Unlocking the potential of macroalgae for a thriving European blue bioeconomy

Policy and investor recommendation on ecosystem services and an understanding of their limits and thresholds

SEAMARK DELIVERABLE 9.2

Wageningen Economic Research

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SEAMARK DELIVERABLE 9.2: POLICY AND INVESTOR RECOMMENDATIONS ON ECOSYSTEM SERVICES AND AN UNDERSTANDING OF THEIR LIMITS AND THRESHOLDS

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Abstract

Seaweed cultivation is a resource production with the potential to enhance biodiversity, uptake excess nutrients and sequester carbon. The European Commission has recognized its potential, and listed actions necessary to unlock the algae potential in the communication from the Commission towards a strong and sustainable EU Algae Sector. Nevertheless, seaweed has not yet been integrated into other strategies, frameworks, or directives. In this policy brief, we outline the potential of seaweed as a sustainable biomass, the quantification and valuation methodologies and give an overview of the current existing credits for the three abovementioned ecosystem services. There are remaining uncertainties in the quantification methodologies, while recognizing this, we also give examples of how the certification process can be done including the uncertainties.

We recommend the following:

- Include blue carbon in the regulatory framework.
- Recognize seaweed cultivation as a carbon-fixing practice.
- Use nutrient remediation as a functioning nature-based solution.
- Support the understanding of the effect of seaweed cultivation on biodiversity.
- Support development of a certification process.
- Adapt the additionality criterion in certification.
- Assess the optimal scale.
- Set limits of acceptable change of the ecosystem with seaweed farms.
- Finance for research.
- Develop investors guidelines.

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INTRODUCTION

Seaweeds are receiving a lot of attention in recent years in Europe, thanks to their regenerative nature and fast-growing biomass. During the cultivation phase, no additional fresh water is needed, no arable land, and no fertilizers for their growth. In addition, they take up carbon and provide habitat and shelter for many marine species[20]. Seaweed biomass is being used for a number of different products, ranging from food and feed to cosmetics and medicine[21].

This policy brief aims to inform decision-makers in the public and private sectors about the ecosystem services provided by seaweed cultivation. We provide recommendations on how decision-makers can take the next step towards integrating of ecosystem services provided in decision-making to the benefit of a sustainable EU seaweed sector.

The policy brief describes the concept of ecosystem services and provides a categorization of the ecosystem services provided by seaweed cultivation. The brief then describes how seaweed cultivation, and the ecosystem services provided, can contribute to the achievement of various policy objectives and to the business case of seaweed cultivation. In the subsequent chapter, we focus on three key ecosystem services provided by seaweed cultivation: carbon sequestration, nutrient (N/P) remediation and biodiversity enhancement. The mechanisms through which the services are provided, the current state of quantification methodologies as well as insights on valuation methods are described. These three ecosystem services are chosen for their impact, but also for their possible future use for credits. Furthermore, a literature review showed that most information on quantification and valuation methodologies is on these three ecosystem services. The concept of carrying capacity is introduced to enable a discussion on the optimal scale of seaweed cultivation.

Figure 1 below visually summarizes the argumentation in this policy brief. It is argued that the ecosystem services provided by seaweed cultivation can contribute to addressing various societal challenges. Quantifying and valuing these ecosystem services can support the business case for seaweed cultivation. Based on our assessment of the state-of-the-art, various actions are needed to take next steps and support the European seaweed sector.

The policy brief is prepared in the SeaMark project and constitutes deliverable 9.1. It is based on an extensive review of literature and expert consultation.

WHAT ECOSYSTEM SERVICES ARE AND WHY THEY ARE IMPORTANT?

Defining ecosystem services

The concept of ecosystem services is used to describe the benefits humans gain from ecosystems. Ecosystem services are key for human life as they provide clean water, good air quality, nutritious food, and contribute to regulate climate and diseases. Additionally, ecosystem provide recreational, cultural and spiritual benefits[22]. The benefits people receive from ecosystems are directly related to ecosystem functions such as pollination, cycling of nutrients, and carbon uptake[23].

Classification of ecosystem services

Ecosystem services can be categorized based on the type of contribution they make beneficial for humans (CICES)[24]. FAO[25], CICES[24] and IPBES[26] all refer to similar ecosystem services but categorize them slightly differently. Table 1 provides an overview based on the general categories (i) provisioning services, (ii) regulatory services, (iii) supporting services and (iv) cultural services in line with FAO[25] and CICES[24]. Regulating services are for example advantages derived through the management of ecological processes, such as the regulation of climate and water. Provisioning services are "products obtained from ecosystems, such as genetic resources, food and fibre, and freshwater,". Supporting services are not always listed as separate services as they describe the support for the production of all other services, for example providing plants and animals with living space[25]. Cultural services are "the non-material benefits people obtain from ecosystems, such as cognitive development, reflection, recreation, and aesthetic experience"[27].

