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Exploring mechanisms to pay for ecosystem services provided by mussels, oysters and seaweeds

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ABSTRACT

This explorative study identifies and evaluates mechanisms for payment for ecosystem services provided by mussel, oyster and seaweed aquaculture. Concerns about the economic profitability of farming mussels, oysters and seaweeds hamper upscaling of production. It is argued that valuing and capitalizing the ecosystem services provided by the production of these lower trophic species can benefit the business case. The Delphi method is used to consult experts across the world in various sectors, including industry, NGO, science and government. Six payment mechanisms for ecosystem services were considered feasible; tax-payer funded payments, tradeable credits, encouraging subsidies, social licenses to produce, production cost-sharing schemes and increased utility for consumers. The latter was deemed most feasible, with little differences in feasibility found in the other five. There are however barriers to implementation in a lack of solid quantification, inadequate regulatory framework and lack of independent validation. Future payment mechanisms for ecosystem services provided by mussels, oysters and seaweeds need solid, science-based measurements based on sound monitoring indicators to quantify effects on the ecosystem services, liaised with relevant existing carbon and nitrogen credit trading schemes and an independent checks-and-balances for long-term trust in such payment schemes. The need for better mechanisms for capitalization justify further development of better data and knowledge of these mechanisms, inclusion of ecosystem services in new regulations and more political and societal support to implement them.

1. Introduction

Mussels, oysters and seaweeds are potential sources of food, feedstock, and input material for non-food applications. Various studies have investigated the potential to use these marine lower-trophic species for the production of food and bio-based materials including bio-stimulants, cosmetics and pharmaceuticals (Stévant, Rebours, and Chapman 2017; Khan et al. 2009; Petersen et al. 2016). The contribution of mussels, oysters and seaweeds to human wellbeing goes beyond the provisioning of biomass. They play an important role in supporting ecosystems, trophic-dynamics, sheltering habitats, as well as regulating atmospheric chemical composition (i.e., maintaining CO_2 and O_2 balance) through carbon sequestration (Duarte et al. 2017) and nutrient recycling. Moreover, oyster beds and seaweed cultivation can also contribute positively to the creation of biodiversity-enhancing habitats (Radulovich et al. 2015; Jiang et al. 2020). Marine aquaculture can support ecosystem services provision beyond solely the production of goods, through provisioning services, regulating services, habitat or supporting services, and cultural services (Hasselström et al. 2018; Alleway et al. 2019).

The economic feasibility of farming mussels, oysters and seaweeds is often a critical issue, hampering further growth of production (Avdelas et al., 2021; Beckensteiner et al., 2020; Kim et al., 2019). In addition to efforts made to innovate and reduce costs of production, valuing the regulatory and cultural ecosystem services provided by the production of these lower trophic species can help the business case (van den Burg et al., 2021; Buschmann et al. 2017).

Despite the vast literature on values of ecosystem services (a search on ScienceDirect in the journal Ecosystem Services only with search string "valuation ecosystem services" resulted in 92 articles published in 2021 alone) and the development of the Ecosystem Services Valuation Database (Foundation for Sustainable Development 2021) and TEEB valuation database (See McVittie and Hussain 2013), there exists no commercial value for the majority of regulating and cultural ecosystem

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services on the market to date.

Without generating market values for existing ecosystem services, a degradation of these services is likely to occur because negative externalities are not being internalised, thus not paid for. Emerging markets that place economic values to ecosystem services have begun to arise, as seen through the carbon and nutrient trading markets. Within the large body of literature that looks at mechanisms to generate payment for ecosystem services and natural capital (Gómez-Baggethun et al. 2010; Binet et al. 2013), the bulk of it was developed with terrestrial ecosystems in mind. Binet et al (2013) claim the fisheries agreement in Mauritania was the first international payment for marine ecosystem services. Willingness to pay for marine ecosystem services was studied in, among others, Japan (Wakita et al., 2019) and Colombia (Castaño-Isaza et al., 2015). In 2019 Hooper et al. (2019) concluded that greater effort is needed to develop methods dedicated to the marine realm.

A recurrent picture emerges for the literature. Although there are various methods studies that quantify and value the ecosystem services provided by mussels, seaweeds and oysters (See among others Hattam et al., 2021; Park et al., 2021; Duarte et al. 2017), there is far less insight into the possibilities for actual financial transactions. Wang et al. (2021) applied the value transfer method to quantify the economic benefits of mussel filtration services to surface water-dependent drinking water companies. Gren (2019) uses the replacement cost method to value mitigation of eutrophication in the Baltic Sea. The concept of ecosystem services is used to select the most favourable cultivation sites (Cabral et al. 2016), including economic considerations. However, such studies do not discuss how the hypothetical calculated value can be transferred to the mussel farmers.

A recent exception here are Barret et al (2022) who quantify and monetise the impacts of bivalve and seaweed farming on a regulating service (removal of nitrogen from nearshore waters) and a supporting service (habitat provision for species with fisheries value) and who – if briefly - mention the potential of credit trading schemes to realise actual payments.

Rather than adding to the existing literature on valuation techniques or valuing new sites of ecosystem services, the objective of this paper is to address the gap in literature in identifying and evaluating mechanisms that can help realize actual payment for ecosystem services provided by marine lower trophic species. The research question guiding this study is: *what are the potential mechanisms for capitalization of ecosystem services from mussels, oysters and seaweeds?* The research question is divided into the following sub-questions:

- What ecosystem services provided by the cultivation of lower trophic species are relevant to capitalize?
- What are mechanisms that can be used to generate payment for ecosystem services?
- What are the strengths and weaknesses of the most promising mechanism designs?
- What actions are needed to bring payments for ecosystem services closer to realization?

The results of this study can also be used to stimulate further discussions on mechanisms for the valuation and capitalization of ecosystem services provided by cultivation of mussels, oysters and seaweeds. The exploration of mechanisms that can generate payment for ecosystem services was conducted through three rounds of expert consultation using the Delphi method. The next section discusses the methodology and its application.

