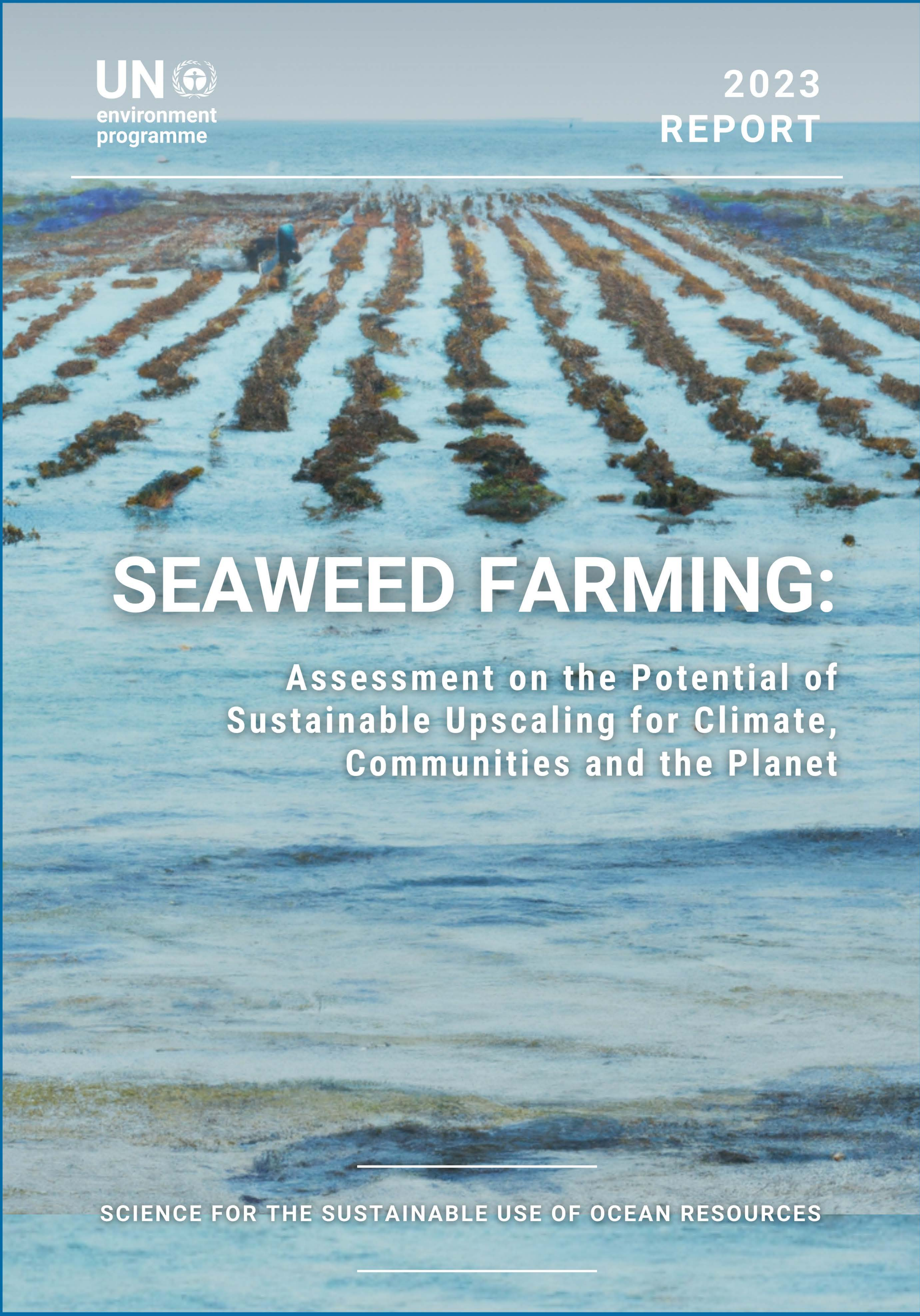

UN environment programme

2023 REPORT

SEAWEED FARMING:

Assessment on the Potential of Sustainable Upscaling for Climate, Communities and the Planet

SCIENCE FOR THE SUSTAINABLE USE OF OCEAN RESOURCES

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ABBREVIATIONS

AMPEP	Acadian Marine Plant Extract Powder
BECCS	Bioenergy with Carbon Capture and Storage
CO_2	Carbon Dioxide
DIC	Dissolved Inorganic Carbon
DOC	Dissolved Organic Carbon
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessment
emLab	Environmental Market Solutions Lab
FAO	Food and Agriculture Organization of the United Nations
GESAMP	Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection
GHG	Greenhouse Gas
HEA	Habitat Equivalency Analysis
IMTA	Integrated Multi-Trophic Aquaculture
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
MPA	Marine Protected Area
MSP	Marine Spatial Planning
NASEM	The National Academies of Sciences, Engineering, and Medicine
NIMBY	Not in My Backyard
NTC	Nutrient Trading Credit
POC	Particulate Organic Carbon
PPP	Public-Private Partnership
RCP	Representative Concentration Pathway
SDG	Sustainable Development Goal
SWOT	Strengths, Weaknesses, Opportunities, and Threats
TEEB	The Economics of Ecosystems and Biodiversity
UN	United Nations
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States Dollar
UV	Ultraviolet
WHO	World Health Organization

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FOREWORD

The United Nations Environment Programme (UNEP) recognizes the existence of a triple planetary crisis – climate breakdown, biodiversity loss and rampant pollution – which puts humanity at risk of irreversibly damaging our relationship with the natural world. Tackling these challenges to achieve climate stability, living in harmony with nature and moving towards a pollution-free planet will require a recalibration of our economies and societies towards more sustainable, circular and equitable models.

The UN Decade on Ecosystem Restoration, the Global Biodiversity Framework and the Sustainable Development Goals point to the need to take a whole-of-society and whole-of-government approach that values the vast potential of the ocean to help tackle this crisis. This means that we must rapidly accelerate solutions such as seaweed aquaculture. Marine and coastal ecosystems are a bedrock of resilience, delivering powerful nature-based solutions to climate change, supporting lives and livelihoods, and providing shelter and food for communities and a diverse range of life forms.