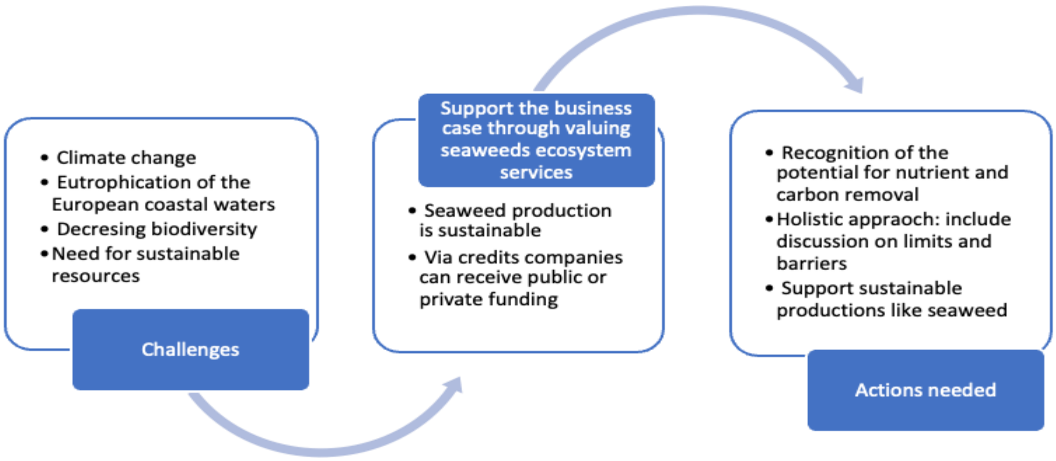

Figure 1: Visual summary of the argument

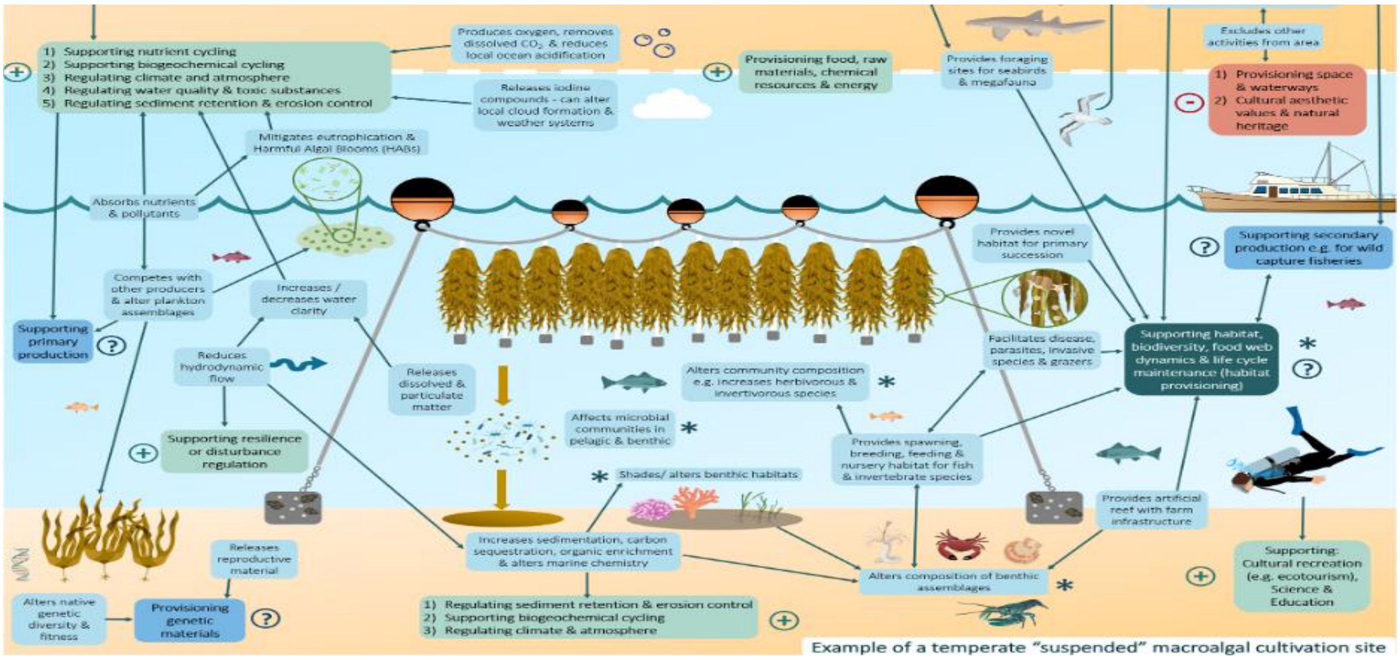

Figure 2: Summary of the proposed environmental impacts and potential effects on ecosystem services. Figure after Corrigan, et al. (2022)[6], and modified by the authors to focus on suspended macroalgae cultivation.

Following the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES)[26], some services could fit into more than one category and would thus belong to more than one category[23]. For instance, the increase in biodiversity thanks to shelter provided by seaweed, can also be beneficial for the cultural and recreational services this ecosystem offers, like scuba diving or hobby fishing. Figure 1 shows the ecosystem services of seaweed cultivation while depicting the environmental impacts and potential effects of it.

Ecosystem services from seaweed cultivation

Cultivation of seaweed implies the creation of a new ecosystem through human intervention (installing structures, seeding, et cetera) and the interaction with biotic elements present (including flora and fauna).

Table 1: List of relevant ecosystem services from seaweed cultivation

Ecosystem services		**Further specification from other sources**
Provisioning	Food	
	Feed	
	Biomass & Hydrocolloids	Fertilizer
		Raw material, natural products
		Fibres
		Resource and biotechnology (Biofuel, biogas, biomethane production)
		Medicine and biomedical products
		Genetic resources
Regulating	Climate regulation	CO_2 draw down, carbon uptake, carbon sequestration, carbon storage, halocarbon retention
		pH increase, pH regulation, regulation of ocean acidification
		Coastal protection (sediment retention)
	Water quality	Nutrient cycling, nutrient assimilation, suspended material removal, regulation of eutrophication
		Improving water quality
	Biologial regulation	Biodiversity species, rare species and habitat
		Photosynthesis
Cultural	Recreation and tourism	
	Symbolic aesthetics	Cultural heritage
		Sense of place
	Education and learning	Inspiration
	Scientific kowledge	
	Social welfare	Coastal livelihoods and economics

To specify the ecosystem services that are provided by a seaweed cultivation ecosystem (in the remainder of the document we will use "seaweed cultivation" only), the generic categories services were matched with services for ocean and coastal marine ecosystems (based on categorization from Halpern, et al. (2012)[28] Heckwolf, et al. (2021)[29] Hasselström, et al. (2018)[30]). An overview of ecosystem services provided by seaweed cultivation was prepared based on a review of scientific literature. Ecosystem services reoccurring in every source are food provisioning, water quality regulation, carbon storage and habitat supporting. There are small inconsistencies in how the services were categorized under regulating, provisioning or supporting, and for this reason the service categories were listed for all coastal ecosystem service references. Other services like nutrient uptake seem even more related to the seaweed itself, but here again, the nutrients come from the surrounding water and form an interconnected system that can provide the service.

Methodology for data collection

Deliverable 9.1 provides the framework for the data collection for life cycle assessments and ecosystem services. It guides the consortium through the process and thus preventing data losses, delays and facilitating the collection process itself. For the final data collection, further decisions with the consortium need to be made. Thus, this framework provides the necessary information to discuss with the partners on what data collection is feasible. For the ecosystem services, this report provides an overview of categorized ecosystem services, an overview of methodologies used to quantify and valuate ecosystem services and the decision process for specific partners to decide and plan the final data collection. The practical protocols for the selected ES will be made by designed by WUR, but in close collaboration with the seaweed cultivators, as it depends on their feasibility.

NUTRIENT REMEDIATION, BIODIVERSITY AND CARBON SEQUESTRATION, FROM SEAWEED CULTIVATION

This chapter gives insight into the state-of-the-art on three key ecosystem services provided by seaweed cultivation: nitrogen and phosphorus remediation, biodiversity and carbon sequestration. Three angles are taken: (1) what is known about quantification of the ecosystem service, (2) what is known about valuation and (3) what is the status of credits for the service provided.

Nutrient remediation

Excess nutrients, particularly nitrogen and phosphorus, can cause eutrophication in aquatic ecosystems. This can have cascading environmental effects, such as harmful algal blooms (microalgae), reduced water quality and "dead zones" with low dissolved oxygen[31,32]. According to the European Environment Agency, 23% of Europe's coastal waters are still subject to intense eutrophication[33]. Seaweed cultivation is a recognized tool for eutrophication mitigation and could be used in targeted eutrophic areas[7].

Seaweed absorbs nitrogen and phosphorus from the water column during growth and reproduction[34] and help to mitigate eutrophication[7]. When harvesting the biomass, the absorbed nutrients are also removed from the local environment[34]. Seaweed aquaculture could be a cost-effective way of nutrient pollution control compared to some other land-based methods[31]. Globally in 2014 around 15-30% of fertilizers used in land enter the ocean[35,36]. Studies modelled the removal of nutrients from seaweed and estimated it to be 576 kg nitrogen/ha/yr = 60,000 kg nitrogen/km2/yr, based on a seaweed cultivation site of *Saccharina* near a fish farm in Scotland[37]. Authors estimated that if seaweed was farmed in 0.03% of the ocean it could globally remove around 30% of the nitrogen introduced into the ocean[38,36]. To think one step further, biostimulants for agriculture can be based on seaweed biomass[39] and could reduce the amount of fertilizers used. This way, seaweed could even contribute to reducing the excess nutrients from agriculture arriving in the water.

Quantification

When quantifying the amount of nutrients absorbed by seaweed, most scientists harvest the seaweed and analyse the content of nitrogen and phosphorus. Nutrient measurements usually are on harvested seaweed samples and then analysed in a lab. It is advised to take various samples, from different locations of the cultivation site, from different depths and from different parts of the seaweed like the stem and the seaweed blade. After determining the nutrient content via molecular laboratory techniques, the percentage of nutrient content in the tissue multiplied by the harvested biomass will yield the estimated nutrient removed from the marine environment. Nutrient content is referred to as the bioextraction potential[40,41,42] and therefore the potential nutrients to be removed. Some researchers go a step further and together with nutrient content in the seaweed they also measure rates of sediment denitrification (i.e., reduction of nutrients in the sediments of marine the environment). To measure the latter, samples of the sediment are compared in terms of their nitrogen content at seaweed cultivation sites and control sites. The nutrient assimilation capacity changes and depends on species and environmental conditions[31].

