social capital, in the form of shared values and agreed norms, allows fishers to form and maintain social relations that ultimately enable a sustained provision of fish through local governance and management, and a fair distribution of food and income among the community.

The forms of capital that enable the co-production of food provision are shared by both fisheries. Yet the levels of co-production slightly differ from one fishery to the other (Figure 2). The beach seine (‘xávega’)

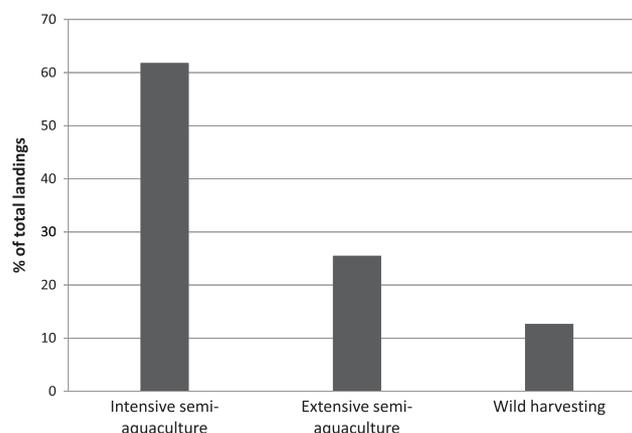


Figure 3. Percentage of the total volume of landings by each of the harvesting shellfisheries systems in the Carril Guild (Galicia case study) in 2016. Source: Based on data from pescadegalia.gal.

fishery is arguably more capital-intensive than the octopus pot ('alcatruz') fishery because it requires a higher number of fishers per haul, more logistics on land, i.e., workers and tractors to pull the nets, and a higher number of workers to sort the catch (Pereira 1999; Antunes 2007). The octopus pot fishery does not require specific logistics on land to operate, and the pots used to catch octopus are highly selective, resulting in limited bycatch and a reduced workforce needed to sort the catch (Pereira 1999).

Clear trade-offs exist with the increased use of manufactured capital by fisheries to increase seafood provision in the short-term. The presence of tractors, fishing gear, and vessels at coastal areas where the beach seine fishery operates may decrease the aesthetic quality of beaches and seascapes to many recreational users and tourists (Table 3). Another trade-off is related with the increasing use of plastic pots by the octopus fishery – instead of traditional clay pots – which can dramatically change seabed conditions, as lost plastic pots do not degrade easily and may negatively affect local habitats and species during long periods of time (Sobrinho et al. 2011). Coastal recreational activities such as diving and snorkeling can also be negatively affected by the increased use of fishing vessels, nets, and pots, as these activities usually compete for the same space (Table 3). In addition, besides generating significant amounts of discards (Cabral et al. 2003), the interaction of seine nets with kelp forests and seagrass meadows present in coastal shallow areas where the fishery operates can contribute to the degradation and destruction of these habitats and their important nursery ES.

5. Discussion

To illustrate the relationships between non-natural capital and marine ES, we presented three shellfish harvesting systems from Galicia (Spain) and two small-scale fisheries from Northern Portugal that differ in co-production levels. By exploring in detail the different systems and types of marine ES co-production, we were able to disentangle relationships that may help to understand the implications of non-natural capital in ES and benefit delivery (Figure 2). Although the case studies are small-scale fisheries at a regional level, we believe that more intense levels of co-production may be related to greater ecosystem disservices and trade-offs (Figure 4). Size upscaling of the intensive or extensive semi-aquaculture to larger scale fleets and larger marine ecosystems might involve greater trade-offs, compromising the resilience of marine SES at a larger scale, as reported in salmon aquaculture (Outeiro and Villasante 2013), or reported from industrial fishing impacts on seagrass (Tanaka and Ota 2015).



Figure 4. Relationships between co-production level and trade-offs associated with marine ecosystem service and benefit provision for the Galician and Northern Portugal shellfish fisheries and small-scale fisheries (SSF).

Figure 4 shows the relative position of each of the case studies that we explored in a two-way graph, depicting the level of co-production and the ES trade-offs. For example, Galician intensive semi-aquaculture shows the largest trade-offs which are paired with a high use of human, manufactured, and financial capital, which can affect the provision of habitat ES (e.g., nursery habitat area for squid or other species) and regulating ES (nutrient cycling).