Modern scientific enquiry must scrutinize the exploitation of marine and coastal ecosystems and their biodiversity to identify pathways that are underpinned by a sustainable blue economy; an economy in which activities that rely on the ocean are nature and climate positive, as well as beneficial to the communities whose livelihoods depend on its health.

Given the rapid growth and expansion of the seaweed farming industry, we must proceed with cautious optimism. We appreciate that the potential benefits of seaweed farming must be balanced against the risks of human interference in the marine environment and ultimately to the communities dependent on healthy blue ecosystems.

I am excited by the outcome of this report. The evidence showcases a range of possible opportunities to utilize seaweed and, importantly, clearly articulates the potential to open a pathway for sustainably upscaling seaweed farming if we take a well-informed precautionary approach and take swift action to fill key environmental and socioeconomic research and policy gaps.

I hope this publication can help set in motion closer global collaboration on the topic of seaweed farming. By bringing together local, national, regional and international stakeholders from both the public and private sectors in a meaningful and inclusive way, we can more safely explore the possibilities while embracing the safeguards and best practices that ensure we deliver sustainable upscaling for communities, people and the planet.

Leticia Carvalho
Head of Marine and Freshwater Branch
United Nations Environment Programm

EXECUTIVE SUMMARY

The United Nations Environment Programme (UNEP) recognizes the growing global interest in seaweed farming as a potentially scalable ocean-based climate change solution that may provide environmental and social co-benefits as part of the advancement of resilient and climate smart aquaculture. To critically examine this potential, a report based on an in-depth literature review and situational analysis was commissioned to scientifically assess the potential for the sustainable expansion of seaweed farming to deliver climate benefits with minimal environmental and social risks.

This report collates and scrutinizes existing research on the quantifiable climate benefits, as well as the associated environmental and social risks and benefits, of global seaweed farming. The scope of the report includes an investigation into the full value chain of seaweed farming with an emphasis on the potential for climate benefits realized through various natural and commercial use pathways, and the feasibility of upscaling global farmed seaweed production. The findings herein are synthesized in a situational analysis with a SWOT design (Strengths, Weaknesses, Opportunities, and Threats) for sustainable expansion of global seaweed farming.

HIGHLIGHTS

Potential for Climate Benefits:

Seaweeds absorb carbon dioxide, converting it into seaweed biomass. The fate of farmed seaweed biomass will in large part determine the potential for climate benefits. Research on the climate benefits of seaweed farming is ongoing and the focus of the literature has been on 2 primary routes by which seaweed farming could contribute to climate mitigation:

***Natural Carbon Sequestration*:** A component of the carbon built into seaweed biomass is exported into the marine environment during cultivation as particulate and dissolved organic carbon. Some of this “unseen production” will be consumed or remineralized in ocean food webs and released as carbon dioxide. Another component may reach long-term oceanic carbon sinks, providing natural carbon sequestration. Research indicates that substantial upscaling of seaweed farming would be required for meaningful climate mitigation to occur via this route. Such upscaling could have unforeseen effects on the Earth System and ocean ecology, and there is therefore a need for dedicated research on the environmental effects of large-scale seaweed farming.

***Commercial Use Pathways for Climate Mitigation*:** The use of seaweed biomass post-harvest will also determine the potential for climate benefits, and various seaweed commercial use pathways have been proposed for carbon sequestration and greenhouse gas emissions reduction. These pathways have had varying levels of scientific assessment and development towards implementation. Progress towards each pathway is summarized below:

Seaweed Biofuels and Other Low Emissions Products: Seaweed biofuels have the potential to be a carbon negative energy replacement for land-based biofuels and fossil fuels, particularly if they are co-produced with seaweed-based replacements for other emissions-intensive commodities, such as land-based proteins or synthetic fertilizers. Cost and energy efficiency have been identified as barriers to the commercial viability of seaweed biofuels, and implementation has occurred at only pilot and experimental scales. Areas for future progress include economies of scale for seaweed cultivation, technological innovations for increased energy conversion efficiency of seaweeds to biofuels, and increased processing capacity for multiple seaweed products in a biorefinery concept.

Seaweed-Enhanced Livestock Feed: Several studies indicate the potential for select seaweeds (primarily *Asparagopsis* species), added in small quantities to ruminant livestock feed, to substantially decrease enteric emissions of methane, a powerful greenhouse gas and contributor to climate change. The experimental trials conducted to date, although limited in scope, indicate little to no negative effects on agricultural production and the co-benefit of higher production in some cases. The seaweed-enhanced livestock feed pathway is limited to ruminant livestock that are nourished by feeds (i.e., excluding free-range livestock), and studies examining safety, efficacy, and practicality at commercial scales are needed.

Intentional Deep Ocean Sinking: The intentional sinking of farmed seaweeds into the deep ocean has the potential to sequester carbon. Cost, technical feasibility, and social license are considered some of the limiting factors to this pathway, and research and development is needed to improve cost efficiency, establish new technology and infrastructure, confirm the veracity of the carbon sequestration, and assess the environmental risks. The intentional sinking of farmed seaweeds for climate mitigation also comes with ethical considerations given the potential for seaweeds to be used as food, feed, or fuel.

Environmental and Socioeconomic Co-Benefits and Risks:

Seaweed farming has several potential environmental and socioeconomic effects that should be considered when assessing whether seaweed farming is a sustainable practice and scalable approach for climate mitigation:

Marine Biodiversity: Research indicates that seaweed farms are linked to altered/enhanced biodiversity when they supersede a less complex habitat (e.g., sandy bottom), but reduce biodiversity when they supersede a naturally biodiverse, complex habitat (e.g., seagrass bed or coral reef). In tropical waters, herbivorous fishes are positively associated with seaweed farms, likely due to the provisioning of food (i.e., farmed seaweeds). Studies on the biodiversity effects of seaweed farming have been largely small-scale and short-term, and large gaps exist in scientific understanding of the effects of seaweed farming on regional-scale patterns of biodiversity, including the effects of farms on nearby ecosystems, and how biodiversity is affected by the scale of seaweed farming and the timing of cultivation and harvesting.