To quantify the potential of seaweed to remove nutrients these two components are considered[7]. Seaweed tissue nitrogen content varies per seaweed species and some average values are, for instance, *Gracilaria* 3% of its dry weight and kelp 2% of its dry weight[36]. The phosphorus content varied between 0.1 and 0.25 %, measured on 5 seaweed species[43]. Taking these numbers and the global production of these species, the total nitrogen extractive potential of seaweed aquaculture can be estimated[36].

It's important to keep in mind the ecosystem as a whole. Seaweed aquaculture can be used for eutrophication mitigation, but in the case of limited nutrient or not excessive nutrients, it may be a direct competition with wild food webs[31,44], for example, primary production (phytoplankton). Section 4 provides further information on the limits of production to an ecosystem.

Valuation

There are a few ways researchers have approached assigning a monetary value to nutrient remediation. First, the value of one unit of nutrient removal is the same as the cost of applying the cheapest alternative to mitigate its effects, the replacement costs[18,45,7]. A concrete example could be to assign a monetary value to nitrogen and phosphorous based on the recovery costs of wastewater treatment facilities. Two components are considered here: 1) the average content of the nutrient in seaweed in percentage (0.35% nitrogen and 0.04% phosphorus; 2) the recovery costs from water treatment facilities amounts to US$10-30/kg of nitrogen, and US$4/kg of phosphorus[46]. Otherwise, the avoided damage costs can be looked at, estimating the reduction in water quality and costs that arise from having the ecosystem service[18]. Another approach is to study the willingness to pay by resource users for the reduction of a specific nutrient[7,47]. The value of nutrient removal is calculated by using nitrogen and phosphorus content of seaweed dry weight are multiplied with the price given for a kg of each nutrient[48].

Valuation of ecosystem services in general
To assign a monetary value to ecosystem services can create an incentive, or economic argument, to invest into nature. For this, a methodology to assess not only the benefits, but also the costs that arise is needed[7,12]. There are a few economic valuation tools for ecosystem services in aquaculture, including replacement cost or avoided damages calculations, benefit transfer to estimate the value via existing studies or resource rent/opportunity cost to calculate the value as revenues/profits minus all production cost. The perception of value and opinion or ranking surveys are examples for noneconomic valuation methods. Weitzman (2019)[15] offer an overview of such methodologies in the paper's Table 2 or the monetary valuation of ecosystem services and assets for ecosystem accounting

Box 1: Valuation of ecosystem services in general

Credits

In terrestrial ecosystems, nutrient trading market follows a similar logic as the one for carbon credits. Practitioners that manage to reduce their nutrient runoff to amounts lower than target levels, can sell their surplus ("credits") to other parties[49]. The process behind the Nutrient Trader Application is based on farmers implementing farming practices that translate into reduced nitrogen pollution, precision farming is one example. So, if a farmer reduces nitrogen (or phosphorus) pollution by 20%, he/she will earn 22 credits/ha and through an app he/she can sell the credits to other farmers that are still polluting over target levels[50].

Credits in general
One way of monetizing the valued ecosystem services from seaweed cultivation can be via credits. Credits are economic instruments used to finance net positive outcomes, like carbon removal, biodiversity gain or eutrophication mitigation. They are a direct way to link creators of the services with beneficiaries. Credits can help the private and public sector achieve an economic system that is nature positive[4].
Carbon credits are widely known by now, nutrient and biodiversity credits less. While the EU already introduced four so-called QU.A.L.ITY criteria to ensure the quality and comparability of carbon removals, such clarity and standardization is not yet in place for nutrient and biodiversity credits.

Box 2: Credits for ecosystem services in general

There are a few examples of systems for nutrient trading for seaweed. For instance, seaweed aquaculture has been proposed to partner up with Water Quality Trading programs (WQT)[31]. In this way, companies with high pollution control costs can benefit from buying offsets from seaweed farming. What a credit is and its duration may also differ. The Maryland Department of Environment for example defines one credit as 1 pound of pollutant reduced for the duration of one year[16]. In a specific case in the UK, a nitrogen credit is considered 1 kg of nitrogen per year for the lifetime of the development, generally 80–125 years[51]. However, since aquaculture activities have a yearly cycle, the value of nitrogen removed in one year, would need to be distributed again this longer time frame and have a guarantee that the activity persists for that time frame. This of course plays a role in the licenses periods[51]. The prices of these nutrient credits vary greatly and depend on the context, market structure and the cost of using alternative remediation options. Therefore, in order to finance seaweed aquaculture through these credits, the price needs to be at a break-even point of production costs: the credit price needs to offset the costs. In the case of nutrient credits from seaweed, the price for such an alternative remediation option depends again on production of costs, which varies per species. For example, the prices per WQT credit needed to offset the production costs for *Gracilaria tikvahiae* would need to be between 2.05-17.17 USD/kg or between 8.33 – 69.79 USD/kg for Eucheuma spp. Such a system is already applied to shellfish aquaculture industry, started in May 2020[31].

The monetary valuation of seaweeds' nutrient removal also depends on the lowest cost-effective alternative measure to mitigate the pollution. Another approach is shown by Greenwave, a network of regenerative ocean farmers. They developed the Kelp Climate Fund methodology to provide payments to farmers for the climate benefits associated to their kelp growing. Farmers receive 1 USD for every foot of grown kelp for sum of ecosystem services that seaweed provides[52]. This is based on studies by the NOAA and The Nature Conservancy that calculated market value of ecosystem services of seaweed and shellfish[7].

Biodiversity

Ecosystems are a complex network of interacting species and the non-living environment they are embedded in. Biodiversity is defined as the number of different species and individuals present at a site. The relationships between these species are dynamic[53]. Both natural seaweed beds and cultivated seaweed provide habitat for a diversity of species and therefore contribute to an enhancement of biodiversity in and around them[54,55]. Living organisms that are present in seaweed farms range from small invertebrates, such as shellfish, jellyfish, and worms, to different species of fish. When balances are disturbed, loss of species or reduction in populations can occur, for example, the well-known phenomena of lost coral reefs, or unrecoverable fish populations. **Some authors say the variety of life that one single kelp forest can sustain is over 7000 individuals of other species[56]**, but it currently seems unlikely that a cultivation farm can provide the same biodiversity outcomes[57]. The harvesting strategy can play a role here: the seaweed lines could be harvested only partially over a series of years, or fully harvested once a year thus leaving the area with no seaweed biomass for several months. There are cultivation methods, where only a percentage of the biomass is harvested, leaving the 'forest' in the water, and therefore the habitat58. The cultivation unit design could also have an impact for the habitat provision for the marine spices, e.g. vertical lines structures providing a 3D habitat or horizontal longline systems that provides a 2D structure[59]. **In summary, biodiversity in the marine environment is crucial for its proper functioning and thus allowing the provision of ecosystem services[26]**.

Some authors believe that seaweed farms rather act as a place for aggregation of biodiversity and that it should thus not be considered as an increase of biodiversity, but instead an attraction of biodiversity to a specific site[55]. Additionally, there is some discussion about seaweed farms attracting invasive species that then disturb ecosystem functioning[56]. While at the same time authors have reported that seaweed farming attract several species of fish and among them one that serves as biological pest control for salmon farms[60]. So both positive and potential negative effects of the cultivation activity at sea.