2. Methodology

2.1. Delphi method

The main technique used in this study is the Delphi method, pioneered by Dalkey and Helmer in the early 1960 s to explore the impact of technology on warfare (Dalkey & Helmer 1963). Since then, the method has been extensively used in various non-military applications that aim to produce forecasts and evaluations of complex social problems (Landeta 2006). The method is used in the exploration of complex problems for which there is little available knowledge, data or lack of agreement within the field (Okoli & Pawlowski 2004). The Delphi method allows interdisciplinary research problems to be dealt with across a group of experts with heterogenous opinions, to bring together different viewpoints (Brunnhofer et al. 2020). Given the complex and interdisciplinary nature of capitalization for ecosystem services, the Delphi method is suitable to bring together experts from different professional backgrounds and explore potential mechanisms and their implementation challenges.

The main elements of the Delphi method are summarised as follows (Landeta 2006; Zartha Sossa et al. 2019):

1) It is a repetitive process. The experts must be consulted at least twice on the same topic, so that they have the opportunity to reconsider their answers, aided by the information they receive from the other experts;
2) The process maintains anonymity of its participants and their responses, as to promote creativity and prevent any influence that could be explicitly or implicitly exercised by participating experts of certain authority or reputation, and eliminate the bandwagon effect of majority opinion;
3) The exchange of information between the experts is controlled. The process is carried out by means of a study group coordinator, so that all irrelevant information is eliminated;
4) The facilitator must have in-depth knowledge of the method and research topic, to ensure correct survey design, conduction or evaluation of results.

Additional elements are the following (Sutterlüty et al., 2017; Peuckert and Quitzow, 2017; Montes Hincapié et al. 2017; Kühnen and Hahn, 2019; and Brunnhofer et al. 2020): First, all studies use 2 or 3 rounds, usually consisting of different elements per round, such as interviews, ranking, rating and questionnaires. Second, the number of experts used depends on the type of study. Some quantitative studies may use up to 300 experts in their consultation (for example, Peuckert and Quitzow, 2017; Kühnen and Hahn, 2019), using statistical analysis to weigh experts' responses. Studies that make use of qualitative analysis, such as interviews and qualitative surveys, may use around 20 experts (for example, Sutterlüty et al., 2017; Brunnhofer et al. 2020). Third, an important and often neglected component of the Delphi method is that participants are provided with sufficient background information to give informed opinions (Humphrey-Murto & de Wit 2019).

2.2. Application of the Delphi method

The study team prepared a longlist of experts from governmental, research, commercial and non-profit organizations, based on contacts in earlier projects, conferences and through relevant scientific literature. In the selection of participants to be contacted, special attention was paid to a variety of sectors (research, corporate, government and others), geographical distribution and gender. Because this is an explorative study, diversity in participants was considered key to gather a diversity of ideas. The total longlist of 78 people was contacted to request their participation in this study. Of those 78 people, 20 confirmed participation and 17 people participated in the study altogether. While the participation of 17 respondents falls marginally below the recommended number of 20 by Sutterlüy et al. (2016) and Brunnhofer et al. (2020), the breadth and coverage of experts who took part in the study was deemed acceptable for exploring potential avenues to capitalize ecosystem services.

Table 1 shows a summary of the characteristics of the respondents.

Table 1
summary statistics of experts that participated in the Delphi study.

Region	Participants	Background	Participants	Gender	Participants
Europe	13	Research	6	Female	6
Pacific	2	Corporate	4	Male	11
USA	1	Government	2		
Other	1	NGOs	3		
		Other	2		

The participants are geographically spread out across Europe (Netherlands, Norway, Sweden, Faeroe Islands, and the UK), the south Pacific (Australia and New Zealand), as well as the United States and Israel. The professional background of the participants consisted of research, corporate, government and non-governmental organisations (NGOs).

The goal of this Delphi study is to explore ideas for the capitalization of marine lower trophic species. Three rounds of expert consultation were organized in the period June-September 2020 to gather these ideas. The Delphi method was applied remotely in support of anonymity required by the method, but also due to the limitations posed by COVID-19: all participants received the questionnaires and submitted the response per e-mail, and the study team merged all replies to be shared in subsequent rounds. For each round, a response deadline was set. When the participants missed a round due to timing or other commitments, they were given the opportunity to contribute answers to the previous round as part of the subsequent round. Table 2 shows the response rate for each of the three rounds. The 2 people that did not participate in the first round did participate in the second and third round, and thereby given the opportunity to make up for their missed response during the first round.

2.3. Design of the rounds

The questionnaire was prepared in Excel, offering participants the freedom to answer and allowing the team to review and collate final results. All questionnaires are available for reference in the Data in Brief. Background information to place the study in context is an important component of the Delphi method.

Participants were presented with three categories under which the ideas for capitalization could fall. These categories were presented as follows:

1) Between government and business: avenue to capitalize is based on the establishment of a market or scheme initiated by governments (and/or lobbied by businesses), in which businesses can take part in
2) Between business and business: based on incentives that may promote businesses to initiate, within the private sector, monetary transactions without the assistance of governments or consumers (e.g. exchange of services for monetary payment across businesses)
3) Between business and consumer: market driven capitalization of ecosystem services that can arise from consumer preferences or demands of businesses. This includes product differentiation based on public image or social license from the business perspective (e.g. eco-labelled goods)

These categories were introduced to stimulate participants to think broadly, and to avoid they focussed too quickly on one particular category. Aside from these categories, each questionnaire was supplemented with an Annex that specified a number of ecosystem services, ecosystem functions and examples. This list of ecosystem services by the marine lower trophic species mussels, oysters and seaweeds, based on CICES 5.1, was provided to help participants conceptualize the exercise.

Table 2
response rate from the 3 rounds of the Delphi study.