Water Quality: Seaweeds absorb pollutants (e.g., nutrients including nitrogen and phosphorous, and heavy metals) in coastal waters. Hence, large-scale seaweed farming in China likely absorbs most of the phosphorus inputs from land and approximately 6 per cent of the nitrogen inputs. At a global scale, substantial upscaling of seaweed farming would be required to significantly mitigate nutrient pollution; an upper estimate for global nitrogen removal by current seaweed farming represents only 0.06 per cent of the total global agricultural nitrogen fertilizer usage estimated for the year 2022. Yet, large spatiotemporal variability in ocean nutrients may still constrain seaweed farming expansion. Given that seaweeds absorb heavy metals in polluted waters, strict safety standards for the use of seaweeds (e.g., for consumption) are needed. Seaweed farms also produce oxygen and remove dissolved carbon dioxide, and may thereby locally mitigate ocean deoxygenation and acidification, respectively.

Other Environmental Effects: Seaweed farming has various environmental risks, including competition with wild habitats for nutrients and light, spillover of diseases and invasive species and genetic pollution from farms to the environment, and entanglement of marine megafauna from seaweed farming infrastructure such as ropes. Mitigation measures can help to protect against some of these environmental risks (e.g., carefully siting seaweed farms); however, disease spillover and genetic pollution are considered difficult to mitigate given the high dispersal of biological material in the ocean. Although there is limited evidence available for negative environmental effects of seaweed farming at the levels of marine populations, communities, and ecosystems, sustainability standards should require the use of preventative measures to avoid risks, and investigation of environmental risks should be an ongoing process.

Socioeconomic Effects: Research on the socioeconomic effects of seaweed farming has focused primarily on small-scale farming in poor rural coastal communities of developing countries (e.g., in Indonesia, the Philippines, and the United Republic of Tanzania). The studies indicate generally positive outcomes of seaweed farming for people, including increased income and standards of living, diversification of livelihoods, food security, and gender equity. Health problems (e.g., respiratory disease due to storing seaweeds in households) and income below the poverty and extreme poverty line (e.g., due to the low value placed on raw seaweed) have, however, been reported by seaweed farmers, and additional research is needed to examine and address these adverse effects. Seaweed farming can provide a source of high-quality food, with the potential to contribute to global food security; however, variation in the nutritional value of seaweeds and the risk of heavy metal exposure must be carefully controlled. Cultural services may be provided by seaweed farming, such as enhanced cultural heritage and social cohesion; however, to realize these benefits, local stakeholders must be fully engaged in the industry and spatial use conflicts must be avoided.

Patterns of Expansion:

Of the greater than 12,000 described marine seaweed species, a small number (approximately 8 genera) dominate the farmed production. Nearly all (99.5 per cent) of farmed seaweed production occurs across 9 countries in East and Southeast Asia. Research indicates that in global regions where the seaweed farming industry has grown rapidly, but access to scientific advancement is limited, growth of the industry has slowed (e.g., due to crop diseases and pests). In regions where seaweed farming is well established and science is advancing, the seaweed farming industry has continued to grow; however, this growth may be threatened by ecosystem carrying capacities and climate change. Where seaweed farming is a nascent industry, barriers to growth include spatial use conflicts, lack of social license, lack of legislative policies and regulatory environments to support seaweed farming and seaweed consumption, and lack of strong domestic markets for high value seaweed products.

SWOT Analysis:

A SWOT analysis (Strengths, Weaknesses, Opportunities, and Threats) for sustainable expansion of global seaweed farming is presented, summarizing the expert view of the author across the themes of climate benefits, environmental co-benefits/risks, socioeconomic co-benefits/risks, and the feasibility of upscaling production. A total of 13 strengths, 18 weaknesses, 19 opportunities, and 9 threats are presented. The SWOT analysis provides context for managing the seaweed farming industry to maximize the potential for climate benefits and other co-benefits, while minimizing risks. The results highlight an urgent need for additional research and sustainability standards, including analysis of carrying capacities for seaweed farming at local and global scales.