Following the decreasing axis of co-production and trade-offs is the extensive semi-aquaculture, with similar interactions with the environment, but in a less intensive manner. However, this harvesting system is also associated with cultural ES and can provide important benefits from shellfish-based tourism. An order below in generating trade-offs and co-production dependence are the two small-scale fisheries from Northern Portugal. The beach seine fishery depends more on human capital and manufactured capital to obtain provisioning ES and potentially generates more trade-offs between provisioning and regulating ES. The wild shellfish harvesting scores the lowest level of co-production while a low level of regulating ES trade-offs due to the low level of manufactured capital and the absence of human intervention on adjacent river banks. All five case studies vary in an exponential fashion in the level of co-production based on the capital inputs needed for service delivery.

More information would be needed to quantify the level of co-production and ES delivery. Further research should be directed to shed light on the links between co-production of ES and the consequent theoretical ecosystem disservices delivery. Empirical approaches such as interviews to key stakeholders will be helpful in the future to quantify these links and further understand the complex

relationships illustrated in this paper. However, applying cultural ES to the rationale of Figure 4 may change the picture completely. Future research should explore to what extent ES can be compromised by co-production and how sustainable ES delivery can be assured.

The argument of low productivity level and existing pressures used by local Guilds to justify changes in the shellfisheries banks leaves an open question: is this level of co-production necessary to enjoy provisioning ES and benefits in the Anthropocene Era? From the Guilds' leaders discourse seems to be necessary to intervene in the wild banks to have a production of shellfish that matches the levels required to satisfy local needs for income and employment (LVG 2014). In fact, the two semi-aquaculture systems were conceived initially as poly-culture – wild harvesting, and they evolved in time toward being more reliant in non-natural capital with higher levels of human intervention. Wild harvesting seems to be pushed toward that state where natural soft-sediment banks are recurrently modified to maximize shellfish production with the consequent halting of dynamics. Other question this argument poses: Have the natural dynamics of the system, modified by decades of economic development, changed to a state that cannot be reliant on natural capital alone? Here, we propose a type of spatial trade-offs at the basin level (Howe et al. 2014; Rodriguez et al. 2006) to partially explain this question. The degree of human intervention in the terrestrial area of this basin, land use change, deforestation jointly with recurrent wildfires, road infrastructures, and wastewater from settlements are key determinants to explain this question.

In addition, given that the interactions of marine ES over space and time may be linear or non-linear, understanding the role of non-natural capital and marine ES could be extremely useful in order to avoid unexpected thresholds and tipping points. Since crossing critical tipping points can lead to abrupt social transformations of marine social-ecological systems, a critical question emerges: Can we identify at what level of co-production do we trigger ES trade-offs? The scientific community does not have a definitive answer and more research would be needed in this direction.

However, ignoring the role of tipping points in the co-production processes of marine ES may increase the risk of unpredictable and potential abrupt changes of marine socio-ecological systems. Considerable management efforts to reverse such changes are usually made, but most of them are very expensive since they are taken after the abrupt changes have taken place (Villasante et al. 2017). In fact, crossing undesirable tipping points has been also recently associated with large social transformations of marine ES, which mean a fundamental and

critical change of societal values, institutional arrangements, and fishermen's practices in the use of natural and non-natural capital (Villasante et al. 2017). Thus, identifying tipping points can be extremely useful to detect early signals of potential abrupt changes which also help to identify windows of opportunity to navigate into new resilient transitions before tipping points are crossed (Villasante and Österblom 2015). Despite the qualitative nature of this paper and for illustrative purposes, a likely sign of a tipping point in the Galicia case study is found when the shellfishing changed their reliance from dynamics alone sustaining their production toward a system where stakeholders systematically perceived artificial seedling as a necessity to secure annual production (AGPPCC 2017). The perception of nature alone is unable to provide ES at the level of production demanded makes the system to enter in a 'new state' in which ecological processes such as regulating ES are depending not only on nature variables, but also on social actions as artificial seedling with allochthonous species (i.e. *Ruditapes philippinarum*).

