Deliverable No. 6.2

Project acronym:

AquaVitae

Project title:

New species, processes and products contributing to increased production and improved sustainability in emerging low trophic, and existing low and high trophic aquaculture value chains in the Atlantic

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Deliverable D6.2

Quantification of Ecosystem Services

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Executive summary

The achievement of sustainable aquaculture requires consideration of the positive and negative impacts of aquaculture on the environment, economy, and society. The identification and quantification of the ecosystem services (ES) derived from LTS aquaculture can provide useful information to support a rigorous sustainability assessment of the three sustainability dimensions. Nature's Contributions to People (NCP) is a novel framework for ES, defined as all the contributions (positive and negative) of nature to people's quality of life, and include the role that humans play in the co-production of benefits from nature. Consequently, this definition fits the scope of AV better than the classical ES approach, and was therefore selected as the framework for valuation of ES as part of the sustainability analysis of Low-trophic Species (LTS) aquaculture in the Atlantic Region. Deliverable (D) 6.2 specifically aims to identify and quantify the NCPs provided by LTS aquaculture, based on the case studies (CS) investigated within AV.

The work in D6.2 was deconstructed into four sub-tasks: i) identification of the NCPs provided by LTS (based on the CS investigated within AV) and of current knowledge gaps in terms of qualitative contributions of LTS aquaculture to the NCPs using expert judgements and literature; ii) selection of specific CS to be included in the evaluation of NCPs provided by LTS aquaculture based on the number of identified NCPs and overall knowledge level (OKL) estimated based on the data quality scoring for the identified NCPs in the previous step; iii) selection of indicators for NCPs quantification based on the framework developed in task 6.1 in WP6 (D6.1, appendix B); and iv) quantification and analysis of selected NCPs using the most appropriate valuation method for each indicator using data from CSs within AV and literature reviews.

Overall, a relatively high number of NCPs were identified and confirmed for all CSs assessed. The highest number of identified NCPs was reported for *CS4 Sea-based IMTA* and *CS9 Mussels*, both with 15 identified NCPs out of 18, followed by *CS2 Offshore macroalgae and CS8 Oysters* both with 14 identified NCPs, and two land-based systems, *CS1 New macroalgae species* (13 NCPs) and *CS3 Land-based IMTA* (11 NCPs). The lowest number of identified NCPs was reported for *CS6 Sea urchins* with 9 identified NCPs, which may be explained by the immaturity of this industry compared to other more established LTS aquaculture industries. Based on defined selection criteria, the CSs *Offshore kelp production*, *Land-based IMTA*, *Oysters*, and *Mussels* were selected for the subsequent NCP analysis and quantification.

The indicators *Nutrient cycling* and *Eutrophication index* were used for the quantification of the NCP *Regulation of coastal water quality*, the *carbon footprint* was used to estimate the NCP Regulation *of climate*, the *Ocean acidification index* indicator was applied to estimate the NCP *Regulation of ocean acidification*, and food and feed production were used for the NCP *Food and feed provision.* The performance of the selected LTS aquaculture systems was subsequently analysed and quantified using the selected indicators and NCPs, and the results were compared to each other, and to other common food production systems. Of the LTS evaluated in this report, sugar kelp production showed lower eutrophication mitigation potential than mussels and oysters and had a much lower farm-gate price compared to oysters and abalone, yet was found to be the only LTS to counteract ocean acidification. Bivalve production (mussel and oyster culture), on the other hand, was found to have a significant bioremediation capacity, with mussels displaying a higher capacity compared to all organism groups in this report. Compared to mussels, oysters obtained a higher farm-gate price, but also demonstrated a higher ocean acidification index, and the highest carbon footprint per unit of food produced among all

LTS culture systems studied. In comparison, most mussel production systems had a lower ocean acidification index and a lower total carbon footprint per unit of food produced, than abalone and oysters. Abalone was the only LTS production system that showed a net release of nutrients, its ocean acidification index was set at the mid-range of values reported for oysters and at the upper range for mussels, and its carbon footprint per unit of food was similar to the higher values reported for mussels, while its farm-gate-price was considerably higher and only comparable to premium price oysters from Northern Europe. In terms of the total carbon footprint, mussels and abalone were found to have the lowest CF of the included LTS production systems, equivalent to primary producers, oysters were found to be comparable to poultry and pig meat, but lower than e.g., lamb, beef, or other farmed marine species (e.g., fish and prawns), while sugar kelp had a residual carbon footprint and consequently may support climate change mitigation. It should be noted that all mussels, abalone, and even oysters may also indirectly support climate change mitigation e.g., by replacing other meat products. However, analysis of indirect effects of LTS aquaculture on the combined CF of food production around the Atlantic is not included in the scope of this report.

The quantification identified significant contributions to society, e.g., in terms of NCP *Regulation of coastal water quality*, as well as sustainable feed and food. Some disservices were also identified, e.g., linked to the NCP *Regulation of climate* as the carbon footprint of bivalve culture was found to be in line with other traditional food sources, but generally lower than other meat products. In view of these results, a well-planned expansion of macroalgae and shellfish aquaculture together with campaigns that promote the consumption of these products over other meat products may contribute to cover the increasing demand for food in the world while mitigating eutrophication effects and reducing the current contribution of food production systems to the global GHG emissions. This includes developing context-dependent recommendations for expansion of LTS aquaculture where regional differences related to species and system performance are accounted for. The results will be integrated in the upcoming sustainability analysis of LTS aquaculture (D6.3 in WP6) and will form the basis for the subsequent economic valuation of marine ecosystem services linked to LTS aquaculture (D7.5 in WP7). Finally, in D6.2, knowledge gaps related to the link between some NCPs and LTS aquaculture, and identified data deficiencies are highlighted to support future research needs in this field.

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Acronyms Table (Abbreviations)

AD: Assessment domain
AV: AquaVitae
B-CF: Biological carbon footprint
B-CO_2: Biological carbon dioxide budget (acidification index)
CICES: Common International Classification of Ecosystem Services (CICES) V5.1
CIIMAR: Interdisciplinary Centre of Marine and Environmental Research
CF: Carbon footprint
CS: Case study
ES: Ecosystem services
FW: Fresh weight
IMTA: Integrated multi-trophic aquaculture
IRG: Industry reference group
IPBES: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
LTS: Low Trophic Species
MA: Millennium Ecosystem Assessment
ME: Matrix elements. The organism groups and production modes included in the mapping of the interconnection between the NCPs and LTS aquaculture.
N: Nitrogen
NA: Not applicable
NCP: Nature's Contributions to People
O-CF: Operations carbon footprint
OKL: Overall knowledge level
P: Phosphorous
SA: South Africa
TEEB: The Economics of Ecosystems and Biodiversity
TEV: Total Economic Value
VC: Value Chain
WP: Work Package

1. Introduction

1.1. Scope of AquaVitae Project and Deliverable 6.2

AquaVitae (AV) is a research and innovation project funded by the EU's Horizon 2020 program. AV's overall objective is to introduce new, and expand existing, low trophic species (LTS) products and processes to marine aquaculture value chains across the Atlantic. The value chains that AV focuses on include macroalgae, integrated multi-trophic aquaculture, echinoderms, underutilized shellfish species and low trophic finfish species. Moreover, AV includes analysis of value chains, market development and profitability, and other biological and socioeconomic aspects, including sustainability, environmental monitoring, and risk assessment of LTS. The achievement of sustainable aquaculture requires consideration of the positive and negative impacts of aquaculture on the environment, economy, and society. The identification and quantification of the Ecosystem Services (ES) derived from LTS aquaculture can provide useful information to support a rigorous sustainability assessment of the three sustainability dimensions. Consequently, ES analysis is proposed in the AV project as part of the sustainability analysis undertaken in Work Package (WP) 6, with the specific aim to identify and quantify ES provided by LTS as a basis for a forthcoming sustainability analysis. The indicators selected in WP6 Task 6.1 (D6.1, Appendix B) were used as a basis for the work and specific LTS value chains were selected for analysis. One part of the work was also to identify knowledge gaps in terms of what ES LTS aquaculture supports, and what data was missing for quantification of the services provided.

1.2. Production of good and services from Low Trophic Species Aquaculture

Sustainable development is a complex endeavour, and identification and assessment of sustainability objectives consequently needs to be holistic in order to consider all aspects that may support or act against the identified objectives. As a result, sustainability assessment should include key environmental, economic, and social impacts of an activity. In this sense, the ES concept – the goods and benefits humans obtain from the interaction with nature – aims to address the constituents of human well-being in an integrated manner and can therefore be useful for a complex task such as sustainability assessment. In this concept, the holistic and interdisciplinary emphasis is present through the integration of ecological, economic, and socio-cultural aspects, and as a result of the applicability of the concept to complex questions, several different definitions and frameworks for ES have been developed. These frameworks describe the benefits using different classifications, the perhaps most well-known and applied being provisioning services, regulating services, habitat or supporting services, and cultural services (Millennium Ecosystem Assessment, MA 2005).

As all food production systems, aquaculture needs a high degree of human intervention and infrastructure yet remains an interconnected part of the ecosystem in which it occurs. Some forms of aquaculture, e.g., bivalve and macroalgae aquaculture, even provide similar services as wild habitats, hence has the potential to compensate for valuable lost ecosystems (Alleway et al., 2019, Barret et al. 2022). Consequently, aquaculture can be considered not only a consumer of goods and services, but also a provider (Figure 1). This is especially true for LTS aquaculture, in particular for extractive culture (organisms such as mussels, oysters and macroalgae which depend on natural available sustenance, e.g., microalgae or nutrients). There are a number of publications describing the qualitative contribution of aquaculture to ES, e.g., Grabowski et al. (2012), Langton et al. (2019), Alleway et al. (2019), Schatte Olivier et al. (2020), Gentry et al. (2021), Mascorda Cabre et al. (2021), Theuerkauf et al. (2021) and The Nature Conservancy (2021). Extractive aquaculture can also be considered to be restorative when it provides net-positive environmental outcomes (Nature Conservancy 2021). The purpose of this report is not to provide a complete review of the ES provided by LTS. For this, please, refer to the above mentioned sources. The major contributions in these references are, however, sumarised below.

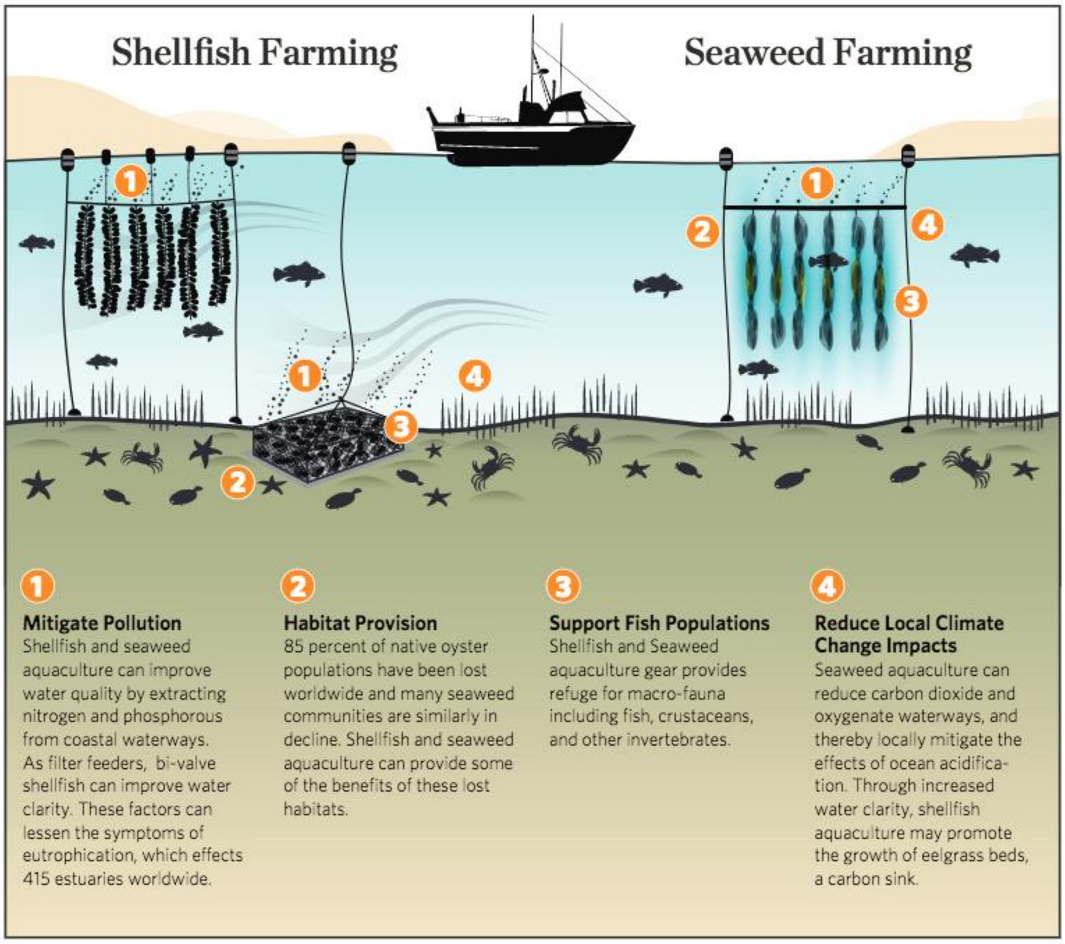

Figure 1. Examples of ecosystem services provided by shellfish and seaweed (macroalgae) aquaculture. Infographic from The Nature Conservancy[4]

A wide range of **regulating** services are associated with LTS aquaculture, e.g., carbon sequestration, nutrient cycling, assimilation and removal, water filtration, sediment stabilisation and the attenuation of wave energy. Filter-feeding organisms and algae have a major role in nutrient uptake through their extractive nature and can remove these elements, organic matter, and other particulates from the water, with significant effects both on water clarity and biogeochemical loops. The presence of surface-based culture structures may reduce waves and bottom based culture may stabilize sediment. The culture structures also contribute to **supporting** services by habitat creation and associated functions which results in increased biodiversity. Additionally, seafood constitutes an important food resource and brings a range of additional **provisioning** services in terms of feed, energy and raw materials. Finally, LTS are important parts of the activities and economies in coastal communities, with use

[4] https://www.nature.org/en-us/what-we-do/our-insights/perspectives/the-aquaculture-opportunity/ 2022-02-11

anchored in a historical perspective, hence LTS may support **cultural** identities, contribute to working waterfronts and associated occupation and cultural experiences related to tourism and recreation.

Although it is well known that LTS aquaculture can contribute to ES provisioning beyond the production of a resource or biomass, the extent and significance of these goods and services are still not well understood (Alleway et al., 2019; Gentry et al., 2020; Barret et al 2022). Quantification of benefits obtained from aquaculture is a key component to move the sector forward as these can be included as positive externalities in sustainability analysis, which in turn can be used to highlight the benefits, impact and development needs of aquaculture. Consequently, there is an urgent need for additional research to generate primary data on the positive and negative contributions of marine aquaculture in the biogeochemical cycles, habitats, and ecosystems of coastal oceans worldwide. Acknowledging and incorporating the values of ES into aquaculture studies and planning has the potential to improve environmental performance and sustainable management and to enable accurate recognition of social, economic, and ecological values of this sector. In this context, ES analysis is starting to be considered in the scope of various European-funded projects and integrated into sustainability assessments (Froehlich et al., 2019), combining the environmental, economic, and social dimensions.

1.3. The Nature Contributions to People Framework

Different ES frameworks have been built with the same core objective: to include nature and the interests of society into decision-making. The ES agenda aims to be inclusive, recognizing the diverse values of nature. However, a pluralistic way of bridging a wider understanding of nature and human interactions is necessary to ensure that any assessment supports the essential mission, i.e., sustainable development, and creates useful knowledge to enable movement towards a more prosperous, biologically rich, and fair (equitable) future for all.

Nature's Contributions to People (NCP) is a novel framework developed by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), and was approved by its General Assembly in 2018 (Díaz et al., 2018) as a wider and more inclusive framework rooted in the ES approach. NCP are defined as all the contributions (positive and negative) of nature to people's quality of life, and include the role that humans play in the co-production of benefits from nature. IPBES objective with this new framework is to integrate different cultures and perceptions regarding humans relations with nature to strengthen the holistic perspective needed in sustainable development. The aim is to achieve this through an enhanced science-policy interface for biodiversity and ecosystem services for the conservation and sustainable use of biodiversity, long-term human well-being and sustainable development. The framework consists of 18 broad categories that are not divided into the classical categories of supplying, regulating, provisioning and cultural. Instead, the NCP framework can be presented as three overlapping groups; m*aterial, non-material,* and r*egulating*, reflecting the fact that there is often fluidity within NCPs (Figure 2).

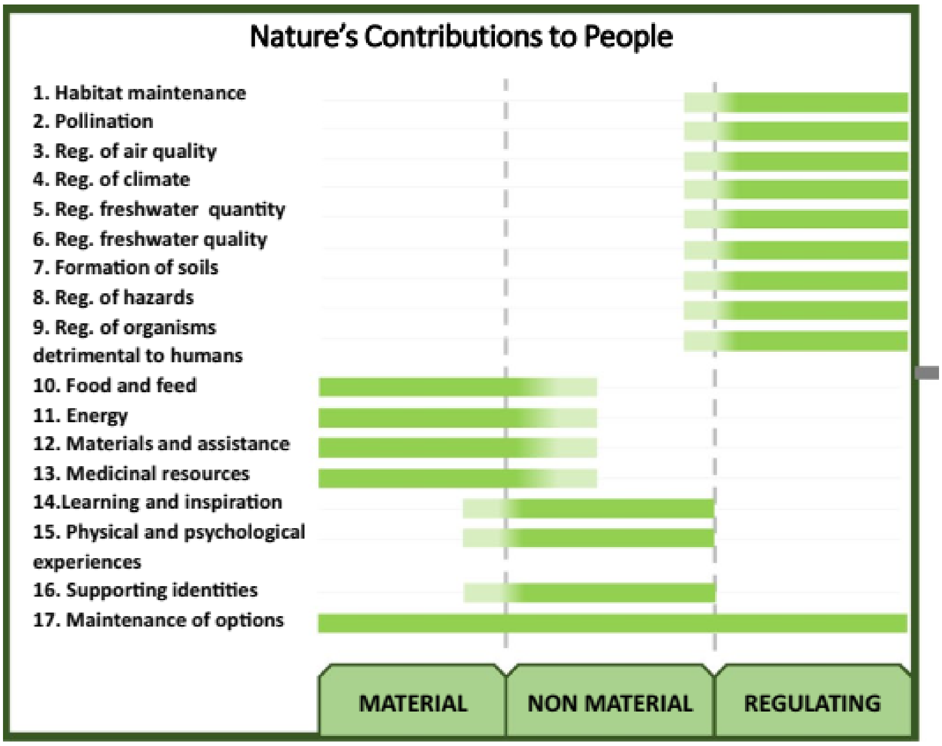

Figure 2. Nature´s Contributions to people grouped into three categories: material, non-material, and regulating. Most NCPs straddle across the categories of material, non-material, and regulating NCP. Figure adapted from Díaz et al. (2018) and (IPBES 2018) by Christie et al., (2019)

The notion of NCPs has arisen partly in response to challenges in the application of its main antecedent, the ES concept, when dealing with different cultural contexts. It has been argued that the ES framework is too narrow because it reduces social–natural relations to monetary values and market commodities and other non-use values of nature have often been neglected (Turnhout et al., 2013). In contrast to the ES framework where cultural ecosystem services are separated in an isolated category, culture permeates through and across all categories of the NCP framework.

Moreover, the ES concept is best suited to characterize the positive services, being the ones that lead to benefits to humans from nature, but it does not account directly for the non-beneficial outputs provided by nature as well, namely *disservices* (Dunn, 2010). NCPs are defined as '"all the positive contributions, losses or detriments, that people obtain from nature" to capture both beneficial and harmful effects of nature on people's quality of life (Pascual et al., 2017). Additionally, the NCP framework intends to better recognize the diverse worldviews of people and nature relations, in opposition to western-science dominated studies based on ES. Consequently, the NCP framework has been reported to provide novel conceptualizations of people and nature relations in terms of diversity, including socio-cultural references, contexts-specific perspectives and relational values (Kadykalo et al., 2019) by including indigenous and local knowledge and integrating positive and negative contributions of nature utilizing an inclusive language and framing. This infers the emergence of new insights that can be uncovered through the adoption of socio-cultural valuation methods and analysis of Indigenous and Local Knowledge. The NCP paradigm, with its focus on instrumental and relational values, treats values more holistically than previous assessment frameworks (Christie et al., 2019).

Despite these fundamental difference in views, the ES concept and the NCPs are closely related, which is illustrated by the alignment between the NCPs and the Millennium Ecosystem Assessment (MA), The Economics of Ecosystems and Biodiversity (TEEB), and the Common International Classification of Ecosystem Services (CICES, 5.1 version, 2016) categories. Hence, studies can be translated between these frameworks. Moreover, even though the categories of the NCP framework are suggested to be indicative and non-exhaustive, they still allow a conversion with other frameworks, which facilitates operationalization. It has also been stated that: "The terms NCP and ES are synonyms and should be used where appropriate for different audiences and purposes (…). It is not ES or NCP, it is ES and NCP and many other ways of identifying peoples' dependency on nature. We suggest building on the past, and use what works together, in order to create a common sustainable future" (De Groot et al., 2018).

Although the NCP framework is built on the classical concept of ES, it provides a novel conceptualization of people and nature relations (Kadykalo et al., 2019) that is very useful in the context of AV for several reasons. First, LTS aquaculture is dependent on human interventions and, in contrast to e.g., exploitation of wild populations which are naturally supported by nature, would not exist without the actions of humans. Moreover, although LTS aquaculture can support a range of ES as discussed in section 1.2, there may also be negative effects of aquaculture, an aspect which is not considered in the classical ES concept. Finally, the multi-cultural scope of AV with the trans-Atlantic perspective infers a better fit to the NCP framework than to the classical approach. The multicultural scope of AV is an advantage that through the NCP framework can be integrated into the forthcoming analysis. This includes the incorporation of a diverse set of knowledge systems and stakeholders and will consequently strengthen the science-policy interface of the project. This undertaking is appropriate in determining the most practical, effective, and innovative key messages and recommendations to be developed in, and communicated from, the project.

1.4. Data management

AquaVitae is a participant in the H2020 Open Research Data Pilot, aiming at facilitating reuse of research data either collected or generated throughout a project. The Open Research Data Pilot aims to make data FAIR, i.e., Findable, Accessible, Interoperable and Reusable. To achieve this, all AquaVitae WPs, including WP6, have prepared data management plans, in short describing expected data collection/generation, and how it will be curated and preserved. As a rule of thumb, all data is to be made available in an online repository according to the time frames provided by the European Commission (EC).

In accordance with the data management plan, T6.2.1 will deposit the dataset "Quantification of the value of selected Nature Contributions to People provided by LTS aquaculture" in the repository Zenodo. The data is still in use and will be uploaded to the repository after publication of the results. First draft manuscripts are planned by the end of 2022, so it is estimate that the data will be uploaded within the first semester of 2023.

2. Framework adaptation and workflow

2.1 Clarification of the NCP framework in relation to LTS aquaculture

The NCPs were broadly described by Díaz et al. (2018) within a general context, and its applicability to LTS aquaculture was not specifically integrated into the descriptions. Hence, to ensure a joint understanding of the concept of NCPs in the context of AV, the definitions were updated with specific linkages to LTS aquaculture by the AV task 6.2.1 (Quantification of ES) team (CIIMAR, Isabel Sousa Pinto, Itziar Burges and Gonçalo Marino) whereafter the descriptions were reviewed and agreed upon by the entire WP6 team. The agreed definitions are presented in Table S1 in appendix A. To enable comparisons to other frameworks, the correspondence of the NCPs to other ES based frameworks (MA, TEEB and CICES classification) was also mapped based on the classification guide presented in CICES V5.1 (2016) and clarified in Table S2 in appendix A.

2.2 Conceptual framework and workflow

The types of NCPs provided by LTS aquaculture and their value, or the degree to which these can be achieved, depend on the functional traits of the cultured species, biotic and abiotic characteristics of the surrounding environment, farm design, and operational standards. In terms of the AV project entailing LTS aquaculture around the Atlantic, the diversity of production systems (as defined by organism group, production system, production mode [monoculture or polyculture], geographical area, value chain step and production location [near-shore and off-shore]) was mapped by WP6 in AV in a structure referred to as an Assessment Domain (Strand et al., 2022). This provides a framework for the identification and quantification of NCPs in this report, and infers the use of both species or organism groups, as well as the deconstruction of these elements into culture systems, as the operational units for the analysis performed.

The above mentioned frameworks (the NCPs and the AD) were used as a basis for the work in this deliverable. However, to further structure the task, it was deconstructed into four sub-tasks. The activities and outputs/results within each sub-task are illustrated and described in Figure 3 and Table 1.

I. Identification of the NCPs provided by LTS (based on the case studies [CS] investigated within AV) and of current knowledge gaps in terms of qualitative contributions of LTS aquaculture to the NCPs using expert judgements and literature (indicated by red colour in Figure 3 and Table 1).
II. Selection of specific CS to be included in the evaluation of NCPs provided by LTS aquaculture based on the number of identified NCPs and overall knowledge level (OKL) estimated based on the data quality/source for the identified NCPs in the previous step (indicated by green colour in Figure 3 and Table 1).
III. Selection of indicators for NCPs quantification based on the framework developed in task 6.1 in WP6 (D6.1, appendix B) (indicated by yellow colour in Figure 3 and Table 1).

IV. Quantification and analysis of selected NCPs using the most appropriate valuation method for each indicator using data from CSs within AV and literature reviews (indicated by blue colour in Figure 3 and Table 1).

As illustrated, the selection of indicators for quantification of NCPs was done in an iterative process according to the spiral development model where results are evaluated and then refined to reach a final target objective. Moreover, the figure also illustrates the continued process of integrating the results from D6.2 into the forthcoming D6.3 and D7.5.

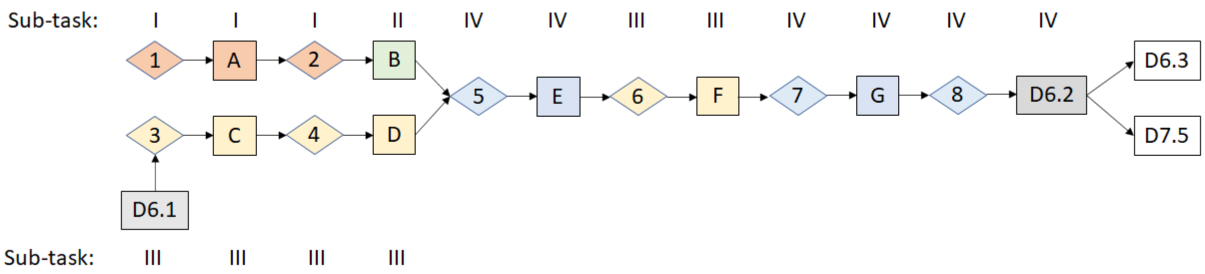

Figure 3. Conceptual workflow for task 6.2 on quantification of NCPs for sustainability assessment. Square shapes represent outputs/results, and diamond shapes represent processes or activities. Each activity is identified with a number, and the outputs/results related to each activity are identified with a letter in the table below (Table 1). The white diamond and square represent the connection of D6.2 to D6.3 in WP6 and D7.5 in WP7 – valuation of ecosystem services, which D6.2 and T6.2.1 will support.

Table 1. Description of Activities and Outputs in the workflow of task 6.2 on quantification of ES for sustainability assessment.

Activity	**Sub-task**	**Outputs / results**
1. Scoping of NCPs identified in AV CSs.	I	A. Identification of NCPs provided by LTS aquaculture and qualitative knowledge gaps
2. Analysis of scoping exercise (1): which CSs or VCs provide a high number of NCPs and which CSs or VCs present a high overall knowledge level (OKL).	I → II	B. Selection of CS for NCP quantification
3. Identify and select indicators from the list of sustainability indicators developed in D6.1 + adapt the NCP indicators to the NCP framework.	III	C. Total list of indicators for quantification of NCPs by CS
4. Structuring indicators for selected CSs: is the indicator relevant, identification of methods/data needs.	III	D. Final list of methods and indicators for NCP quantification and data collection by selected CSs
5. Data collection – step 1.	IV	E. Identification of data deficiencies
6. Refine indicator selection.	III	F. Refined list of indicators for NCP quantification
7. Data collection – step 2.	IV	G. Final dataset for NCP quantification
8. Data analysis.	IV	D6.2

2.3 Covid-19 effects on the planned workflow

The Covid-19 pandemic has had a significant impact on the ES quantification task (task 6.2.1), and subsequently on the D6.2:

- Due to the imposed restrictions to physical meetings, participatory exercises could no longer be performed. On-line solutions were considered but were deemed to be unsuited for the type of interaction required. This affected the valuation of the cultural (non-material) NCPs which are based on these methods and consequently, they had to be excluded from the analysis.
- AV industrial partners were forced to reorganize and prioritize their activities often with a reduced staff, and consequently could not put as much effort into the data collection required for the quantification of NCPs as expected.
- The covid-19 pandemic delayed the work in CSs, and hence the expected data was not available or was delivered very late, causing a delay in data analysis and subsequently in the delivery of D6.2
- This was further exacerbated by the limited stakeholder interactions which further slowed down the training and data collection process.

3. Identification of NCPs and CS selection (sub-tasks I and II)

To map which NCPs are connected to LTS was the first step of the workflow. The identification of relevant NCPs before selection of what NCPs to assess was critical for providing a relevant and context-specific understanding of the state-of-the-art in terms of the connection between LTS aquaculture and the NCPs. This step supported delineation of the boundaries of the task with the aim of choosing the most suitable NCPs to target and identify possible knowledge gaps in terms of the interdependencies of LTS aquaculture and the NCPs.

3.1. Methods

A matrix was constructed based on the marine organism groups included in the AV project (based on CSs), the mode of production (monoculture or polyculture) and culture system (land based or sea based, based on the AD), and the 18 NCPs in the NCP framework (Table S1 in appendix A). The selected organism groups included: monoculture of red/green macroalgae (CS1), brown macroalgae (CS2), echinoderms (CS6 and 7), and bivalves (CS8 and 9), as well as polyculture systems (Integrated multi-trophic aquaculture, IMTA) of abalone in land-based IMTA (CS3) and sea-based IMTA (CS4), and shrimp in biofloc (CS5). Of these, half were land-based (CS1, 3, 5, 6, and 7) and the rest were sea-based production. Finfish was excluded from the analysis despite being included in AV (CS10 and 11) as CS10 has a focus on freshwater culture, as CS11 was experiencing some problems which reduced the possibility of the CS to supply data, and due to the existence of several other EU projects (e.g., Diversify[5], ClimeFish[6] and others) that already cover sustainability related to fish aquaculture. These categories are from here on referred to as matrix elements (ME). The NCPs were stated on rows and all selected ME were aligned in columns. The purposes of the matrix were to, in a structured way, collect data to:

i) identify the presence of NCPs for each ME
ii) define the data quality for each existing NCP

[5] https://www.diversifyfish.eu/
[6] https://climefish.eu/

iii) validate the identified NCPs by literature references

Consequently, the participants in this mapping were required to identify not only the existence of NCPs for their specific ME, but also the quality of the data available for each intersection in the matrix by indicating the appropriate scoring number of data quality according to Table 2. The data quality scoring table was adapted from the work of Hare et al. (2016) to identify the level of certainty of the provision of NCPs from each LTS system. Additionally, participants were requested to provide a bibliographic reference (e.g., article, report), whenever the presence of the NCP was supported by data from literature and the data scoring was marked as 3: adequate data.