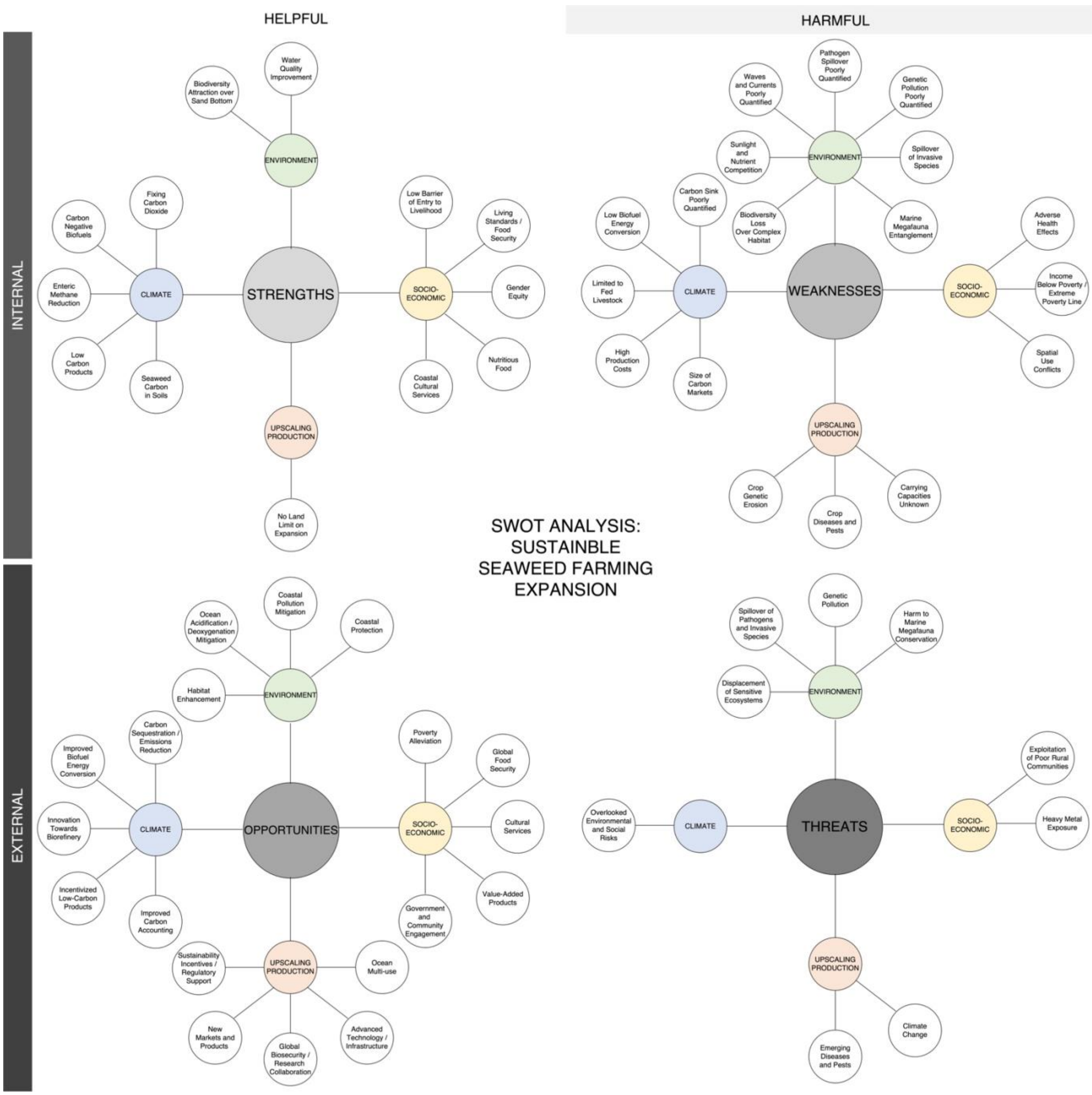

Fig. ES1. Graphical abstract. Credit: UNEP

PART 1: INTRODUCTION

The global increase in atmospheric carbon dioxide (CO_2) and other greenhouse gases (GHGs), arising from anthropogenic activities, is driving global climate change and associated degradation of ocean- and land-based ecosystems upon which humans depend (IPCC 2019a; IPCC 2019b; IPCC 2021). To avoid the worst outcomes of climate change and limit warming of the planet to 2°C, as laid out in the Paris Agreement on Climate Change (UNFCCC 2015), negative emissions technologies are needed to recapture the substantial GHGs already released into the atmosphere (i.e., 100–900 gigatons), in addition to curbing further GHG emissions (Bach *et al*. 2021; IPCC 2021). This knowledge has prompted increasing interest to identify nature- and ocean-based solutions to capture and securely store (sequester on >100-year timescales; GESAMP 2019) atmospheric CO_2 and reduce carbon emissions, while also providing co-benefits such as biodiversity enhancement (Hoegh-Guldberg *et al.* 2019).

Protection and restoration of "blue carbon" ecosystems (i.e., vegetated coastal and marine ecosystems that support carbon sequestration) has received growing attention as a nature-based solution to mitigate climate change while provisioning biodiversity (Duarte *et al*. 2013; Macreadie *et al.* 2022). Traditional blue carbon ecosystems include mangrove forests, salt marshes, and seagrass beds, which sequester carbon in the soft sediments below them (Duarte *et al.* 2013). More recently, seaweed forests, despite growing primarily on rocky substrates, have been suggested to contribute to carbon sequestration in sinks beyond the locality in which they are situated (Krause-Jensen and Duarte 2016; Ortega *et al.* 2019). Seaweeds are primary producers in shallow nearshore waters (less than 50 meters depth) that support marine biodiversity by provisioning food and habitat (Dayton 1985). Protection and restoration of seaweed forests therefore also represents a promising nature-based solution to climate change, although it is challenging to quantify the contribution (Krause-Jensen *et al.* 2018; Hurd *et al.* 2022).

Along with the potential to provide nature-based solutions to climate change, there is increasing evidence that the oceans can supply food to support the growing human population, helping to safeguard future food security (Duarte *et al.* 2017; Costello *et al.* 2020; Free *et al.* 2022). Ocean-based foods are particularly relevant in the face of increasingly limited resources for land-based food production, including arable land, freshwater, and fertilizer, and the carbon-intensive nature of land-based food production (e.g., via land use changes) (Vermeulen *et al.* 2012). Given that many of the world's capture fisheries are considered overexploited, the advancement of resilient and climate smart aquaculture has come to the forefront as a solution for future food security (Duarte *et al*. 2022a; Free *et al.* 2022).

Seaweed farming, or the aquacultural production of marine multicellular photosynthetic algae, is a rapidly growing sector of the aquaculture industry, currently accounting for over half of marine aquaculture production (FAO 2020; Chopin and Tacon 2021). Seaweeds are diverse organisms encompassing over 12,000 identified species, taxonomically assigned to 3 phyla: reds (*Rhodophyta*), browns (*Ochrophyta* including kelps), and greens (*Chlorophyta*) (Hurd *et al*. 2022). The enormous biological diversity represented across these taxonomic groups is best exemplified by the fact that they do not share a common multicellular ancestor; rather, multicellularity arose separately across the groups (akin to the separate origins of multicellularity in land plants and animals) (Cock *et al*. 2010). Seaweeds are also highly diverse in their environmental tolerances, life cycles, growth forms, habitats, physiology, and chemical composition, including their nutritional value to humans (Roleda and Hurd 2019; FAO and WHO 2022).

Farmed seaweeds are an important component of human diets in several Asian countries (FAO 2020). 97 per cent of the approximately 30 million tons of seaweed biomass used by humans in 2018 was farmed, and the estimated farm gate value of the global seaweed farming industry is USD 13.3 billion (FAO 2020). This represents 5 per cent of the estimated USD 250 billion value of aquatic animal aquaculture, including finfish (FAO 2020). Yet, seaweed farming occurs in a relatively small number of countries, which in order of annual production include China, Indonesia, the Republic of Korea, the Philippines, the Democratic People's Republic of Korea, Japan, Malaysia, the United Republic of Tanzania, Chile, Viet Nam, Solomon Islands, Madagascar, India, and the Russian Federation (FAO 2020). The top 9 producing countries, all of which are in East or Southeast Asia, account for 99.5 per cent of production (FAO 2020; Chopin and Tacon 2021).