Quantification

Quantifying biodiversity is a challenging task due to the complexity of ecosystems and the species that form them. The Wallacea Trust Foundation (a UK-based non-profit) working group[61,62] proposed three approaches for quantifying the change in biodiversity:

1) The uplift in biodiversity in a specific site: For this, at the same site, biodiversity values are measured at agreed interim time intervals and at the end to see the change at that site.

2) Future uplift in biodiversity in a specific site: Using consistent combination of metrics and methods, biodiversity values are measured at the project site and at a reference site (with the same management approach) simultaneously. The comparison of the two will give indication of the increase in biodiversity in the project site. Measures are taken at the initiation of a project and a set number of times with the same interval of time. These values will give additional information to the progression of biodiversity change, and actual measured uplift of biodiversity.

3) Quantify avoided biodiversity degradation: Similar to the second method, here the project site may be a site under threat of development where a biodiversity loss is expected, and the reference site is a site with the same type of development already there, which can help to estimate the likely decrease in each of the metrics in case of development.

But besides the choice of which approach to use to quantify, the different methods and their metrics (indicator methods chosen to quantify biodiversity) still have to be defined. The Wallacea trust working[62] group has further details on how to use the selected metrics in detail and within the chosen quantification approach, but there's not yet a standardized set of indicators (metrics) or methodology as a whole, to be used for seaweed aquaculture.

For seaweed aquaculture, researchers have used different methods, and each of them has advantages and disadvantages associated. Fish and macroinvertebrate species are sampled in different transects by **visual census**, meaning that scuba divers observe and take note of the different species and numbers observed. This method however requires expert knowledge and is therefore performed by marine biologists[60,55,63].

An alternative is to use **remote operated vehicles**, that are equipped with cameras. They are especially useful in deeper regions difficult to reach by divers. Fixed cameras can also be used to observe abundance and diversity. These should be positioned at different depths and locations of the ocean cultivation unit(s). Just as marine species are observed, seabird species and abundance, as well as mammals could also be monitored[64]. The radius would have to be bigger.

To monitor the invertebrate communities underneath the cultivation, **sediment samples** can be taken[68]. The results would then have to be multiplied by the area to get a result for the whole cultivation area.

Finally, biodiversity in seaweed cultivation areas can be quantified by using **molecular techniques of eDNA** sequencing to measure types and abundance of species in a sample of water or sediment. Although this technique appears to be more costly, it does not require as many experts to look at and identify the different individuals observed, because it can identify several species at the same time. Pilot studies measuring biodiversity in seaweed farms cultivation areas in the Netherlands have shown promising results[56]. For this, water samples at various depths and sediment samples would be taken and analysed for an increase in species richness. However, this doesn't give an indication on the quantity of individuals[55]. Additionally, there is some discussion about seaweed farms attracting invasive species that then disturb ecosystem functioning[56]. While at the same time authors have reported that seaweed farming attract several species of fish and among them one that serves as biological pest control for salmon farms[60]. So, both positive and potential negative effects of the cultivation activity at sea.

Valuation

The CBD's conference of the parties (COP) Decision IV/10 states that "the importance of economic valuation is recognized in the CBD context. CBD's "economic valuation of biodiversity and biological resources is an important tool for well-targeted and calibrated economic incentive measures"[66].

Biodiversity in seaweed beds and cultivation sites has high value for fishing and coastal communities. These rich ecosystems provide a series of marine resources, like seaweed itself, fish and other edible organisms, accounting for the major source of livelihood for these communities[67]. According to the OECD, more than three billion people are directly dependent on coastal and marine biodiversity both for their livelihoods and main source of protein[68]. A consensus exists around the imperative of protecting as much biodiversity as possible, the cost of it is the question. This can be measured in terms of species, features and functions, which is subject to a philosophical question of the value of each. There is no one fixed value for diversity yet, as there is for instance for carbon via the trade market. But similarly, to the different carbon prices (social cost, marginal cost or market cost of carbon or view box 4), or with the valuation of nutrient remediation, in biodiversity there can also be a value assigned to the uplift of it, the future uplift of it or the avoidance of degradation. When valuing biodiversity economically, cost-benefit analysis and multi-criteria analysis may be used. One example of economic valuation of the loss of biodiversity, is to calculate what the replacement of that service would cost if humans would have to do it, for example, almond tree pollination[69]. Willingness to pay is another way to approach it, but just as there is no 'one biodiversity' there is no one 'thing' to pay for. What is valued monetarily changes with every situation: amount of fish or corals to see while snorkelling, restoration of coasts, replacement costs of the services provided by the species, protection of breeding grounds of birds, etc. The System of Environmental-Economic Accounting – Ecosystem Accounting (SEEA EA) does also not yet include biodiversity accounting and monetary valuation in their technical report, only nursery population and habitat maintenance, which basically means the market value of the added biomass produced[18]. But the OECD published a handbook for biodiversity valuation which outlines the different methodological approaches and discusses the limitations[70]. Valuation of biodiversity is an emerging field of work and the challenges of how to value biodiversity are a topic of current research.

Credits

The quantification of biodiversity increase or avoided loss is very complex, as described in section 3.2.1. Therefore, the process of having biodiversity credits had been delayed over years of disagreement over the design and application[71]. Various relevant initiatives are ongoing, there are several credits one must differentiate between (ecosystem credits and species credits) and what a credit is worth may change from credit to credit. Generally, for a biodiversity credit, a threatened area is surveyed to establish the habitat's baseline, the progress is then monitored and once the agreed upon goal is reached, the credit is given.

Social and biodiversity impacts can be seen as 'co-benefits' and for instance improve the value of carbon credits[72], the Plan Vivo Biodiversity+13 is such an example, but this would devalue biodiversity in comparison to climate change as challenges/issues society faces. The Plan Vivo Foundation (PVF)[73] is therefore also increasing the effort to having also a second approach for financing for biodiversity, a standalone biodiversity standard (**PV Nature**)[41].

The Wallacea Trust Foundation working group is partnering with Plan Vivo and developed a methodology for the quantification of biodiversity for its certification. They define one biodiversity credit as a one-percent improvement, or avoided loss, per hectare at the submitted site as compared to its initial state[61]. The number of credits that can be awarded is determined by calculating the proportion of biodiversity uplift, or avoided loss, applied over the area of the site. The methodology incorporates leakage, where loss is simply transferred to another site/country, and buffer, to cover potential shortcomings of the project's promises, into their formula[62]. Verra, currently having a Climate, Community and biodiversity standard, said it will reveal a standard for biodiversity in 2023[74] and is currently working on the methodology[75].

Third party **certifiers** can have the role to assessing the validity of the carbon or nutrients removed, or biodiversity gained. Globally accepted institutions like the Gold Standard[2] and the Verified Carbon Standard (VCS)[8] administered by Verra[10], specifically certifying carbon credits, or the Plan Vivo Foundation developing biodiversity credit certification[13] in addition to their carbon credit certification[14]. In the US, for example the Maryland department of environment, certifies nutrient credits as part of the Water Quality Trading Program[16]. There are many other, smaller and lesser-known ones. These are part of a voluntary market credit system, mainly operated and managed by the US and Europe (UK)[19].

Box 3: Certifiers for credits

For marine ecosystems there are frameworks and methodologies for biodiversity offsetting, for instance by using a levy on fisheries bycatch to fund conservation and preservation actions. These offsetting credits are still in the early stages, and biodiversity credits are to our knowledge not yet standardized for the marine ecosystems. Open Earth, a California based non-profit, announced in November 2022 the creation of a Marine Ecosystem credit (MEC), for four types or credits including Marine biodiversity which are each split into protection credits and restoration credits. For their first prototype of a marine biodiversity credit, they are factoring species diversity and ecosystem resilience in their metrics[76].