Table 2. Data Quality scoring table. Modified from Hare et al., 2016.

Score	Data Quality	Description
3	Adequate Data	The identification was based on data which have been observed, modelled, or empirically measured for the NCP in question. References to the data sources were provided.
2	Limited Data	The identification was based on data that has a higher degree of uncertainty. The data used to score the attribute may be based on related or similar species, come from outside the study area or different species, or the reliability of the source may be limited.
1	Expert Judgement	The identification reflects the expert judgment of the reviewer and is based on their general knowledge of the species, or related case studies and their relative significance in NCP assessment.
0	No Data	No information was reported but based on expert judgment, this interaction exists. Very little is known about the production of these contributions or how to adequately measure them. There is no basis, this is a formed opinion/hypothesis and needs to be tested.
NA	Not Applicable	This interaction does not exist. This NCP is not provided by this system or species.

The matrix was distributed, along with instructions, to CS leaders and other selected partners in the AV consortium. External input from project-related stakeholders and contributors was requested when needed. Each response was kept separate, i.e., responses related to the same ME were not merged. The completion of the matrix was followed by quality control of the received input in terms of literature reviews and expert consensus processes, which resulted in extensive direct contact with identified experts for data validation. Following data validation, the received input was analysed using an indicator, the overall knowledge level (OKL), describing the overall knowledge level for each ME in relation to the NCPs. This procedure also supported identification of qualitative knowledge gaps in terms of NCPs provided by LTS aquaculture. Using this index, a numeric score summarizing the data quality for each ME that could be plotted against the number of NCPs was obtained.

The OKL was calculated using the following procedure:

1. First, the data quality scores were assigned a numerical value (0–3 and NA, Table 2). These values were already assigned by the consulted experts and validated before the calculation of the OKL.
2. Second, an average score for each NCP within each ME was calculated as the weighted mean of the experts' data quality scoring for each group and NCP (Table 4).

3. Finally, the OKL was calculated using a logic rule (Table 3).

Table 3. Logic Rule for the Overall Knowledge Level summary

Overall Knowledge Level (OKL)	**Numeric Score**	**Logic Rule**
Very high	4	6 or more NCPs with mean data quality score ≥ 2,5
High	3	4 or more NCPs with mean data quality score ≥ 2,0
Moderate	2	3 or more NCPs with mean data quality score ≥ 1,5
Low	1	3 NCP with mean data quality score > 0
No Data	0	(Other cases) = 0
NA	NA	Not applicable

3.2. Results and discussion - NCPs links to LTS aquaculture and data quality

Overall, a relatively high number of NCPs was identified and confirmed using the data quality score and literature for all ME assessed (Table 4). The highest number of identified NCPs was reported for *Sea-based IMTA* and *Mussels*, both with 15 identified NCPs out of 18, followed by *Offshore macroalgae* and *Oysters* both with 14 identified NCPs. The lowest number of identified NCPs was reported for *Sea urchins* with 9 identified NCPs. The low number for this ME may be a result of the very specific type of culture this CS entails, i.e., mainly land-based, short-term, live storage for conditioning and product priming, compared to the other ME. Moreover, it is also possible that the low number of NCPs identified is a result of significant knowledge gaps as this is an emerging and immature aquaculture activity. No data was received for two ME, *Shrimp in biofloc* and *Sea cucumbers*, which may perhaps be explained by the immaturity of these emerging aquaculture activities, and these CS were consequently excluded from further analysis.

Most of the NCPs were reported to be provided by almost all the ME with a few exceptions. Supporting NCPs, such as *Habitat creation and maintenance* was only identified for the ME that are sea-based, where other organisms can utilize the structures and organisms from the aquaculture production systems as habitats. A few ME were also identified to not be connected to *Energy production*, e.g., oysters, sea urchins and abalone, for which little waste in terms of discarded animals are obtained during production and which are of comparably high value in relation to the other ME, hence this result was not unexpected. Moreover, the NCPs related to *Regulation of air quality*, and *Regulation of freshwater quantity, location, and timing* were not reported to be provided by any of the ME assessed (Table 4). These NCPs are more related to terrestrial environments and are not related to the processes that occur in marine aquaculture systems.

Some ambiguities in the expert judgements of LTS contributions to the NCPs were discovered during the data collection process. Several examples illustrate this problem, e.g., two of the land-based systems (new macroalgae species and land-based IMTA) were not identified to contribute to *Habitat creation and maintenance* or *Formation, protection, and decontamination of soils and sediments* although it can be argued that some land-based aquaculture systems, e.g., marine ponds in which new macroalgae species may be cultured, can support the development of terrestrial and aquatic organisms. Similarly, the particulate organic material produced in land-based IMTA systems with abalone could potentially be a source of soil or sediment formation depending on end use of that product. In a similar way, it can be debated whether offshore cultivation of macroalgae is interconnected to *Regulation of detrimental organisms and biological processes* as offshore culture systems may potentially act as a vector or a stepping stone for non-native species or pathogens, and they can also, e.g., affect nutrient cycles and availability to other organisms and can thereby affect biological processes. Also, the lack of valid cases for the NCP *Pollination and dispersal of seeds and other propagules*, is surprising as cultured organisms can provide seeds to the natural environment e.g., through incidental spatfall during the culture cycle in open, sea-based culture systems. There are two plausible explanations to these results. One alternative is that the terrestrial terminology used in the NCP titles caused a bias in interpretation of the modified NCP descriptions. Alternatively, these ambiguities are knowledge gaps that should be explored further. It is concluded that the adapted NCP descriptions should be further clarified in an iterative process until consensus in these matters are reached. Nevertheless, the data still provided sufficient information for the CS selection process to continue.

Nearly 90 references (articles and reports) were provided by the consulted experts to verify the identified NCPs (see appendix C). The collected references served as a fundamental bibliography from where to start the mapping of indicators to the NCP framework and identification of the method for quantification of selected indicators (sub-task III) and for the data collection (sub-task IV). The average data quality score for each NCP by CS is presented in Table 4. Not surprisingly, the data quality score for non-material (or cultural) NCPs –*Learning and inspiration*, *Physical experiences*, *Supporting identities* and *Maintenance of options* were in general low with few references identified. Likewise, even though *Regulation of hazards and extreme events* and *Regulation of detrimental organisms and biological processes* were present in the majority of the ME they also showed low data quality scores and limited number of references and studies related specifically to aquaculture case studies. The material benefits, on the other hand, *Food and Feed*, *Materials, companionship, and labour*, and *Medicinal, and biochemical resources* were found to have high data quality scores and consequently were supported by several references.

Table 4. Summary of Nature's Contribution to People (NCPs) identified and overall knowledge level by case study (CS) within the AquaVitae project. Colour codes are provided to facilitate the interpretation of the results ranging from red representing the knowledge gaps to green identifying the highest data quality score. See tables 2 and 3 to interpret the numerical scores. NA: Not applicable.

	GREEN/RED MACROALGAE	BROWN MACROALGAE	ABALONE	POLYCULTURE	ECHINODERMS	SHELLFISH	
#CS	**CS1**	**CS2**	**CS3**	**CS4**	**CS6**	**CS8**	**CS9**
CS	New Species (Land based)	Offshore	Land-based IMTA	Sea-based IMTA	Sea urchin roe-enhacement	Oysters	Mussels
Habitat creation and maintenance	NA	3	NA	2.3	2	3	3
Pollination and dispersal of seeds and other propagules	NA	NA	NA	NA	NA	NA	NA
Regulation of air quality	NA	NA	NA	NA	NA	NA	NA
Regulation of climate	2	2	NA	2.4	2	3	3
Regulation of ocean acidification	1.5	2	3	1.7	0	3	3
Regulation of freshwater quantity, location, and timing	NA	NA	NA	NA	NA	NA	NA
Regulation of coastal water quality	2	3	2	2.4	NA	3	3

Formation, protection, and decontamination of soils and sediments	NA	1	NA	3.0	NA	3	3
Regulation of hazards and extreme events	0.5	2	0	0.8	0	3	0.5
Regulation of detrimental organisms and biological processes	0.5	NA	0.5	0.8	2	2	2
Energy	3	2	NA	1.4	NA	NA	2
Food and feed	3	3	3	2.6	0	3	3
Materials, companionship, and labor	1	2	3	2.0	NA	3	3
Medicinal, biochemical resources	2.5	2	3	1.9	1	2	2
Learning and inspiration	1	2	1	1.3	NA	3	3
Physical and psychological experiences	1.5	2	2	1.3	NA	2	2
Supporting identities	1	2	1.5	0.9	2	1	1
Maintenance of options	1	2	1.5	0.9	3	1	1
Total Number on NCPs provided by summary CS	13	14	11	15	9	14	15
Overall knowledge level	3	3	3	3	2	4	4

When combining the data quality scores and number of identified NCPs in the OKL (Figure 4), bivalves were identified as representing the highest overall knowledge level (4). This is not surprising given the substantial production of these organisms around the Atlantic. However, it should be recognized that AV addresses culture of these organisms in areas where they are currently underutilized, hence despite an overall high data quality score, it is possible that there may be data deficiencies in the actual regions where AV operates. The second highest OKL was observed for the *Macroalgae* value chain and the polyculture ME, indicating the possibility to include also these ME into the forthcoming data collection for quantification of NCP.

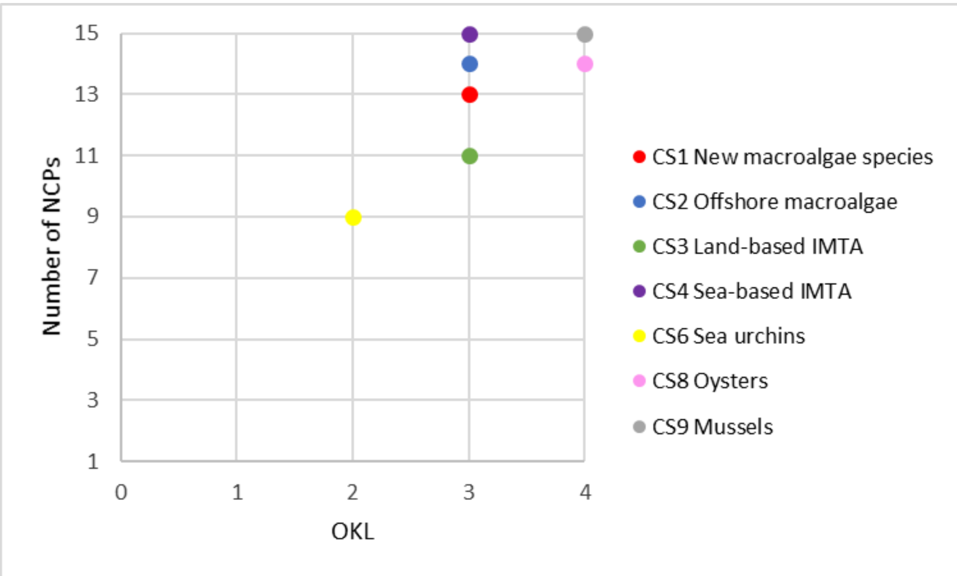

Figure 4. The number of Nature's Contribution to People (NCPs) vs Overall Knowledge Level (OKL) to identify the most suitable case studies (CS) to include in quantification of NCPs provided by low-trophic species aquaculture.

To summarise, the ambiguities observed in identification of LTS associations to the NCPs is not unexpected for emerging activities such as sea-urchin roe enhancement and offshore activities, and these NCPs should therefore be explored further. Likely for the same reason, novel species of macroalgae (green and red, CS1) also scored a low OKL, even though this ME was reported to provide at least 13 out of the 18 analysed NCPs. Moreover, the weakest data quality score was identified for non-material benefits. Even though they were generally reported to be present across all CS and ME, studies related to these cultural benefits specific for aquaculture are very scarce, which translated in low data quality scores. Likewise, the regulating NCPs *Regulation of ocean acidification*, *Regulation of hazards and extreme events*, and *Regulation of detrimental organisms and biological processes* are poorly investigated with few studies and reports available, even though they were also reported to be present in most of the CS and ME evaluated. This may pose challenges during the following steps of the data collection and it is therefore recommended that research efforts are directed to quantify these interconnections more thoroughly in future research projects.

3.3. Selection of CS for quantification of NCPs

The criteria for selecting CSs and VCs for analyses were determined by the WP6 team and were:

- OKL: overall knowledge level ≥ 3 (points: 0-4 according to the OKL)
- Number of NCPs provided > 10 (2/3 of the maximum number of NCPs identified as possible for marine aquaculture) (points: 1 if >10 NCPs)
- Synergies with other WP within the project (points: 1 if yes)
- Industry partner participating (hence high probability of access to farm data, points: 1 if yes)
- Scale of operation of domain element (large commercial scale, medium commercial scale, emerging activity, points: 2 for large commercial scale, 1 for medium commercial scale, 0 for emerging activity)

For each criteria a number of points were awarded and all matrix elements scoring >2/3 of the maximum points (max 10, > 2/3 = 7) were identified as suitable candidates to proceed to the next stage of the work (Table 5). These were:

- CS2: Offshore macroalgae (sea-based, monoculture)
- CS3: Abalone (land-based, mono- and polyculture)
- CS8: Oysters
- CS9: Mussels

Table 5. Selection criteria for identification of case studies (CS) to proceed to the data collection stage for quantification of Nature's Contributions to People (NCPs) provided by low-trophic species aquaculture.

#CS	Case Study	OKL	Number of NCPs	Synergies with other WP	Industry partners	Scale of operation	Combined selection score	Candidate
CS1	Macroalgae, new species	3	13	Yes	Yes	EA	6	No
CS2	Offshore macroalgae	3	14	Yes	Yes	MS	7	Yes
CS3	Land-based IMTA	3	11	Yes	Yes	MS	7	Yes
CS4	Sea-based IMTA	3	15	Yes	Yes	EA	6	No
CS6	Sea urchin roe-enhancement	2	9	Yes	No	EA	2	No
CS8	Oysters	4	13	Yes	Yes	MS	8	Yes
CS9	Offshore production of blue mussels	4	15	Yes	Yes	MS	8	Yes

OKL: overall knowledge level; WP: work package; EA: emerging activity; MS: medium scale.

4. Selection of indicators and data collection to evaluate NCPs from LTS (sub-tasks III and IV)

4.1. Indicator set development

Sustainability indicators are variables defined to reflect a phenomenon or a process in a simplified way. They measure specific attributes of a system and define them with a number, score, or status level (e.g., good, poor, bad). They can be used individually or as aggregated indexes, in which individual scores are combined to produce a simpler value of the process, or attribute (Valenti et al., 2018). In order to calculate each indicator, all parameters that are required for the indicator need to be accounted for. The NCPs selected in this report represent some of the parameters and indicators needed for the forthcoming sustainability analysis in task 6.2.2 in WP6. To fully integrate the two tasks (T6.2.1 - quantification of ecosystem services and T6.2.2 – sustainability analysis) the NCPs in T6.2.1 were based on, and connected to, the indicator set developed in D6.1 where a comprehensive list of sustainability indicators was presented. Additional indicators specific for NCPs estimation were added to that "master" list. Therefore, the quantification of NCPs including both the benefits and detrimental effects derived from LTS aquaculture could be accounted for and integrated as externalities in the economic indicators proposed for the sustainability analysis.

WP6 set out to build a set of sustainability indicators for the forthcoming WP6 sustainability analysis on the basis of the work performed by Valenti et al. (2018). That original set of indicators refers to a portfolio of quantitative indicators of economic, environmental and social aspects of sustainability in aquaculture. Acknowledging that this set of indicators was not developed with the AV objectives or context in mind, WP6 has adapted and supplemented it with additional indicators. The compiled "master" list of indicators presented in Deliverable 6.1 comes from different sources and it was designed and refined in an interactive process according to the spiral development model where results are evaluated and then refined to reach a final target objective, in this case include indicators suitable for the assessment of sustainability for LTS aquaculture. The full list of indicators in D6.1 is available in appendix B. In the work associated to quantification of NCPs, the original indicator set was assessed and modified according to these iterative processes, with the focus on indicators relevant for the NCP concept.

The indicator selection for quantification of ES was performed according to the following workflow:

i) A preliminary list of indicators and methods relevant for the NCP analysis was retrieved from the list of indicators presented in D6.1. This step was conducted using a top-down approach based on expert opinions of the members of the task leader CIIMAR, and other members of WP6 core team. Each indicator on the list was assessed individually and those with the capacity to provide meaningful information to describe and quantify NCPs were selected. Whenever an NCP seemed not to be properly assessed by the indicators retrieved from D6.1, additional suitable indicators were retrieved from literature, or established based on expert opinion.

ii) The resulting preliminary list of NCP indicators, along with information regarding their specification and methodology for determination, was then sent to selected experts within the AV consortium to validate the relevance of each indicator for the assessment of each of the NCPs identified for LTS. The experts were asked to provide feedback in the form of yes, no, or NA, and also to justify their answers.

iii) The expert feedback provided was revised by members from task 6.2.1 (quantification of NCPs) and from task 6.2.2 (sustainability analysis). The indicators and respective methods with an approval rate equal to, or higher than, 50% were selected and included in the final list of indicators of NCPs. Comments from experts were also incorporated and sometime resulted in modifications to the indicators and/or methodology. The NCP indicators and methods were also added to the "master" list of sustainability indicators for aquaculture compiled in D6.1.

The final list of selected indicators and methods for their determination is presented in Table 6. Some NCPs are defined and assessed by one single indicator and method, for example, *Regulation of climate*, *Regulation of ocean acidification*, and the provisional NCPs. Others such as *Habitat creation and maintenance*, *Regulation of coastal water quality*, and *Formation, protection, and decontamination of soils and sediments* were proposed to be assessed using several indicators. The inclusion of several indicators for some NCPs was deliberate and desired as this increases the likelihood of obtaining at least some data for that NCP and hence increases robustness of that NCP. Moreover, higher numbers of indicators for one NCP infers a more holistic assessment of that specific NCP, which is beneficial in terms of diverse types of production systems to be assessed.

In the case of *Regulation of ocean acidification*, while the proposed indicator was validated as relevant for the assessment of the NCP, some experts including industrial partners pointed out that the methodology was hard to implement and expensive: "...Require multiple probes with reliable logging of pH over time. With our experience, this is not realistic because such probes/loggers are too expensive and would require regular maintenance.", or "A good indicator, but hard to measure". In this context, the proposed indicator and method was replaced by an ocean acidification index based on the CO_2 budget from the cultured species, which is described in detail in section 5.

Table 6. Indicators selected for data collection for quantification of Nature's Contribution to People (NCPs) provided by low trophic species (LTS). Each indicator is linked to the selected method and described in relation to its value for the NCPs. Regulating (orange) and material (blue) NCPs. Cells with darker colour indicate that the indicator was included and quantified in the final analysis.

NCP	Specification	Indicators	Method	Reference
Habitat creation and maintenance	Shannon-Wiener diversity index (S-W, based on species richness and abundance) is used to measure the difference of environment impacted by the farm (´2) and a similar environment unimpacted by the farm (´1), which is then divided by the mass or units produced.	Change in surrounding biodiversity (e.g., nekton, sessile epifauna, birds)	= (S-W'2 – S-W'1) / ha	Valenti et al., 2018
		Change in biodiversity in sediment (e.g., benthic macrofauna)	= (S-W'2 – S-W'1) / ha	Task 6.2.1
		Extinction prevention	= (S-W'2 – S-W'1) / ha	Valenti et al., 2018
		Habitat for migratory species	= (S-W'2 – S-W'1) / ha	Valenti et al., 2018
		Nursery areas/habitat	= (S-W'2 – S-W'1) / ha	Task 6.2.1

	Classification of farmed animals/algae according to a set of defined characteristics and culture conditions, and their potential impact on the native species of the surrounding environment. For a detailed description of the criteria, please refer to Valenti et al-, 2018.	Potential to change the gene pool of the native community	PCGP* = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 or 12}	Valenti et al., 2018
Regulation of climate	Biological carbon footprint (B-CF) is used to measure the net long-term production of CO_2	Potential for global warming	= (CO_2-eq removal – CO_2-eq release)/t or ha/yr	Valenti et al., 2018
Regulation of ocean acidification		Change in water pH	Temporal and spatial scale change in water pH (See Krause-Jensen et al., 2015)	Schernewski et al., 2018
	CO_2 budget (B-CO_2) during the culture cycle is used as an indicator of the impact of LTS on ocean acidification. Includes the short-term organic CO_2 stored in the biomass	Ocean Acidification Index	= (CO2-eq removal – CO2-eq release)/t or ha/yr	T6.2.1
Regulation of coastal water quality		Water purification (wastewater treatment)	= (load of N and P in the inlet water – load of N and P in the outlet water)/t/ha/yr	Valenti et al., 2018
	N and P budgets are used as indicators of the impact of LTS aquaculture in N and P cycling	Nutrient cycling	= (N removal – N release)/t or ha/yr = (P removal – N release)/t or ha/yr	Valenti et al., 2018
	Phosphate equivalents (PO_4 eq.) budget is used to measure the eutrophication potential	Eutrophication index	= (PO_4 eq. removal – PO_4 eq. release)/t or ha/yr	T6.2.1 adapted from Thomas et al., 2021

		Siltation	= (Load of total suspended inorganic solids in source water – Load of suspended inorganic solids released in effluents) / mass or units produced	Task 6.2.2
		Organic Pollution	= (Load of organic matter in source water – Load of organic matter released in effluents) / mass or units produced	Task 6.2.2
Formation, protection, and decontaminatio n of soils and sediments		Buffering and attenuation of mass flows	cm/year	Schernewski et al., 2018; Valenti et al., 2018
		Soil building	= (kg of organic matter deposited – kg organic matter content in the local soil) / ha	Valenti et al., 2018
		Accumulation of phosphorus	=Load (mass) of P accumulated in sediment per mass or units of organism produced	Task 6.2.2; Valenti et. al., 2018
		Accumulation of organic matter	=Load (mass) of organic matter accumulated in sediment per mass or units of organism produced	Task 6.2.2
		Accumulation of particulate material	=Load (mass) of Particulate Material accumulated in sediment per mass or units of organism produced	Task 6.2.2
Regulation of hazards and extreme events	Wave Energy attenuation	Wave height or current velocity	m or cm/s	Task 6.2.1

Food and Feed	Provision of food (biomass for human consumption)	Food production	= t/ha/year or t/year	Valenti et al., 2018
	Provision of feed (biomass for human-consumed animals)	Feed production	= t/ha/year or t/year	Valenti et al., 2018
Materials, companionship and labour		Raw material	= mass of raw material (e.g., mollusc shell) per t, ha/yr, or yr	Valenti et al., 2018
Medicinal, biochemical resources		Medicinal resources	= mass of pharmaceuticals per mass of organism produced or /ha/yr or /year	Valenti et al., 2018

*Potential to change the gene pool of the native community (PCGP): 1 = Farming exotic species, genetically modified organism (GMO), or hybrids, fertile, in open systems without control of escapes; 2 = Farming exotic species, genetically modified organism (GMO), or hybrids, fertile, in open systems with control of escapes; 3 = Farming exotic species, genetically modified organism (GMO), or hybrids, infertile, in open systems without control of escapes; 4 = Farming exotic species, genetically modified organism (GMO), or hybrids, infertile, in open systems with control of escapes; 5 = Farming genetically-improved autochthone species, in open systems without control of escapes; 6 = Farming genetically-improved autochthone species, in open systems with escapes control or strains incapable of mating in open systems without control of escapes; 7 = Farming exotic species or genetically modified organism (GMO), fertile, in closed systems; 8 = Farming exotic species or genetically modified organism (GMO), infertile, in closed systems; 9 = Farming genetically-improved autochthone species, fertile, in closed systems; 10 = Farming genetically-improved autochthone species, infertile, in closed systems; 11 = Farming non-genetically-improved local strain, in open systems; 12 = Farming non-genetically-improved local strain, in closed systems.

4.2 Data collection

Based on the selected indicators (Table 6), a data collection template was developed including all parameters required to compute the indicators. The file was sent to the CS leaders of the selected CSs (see section 3.3), and other relevant partners from the AV consortium (i.e., full partners from industry and industry partners in the industry reference group, IRG). The partners were requested to provide data with the following priority; 1) data from ongoing work in the CSs, 2) data from previous production cycles (priority 1 and 2 was referred to as primary data), 3) data from literature (referred to as secondary data). Partners were asked to provide numbers for each parameter required to calculate each indicator and the corresponding reference (own data or literature), by species and geographical region as defined in the AD (Strand et al., 2022). To explain the data collection process and the methods used to calculate the indicators, a training workshop on ecological indicators was hosted. This was followed by a series of workshops held throughout the data collection process where participants in the data collection had the opportunity to discuss progress and difficulties identified during the data collection process.

Shortly after starting the data collection process, it was evident that both CS leaders and industrial partners were struggling to provide the amount of data required to compute all indicators for several reasons:

- The covid-19 pandemic had a severe impact on the business of the industrial partners, who had to reorganize and prioritize their activities often with a reduced staff, and consequently could not put as much effort into the data collection as expected.
- The covid-19 pandemic had delayed the work in CSs, and hence the expected data was not available.
- Some of the indicators and data required to quantify the NCPs was not anticipated in the project proposal (as this is an outcome of sub-task III in this deliverable, see section 4.1), and consequently there was no time or budget allocated to add this data to the data collection in the CS activities.

Obviously, this had a significant impact on the availability of primary data for the analysis. Moreover, access to secondary data (literature) was non-existent or limited for some indicators. Indicators that could not be documented were hence identified as data deficient (Table 6). In this context, it was necessary to prioritize and reduce the total number of NCPs to be included in the analysis and in some cases also reduce the total number of indicators to analyse per NCP. The selection of the NCPs to be prioritized for the analysis was discussed within the WP6 core team and was decided based on the following criteria:

- Data availability (both primary and/or secondary data) based on preliminary input from partners leading the data collection.
- Number of indicators required to assess the NCP.
- Which NCPs may be more readily integrated in decision making and management plans for LTS aquaculture.
- Which NCPs may be closer to provide additional value to LTS aquaculture besides biomass production.

As a result of this process four NCPs and supporting indicators were prioritized and selected for quantification, namely: *Regulation of climate* (Potential for global warming), *Regulation of ocean acidification* (Acidification index), *Regulation of coastal water quality* (Nutrient cycling—N and P), and provision of *Food and feed* (Food or feed production). *Habitat creation and maintenance* was considered as a fifth alternative, however due to low data availability and the publication of a recent review of biodiversity effects of LTS aquaculture (The Nature Conservancy 2021), priority was given to the other four NCPs.

5. Evaluation of NCPs (sub-task IV)

5.1. Methods

5.1.1 Nutrient budget and Eutrophication index

To evaluate the connection between LTS aquaculture and the NCP *Regulation of costal water quality*, the indicators *Nutrient cycling* and *Eutrophication index* were used. Nitrogen (N) and phosphorous (P) budgets of the selected LTS systems were estimated as the mass balances between the nutrient input (released) and output (removal) in each system. For nutrient release the amount of nutrient supplied through the diet (i.e., abalone), or fertilizers (i.e., macroalgae) was determined based on the content of N and P in the diet/fertilizer and the total amount of diet/fertilizer provided during the production cycle per tonne (t) of harvested biomass. This applied only to the co-culture of abalone and macroalgae in CS3, where 1) the abalone was fed a formulated diet; 2) the *Ulva* produced in the effluent from abalone farming was further supplemented with fertilizers, and 3) the *Ulva* produced in monoculture was fertilized exclusively with artificial fertilizers. All other production systems included extractive species where no nutrients or feed were added during the grow-out stage of the value chain.

For nutrient removal, two processes were considered:

- N and P stored in the biomass during the production cycle. This was estimated based on the biomass weight at seeding and harvesting times and the respective N and P content. In the case of sugar kelp (CS2), oyster (CS8), and mussel (CS9) aquaculture the biomass weight at seeding time can be omitted as it has a minor impact on the calculation compared to the final biomass due to the small size of the organisms at seeding. For shellfish culture the contribution of the shell and flesh for this process was accessed separately, and then combined.
- The N and P storage linked to biodeposits production, and their subsequent microbial degradation and preservation in the sediments: N and P in biodeposits were estimated as the product of the N and P content of faeces and pseudofaeces by the integrated egestion rates between seeding and harvesting times. These data were provided by AquaVitae partners or obtained from the literature (see Table S3 in appendix A). The pathways of biodeposits integration into the nutrient cycles are 1) degradation in the water column and on the sediments; and 2) burial in the sediments. Only the fraction buried in the sediment contributes to the net removal of N and P while the rest is recycled back into the ecosystem food webs.

Nutrient budgets are reported in kg N and P per t of fresh biomass, but were also combined and transformed into PO_4 equivalents per t of FW biomass, food and/or proteins to allow comparison with other food production systems. The eutrophication index, which illustrates the net $PO_{4\text{-eq}}$ budget for the target species is given by:

$$PO_{4\text{-eq budget}} = 0.42 * N_{budget} + 3.07 * P_{budget} \qquad \textit{(Equation 1)}$$

Where 0.42 and 3.07 are the stoichiometric factors to transform N and P into PO_4 equivalents used in other studies (GHK & BioIS, 2006; Thomas et al., 2021).

5.1.2 Ocean acidification index and Carbon footprint

The carbon footprint of LTS aquaculture is not only related to the CO_2 released to the atmosphere during the production of all the capital goods, consumable materials used, and the operations needed to perform the culture, but it is also related to the impact of the culture system on the carbonate chemistry of the water column. Therefore, the biological processes that release to, or remove, CO_2 from the water column during LTS growth in aquaculture were considered to estimate both the ocean acidification index and the biological carbon footprint. While the acidification index measures the potential to contribute to a decrease in seawater pH, the carbon footprint measures the potential to contribute to global warming. The acidification index (B-CO_2) is estimated as the balance between all relevant biological processes that remove or release CO_2. Whereas only those that involve long-term CO_2 release or removal should be considered to estimate the biological carbon footprint (B-CF). These processes are different for macroalgae (photosynthetic organisms, Figure 5a), and shellfish (heterotrophic calcifying organisms, Figure 5b).

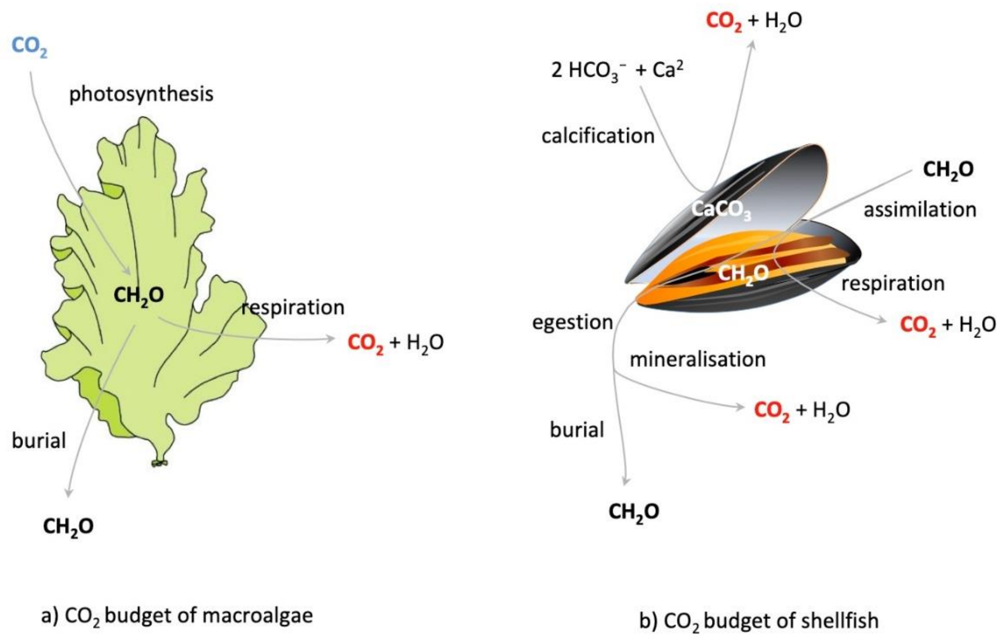

Figure 5. Processes involved in the estimation of the CO_2 budget of the low trophic species studied in AquaVitae.