Provisioning co-production of ES is developed under different property right regimes. Property rights are exercised with a series of conditions, rules, instruments, and policies regarding access to, use of, and control over natural resources and provisioning ES (Schlager and Ostrom 1992). They are governed by different institutional regimes and authorities who are often overlapped and interacted under multiple scales (Ostrom 2010), for example regional governments and the EU Common Fisheries Policy. Property rights can be conceived as a key instrument of governance to achieve societal goals such as economic development, resource conservation, and equity justice (Chomba and Nkhata 2016). Under specific property rights, managers and users can make specific decisions and carry out actions regarding a particular production of ES. For instance, in the case studies, intensive farmers and shellfishers in Galicia may have exclusive individual private rights to access and use the coastal area while wild harvesting and industrial fishing have the 'rights' to use the area and resources, but under public or common property regimes. Globally, property rights and co-production are following similar patterns as our study cases. In Chile where salmon aquaculture, shellfish gathering, and open shellfishing and fishing exist, the gradient of co-production increases from open systems to TURF's to aquaculture private concessions (Outeiro et al. 2015). In British Columbia (Canada) too it is quite similar; however, in this region the existence of highly priced individual licenses (i.e. giant clam) and the inexistence of TURF's systems differ slightly the property regime and co-production gradient (Pinkerton 2015).

Finally, further development for linking marine ES and co-production will also need to consider the drivers of change and the different actors related to seafood production and provisioning operating at different scales. As pointed out by Rocha et al. (2014), this information will inform and promote the development of more sustainable forms of management actions.

6. Final remarks

We have depicted the relationships and trade-offs between provisioning, regulating, cultural, and supporting ES that are co-produced in the marine environment. Current science and policy is discussing the implications of non-natural capital in the production and delivery of ES. The degree to which co-production sustains desirable ES flows, produces ES trade-offs, and can be regulated by different property regimes are highly relevant questions that are addressed here in order to fill this gap. We contribute to the state of the art by exploring these relationships empirically, for the case of Galician shellfisheries and Northern Portuguese beach seine ('xávega') and octopus pot ('alcatruz') small-scale fisheries, where information exists about the pathways to co-produce marine ES.

The analysis presented here contributes to existing research gaps on understanding the relationship between different marine ES and co-production levels. Our main conclusion is that while the relationship can be linear for some ES (e.g., provisioning), it may not be the case for others (e.g., cultural ES). We also find that management practices may have a very important role in the set of the co-production of ES. Future research can illustrate these relationships in different ES and case studies and contrast the level of ES and co-production with stakeholder preference analysis and sustainability assessments in order to inform policymaking.

These five cases constitute an example of the transition from wild reliant harvesting where the process of production relies mainly on natural capital, toward aquaculture production systems which are called to be the new paradigm of seafood production (Molares and Freire 2003). In the case of Galicia, when the wild harvesting is not yielding accordingly to stakeholders or is not in good shape in terms of economic yielding, communities and authorities found co-produced semi-aquaculture harvesting as the solution along with individual and sometimes private property regimes. In Northern Portugal, a likely next step would imply an eventual setting up of octopus aquaculture (Iglesias et al. 2004; Vaz-Pires et al. 2004) or fish aquaculture (Matos et al. 2006; Santos et al. 2006). A higher input of non-natural capital may create

new trade-offs, especially between provisioning and regulating ES. So, one question arises: What are the limits of non-natural capital inputs in the co-production process? We believe that the co-production process is inherently facilitating the delivery of ES but, at the same time, it can exacerbate the provision of ecosystem disservices, potentiate unsustainable practices, and thus result in detrimental environmental conditions. In a growing global scenario with policies directed to the provision of ES, special attention is needed to understand and address the implications of co-production to the system, going further from the ES approach.

This work with its historical and spatial perspective addressed some interesting messages toward the policy arena. Evidence from this paper shows that the intensity of co-production (i.e. artificial seedling) is already incorporated in fishers, shellfishers, and local-regional authorities reliance for production and thus to achieve decent livelihoods. The intensity of non-natural capital used in the co-production of ES has been increasing in all case studies steadily from the last 25 years. This has important trade-offs not only on regulating but also the biodiversity and conservation management plans in time of climate and global change. Specially relevant in the context of the EU-27 Marine Strategy Framework Directive where the objectives to achieve an ecosystem approach in marine ecosystems seem to find an opposed view local and regional authorities which are actually progressing in the contrary way. Eventually in terms of policy, we are in a 'policy train crash,' local regional policy going in one direction, and another supra national level in the opposite direction. Thus, an effective supra national level policy should take into account this type of micro realities and specificities if that policy does want to make a smooth and effective socio-economic transformation of marine socio-ecological systems management toward ecosystem approach.

Note

1. Semi-aquaculture or cultured-based fisheries is the release of hatchery-reared animals into the wild for capturing fisheries enhancement, being aquaculture-driven (Ottolenghi et al. 2004).

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