Carbon sequestration

Urgent action is needed to not only reduce greenhouse gas (GHG) emissions but also sequester CO_2 to reach our climate goals[77]. Seaweed has received increasing attention in the international scene due to its ability to capture carbon during its growth phase. Many scientists have demonstrated its capacity to take up anthropogenic CO_2 and fix it into organic matter[78,79,80,81]. For a proper description of the potential, it is necessary to separate between the different pathways for carbon. Carbon uptake itself can indirectly be seen as a service, as products made out of seaweed can be used to replace other products made from fossil fuels (view figure 2, pathway 3). If it is consumed by other marine organisms or post-harvest as food and feed by animals and humans, it ends up in the short-term carbon cycle and is released back into the atmosphere. If seaweed extracts are used to reduce GHG emissions in other production processes (like ruminants), GHG emissions are avoided (figure 2, pathway 2).

Our focus is on the sequestration of carbon from the atmosphere into the long-term carbon cycle, where the carbon from seaweed could be stored away for longer timescales (according to IPCC 100 or more years counts as sequestration[82]). Only this amount of carbon can be considered sequestered and is actually mitigating climate change by contributing to the reduction of the current amount of atmospheric CO_2. This however is more complicated than the uptake of carbon from seaweed. There are different ways how carbon from seaweed can be sequestered, land-based, as part of the post-harvest processes and marine-based, during the growth phase of seaweed (cultivated or natural kelp bed)[83,81,84,85]. Please view figure 2, pathway 1.

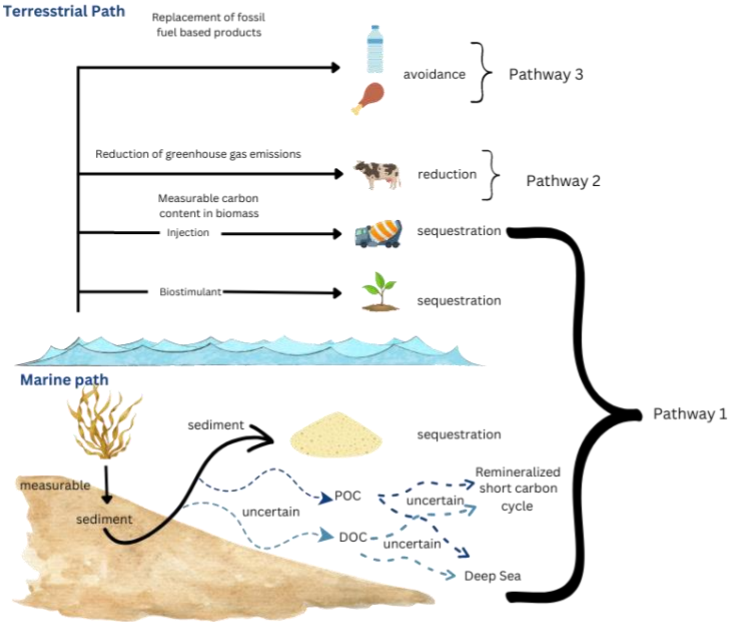

Figure 3: Pathways for climate mitigation

For the post-harvest sequestration path (view terrestrial path in figure 3), the seaweed biomass containing the carbon can for instance be injected into cement [86,87,88] where it can be stored for time periods long enough to be considered sequestered. The number of applications possible depends on the potential innovations and their viability. With the current need for climate solutions, there is fertile ground for further material using seaweed fibre for carbon storage. Another post-harvest carbon sequestration from seaweed can be via seaweed-based biostimulants, drawing down more carbon into the soil[89]. View the options above the water surface line, the terrestrial path for pathway 1 in figure 2.

The marine-based path may seem more direct, as no processing action needs to be taken into account, but it is more complicated to verify and quantify. Seaweed biomass in the form of particulate organic carbon (POC) and dissolved organic carbon (DOC) gets detached or erodes during the growth phase. If this carbon ends up in sediments, either right below the seaweed, or for instance in the deep sea, where it is not exposed to decomposition and remineralization (turnover of biomass), it can be considered sequestered. Research is ongoing on the proportion of the seaweed fragments or eroded carbon from seaweed that ends up in the long-term carbon cycle and thus sequestered and the proportion that is remineralized and thus in the short-term carbon cycle90. The scientific community is not yet decided on the potential of the amount drifting off into the deep sea[91,92,93]. (dotted lines in figure 2).

Quantification

For the quantification of carbon sequestration from seaweed in the **terrestrial environment**, no currents and remineralization processes need to be considered. When using seaweed-based biomass for injection in for instance building materials, the final content of carbon in the biomass can be determined, the carbon uptake in seaweed. Carbon uptake measurements is done in a similar way to nutrient analysis, in the tissue of the seaweed. If one cannot sample themselves, a rough assumption of 30% carbon content on a dry weight basis in cultivated seaweeds can be made[36,94]. This is based on the carbon content measures on wild seaweed since seaweed productivity still varies from location to location and between seasons. If carbon is sequestered via the terrestrial biostimulant path, the carbon content of the soil can be measure and monitored regularly to provide the carbon content increase.

To quantify carbon sequestration in the **marine environment**, the fate of carbon captured through seaweed cultivation is needed[95]. This is not yet fully understood, even though there is strong evidence that some of this material ends up in the deep ocean. There are several parts that can be calculated and assumptions need to be made, in order to come up with an estimate of carbon sequestered via the marine pathway. It is necessary to understand the quantity:

1) of carbon capture, also called the carbon uptake,
2) the amount of biomass being 'lost', meaning ripped off and drifted off,
3) the proportion of the drift off ending up in the short and long carbon cycle, which is linked to
4) the duration (permanence) of carbon settled in either deep sea or coastal sediment, the so-called sequestered carbon[81,93,96].

For further details on the quantification methods, please view the Annex.

Looking at this potential, a lot of research- and financial efforts are invested into solving the remaining questions of the actual amount of carbon removal[97], future climatic changes[90], and limits to growth[98]. Furthermore, it is important to look at the net balance of seaweed cultivation, if we claim it to be a climate-friendly product. LCA studies show that transportation for seaweed is still a hotspot in greenhouse gas emissions[99]. To evaluate the net carbon benefits, the whole system needs to be considered.

Valuation

Carbon sequestration has value to society since it reflects the removal of carbon from the atmosphere and thus mitigating the effects of climate change. The valuation of carbon sequestration calculates the net ecosystem carbon balance, taking all capture and release of carbon into consideration, all changes in the carbon stock. For forests, this should include respiration, timber harvest, forest fires, etc. According to Sondak, et al. (2017)[100], most studies calculating the carbon sequestration from seaweed, calculated the benefits of carbon between US$ 5-25 per tonne of CO_2e[101,100]. In a calculation on eelgrass, which could be used as an example for seaweed, Röhr, et al. (2016)[102] did not only use the carbon price on the market, but calculated the social cost of carbon (40.3 Euro for the ton of carbon)[103] for their eelgrass carbon sequestration calculation.

In light of the discussion on quantification of carbon sequestration by seaweed (see section 3.3.1), to value only the total carbon uptake isn't of much use. Depending on what is done with the biomass parts of the carbon may stay in the short carbon cycle, and therefore are not sequestered. Despite their potential, the reduced and avoided emissions (view pathway 2 and 3 in the figure 2) are very complex to calculate and cannot be standardized, it depends on the product.