	Round 1	Round 2	Round 3
Respondents	15/17	11/17	10/17
Response rate	88%	65%	59%

Given the explorative nature of this study, the Delphi method was applied through a ‘funnel’ model: from less structured to more structured. In the first round, participants were given the freedom to suggest a wide range of ideas for mechanisms for capitalization. A structure was applied that participants needed to select the species for which the mechanism is relevant (mussels, oysters and/or seaweeds) and the category the mechanism would fall under. In the second round, these ideas were collated by the team. Similar ideas were grouped together under each category. This resulted in a longlist of creative ideas, some more elaborated than others. The ideas with more elaboration contained thoughts on the strengths of the mechanism, the potential barriers and challenges, and the structural changes needed to improve the achievability of the mechanism. This provided the inspiration for round 2, in which the experts were asked to reflect on these aspects for all the ideas. In case this exercise sparked other ideas for mechanization, the participants were also given the opportunity to add new ideas to the list. At the end of this round, the study team collated the ideas in 6 mechanisms for capitalization. These 6 mechanisms were presented to the participants in round 3, in which they were asked for a further reflection on implementation and feasibility. The phases are described in Fig. 1. The following sections describe the individual rounds in more detail.

2.3.1. Round 1

The purpose of round 1 was to engage the participants in an individual brainstorm and come up with ideas for capitalizing ecosystem services. Participants were explicitly asked to come up with ideas for capitalization of services other than provisioning, as there is already a market value for goods (i.e., food and raw materials) provided from mussels, oysters and seaweeds.

To add some structure in this phase, participants were asked to contribute a minimum of 1 and a maximum of 3 ideas that could yield payment for ecosystem services. This made sure the participants provided their ‘best’ ideas and not just anything they could come up with. In addition, participants had to specify the species the mechanism for capitalization could apply to (a choice between mussels, oysters and/or seaweeds), as well as the category the mechanism falls under. This to make sure the ideas could be collated well in a later stage. At the end of round 1, the project team collected all ideas and collated these per category, resulting in a list of 17 ideas for mechanisms.

2.3.2. Round 2

In round 2 participants were asked to reflect on the ideas collected in round 1, provide additional ideas on capitalisation and comment on the feasibility of implementing the ideas in reality. Participants were asked also to provide input on potential challenges, solutions and achievability of the ideas from round 1. To keep the survey manageable for both participants and facilitators, this was carried out through a scoring system to identify the mechanisms with the highest potential. Participants had to assign a score of between 1 and 5 to the 17 ideas from round 1, with 5 being the most achievable and 1 being the least, and provide a brief explanation for the choice of score. For the 3 mechanisms with the highest score, participants were asked to comment on the following:

- Strengths of the mechanism for capitalization;
- Potential barriers and challenges to the mechanism for capitalization;
- Changes needed to improve achievability (e.g. changes to policy and market structure).

Finally, participants had the opportunity to add other new ideas to the existing list of ideas for mechanisms. The results from round 2 were collated, and based on the rankings and additions to the mechanisms

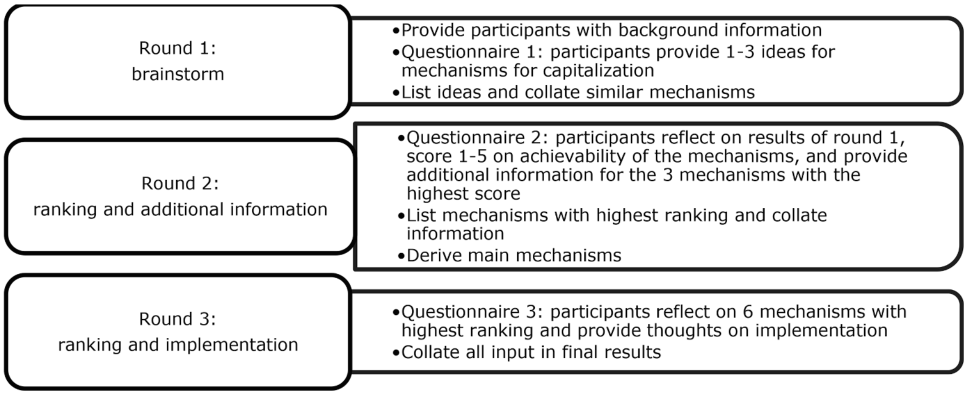


Fig. 1. Delphi study rounds.

described, a list of 6 mechanisms were summarized. These 6 mechanisms reflected the distinctive concepts of capitalization that were repeated across the various species and ecosystem services.

2.3.3. Round 3

In this round, participants were asked to first rank the mechanisms based on feasibility. After that, participants had the opportunity to reflect on the strengths, weaknesses and changes needed to improve achievability from the responses of other participants in round 2. Finally, participants were asked to comment on the type of stakeholders that would need to be involved and the necessary actions from them in order to make the mechanism applicable to implement in reality. There was also an opportunity for participants to provide additional feedback, comments or reflection.

The next section presents the findings of the rounds.

3. Results

3.1. Results round 1: relevant ecosystem services and mechanisms

Round 1 resulted in a list of relevant ecosystem services and a first list of potential mechanisms for capitalization. As the process of collecting potential mechanisms was iterative, participants were given the opportunity to reflect on and add to the first list in the second round. This resulted in a long-list of mechanisms presented in the results of round 2 (see Table 3). This section therefore highlights only the ecosystem services to consider for capitalization as mentioned by the participants.

In the category of government-business, the following benefits were mentioned by the participants:

i. Low trophic species are seen as loop closing agents for phosphorus, capturing it from marine environments before it ends up in sediment sinks, and farming and harvesting of these species should be remunerated as such,
ii. Production of lower trophic species is seen as alternative to using natural coastal systems for seafood production, releasing some of the pressure from already over-utilised and often degraded areas,
iii. It is argued that cultivating seaweeds leads to more fish in the sea through habitat support services, enriching the ecosystem and making it more biodiverse by creating a new biotope. The regional enrichment of the sea will lead to better fish stocks in the area which can be exploited (herding),
iv. Seaweed farms can be co-located with offshore wind and fish farms, increasing societal license to produce for offshore wind energy development.

Other benefits mentioned stem from the use of lower trophic species in various applications. It was mentioned that when fermented seaweed is used in cattle feed, it can reduce methane emissions from ruminant animals. Also, it was argued that seaweed has been shown to positively affect the gut system of animals and humans. Seaweed can strengthen the immune system and thereby reduce the need for antibiotics, decreasing the risk of antibiotic resistance. Besides, the laminarin in seaweed can be used as to enhance artificial fullness in humans, and in that way contribute to the fight against obesity, which is a huge cost for society.