The biological CO_2 budget of macroalgae aquaculture (B-CO_2) was accessed based on the CO_2 stored in the biomass during growth (Figure 5a). The contribution of this process is estimated considering the biomass weight of macroalgae at seeding and harvesting times and their respective organic carbon content (Figure 5a). As pointed out in Section 5.1.1, biomass weight of sugar kelp (CS2) at seeding time can be omitted as it has a minor impact on the calculation. Multiplying the organic carbon content of the biomass by 3.67 (=44/12), i.e., the ratio between the CO_2 molecular and C atomic weights, the corresponding stored CO_2 is obtained. This value, in kg CO_2 per ton of fresh macroalgae can be used as an acidification index. Note that the CO_2 removed during growth is released back to the atmosphere after the consumption or degradation of macroalgae and, consequently, we can assume a balanced biological carbon footprint for this culture system.

The contribution of the biological processes involved in the carbon footprint of shellfish aquaculture (Figure 5b) is estimated as follows (Filgueira et al., 2019; Álvarez-Salgado et al., under review):

- CO_2 removal by the carbon stored in the organic components of shell (OS) and flesh (OT) during shellfish (in this report mussels, oysters and abalone) growth. The contribution of these processes (in g CO_2 per individual) is estimated as the product of shell and flesh weight gain during culture by their respective organic carbon content, which were provided by AquaVitae partners or obtained from the literature (see supplementary Table S3). This carbon storage is transformed into CO_2 removal by multiplying by 3.67 (=44/12). Note that organic shell and flesh weight at harvest can be used as an estimate of weight gain given that shellfish seeds weight is negligible in comparison with the weight of market size individuals.

- CO_2 released by calcification. The synthesis of $CaCO_3$ during growth comprises the removal of inorganic carbon (C_{IS}) from the water column in the form of bicarbonate (HCO_3^-) and a release of CO_2 proportional to this HCO_3^- removal. Therefore**,** the contribution of calcification to the CO_2 budget (in g CO_2 per individual) is estimated as the product of the CO_2 content of shells and the CO_2 release to fixation ratio, Φ. The CO_2 content of bivalve shells is obtained by multiplying the shell weight by the percentage of $CaCO_3$ in the shells and by 0.44 (=44/100), i.e., the ratio between the molecular weights of CO_2 and $CaCO_3$. Φ is estimated as a function of the seawater temperature, salinity and total alkalinity of the water column assuming a pCO_2 of equilibrium with the current atmosphere (412 uatm) following Frankignoulle et al. (1994), and using the carb function in the seacarb package of R (Gattuso, et al., 2020, R Core Team, 2022).

- CO_2 release by respiration (resp). This parameter was estimated by integration of the oxygen respiration rate between seeding and harvesting times transformed to CO_2 units (g CO_2 per individual) using a respiration coefficient of RQ = 0.85 mol C mol O_2^{-1}. Oxygen respiration rates (ml $O_2 \cdot h^{-1}$) were provided by AquaVitae partners or obtained from the literature (see supplementary Table S3). If respiration rates were not available for a given species/environment, the equation resp = 2.19·(CO_2 stored in flesh weight) was used as reference estimator following Schwinghamer et al. (1986).

- Net CO_2 storage linked to faeces egestion and pseudofaeces production, subsequent microbial degradation and preservation in the sediments (biodeposits). Organic carbon in faeces and pseudofaeces (in g CO_2 per individual) was estimated as the product of their carbon content by the integrated egestion rates between seeding and harvesting times. Data were provided by AquaVitae partners or obtained from the literature (see supplementary Table S3). Biodeposits can be 1) degraded in the water column and the sediments; and 2) buried in the sediments. Since the CO_2 removed during biodeposit production is released during degradation, only the fraction buried in the sediments contributes to the net removal of CO_2.

Considering all these processes, the biological CO_2 budget of shellfish aquaculture activities (B-CO_2) is estimated as the balance between the CO_2 released by respiration and calcification minus the CO_2

removed through organic carbon storage in shell and flesh and preservation of biodeposits. Some authors argue that respiration does not contribute to this budget as the CO_2 release during respiration is assumed to enter a short-term biological cycle and get recycled through phytoplankton photosynthesis (Vélez-Henao et al., 2021). To account for both possibilities, two different modes of calculating the biological CO_2 budget were used, a lower estimate without the respiration and a higher estimate including the respiration:

$$B\text{-}CO_{2,high} = CO_{2,\,resp} + CO_{2,\phi} - (CO_{2,\,OT} + CO_{2,\,OS} + CO_{2,\,biodeposits}) \quad \textit{(Equation 2)}$$

$$B\text{-}CO_{2,low} = CO_{2,\phi} - (CO_{2,\,OT} + CO_{2,\,OS} + CO_{2,\,biodeposits}) \quad \textit{(Equation 3)}$$

This value, initially in g CO_2 per individual, can be converted to kg CO_2 per ton of shellfish fresh weight and used as an acidification index (B-CO_2).

Note that shellfish flesh is consumed as fresh or processed/canned food and hence the CO_2 stored in the flesh is released back to the atmosphere. Therefore, the removal of this flesh organic carbon should not be considered in biological carbon footprint (B-CF) estimates of shellfish aquaculture. The same is applicable to the organic carbon stored in mussel shells (OS). Furthermore, as above, in order to accommodate the different views on the role of respiration, a lower and higher estimate of the biological carbon footprint (B-CF) of shellfish aquaculture activities was calculated:

$$B\text{-}CF_{high} = CO_{2,\,resp} + CO_{2,\phi} - CO_{2,\,biodeposits} \quad \textit{(Equation 4)}$$

$$B\text{-}CF_{low} = CO_{2,\phi} - CO_{2,\,biodeposits} \quad \textit{(Equation 5)}$$

The B-CF is reported in kg CO_2 per ton of shellfish fresh weight. It should be noted that the CO_2 stored in the form of shell $CaCO_3$ has not been included either in the B-CO_2 or in the B-CF estimates. Considering the $CaCO_3$ in shells as a CO_2 removal mechanism has been a common practice in shellfish aquaculture studies (e.g., Munari et al., 2013; Filgueira et al., 2015; 2019; Jansen and van den Bogaart, 2020) although this practice has been challenged, and changed, recently (Morris and Humphreys, 2019; Warmerdam et al., 2021; Alvarez-Salgado et al., under review) in alignment with other disciplines, which rightly do not include shell $CaCO_3$ in CO_2 budgets. Calcification removes inorganic carbon (HCO_3^-) but not CO_2 from the water column and consequently shell $CaCO_3$ does not reduce the carbon footprint because it does not contribute to reduce atmospheric CO_2. Furthermore, when bivalve shells are incinerated together with organic wastes in municipal waste management plants, they release CO_2 according to the equation $CaCO_3 \rightarrow CO_2 + CaO$, increasing the overall carbon footprint of shellfish aquaculture in cradle-to-grave estimates considerably. However, using shell $CaCO_3$ in industrial applications that ensure the inertization of this $CaCO_3$ for prolonged periods of time, will contribute to avoid this carbon footprint increase (Alonso et al., 2021). In any case, the most effective way to cancel out the carbon footprint associated to shell synthesis (i.e. the release of CO_2 during shell formation, see above) would be returning the shells to sea, where eventual dissolution of the shell $CaCO_3$ would take place in carbonate undersaturated waters (Alvarez-Salgado et al., under review).

Concerning the cradle-to-farm gate CF associated with capital goods (e.g., ships, mussel rafts, etc.) and operations in shellfish aquaculture activities, a literature review covering the species, geographical areas and cultivations methods relevant for AquaVitae CS was performed (see supplementary Table S4). Estimation of CF associated to capital goods and operations for offshore sugar kelp production (CS2) was provided by Ocean RainForest. The carbon footprint of fertilizers production should also be included in the cradle-to-farm gate CF of abalone in IMTA (CS3). Capital goods have rarely been estimated, and were therefore excluded from further analysis. These cradle-to-farm gate CF from operations (O-CF) was added to the biological CF (B-CF) to obtain a total cradle-to-farm gate CF (B-CF + O-CF) estimate that can be compared with the CF of other food production systems. All formulas used in the calculations can be found in Table S5 in appendix A.

5.1.3 Market application and value

Data on biomass production and respective market value (at farm gate) were provided by AquaVitae partners, primary CS leaders, full industry partners and industry reference group partners, as well as other external industry partners, or obtained from the literature (see supplementary Table S3). Major secondary data sources included FAO statistics[7] and EUROSTAT[8]. The market value of the LTS under study were usually reported in the respective local currency. Exchange rates found on the European Central Bank webpage were applied to convert all other currencies into euros (EUR). Oyster prices were typically provided per individual oyster, hence prices were recalculated to EUR/kg FW based on market sizes for comparative purposes. Prices in EUR/kg flesh (edible part) were also estimated to obtain its value per unit of food.

5.2. Results and discussion

Based on the obtained data, analyses were done on different geographical scales from local (farm specific data, CS2 and CS3), to regional (organism groups farmed in different geographical areas, CS8 and CS9) and transatlantic (based on yearly overall production of each organism group). The selected cases were confronted with different challenges in terms of data acquisition. It was apparent that for emerging activities such as kelp production and IMTA of abalone and *Ulva*, literature data were limited and data were consequently, received primarily on farm level, and there were, not unexpectedly, not sufficient data to achieve replication on farm level. Consequently, for farm level data, extrapolations between geographical areas and to transatlantic scale was challenging and the results should be considered as examples representing unique cases. For well-established organism groups (e.g., oysters and mussels), this challenge could be addressed by combining data from literature (often based on production in areas where the species is produced extensively) and local data from areas where the species is underutilized. Consequently, this approximation resulted in a regional scope in contrast to the local scope of the farm data analysis.

General characteristics of LTS aquaculture that impacts NCP contributions

Some characteristics of the shellfish aquaculture systems under study (abalone, oysters and mussels) are expected to have a significant role in their NCP contribution. These parameters were flesh yield, organic to inorganic shell ratios, culture length and O-CF (Figure 6). Accordingly, the flesh yield (reported as wet weight of meat in relation to total wet weight) was observed to vary between species, locations and culture practices. Abalone (40%) and mussels (25–49%) had higher meat content than oysters (16–29%). These differences, as well as the higher organic content of abalone and mussel shells (≈5%) in comparison with oysters (1%), were, consequently, reflected in the contribution of each culture system to nutrient removal and in its carbon footprint. Figure 6 (center) shows that abalone required by far the longest time from initiation of grow-out to market size, almost 1 500 days

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[7] https://www.fao.org/fishery/statistics-query/en/aquaculture
[8] https://ec.europa.eu/eurostat/web/fisheries/overview

(approximately 4 years), however, the culture lengths can vary between locations and culture practices similarly to the ones observed for mussels and oysters, with shorter cycles in tropical (Brazil) and warm temperate (southern Europe) areas and longer cycles in colder temperate regions (Scandinavia). These differences have a significant impact on the biological carbon footprint of bivalves, as the longer the culture cycle, the larger the CO_2 release by respiration. The carbon footprint of calcification also increased with latitude given its dependence on seawater temperature. Finally, operations linked to oyster aquaculture had a higher carbon footprint (O-CF) than those required for the culture of abalone and mussels (Figure 6, right).

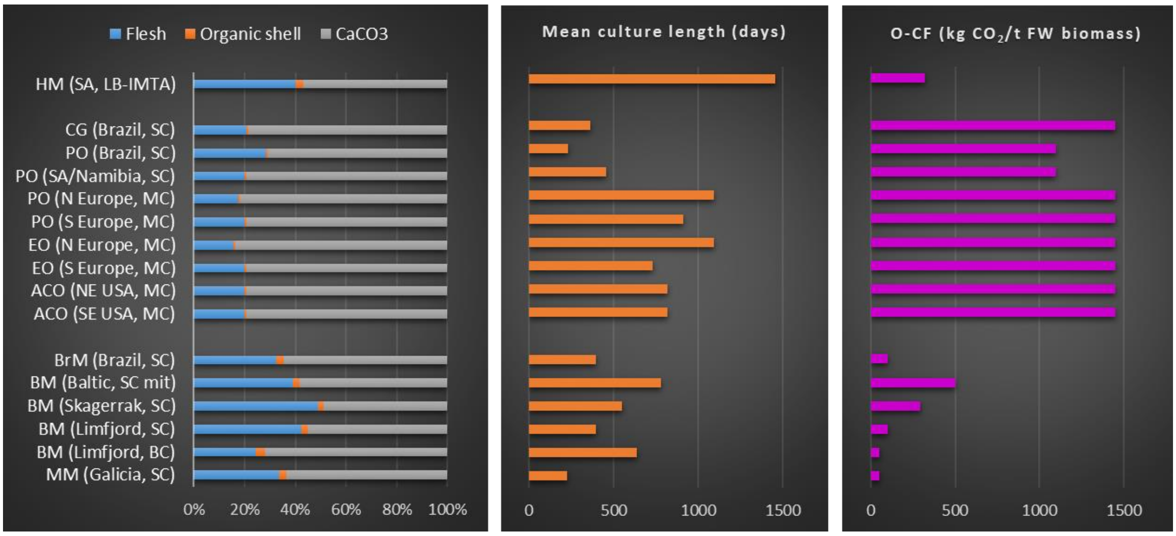

Figure 6. Proportions of flesh (FW) and organic and inorganic ($CaCO_3$) shell content (left), length of the culture cycle (days) from initiation of grow-out to market size (center), and CO_2 release per t FW of harvested biomass associated to operations (O-CF [right]) for the different shellfish aquaculture production systems included in NCP quantification. HM: Haliotis midae (abalone); CG: Crassostrea gasar; PO: Pacific oyster; EO: European oyster; ACO: American cupped oyster; BrM: Brown mussel; BM: Blue mussel; MM: Mediterranean mussel. N: northern, S: southern, NE: northeaster; SE: southeastern; SC: suspended culture, BC: bottom culture; and MC: mixed culture (SC and BC); mit: mitigation of eutrophication.

5.2.1 Nutrient budget (N and P) and Eutrophication index (PO_4-eq)

<u>Nutrient budget of offshore kelp cultivation in the Faroe Islands (CS2, farm level data, local and transatlantic scope)</u>

One of the key environmental services provided by macroalgae farming is the bioremediation of nutrients. The nitrogen removal by sugar kelp, *S. latissima*, produced offshore at the Faroe Islands ranged from 2.46 to 2.57 kg per t of harvested FW biomass (Table S6). Considering the current annual production of 200 t of sugar kelp, this corresponds to a total N removal of 515 kg per year. Phosphorous removal was found to be 0.47 kg/t of harvested biomass, which corresponds to a total P removal of 93.6 kg per year at present production figures. Based on the current annual sugar kelp production of 376 t FW around the Atlantic (Araújo et al. 2021), and extrapolating the nutrient removal quantified in this report, it can be estimated that a total of 968 kg of N and P 176 kg of P may be removed for the entire Atlantic area by the current production.

Nutrient budget of land-based IMTA of abalone and *Ulva* in South Africa (CS3, farm level data, local scope)

Abalone culture is the only land-based and fed aquaculture production system analysed in this report. As for other fed aquaculture systems, analysis of the nutrient budget for the land-based IMTA in CS3 in South Africa showed a net release of N and P. The monoculture *Ulva* sp. cultured exclusively on artificial fertilizers presented a net release of nutrients, 21.1 kg of N and 9.2 kg of P per t FW of produced macroalgal biomass (Table S6). This net production is a result of the large amounts of fertilizers added to the system during the culture cycle, which is required to sustain the high growth rates of the macroalga. The abalone unit was responsible for a net release of 65.7 kg N and 15.5 kg P per t of abalone produced (Table S6). The net release of nutrients in effluents from the *Ulva* sp. farmed in the abalone effluent (IMTA) was lower compared to the monoculture of *Ulva*, and released 11.3 kg N and 3.4 kg P per t FW of produced macroalgal biomass. Consequently, IMTA culture of *Ulva* sp. reduced the net release of nutrients per unit of macroalgal biomass produced by approximately 46% and 63% for N and P, respectively, compared to the monoculture system of *Ulva* sp. Based on the reported annual production of 156 t of abalone, 660 t of *Ulva* sp. produced in IMTA and 120 t of *Ulva* sp. produced in monoculture, an overall net release of 20.3 t of N and 5.8 t of P was estimated for the entire farm annually.

In contrast to the kelp production analysis (CS2) in which the farm used in this analysis is a major contributor to the transatlantic production reported by FAO statistics, it should be noted that the estimations for the IMTA system were based on data from a production system representing 11% and 27% of the total abalone and *Ulva* production on a transatlantic scale, respectively, and it is unknown to what extent IMTA systems contribute to this production. There are also various configurations of land-based IMTA production systems for abalone along the Atlantic which may result in different outcomes. Consequently, extrapolation of farm data to regional analysis is not possible. It is clear, however, from the obtained data that significant benefits can be obtained through optimization of the production processes at farm level, e.g., through optimization of the production to increase the use of waste nutrients derived from abalone production, reduction of the supplementary use of fertilizers, and if technically feasible, removal of the use of fertilizers all together. This is also the case for this specific farm, where the work to optimize the use of nutrients and fertilizers and reduce the release of waste nutrients is already ongoing. Consequently, more data is needed to describe in more general terms the nutrient budgets of abalone/*Ulva* IMTA systems, and this CS should be regarded as a first example of nutrient budgets in this type of systems. Moreover, this CS also illustrates the applicability of NCP indicators as a tool to monitor farm development through improved production procedures.

Nutrient budget of oysters (CS8, regional and transatlantic scale)

All analysed oyster culture systems showed a net removal of N and P which indicates a nutrient biomitigation potential. N removal by harvested Pacific oysters (*C. gigas*) and American cupped oysters (*C. virginica*) farmed in the North Atlantic (i.e., North America and Europe) was very similar and ranged between 5.67-7.2 kg N per t FW of harvested biomass (meat + shell, Table S6). Nitrogen removal in Pacific oysters in South Africa and Namibia was also within this range of values (5.84 kg N per t FW biomass), while the same species cultured in Brazil demonstrated somewhat higher values, 9.37 kg N per t FW biomass. Similarly, the native oyster *C. gaza*r in Brazil also had a higher N removal compared to oysters in Northern Atlantic and Africa (8.52 kg N per t FW biomass).

Similarly, P removal in oysters differed between geographical regions with the highest values obtained in Pacific oysters in Brazil (1.32 and 1.4 kg P per t FW biomass for Pacific oysters and *C. gasar*, respectively), followed by American cupped oysters in North America (1.05–1.06 kg P per t FW biomass) and Pacific oysters in Europe (0.82 to 0.94 kg P per t FW biomass) to the lowest removal in oysters in South Africa and Namibia (0.80 kg P per t FW). The high nutrient removal in Brazilian oysters may be explained by the higher flesh yield reported for oysters farmed in this area (Figure 6, Table S3). In comparison to the *Crassostrea* genus, the native European oyster (*O. edulis*) in North and South Europe demonstrated lower nutrient removal, 4.68 to 4.87 kg N and 0.75 to 0.76 kg P per t FW biomass, which was largely explained by the lower burial rates of faeces and pseudofaeces in sediment.

Based on the above stated nutrient removal and total production of these oyster species in the Atlantic (233 276 t FW, average 2015–2019) as reported by FAO (2022), it was estimated that 1 525 t of N and 231 t of P may be removed from the ocean by oyster aquaculture on a yearly basis.

<u>Nutrient budget of mussels (CS9, regional and transatlantic scope)</u>

Finally, similar to the oyster production, mussel culture systems showed a net removal of N and P which again indicates a nutrient biomitigation effect (Table S6). The N removal by suspended cultured mussels was found to increase from Galicia (Spain, *M. galloprovincialis*, 11.3 kg N per t FW biomass) to the Limfjord (Denmark, *M. edulis*, 14.1 kg N per t FW biomass) to Skagerrak (Sweden, *M. edulis*, 15.1 kg N per t FW biomass) to the Baltic (Sweden, *M. trossulus*, 22.2 kg N per t FW biomass). Similarly, the P removal was also found to increase across this latitudinal gradient with 0.63, 0.83, 1.43, and 2.18 kg P per t FW biomass for mussels in Spain, Denmark, Skagerrak and the Baltic, respectively. Bottom culture of blue mussels (*M. edulis*) in the Limfjord, Denmark, removed similar levels of nutrients (11.7 kg N and 0.57 kg P per t of FW biomass) as Mediterranean mussels in Galicia. Finally, the P and N removal rates reported by Brown mussels (*P. perna*) cultured in Brazil were similar to those observed in the Skagerrak. The differences between geographical regions can, as for oysters, be related to differences in flesh yield and a higher N content in suspended compared to bottom cultured mussels, and higher P content in the flesh of mussels from the Skagerrak and the Baltic, and to the larger burial rates of faeces and pseudofaeces in sediment in the Baltic Sea and Brazil. Note that mussels in the Baltic Sea, which have reported the largest removal potential, are cultured for the sole purpose of eutrophication mitigation, unlike all other cases discussed in this report which are primary food production systems.

Based the total aquaculture production of mussels in the Atlantic (535 051 t FW; average 2015–2019) as reported by FAO (2022) and extrapolating the above stated nutrient removals it was estimated that 8 000 t of N and 623 t of P may be removed from the Atlantic Ocean annually by mussel aquaculture.

<u>Summary of Nutrient budgets</u>

To summarise, the nutrient extraction potential of different LTS increased from macroalgae (*S. latissimi*a, 2.46–2.57 kg N and 0.47 kg P per t FW biomass), to oysters (*Crassostrea* genus, 5.67–9.37 kg N and 0.8–1.32 kg P per t FW biomass) and to blue mussels (*Mytilus* complex, 11.3–22.2 kg N and 0.57–2.18 kg P per t FW biomass). Consequently, organism group had a greater impact on nutrient extraction potential than within genus differences between species. The nutrient extraction potential was found to be significantly impacted by flesh yield, although some differences in nutrient content of the flesh was also observed between geographical regions. The only system not observed to have a net extraction of nutrients was the land-based IMTA culture of abalone. Again, as state above, CS3 results were based on the production figures from one single land-based system, and is not claimed to apply to other system configurations.

Eutrophication index (PO_{4-eq} budget)

In accordance with the nutrient extraction potential, all LTS aquaculture systems studied in this report with the exception of abalone production in land-based IMTA demonstrated negative PO_{4-eq} budgets. In general, mussels presented the highest eutrophication mitigation potential (-16.0 to -6.7 g PO_{4-eq} per kg FW), followed by oysters (-8.0 to -4.3 g PO_{4-eq} per kg FW), and sugar kelp (-2.5 g PO_{4-eq} per kg FW [Figure 7]). The mussels farmed in the highly eutrophicated Baltic Sea for the sole purpose of nutrient mitigation presented the highest biomitigation potential among all LTS culture systems. When the PO_{4-eq} budgets were weighted against unit of food produced (edible part of the product only) the mitigation effect of oysters (-38.1 to -21.8 g PO_{4-eq} per kg food) was comparable to, and for some species and locations even higher, than that of mussels (-32.4 to -20.0 g PO_{4-eq} per kg food) [Figure 8]. In contrast, abalone production in land-based IMTA (CS3) presented a net release of 168.4 g PO_{4-eq} per kg FW abalone, the equivalent to 421 g PO_{4-eq} per kg food. This can be explained by the input of nutrients and fertilizers to the system through the formulated diet fed to the abalone throughout the extensive 4-year production cycle, and by the fertilizers added to the *Ulva* production units. The production of *Ulva* was responsible for about 55% of the net PO_{4-eq} released. As highlighted in the nutrient (N and P) analysis section, results from CS3 were obtained based on data from one single land-based IMTA system, and are not claimed to represent other configurations found around the Atlantic. Additionally, optimization of production processes may significantly change the results and should be followed up in future studies.

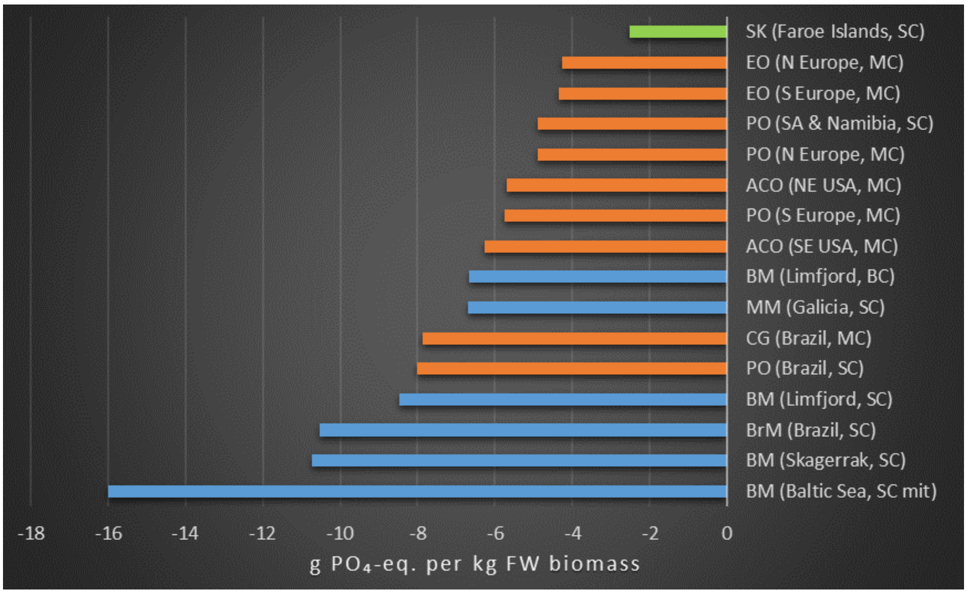

Figure 7. Eutrophication index measured in grams of phosphate equivalents (PO_4-eq) per kg FW of whole biomass of sugar kelp (green), oysters (orange), and mussels (blue). CG: Crassostrea gasar; PO: Pacific oyster; EO: European oyster; ACO: American cupped oyster; BrM: Brown mussel; BM: Blue mussel; MM: Mediterranean mussel. N: northern, S: southern, NE: northeaster; SE: southeastern; SC: suspended culture, BC: bottom culture; and MC: mixed culture (SC and BC); mit: mitigation of eutrophication.

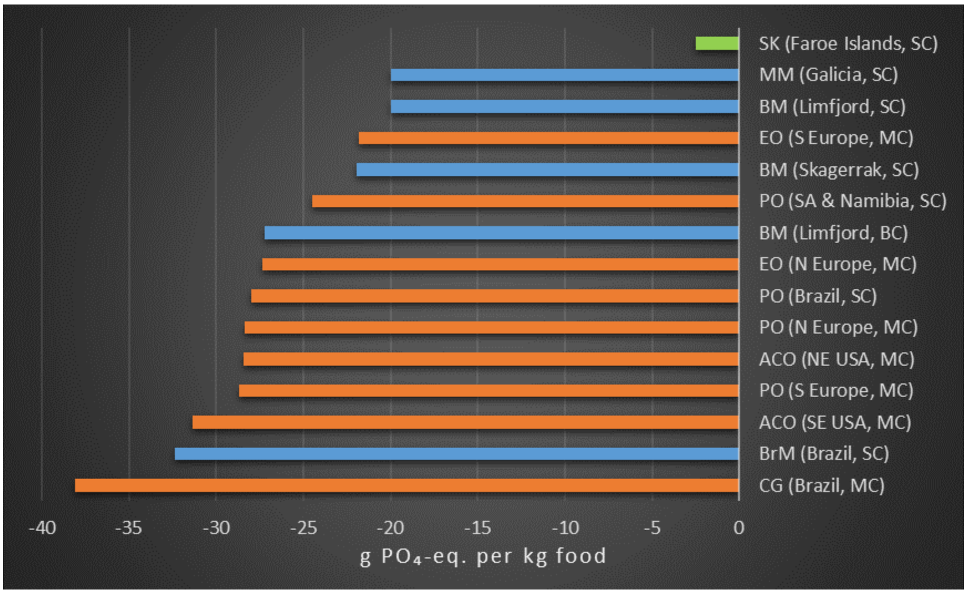

Figure 8. Eutrophication index measured in grams of phosphate equivalents (PO_4-eq) per kg of food (edible part, FW) from sugar kelp (green), oysters (orange), and mussels (blue, Baltic eutrophication mitigation culture excluded). CG: Crassostrea gasar; PO: Pacific oyster; EO: European oyster; ACO: American cupped oyster; BrM: Brown mussel; BM: Blue mussel; MM: Mediterranean mussel. N: northern, S: southern, NE: northeaster; SE: southeastern; SC: suspended culture, BC: bottom culture; and MC: mixed culture (SC and BC).

All LTS aquaculture systems in this report, with exception of CS3, performed better in terms of eutrophication potential compared to other food production systems (Figure 9). In fact, sugar kelp, oyster and mussel aquaculture presented net $PO_{4\text{-eq}}$ removals ranging from -2.52 to -38.09 g $PO_{4\text{-eq}}$ per kg food, and thereby, acted as biological nutrient mitigation tools. Production of one kg of sugar kelp mitigates the equivalent to the $PO_{4\text{-eq}}$ released by some vegetables and fruits e.g., root vegetable, citrus fruit, and apples (1.45–2.43 g $PO_{4\text{-eq}}$ per kg, Poore & Nemecek, 2018), while the production of one kg of mussels or oyster (flesh FW) mitigates the equivalent emissions to the production of one kg of rice or eggs (21.76–35.07 g $PO_{4\text{-eq}}$ per kg), and is close to mitigate the equivalent emissions derived from poultry meat (48.7 g $PO_{4\text{-eq}}$ per kg). The production of pig meat, farmed prawns and fish, and beef releases 76.4, 227.2, 235.1, and 301.4–365.3 g $PO_{4\text{-eq}}$ per kg of food product, respectively (Poore & Nemecek, 2018).