In the carbon quantification section (section 3.3.1), we have addressed the carbon that can be sequestered via cultivation of seaweed, this can be seen as additional carbon stored in the environment.

But if the current carbon stock of an ecosystem is to be measured, for instance, to argue for the protection of its ecosystem, the carbon stock can be calculated. The valuation of the carbon stock consists of estimating/calculating the carbon stock in the relevant carbon pools, multiplying it by the

For carbon valuation it is important to choose an **appropriate price**:

1) The social cost: an estimate based on the value of damages avoided, in other words, an estimate of the cost of the damage done by each additional tonne of carbon emission.
2) the marginal costs of abatement of carbon: an estimate of the cost of avoiding the emissions, for instance the cost of better insulation of buildings, or the cost for carbon capture, either technologically or biologically (e.g. afforestation, or seaweed cultivation).
3) The observed market prices: the price carbon has on existing markets such as emission permits in the European Emission Trading System (EU-ETS). Currently 87,37 EUR/tonne (25.05.2023)[5]

Box 4: Carbon pricing

suitable carbon price (please view box 4), and multiplying this by a suitable value of return to get an annual service flow[18]. This includes, but goes beyond, the carbon uptake, and covers the existing carbon stock in, for instance, the sediment.

Credits

A market mechanism taking the price for externalities into consideration is carbon pricing. The most known carbon pricing mechanisms are carbon taxes or emission trading schemes, both mandatory as compared to the voluntary credits from before. The polluter pays and is being held responsible for serious costs emitting GHG as well as having an incentive for reducing the emissions[104]. The ETS of the European Union had carbon credit prices ranging between 20-30 EUR per tonne CO_2 until 2021 and then steadily rose up to 87 EUR (May 2023) per carbon permit[5]. In Verra the price of such credits depends on the certification standard used and is sold as $USD per tonne of CO_2e or $USD per tonne of GHG. Many variables influence the price, leading to price ranges from $2.55 USD per tonne of carbon to over $70 USD per tonne of carbon, however, majority of offsets are sold around $10 to $25 per tonne of carbon[105,106]. The Gold standard has prices in their project portfolio ranging from $15 USD per tonne of carbon to $52 USD per tonne of carbon[107], as it qualifies for emission reduction under the Kyoto protocol[105, 106] and thus tends to achieve premium prices. Looking at the current price developments in the emission trading schemes, it is expected that the price for carbon can become higher. This would be in line with the rising pressure for action in the carbon reduction policies.

The emission trading schemes doesn't include carbon credits from aquaculture, only the industries that would use products for aquaculture (or seaweed)[108]. The current IPCC framework considers saltwater marshes, mangroves and seagrass as ecosystems to sequester carbon, the blue carbon ecosystems. Seaweed is not acknowledged as a Blue carbon ecosystem under emission trading schemes, even though suggested to become one by researchers[83,85,109,110].

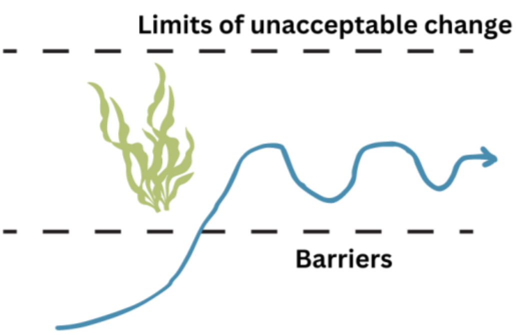

Figure 4: The optimal scale of seaweed farming considers the carrying capacity

However, there are advances in developing guidelines on blue carbon quantification and guidelines for creating blue carbon credits have been developed[19]. The Australian government has developed comprehensive guidelines and thus included blue carbon ecosystems in its national greenhouse gas accounts[111]. Furthermore IPCC[112], Conservation of Nature[113] and UNEP[114] or Verra[115].

THE CONCEPT OF CARRYING CAPACITY

The limits to growth are a well understood and accepted concept that also applies to seaweed cultivation. The activity may alter the physical and biochemical environment when production if upscaled[116]. And now first publications talk about the negative impact seaweed cultivation[65,116,117] and others are touching on the subject of when it is too much cultivation[118,119].

This is where the concept of carrying capacity comes not play. It can be defined by the intensity or areal dispersal an aquaculture can have until it reaches the "limits of acceptable change"[120] of an ecosystem, a society, or an economic system. The importance of carrying capacity has been recognized and it has been studied for other cultivated species, such as bivalve aquaculture[121,122,123] of finfish[124,125], and has started for seaweed[119,126]. Holistic approaches to it are being developed within the SeaMark project.

A key concern is that the increase in seaweed cultivation may reduce the nutrient concentration below levels in the water which is needed to maintain ecosystem quality, is one of the main concerns[118]. To avoid negative impacts like nutrient depletion[118] and its consequences that have not yet been fully mapped out, the size of the production or cultivation should therefore consider the carrying capacity of the system it is in. There is a lack of data, although some initial work has been done mainly involving modelling studies[119,126].

Knowing about the carrying capacity can be vital information for decision-makers when it comes to developing the industry in a safe and sustainable way. **Quantifying the ecosystem health is a necessity for a resilient, restorative, and regenerative circular bioeconomy. The ecosystem won't be able to provide the services, or in other words the resource flow and performance for future generations, if the ecosystem health is not preserved**[127]. Van den Burg, et al. (2019)[128] also emphasizes that from a "people, planet, profit" perspective, the focus of algae farming should rather be on environmentally friendly production systems that produce the right amount of the right algae based on the carrying capacity of the European seas, rather than concentrating on how to produce large amounts of algae. Avoiding crossing thresholds by monitoring and measuring social-ecological systems is important for effective environmental management[129]. It is argued that each carrying capacity component has discrete input into decision-making and as such all carrying capacity components reflect to some degree social values (for example for recreation)[130] and therefore the carrying capacity approach should be more inclusive of the social aspects[131].

Understanding the stakeholders' needs, conflicts and perceptions is considered essential to determining the carrying capacity[132]. The FAO Ecosystem Approach to Aquaculture embraces holistic thinking[133] and to advance these, carrying capacity has been recognized as a major component of it[134]. With its four types of carrying capacity already well developed[132], carrying capacity offers a possibility to make the next step and working on a truly holistic approach.

RECOMMENDATIONS FOR POLICYMAKERS AND INVESTORS

This policy brief gives an overview of the potential of seaweed to contribute to improving marine ecosystems, providing a valuable source of biomass, tackling the effects of climate change and supporting the economic development in coastal regions. It provides recommendations that support inclusion of the value of ecosystems in decision-making by policy-makers and thus make them more accessible for investors.

Include blue carbon in the regulatory framework

The communication from the European Commission on the Sustainable Carbon Cycles[3] states that a regulatory framework for the certification of carbon removals[135] is key to reaching the objective of climate neutrality. With this communication, the Commission has set out to provide the necessary rules and criteria to spur the development of a Union certification framework for carbon removals[135], but it does not give specific attention to the large potential of marine ecosystems and their potential for carbon sequestration. The Commission misses an opportunity by ignoring the pivotal role of the oceans in their climate change mitigation potential. **With the ambition to being a global leader, the Commission should include seaweed blue carbon into their regulatory framework and thus facilitate what smaller pioneers, NGO's, private companies have already set out to do.**

Recognize seaweed cultivation as a carbon farming practice

The communication from the Commission on the Sustainable Carbon Cycles recognizes the need to develop blue carbon ecosystems as carbon farming through nature-based solutions[3]. **We propose that seaweed farming qualifies as a carbon farming practice.** This way it could benefit from the following suggested actions, that we see also necessary for the algae sector:

- The communication promotes improving knowledge, data management and tailored advisory services to land managers[3]. Once seaweed cultivation is recognized the sector would benefit from knowledge sharing and data management.