One ecosystem service provided by the cultivation of lower trophic species was deemed relevant for both the categories government-to-business and business-to-business, which was sequestration from seaweed farming for various chemical elements such as carbon, nitrogen, phosphorous and other minerals. Farmed seaweed biomass is considered to have added value by offsetting and mitigating emissions and effluents from industrial farming activities on land and at sea.

In the category business-business, the following benefits were mentioned by the participants. The bottom structures created by farms cultivating lower trophic species provide a habitat for other valuable fisheries species (e.g. lobsters and crabs). Rather than have a collection of monoculture systems, Integrated Multi Trophic Aquaculture (IMTA) designed for a range of specific products (e.g. oysters, seaweeds, lobsters, mussels, abalone, sea urchins etc.) can also support the myriad of marine flora and fauna that undertake the regulatory functions performed by reef ecosystems and enable the ecosystem aquaculture systems to perform in a circular economy concept. For example, seaweed farms can function as a supportive system for ocean-based aquaculture – assuming multi-role functions including natural lice shield, wave damping, water filtration, nutrient and carbon offsetting. Both oysters and mussels are efficient filter feeders that process large volumes of seawater and are able to capture free living pathogens in the water column, thereby helping fish farmers address challenges in the growth cycle. Shellfish farmers working in concert with finfish farmers in this context is a good example of IMTA related synergies. Lastly, it was argued that oysters farming can play a role in scour protection for offshore wind farms.

In the category business - consumer the following benefit was mentioned by the participants: consumers would obtain a greater utility per unit, similar to “organic” vegetables, from items that have greater sustainability and planetary care credentials.

3.2. Results round 2: from 29 ideas to 8 mechanisms

In the second round, the participants were asked to add ideas for capitalization to the list of ideas resulting from round 1 and provide reflections on the strengths and barriers of these mechanisms. As the collection of strengths and barriers was an iterative process, the participants were given the opportunity to revise and reflect on their answers and the answers of others in the third round. The results of this are therefore presented in the next section. In total, the participants

Table 3
29 ideas for capitalization.

Category	Idea for capitalization
Government to business	1. Tax-payer funded payment for nitrogen and phosphorus uptake upon biomass harvest
	2. Carbon offset programs cultivated seaweed for carbon capture and removal and for reduced ocean acidification
	3. Phosphorus pricing mechanism
	4. Subsidy for farmers who use seaweeds in their animal diets
	5. Habitat tax for area access (licensed access)
	6. Habitat tax: payment for compensation (for fishing in seaweed cultivation areas
	7. Biodiversity offset credit (tradeable certificate)
	8. Tax on negative impact of natural resources (habitat tax; or Ecosystem Tax?)
	9. Habitat tax for area access (all negative activities)
	10. Subsidy for business improvements when space is co-located with other uses
	11. Payments into a fund for compensation
	12. Public (shared) infrastructure plan (co-locations seaweed and wind/fish farms)
	13. Co-locations legal framework; risk mitigating guarantees (financial, liability) for large volume and low cost solutions
	14. Offset credit regulation (tradeable certificate) biodiversity (requirements for compensating N&P emission with uptake)
	15. Governmental mariculture licenses with a finite period: offshore licenses aquaculture only to operators that are either prepared to move offshore and retire inshore licenses or to operators who purchase inshore licenses and retire them
	16. Subsidy for healthy products: i.e. sea-based products with proven positive health effects
	17. Subsidy to seaweed farmers (lower priced than unhealthy alternatives)
	18. Ecosystem Tax: capitalized through the market price of the product
	19. Enabling legislation to allow multi-species / trophic aquaculture (sustainability demands, targeting species that improve water quality)
	20. Offset credits for ecosystem benefits (biodiversity, ecology)
Business to business	21. Payment for nutrient uptake through offsetting scheme where permission to emit is based on a compensation framework
	22. Private sector payed credits (carbon, nitrogen, biodiversity
	23. Cost sharing or payments between fishing companies and seaweed farms to fish in more productive localities near seaweed farms
	24. Biodiversity credits: species or ecosystem oriented
	25. Re-invent aquaculture and grow a range of species by taking an ecosystem approach
	26. Payment for scour protection by offshore wind farm sector
Business to consumer	27. Business promotion: ecosystem & climate friendly products
	28. Pilot scale R&D driven by "green" investments; crowd sourcing
	29. Marketing systems to promote ecosystem friendly aquaculture

delivered 29 ideas for mechanisms for capitalization, which are briefly summarised in Table 3.

To advance the discussion on these ideas, expert assessment by the project team was used to group the 29 ideas into 8 distinct mechanisms. Table 4 summarizes this grouping, illustrating prevalence of tradeable credits and benefits sharing among ideas provided. Two ideas could not be grouped with others: taxes on ecosystem damage and reinvent aquaculture. In both cases the link to ecosystem services provided was not clear and these have been omitted from the subsequent analysis.

3.3. Round 3: six mechanisms for capitalization

The third round consisted of the evaluation of six distinct mechanisms for capitalization of ecosystem services. First, participants were asked to rank the feasibility of these mechanisms. Then, input on the strengths, barriers and implementation was given. The results of this are summarized in the following sections.

Table 4
grouping of ideas into 8 mechanisms.

8 mechanisms	Grouping of ideas (see table 3)
Tax-payer funded payment for ecosystem services	1, 2, 3, 8
Tradeable credits for ecosystem services	7, 14, 20, 21, 22, 24
Taxes on ecosystem damage and other negative impacts	18
Subsidy for positive impacts	4, 16, 17, 19
Improved license to produce (regulation included)	10, 13, 15
Sharing the costs of production among different beneficiaries (e.g. fisheries or offshore wind)	5, 6, 9, 11, 12, 23, 26
Increasing value for consumer resulting in higher prices, through e.g. labelling	27, 28, 29
Reinvent aquaculture	25

3.4. Ranking of feasibility

Participants were asked to rank the feasibility of the mechanisms from 1 to 6, 1 being most feasible and 6 least feasible. The results are shown in Table 5 below. The deviation in ranking the mechanisms is clearly visible. While option 6 is slight higher ranked than the others, the other 5 mechanisms still receive an average score between 3.2 and 3.6. Therefore, there is no clear consensus on which is the most feasible mechanisms, nor are there any mechanisms that are clearly deemed unfeasible.