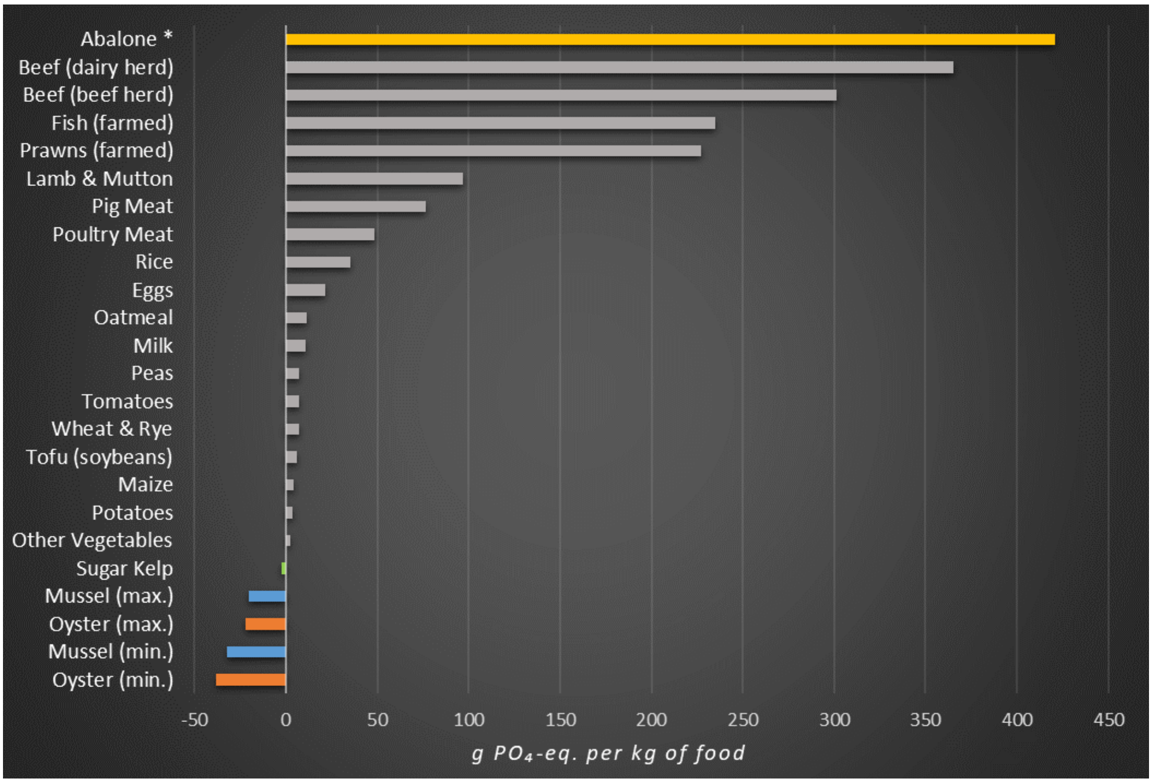

*Figure 9. Eutrophication index measured in grams of phosphate equivalents (PO_4-eq.) per kg of food (edible part, FW) from abalone (yellow), sugar kelp (green), mussels (blue, Baltic eutrophication mitigation culture excluded), and oyster (orange) aquaculture, compared to other food production systems (Modified from Poore & Nemecek, 2018). *Based on one single land-based IMTA system for abalone production, not claimed to be representative of the various abalone land-based IMTA system configurations around the Atlantic.*

5.2.2 Ocean acidification index (B-CO_2) and Biological carbon footprint (B-CF)

B-CO_2 and B-CF for Offshore kelp cultivation (CS2, farm level data, local and transatlantic scope)

The estimated B-CO_2 budget for the offshore cultivation of sugar kelp in Faroe Islands resulted in an ocean acidification index of -93.1 kg CO_2/t FW of harvested biomass (supplementary Table S6), equivalent to -18.6 t of CO_2 for the entire farm annually, i.e., a reduction of CO_2 and consequently the culture of sugar kelp counteracts ocean acidification.

The B-CF will depend on the fate of the biomass produced. If the biomass is sold for the food/feed market, which is at present the main application for sugar kelp produced by the industrial partner, then the C stored in the biomass is released back to the atmosphere in the form of CO_2 after consumption, which results in a neutral B-CF (0.0 kg CO_2/t of biomass). However, a rough estimation of the biomass lost during cultivation (i.e., fall off) of 5 to 10% has been made by the industry partner supplying the data. This may impact the B-CF but presently, the extent of production losses in terms of fall offs, as well as the fate of the fall offs (degraded in water column and/or sediment, preserved buried in the sediment), is unknown. Therefore, there is a need for empirical evaluation of these factors so its potential value as a carbon sink can be assessed.

B-CO_2 and B-CF for Land-based IMTA (CS3, farm level data, local scope)

The estimated B-CO_2 budget of abalone production resulted in an ocean acidification index of 78.3–269.6 kg CO_2 (low–high estimates) per t FW biomass. Additionally, its B-CF was estimated at 181–372 kg per t FW biomass. In contrast, the B-CO_2 of *Ulva* sp. produced in IMTA and monoculture systems was estimated to be negative at -125.4 and -113.7 kg of CO_2 per t of fresh biomass, respectively. However, since this biomass is readily used within the farm to feed the abalone, this CO_2 goes back to the atmosphere, and any local changes in water pH during *Ulva* culture are readily reversed, which makes both the acidification index (B-CO_2) and the B-CF of *Ulva* sp. production neutral (0.0 kg CO_2/t of FW biomass [Table S6]). Consequently, the B-CF for the entire farm was determined by the farming of abalone. Based on the annual production of abalone, an annual B-CF of 28.2 to 58.0 t of CO_2 was estimated for the entire farm. A closer look into the different processes that contribute to the B-CF of the abalone production showed that calcification and respiration contributed roughly equally to this. As discussed in Section 3.2 it is possible that the particulate organic material produced in land-based IMTA systems with abalone could potentially be a source of soil or sediment formation depending on end use of that product. This in turn affects the potential contribution to carbon sequestration. There is, today, not enough data to determine the fate of C in sludge from the farm, and this should be evaluated further for enhanced calculations of the overall B-CF of land-based IMTA systems. Consequently, as for kelp production, due to data deficiencies C burial from sludge deposits was not included in the analysis.

B-CO_2 and B-CF for Oysters (CS8, regional and transatlantic scope)

The balance between CO_2 storage, burial and calcification (B-$CO_{2\text{-low}}$) showed a net CO_2 release for all oyster production systems. Differences in the acidification index were mostly related with the geographic culture area, lower B-$CO_{2\text{-low}}$ were found for Pacific oysters and *C. gasar* in Brazil (22.0–48.1 kg CO_2/t FW biomass), intermediate values (128.3–160.4 kg CO_2/t FW biomass) were found for American cupped oysters from the Northern and Southern Atlantic coast of USA, for European oysters in Southern Europe, and for Pacific oysters in Southern Europe and South Africa, whereas higher values (198.5–217.4 kg CO_2/t FW biomass) were found for European oysters and for Pacific oysters in North Europe (Figure 10, Table S6). These results are mostly explained by the shorter production cycle and the higher burial rates reported for oysters from Brazil compared to the oysters from North Europe which had longer production cycles and higher calcification rates (Figures 6 and Table S3). Incorporation of the CO_2 release linked to respiration (B-$CO_{2,\text{ high}}$) resulted in a large increase of the B-CO_2 budget of all oyster production systems, with the highest impact for Pacific oysters in Brazil (191.8 kg CO_2/t FW biomass), and American cupped oysters on the east coast of the northern and southern parts of North America (300.2–336.6 kg CO_2/t FW biomass), followed by *C. gasar* in Brazil (171.2), Pacific oysters in South Africa and Namibia (296.0) and southern Europe (276.7), and the lowest for Pacific oysters from northern Europe (299.9 kg CO_2/t FW biomass) and European oysters from the northern (314.7 kg CO_2/t FW biomass) and southern parts of Europe (248.2 kg CO_2/t FW biomass).

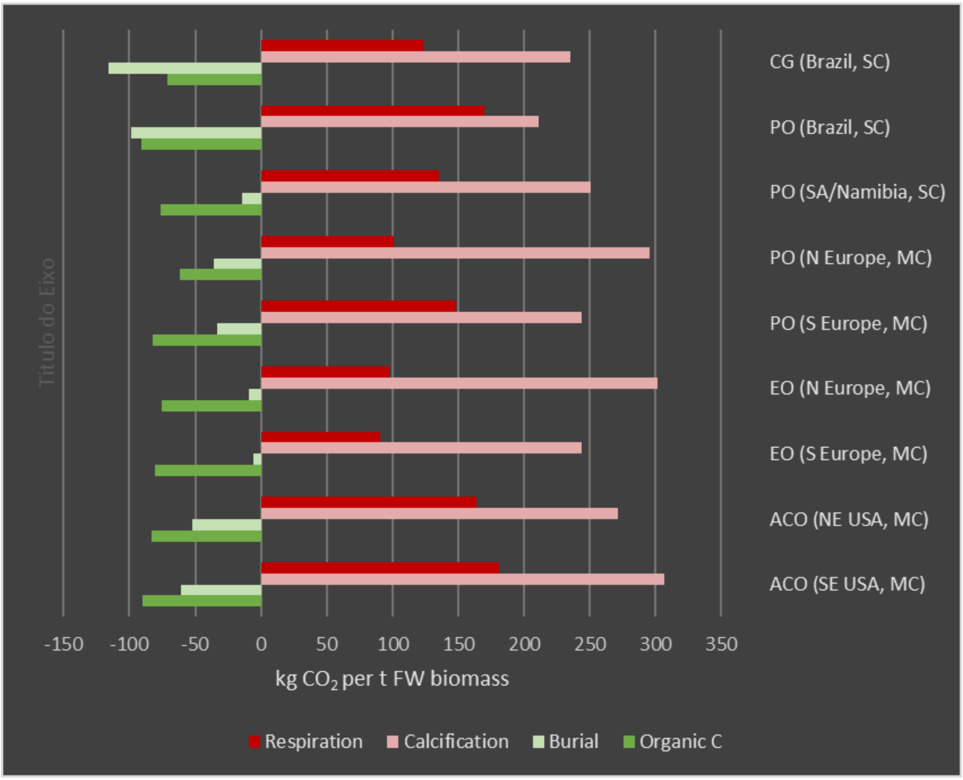

Figure 10. Contribution of the different processes for the B-CO_2 (acidification index, kg CO_2 per t FW biomass; shell-on) of oyster production systems. CG: Crassostrea gasar; PO: Pacific oyster; EO: European oyster; ACO: American cupped oyster; N: northern, S: southern, NE: northeaster; SE: southeastern; SC: suspended culture, BC: bottom culture; and MC: mixed culture (SC and BC).

In the B-CF, CO_2 release by calcification was larger than CO_2 removal through the burial of biodeposits resulting in positive B-CF for all oyster production systems (Figure 10). Culture of Pacific oysters and *C. gasar* in Brazil had the lowest B-CF among all studied oyster culture systems, species and geographic regions (Figure 11). The B-CF increased considerably when the contribution of respiration was added to obtain the B-CF_{high}.

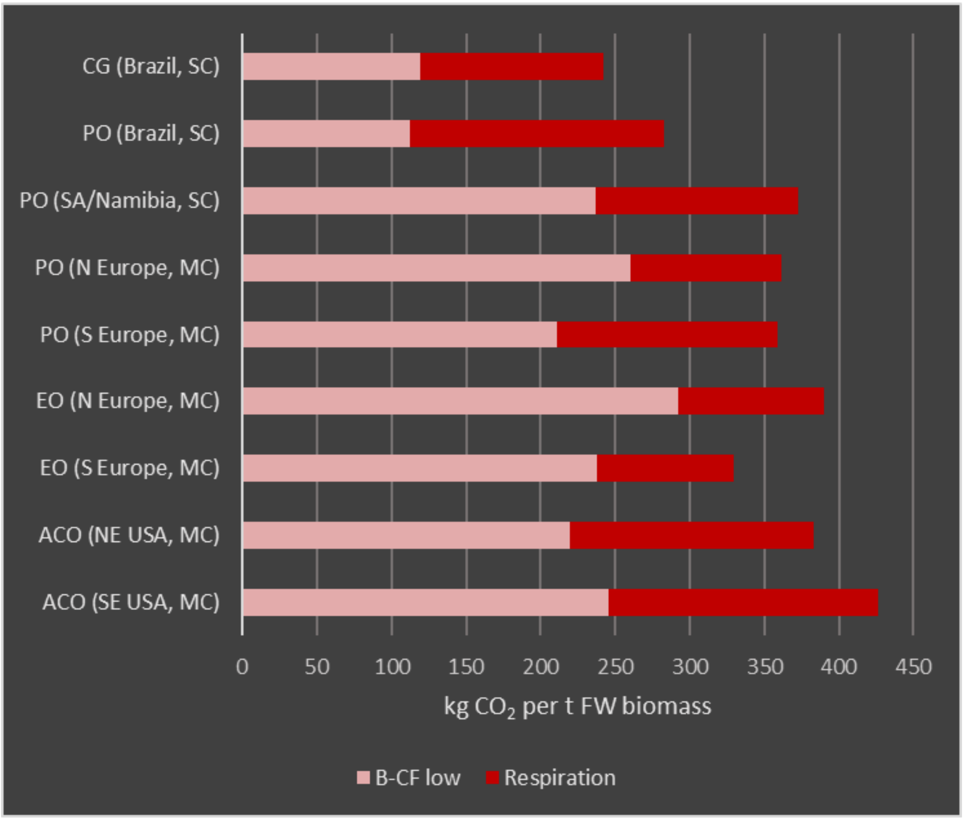

Figure 11. Lower estimate of the biological carbon footprint (B-CF$_{low}$ [pink]) + respiration (red) from oyster production systems (kg CO_2 per t FW biomass, shell-on). CG: Crassostrea gasar; PO: Pacific oyster; EO: European oyster; ACO: American cupped oyster; N: northern, S: southern, NE: northeaster; SE: southeastern; SC: suspended culture, BC: bottom culture; and MC: mixed culture (SC and BC).

B-CO_2 and B-CF for Mussels (CS9)

Suspended culture of Mediterranean mussels in Galicia (19.6 kg/t FW biomass) and bottom culture of blue mussels in the Limfjord (57.9 kg/t of biomass) presented a net CO_2 release, when the balance between CO_2 stored as organic carbon in flesh and shell, burial and calcification was estimated (B-$CO_{2\text{-}low}$, Figure 12, Table S6). In contrast, the suspended culture of blue mussels in the Limfjord and other areas (-34.8 to -202 kg/t FW biomass) and brown mussels in Brazil (-66.8 kg/t FW biomass) presented a net CO_2 removal. These differences are determined by the low burial rate of biodeposits in Galicia and the combination of low meat content and a long culture cycle for bottom culture in the Limfjord (Figure 6). Incorporation of the CO_2 release linked to respiration (B-$CO_{2\text{-}high}$) reported a large increase of the B-CO_2 budgets, mainly for suspended cultured mussels in the Limfjord (310.5 kg/t of biomass), Skagerrak (220.6 kg/t of biomass) and Baltic Sea (129.6 kg/t), whereas respiration had a lower impact on the B-CO_2 budget of Mediterranean mussels in Galicia (125 kg/t of biomass) and brown mussels in Brazil (144 kg/t of biomass), as their culture cycles are shorter than those of blue mussel culture in the Limfjord and Skagerrak.

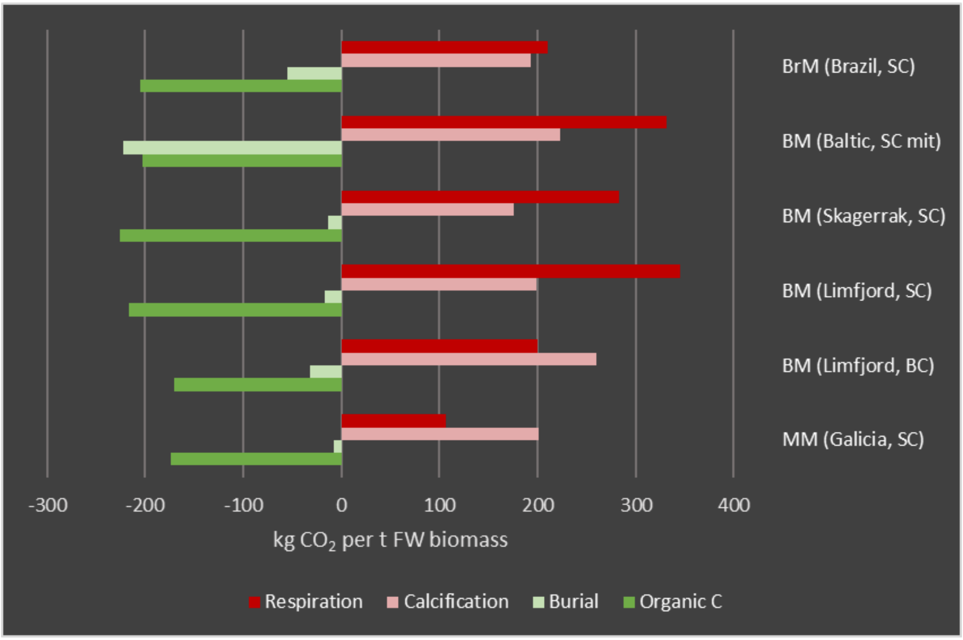

Figure 12. Contribution of the different processes for the B-CO2 (acidification index, kg CO_2 per t FW biomass, shell-on) of mussel production systems. BrM: Brown mussel; BM: Blue mussel; MM: Mediterranean mussel; SC: suspended culture, and BC: bottom culture; mit: mitigation of eutrophication.

Focusing on the B-CF, CO_2 release by calcification was larger than CO_2 removal through the burial of biodeposits resulting in positive B-CF_{low} for all mussel production systems, except the eutrophication mitigation culture in the Baltic that reports a null balance (Figure 12). When respiration is included in B-CF estimates (Figure 13), B-CF ranges from a minimum of 300 kg CO_2/t FW for the culture in the Galicia to >500 kg CO_2-eq/t FW for the suspended culture in Limfjord.

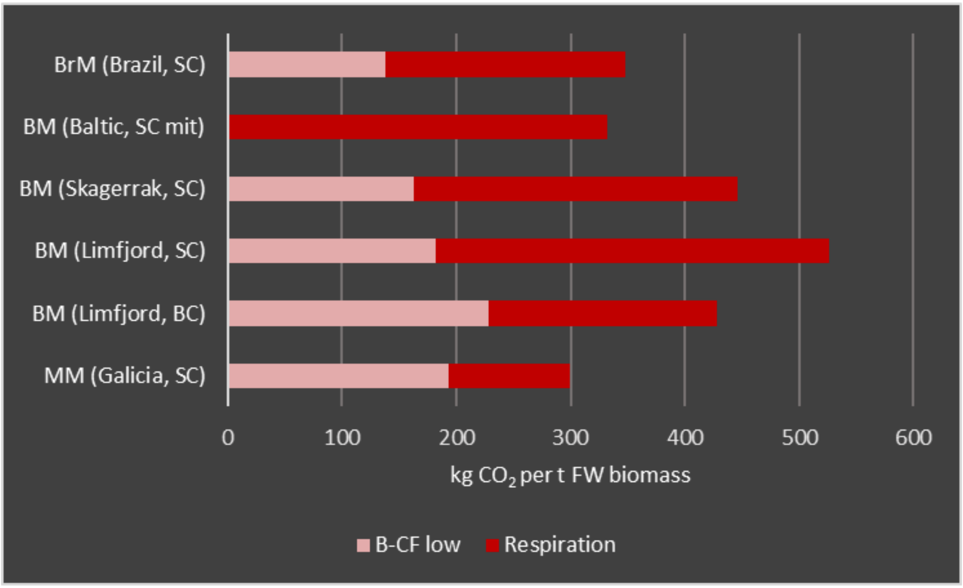

Figure 13. Lower estimate of the biological carbon footprint (B-CF_{low} [pink]) + respiration (red) from mussel production systems (kg CO_2 per t FW biomass, shell-on). BrM: Brown mussel; BM: Blue mussel; MM: Mediterranean mussel; SC: suspended culture, and BC: bottom culture; mit: mitigation of eutrophication

Summary of ocean acidification index (B-CO_2) and biological carbon footprint (B-CF)

In summary, these results report significant differences in acidification index and carbon footprint between different organism groups and culture systems. Production of sugar kelp, for instance, resulted in negative B-CO_2 values, i.e., reduction of ocean acidification, while mussels, oysters and abalone contributed to ocean acidification, although the contribution differed between species and geographical regions. Similarly, the B-CF ranged from neutral for kelp and blue mussels in the Baltic (for the low estimate of B-CF of mussels), to positive for the rest of the cases. These differences are linked to the biochemical composition of each species and the environmental conditions of the different culture areas. In this regard, calcification ranged from 176 to 307 kg CO_2 per t of FW, being higher for oysters than for mussels and abalone (Table S7). This is related to the lower flesh yield of oysters (16 to 29%) in comparison to mussels (25 to 49%) and abalone (40%). Respiration ranged from 91 to 345 kg CO_2 per ton of FW, and increased with latitude in parallel to the increased production time to market size. Finally, biodeposits burial ranged from 6 to 222 kg CO_2 per ton of FW, depending on the estimated burial rate in the different studied ecosystems. The relative contribution of the three processes to the B-CF ranged from 38 to 97% (calcification), 25 to 100% (respiration) and -2 to -67% (burial).

Cradle-to-farm gate total carbon footprint (CF)

The CF of operations (O-CF) was found to vary among culture method, e.g., higher O-CF for suspended than for bottom based culture systems, and across location, e.g., higher O-CF at high latitudes where production times are longer and require more operation. Based on the CF literature review (Table S4), an O-CF value of 50 kg CO_2 per t of FW was identified for the Mediterranean mussels cultured in Galicia (suspended culture) and abalone cultured in South Africa (land-based culture), 100 kg CO_2 per t of FW for suspended culture of blue mussels in Denmark and of brown mussel in Brazil, 290 kg CO_2 per t of FW for suspended culture of blue mussels in the Skagerrak, 500 kg CO_2 per t of FW for suspended culture of blue mussel for mitigation of eutrophication in the Baltic Sea, 1100 kg CO_2 per t of FW for bottom culture of American cupped oyster, Pacific oyster and European oyster, and 1800 kg CO_2 per t of FW for the same species in suspended culture. No data was found for bottom culture of mussels in the Limfjord, Denmark, hence that production type was excluded in further analysis.

Consequently, the relative importance of culture operations (O-CF) and the biological component (B-CF) of the CF of shellfish aquaculture was found to depend on the species, the culture method and the geographic location. The biological component was the main contributor to the CF for mussel aquaculture in Galicia (Mediterranean mussel), Denmark (Blue mussel) and Brazil (Brown mussel), representing from 58 to 90% of the total cradle-to-farm gate CF (Figure 14, Table S8). Conversely, the contribution was <40% for the blue mussels grown in the Baltic Sea to remediate eutrophication. For oyster aquaculture, the contribution of the biological component ranged from 8 to 25% (Table S8), indicating that most of the cradle-to-farm gate CF of oyster production systems was related to culture operations. Optimization of production procedures and consideration of climate impact of infrastructure and logistic solutions is therefore of high importance to improve the performance of e.g., oyster culture. Biological processes accounted for the 53% (35% if respiration was not included) of the CF for the IMTA abalone culture in South Africa, where the use of fertilizers was a major contributor to the O-CF. As highlighted before, results from CS3 were obtained based on data from one single land-based IMTA system, and are not claimed to representative of other configurations found around the Atlantic. Additionally, optimization of nutrient (i.e., fertilizers) use may be considered and possibly achieved for this specific production system.

Combination of the B-CF_{high} and cradle-to-farm gate O-CF enables a conservative comparison with other food production systems. The total CF for shellfish aquaculture ranged from 350 to 1 876 kg CO_2 per t of FW biomass or from 1 044 to 11 790 kg CO_2 per t of fresh food (edible part only). The total CF of mussels ranged from 1 044 kg/t food for the suspended culture of Mediterranean mussels in Galicia to 1 508 kg/t food for the suspended culture of blue mussels in Skagerrak, which was slightly lower than the 1 734 kg/t food of the IMTA of abalone in South Africa. The total CF of oysters ranged between 4 830 kg/t for Pacific oysters in Brazil and 11 790 kg/t for European oysters in northern Europe (Figure 14).

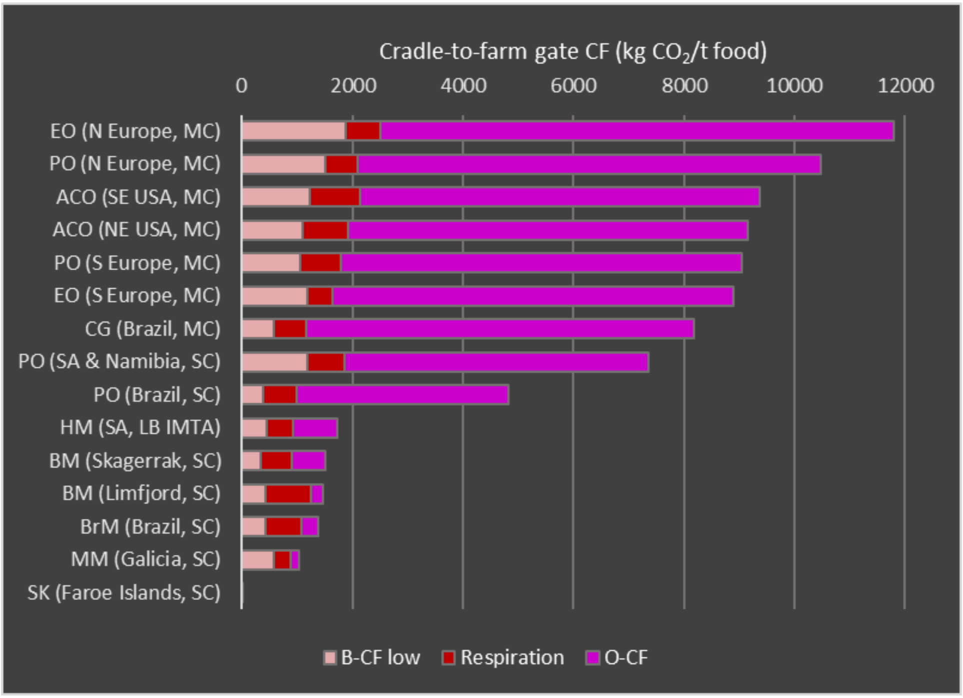

Figure 14. Cradle-to-farm-gate carbon footprint (CF, kg CO_2 per t FW food, edible parts only) of abalone, mussel (Baltic mitigation culture and bottom culture in Limfjord excluded), oyster and sugar kelp culture. B-CF_{low} (pink) + respiration (red) + operations (O-FC [violet]). HM: Haliotis midae (abalone); CG: Crassostrea gasar; PO: Pacific oyster; EO: European oyster; ACO: American cupped oyster; BrM: Brown mussel; BM: Blue mussel; MM: Mediterranean mussel; SK: sugar kelp (B-CF of kelp is neutral, so emissions come only from O-CF, the value, 16g CO_2/t FW, is not visible in the figure due to the scale used). N: northern, S: southern, NE: northeaster; SE: southeastern; SC: suspended culture; MC: mixed culture (SC and bottom culture); and LB IMTA: land-based integrated multi-trophic aquaculture.

Compared to other food production systems, sugar kelp (16 kgCO_2 per t of food) was observed to have the lowest carbon footprint, just higher than the CF of nuts and smaller than any other primary production system. Mussels and abalone are within the lowest CF production systems, equivalent to primary producers, while oysters are comparable to poultry and pig meat, essentially as a consequence of the low flesh yield of oysters, but lower than other farmed marine species (e.g., fish and prawns, Figure 15).

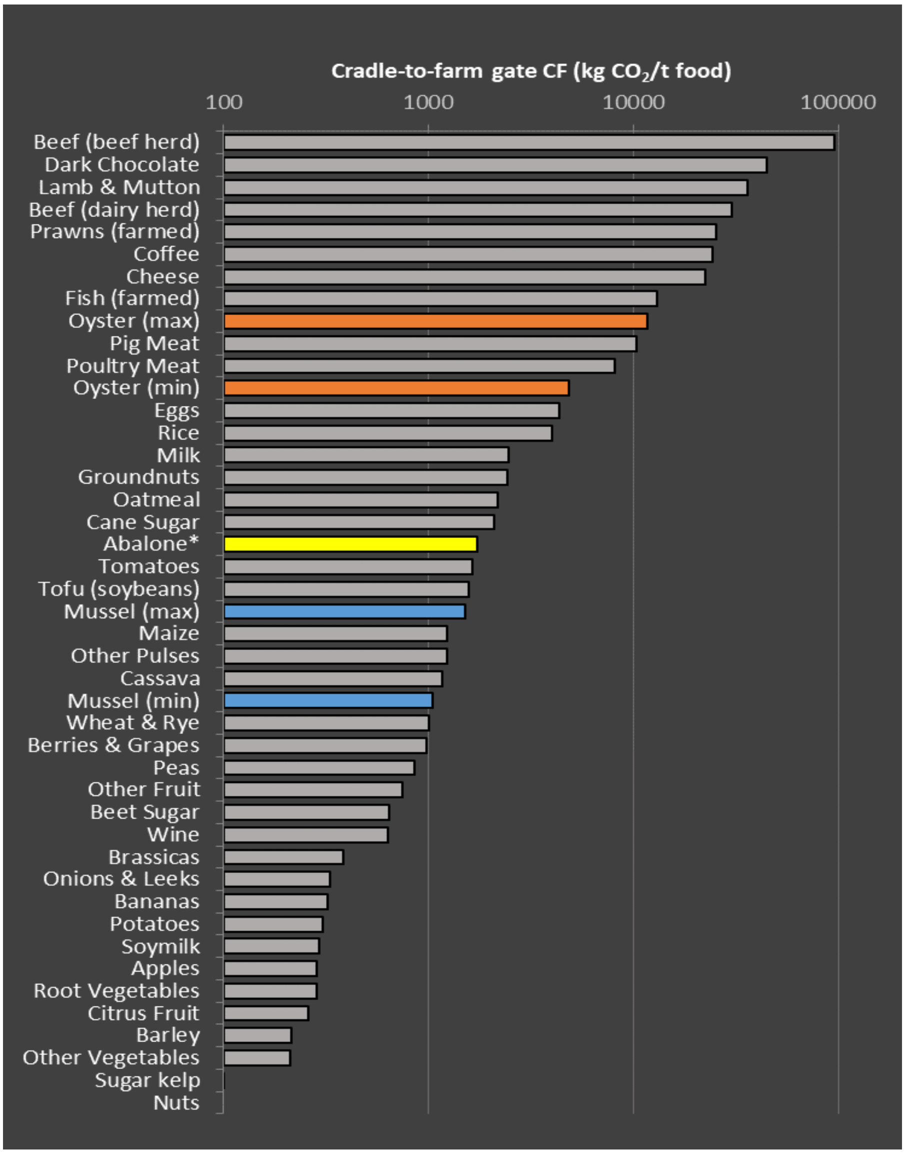

*Figure 15. Cradle-to-farm-gate carbon footprint (CF_{high} [kg CO_2 per t FW food]) of oyster (orange), abalone (yellow), mussels (blue, Baltic Sea mitigation culture and bottom culture in Limfjord excluded) and sugar kelp (green) aquaculture, compared to other food production systems (Modified from Poore & Nemecek, 2018). *Based on one single land-based IMTA system for abalone production, not claimed to be representative of the various abalone land-based IMTA system configurations around the Atlantic.*

5.2.3 Market application and value

Offshore kelp cultivation (CS2)

The majority of the kelp production is sold as a fermented feed ingredient to be incorporated in the production of commercial feed for the pig industry, due to its ability to reduce diarrhea and the use of antibiotics in pig production. Fresh biomass is stored in intermediate bulk containers (IBC) where the fermentation process is initiated using lactic acid bacteria before shipping to customers. The farm gate price for this biomass was not disclosed by the company, but this is a higher volume/lower value market (pers. comm. Urd Bak, ORF).