- Research and innovation are supposed to be fostered which is needed for the quantification methodologies of the seaweed ecosystem service, which then are the bases for the certification processes.

- There will be funding opportunities for carbon farming, which would then also reach seaweed cultivation and jump-start smaller businesses or aid innovative smaller companies.

> **Carbon farming** is defined as "*a green business model that rewards land managers for taking up improved land management practices, resulting in the increase of carbon sequestration in living biomass, dead organic matter and soils by enhancing carbon capture and/or reducing the release of carbon to the atmosphere, in respect of ecological principles favorable to biodiversity and the natural capital overall.*"[3]

Box 5: Carbon farming

Use nutrient remediation as a functioning nature-based solution

The new approach for a sustainable blue economy in the EU[11] states to have recognized the economic value of ecosystem services and the benefits derived from a healthy marine environment and thus set out to release a stable methodology to be able to integrate the concept of 'natural capital' in economic decisions. **Seaweed cultivation's ecosystem services need to be considered in these natural capitals**, and more attention needs to be given to implementation steps. The quantification methodology for nutrient removal is tested and validated, and thus ready to be integrated as a nature-based solution. The Commission should recognize seaweed cultivation as such and consider it as a eutrophication mitigation action.

Support the understanding of the effect of seaweed cultivation on biodiversity

The **quantification methodology for biodiversity** enhancement thanks to seaweed cultivation is not scientifically sound yet, and thus **needs further support via research**. Given the competition for licenses and space on the coast, it is good to understand the various positive and negative impacts different aquacultures have. Seaweed aquaculture has proven positive impacts on eutrophication and even if it may not offer year-round additional shelter, it may still have a net positive effect, or simply not a negative effect, compared to other forms of aquaculture. **Taking the impacts to an ecosystem of an industry into consideration should be taken into consideration by marine spatial planners and local governments.**

Support development of a certification process

The new approach for a sustainable blue economy in the EU[11] acknowledges the economic value of ecosystem services and the benefits derived from a healthy marine environment. In our opinion seaweed cultivation qualifies as a carbon farming practice and would then benefit from the **support of a certification process and stable methodology for accounting of ecosystem services.** Several entities have started the process for a methodology to quantify the ecosystem services from seaweed, in order to certify them. There are ways to deal with the remaining uncertainties, like for instance with a buffer, and the urgency to act regarding climate change outweighs remaining uncertainties[136]. With time and further research, the methodologies will be updated and become more thorough. This allows to open the road for projects and actions mitigating climate change, that would have otherwise been neglected. Advancements that have been done with carbon, could be a pathway for the **establishment and integration of nutrient remediation credits from seaweed cultivation.**

Adapt the additionality criterion in certification

Credits for ecosystem services are generally only given when the additionality criterion is met. Additionality wouldn't be met if the seaweed cultivation company would exist and produce even without the credits. **We argue to rethink and adapt the additionality criterion for practices like seaweed cultivation.** The benefit of nutrient removal and carbon sequestration will still be additional and will not be valued otherwise. The company may not solely exist on the financing from credits, but it may aid it to profitability and survival in the long term. When it comes to promoting green and sustainable businesses, this may be a direct way to uplift businesses with positive effects on the ecosystem compared to ecosystem-degrading businesses. The Commission's communication on the sustainable carbon cycle states that carbon farming credits should become an "additional" product to traditional products such as food or biomass[3]. There are ways to deal with it, for instance ONCRA certifies additionality, if the carbon income is reinvested[136,137].

Assess the optimal scale

The communication of the Commission for a strong and sustainable EU algae sector[21] has identified several barriers (problems) to upscaling. Assuming that barriers will be removed, a new question comes into play: can we cultivate too much seaweed? Other long-term challenges like social acceptance or profitability of a company, might be limiting the positive impact of such a regenerative aquaculture activity, like seaweed. Research is ongoing about the limiting and favouring factors of seaweed cultivation, as well as indicators to determine a locally specific threshold for acceptable limits, socio-economic or ecological. **For future projections**, knowing the limits of benefitting sustainably from the ecosystem services of seaweed, creates an attractive climate-friendly business case out of seaweed farming. Being able to know how much can be cultivated will allow to quantify (and eventually monetize) the ecosystem services of a number of ocean cultivation units in a given area while still staying in sustainable limits. This information could help governments, international development organizations and investors, making decisions on the best economic and environmental returns on investment[138]. Data on when exactly such tipping points are reached has not yet been documented, but it is a topic of interest for further research and **research support needs to be focused on this.**

Set limits of acceptable change of the ecosystem with seaweed farms

The European Commission could set a global example of promoting the assessment of the carrying capacity of a system as a base for license or permissions. This goes in line with the recommendation on 'considering the impact of an activity': we need to know when one activity or industry exceeds the limits in a system and this could then be a decision-making tool and basis of a trade-off discussion. Facing environmental degradation, decline in biodiversity, and climate change, **regenerative aquaculture practices, practices that stay within the limits of a balanced ecosystem, should be given more priority.**

Finance for research

There are remaining questions on the potential carbon sequestration rate of seaweed. With the pressing need for global carbon dioxide removal, this pathway needs to be understood, so that it can be adequately used as a removal method within policies and/or private offsetting methods. Research in this area should be further financed. This will also support the methodology for certification.

Develop investor´s guidelines

Seaweed cultivation is growing in Europe, as is the awareness for consuming more sustainable products[20]. The Commission has started recognizing algae's potential and proposed first steps to unlock it[21]. Investors play a pivotal role in advancing the seaweed sector, enabling private sector development. The positive impacts of seaweed cultivation on climate mitigation, nutrient remediation and biodiversity can be seen in light of corporate sustainability agendas and be an impetus for investors to direct financing into this emergent sector. To substantiate claims on beneficial impacts, the methods discussed above can be relevant. **Investor guidelines should be developed to direct investments in seaweed cultivation and validate claims on positive ecosystem services impacts.** Our recommendation to investors, companies or individuals is to consider seaweed credits as promising avenue to reach corporate goals. Furthermore, by investing in seaweed aquaculture, one invests into carbon removal, instead of paying for avoided additional damage (offsetting credits).

THE RELEVANCE OF ECOSYSTEM SERVICES PROVIDED BY SEAWEED CULTIVATION

Relevance for achieving EU objectives

The potential of seaweed to contribute to human well-being is acknowledged in various policy documents and communications. The link between a healthy planet, healthy people and healthy societies underlies European strategies like the European Green Deal[17] and the Farm to Fork (F2F)[9] strategy.

The F2F Strategy[9] promotes algae to become a source of alternative protein for a sustainable food system and global food security and sets out support specifically tailored to reach the algae industry. The strategy will also lay out a new approach to ensure that aquaculture can contribute to the process of reaching climate neutrality of the union by 2050, the objective of the Climate Law[139].

The European **Green Deal**[17] recognizes that achieving a climate-neutral and circular economy requires the full mobilization of industry. With the help of a new policy framework, the new circular economy action plan, lead markets for climate-neutral and circular products, in the EU and beyond will be developed and stimulated. It also acknowledges the role of the ocean in mitigating and adapting to climate change. Not only through preserving and restring ecosystem and biodiversity, but also by making use of it in a sustainable blue economy. For instance, promoting the production and use of alternative food and feed sources from the ocean can relieve pressure on terrestrial forms of production. The importance of nature-based solutions as solutions to climate change in general is recognized, and also, that the basis for this is healthy and resilient seas and oceans.