In the second and third round, participants were given the opportunity to reflect on the strengths, barriers and implementation of the mechanisms. The following sections discuss the results of this consultation per mechanism, in order of the feasibility as indicated by the participants (see Table 5).

3.5. Increasing value for consumers

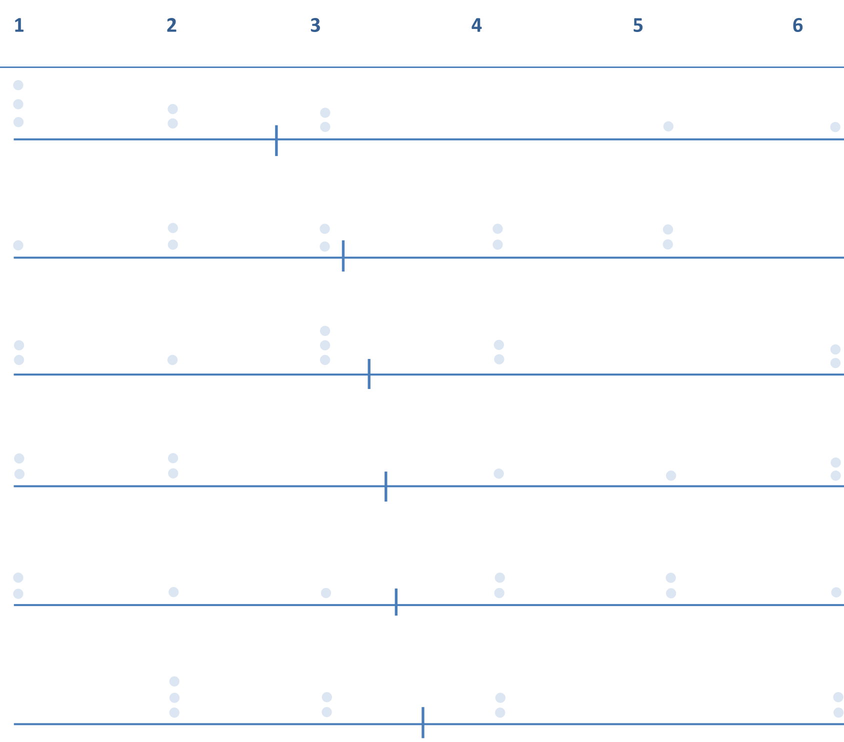
The value of ecosystem services is capitalized as the increased utility for consumer that leads to higher prices being paid for the products. This would require consumer awareness of the provision and importance of ecosystem services provided, created by for example eco-labelling. Such a mechanism can be applied to all ecosystem services which are important to consumers. The strength of this mechanism is that labels already exist and are a well-proven concept (i.e. MSC, Rainforest Alliance, Organic labels) that align with emerging international trends (e.g. the United Nations Sustainable Development Goals). As such, there is less need for education and development of public and consumer acceptance. Eco-labelling can also be an opportunity to generate capital from investment schemes (especially philanthropy) to expand production and certification of lower trophic species. In this mechanism, consumers pay the costs via price premiums on final products.

Potential barriers of this mechanism are that the implementation requires strong marketing campaigns to advertise the benefits of the products in order to justify a higher price, as well as providing the necessary information to the public on good and bad aquaculture practices. The final products may be perceived by consumers as elitist or high-end, which could hinder wide adoption. Moreover, changes in consumer behaviour are difficult to achieve, as seen in for example organic farming, reducing meat consumption and changing air travel habits.

To implement this mechanism, marketing systems to promote ecosystem friendly aquaculture are needed, which includes stronger pressure from NGOs to move in this direction. Educating the public on the benefits from aquaculture of lower trophic species, and demonstrating how artificial systems can be used to move pressure from coastal systems, could help create public awareness. Eco-labelling organisations should work with scientists and industry to ensure labels have the

Table 5
Ranking of feasibility of mechanisms.

Mechanism	Ranking (1 2 3 4 5 6)	
Increasing value for consumers		2,7
Tradeable credits for ecosystem services		3,2
Creating a social license to produce		3,3
Subsidy for positive impacts		3,4
Tax-payer funded payment for ecosystem services		3,4
Sharing the costs of production among beneficiaries		3,6



desired effect and are credible. NGOs or independent parties should take the role of providing support for labels or issue the label. There can be concerns about the validity of claims made. Therefore. industry will need to push government and NGOs to prevent false advertising or misinformation, and stakeholders should agree on an independent body responsible for the monitoring and regulation of labels. A credible mediator outside of industry and government may be needed to oversee that information and educational schemes provide fair and transparent information to avoid misleading or consumer deceiving behaviour. This mechanism would benefit from policies that require aquaculture producers to label the environmental footprint of their production (and along supply chains).

3.6. Tradeable credits for ecosystem services

Tradeable credits for ecosystem services can be traded business-to-business when companies need extra nitrogen credits to expand production, such as the Maryland Credit Generation for Oyster Aquaculture.[1] The extractive species (e.g. seaweeds, mussels, oysters etc.) can capture or remove particles and nutrients from the water, improving water quality. Seaweed farming then creates new biomass that sequesters carbon, nitrogen, phosphorous and other minerals. This can potentially replace the harvesting of natural kelp forests, while at the same time, offset and mitigate emissions and effluents from industrial farming activities on land and at sea. Improving public understanding of what ecosystem services are will help promote the acceptance of ecosystem service enhancing farming systems. There are parallel examples from forestry (Carton and Andersson 2017) and mangroves (Thompson, Primavera, and Friess 2017). The mechanisms can be supported by the industry itself.