A small fraction of the production is sold to the European food ingredient market where it´s incorporated in the production of healthy food products. This is still a niche market, but it is growing rapidly. This biomass has a farm gate price of 10–20 EUR per kg of dried biomass, corresponding to 1.2–2.3 EUR/kg FW based on a moisture content of 88% (pers. comm. Urd Bak, ORF; Figure 16).

Land-based IMTA (CS3)

Farm gate price for abalone produced in South Africa ranges from 25 to 31 EUR/kg FW whole biomass (pers. comm. Peter Britz, Rhodes University; Figure 16, left). The current production is mainly exported, as the domestic market is very small. Most South Africans cannot afford the product, and as abalone is not a traditional food, consumer demand is not very high. South African abalone production targets the Asian markets that are willing to pay the premium price, e.g., Hong Kong, Singapore and Taiwan, where there is a tradition of eating abalone and preparing high-end dishes. Farm gate price converted to, and expressed, per unit of food (edible part only) reach 62–77 EUR/kg FW (Figure 16, right), which make abalone an expensive and exclusive delicacy. *Ulva* sp. biomass produced to supplement the aquafeed provided to the abalone during the culture cycle is valued at 0.95 EUR/kg FW (pers. comm. Emmanuel Falade, Rhodes University).

Oysters (CS8)

The market for oysters is very diverse and ranges from mature markets where oysters have been produced and consumed for a long time, to developing markets where oysters are considered a novel food. Farmed American cupped oysters are used mainly for the half-shell market or sold unprocessed as food. The reported farm gate price ranges from 9.4 to 13.5 EUR/kg FW whole biomass (shell-in; Figure 16, left), which corresponds to a paid price of 46.9 to 67.5 EUR/kg of food if considering only the edible parts (flesh; Figure 16, right) of the oysters. Farm gate price for Pacific oysters range from 4.0 to 4.4 EUR in southern Europe but can reach up to 7.2–16.7 EUR/kg FW in Skandinavia. In Skandinavia, production does not meet the market demand and most oysters are used for domestic markets. Imports come from major oyster producing countries in Europe (the Netherlands and France) and size 3 (approximately 60-80 g) are favoured. The price in South Africa ranges from 2.8–6.1 EUR/kg FW, the top selling oysters on the domestic market are about 70–90 gram and realize 0.44 EUR/oyster at farm gate. The domestic market is small, with the majority of South Africans being economically disadvantaged and not being traditionally accustomed to seafood. Exports are primarily to the East (Hong Kong, China, Taiwan) and are priced in USD landed at destination (pers. comm. Toni Tonin, Saldanha Bay Oyster Company). In Brazil, the price at farm gate ranges from EUR 0.78 to 2.8/kg FW for Pacific oysters (equivalent to 2.7–9.8 EUR/kg FW food). Consumers often buy the oysters directly from the farmer reaching a gate price of 2.8 EUR/kg FW (pers. comm. Simone Sühnel).

The European oyster is considered more exclusive compared to Pacific oysters and consequently acquire a premium price. Farm gate prices usually range from approximately 6 EUR/kg FW in southern Europe up to 19–31 EUR/kg FW in Sweden (pers. comm. Åsa Strand, IVL). This corresponds to a paid price of 30 EUR/kg FW food for European oysters produced in southern Europe and 121–200 EUR/kg FW food for European oysters produced in Sweden.

Mussels (CS9)

Mediterranean mussels in Galicia are produced for human consumption. Around 61% of the total production is consumed unprocessed, with farm gate prices ranging from 0.42 EUR/kg (small mussels, 5-6 cm) to 0.59 EUR/kg FW whole biomass (large mussels, ≥ 7.5 cm), the remaining 39% is sold to the food processing industry with a mean price of 0.40 EUR/kg (Pesca de Galicia[9]).

Farm gate price for mussels produced in suspended culture in Europe ranged from 0.48 EUR/kg FW for Mediterranean mussels to 1.9 EUR/kg FW for blue mussels from Skagerrak (pers. comm. Anton Salgado, IIM-CSIC), which corresponds to 1.5 to 3.9 EUR/kg FW food (edible part only), respectively. Farm gate prices obtained for blue mussels from suspended culture in the Limfjord (Denmark) start at 0.9 EUR/kg FW (pers. comm. Pernille Nielsen, DTU), yielding approximately 2.12 EUR/kg FW food. The price obtained for the mussels farmed in bottom culture in the Limfjord is lower (0.35–0.4 EUR/kg FW; equivalent to 1.4–1.6 EUR/kg food) as a result of lower flesh yield proportion (condition index). A large variation in farm gate prices was reported for brown mussel produced in Brazil ranging from 0.3 to 3.1 EUR/kg FW (pers. comm. Simone Sühnel). It is also common that consumers buy brown mussels directly from the farmers in which case the paid price usually is around 1.9 EUR/kg FW.

Summary of market application and value

To summarise, the farm gate value of farmed LTS differed greatly among organism groups and geographical regions (Figure 16, left). Overall, farm gate prices for sugar kelp (1.2–2.3 EUR/kg FW) and mussels (0.3–3.1 EUR/kg FW) were in the same order of magnitude, and were in the lower end of values reported to be paid for the different LTS investigated in this report. Generally, oysters presented significantly higher values but with large variation between species and geographic regions, e.g., Pacific oysters from southern Europe, Brazil, or South Africa and Namibia was observed to have lower farm-gate values, whereas the highest prices were paid for the European oyster produced in northern Europe, as this native species is considered a more excusive product in this region and receives a premium price. Abalone presented a significantly higher farm gate value compared with all other production systems, with the exception of European oysters produced in North Europe. Considering only the edible part of shellfish the estimated corresponding paid prices ranged from 0.92 to 9.5 EUR/kg FW food for mussels, 2.7 to 200 EUR/kg FW food for oysters, and 61.6 to 77.1 EUR/kg FW food for abalone (Figure 16, right). Thus, sugar kelp and mussels seem to be affordable food sources, some oyster species from specific geographic regions can represent an affordable food source, while for other oyster species and locations they can be a rather expensive delicacy. Similarly, abalone produced in South Africa is a rather expensive food aimed for the exports market. High farm gate prices are obviously beneficial from a farm perspective, but may reduce the access to the products by local markets and/or customers. The prices may also be affected by an increase in production according to general economic principles of access and demand, as well as by economies of scale, which may have significant impact on farm economics as production is increased.

[9] https://www.pescadegalicia.gal/Publicaciones/AnuarioAcuicultura2020/indice.html

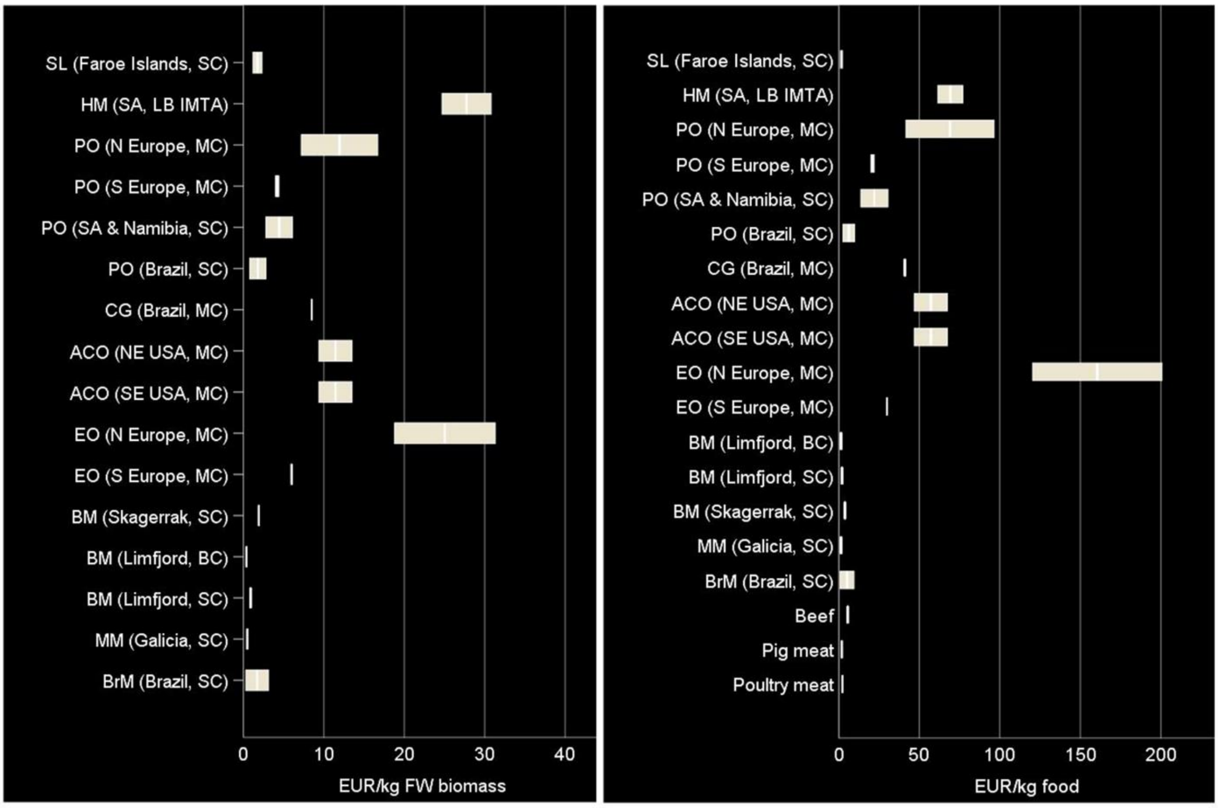

Figure 16. Farm-gate price for TLS biomass (EUR/kg FW whole biomass; i.e., shell-on for shellfish [left]), and food (EUR/kg FW food; i.e., shell-off for shellfish [right])

6. Concluding remarks and future perspectives

Knowledge gaps and data deficiencies

Overall, a high number of NCPs were identified for the LTS systems included in this report. Most of these were supported by sufficient data to verify the existence of the NCPs, yet some lacked enough data for quantification, mostly linked to the lack of maturity of these particular industries (e.g., sea urchin roe enhancement). There were also some ambiguities observed in terms of linkages between NCPs and different LTS culture systems, indicating either a knowledge gap or a need for additional clarifications of the definitions of the NCPs adapted to LTS aquaculture. In particular cultural NCPs specific to LTS production were found to be poorly investigated, with very few studies addressing the identification of these NCPs, and quantification mostly non-existent. Moreover, the developed indicator set for NCP quantification highlighted several critical knowledge gaps, including the NCP indicators required to quantify the role of LTS aquaculture systems for *Habitat creation and maintenance*, *Regulation, formation, protection, and decontamination of soils and sediments,* and *Regulation of hazards and extreme events* (see Table 6). In addition to these aspects, the data collection process for the final NCPs selected revealed additional data deficiencies. These related specifically to biomass falls offs and its fate (i.e., degraded in water column and/or sediment, or buried in the sediment) during sugar kelp production, and the fate of sludge/sediment produced in land-based IMTA systems. This information was lacking for proper quantification of the value of this process as a nutrient and carbon sink, and the subsequent impact on the biological carbon footprint of these systems. Data deficiencies were also identified for some shellfish species in specific production areas with respect to the composition of shell, flesh and biodeposits (faeces and/or pseudofaeces), as well as specific respiration and faeces/biodeposit production rates covering the entire production cycles. This is not unexpected considering that LTS aquaculture is an emerging sector in new geographical areas, yet these knowledge gaps should be filled through comprehensive studies in order to increase the robustness of future NCP quantification analysis.

Regulation of coastal water quality

The nutrient removal potential of different LTS production systems was found to increase from macroalgae (*S. latissima*, 2.46 to 2.57 kg N and 0.47 kg P per t FW biomass), to oysters (*Crassostrea* genus, 5.67–9.37 kg N and 0.8–1.32 kg P per t FW biomass) and to blue mussels (*Mytilus* complex, 11.3–15.1 kg N and 0.63–2.18 kg P per t FW biomass). Consequently, mussels presented the highest eutrophication mitigation effect (expressed as PO4-eq per kg FW), followed by oysters, and then by sugar kelp. Not unexpectedly, the nutrient extraction potential of mussels and oysters was closely linked to flesh yield and burial rates. Differences in yield were observed between different geographical regions (for the same species) and between species, indicating the importance of context relevant data for accurate evaluations of the nutrient remediation potential. The performance of abalone/Ulva IMTA systems is hard to evaluate in relation to other organism groups and production systems due to data deficiencies and ongoing improvement work in farm protocols. The results, however, indicate significant potential for optimization, and it is clear that more research is needed to evaluate the performance of similar systems.

Compared to other common food production systems, all LTS aquaculture systems in this report, with exception of CS3, presented negative PO_4-eq budgets (ranging from -2.52 to -38.09 g $PO_{4\text{-eq}}$ per kg food), and thus, may act as biological nutrient mitigation tools. In fact, production of one kg of sugar kelp can e.g., compensate for the PO_4-eq emissions of some vegetables and fruits such as root vegetables, citrus fruit and apples (1.45–2.43 g $PO_{4\text{-eq}}$ per kg; Poore & Nemecek, 2018), while the production of one kg of mussels or oyster (flesh FW) can compensate for the emissions from the production of one kg of rice or eggs (21.76–35.07 g $PO_{4\text{-eq}}$ per kg), and is close to mitigating the equivalent emissions derived from production of poultry meat (48.7 g $PO_{4\text{-eq}}$ per kg).

The results in this report agree with those observed for other species and in other geographical areas (Nelson et al. 2005, Newell et al. 2005, Higgins et al. 2011, Songsangjinda et al. 2000, Jones and Preston 1999, Gifford et al. 2004, Kotta et al. 2021). This mitigation effect is of great importance considering the current state of coastal areas, as 60% of these areas are estimated to suffer from eutrophication (Theuerkauf et al. 2019). Remediation of eutrophication may positively impact water quality, with direct benefits to nearby habitats, e.g., seagrass meadows, which in turn are important as nursery areas and for carbon sequestration (Cloern 1982, Cerrato et al. 2004, Newell 2004, Wall et al. 2008, Sousa et al. 2009, Cerco & Noel 2010). Consequently, extractive aquaculture conforms to the definition of restorative aquaculture ("when commercial or subsistence aquaculture provides direct ecological benefits to the environment, with the potential to generate net-positive environmental outcomes", The Nature conservancy, 2021). This infers significant values to society, and should consequently be a priority in present-day food production, especially in areas highly impacted by eutrophication.

Moreover, the uptake and incorporation of nutrients into extractive species has implications for the biogeochemical cycles of nitrogen and in particular, for phosphorous. While nitrogen can be fixed and transferred from air to the sea by cyanobacteria, phosphorous is a limited substance whose biogeochemical process spans thousands of years. Currently, phosphorous is mined from mountains, and projections states that given the current use, the phosphorous reserves will be depleted in approximately 50 years (Cordell et al. 2009, Sverdrup et al. 2013). This is often referred to as “the phosphorous crisis” as 80% or the phosphorous is used in agriculture (Achary et al. 2017), and then transported with runoff and nutrient leakage to the sea which acts as a phosphorous sink. The significance of this is indicated by the eutrophicating emissions from production of one kg of pig meat, farmed prawns or fish, and beef, ranging from 76.4 to 365.3 g $PO_{4\text{-eq}}$ per kg of food product (Poore & Nemecek, 2018). As apparent in the presented data in this report, extractive culture has the potential to act as a link between the sea and land, and contribute to loop closure by bringing nutrients back from the sea to different uses on land (Thomas et al. 2021, Sinha et al. 2022). Adhering to the planetary boundaries is of uttermost importance for our very existence (Steffen et al. 2015), and the potential of extractive species to support this objective should therefore be carefully considered and merits promotion in modern food production systems.

Regulation of climate change impacts and carbon footprint

The lower estimate of the ocean acidification index ($B\text{-}CO_{2\text{-low}}$) was highest for oysters (22.0–217.4 kg CO_2/t FW) and abalone produced in land-based IMTA (78.3 kg CO_2/t FW). In contrast, some mussel production systems (-202.0–57.9) and sugar kelp (-93.1 kg CO_2/t FW) presented negative ocean acidification index values, indicating that these species may contribute to counteracting ocean acidification. A more conservative estimate of $B\text{-}CO_2$, which incorporates respiration, resulted in a significant increase of the ocean acidification index ($B\text{-}CO_{2\text{-high}}$) for all shellfish species and, consequently, led to net emissions of $B\text{-}CO_2$ for all shellfish aquaculture systems (125–336 kg CO_2/t FW) while kelp net emissions remained unaltered.

The total CF_{high} (B-CF + O-CF) for shellfish aquaculture ranged from 350 to 1 876 kg CO_2 per t of FW biomass or from 1 044 to 11 790 kg CO_2 per t of fresh food (edible part only). The total CF of mussels ranged from 1 044 kg/t food for the suspended culture of Mediterranean mussels in Galicia to 1 508 kg/t food for the suspended culture of blue mussels in Skagerrak, which was slightly lower than the 1 734 kg/t food of the IMTA of abalone in South Africa. The total CF of oysters ranged between 4 830 kg/t for Pacific oysters in Brazil and 11 790 kg/t for European oysters in northern Europe.

As detailed above, the conservative estimates (CF_{high}) of cradle-to-gate carbon footprints of macroalgae and shellfish aquaculture reported net GHG emissions for all the species and culture practices under study, but with large differences between species and geographic areas. However, in comparison with other food production systems, LTS aquaculture has a low carbon footprint. In particular the carbon footprint of sugar kelp is one order of magnitude lower than the CF of vegetables (16 kg CO_2/t food vs more than 200 kg CO_2/t food). Mussel and abalone aquaculture, with a CF in the range of primary producers, provide nutrient rich food with much lower GHG emissions than any meat production industry. Finally, although the CF of oyster culture is larger than that of the other bivalve culture systems in this study, and comparable with poultry or pig farming, the large contribution of operations to this CF leaves room for managers to adapt their practices in order to improve the sustainability of this production system.

Food and Feed

Harvest of seafood that, on average, is from a lower trophic level has been recognized as a promising way to significantly increase food and biomass production (> 100 Mt) from the ocean. LTS production through marine aquaculture seems to have the highest potential to achieve such a realisation (SAPEA

2017). Farm gate prices converted to, and expressed, per unit of food produced (edible parts only) ranged from 1.2 to 2.3 EUR/kg FW for sugar kelp, 0.92 to 9.5 EUR/kg FW food for mussels, 2.7 to 200 EUR/kg FW food for oysters, and 62 to 77 EUR/kg FW food for abalone. Additionally, the *Ulva* sp. produced to feed to the abalone in land-based IMTA was priced at 0.95 EUR/kg FW. Variations in value are determined by geographic regions and species particularly for oyster production, e.g., Pacific oysters from southern Europe, Brazil, or South Africa and Namibia had the lowest values, while the highest prices were achieved for native European oysters from North Europe, which are considered a more exclusive product compared to the Pacific oysters. Thus, the LTS production system presented in this report have the capacity to provide affordable food (sugar kelp, mussels and to some extent oysters) and feed biomass (sugar kelp and *Ulva* sp.), but some LTS are also considered a delicacy food (oysters and abalone) usually exported to markets that are willing to pay the premium to supply e.g., high-end restaurants and hotels.

At present, the combined annual aquaculture production for the entire Atlantic region for the LTS included in this report reach 770 253 t FW biomass (average 2015–2019; FAO 2022), the equivalent to approximately 261 700 t FW of food (edible parts only). The highest production is presently mussels (214 020 t FW food), followed by oysters (46 655 t FW food), abalone (590 t FW food), and at last brown macroalgae (mostly kelp species; 450 t FW food). It should be noted that aquaculture production of kelp is still an emerging activity in the North Atlantic region, which gained increasing attention over the last decade and has the potential develop rapidly, and thereby, provide more food. The other LTS production systems are better established, and have the potential to further expend and provide more food.

Conclusions

Of the LTS evaluated in this report, sugar kelp production showed lower eutrophication mitigation potential than mussels and oysters and had a much lower farm-gate price compared to oysters and abalone, yet was found to be the only LTS to counteract ocean acidification. Bivalve production (mussel and oyster culture), on the other hand, was found to have a significant bioremediation capacity, with mussels displaying a higher capacity compared to all organism groups in this report. Compared to mussels, oysters obtained a higher farm-gate price, but also demonstrated a higher ocean acidification index, and the highest carbon footprint per unit of food produced among all LTS culture systems studied. In comparison, most mussel production systems had a lower ocean acidification index and a lower total carbon footprint per unit of food produced, than abalone and oysters. Abalone was the only LTS production system that showed a net release of nutrients, its ocean acidification index was set at the mid-range of values reported for oysters and at the upper range for mussels, and its carbon footprint per unit of food was similar to that reported for mussels, while its farm-gate-price was considerably higher and only comparable to premium price oysters from Northern Europe. In terms of the total carbon footprint, mussels and abalone were found to have the lowest CF reported for other food production systems, equivalent to primary producers, oysters were found to be comparable to poultry and pig meat, essentially because the low flesh yield of oysters, but lower than e.g., lamb, beef, or other farmed marine species (e.g., fish and prawns), while sugar kelp had a residual carbon footprint and consequently may support climate change mitigation.

The quantification of the selected list of NCPs offered by LTS aquaculture identified significant contributions to society, e.g., in terms of *Regulation of coastal water quality*, as well as sustainable feed and food supply. Some disservices were also identified, e.g., linked to the NCP *Regulation of* *climate* as the carbon footprint of bivalve culture was found to be in line with other traditional food sources, but lower compared to other meat food products. As illustrated in Table 7, the only production system providing only services (i.e., no disservices) in this study was sugar kelp production, while all other systems were found to have some services and some disservices. Based on the NCPs evaluated in this study, kelp production show great promise for future expansion, yet a full evaluation including additional sustainability indicators (i.e., also social and economic) should be performed to ensure that an expansion does not infer any unwanted, and unpredicted, negative effects. The results for the other organism groups are not unexpected. It is well established that all food production entails positive, as well as negative, impacts. As noted, both oyster and mussel production compared well to other food production sectors, and perform better than other meat production industries, and it is plausible that the impact from the production can be reduced by strategic investments in improved culture practices, infrastructure and logistics. Moreover, as stated previously, the results for land-based IMTA (abalone/*Ulva* co-culture) should be interpreted with caution. A more comprehensive analysis of the joint effects of services and disservices of different LTS aquaculture systems will be presented in D6.3 – sustainability analysis.

It is important to note that the services discussed in this report are primarily direct services. The contribution of LTS aquaculture to the NCPs from a larger perspective, i.e., including indirect services such as replacement of food products with higher CF or eutrophication index, has not been evaluated. This may, however, be an important aspect that although being complicated, should be studied further.

Table 7. Illustration of services (green) and disservices (orange) produced by LTS. For NCPs Regulation of costal water quality and Regulation of climate, the colours indicate a positive or negative contribution, while for Food and feed the colours represent value (farm perspective) and market application (consumer segment, i.e., low-end or high-end market.

NCP	Organism group	Kelp	Abalone/Ulva IMTA*	Oysters	Mussels
Regulation of coastal water quality	N and P removal	green	orange	green	green
	Eutrophication potential	green	orange	green	green
Regulation of climate	Ocean acidification index	green	orange	orange	orange
	B-CF	green	orange	orange	orange
Food and feed	Farm perspective (price)	green	green	green	green
	Costumer perspective (price)	green	orange	green	green

**Based on one single land-based IMTA system for abalone production, not claimed to be representative of the various abalone land-based IMTA system configurations around the Atlantic.*

As evident, the LTS studied demonstrated both services and disservices, and production should consequently be developed to promote the beneficial contributions while minimizing the negatives. It is worth mentioning that in addition to the above mentioned aspects, benefits from the LTS aquaculture systems presented in this report in relation to other common land-based food production systems include the lack of dependencies of large land areas for production and fresh water resources. In view of these results, a well-planned expansion of macroalgae and shellfish aquaculture together with campaigns that promote the consumption of these products may contribute to cover the increasing demand for food in the world while mitigating eutrophication effects and reducing the current contribution of food production systems to the global GHG emissions (29%, IPCC, 2021). This includes developing context-dependent recommendations for expansion of LTS aquaculture where regional differences related to species and system performance are accounted for. Moreover, future research efforts should focus on filling the identified knowledge and data gaps in order to allow for a more holistic assessment of NCPs provided by LTS aquaculture systems in relation to other food production systems.

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References

Achary et al. (2017) Phosphite: a novel P fertilizer for weed management and pathogen control. Plant Biotechnol. J. 15:1493-1508.

Alleway, H. K., Gillies, C. L., Bishop, M. J., Gentry, R. R., Theuerkauf, S. J., and Jones, R. (2019). The ecosystem services of marine aquaculture: valuing benefits to people and nature. Bioscience 69, 59–68.

Alonso, A.A., Álvarez-Salgado, X.A., Antelo, L., (2021). Assessing the impact of bivalve aquaculture on the carbon circular economy. J. Clean. Prod. 279, 123873.

Álvarez-Salgado X.A., M.J. Fernández-Reiriz, I. Fuentes-Santos, L.T. Antelo, A.A. Alonso, U. Labarta. CO2 budget and carbon footprint of mussels cultured in the highly productive Northwest Iberian upwelling system. Frontiers in Marine Sciences, accepted.

Araújo R., Vázquez Calderón F., Sánchez López J., Azevedo I.C., Bruhn A., Fluch S., Garcia Tasende M., Ghaderiardakani F., Ilmjärv T., Laurans M., Mac Monagail M., Mangini S., Peteiro C., Rebours C., Stefansson T., Ullmann J., (2021) Current Status of the Algae Production Industry in Europe: An Emerging Sector of the Blue Bioeconomy. Front. Mar. Sci. 7:626389.

Barrett, L. T., Theuerkauf, S. J., Rose, J. M., Alleway, H. K., Bricker, S. B., Parker, M., Petrolia, D. R., & Jones, R. C. (2022). Sustainable growth of non-fed aquaculture can generate valuable ecosystem benefits. *Ecosystem Services*, *53*, 101396.

Cerco, C.F., Noel, M.R. 2010. Monitoring, modelling, and management impacts of bivalve filter feeders in the oligohaline and tidal fresh regions of the Chesapeake Bay system. Ecol. Modell., 22: 1054–1064.

Cerrato, R., Lonsdale, D.J., Caron, D.A., Schaffner, A. (2004). Effect of the northern quahog Mercenaria mercenaria on the development of blooms of the brown tide alga Aureococcus anophagefferens. Mar. Ecol. Prog. Ser., 281: 93–108.

Christie, M., Martín-López, B., Church, A., Siwicka, E., Szymonczyk, P., and Mena Sauterel, J. (2019). Understanding the diversity of values of "Nature's contributions to people": insights from the IPBES Assessment of Europe and Central Asia. Sustain. Sci. 14, 1267–1282.

Cloern, J. E. 1982. Does the benthos control phytoplankton biomass in south San Francisco Bay? Mar. Ecol. Prog. Ser., 9: 191–202.

Cordell, D., Drangert, J.-O., White, S. (2009). The story of phosphorus: Global food security and food for thought. Global Environmental Change, 19(2), 292–305.

Costa-Pierce, B. A. (2010). Sustainable ecological aquaculture systems: The need for a new social contract for aquaculture development. Mar. Technol. Soc. J. 44, 88–112.

Costa-Pierce, B. A. (2016). Ocean foods ecosystems for planetary survival in the anthropocene. World Nutr. Forum, 301–320.

De Groot, R., Costanza, R., Braat, L., Brander, L., Burkhard, B., Carrasco, L., Crossman, N., Egoh, B., Geneletti, D., Hansjuergens, B., Hein, L., Jacobs, S., Kubiszewski, I., Leimona, B., Li, B., Liu, J., Luque, S., Maes, J., Marais, C., Maynard, S., Montanarella, L., Moolenaar, S., Obst, C., Quintero, M., Saito, O., Santos-Martín, F., Sutton, P., Van Beukering, P., Van Weelden, M. and Willemen, L., RE: Ecosystem Services are Nature's Contributions to People, SCIENCE, ISSN 0036-8075, 359 (6373), 2018, p. 270-272, JRC110922.

Díaz, S., Pascual, U., Stenseke, M., Martín-López, B., Watson, R. T., Molnár, Z., et al. (2018). Assessing nature's contributions to people. Science 359, 270–272.

Dunn, R. R. (2010). Global Mapping of Ecosystem Disservices: The Unspoken Reality that Nature Sometimes Kills us. Biotropica 42, 555–557.

Filgueira, R., Byron, C., Comeau, L., Costa-Pierce, B., Cranford, P.J., Ferreira, J., Grant, J., Guyondet, T., Jansen, H., Landry, T., others, 2015. An integrated ecosystem approach for assessing the potential role of cultivated bivalve shells as part of the carbon trading system. Mar. Ecol. Prog. Ser. 518, 281–287

Filgueira, R., Strohmeier, T., & Strand, Ø. (2019). Regulating Services of Bivalve Molluscs in the Context of the Carbon Cycle and Implications for Ecosystem Valuation. In Goods and Services of Marine Bivalves (pp. 231–251). Springer International Publishing.

Frankignoulle, M., Canon, C., & Gattuso, J. P. (1994). Marine calcification as a source of carbon dioxide: Positive feedback of increasing atmospheric CO2. *Limnology and Oceanography*, *39*(2), 458-462.

Froehlich, H. E., Afflerbach, J. C., Frazier, M., and Halpern, B. S. (2019). Blue Growth Potential to Mitigate Climate Change through Seaweed Offsetting. Curr. Biol. 29, 3087-3093.e3.

Gattuso, J.P., Epitalon, J.M., Lavigne, H., Orr, J., 2020. seacarb: seawater carbonate chemistry. R package version 3.2.13. http://CRAN.R-project.org/package=seacarb

Gentry, R. R., Alleway, H. K., Bishop, M. J., Gillies, C. L., Waters, T., and Jones, R. (2020). Exploring the potential for marine aquaculture to contribute to ecosystem services. Rev. Aquac. 12, 499–512.

GHK, & BioIS. (2006). Costs and benefits of the ELV directive. Annex 5 – Environmental impacts analysed and characterisation factors. https://ec.europa.eu/environment/waste/elv/study.htm

Gifford, S., R.H. Dunstan, W. O'Connor, T. Roberts and R. Toia. (2004). Pearl aquaculture-profitable environmental remediation. The Science of the Total Environment 319 (1-3): 27-37.

Grabowski, J. H., Brumbaugh, R. D., Conrad, R. F., Keeler, A. G., Opaluch, J. J., Peterson, C. H., et al. (2012). Economic Valuation of Ecosystem Services Provided by Oyster Reefs. Bioscience 62, 900–909.

Higgins CB, Stephenson K, Brown BL (2011) Nutrient bioassimilation capacity of aquacultured oysters: quantification of an ecosystem service. J Environ Qual 40:271−277

IPBES (2018) Summary for policymakers of the regional assessment report on biodiversity and ecosystem services for Africa of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. In: Archer E, Dziba LE, Mulongoy KJ, Maoela MA, Walters M, Biggs R, Cormier-Salem M-C, DeClerck F, Diaw MC, Dunham LAE, Failler P, Gordon C, Halmy MW, Harhash KA, Kasisi R, Kizito F, Mensah A, de T, Morais L, Nyingi WD, Oguge N, Osman-Elasha B, Stringer LC, Assogbadjo A, Egoh BN, Heubach K, Pereira L, Sitas N (eds). IPBES secretariat, Bonn, Germany

IPCC (2021): Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, et. al. (eds.)]. Cambridge University Press. In Press.