Most of the global farmed seaweed production is processed for direct human consumption or hydrocolloids (i.e., carrageenan, alginate, and agar) used as stabilizing, thickening, suspending, and gelling agents in food, cosmetics, and pharmaceuticals (Valderrama *et al*. 2013; Marquez *et al*. 2015; Charrier *et al*. 2017). A limited number of seaweeds make up 96.8 per cent of global production[1] (Chopin and Tacon 2021). Three groups dominate for direct human consumption: *Saccharina*/*Laminaria* (kombu), *Undaria* (wakame), and *Porphyra*/*Pyropia* (nori) (Chopin and Tacon 2021). A species of kelp[2] and a group of tropical red seaweeds[3] are the most farmed in terms of wet weight production (FAO 2020). The kelp species is grown primarily in China for food and the extraction of alginate, while the tropical red seaweeds are grown primarily in Indonesia for carrageenan that is processed largely in China from imported raw seaweed (Porse and Rudolph 2017; FAO 2020; Chopin and Tacon 2021). Europe and North America (primarily the United States of America) are the largest international markets for carrageenan (Valderrama *et al*. 2013).

Seaweed farming does not require the use of arable land, freshwater, or fertilizer (Roleda and Hurd 2019). Seaweeds extract inorganic nutrients (e.g., nitrogen and phosphorus) directly from the marine environment to produce biomass (Roleda and Hurd 2019). Hence, seaweed farming is considered an extractive form of aquaculture (as opposed to fed aquaculture such as finfish), requiring no addition of feed (FAO 2020). The primary methods of seaweed cultivation are the fixed-off-bottom method and the floating longline, net, or raft method (Robledo *et al*. 2013; Buschmann *et al*. 2017) (Fig. 1). Clonal seaweeds[4] are cultivated through vegetative propagation, a form of asexual reproduction, while unitary seaweeds, such as kelps[5], require sexual reproduction in a hatchery or nursery for cultivation (Buschmann *et al*. 2017).

While global seaweed production tripled from 2000 to 2018, the growth rate of the industry has slowed since 2015, largely due to a reduction in tropical seaweed production in Southeast Asia, and primarily Indonesia (FAO 2020). Seaweed farming production also has declined in Chile since 2000 (FAO 2020). While seaweed farming is reported to occur at pilot and pre-commercial scales in several countries in Europe and North America (Buschmann *et al*. 2017), data are limited for these regions due to data confidentiality (FAO 2020). Seaweed farming is an emerging industry in several African countries, including Kenya, Mozambique, and Namibia, with a perceived potential for expansion in these regions (Msuya *et al*. 2022). Available data for Europe indicate that 68 per cent of seaweed producers/companies currently use wild stocks rather than farmed seaweeds, indicating a nascent European seaweed farming industry (Araújo *et al*. 2021). However, Vincent *et al*. (2020) predict substantial growth in the European seaweed farming industry within the next decade. Similarly, while 95 per cent of edible seaweed products in the United States of America are currently sourced from overseas, an economic analysis for the state of Maine indicated that the regional seaweed farming industry could grow by 12–15 per cent annually over the next approximately 15 years (Piconi *et al*. 2020). Such growth assumes a growing market for seaweed products and the capacity for marine ecosystems to sustain seaweed farms (Piconi *et al*. 2020; Vincent *et al*. 2020; Msuya *et al*. 2022).

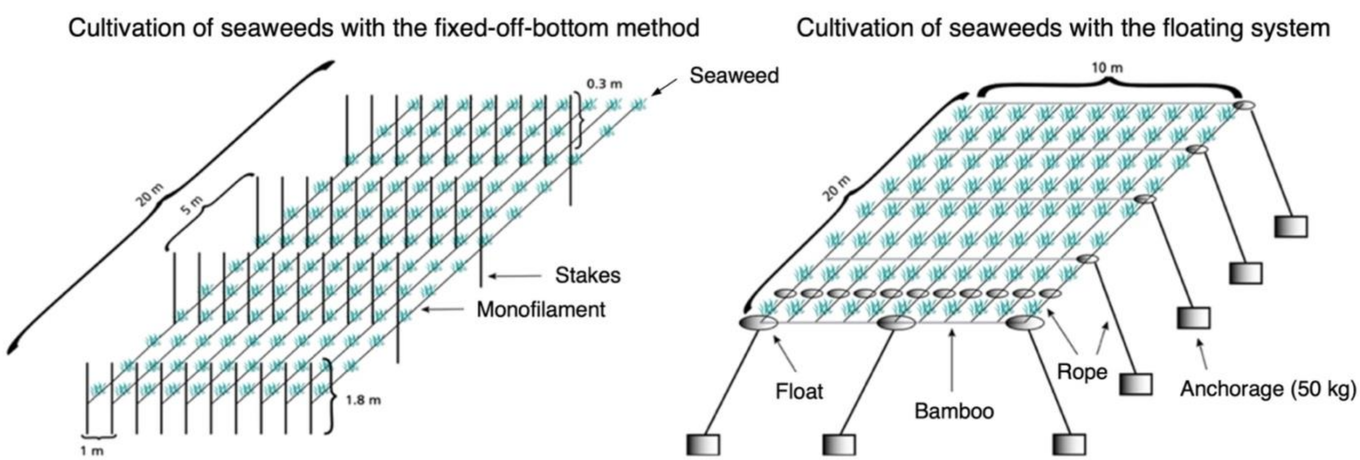

Fig. 1. Two primary methods for seaweed cultivation: fixed-off-bottom method and floating method. Dimensions, depths, materials, and anchorage weights will vary. Reproduced from Robledo *et al*. (2013) with permission.

[1] *Saccharina/Laminaria*, *Eucheuma/Kappaphycus*, *Gracilaria*, *Porphyra/Pyropia*, *Undaria*, and *Sargassum*
[2] Saccharina japonica (previously Laminaria japonica)
[3] *Eucheuma/Kappaphycus*
[4] For example, *Kappaphycus*
[5] For example, *Saccharina japonica*

The seaweed farming full value chain runs from seaweed harvesters to the users of seaweed products, and typically includes 4 stages: cultivation, post-harvest treatment, trading, and processing (Cai *et al*. 2013). Cultivation involves production and harvest of fresh seaweed biomass in the ocean (Cai *et al*. 2013). Post-harvest treatment involves removing impurities (e.g., sand, shells, and litter) and drying fresh seaweeds (Cai *et al*. 2013; Wei *et al*. 2013). Removal of impurities is necessary to avoid equipment problems during the processing stage (Marquez *et al*. 2015). Trading involves consolidating seaweed from multiple sources and delivering it to processors dried or powdered (Cai *et al*. 2013). Processing involves turning the raw seaweed into commercial products, which in addition to human food and hydrocolloids, may include animal feeds, fertilizers and biostimulants, bioactives, pigments and colorants, bioplastics, and biofuels (Holdt and Kraan 2011; Cai *et al*. 2013; Rouphael *et al*. 2018; Torres *et al*. 2019; FAO 2020; Thomsen and Zhang 2020; Chopin and Tacon 2021). There is a lack of information on the transportation of farmed seaweeds; however, transportation of wild harvested seaweed, which can have 80–85 per cent moisture content, has been cited as a generally costly stage in that value chain (Bruton *et al*. 2009).