The participants consider the implementation of this type of trading mechanism challenging. It could be viewed as allowing one sector to 'pollute', i.e. to be compensated, by another sector. Tradeable credits enable the trade-off between positive outcomes (increased ecosystem services) in one place against negative outcomes (degraded ecosystem services) in another. A more comprehensive environmental goal would be for all sectors to minimise their footprints. Nevertheless, the mechanism does provide an avenue for internalising negative externalities, and in doing so, make polluting economically unaffordable for inefficient firms. The other challenge is that quantification of services provided is likely to be controversial; quantification of true sequestration and not just uptake, is essential for legitimacy. It is a risk that, if creating valuable credits, lower trophic species aquaculture will become too intensive, increasing the risk that the marine ecosystem will be overexploited. Negative effects include for example reduced availability of nutrients for phytoplankton and shading of the sea floor.

The implementation requires a regulatory framework that allows for business-to-business transactions; an exchange market for credits could then be created. Regulators should set up the framework and monitor performance. Such a framework must enable farmers, fishers and industry to manage biodiversity assets and risks, with independent brokers involved in the transactions. Community support and pressure are necessary to push both governments and business to prioritise sustainable growth agendas. NGOs could ensure the validity of the system and help governments to ensure credibility, also by being critical to the implementation. Eventually, consensus must be reached on how services are quantified, monetarised and in general put to work.

[1] https://mde.maryland.gov/programs/Water/WQT/Documents/Guidance%20PDFs/Oyster%20Aquaculture_FAQ.pdf

3.7. Creating a social license to produce

There are currently strong societal sentiments against offshore wind energy and aquaculture. Social resistance can hamper further development of these sectors. Under this mechanism, the production of lower trophic species is supported to overcome the negative sentiments. This can include supportive regulation to enable co-location of aquaculture in offshore wind farms or the production of lower trophic species as an alternative to using natural coastal systems for seafood production. Increased support from governments and NGOs can contribute to the development of new aquaculture systems that deliver positive benefits and that take the pressure off of inshore systems.

When integrating lower tropic species aquaculture in offshore wind farms, it is not clear what the mutual benefits are for aquaculture on the one hand and the wind farms on the other hand. In addition, another potential barrier could be that integration may lower the chance of successful operations of the sectors concerned (Steins et al. 2021). The financial viability of producing lower trophic species may not be equivalent to monoculture of higher trophic species and thus an additional mechanism needs to be put in place to encourage a shift to these culture systems. There is here the danger of the 'Valley of Death' of technology/product development, where new solutions are unable to reach a market due to insufficient incentives.

To implement this mechanism, the feasibility of integration should be tested and subsidised if needed to compensate for any economic losses of integration relative to monoculture. Synergies should be investigated for benefit maximising solutions, supported by necessary monitoring and reporting structures. Transparency is here key to justify investments and create support. Governments may need to compensate for the extra risks of the integration, finance initial prototype developments and implement regulations and/or legislations to facilitate co-location. Stakeholders should be involved all stages of the process, and agree on regulatory framework and how the application is monitored. NGOs could add quality by a critical engagement in the monitoring en improvement of issues like co-use of space at sea, sustainable farming practices. Lastly, a broad consultation could add quality to both the legal framework and business practises.

3.8. Pigouvian subsidy for positive impacts

Encouragement through subsidies can be provided to the users of lower trophic species, justified by the societal benefits brought about by using them. The use of low trophic species in aquaculture, agriculture and food production has demonstrated positive effects on the gut system of animals and humans. Adding seaweed extract to the diet of ruminant animals can reduce methane emissions. Seaweed is also shown to strengthen the immune systems of both land and marine animals farmed, reducing the need for antibiotics and in turn, decreasing the risk of antibiotic resistance passed down to human consumption. And laminarin in seaweed can be used to create artificial fullness in humans, contributing to the fight against obesity, which is a huge cost for society. Subsidies on healthier or more sustainable sea-products could encourage consumers to change through lower prices. A strength of this mechanism is that subsidies can be given temporary; market actors can take over once a market is created. It is however important to be aware of negative impacts, such as adverse effects of bromides when adding seaweed to feed (Abbott et al. 2020). A point brought forward is also that a subsidy is hardly enough to change behaviour as eating patterns, just like other habits, are the outcome of long-standing cultural or household habits and hard to change.

The implementation of this mechanism requires science based documentation on the positive effects of consuming lower trophic animals and plants. Eco-labelling companies should work with scientists and industry to ensure that labels have the desired effect and remain credible, with NGOs or independent parties taking the role of providing support for labels or issuing them (e.g. the Aquaculture Stewardship Council, VeriFlora, Fair Trade Certified etc.). Stronger pressure from NGOs and environmental lobbyists in this direction are deemed necessary. Efforts to implement labelling, e.g. with respect to the environmental footprint of products (and supply chains) can ease the implementation. An external independent organization is needed to oversee that information and educational schemes provide fair, transparent and accurate information to avoid misunderstanding about the cultivation of lower trophic species. Moreover, the implementation of this mechanism requires governments not only to recognize that certain food products are more healthy but also subsidize those.

3.9. Tax-payer funded payment for ecosystem services

Producers of lower trophic species can be paid for the ecosystem services provided through general taxes collected from consumers or businesses. Tax-payer funded payment for ecosystem services is deemed relevant for sequestration of carbon, nitrogen, phosphorous and other minerals by lower-trophic species. This mechanism can also enrich the ecosystem by making it more biodiverse by creating a new biotope. Tax-payer funded payment for ecosystem is not considered to be very costly, and politically not so hard to achieve. A substantial effect is expected for nitrogen and phosphorus sequestration and these effects are considered easy to measure. One of the main barriers to implementation is funding, which would require a long-term, enduring structure essential to drive investments. In addition, the experiences with carbon credits illustrate that prices for (carbon) sequestration can be too low to compensate for the production costs, rendering the mechanism ineffective. To have lasting effects net negative emissions are required, and this is a challenge if the production of lower trophic species only lead to short term storage of carbon and/or nutrients. Last, agreement is needed on how to measure the sequestered content; on the conditions for the use of biomass to ensure that nutrients are removed from the marine environment for the long-term, and on the monetarised valuation of nutrients sequestered or biodiversity effects realised.