Jansen, H., van den Bogaart, L., (2020). Blue carbon by marine bivalves: Perspective of Carbon sequestration by cultured and wild bivalve stocks in the Dutch coastal areas. Wageningen Marine Research.

Jones, A.B. and Preston, N.P. (1999). Sidney rock oyster, Saccostrea commercialis (Iredale & Roughley), filtration of shrimp farm effluent: the effects on water quality. Aquacult. Res., 30: 51-57.

Kadykalo, A. N., López-Rodriguez, M. D., Ainscough, J., Droste, N., Ryu, H., Ávila-Flores, G., et al. (2019). Disentangling 'ecosystem services' and 'nature's contributions to people.' Ecosyst. People 15, 269–287.

Nelson K. A., Leonard L. A., Posey M. H., Alphin T. D., Mallin M. A., (2005). Using transplanted oyster (Crassostrea virginica) beds to improve water quality in small tidal creeks: a pilot study, Journal of Experimental Marine Biology and Ecology, Volume 298, Issue 2, Pages 347-368.

Kotta, J., Futter, M., Kaasik, A., Liversage, K., Rätsep, M., Barboza, F.R., Bergström, L., Bergström, P., Bobsien, I., Díaz, E., Herkül, K., Jonsson, P.R., Korpinen, S., Kraufvelin, P., Krost, P., Lindahl, O., Lindegarth, M., Lyngsgaard, M.M., Mühl, M., Sandman, A.N., Orav-Kotta, H., Orlova, M., Skov, H., Rissanen, J., Šiaulys, A., Vidakovic, A., Virtanen, E., (2020). Cleaning up seas using blue growth initiatives: mussel farming for eutrophication control in the Baltic Sea. Sci. Total Environ. 709.

Langton, R., Simona Augyte, Nichole Price, John Forster, Thomas Noji, Gretchen Grebe, Adam St. Gelais, and Carrie J. Byron. (2019). An Ecosystem Approach to the Culture of Seaweed. NOAA Tech. Memo. NMFS-F/SPO-195, 24 p

Millennium Ecosystem Assessment [MA] (2005) Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC. Pp 155.

Mascorda Cabre, L., Hosegood, P., Attrill, M.J., Bridger, D. and Sheehan, E.V. (2021), Offshore longline mussel farms: a review of oceanographic and ecological interactions to inform future research needs, policy and management. Rev Aquacult, 13: 1864-1887.

Morris, J.P., Humphreys, M.P., (2019). Modelling seawater carbonate chemistry in shellfish aquaculture regions: Insights into CO2 release associated with shell formation and growth. Aquaculture 501, 338–344.

Munari, C., Rossetti, E., Mistri, M., (2013). Shell formation in cultivated bivalves cannot be part of carbon trading systems: a study case with Mytilus galloprovincialis. Mar. Environ. Res. 92, 264–267.

Newell, R. I. E., T. R. Fisher, R. R. Holyoke & J. C. Cornwell, (2005). Influence of eastern oysters on nitrogen and phosphorus regeneration in Chesapeake Bay. In Dame, R. F. & S. Olenin (eds), The Comparative Rates of Suspension Feeders in Ecosystems. Springer, Dordrecht: 93–120.

Newell, R.I.E. (2004). Ecosystem influences of natural and cultivated populations of suspension-feeding bivalve molluscs: a review. Journal of Shellfish Research, 23: 51-61.

Pascual, U., Balvanera, P., Díaz, S., Pataki, G., Roth, E., Stenseke, M., et al. (2017). Valuing nature's contributions to people: the IPBES approach. Curr. Opin. Environ. Sustain. 26–27, 7–16.

Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. Science, 360(6392), 987-992.

R Core Team (2022). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.   URL https://www.R-project.org/.

SAPEA, Science Advice for Policy by European Academies (2017). Food from the oceans: how can more food and biomass be obtained from the oceans in a way that does not deprive future generations of their benefits? Berlin: SAPEA.

Schwinghamer, P., Hargrave, B., Peer, D., Hawkins, C. M. (1986). Partitioning of production and respiration among size groups of organisms in an intertidal benthic community. 31, 131–142.

Sinha, R., Thomas, J.-B.E., Strand, Å., Söderqvist, T., Stadmark, J., Franzen, F., Ingmansson, I., Gröndahl, F., Hasselström, L. (2022). Quantifying nutrient recovery by element flow analysis: Harvest and use of seven marine biomasses to close N and P loops. Resources, Conservation and Recycling, 178, 106031.

Songsangjinda, P., O. Matsuda, T. Yamamoto, N. Rajendran andH. Maeda (2000): The role of suspended oyster culture onnitrogen cycle in Hiroshima Bay. J. Oceanogr.,56, 223– 231

Sousa, R., Gutiérrez, J.L., Aldridge, D.C. (2009). Non-indigenous invasive bivalves as ecosystem engineers. Biol. Inv., 11: 2367–2385.

Steffen et al. 2015. Planetary Boundaries: Guiding human development on a changing planet. Science Vol. 347 no. 6223

Strand, Å., Rydstedt, A., Lindblom, E. (2022). Mapping existing and emerging LTS aquaculture in the Atlantic Region, AquaVitae, Tromsø, pp 18.

Sverdrup et al. (2013). Peak metals, minerals, energy, wealth, food and population; urgent policy considerations for a sustainable society. J. Earth Sci. Eng. (2013), pp. 499-534.

The Nature Conservancy. 2021. Global Principles of Restorative Aquaculture. Arlington, VA. Pp 81.

Theuerkauf, SJ, Barrett, LT, Alleway, HK, Costa-Pierce, BA, St. Gelais, A, Jones, RC. Habitat value of bivalve shellfish and seaweed aquaculture for fish and invertebrates: Pathways, synthesis and next steps. Rev Aquac. 2021; 14: 54– 72.

Thomas J-BE, Sinha R, Strand Å, et al. Marine biomass for a circular blue-green bioeconomy? A life cycle perspective on closing nitrogen and phosphorus land–marine loops. J Ind Ecol. 2021;1–18.

Turnhout, E., Waterton, C., Neves, K., and Buizer, M. (2013). Rethinking biodiversity: From goods and services to “living with.” Conserv. Lett. 6, 154–161.

Valenti, W. C., Kimpara, J. M., Preto, B. de L., and Moraes-Valenti, P. (2018). Indicators of sustainability to assess aquaculture systems. Ecol. Indic. 88, 402–413.

Schatte Olivier, A., Jones, L., Vay, L.L., Christie, M., Wilson, J. and Malham, S.K. (2020), A global review of the ecosystem services provided by bivalve aquaculture. Rev Aquacult, 12: 3-25.

Vélez-Henao, J. A., Weinland, F., & Reintjes, N. (2021). Life cycle assessment of aquaculture bivalve shellfish production—a critical review of methodological trends. The International Journal of Life Cycle Assessment, 26(10), 1943-1958.

Wall, C.C., Peterson, B.J., Gobler, C.J. (2008). Facilitation of seagrass Zostera marina productivity by suspension-feeding bivalves. MEPS, 357: 165-174.

Warmerdam, S., Vickers, J., and Palairet, N. (2021). Sustainability Engineer LCA of New Zealand Mussels & Oystes On behalf of Aquaculture New Zealand and the Ministry for Primary Industries, 137 pp.

Appendix A. Supplementary Tables

Table S1. *Definitions of NCPs adapted from Díaz et al. (2018) to the Low Trophic Systems (LTS) in the context of the AquaVitae project*

Number	*Reporting categories of NCPs*	*A brief explanation and some examples*	*Adapted Description of NCPs for LTS in the AquaVitae project*
1	Habitat creation and maintenance	The formation and continued production, by ecosystems or organisms within them, of ecological conditions necessary or favorable for living beings of direct or indirect importance to humans. E.g. growing sites for plants (12), nesting, feeding, and mating sites for animals, resting and overwintering areas for migratory mammals, birds, and butterflies (12, 13), roosting places for agricultural pests and disease vectors (14), nurseries for juvenile stages of fish (15-18), habitat creation at different soil depths by invertebrates (19).	The creation of the ecological conditions necessary or favorable for the living being direct or indirect by Low trophic Species Cultivation Systems deployment. E.g. An Open-ocean macroalgae farm provides a similar ecological structure as a natural macroalgae forest and may act as a habitat for other living beings.
2	Pollination and dispersal of seeds and other propagules	Facilitation by animals of movement of pollen among flowers (20-22), and dispersal of seeds, larvae or spores of organisms beneficial or harmful to humans (20, 23-28)	Facilitating the movement of propagules of organisms beneficial or harmful to humans. E.g., the presence of a cultivated species in an area might enhance the distribution of that species. (with positive or negative consequences)
3	Regulation of air quality	Regulation (by impediment or facilitation) by ecosystems, of CO2/O2 balance, O3, sulfur oxide, nitrogen oxides (NOx), volatile organic compounds (VOC), particulates, aerosols, allergens (29-34) Filtration, fixation, degradation or storage of pollutants	Regulation of the composition and particles in the air. Related to the production or assimilation of volatile compounds.
4	Regulation of climate	Climate regulation by ecosystems (including regulation of global warming) through positive or negative effects on emissions of greenhouse gases (e.g.	Climate regulation by Low Trophic Systems Production (including regulation of global warming) through positive or negative effects on emissions of greenhouse

		biological carbon storage and sequestration; methane emissions from wetlands) (32, 39-41)	gases (e.g. biological carbon storage and sequestration)
5	Regulation of ocean acidification	Regulation, by photosynthetic organisms (on land or in water), of atmospheric CO2 concentrations and so seawater pH, which affects associated calcification processes by many marine organisms important to humans (such as corals) (56-58)	Regulation, by photosynthetic organisms (on land or in water in Cultivation Systems), of atmospheric CO2 concentrations and so seawater pH, which affects associated calcification processes by many marine organisms important to humans (such as corals) (56-58)
6	Regulation of freshwater quantity, location, and timing (59)	Regulation, by ecosystems, of the quantity, location and timing of the flow of surface and groundwater used for drinking, irrigation, transport, hydropower, and as the support of non-material contributions (NCP 15, 16, 17) (60-62) Regulation of flow to water-dependent natural habitats that in turn positively or negatively affect people downstream, including via flooding (wetlands including ponds, rivers, lakes, swamps) (63-67) Modification of groundwater levels, which can ameliorate dryland salinization in unirrigated landscapes (68-71)	Regulation, by Low Trophic Cultivation Systems deployments, of the quantity, location, and timing of the flow of surface and groundwater. Regulation of flow to water-dependent natural habitats. Modification of groundwater levels.
7	Regulation of freshwater and coastal water quality	Regulation – through filtration of particles, pathogens, excess nutrients, and other chemicals – by ecosystems or particular organisms, of the quality of water used directly (e.g. drinking, swimming) or indirectly (e.g. aquatic foods, irrigated food and fiber crops, freshwater and coastal habitats of heritage value) (60, 72-76)	Regulation through filtration of particles, and natural processes, the excess nutrients, other chemicals or pathogens by Low Trophic Cultivation Systems and the particular organisms, that affects the quality of water used directly or indirectly (e.g. aquatic foods produced/cultivated, freshwater and coastal habitats of heritage value: Cultural value component)

8	Formation, protection, and decontamination of soils and sediments	Formation and long-term maintenance of soil structure and processes by plants and soil organisms. Includes: physical protection of soil and sediments from erosion (77, 78), and supply of organic matter and nutrients by vegetation; processes that underlie the continued fertility of soils important to humans (e.g. decomposition and nutrient cycling) (79-81); filtration, fixation, attenuation or storage of chemical and biological pollutants (pathogens, toxics, excess nutrients) in soils and sediments (81-85)	Formation and long-term maintenance of marine sediments and marine bottom by organisms that are on Low Trophic Cultivation Systems, by supplying organic or inorganic matter in a process that underlies the formation of sediments that might be important to humans. Also, filtration, fixation, attenuation, or storage of chemical and biological pollutants in the newly formed soil and sediments. (E.g., Shells from mollusc cultivation can contribute to the formation of sands, that can be extracted, have a role in the ecosystem or natural form sandy areas in the coastal line)
9	Regulation of hazards and extreme events	Amelioration, by ecosystems, of the impacts on humans or their infrastructure caused by e.g. floods, wind, storms, hurricanes, heat waves, tsunamis, high noise levels, fires, seawater intrusion, tidal waves (86-90) Reduction or increase, by ecosystems or particular organisms, of hazards like landslides, avalanches (91-94)	Amelioration, by the Low Trophic cultivation Systems, of the impacts on humans or their infrastructure caused by e.g. floods, wind, storms, hurricanes, heat waves, tsunamis, high noise levels, fires, seawater intrusion, tidal waves Reduction or increase, by Low Trophic Cultivation Systems of particular organisms, of hazards like landslides, avalanches.
10	Regulation of detrimental organisms and biological processes	Regulation, by organisms, of pests, pathogens, predators, or competitors that affect humans (materially and non-materially), or plants or animals of importance for humans. Also the direct detrimental effect of organisms on humans or their plants, animals or infrastructure	Regulation, by Low Trophic Cultivation Systems organisms, of pests, pathogens, predators, or competitors that affect humans (materially and non-materially), or another biodiversity of importance for humans. Also the direct detrimental effect of Low Trophic Cultivation Systems and its infrastructure on humans or other infrastructure or the

			biodiversity of importance to humans.
11	Energy	Production of biomass-based fuels, such as biofuel crops, animal waste, fuelwood, agricultural residue pellets, peat (119-123)	Production of biomass-based fuels, such as biofuel from macroalgae or animal waste.
12	Food and feed	Production of food from the wild, managed, or domesticated organisms, such as fish, bush meat and edible invertebrates, beef, poultry, game, dairy products, edible crops, wild plants, mushrooms, honey (22, 124-138) Production of feed (forage and fodder) for domesticated animals (e.g. livestock, work and support animals, pets) or for aquaculture, from the same sources (127, 128, 130, 139, 140)	Production of food from the cultivation of Low Trophic organisms for human consumption. Production of feed for domesticated animals (e.g. livestock, work and support animals, pets) or aquaculture, from the cultivation of Low Trophic organisms.
13	Materials, companionship, and labor	Production of materials derived from organisms in cultivated or wild ecosystems, for construction, clothing, printing, ornamental purposes (e.g. wood, peat, fibers, waxes, paper, resins, dyes, pearls, shells, coral branches) (119, 128, 141- 146) Live organisms being directly used for decoration (i.e. ornamental plants, birds, fish in households and public spaces), company (e.g. pets), transport, and labor (including herding, searching, guidance, guarding) (141, 147-157)	Production of materials derived from Low Trophic Cultivated organisms, for construction, clothing, printing, ornamental purposes (e.g. any material that is not edible: peat, fibers, waxes, paper, resins, dyes, pearls, shells, bio-plastics, alginates, pigments). Live organisms being directly used for decoration (i.e. ornamental plants of aquarofilia materials for households and public spaces).
14	Medicinal, biochemical resources	Production of materials derived from organisms (plants, animals, fungi, microbes) used for medicinal, veterinary, and pharmacological (e.g. poisonous, psychoactive) purposes. Production of genes and genetic information used	Production of materials derived from Low trophic Cultivated organisms (Macroalgae, shellfish, sea urchins, sea cucumbers, shrimp, and fin-fish) used for medicinal, veterinary, and pharmacological (e.g. poisonous, psychoactive)

		for plant and animal breeding and biotechnology (12, 158-164)	purposes. Production of genes and genetic information used for breeding and biotechnology for the cultivated organisms and further applications.
15	Learning and inspiration	Provision, by landscapes, seascapes, habitats or organisms, of opportunities for the development of the capabilities that allow humans to prosper through education, acquisition of knowledge and development of skills for well-being, information, and inspiration for art and technological design (e.g. biomimicry) (165-174)	Provision, by Low Trophic Cultivation Sites of opportunities for the development of the capabilities that allow humans to prosper through education, acquisition of knowledge and development of skills for well-being and thriving (capacity building), information, and inspiration for art and technological design. Allowing the further development of aquaculture and the inclusion of new species.
16	Physical and psychological experiences	Provision, by landscapes, seascapes, habitats or organisms, of opportunities for physically and psychologically beneficial activities, healing, relaxation, recreation, leisure, tourism and aesthetic enjoyment based on the close contact with nature (e.g. hiking, recreational hunting and fishing, birdwatching, snorkeling, diving, gardening) (175-187)	Provision, by Low Trophic Cultivation Sites of opportunities for physically and psychologically beneficial activities, healing, relaxation, recreation, leisure, tourism, and aesthetic enjoyment based on the close contact with Low Trophic Cultivation Sites.
17	Supporting identities	Landscapes, seascapes, habitats or organisms being the basis for religious, spiritual, and social-cohesion experiences: • Provisioning of opportunities by nature for people to develop a sense of place, belonging, rootedness or connectedness, associated with different entities of the living world (e. g. cultural, sacred and heritage landscapes, sounds, scents and sights associated with childhood experiences, iconic animals, trees or flowers) (187-	Low Trophic Cultivation Systems as the basis for social-cohesion experiences: • Provisioning of opportunities by nature for people to develop a sense of place, belonging, rootedness or connectedness, associated with different entities of the living world included the organism cultivated in LTS • Basis for narratives, rituals, and celebrations provided by landscapes, seascapes, habitats, species or organisms that are cultivated

		198) • Basis for narratives, rituals, and celebrations provided by landscapes, seascapes, habitats, species or organisms (13, 21, 169, 188, 189, 191, 199) • Source of satisfaction derived from knowing that a particular landscape, seascape, habitat or species exists (200, 201)	in LTS • Source of satisfaction derived from knowing that a particular Production system exists, and also proudness of having that type of cultivations systems.
18	Maintenance of options (202)	The capacity of ecosystems, habitats, species, or genotypes to keep options open in order to support a good quality of life. Examples include Benefits (including those of future generations) associated with the continued existence of a wide variety of species, populations, and genotypes. This includes their contributions to the resilience and resistance of ecosystem properties in the face of environmental change and variability (6, 7, 203-206) • Future benefits (or threats) derived from keeping options open for yet unknown discoveries and unanticipated uses of particular organisms or ecosystems that already exist (e.g. new medicines or materials) (5) • Future benefits (or threats) that may be anticipated from ongoing biological evolution (e.g. adaptation to a warmer climate, to emergent diseases, development of resistance to antibiotics and other control agents by pathogens and weeds) (5, 207)	The capacity of Low Trophic Cultivation Systems to keep options open in order to support a good quality of life. Examples include • Benefits (including those of future generations) associated with the learning and developing experience of this cultivation activity and the knowledge of these genotypes. This includes their contributions to the resilience and resistance of future cultivation systems in the face of hazardous events, disease outbreaks, or environmental change and variability. • Future benefits (or threats) derived from keeping options open for yet unknown discoveries and unanticipated uses of the cultivated organisms that already exist (e.g. new medicines or materials)• Future benefits (or threats) that may be anticipated from ongoing biological evolution (e.g. adaptation to a warmer climate, to emergent diseases, development of resistance to antibiotics and other control agents by pathogens and weeds)

Table S2. *Nature's Contributions to People Equivalencies to other ES frameworks (from CICES V 5.1).*

** More than one equivalency as it several services in one NCP; **[1] Suggested being added, as this Habitat and Biodiversity has an important cultural component as well; **[2] Suggested as Food also has a cultural component; **[3] Suggested as some materials from nature can also have a cultural value and represent a benefit. E.g. Using shells for church constructions (Galicia) or using macroalgae for roof isolation (Denmark); ***Suggested as there are no equivalencies (Ocean acidification, Maintenance of options) or equivalencies were not clear for the scope of LTS (Materials, companionship, and labour). Regulating (blue), Material (green), and Non-material (orange) categories are highlighted with the respective colour.*

Type	IPBES Code	IPBES Name	MA	TEEB	CICES Section	CICES Division
	1	***Habitat creation and maintenance***	No equivalent	Biological control	Regulation & Maintenance (Biotic)	Regulation of physical, chemical, biological conditions
	1[1]**	***Habitat creation and maintenance***			****Cultural (Biotic)**	Direct, in-situ and outdoor interactions with living systems that depend on the presence in the environmental setting
	2	***Pollination and dispersal of seeds and other propagules***	Pollination	Pollination/Biological Control	Regulation & Maintenance (Biotic)	Regulation of physical, chemical, biological conditions
	3*	***Regulation of air quality***	Water purification and water treatment, air quality regulation	Waste treatment (water purification), air quality regulation	Regulation & Maintenance (Biotic)	Transformation of biochemical or physical inputs to ecosystems
	3*	***Regulation of air quality***	Atmospheric regulation	Climate regulation	Regulation & Maintenance (Biotic)	Regulation of physical, chemical, biological conditions
	4	***Regulation of climate***	Atmospheric regulation	Climate regulation	Regulation & Maintenance (Biotic)	Regulation of physical, chemical,

						biological conditions
	5***	***Regulation of ocean acidification***	No equivalent	No equivalent	***Regulation & Maintenance (Biotic)	***Regulation of physical, chemical, biological conditions
	6	***Regulation of freshwater quantity, location, and timing***	Water regulation	Regulation of water flows, regulation of extreme events	Regulation & Maintenance (Biotic)	Regulation of physical, chemical, biological conditions
	6[1]**	***Regulation of freshwater quantity, location, and timing***			**Cultural (Biotic)**	Direct, in-situ and outdoor interactions with living systems that depend on the presence in the environmental setting
	7	***Regulation of freshwater and coastal water quality***	Water regulation	Water	Regulation & Maintenance (Biotic)	Regulation of physical, chemical, biological conditions
	8*	***Formation, protection, and decontamination of soils and sediments***	Erosion regulation	Erosion prevention	Regulation & Maintenance (Biotic)	Regulation of physical, chemical, biological conditions
	8*	***Formation, protection, and decontamination of soils and sediments***	Soil formation (supporting service)	Maintenance of soil fertility	Regulation & Maintenance (Biotic)	Regulation of physical, chemical, biological conditions
	8*	***Formation, protection, and decontamination of soils and sediments***	Water purification and water treatment, air quality regulation	Waste treatment (water purification), air quality regulation	Regulation & Maintenance (Biotic)	Transformation of biochemical or physical inputs to ecosystems
	9*	***Regulation of hazards and extreme events***	Water purification and water treatment, air quality regulation?	Water purification and water treatment, air quality regulation?	Regulation & Maintenance (Biotic)	Transformation of biochemical or physical inputs to ecosystems

	9*	***Regulation of hazards and extreme events***	Erosion regulation	Erosion prevention	Regulation & Maintenance (Biotic)	Regulation of physical, chemical, biological conditions
	9*	***Regulation of hazards and extreme events***	Natural hazard regulation	Regulation of water flows, regulation of extreme events	Regulation & Maintenance (Biotic)	Regulation of physical, chemical, biological conditions
	10*	***Regulation of organisms detrimental to humans***	Pest regulation and disease control	Biological control	Regulation & Maintenance (Biotic)	Regulation of physical, chemical, biological conditions
	10*	***Regulation of organisms detrimental to humans***	Water purification and water treatment, air quality regulation	Waste treatment (water purification), air quality regulation	Regulation & Maintenance (Biotic)	Transformatio n of biochemical or physical inputs to ecosystems
	11	***Energy***	Fibre, Timber, Ornamental , Biochemical	Raw materials, medicinal resources	Provisioning (Biotic)	Biomass
	12	***Food and feed***	Food	Food	Provisioning (Biotic)	Biomass
	12[2]**	***Food and feed***			****Cultural (Biotic)**	Direct, in-situ and outdoor interactions with living systems that depend on the presence in the environmental setting
	13	***Materials, companionship, and labor***	Natural hazard regulation?	Regulation of water flows, regulation of extreme events?	Regulation & Maintenance (Biotic)	Regulation of physical, chemical, biological conditions
	13[3]**	***Materials, companionship, and labor***			****Cultural (Biotic)**	Direct, in-situ and outdoor interactions with living systems that depend on the presence in the

						environmental setting
	13***	***Materials, companionship, and labor***	Fibre, Timber, Ornamental, Biochemical	Raw materials, medicinal resources	***Provisioning (Biotic)	Biomass
	14	***Medicinal, biochemical and genetic resources***	Genetic materials	Genetic materials	Provisioning (Biotic)	Genetic material from all biota (including seed, spore or gamete production)
	15	***Learning and inspiration***	Knowledge systems and educational values, cultural diversity, aesthetic values	Information and cognitive development	**Cultural (Biotic)**	Direct, in-situ, and outdoor interactions with living systems that depend on the presence in the environmental setting.
	16	***Physical and psychological experiences***	Recreation and ecotourism	Recreation and ecotourism	**Cultural (Biotic)**	Direct, in-situ, and outdoor interactions with living systems that depend on the presence in the environmental setting.
	17	***Supporting identities***	Spiritual and religious values	Inspiration for culture, art and design, aesthetic information	**Cultural (Biotic)**	Indirect, remote, often indoor interactions with living systems that do not require presence in the environmental setting.

	18*	***Maintenance of options***	No equivalent	No equivalent	*****Cultural (Biotic)**	Indirect, remote, often indoor interactions with living systems that do not require presence in the environmental setting.

__Table S3 (a).__ Data from mussel production systems around the Atlantic

Species common name		**Mediterranean mussel**	**Blue mussel**				**Brown mussel**
Species scientific name		*Mytilus galloprovincialis*	*Mytilus edulis*			*Mytilus trossulus*	*Perna perna*
Production area		Galicia	Denmark (Limfjord)		Skagerrak	Baltic sea	Brazil
Culture methods		SC	BC	SC	SC	SC	SC
Culture length (days)		6–11	18–24	12–14	12–22	21–30	12–14
Mean culture length (days)		226	640	395	547.5	780	395
Annual production (t)		225 000	4 500	6 500	1 811	50	14 603
Productivity (t/ha/year)		68		18.6	19.0	11.25	180
Harvest size	**Shell length (mm)**	75	> 45	45-55	61	20	80-100
	Total fresh weigth (g)	16.6	14	16.25	29.2	1.6	72.83
	Flesh yield (%)	33.5	24.5	42.4	48.8	39.00	32.53
Shell	**Fresh shell weight (g)**	11.0	10.6	9.4	13.9	1.0	49.1
	% organic dry weight	4.53	4.53	4.53	4.53	4.53	4.53
	% organic C	2.30	2.86	2.77	1.94	2.30	2.124
	% organic N	0.80	1.00	0.97	0.68	1.00	0.84
	% organic P	0.004	0.004	0.004	0.02	0.004	0.05
	Fresh flesh weight (g)	5.6	3.4	6.9	6.1; 8.9	0.6	23.7

Flesh/tissue	DW/FW ratio	0.211	0.221	0.221	0.23	0.23	0.279
	% organic C	45.5	46.0	46.0	46.0	46.0	45.75
	% organic N	7.92	5.85	8.57	9.93	9.83	8.23
	% organic P	0.81	0.81	0.81	1.15	1.41	0.89
Faeces	Total weight (g)	4.3	9.2	5.7	7.9	3.8	77.1
	% organic C	10.0	8.82	8.82	8.82	12.88	9.43
	% organic N	1.75	1.04	1.04	1.04	1.54	1.39
	% organic P	0.17	0.10	0.10	0.10	0.19	0.13
	% C buried in sediment	8	15	15	15	20	15
Respiration (ml O_2)		1056	1673	3361	4950	318	9184
Calcification ratio (Φ)		0.72	0.82	0.82	0.82	0.87	0.68
FG-Market value (reported currency/kg biomass, shell-on)		-	-	-	19 SEK	NA (mit)	1.8–20 BRL
FG-price (EUR/kg FW biomass, shell-on)		0.48	0.35–0.4	0.9	1.9	NA (mit)	0.3–3.1
FG-price (EUR/kg FW food, shell-off)		1.47	1.43–1.63	2.12	3.89	NA (mit)	0.92–9.5

SC: Suspended culture; BC: bottom culture; FW: fresh weight; DW: dry weight; Calcification ratio: CO_2 release/$CaCO_3$ production ratio (molar); FG: farm gate; NA: not applicable; mit: eutrophication mitigation mussel culture in the Baltic Sea

Table S3 (b). *Data from oyster production systems around the Atlantic*

Species common name		American cupped oyster		European oyster		Pacific Oyster				Mangrove Oyster
Species scientific name		*Crassostrea virginica*		*Ostrea edulis*		*Crassostrea gigas*				*Crassostrea gasar*
Production area		Southeastern US	Northeastern US	Southern Europe	Northern Europe	Southern Europe	Northern Europe	South Africa Namibia	Brazil	Brazil
Culture methods		MC	MC	MC	MC	MC	MC	SC	SC	MC
Culture length (months)		18–36	18–36	24	36	24–36	36	6–24	5–10	12
Mean culture length (days)		821	821	730	1095	913	1095	456	228	365
Annual production (t)		148 021		2 268		88 125		543	2 579	183
Productivity (t/ha/year)		13.3	13.3	–	–	–	–	7 to 10	55.4	173
Harvest size	Shell length (mm)	76-85	76-85	–	78-85	80-100	65 approx.	50; 100-150;	90-100	60-70
	Total fresh weigth (g)	47	47	90	75.5	76	85	90	82	37.9
	Flesh yield (%)	20	20	20	15.6	20	17.3	20	28.6	20.7
Shell	Fresh shell weight (g)	37.6	37.6	72.0	63.7	60.4	70	72.0	58.8	30.1
	% organic dry weight	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	% organic C	0.73	0.50	0.613	0.613	0.5	0.5	0.5	0.5	0.5

	% organic N	0.20	0.13	0.19	0.19	0.21	0.21	0.21	0.21	0.21
	% organic P	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Flesh/tissue	**Fresh flesh weight (g)**	9.4	9.4	18.0	11.8	15.1	15	18.0	23.6	7.8
	DW/FW ratio	0.21	0.21	0.194	0.222	0.21	0.166	0.19	0.168	0.17
	% organic C	44.5	44.5	44.3	44.3	44.0	44.0	44.0	44.0	44.3
	% organic N	8.57	7.5	8.15	8.15	9.65	9.65	9.65	9.65	8.82
	% organic P	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.30
Faeces	**Total weight (g)**	95.0	90.3	21.1	26.6	91.3	109.5	45.6	296	160
	% organic C	5.5	4.94	4.6	4.6	5.0	5.0	5.0	5.0	5.0
	% organic N	0.66	0.59	0.552	0.552	0.6	0.6	0.6	0.6	0.6
	% organic P	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	% C buried in the sediment	15	15	15	15	15	15	15	15	15
Respiration (ml O_2)		5090	4610	4910	4400	6710	5166	7313	8374	2793
Calcification ratio (Φ)		0.88	0.78	0.70	0.82	0.70	0.82	0.72	0.68	0.68
FG-Market value (reported currency/oyster)		0.50–0.72 USD/oyster	0.50–0.72 USD/oyster		15 to 25 SEK/oyster		6.5 –15 SEK/oyster	4.5–10 ZAR/oyster	5–18 BRL/12 oysters	up to 25 BRL/12 oysters
FG-price (EUR/kg FW biomass, shell-on)		9.4–13.5	9.4–13.5	6	18.8–31.3	4.0–4.4	7.2–16.7	2.8–6.1	0.78–2.8	8.5