It has been posited that seaweed farming represents the expansion (afforestation) of seaweed habitats that can provide climate benefits and other ecosystem services if sustainability standards are considered (Duarte *et al*. 2017; Duarte *et al*. 2022a). Various global entities such as the Lloyd's Register Foundation, United Nations Global Compact, and World Resources Institute have therefore identified seaweed farming as a promising option to mitigate and adapt to climate change, feed the world, and provide additional co-benefits, such as provisioning biodiversity and ameliorating coastal pollution (e.g., Hoegh-Guldberg *et al*. 2019; Doumeizel *et al*. 2020). In recognition of this growing global movement, UNEP has solicited a literature review and situational analysis to scrutinize existing evidence for the potential of a well-managed seaweed farming industry to address multiple United Nations (UN) Sustainable Development Goals (SDGs) (including SDG2: zero hunger; SDG13: climate action; and SDG 14: life below water), and to contextualize the risks and benefits of seaweed farming so that, if necessary, interventions/guidance can be delivered to maximize the benefits and avoid undue harm to ecosystems and people.

To this end, this report begins with an in-depth review of the potential for climate benefits of seaweed farming, including examination of the full value chain with an emphasis on the carbon sequestration and GHG emissions reduction potential during cultivation and through various seaweed commercial use pathways. This is followed by a review of the environmental and socioeconomic co-benefits and risks of seaweed farming. Information is then reviewed on the feasibility of upscaling seaweed farming, taking into consideration current environmental, social, and economic limitations to production. The report ends with a situational analysis for sustainable expansion of global seaweed farming following a SWOT design (Strengths, Weaknesses, Opportunities, and Threats). The inclusion herein of any environmental or socioeconomic benefit/risk or commercial use pathway does not imply endorsement by UNEP.

PART 2: REVIEW OF EVIDENCE FOR THE POTENTIAL CLIMATE BENEFITS OF SEAWEED FARMING

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2.1. Potential for Natural Carbon Sequestration

Several studies indicate the potential for wild seaweed forests to contribute to ocean carbon sequestration (e.g., Krause-Jensen and Duarte 2016; Ortega *et al*. 2019; Feng *et al*. 2022; Filbee-Dexter *et al*. 2022). Under an atmospheric CO_2 removal and sequestration scenario for seaweed forests, seaweeds absorb dissolved inorganic carbon (DIC) in surface waters, reducing the partial pressure of aqueous (i.e., dissolved) CO_2, and eventually driving the flux of CO_2 from the atmosphere into the ocean (Delille *et al*. 2000). The inorganic carbon converted by seaweeds to organic carbon (i.e., built into seaweed biomass) is sequestered when a component of the biomass that is not consumed or remineralized in ocean food webs is exported as dissolved and particulate organic carbon (DOC and POC) to long-term carbon sinks in ocean sediments and the deep ocean (greater than 200 meters depth) (Krause-Jensen and Duarte 2016). Yet, tracking carbon across the air-sea interface, into seaweed forests, and to oceanic carbon sinks is highly complex, and therefore questions remain regarding the extent of carbon sequestration by seaweed forests (Macreadie *et al*. 2019; Gallagher *et al*. 2022; Hurd *et al*. 2022). Accordingly, research is underway to understand the extent to which seaweed farms can sequester carbon in the ocean through atmospheric CO_2 removal and the export of seaweed DOC and POC from farms to oceanic carbon sinks (Chung *et al*. 2011; Duarte *et al*. 2017).

Since farmed seaweed biomass is removed from the ocean during harvest, the post-harvest usage of seaweeds will also determine the potential for climate benefits. For example, a component of seaweed carbon could be stored in soils following seaweed biochar or biofertilizer application (Chung *et al*. 2011; Duarte *et al*. 2017; Sondak *et al*. 2017), or climate benefits could occur if farmed seaweeds are used to replace more carbon-intensive commercial products, such as seaweed biofuels replacing fossil fuels (Thomsen and Zhang 2020). In this section, current understanding of the potential for carbon sequestration to occur in the ocean during seaweed cultivation is reviewed, referred to here as “natural carbon sequestration”. Other potential pathways for climate mitigation that may occur post-harvest are discussed under section 2.2 *Potential Commercial Use Pathways for Climate Mitigation*.

2.1.1 *Absorption of CO_2*

The potential for absorption of CO_2 by seaweed farms was assessed by Jiang *et al*. (2013) in Lidao town, China. They found that seaweed farms[6] had significantly lower ocean surface dissolved CO_2 and greater air-sea CO_2 flux (i.e., increased CO_2 flux into the ocean) as compared to reference areas outside seaweed farms, indicating an atmospheric CO_2 sink (Appendix A, Table A1). The extent of the atmospheric CO_2 sink varied throughout the year in response to the seasonal cultivation of seaweeds, with the greatest sink occurring during the period of fastest seaweed growth and a reduction in the sink during summer, likely due to seaweed biomass decay (Jiang *et al*. 2013). Given the localized nature of this study and the complexity of air-sea gas exchange globally, additional research is needed to fully assess the extent to which seaweed farms can accomplish atmospheric CO_2 removal (Hurd *et al*. 2022).