All the elements above contribute to the acceptance, or a sense of fairness, of the taxes paid by the emitting industry. A part of the tax revenues could also be used for the mitigation of emissions (e.g. paid to seaweed cultivators). Regulations for payment for carbon captured by low trophic species can be implemented within existing carbon credit programs and other nutrient trading programs.

3.10. Sharing the costs of production among beneficiaries

In this mechanism, the cost of producing lower trophic species are partially paid for by other beneficiaries of ecosystem services provided. Cost-sharing can be between businesses or via targeted Pigouvian taxes. This mechanism can be applied to the benefits that one industry or sector receives from another. For example, fisheries have the potential of benefiting from seaweed cultivation due to an enriched or more biodiverse ecosystem resulting from habitat support services (incl. provision of nursery grounds and better predator protection) provided by seaweed cultivation. Therefore, taxes could be applied to the relevant commercial species fishery to allow for the sharing of cost for seaweed cultivation. This is a market-driven mechanism, and could run on its own with limited government intervention.

Government support is likely needed, according to the respondents, to initiative the mechanism and establish rules for ecosystem services delivered. But the regulatory rules for cost-sharing are not well developed, as well as insurance and finance support. Cost-sharing is complex and risky and will require experience and trust that takes time to build. If Pigouvian taxes are used to facilitate cost-sharing, taxes would be imposed on fishing companies. Open dialogue and discussions on different compensation schemes are required, as the fisheries sector is likely to be against new taxes. Government could provide seed funding for risk modelling in collaboration with financial and insurance companies. Effective engagement and consultation between other users of the sea, government, co-location industries and NGOs are necessary to ensure equitable and just development. NGOs should be brought in to understand the operation, address concerns and help the aquaculture industry to validate the business model.

3.11. Actions needed for the implementation

The respondents identified a number of action needed to implement the mechanisms described above. Five actions can be distinguished that span across multiple mechanisms (see Table 6 below).

1. The need for a better understanding and science-based quantitative assessment of ecosystem services provided, be it nutrient uptake, biodiversity enhancement or the many other services
2. Building a relationship with existing credit programs
3. Strong pressure from governments and NGOs to develop and implement the mechanisms and to provide political and societal support for them
4. Independent validation, possibly in the form of external certification and research, of claims made on ecosystem services provided
5. The establishment of a supportive regulatory framework

3.12. Actors needed for implementation

Participants were asked which actors should be involved in the implementation of each mechanisms. The results are summarized Table 7.

Table 6 shows that the respondents point to three stakeholders groups that are always necessary to involve, irrespective of the mechanisms: government, the lower trophic species farmers and NGOs. The scientific community is deemed relevant for 5 out of 6 mechanisms. It is also notable that no mechanism requires less than 5 groups of stakeholders. In addition, the general public, emitting industries and financial institutions are hardly seen as being needed.

4. Discussion

This study set out to identify and evaluate mechanisms to attribute an actual market value to ecosystem services provided by the cultivation of lower trophic marine species and to reward the primary producers. The discussion on the mechanisms, and the actions and actors need to implement these mechanisms, points to some overarching concerns.

4.1. Increasing value for costumers: engagement from the whole value chain

Certificates and labels might legitimise higher prices for lower trophic species and this has been brought forward by the respondents as the most feasible option. As pointed out by Brayden et al (2018), as a market-based method of altering consumer behaviour, labels can also promote sustainable practices and increase product value. Labelling can create more awareness and push quality demands, but consumer behaviour is hard to change. The process of certification puts a spotlight on the production processes involved and as such it might help to acknowledge the ecosystem services provided. Respondents also state that it is a process that demands involvement of many stakeholders; governments, farmers/businesses, retail, NGOs and local communities. Triggering such involvement from the whole value chain is then important for the further development.

4.2. Benefits are attractive but hard to prove

It is not hard to point out benefits from lower trophic aquaculture, but it is challenging to quantify the ecosystem services provided. These are at times estimated by a simple multiplicative extrapolation from the individual organism to the ecosystem level, an estimation that oversimplifies the role of the species in question in the ecosystem. Ideally the impact on the entire community would need to be established, and not just for one single species (Lejart et al. 2012; Waldbusser et al. 2013). Moreover, ecosystem services are often interrelated, and well established weighing mechanisms between positive and negative contributions depend on scale, ecosystem type, ecosystem use, and other related activities. Scaling these numbers up from the individual to the ecosystem level is not a trivial task, yet proving benefits at a relevant scale is vital to legitimize tax-payer funded payments and to create a social license to produce. It is important to select indicators and metric units that bridge ecological complexity with the information needed to assess and access the specific economic market in question in terms of price, quantity, quality and provided number of ecosystem services.

4.3. Trustworthy monitoring and accounting systems are needed

The independent validation of mechanisms like certificated labels for increasing consumer value, ecosystem services payment schemes and tradeable credits requires a monitoring and accounting system that is transparently providing insights into the number of services provided and their economic values, and the allocation of services to an activity. This calls for a system of monitoring that is more systemic and comparable from one location to another. There is the question of responsibility for setting up such a monitoring system, with either government or independent third parties being considered. The complexity of the environmental system requires well defined monitoring indicators to achieve a tailor made monitoring approach. Without such a monitoring system, we might be left with too many and fragmented types of monitoring schemes with limited transparency. Uncertain and controversial valuations would be a threat to the implementation of payment mechanisms. There is no scientific consensus on the approaches to take into account. For example, four different options are available for mussels (Ray et al. 2018; Munari, Rossetti, and Mistri 2013); Tang et al. 2011).

4.4. Tradable credits not yet common

International carbon credits represent a financial mechanism to

Table 6
Actions needed for implementation.

Mechanism	Quantitative assessment	Relationship with existing credit programs	Stronger pressure from government and NGO	Independent validation	Supportive regulatory framework
Tax-payer funded payment for ecosystem services	X	X			
Tradeable credits for ecosystem services	X	x	X		X
Subsidy for positive impacts			X	X	
Support through regulation, creating a social license to produce	X		X		X
Sharing the costs of production among different beneficiaries			X	X	X
Increasing value for consumers			x	X	X

Table 7
Summary of stakeholders needed.