FG-price (EUR/kg FW food, shell-off)	46.9–67.5	46.9–67.5	30	120–201	20–22	41.8–96.4	13.8–30.6	2.7–9.8	41

SC: Suspended culture; MC: SC and bottom culture; FW: fresh weight; DW: dry weight; Calcification ratio: CO_2 release/$CaCO_3$ production ratio (molar); FG: Farm gate

Table S3 (c). *Data from CS2 Offshore macroalgae production and CS3 Land-base IMTA*

		CS3 Land-based IMTA			***CS1 Offshore macroalgae***
Production area		**South Africa**			**Faroe Islands**
Species common name		**South African Abalone**	**Sea lettuce**		**Sugar kelp**
Species scientific name		*Haliotis midae*	*Ulva sp.*		*Saccharina latissima*
Production mode		IMTA	IMTA	Monoculture	Monoculture
Culture methods		LB	LB	LB	SC
Culture length (month)		48	1	1	6*
Mean culture length (days)		1460	30	30	183
Annual production (t) for the region		1 500	2 884	–	210
Annual production (t) for the farm		156	660	120	200
Productivity (t/ha/year)		242	446	556	12.5
Harvest size	**Shell length (mm)**	95 - 110	NA	NA	NA
	Total fresh weigth (g)	150	NA	NA	NA
	Flesh yield (%)	40	NA	NA	NA
Shell	**Fresh shell weight (g)**	90	NA	NA	NA

	% organic dry weight	5	NA	NA	NA
	% organic C	1.51	NA	NA	NA
	% organic N	0.51; 0.24	NA	NA	NA
	% organic P	0.03; 0.01	NA	NA	NA
Flesh/tissue	**Fresh flesh weight (g)**	60	NA	NA	NA
	DW/FW ratio	0.114	0.099	0.100	0.117
	% organic C	41.28	34.51	30.87	21.7
	% organic N	9.51	4.79	3.95	2.2
	% organic P	0.5	0.38	0.25	0.4
Respiration (mlO_2)		17 183	–	–	–
Calcification ratio (Φ)		0.72	NA	NA	NA
FG-price (reported currency/kg)		USD 28–35/Kg	ZAR 15.61/kg	ZAR 15.61/kg	
FG-price (EUR/kg FW biomass [shell-on for abalone])		24.7–30.8	0.96	0.96	EUR 1.2–2.3/kg FW (EUR 10–20/kg DW)
FG-Market value (EUR/kg FW food [shell-off for abalone])		61.6–77.1	0.96	0.96	EUR 1.2–2.3/kg FW (EUR 10–20/kg DW)

IMTA: integrated multi-trophic aquaculture; LB: land-based; SB: sea-based; FW: fresh weight; DW: dry weight; Calcification ratio: CO_2 release/$CaCO_3$ production ratio (molar); FG: Farm gate; NA: Not applicable

**Multiple harvests, every 6 months over three years, from one single batch deployed at sea*

Table S4. *Cradle-to-farm gate carbon footprint (CF, kg eq-CO_2/t FW whole biomass) associated to capital goods (CG-CF) and operations (O-CF) from LTS aquaculture activities.*

Name	**Species**	**Culture methods**	**Cradle to Gate**	**CG-CF**	**O-CF**	**Reference**	**Comments**
Mediterranean mussel	*Mytilus galloprovincialis*	suspended culture (mussel raft)	Galicia	480	34	Iribarren et al. (2011)	
Mediterranean mussel	*Mytilus galloprovincialis*	suspended culture (longline)	Adriatic	89	48	Tamburini et al. (2020)	flesh yield =137/391
Mediterranean mussel	*Mytilus galloprovincialis*		Algeria		141	Lourguioui et al. (2017)	
Blue mussel	*Mytilus edulis*	suspended culture (longline)	Scotland		252	Fry (2012)	
Blue mussel	*Mytilus edulis*	suspended culture (longline)	Norway	24	274	SINTEF (2009), Ziegler et al (2013)	
Blue mussel	*Mytilus edulis*	Bouchot	France		165	Aubin et al. (2018)	
Blue mussel	*Mytilus edulis*	suspended culture (nets)	Baltic proper		505	Spangberg et al. (2013)	20 mm individuals
Blue mussel	*Mytilus edulis*	Net > suspended culture (ropes)	Skagerrak		120 to 460	Frossel (2019)	
Blue mussel	*Mytilus edulis*	Bouchot, suspended (review)	Europe		avg: 95, sd:89	Runneson (2021)	
Greenshell mussel	*Perna canaliculus*	suspended (longline)	New Zealand		285	Aquaculture NZ (2021)	
Pacific Oyster	*Crassostrea gigas*	Intertidal	Scotland		1281	Fry (2012)	

Pacific Oyster	*Crassostrea gigas*	Intertidal	New Zealand		651	Aquaculture NZ (2021)	
Pacific Oyster	*Crassostrea gigas*	suspended culture (floating cages)	Adriatic		1850	Tamburini et al. (2019)	
Pacific Oyster	*Crassostrea gigas*	Suspended (longline)	Santa Catarina (Bazil)			Alvarenga et al. (2012)	
Pacific Oyster	*Crassostrea gigas*	beach grown, tide tumbled	Washington (Pacific)		0.11 to 0.12 kg CO_2/12 oysters	Pucylowski (2017)	12 oysters = 1 kg
Abalone	*Haliotis midae*	Land-based culture	South Africa		48 (monoculture), 47 (IMTA)	Nobre et al. (2009)	

CG-CF: capital goods' carbon footprint; operations' carbon footprint: O-CF operations.

Alvarenga, R. A. F. de, Galindro, B. M., Helpa, C. de F., & Soares, S. R. (2012). The recycling of oyster shells: an environmental analysis using Life Cycle Assessment. Journal of Environmental Management, 106, 102–109. https://doi.org/10.1016/J.JENVMAN.2012.04.017

Aubin, J., Fontaine, C., Callier, M., & Roque d'orbcastel, E. (2017). Blue mussel (Mytilus edulis) bouchot culture in Mont-St Michel Bay: potential mitigation effects on climate change and eutrophication. The International Journal of Life Cycle Assessment 2017 23:5, 23(5), 1030–1041. https://doi.org/10.1007/S11367-017-1403-Y

Aquaculture NZ (2021) LCA of New Zealand Mussels & Oysters On behalf of Aquaculture New Zealand and the Ministry for Primary Industries. Retrieved April 11, 2022, from www.thinkstep-anz.com

Ecological and economic assessment of the role of seaweeds in abalone integrated multi-trophic aquaculture - a South African case study. (n.d.). Retrieved April 11, 2022, from https://www.cabdirect.org/cabdirect/abstract/20203482922

Forbord, S., Skjermo, J., Arff, J., Handå, A., Reitan, K. I., Bjerregaard, R., & Lüning, K. (2012). Development of Saccharina latissima (Phaeophyceae) kelp hatcheries with year-round production of zoospores and juvenile sporophytes on culture ropes for kelp aquaculture. Journal of Applied Phycology, 24(3), 393–399. https://doi.org/10.1007/s10811-011-9784-y

Frösell, Märta, 2019. Mussel farming using various techniques evaluated using Life Cycle Assessment (LCA). First cycle, G2E. Uppsala: SLU, Dept. of Energy and Technology

Iribarren, D., Moreira, M., & Feijoo, G. (2011). Life cycle assessment of mussel culture. Mussels: Anatomy, Habitat and Environmental Impact, 357–377.

Lourguioui, H., Brigolin, D., Boulahdid, M., & Pastres, R. (2017). A perspective for reducing environmental impacts of mussel culture in Algeria. The International Journal of Life Cycle Assessment 2017 22:8, 22(8), 1266–1277. https://doi.org/10.1007/S11367-017-1261-7

Nobre, A. M., Robertson-Andersson D. V., Neori A., Sankar K Ecological and economic assessment of the role of seaweeds in abalone integrated multi-trophic aquaculture, a South African case study. EC FP7 Project, SARNISSA

Pucylowski, T. (2017). Life Cycle Assessment (LCA) of oyster farming in Washington State.

Runesson, Elisabet, 2020. Compilation of life cycle assessments of cultivated blue mussels: recalculation of the inventory assessments. Second cycle, A2E. Uppsala: SLU, Department of Molecular Sciences

Spångberg, J., Jönsson, H., & Tidåker, P. (2013). Bringing nutrients from sea to land – mussels as fertiliser from a life cycle perspective. Journal of Cleaner Production, 51, 234–244. https://doi.org/10.1016/J.JCLEPRO.2013.01.011

SARF (2011). Carbon Footprint Of Scottish Suspended Mussels And Intertidal Oysters, Scottish Aquaculture Research Forum ISBN: 978-1-907266-44-7

SINTEF (2009) Carbon footprint and energy use of Norwegian seafood products - Final report (2009). (n.d.). Retrieved April 11, 2022, from https://www.researchgate.net/publication/301694542_Carbon_footprint_and_energy_use_of_Norwegian_seafood_products_-_Final_report_2009

Tamburini, E., Turolla, E., Fano, E. A., & Castaldelli, G. (2020). Sustainability of Mussel (Mytilus Galloprovincialis) Farming in the Po River Delta, Northern Italy, Based on a Life Cycle Assessment Approach. Sustainability 2020, Vol. 12, Page 3814, 12(9), 3814. https://doi.org/10.3390/SU12093814

Ziegler, F., Winther, U., Hognes, E. S., Emanuelsson, A., Sund, V., & Ellingsen, H. (2013). The Carbon Footprint of Norwegian Seafood Products on the Global Seafood Market. Journal of Industrial Ecology, 17(1), 103–116. https://doi.org/10.1111/J.1530-9290.2012.00485.X

Table S5. *Formulas used to calculate the different parameters and indicators.*

Parameter or indicator	Expression
N removal kgN/t FW biomass	$10^3[N_{shell}$ (1-Rflesh) + N_{flesh}Rflesh(DWt/FWt)+$R_{burial}N_{faeces}(DW_{Faeces}$/TFW)]
N removal in shell (%)	$10^{-1}N_{shell}$ (1-Rflesh)/Nremoval
N removal in flesh (%)	$10^{-1}N_{flesh}$Fflesh(DWt/FWt)/Nremoval
N removal in faeces (%)	$10^{-1}R_{burial}N_{faeces}(DW_{Faeces}$/TFW)/Nremoval
P removal kgN/t FW biomass	$10^3[P_{shell}$ (1-Rflesh) + P_{lfesh}Rflesh(DWt/FWt)+$R_{burial}P_{faeces}(DW_{Faeces}$/TFW)]
P removal in shell (%)	$10^{-1}P_{shell}$ (1-Rflesh)/Premoval
P removal in flesh (%)	$10^{-1}P_{flesh}$Rflesh(DWt/FWt)/Premoval
P removal in faeces (%)	$10^{-1}R_{burial}P_{faeces}(DW_{Faeces}$/TFW)/Premoval
CO_2 as $CaCO_3$ (Kg/t)	$10^3 44 R_{Ishell}$(1-Rflesh)
Organic (shell + flesh) CO_2 (kg/t)	10^3[Roshell(1-Rflesh)C_{Oshell}+Rflesh(DWt/FWt)C_{flesh})44/12
Calcification (kgCO_2/t)	Calc_rate (Φ)*CO_2 in $CaCO_3$
Respiration (kgCO_2/t)	(0.85*44/22.4)mlO_2/TFW
Burial (kgCO_2/t)	$R_{burial}C_{faeces}(DW_{Faeces}$/TFW)44/12
B-CO_2 acidification (low, kg/t)	CO_{2calc}-(CO_{2flesh}+$CO_{2burial}$)
B-CO_2 acidification (high, kg/t)	CO_{2resp} + CO_{2calc}-(CO_{2flesh}+$CO_{2burial}$)
Biological-CF (low, kg/t)	$CO2_{calc}$-$CO2_{burial}$
Biological-CF (high, kg/t)	CO_{2resp} + CO_{2calc}-$CO_{2burial}$
Operations-CF (kg/t)	Cradle to gate (other studies)
Total CF (low, kg/t)	Biological-CF (low) + Operations-CF
Total CF (high, kg/t)	Biological-CF (high) + Operations-CF
N removal (kg/ha/year)	N removal*Productivity
N removal (kg year for entire region/country)	N removal*TotalProd
P removal (kg/ha/year)	P removal*Productivity
P removal (kg year for entire region/country)	P removal*TotalProd

B-CO_2 acidification (low, t year per region/country)	CO_2acidif_low*TotalProd/1000
B-CO_2 acidification (high, t year per region/country)	CO_2acidif_high*TotalProd/1000
B-CF low (kg/ha/year)	Carbon Footprint_low (kg/t)*Productivity(t/ha/year) (c)
B-CF high (kg/ha/year)	Carbon Footprint_high*Productivity
B-CF (low, t year per region/country)	CarbonFootprint_low *TotalProd/1000
B-CF (high, t year per region/country)	CarbonFootprint_low *TotalProd/1000

Table S6. *Nitrogen (N) and Phosphorous (P) net removal or release (kg/t FW of whole biomass), ocean acidification index (B-CO_2) and biological carbon footprint (B-CF) in Kg CO_2/t FW of whole biomass [low–high estimates] for the analysed LTS aquaculture systems.*

	Species common name (scientific name)	**Production mode**	**Production area**	**Production method**	**N net removal or release**	**P net removal or release**	**B-CO_2**	**B-CF**
Offshore kelp production (CS2)	Sugar kelp (*Saccharina latissima*)	*Mono*	Faroe Islands	SB, SC	-2.46– (-2.57)	-0.468	-93.1	0.0 – (-93.1)
Land-based IMTA (CS3)	South African abalone *(Haliotis midae)*	*IMTA*	South Africa	LB, TC	65.7	15.5	**78.3–269.6**	180.6–371.8
	Sea lettuce (*Ulva* sp.)	*IMTA*	South Africa	LB, TC	11.3	3.43	0.0	0.0
	Sea lettuce (*Ulva* sp.)	*Mono*	South Africa	LB, TC	21.1	9.20	0.0	0.0
Oysters (CS8)	American cupped oyster (*C. virginica*)	*Mono*	Northeastern US	SB, MC	-5.90	-1.05	**136.4–300.2**	219.6–383.4
		Mono	Southeastern US	SB, MC	-7.20	-1.06	**155.7–336.5**	245.5–426.3
	European oyster (*O. edulis*)	*Mono*	Northern Europe	SB, MC	-4.68	-0.75	**217.4–314.7**	292.6–389.9
		Mono	Southern Europe	SB, MC	-4.84	-0.76	**157.1–248.2**	238.0– 329.1
	Pacific Oyster (*C. gigas*)	*Mono*	Northern Europe	SB, MC	-5.67	-0.82	**198.5–299.9**	260.0–361.4
		Mono	Southern Europe	SB, MC	-6.82	-0.94	**128.3–276.7**	210.7–359.1
		Mono	South Africa and Namibia	SB, SC	-5.84	-0.80	**160.4–296.0**	237.0–372.6
		Mono	Brazil	SB, SC	-9.37	-1.32	**22.0–191.8**	112.6–282.4
	Mangrove Oyster (*C. gasar*)	*Mono*	Brazil	SB, MC	-8.52	-1.40	**48.1–171.2**	118.8–241.9
Mussels (CS9)	Mediterranean mussel (*M. galloprovincialis*)	*Mono*	Galicia	SB, SC	-11.3	-0.63	**19.6–125.8**	193.5–299.7
	Blue mussel	*Mono*		SB, BC	-11.7	-0.57	**57.9–257.5**	228.1–427.7

	(*Mytilus edulis*)		Denmark (Limfjord)					
		Mono		SB, SC	-14.1	-0.83	**(-34.8)–310.5**	181.4–526.8
		Mono	Skagerrak	SB, SC	-15.1	-1.43	**(-62.7)–220.6**	163.1–446.4
	Blue mussel (*Mytilus trossulus*)	*Mono*	Baltic Sea	SB, SC	-22.2	-2.18	(-**201.8)–129.6**	0.90–332.2
	Brown mussel (*Perna perna*)	*Mono*	Brazil	SB, SC	-15.3	-1.33	**(-66.8)–143.7**	137.8–348.4

Mono: monoculture; SB: sea-based culture; TC: tank-based culture; SC: suspended culture; BC: bottom culture; MC: mixed culture (SC and BC)

Table S7. *Proportion of Nitrogen (N) and Phosphorous (P) stored in the different components considered for the nutrient budget– shell (for shellfish), flesh/tissue, and biodeposit burial (%), and the contribution of different processes for the ocean acidification index (B-CO_2) and biological carbon footprint (B-CF) of the LTS analysed: CO_2 storage (organic carbon), calcification, respiration, and biodeposit burial (kg CO_2 per t FW of whole biomass).*

	Species common name (scientific name)	**Prod. mode**	**Prod. area**	**Prod. method**	**% N in shell**	**%N in flesh/tissue**	**% N in burial**	**% P in shell**	**% P in flesh/tissue**	**% P in burial**	**CO2 storage**	**Calcification**	**Respiration**	**Burial**	**CO_2 as $CaCO_3$ in the shell (*)**
Offshore kelp production (CS2)	Sugar kelp (*Saccharina latissima*)	*Mono*	Faroe Islands	SB, SC	NA	100	ND	NA	100	ND	NA	NA	–	ND	
Land-based IMTA (CS3)	South African abalone *(Haliotis midae)*	IMTA	South Africa	LB, TC	41.4	58.6	ND	42.2	57.8	NA	-102.3	180.6	191.3	ND	(-250.8)
	Sea lettuce (*Ulva* sp.)	IMTA	South Africa	LB, TC	NA	100	NA	NA	100	NA	NA	NA	–	NA	NA
	Sea lettuce (*Ulva* sp.)	*Mono*	South Africa	LB, TC	NA	100	NA	NA	100	NA	NA	NA	–	NA	NA
Oysters (CS8)	American cupped oyster (*C. virginica*)	*Mono*	Northeastern US	SB, both SC and BC	17.6	53.4	29.0	30.6	41.8	27.6	-83.2	271.8	163.8	-52.2	(-348.5)
		Mono	Southeastern US	SB, both SC and BC	22.2	50.0	27.8	30.2	41.2	28.6	-89.8	306.7	180.8	-61.2	(-348.5)
	European oyster (*O. edulis*)	*Mono*	Northern Europe	SB, both SC and BC	33.4	60.4	6.23	45.0	48.0	7.03	-75.2	301.5	97.3	-8.9	(-367.6)
		Mono	Southern Europe	SB, both SC and BC	30.6	65.4	4.02	42.2	53.2	4.64	-80.9	243.9	91.1	-5.9	(-348.5)

	Species common name (scientific name)	Prod. mode	Prod. area	Prod. method	% N in shell	%N in flesh/tissue	% N in burial	% P in shell	% P in flesh/tissue	% P in burial	CO2 storage	Calcification	Respiration	Burial	CO_2 as $CaCO_3$ in the shell (*)
	Pacific Oyster (*C. gigas*)	*Mono*	Northern Europe	SB, both SC and BC	30.6	48.9	20.46	40.21	36.3	23.49	-61.5	295.4	101.5	-35.4	(-360.2)
		Mono	Southern Europe	SB, both SC and BC	24.6	59.4	15.95	34.1	46.6	19.33	-82.4	243.9	148.4	-33.2	(-348.5)
		Mono	South Africa and Namibia	SB, SC	28.8	63.4	7.81	40.2	50.2	9.56	-76.6	250.9	135.7	-13.9	(-348.5)
		Mono	Brazil	SB, SC	16.0	49.5	34.52	21.6	37.7	40.7	-90.6	211.5	169.8	-98.9	(-311.0)
	Mangrove Oyster (*C. gasar*)	*Mono*	Brazil	SB	19.5	35.9	44.60	22.66	32.1	45.23	-70.7	235.0	123.1	-116.1	(-345.5)
Mussels (CS9)	Mediterranean mussel (*M. galloprovincialis*)	*Mono*	Galicia	SB, SC	47.3	49.5	3.19	4.23	90.3	5.46	-173.9	201.1	106.2	-7.6	(-279.3)
	Blue mussel (*Mytilus edulis*)	*Mono*	Denmark (Limfjord)	SB, BC	64.3	26.9	8.75	5.37	77.2	17.42	-170.2	260.1	199.5	-31.9	(-317.2)
		Mono		SB, SC	39.5	56.6	3.86	2.80	90.9	6.34	-216.2	198.4	345.3	-17.0	(-242.0)
		Mono	Skagerrak	SB, SC	23.1	74.1	2.80	7.13	90.0	2.83	-225.9	176.2	283.3	-13.1	(-214.9)
	Blue mussel (*Mytilus trossulus*)	*Mono*	Baltic sea	SB, SC	27.5	39.8	32.68	1.20	57.9	40.90	-202.7	222.9	331.3	-222.0	(-256.2)

	Species common name (scientific name)	Prod. mode	Prod. area	Prod. method	% N in shell	%N in flesh/tissue	% N in burial	% P in shell	% P in flesh/tissue	% P in burial	CO2 storage	Calcification	Respiration	Burial	CO_2 as $CaCO_3$ in the shell (*)
	Brown mussel (*Perna perna*)	*Mono*	Brazil	SB, SC	36.9	48.7	14.42	23.3	60.7	16.0	-204.7	192.7	210.5	-54.9	(-283.4)

*Mono: monoculture; SB: sea-based culture; TC: tank-based culture; SC: suspended culture; BC: bottom culture; MC: mixed culture (SC and BC); NA: not applicable; ND: no data; *Only to allow comparison with previous studies, $CaCO_3$ is not considered a CO_2 removal mechanism in this study in line with other recent shellfish aquaculture studies (for a detailed explanation please refer to the method section –5.1.2); variation coefficient around 25%.*

Table S8. *LTS aquaculture cradle-to-farm gate carbon footprint (CF) associated to biological processes (B-CF) and operations (O-CF) expressed in kg CO_2/t FW food (shell-off [low–high estimates]) and in kg CO_2/t of protein (low–high estimates), and contribution of B-CF (%) to the total CF (B-CF + O-CF [low–high estimates]).*

	Species common name (scientific name)	**Production mode**	**Production area**	**Production method**	**B-CF per t of food**	**O-CF per t of food**	**B-CF per t of protein**	**O-CF per t of protein**	**Total CF per t of food**	**Total CF per t of protein**	**B-CF (% total CF)**
Offshore kelp production (CS2)	Sugar kelp (*Saccharina latissima*)	*Mono*	Faroe Islands	SB, SC	0.0	16.4	0.0	1272.7	16.4–(-76.8)	1272.7–(-5963.7)	0.0–121.3
Land-based IMTA (CS3)	South African abalone *(Haliotis midae)*	*IMTA*	South Africa	LB, TC	451.4–929.6	125.0	6650.8–13695.2	1841.5	576.4–1054.6	8492.3–15536.8	78.3 88.1
	Sea lettuce (*Ulva* sp.)	*IMTA*	South Africa	LB, TC	0.0)	ND	0.0	ND	ND	ND	0.0
	Sea lettuce (*Ulva* sp.)	*Mono*	South Africa	LB, TC	0.0	ND	0.0	ND	ND	ND	0.0
Oysters (CS8)	American cupped oyster (*C. virginica*)	*Mono*	Northeastern US	SB, both SC and BC	1098.0–1916.8	7250.0	11153.9–19472.2	73650.8	8348.0–9166.8	84804.7–93123.0	13.2–20.9
		Mono	Southeastern US	SB, both SC and BC	1227.5–2131.6	7250.0	10919.3–18961.7	64492.8	8477.5–9381.6	75412.1–83454.5	14.5–22.7
	European oyster (*O. edulis*)	*Mono*	Northern Europe	SB, both SC and BC	1875.4–2499.2	9294.9	16584.8–22100.6	82196.4	11170.3–11794.0	98781–104297	16.8–21.2
		Mono	Southern Europe	SB, both SC and BC	1190.0–1645.5	7250.0	12042.3 –16651.2	73366.6	8440.0 –8895.5	85409.0–90017.8	14.1–18.5
	Pacific Oyster (*C. gigas*)	*Mono*	Northern Europe	SB, both SC and BC	1502.7–2089.2	8381.5	15009.4 –20867.6	83715.6	9884.2 –10470.7	98725.0 – 104583.2	15.2–20.0

		Mono	Southern Europe	SB, both SC and BC	1053.5–1795.5	7250.0	8317.8–14175.9	57241.5	8303.5–9045.5	65559.3–71417.5	12.7–19.8
		Mono	South Africa and Namibia	SB, SC	1184.9–1863.2	5500.0	10232.0–16090.1	47495.7	6684.9–7363.2	57727.6–63585.8	17.7–25.3
		Mono	Brazil	SB, SC	393.5–987.1	3844.8	3884.0 9742.1	37945.3	4238.4 4831.9	41829.3–47687.4	9.3–20.4
	Mangrove Oyster (*C. gasar*)	*Mono*	Brazil	SB	574.6–1169.8	7011.6	6223.0–12668.8	75937.1	7586.2–8181.4	82160.1–88606.0	7.6–14.3
Mussels (CS9)	Mediterranean mussel (*M.galloprovincialis*)	*Mono*	Galicia	SB, SC	577.8–894.8	149.3	5531.6–8566.7	1429.0	727.0–1044.0	6960.6–9995.7	79.5–85.7
	Blue mussel (*Mytilus edulis*)	*Mono*	Denmark (Limfjord)	SB, BC	931.1–1745,6	204.1	11549.8–21652.5	2531.4	1135.2–1949.7	14081.2–24183.9	82.0–89.5
		Mono		SB, SC	427.9–1242.4	235.8	3624.4–10523.3	1997.7	663.7–1478.2	5622.1–12521.0	64.5–84.0
		Mono	Skagerrak	SB, SC	334.0–914.0	593.8	2339.7–6403.3	4159.7	927.7–1507.8	6499.4–10563.1	36.0–60.6
	Blue mussel (*Mytilus trossulus*)	*Mono*	Baltic Sea	SB, SC	NA (Mit)	NA (Mit)	NA (Mit)	NA (Mit)	NA (Mit)	NA (Mit)	0.2–39.9
	Brown mussel (*Perna perna*)	*Mono*	Brazil	SB, SC	423.7–1071.0	307.4	2953.5–7464.9	2142.7	731.1–1378.4	5096.2–9607.7	58.0–77.7

Mono: monoculture; SB: sea-based culture; SC: suspended culture; BC: bottom culture; NA: not applicable; ND: no data; Mit: Eutrophication mitigation not food production

Appendix B. List of ecologic sustainability indicators presented in D6.1

The table below shows the connection between the desired state and proposed ecologic sustainability indicators. To each indicator there is also some extra information to bring context to it.

Desired state: Specific sustainability aspects	Tentative selection of sustainability indicators	Unit or description	Quantitative or Qualitative	Geographic scope	Reference
Low use of natural resources	**Use of Space**	This indicator measures the area used (ha, m2) per unit of production (kg, t, units)	Quantitative	Farm, Sector	Valenti et al., 2018
	Use of Energy	This indicator measures the total energy applied to the system in its various forms, such as food, fertilizer, electricity, fossil fuels, and others, per unit of production.	Quantitative	Farm, Sector	Valenti et al., 2018
	Dependence of water	This indicator measures the volume of water used per unit of production. Only the consumed water should be considered. The water that returns to the environment in a similar condition to which it was withdrawn is not considered consumed, but if it returns polluted, it should be considered consumed. W = consumed volume/production	Qualitative	Farm, Sector	Valenti et al., 2018
	Use of Energy	This indicator measures the total energy applied to the system in its various forms, such as food, fertilizer, electricity, fossil fuels, and others, per unit of production.	Quantitative	Farm, Sector	Valenti et al., 2018
	Use of Nitrogen	A measurement of the mass of nitrogen applied per unit of production	Quantitative	Farm, Sector	Valenti et al., 2018
	Use of Phosphorus	A measurement of the mass of phosphorus applied per unit of production	Quantitative	Farm, Sector	Valenti et al., 2018

Use renewable energy and materials	**Proportion of Renewable Energy**	Measures the relative amount of renewable energy applied in the system, relative the total applied energy. Renewable energy sources include food, organic fertilizer, ethanol, biodiesel and other energy obtained from live organisms, and solar (photovoltaic), wind, tidal and geothermal energy. Hydropower is not considered renewable because water reservoirs have a limited life span.	Quantitative	Farm, Sector	Valenti et al., 2018
Releases little to no greenhouse gases	**Potential of Global Warming**	Load of greenhouse-effect gases released to the atmosphere per mass or units produced	Quantitative	Farm, Regional, Global, Sector	Valenti et al., 2018
Use natural resources efficiently	**Efficiency in the Use of Energy**	Energy recovered in production divided by energy applied	Quantitative	Farm, Sector	Valenti et al., 2018
	Efficiency in the Use of Nitrogen	Proportion of mass of nitrogen recovered in production relative to the mass of nitrogen applied	Quantitative	Farm, Sector	Valenti et al., 2018
	Efficiency in the Use of Phosphorus	Proportion of mass of phosphorus recovered in production relative to mass of phosphorus applied	Quantitative	Farm, Sector	Valenti et al., 2018
Generate low quantity of pollutants and unused by-products	**Potential of Organic Pollution**	Load (mass) of organic matter released in effluents per mass or units produced	Quantitative	Farm, Regional, Global, Sector	Valenti et al., 2018
	General Chemical Pollution	Load of applied chemical products = mass of herbicides, insecticides, anti-algals, antibiotics, and other chemicals applied per mass or units produced	Quantitative	Farm, Regional, Sector	Valenti et al., 2018
	Pollution by Hormones	Load (mass) of hormones applied per mass or units produced	Quantitative	Farm, Regional, Sector	Valenti et al., 2018