2.1.2 *Carbon Built into Biomass*

Various studies have assessed the capacity of seaweed farms to build carbon into seaweed biomass (Chung *et al*. 2013; Kim *et al*. 2014; Kim *et al*. 2015; Zheng *et al*. 2019). Kim *et al*. (2014; 2015) found that seaweed farms[7] in Long Island Sound and Bronx River Estuary, United States of America, held up to 300–1,800 kilograms of carbon per hectare during cultivation (Appendix A, Table A1). In the Republic of Korea, Chung *et al*. (2013) estimated that a pilot-scale seaweed farm[8], purposed with removing CO_2 from the atmosphere, held approximately 10 tons of CO_2 per hectare per year during cultivation (Appendix A, Table A1). Across China, Zheng *et al*. (2019) estimated that seaweed farms, of various species, hold 421.78 tons of carbon per square kilometer per year (Appendix A, Table A1). Kelp[9] is responsible for most of the carbon held in seaweed farms annually in China due to the magnitude of total production (Zheng *et al*. 2019; Gao *et al*. 2022). However, a red seaweed[10] has the greatest carbon holding capacity per unit area farmed based on its relative carbon content (Gao *et al*. 2022).

Given that farmed seaweed biomass is harvested, the carbon storage period is limited to the period of cultivation and does not represent natural carbon sequestration (e.g., as defined by GESAMP 2019). However, some seaweed production that is released during cultivation into the environment as DOC and POC and reaches long-term oceanic carbon sinks can be sequestered. It has been posited that the magnitude of natural carbon sequestration from DOC export during seaweed cultivation is similar (per unit area) to that of wild seaweed forests; however, this assumption is still being tested (Hughes *et al*. 2012; Gao *et al*. 2022) (Appendix A, Table A1). Studies have examined the release of POC from seaweed farms due to breakage, erosion, and loss of seaweed fronds; however, the fate of this material was not assessed (Zhang *et al*. 2012; Fieler *et al*. 2021). At a seaweed farm[11] in Sungo Bay, China, 58 per cent of gross wet weight and 61 per cent

[6] *Saccharina japonica* and *Gracilaria lemaneiformis*
[7] *Gracilaria tikvahiae* and *Saccharina latissima*
[8] *Ecklonia cava* and *Ecklonia stolonifera*
[9] *Saccharina japonica*
[10] *Gracilariopsis lemaneiformis*
[11] *Saccharina japonica*

of carbon gross production were exported as POC during cultivation (Zhang *et al*. 2012) (Appendix A, Table A1). At seaweed farms[12] in Norway, 8–49 per cent of gross dry weight and 63–88 grams of carbon per square meter per year were released as POC (Fieler *et al*. 2021) (Appendix A, Table A1).

2.1.3 *Estimates of Natural Carbon Sequestration*

Regional estimates of the total carbon built into farmed seaweed biomass annually during cultivation (see section 2.1.2 *Carbon Built into Biomass*) have been extrapolated by various authors to estimate the upper-bound global carbon sequestration potential of seaweed farming. These upper-bound global estimates assume that all the carbon built into farmed seaweed biomass is sequestered (an unrealistic scenario but useful for considering the current maximal potential for sequestration). They range from 0.67 to 0.78 teragrams of carbon per year (Turan and Neori 2010; Duarte *et al*. 2017; Kim *et al*. 2017; Sondak *et al*. 2017) (Appendix A, Table A1) and equate to only approximately 0.4 per cent of the estimated natural carbon sequestration of global wild seaweed forests (Duarte *et al*. 2017). These results indicate that under even the most idealistic scenario, substantial upscaling of farmed seaweed production would be necessary to accomplish a globally relevant carbon sink.

In a more realistic scenario, Gao *et al*. (2022) used the ratio of natural carbon sequestration to overall productivity of wild seaweed forests from various literature sources to estimate that 58.6 per cent of farmed seaweed carbon across China is sequestered in oceanic carbon sinks (Appendix A, Table A1). This estimate considers that a portion of seaweed DOC and POC released into the ocean is consumed and remineralized, which does not contribute to sequestration. Yet, the estimate of Gao *et al*. (2022) is still considered coarse, and other calculations of natural carbon sequestration from seaweed farms range greatly from 0–205 kilograms of CO_2 per megaton of seaweed dry weight produced per year (emLab 2019) (Appendix A, Table A1). As a result, a life cycle analysis for seaweed farming, that considered both this potential range of natural carbon sequestration and the pre-processing seaweed farming carbon footprint[13], yielded net carbon emissions from seaweed farming ranging from a carbon sink to a carbon source (emLab 2019) (Appendix A, Table A1). This indicates the great need for additional research that refines estimates of natural carbon sequestration at seaweed farms to fully assess the potential for carbon negative farmed seaweed production.

The development of new methods to analyze seaweed carbon dynamics in the ocean, including fingerprinting seaweed carbon beyond the habitat (or farm), is considered a high research priority in the medium-term (by 2025) to accomplish quantifiable ocean-based climate mitigation (Hoegh-Guldberg *et al*. 2019). Such technology will be needed to verify the natural carbon sequestration function of seaweed farms and parameterize life cycle analyses for the carbon footprint of seaweed farming. It will also be critical to develop a clearer understanding of how seaweed farming effects air-sea CO_2 flux (i.e., determining when and where air-sea exchange occurs at timescales relevant for atmospheric CO_2 removal) (Bach *et al*. 2021; Hurd *et al*. 2022). Moreover, the trade-offs between farmed seaweed production and the primary productivity of wild ecosystems that currently drawdown CO_2 (i.e., competition with phytoplankton), the effects of farms on ocean albedo and associated radiative forcing, and the effects of farm-associated fauna on overall carbon budgets (given their respiration and calcification), also will be necessary to fully assess the climate mitigation potential of seaweed farming (Bach *et al*. 2021; Hurd *et al*. 2022).