The **new approach for a sustainable blue economy in the EU**[11] recognizes that restoring seabed habitats, like macroalgal forests and others, can help fight eutrophication and as a consequence enhance the resilience of coastal ecosystems. Seaweed's potential is also highlighted **as the biomass for bio-based products, bio-fuels and sustainable alternative food and feed material, being a resource that alleviated less pressure on the environment than other agriculture, fisheries or aquacultures.** Within the new approach for a sustainable blue economy in the EU[11], the EU calls the introduction of new algae-based and sea-based food and feed products into our markets a major opportunity in the aim to develop a sustainable food sector. This choice towards algae-based products is an example where blue economy and F2F strategies align their objectives. The SeaMark project[140] contributes to this need by developing 12 innovative seaweed-based products for market uptake.

The communication from the Commission on the **Sustainable Carbon Cycles[3]** promotes carbon farming as a business model for healthier ecosystems and uses it as a way to upscale carbon removal solutions. The Commission acknowledges seaweeds' potential as a blue carbon ecosystem, despite being neglected in their assessment. But with carbon farming, the **communication refers mostly to terrestrial approaches.**

Relevance for the business case of seaweed cultivation

As outlined in the communication from the Commission **towards a Strong and Sustainable EU Algae Sector[21]**, the European algae sector has the potential to become a significantly contribute to the EU blue bioeconomy and the objectives of the European Green Deal. The communication summarizes, that the current momentum based on enthusiastic entrepreneurs, research and innovation, helped to expand the sector, is even called a Seaweed Revolution by the UN Global Compact[20]. The strategy looked at the potential for the algae sector in Europe and concludes that "Europe in a very good position to harness its algae potential over the next decade"[21].

As recognized by the communication from the Commission towards a Strong and Sustainable EU Algae Sector[21], promoting algae as safe, competitive and renewable resources can play an important role in "turning the current environmental and climate-related challenges into business opportunities". The EU algae sector could be an inspiration to other industries to also become more regenerative, innovative and socially exemplary[21]. Green businesses are the way forward in combining a growing economy with climate change mitigation ambitions.

The seaweed industry is in its infancy in Europe and profitability is a challenge for many small companies. It is expected that the demand in algae-based products is growing in Europe[21], but local products have difficulties competing with Asian imports. In Europe, high-end value products are what can make a business profitable[141]. Financially, **supporting the ecosystem service aspect of seaweed farming could be a way to foster businesses.** There are public financing mechanisms available for green businesses in the EU, that could potentially be extended to reach seaweed farming (See Box 6).

Besides EU funding, private investors can support sustainable aquaculture by buying credits for ecosystem services. Once the methodologies and certification frameworks are established, the private or public sector funding through credits could drive the development of further regenerative businesses, and thus help both the climate and biodiversity goals. As foreseen for the concept of carbon farming on land, carbon farming in the marine ecosystem and as well credits for other services, could be an additional "product" that seaweed cultivators sell[3].

Eu financing mechanisms for sustainable businesses

- **InvestEU**[1]: program to support sustainable aquaculture
- **Carbon farming**: according to the F2F strategy[9], green business models should be rewarded via the common agricultural policy (CAP) or other public or private initiatives (carbon market)
- **BlueInvest**[11]: a platform supported by the Commission, to access to investors and investment-readiness advice, for smaller businesses that have transformative ideas
- '**eco-schemes**': offer a major stream of funding to boost sustainable practices, including carbon farming, from within the F2F strategy[9]
- **green finances and investments**: the European Green Deal will make it easier for investors and companies to identify sustainable and credible investments[17] to ensure a just transition.

Box 6: EU financing mechanisms for sustainable businesses, that could be extended to seaweed

Buyers of these credits could for instance offset their own emissions, meet some requirements on eutrophication mitigation limits or benefit from promoting biodiversity increase. These planet-positive effects will become more and more important, as consumer awareness rises and policies become stricter regarding environmental degradation and CO_2 emissions. Buyers of these credits could also be companies or individuals who want to invest into climate actions or to neutralize their own footprints[3].

Globally the tool of credits is being increasingly used and implemented. Carbon offsetting has become part of the individual, entrepreneurial and governmental solutions to contribute to climate change mitigation[142]. The World Economic Forum calls biodiversity credits a mechanism to help businesses deliver nature-positive outcomes[4]. There is growing political interest to set targets for the protection of marine ecosystems and biodiversity and crediting mechanisms can create the needed incentives for it[143].

CONCLUSION

Seaweed aquaculture should be planned and established to function as a nature-based solution, that delivers not only food and feed products but also ecosystem services that help regulate nutrients, mitigate climate change and uplift biodiversity[51].

There are still uncertainties in the ecosystem service quantification methodologies, necessary for the economic valuation of them. These need to be given priority in research, but shouldn't stop the process of using ecosystem services to promote the business case of seaweed cultivation. Seaweed cultivation enjoys a widely positive image, leading to a neglectful view on the negative aspects of it from many stakeholders. To unlock the potential of seaweed, with its capacity to mitigate climate change, provide nutrients, regenerate ecosystems etc., it is crucial to stay within the limits of sustainability. At this moment in time, we cannot make further mistakes with fast-tracked solutions, not thought-through consequences of development and short-lived uprisal of industries. The industry needs to be looked at holistically, including positive and negative impacts as well as barriers to development and limits of unacceptable change.

This policy brief may give guidance to the policymakers of how to make use of the ecosystem services of seaweed cultivation and thus contribute to reaching the ambitious goals within, among others, the Green Deal, Farm to Fork strategy, the new approach for a sustainable blue economy and help to regenerate marine ecosystems.

ANNEX

Carbon sequestration quantification

To calculate these steps of the sequestration potential, various methodologies have been proposed. the carbon, that sequesters below the ocean cultivation unit or kelp forest, the significantly smaller fraction, can be measured with relative certainty. Sediment samples need to be collected and analysed[83]. If the cultivation units are placed at locations with rocky seabed it can be challenging/impossible to use this approach. Sediment samples can also be taken in the deep sea, but due to the distance, it cannot be said where they originated. These samples can also give insight on the existence and amount of seaweed-derived carbon in the deep sea[144,145,81]. Environmental DNA (eDNA) is a method capable of identifying specific species contribution to the carbon in the sediment[146,147] from which permanence can be concluded. But this doesn't give insight on the quantity of carbon sequestered from this species. Sediment core sampling and eDNA can complement each other. eDNA samples would provide the species identification to the sediment cores, and the latter would provide the quantity of organic material in marine sediments[81], however, it cannot be determined from this information alone, from how much biomass this carbon came (the ratio of sequestration). Blade erosion, drift off and remineralization would have to be assessed in addition. eDNA does not account for the carbon that is consumed and then sunk to the sediment, the so-called carbon flows in the food web[81,147]. The degradation or erosion rates of seaweed, leading to particular organic carbon and dissolved organic carbon being transported and partly remineralized can be understood via mesocosm experiment assessing these rates under various conditions and time periods to assess permanence[148,81]. Other authors used several of these methods mixed, to get an insight on the proportion of blades falling off, using physical biomass sampling, and numerical modelling to estimate the amount of carbon lost through erosion and exudation[93]. Purely numerical models are also used, to estimate the sequestration potential of macroalgae[149,96,150], though the authors of these studies noted that many uncertainties remain. There are no established monitoring, reporting, and verification (MRV) protocols available at this point[150,81].

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