	Pollution by Heavy Metals	Load (mass) of heavy metals applied per mass or units produced	Quantitative	Farm, Regional, Sector	Valenti et al., 2018
	Potential of Organic Pollution	Load (mass) of organic matter released in effluents per mass or units produced	Quantitative	Farm, Regional, Sector	Valenti et al., 2020
	Production Actually Used	Proportion of unused wastes in the biomass of the farmed species relative to total mass produced. Examples of wastes are fish guts and heads, shrimp heads and shells, mollusk shells and others.	Quantitative	Farm, Sector	Valenti et al., 2018
Shows little to no intrinsic pollution and accumulation of by-products	**Production Actually Used**	Proportion of unused wastes in the biomass of the farmed species relative to total mass produced. Examples of wastes are fish guts and heads, shrimp heads and shells, mollusk shells and others.	Quantitative	Farm, Sector	Valenti et al., 2018
	Accumulation of Phosphorus	Load (mass) of phosphorous accumulated in sediment per mass or units of organism produced	Quantitative	Farm, Regional, Sector	Valenti et al., 2018
	Accumulation of Organic Matter	Load (mass) of Organic Matter accumulated in sediment per mass or units of organism produced	Quantitative	Farm, Regional, Sector	Valenti et al., 2018
	Accumulation of Particulate Material	Load (mass) of Particulate Material accumulated in sediment per mass or units of organism produced	Quantitative	Farm, Regional, Sector	Valenti et al., 2018
Shows capacity of recycling and reusing materials	**Rate of circularity**	Measures the rate use of the Circular Economy in the farm	Qualitative	Farm	Valenti et al., 2020
Produce little changes in the surrounding environment,	**Changes in water flow**	Changed patterns in current speed or direction as a consequence of the culture units	Qualitative	Farm, Regional, Sector	Valenti et al., 2020

including biotic communities	**Shading**	Light attenuation may be an important environmental impact in coastal and oceanic areas as well as in freshwater lakes. Shading is produced by net-cages, trays, long-lines, and other floating structures, as well as, most of the submerged systems.	Qualitative	Farm, Regional, Sector	Valenti et al., 2020
	Risk of Farmed Species	Risk of genetic effects on wild populations from escapees	Qualitative	Regional, Sector	Valenti et al., 2018
	Change in alpha-biodiversity	Shannon-Winner diversity index is used to measure the difference of environment impacted by the farm and a similar environment unimpacted by the farm, which is then divided by the mass or units produced.	Qualitative	Regional, Sector	Valenti et al., 2020
	Potential to change water environment	Linear combination of eutrophication, oxygen depletion, organic pollution, siltation, global warming, chemical pollution, and pollution by heavy metals.	Qualitative	Farm, Regional, Sector	Valenti et al., 2020
	Impacts of seed acquisition	Classification of seed stock according to a set of defined characteristics and its impact on the surrounding environment.	Qualitative	Farm, Regional, Sector	Valenti et al., 2020
	Potential to change the gene pool of the native community	Classification of farmed animals according to a set of defined characteristics and culture conditions, and their potential impact on the native species of the surrounding environment.	Qualitative	Regional, Sector	Valenti et al., 2020
Shows low risk of damaging genetic	**Risk of farmed species**	Risk of genetic effects on wild populations from escapees	Qualitative	Regional, Sector	Valenti et al., 2018

diversity and biodiversity	**Changing alpha-biodiversity**	Shannon-Winner diversity index is used to measure the difference of environment impacted by the farm and a similar environment unimpacted by the farm, which is then divided by the mass or units produced.	Qualitative	Regional, Sector	Valenti et al., 2020
	Potential to change water environment	Linear combination of eutrophication, oxygen depletion, organic pollution, siltation, global warming, chemical pollution, and pollution by heavy metals	Qualitative	Regional, Sector	Valenti et al., 2020
	Impacts of seed acquisition	Classification of seed stock according to a set of defined characteristics and its impact on the surrounding environment.	Qualitative	Farm, Regional	Valenti et al., 2020
	Potential to change the gene pool of the native community	Classification of farmed animals according to a set of defined characteristics and culture conditions, and their potential impact on the native species of the surrounding environment.	Qualitative	Farm, Regional, Sector	Valenti et al., 2020
Mitigates environmental degradation	**Eutrophication**	Eutrophication potential = (Load of nitrogen in source water - Load of nitrogen released in effluents) / mass or units produced	Quantitative	Farm, Regional, Sector	Valenti et al., 2020
	Oxygen depletion	(BOD5 in source water – BOD5 released in effluents) / mass or units produced	Quantitative	Farm, Regional, Sector	Valenti et al., 2020
	Organic Pollution	(Load of organic matter in source water – Load of organic matter released in effluents) / mass or units produced	Quantitative	Farm, Regional, Sector	Valenti et al., 2020
	Siltation	(Load of total suspended inorganic solids in source water – Load of suspended inorganic solids released in	Quantitative	Farm, Regional, Sector	Valenti et al., 2020

		effluents) / mass or units produced			
	Global Warming	(Load of greenhouse gases absorbed – load of greenhouse gases released to the atmosphere) / mass or units produced Greenhouse gases = mass of CO2 + CH4 + N2O, measured in CO2 equivalents	Quantitative	Farm, Regional, Global, Sector	Valenti et al., 2020
	Chemical Pollution	(Load of chemicals in source water – Load of chemicals in effluents) / mass or units produced Chemical products = mass of herbicides, insecticides, anti-algals, antibiotics, and other chemicals applied	Quantitative	Farm, Regional, Sector	Valenti et al., 2020
	Pollution by Heavy Metals	(Load of heavy metals in source water – Load of heavy metals in effluents) / mass or units produced	Quantitative	Farm, Regional, Sector	Valenti et al., 2020
	Changing alpha-biodiversity	Shannon-Winner diversity index is used to measure the difference of environment impacted by the farm and a similar environment unimpacted by the farm, which is then divided by the mass or units produced.	Quantitative	Farm, Regional, Sector	Valenti et al., 2020
Complies with principles of animal welfare	**Environmental comfort**	The indicator is measured as Number of water variables suitable for the farmed species / total measured variables. The minimum measured variables are dissolved oxygen, temperature, ammonia, nitrite, pH, and salinity.	Quantitative	Farm, Regional	Valenti et al., 2020
	Animal Health	Number individuals with of body damaged +number of diseased individuals / total individuals harvested	Quantitative	Farm, Regional	Valenti et al., 2020

Appendix C. Reference list for the identification of NCPs provided by LTS

List of references (articles and reports) provided by the consulted experts to verify the identified NCPs.

ICES Code of Practice on the Introductions and Transfers of Marine Organisms 2005 Code de Conduite du CIEM pour les Introductions et Transferts d ' Organismes Marins 2005. (2005). *Practice*.

Abreu, M. H., Pereira, R., Yarish, C., Buschmann, A. H., & Sousa-Pinto, I. (2011). IMTA with Gracilaria vermiculophylla: Productivity and nutrient removal performance of the seaweed in a land-based pilot scale system. *Aquaculture*, *312*(1–4), 77–87. https://doi.org/10.1016/j.aquaculture.2010.12.036

Adams, J. M., Gallagher, J. A., & Donnison, I. S. (2009). Fermentation study on saccharina latissima for bioethanol production considering variable pre-treatments. *Journal of Applied Phycology*, *21*(5), 569–574. https://doi.org/10.1007/s10811-008-9384-7

Anonyme. (2003). Report of the working group on marine shellfish culture. *ICES C.M. 2003/F : 05 Ref. ACME*, *April*, 70 p.

Bartsch, A., Robinson, S. M. C., Liutkus, M., Ang, K. P., Webb, J., & Pearce, C. M. (2013). Filtration of sea louse, Lepeophtheirus salmonis, copepodids by the blue mussel, Mytilus edulis, and the Atlantic sea scallop, Placopecten magellanicus, under different flow, light and copepodid-density regimes. *Journal of Fish Diseases*, *36*(3), 361–370. https://doi.org/10.1111/jfd.12069

Beaulieu, L., Thibodeau, J., Bonnet, C., Bryl, P., & Carbonneau, M. E. (2013). Evidence of anti-proliferative activities in blue mussel (Mytilus edulis) by-products. *Marine Drugs*, *11*(4), 975–990. https://doi.org/10.3390/md11040975

Bernard, F. R. (1989). Uptake and elimination of coliform bacteria by four marine bivalve mollusks. *Canadian Journal of Fisheries and Aquatic Sciences*, *46*(9), 1592–1599. https://doi.org/10.1139/f89-203

Bikker, P., van Krimpen, M. M., van Wikselaar, P., Houweling-Tan, B., Scaccia, N., van Hal, J. W., Huijgen, W. J. J., Cone, J. W., & López-Contreras, A. M. (2016). Biorefinery of the green seaweed Ulva lactuca to produce animal feed, chemicals and biofuels. *Journal of Applied Phycology*, *28*(6), 3511–3525. https://doi.org/10.1007/s10811-016-0842-3

Birkbeck, T. H., & McHenery, J. G. (1982). Degradation of bacteria by Mytilus edulis. *Marine Biology*, *72*(1), 7–15. https://doi.org/10.1007/BF00393942

Broch, O., Ellingsen, I., Forbord, S., Wang, X., Volent, Z., Alver, M., Handå, A., Andresen, K., Slagstad, D., Reitan, K., Olsen, Y., & Skjermo, J. (2013). Modelling the cultivation and bioremediation potential of the kelp Saccharina latissima in close proximity to an exposed salmon farm in Norway. *Aquaculture Environment Interactions*, *4*(2), 187–206. https://doi.org/10.3354/aei00080

Bulleri, F., Airoldi, L., Branca, G. M., & Abbiati, M. (2006). Positive effects of the introduced green alga, Codium fragile ssp. tomentosoides, on recruitment and survival of mussels. *Marine Biology*, *148*(6), 1213–1220. https://doi.org/10.1007/s00227-005-0181-4

Burge, C. A., Closek, C. J., Friedman, C. S., Groner, M. L., Jenkins, C. M., Shore-Maggio, A., & Welsh, J. E. (2016). The Use of Filter-feeders to Manage Disease in a Changing World. *Integrative and Comparative Biology*, *56*(4), 573–587. https://doi.org/10.1093/icb/icw048

Cabral, P., Levrel, H., Viard, F., Frangoudes, K., Girard, S., & Scemama, P. (2016). Ecosystem services assessment and compensation costs for installing seaweed farms. *Marine Policy*, *71*, 157–165.

Castelar, B., Pontes, M. D., Costa, W. de M., Moura, L. C. F., Dias, G. E., Landuci, F. S., & Reis, R. P. (2015). Eficiência biofiltradora e desempenho produtivo de macroalgas com potencial para aquicultura multi-trófica integrada (AMTI). *Boletim Do Instituto de Pesca*, *41*, 763–770. https://doi.org/10.20950/1678-2305.2015v41nep763

Chung, I. K., Beardall, J., & Mehta, S. (2011). *Using marine macroalgae for carbon sequestration: a critical appraisal*. 877–886. https://doi.org/10.1007/s10811-010-9604-9

das Chagas Faustino Alves, M. G., Dore, C. M. P. G., Castro, A. J. G., do Nascimento, M. S., Cruz, A. K. M., Soriano, E. M., Benevides, N. M. B., & Leite, E. L. (2012). Antioxidant, cytotoxic and hemolytic effects of sulfated galactans from edible red alga Hypnea musciformis. *Journal of Applied Phycology*, *24*(5), 1217–1227. https://doi.org/10.1007/s10811-011-9763-3

Depiper, G. S., Lipton, D. W., & Lipcius, R. N. (2017). Valuing Ecosystem Services: Oysters, Denitrification, and Nutrient Trading Programs. *Marine Resource Economics*, *32*(1), 1–20. https://doi.org/10.1086/688976

D’Orazio, N., Gemello, E., Gammone, M. A., De Girolamo, M., Ficoneri, C., & Riccioni, G. (2012). Fucoxantin: A treasure from the sea. *Marine Drugs*, *10*(3), 604–616. https://doi.org/10.3390/md10030604

Duarte, C. M., Wu, J., Xiao, X., Bruhn, A., & Krause-Jensen, D. (2017). Can Seaweed Farming Play a Role in Climate Change Mitigation and Adaptation? *Frontiers in Marine Science*, *4*(April). https://doi.org/10.3389/fmars.2017.00100

Fagerli, C. W., Stadniczeñko, S. G., Pedersen, M. F., Christie, H., Fredriksen, S., & Norderhaug, K. M. (2015). Population dynamics of Strongylocentrotus droebachiensis in kelp forests and barren grounds in Norway. *Marine Biology*, *162*(6), 1215–1226. https://doi.org/10.1007/s00227-015-2663-3

Furtado, P. S., Gaona, C. A. P., Poersch, L. H., & Wasielesky, W. (2014). Application of different doses of calcium hydroxide in the farming shrimp Litopenaeus vannamei with the biofloc technology (BFT). *Aquaculture International*, *22*(3), 1009–1023. https://doi.org/10.1007/s10499-013-9723-9

Gao, G., Clare, A. S., Rose, C., & Caldwell, G. S. (2018). Ulva rigida in the future ocean: potential for carbon capture, bioremediation and biomethane production. *GCB Bioenergy*, *10*(1), 39–51. https://doi.org/10.1111/gcbb.12465

Glantz, M. H. (1991). Environmental research. *Scientist*, *5*(3), 43–50.

Grant, J., & Strand, Ø. (2018). Introduction to provisioning services. *Goods and Services of Marine Bivalves*, 3–5. https://doi.org/10.1007/978-3-319-96776-9_1

Hallegraeff, G. M., Anderson, D. M., & Cembella, A. D. (2003). Manual on Harmful Marine Microalgae, Monographs on Oceanographic Methodology. In *Monographs on oceanographic methodology*.

Hasselström, L., Visch, W., Gröndahl, F., Nylund, G. M., & Pavia, H. (2018). The impact of seaweed cultivation on ecosystem services - a case study from the west coast of Sweden. *Marine Pollution Bulletin*, *133*(October 2017), 53–64. https://doi.org/10.1016/j.marpolbul.2018.05.005

Henriksson, L., Ståhle, J., Sundberg, C., & Svensson, N. (2018). *Using Blue Mussels as a Tool for Mitigating Eutrophication in the Baltic Sea*. www.liu.se

Herbert, R. J. H., Humphreys, J., Davies, C. J., Roberts, C., Fletcher, S., & Crowe, T. P. (2016). Ecological impacts of non-native Pacific oysters (Crassostrea gigas) and management measures for protected areas in Europe. *Biodiversity and Conservation*, *25*(14), 2835–2865. https://doi.org/10.1007/s10531-016-1209-4

Je, J. Y., Park, J. Y., Jung, W. K., Park, P. J., & Kim, S. K. (2005). Isolation of angiotensin I converting enzyme (ACE) inhibitor from fermented oyster sauce, Crassostrea gigas. *Food Chemistry*, *90*(4), 809–814. https://doi.org/10.1016/j.foodchem.2004.05.028

Jung, W. K., & Kim, S. K. (2009). Isolation and characterisation of an anticoagulant oligopeptide from blue mussel, Mytilus edulis. *Food Chemistry*, *117*(4), 687–692. https://doi.org/10.1016/j.foodchem.2009.04.077

Kang, Y. H., Shin, J. A., Kim, M. S., & Chung, I. K. (2008). A preliminary study of the bioremediation potential of Codium fragile applied to seaweed integrated multi-trophic aquaculture (IMTA) during the summer. *Journal of Applied Phycology*, *20*(2), 183–190. https://doi.org/10.1007/s10811-007-9204-5

Kennedy, F. G. R., Roukri, W., & Dennis, A. (1978). *U r i A K E O F INORGANIC Nl I ROGEN BY COPIUM tRAGlLE SUBSP . TOMENTOSOIDES (CH LOROI ' HYTA)' No ,*. 450–455.

Kim, J. K., Kraemer, G. P., & Yarish, C. (2015). Use of sugar kelp aquaculture in Long Island Sound and the Bronx River Estuary for nutrient extraction. *Marine Ecology Progress Series*, *531*, 155–166. https://doi.org/10.3354/meps11331

Kim, J. K., Yarish, C., Hwang, E. K., Park, M., & Kim, Y. (2017). Seaweed aquaculture: Cultivation technologies, challenges and its ecosystem services. *Algae*, *32*(1), 1–13. https://doi.org/10.4490/algae.2017.32.3.3

Kjerulf, J., Camille, P., & Pernille, S. (2015). The use of shellfish for eutrophication control. *Aquaculture International*. https://doi.org/10.1007/s10499-015-9953-0

Kraan, S. (2013). Mass-cultivation of carbohydrate rich macroalgae, a possible solution for sustainable biofuel production. *Mitigation and Adaptation Strategies for Global Change*, *18*(1), 27–46. https://doi.org/10.1007/s11027-010-9275-5

Krause-Jensen, D., & Duarte, C. M. (2016). Substantial role of macroalgae in marine carbon sequestration. *Nature Geoscience*, *9*(10), 737–742. https://doi.org/10.1038/ngeo2790

Krause-Jensen, D., Lavery, P., Serrano, O., Marba, N., Masque, P., & Duarte, C. M. (2018). Sequestration of macroalgal carbon: The elephant in the Blue Carbon room. *Biology Letters*, *14*(6). https://doi.org/10.1098/rsbl.2018.0236

Lahaye, M., & Robic, A. (2007). Structure and function properties of Ulvan, a polysaccharide from green seaweeds. *Biomacromolecules*, *8*(6), 1765–1774. https://doi.org/10.1021/bm061185q

Lawton, R. J., Mata, L., de Nys, R., & Paul, N. A. (2013). Algal Bioremediation of Waste Waters from Land-Based Aquaculture Using Ulva: Selecting Target Species and Strains. *PLoS ONE*, *8*(10). https://doi.org/10.1371/journal.pone.0077344

Lee, T. G., & Maruyama, S. (1998). Isolation of HIV-1 protease-inhibiting peptides from thermolysin hydrolysate of oyster proteins. *Biochemical and Biophysical Research Communications*, *253*(3), 604–608. https://doi.org/10.1006/bbrc.1998.9824

Liu, Z., Dong, S., Xu, J., Zeng, M., Song, H., & Zhao, Y. (2008). Production of cysteine-rich antimicrobial peptide by digestion of oyster (Crassostrea gigas) with alcalase and bromelin. *Food Control*, *19*(3), 231–235. https://doi.org/10.1016/j.foodcont.2007.03.004

Løvås, S. M., & Tørum, A. (2001). Effect of the kelp Laminaria hyperborea upon sand dune erosion and water particle velocities. *Coastal Engineering*, *44*(1), 37–63. https://doi.org/10.1016/S0378-3839(01)00021-7

Lüning, K., & Mortensen, L. (2015). European aquaculture of sugar kelp (Saccharina latissima) for food industries: Iodine content and epiphytic animals as major problems. *Botanica Marina*, *58*(6), 449–455. https://doi.org/10.1515/bot-2015-0036

Ma, X., Li, X., Sun, G., Sharawy, Z. Z., Qiu, T., Du, Y., & Liu, Y. (2017). The biofilteration ability of oysters (Crassostrea gigas) to reduce Aeromonas salmonicida in salmon culture. *Applied Microbiology and Biotechnology*, *101*(14), 5869–5880. https://doi.org/10.1007/s00253-017-8296-3

Maia, M. R. G., Fonseca, A. J. M., Oliveira, H. M., Mendonça, C., & Cabrita, A. R. J. (2016). The potential role of seaweeds in the natural manipulation of rumen fermentation and methane production. *Scientific Reports*, *6*(May), 1–10. https://doi.org/10.1038/srep32321

Maiguizo-Diagne, H., Ndiaye, N. A., Ndour-Badiane, Y., Masse, D., Torrijos, M., Sousbie, P., Gaye, M. L., Ndoye, I., Hamelin, J., & Fall, S. (2019). The use of green macroalgae (Ulva lactuca and Codium tomentosum) that have a high methane potential, as a source of biogas in Senegal. *Journal of Applied Biosciences*, *132*(1), 13404. https://doi.org/10.4314/jab.v132i1.2

Marinho-Soriano, E., Morales, C., & Moreira, W. S. C. (2002). Cultivation of Gracilaria (Rhodophyta) in shrimp pond effluents in Brazil. *Aquaculture Research*, *33*(13), 1081–1086. https://doi.org/10.1046/j.1365-2109.2002.00781.x

Morris, J. P., Backeljau, T., & Chapelle, G. (2019). Shells from aquaculture: a valuable biomaterial, not a nuisance waste product. *Reviews in Aquaculture*, *11*(1), 42–57. https://doi.org/10.1111/raq.12225

Msuya, F. E., Kyewalyanga, M. S., & Salum, D. (2006). The performance of the seaweed Ulva reticulata as a biofilter in a low-tech, low-cost, gravity generated water flow regime in Zanzibar, Tanzania. *Aquaculture*, *254*(1–4), 284–292. https://doi.org/10.1016/j.aquaculture.2005.10.044

Neori, A., Chopin, T., Troell, M., Buschmann, A. H., Kraemer, G. P., Halling, C., Shpigel, M., & Yarish, C. (2004). Integrated aquaculture: Rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture. *Aquaculture*, *231*(1–4), 361–391. https://doi.org/10.1016/j.aquaculture.2003.11.015

Pechsiri, J. S., Thomas, J. B. E., Risén, E., Ribeiro, M. S., Malmström, M. E., Nylund, G. M., Jansson, A., Welander, U., Pavia, H., & Gröndahl, F. (2016). Energy performance and greenhouse gas emissions of kelp cultivation for biogas and fertilizer recovery in Sweden. *Science of the Total Environment*, *573*, 347–355. https://doi.org/10.1016/j.scitotenv.2016.07.220

Peña-Rodríguez, A., Mawhinney, T. P., Ricque-Marie, D., & Cruz-Suárez, L. E. (2011). Chemical composition of cultivated seaweed Ulva clathrata (Roth) C. Agardh. *Food Chemistry*, *129*(2), 491–498. https://doi.org/10.1016/j.foodchem.2011.04.104

Pereira, S. (2019). *Viabilidade Economica e sustentabilidade do cultivo da macroalga Hypnea pseudomusciformis*. 69.

Probst, Y. (2015). A review of the nutrient composition of selected rubus berries. In *Nutrition and Food Science* (Vol. 45, Issue 2). https://doi.org/10.1108/NFS-07-2014-0063

Probst, Y. (2015). A review of the nutrient composition of selected rubus berries. In *Nutrition and Food Science* (Vol. 45, Issue 2). https://doi.org/10.1108/NFS-07-2014-0063

Qian, Z. J., Jung, W. K., Byun, H. G., & Kim, S. K. (2008). Protective effect of an antioxidative peptide purified from gastrointestinal digests of oyster, Crassostrea gigas against free radical induced DNA damage. *Bioresource Technology*, *99*(9), 3365–3371. https://doi.org/10.1016/j.biortech.2007.08.018

Radulovich, R., Umanzor, S., Cabrera, R., & Mata, R. (2015). Tropical seaweeds for human food, their cultivation and its effect on biodiversity enrichment. *Aquaculture*, *436*(October), 40–46. https://doi.org/10.1016/j.aquaculture.2014.10.032

Rafiquzzaman, S. M., Ahmed, R., Lee, J. M., Noh, G., Jo, G. a., & Kong, I. S. (2016). Improved methods for isolation of carrageenan from Hypnea musciformis and its antioxidant activity. *Journal of Applied Phycology*, *28*(2), 1265–1274. https://doi.org/10.1007/s10811-015-0605-6

Rajapakse, N., Mendis, E., Jung, W. K., Je, J. Y., & Kim, S. K. (2005). Purification of a radical scavenging peptide from fermented mussel sauce and its antioxidant properties. *Food Research International*, *38*(2), 175–182. https://doi.org/10.1016/j.foodres.2004.10.002

Referencias, V. I. I. (2007). Identidad Perfil. *Programa de Información de Especies Acuáticas Oreochromis*, *9*(10), 11–15. http://www.revistaaquatic.com/aquatic/pdf/34_3.pdf

Rinde, E., Christie, H., Fagerli, C. W., Bekkby, T., Gundersen, H., Norderhaug, K. M., & Hjermann, D. (2014). The influence of physical factors on kelp and sea urchin distribution in previously and still grazed areas in the NE Atlantic. *PLoS ONE*, *9*(6). https://doi.org/10.1371/journal.pone.0100222

Robertson-Andersson, D. V., Maneveldt, G. W., & Naidoo, K. (2011). Effects of wild and farm-grown macroalgae on the growth of juvenile South African abalone Haliotis midae Linnaeus. *African Journal of Aquatic Science*, *36*(3), 331–337. https://doi.org/10.2989/16085914.2011.636910

Samocha, T. M., Fricker, J., Ali, A. M., Shpigel, M., & Neori, A. (2015). Growth and nutrient uptake of the macroalga Gracilaria tikvahiae cultured with the shrimp Litopenaeus vannamei in an Integrated Multi-Trophic Aquaculture (IMTA) system. In *Aquaculture* (Vol. 446). Elsevier B.V. https://doi.org/10.1016/j.aquaculture.2015.05.008

Sanderson, J. C., Dring, M. J., Davidson, K., & Kelly, M. S. (2012). Culture, yield and bioremediation potential of Palmaria palmata (Linnaeus) Weber & Mohr and Saccharina latissima (Linnaeus) C.E. Lane, C. Mayes, Druehl & G.W. Saunders adjacent to fish farm cages in northwest Scotland. *Aquaculture*, *354–355*, 128–135. https://doi.org/10.1016/j.aquaculture.2012.03.019

Schiener, P., Black, K. D., Stanley, M. S., & Green, D. H. (2014). The seasonal variation in the chemical composition of the kelp species Laminaria digitata, Laminaria hyperborea, Saccharina latissima and Alaria esculenta. *Journal of Applied Phycology*, *27*(1), 363–373. https://doi.org/10.1007/s10811-014-0327-1

Schmidt, A. L., & Scheibling, R. E. (2006). A comparison of epifauna and epiphytes on native kelps (Laminaria species) and an invasive alga (Codium fragile ssp. tomentosoides) in Nova Scotia, Canada. *Botanica Marina*, *49*(4), 315–330. https://doi.org/10.1515/BOT.2006.039

Shand, P. (1987). Biological control of marine sediments stability by the mussels Mytilus edulis and Modiolus modiolus. In *University of Glasgow*.

Smaal, A. C., Ferreira, J. G., Grant, J., Petersen, J. K., & Strand, Ø. (2018). Goods and services of marine bivalves. In *Goods and Services of Marine Bivalves* (Issue February). https://doi.org/10.1007/978-3-319-96776-9

Smaal, A. C., Ferreira, J. G., Grant, J., Petersen, J. K., & Strand, Ø. (2018). Goods and services of marine bivalves. In *Goods and Services of Marine Bivalves*. https://doi.org/10.1007/978-3-319-96776-9

Souza, R. B., Frota, A. F., Silva, J., Alves, C., Neugebauer, A. Z., Pinteus, S., Rodrigues, J. A. G., Cordeiro, E. M. S., de Almeida, R. R., Pedrosa, R., & Benevides, N. M. B. (2018). In vitro activities of kappa-carrageenan isolated from red marine alga Hypnea musciformis: Antimicrobial, anticancer and neuroprotective potential. *International Journal of Biological Macromolecules*, *112*(2017), 1248–1256. https://doi.org/10.1016/j.ijbiomac.2018.02.029

Steneck, R. S., Graham, M. H., Bourque, B. J., Corbett, D., Erlandson, J. M., Estes, J. A., & Tegner, M. J. (2002). Kelp forest ecosystems: Biodiversity, stability, resilience and future. *Environmental Conservation*, *29*(4), 436–459. https://doi.org/10.1017/S0376892902000322

Stirk, W. A., & Van Staden, J. (2000). Removal of heavy metals from solution using dried brown seaweed material. *Botanica Marina*, *43*(5), 467–473. https://doi.org/10.1515/BOT.2000.047

Tacon, A. G. J., Cody, J. J., Conquest, L. D., Divakaran, S., Forster, I. P., & Decamp, O. E. (2002). Effect of culture system on the nutrition and growth performance of Pacific white shrimp Litopenaeus vannamei (Boone) fed different diets. *Aquaculture Nutrition*, *8*(2), 121–137. https://doi.org/10.1046/j.1365-2095.2002.00199.x

Thomas, Y., Pouvreau, S., Alunno-Bruscia, M., Barillé, L., Gohin, F., Bryère, P., & Gernez, P. (2016). Global change and climate-driven invasion of the Pacific oyster (Crassostrea gigas) along European coasts: A bioenergetics modelling approach. *Journal of Biogeography*, *43*(3), 568–579. https://doi.org/10.1111/jbi.12665

Trianti, C. M., & Adharini, R. I. (2020). The Utilization of Gracilaria verrucosa as shrimp ponds wastewater biofilter. *E3S Web of Conferences*, *147*, 4–11. https://doi.org/10.1051/e3sconf/202014702023

Trigueiro, T. G., Pereira, D. C., Martins, A. P., Colepicolo, P., & Marinho-Soriano, E. (2017). Cultivation of three color strains of Gracilaria domingensis in an integrated organic system. *International Aquatic Research*, *9*(3), 225–233. https://doi.org/10.1007/s40071-017-0171-4

Troell, M., Robertson-Andersson, D., Anderson, R. J., Bolton, J. J., Maneveldt, G., Halling, C., & Probyn, T. (2006). Abalone farming in South Africa: An overview with perspectives on kelp resources, abalone feed, potential for on-farm seaweed production and socio-economic importance. *Aquaculture*, *257*(1–4), 266–281. https://doi.org/10.1016/j.aquaculture.2006.02.066

Troell, M., Rönnbäck, P., Halling, C., Kautsky, N., & Buschmann, A. (1999). Ecological engineering in aquaculture: Use of seaweeds for removing nutrients from intensive mariculture. *Journal of Applied Phycology*, *11*(1), 89–97. https://doi.org/10.1023/A:1008070400208

Unit, B., Biology, E., & Building, G. K. (1998). *Prevailing wind*. 331–347.

van der Wal, H., Sperber, B. L. H. M., Houweling-Tan, B., Bakker, R. R. C., Brandenburg, W., & López-Contreras, A. M. (2013). Production of acetone, butanol, and ethanol from biomass of the green seaweed Ulva lactuca. *Bioresource Technology*, *128*, 431–437. https://doi.org/10.1016/j.biortech.2012.10.094

Viera, M. P., Gómez Pinchetti, J. L., Courtois De Vicose, G., Bilbao, A., Suárez, S., Haroun, R. J., & Izquierdo, M. S. (2005). Suitability of three red macroalgae as a feed for the abalone Haliotis tuberculata coccinea Reeve. *Aquaculture*, *248*(1–4), 75–82. https://doi.org/10.1016/j.aquaculture.2005.03.002

Vivekanand, V., Eijsink, V. G. H., & Horn, S. J. (2012). Biogas production from the brown seaweed Saccharina latissima: Thermal pretreatment and codigestion with wheat straw. *Journal of Applied Phycology*, *24*(5), 1295–1301. https://doi.org/10.1007/s10811-011-9779-8

wa Kangeri, A. K., Jansen, J. M., Joppe, D. J., & Dankers, N. M. J. A. (2016). In situ investigation of the effects of current velocity on sedimentary mussel bed stability. *Journal of Experimental Marine Biology and Ecology*, *485*, 65–72. https://doi.org/10.1016/j.jembe.2016.08.011

wa Kangeri, A. K., Jansen, J. M., Joppe, D. J., & Dankers, N. M. J. A. (2016). In situ investigation of the effects of current velocity on sedimentary mussel bed stability. *Journal of Experimental Marine Biology and Ecology*, *485*, 65–72. https://doi.org/10.1016/j.jembe.2016.08.011

Wang, B., Li, L., Chi, C. F., Ma, J. H., Luo, H. Y., & Xu, Y. F. (2013). Purification and characterisation of a novel antioxidant peptide derived from blue mussel (Mytilus edulis) protein hydrolysate. *Food Chemistry*, *138*(2–3), 1713–1719. https://doi.org/10.1016/j.foodchem.2012.12.002

Wollak, B., Forss, J., & Welander, U. (2018). Evaluation of blue mussels (Mytilus edulis) as substrate for biogas production in Kalmar County (Sweden). *Biomass and Bioenergy*, *111*(September 2017), 96–102. https://doi.org/10.1016/j.biombioe.2018.02.008

Wu, R. S. S. (1999). Eutrophication, water borne pathogens and xenobiotic compounds: Environmental risks and challenges. *Marine Pollution Bulletin*, *39*(1–12), 11–22. https://doi.org/10.1016/S0025-326X(99)00014-4

Zhou, Y., Yang, H., Hu, H., Liu, Y., Mao, Y., Zhou, H., Xu, X., & Zhang, F. (2006). Bioremediation potential of the macroalga Gracilaria lemaneiformis (Rhodophyta) integrated into fed fish culture in coastal waters of north China. *Aquaculture*, *252*(2–4), 264–276. https://doi.org/10.1016/j.aquaculture.2005.06.046