Mechanism	Government	Lower trophic species farmers	NGO	Science	Communities	Independent authority	Retail	Food authority	General public	Emitting businesses	Financial institutions
Tax-payer funded payment for ecosystem services	x	x	x						x	x	
Tradeable credits for ecosystem services	x	x	x	x		x					
Subsidy for positive impacts	x	x	x	x	X	x	x	x			
Support through regulation, creating a social license to produce	x	x	x	x							x
Sharing the costs of production among different beneficiaries	x	x	x	x	x						
Increasing value for consumers	x	x	x	x	x	x	x	x			

reduce CO_2 concentration in the atmosphere. A carbon credit is equal to an amount of carbon which is reduced or removed from the atmosphere. To obtain credits, industrialised countries invest in carbon reduction programs in developing countries or projects in other industrialised countries. Carbon offsetting — receiving credit for reducing, avoiding, or sequestering carbon — has become part of the portfolio of solutions to mitigate carbon emissions, and thus climate change, through policy and voluntary markets, primarily by land-based re- or afforestation and preservation. Nevertheless, it is not yet common for marine ecosystems, i.e. blue carbon (Froehlich et al. 2019).

The Wetlands Supplement of IPCC provides methodological guidance for estimating anthropogenic greenhouse gas emissions (CO_2, CH_4, N_2O) and removals from wetlands, coastal wetlands, tidal marshes, seagrass meadows and constructed wetlands for wastewater. The emission factors for each greenhouse gas are surrounded by many scientific uncertainties and different for mentioned ecosystems. A robust verification system for wetlands and open water is still in its infancy in many European Union (EU) countries, and there are considerable differences between countries.

Carbon offset projects on land have a monetary value of around 5€/ton CO_2-eq according to Hamrick and Gallant (2018). At this carbon price, and the current realized carbon sequestration, the potential benefits for land owners are approximately 30-120€/ha/year (Veraart et al. 2019). These benefits are, in general, not enough stimulant for entrepreneurs to invest in carbon sequestration measures. Furthermore, carbon credits could be seen as an advance *payment* based on the sequestered carbon in the future. On the basis of progressing scientific insights, it may appear in future that more or less greenhouse gases have been sequestered than assumed at the moment the carbon credit payment was issued.

Carbon sequestration from new biomass produce currently gets significant attention in the scientific community (Duarte et al. 2017). However, the majority of this new biomass is part of the short carbon cycle and the sequestered carbon soon become biological available again via decomposition as dissolved organic matters. Different theories to calculate the contribution to carbon sequestration are described, such as accounting for carbon in the long carbon chain, or accounting for the life span of alternative products. Leakage of carbon can occur when carbon is being transferred between trophic stages in the biological food web, for instance by grazing or predation (Velthuis et al. 2018). In natural systems, a small but relevant fraction is transformed by microbes to more stable organic molecules that may remain in the water column for hundreds or thousands of years, also referred to as recalcitrant dissolved organic carbon (RDOC), resulting in sequestration within the long carbon cycle (Krause-Jensen et al. 2018). The introduction of aquaculture (e.g. seaweed farming) into a natural marine ecosystem adds more complexity to carbon fixation as it is eventually harvested.

4.5. *Limits to the methodology*

The Delphi method was applied to use the knowledge of a variety of stakeholders. Limitations to this method lie in the selection of experts and their varying background and experiences. Given the explorative character of the study, the limited number of participants does not negatively impact on the results achieved. A critical methodological question is whether or not all respondents had a shared understanding of what was asked of them. In our study design, we have communicated consistently on the objectives and next step in the process. Respondents do have very different backgrounds. In particular, the study could have benefitted from respondents in Asia, being the most important continent in terms of production volumes. Lastly, there is a risk that the respondents emphasize benefits of lower trophic species for which a meagre scientific base exists. Their status as scientists should prevent such input but they are free to bring to table what they want, although they are 'steered' by the type of questioning. Scientific uncertainties also exists in relation to carbon sequestration potential (Duarte et al., 2017) and reduction of methane emissions by ruminants through addition of seaweed to feed (Muizelaar et al., 2021).

5. Conclusion

Cultivation and use of lower trophic species comes with expected societal benefits, including carbon and nitrogen sequestration, ecosystems recovery and much more. The economic feasibility of lower trophic marine species aquaculture is often a critical issue. The objective of this explorative study was to identify and evaluate mechanisms that can help realize actual payment for ecosystem services provided, in support of the business case for aquaculture of these species. The Delphi method was applied to collect input from experts across the globe. Six potential mechanisms for payment for marine ecosystems services were identified and evaluated:

1. Tax-payer funded payment for ecosystem services
2. Tradeable credits for ecosystem services
3. Pigouvian subsidy for positive impacts
4. Creating a social license to produce
5. Sharing the costs of production among beneficiaries
6. Increased utility for consumers

The valuation of ecosystem services has been on the agenda for a long time, as pointed out by Acharaya et al. (2019), but work on valuations has increased considerably in the past two decades. The question is to what extent science can drive valuations towards consensus. Eventually it is a policy choice, but science must play an active role in the collection and analysis of data. An active engagement of a broader group of societal stakeholders and certification schemes would be beneficial for the enduring support needed.

A number of barriers to the implementation of these mechanisms remain, including the lack of understanding and consensus on the method for quantification of ecosystem services provided, inadequate regulatory framework and lack of independent validation. The general interest and consensus on the achievability of mechanisms for payment provides justification for further development of knowledge, regulations, and political and societal support to advance them. Drawing upon the results of this study and lessons learned in the carbon market, the following actions are considered priority:

- Create a solid, science-based understanding of the quantity of ecosystem services provided by mussels, oysters and seaweeds
- Establish sound monitoring indicators to support quantification of ecosystem services
- Liaise with relevant existing credit trading schemes and include mussels, oysters and seaweeds as a part of the carbon market and nitrogen trading
- Establish a governance structure, including independent check-and-balances, to secure long-term societal trust in payment for marine ecosystem services

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sander van den Burg reports financial support was provided by Ministry of Agriculture Nature and Food Safety.

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