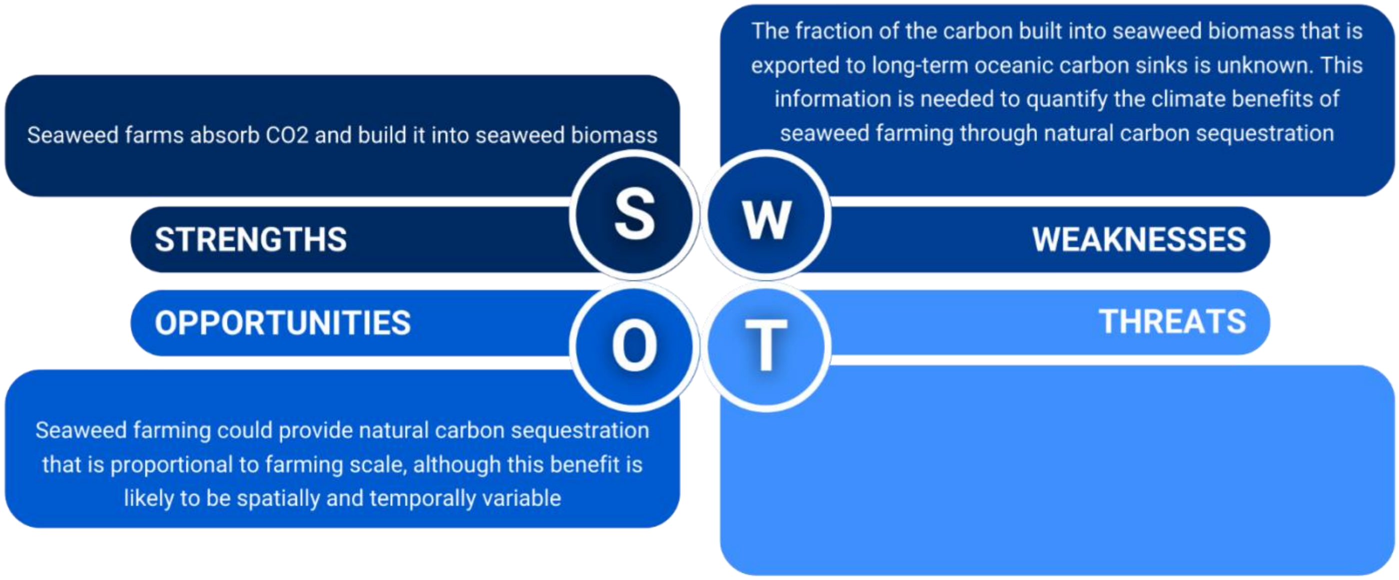
2.1.4 *Summary of the Potential for Natural Carbon Sequestration*

There is evidence that wild seaweed forests sequester carbon in the ocean through the export of DOC and POC to oceanic carbon sinks (Krause-Jensen and Duarte 2016; Feng *et al*. 2022). While the extent of this sequestration is challenging to estimate, protection and restoration of wild seaweed habitats represents a promising nature-based solution to climate change (Duarte *et al*. 2013; Hurd *et al*. 2022; Macreadie *et al*. 2022). Accordingly, it has been posited that seaweed farms also can sequester carbon in the ocean through the export of DOC and POC during cultivation (Gao *et al*. 2022). Yet, estimates of natural carbon sequestration during seaweed cultivation remain coarse and are based largely on an unconfirmed assumption that seaweed farms function similarly to wild seaweed forests. Hence, it is currently difficult to discern when and where seaweed farming acts as a carbon sink (emLab 2019). Notwithstanding, even upper-bound estimates for the global natural carbon sequestration potential of current seaweed farming represent a small climate benefit when compared to the estimated natural carbon sequestration of wild seaweed forests, indicating limited climate mitigation potential through natural carbon sequestration at current farming scales. Scientific advancements that allow for accurate measurements of natural carbon sequestration by seaweed farms, and the direct and indirect effects of seaweed farming on atmospheric CO_2 concentrations, will be crucial for implementing upscaled seaweed farming as a climate mitigation tool.

[12] *Saccharina latissima*

[13] 143–287 kilograms of CO_2 per megaton of seaweed dry weight produced

The evidence reviewed here on the natural carbon sequestration potential of seaweed farming indicates various inherent ***strengths*** and ***weaknesses*** of seaweed farming as well as ***opportunities*** for the future that can be taken advantage of to maximize the benefits of seaweed farming expansion.



2.2 Potential Commercial Use Pathways for Climate Mitigation

In addition to the potential for seaweed farming to yield climate benefits through natural carbon sequestration in the ocean (see section 2.1. *Potential for Natural Carbon Sequestration*), various post-harvest commercial uses of seaweeds have been discussed in the literature for carbon sequestration and GHG emissions reduction. In this section, information is reviewed on these commercial use pathways, and progress and limitations towards implementation of each pathway are discussed.

2.2.1 *Displacing Carbon-Intensive Energy*

Fossil fuels are a finite resource, and their continued use is considered unsustainable due to the production of GHGs that are major contributors to climate change (CO_2, sulfur dioxide, and nitrogen oxides) (Wei *et al*. 2013; IPCC 2021). Climate benefits could be realized from seaweed farming through the replacement of fossil fuels with seaweed biofuels (Duarte *et al*. 2017). While various hurdles exist to implementing commercial scale seaweed biofuels, there is great interest in seaweed biofuels as a renewable energy source that could bring about energy security and “bioenergy with carbon capture and storage” (BECCS), a category of negative emissions technology (Hughes *et al.* 2012; Wei *et al*. 2013; Kraan 2013; Marquez *et al*. 2015; Pechsiri *et al*. 2016; Melara *et al*. 2020). Duarte *et al*. (2017) estimate that the broad adoption of seaweed biofuels has the potential to avoid fossil fuel emissions of 1,500 tons of CO_2 per square kilometer of farmed area per year (Appendix A, Table A2). Yet, production of seaweed biofuels remains at experimental and pilot scales (FAO 2020; Mouritsen *et al*. 2021).

Unlike first-generation biofuels that are derived from land-based food crops (e.g., corn grain, sugar cane, soybean oil, or oil palm), second- and third-generation biofuels do not compete with human food production by utilizing either the wastes of food crops or novel non-agricultural/non-staple crops, respectively (Turan and Neori 2010; Wei *et al*. 2013; Mouritsen *et al*. 2021). While the use of seaweeds for biofuels must be traded off against other potential uses, such as human food (Duarte *et al*. 2022a), seaweeds are considered a viable option as a third-generation biofuel feedstock given their fast growth rates and lack of need for arable land, freshwater, and fertilizer for growth (Hughes *et al*. 2012; Kraan 2013; Wei *et al*. 2013; Marquez *et al*. 2015). Moreover, seaweed biofuels are considered less toxic and produce fewer pollutants than fossil fuels (Wei *et al*. 2013). Technologies considered feasible for seaweed biofuel production include anaerobic digestion for biogas, ethanol fermentation, and hydrothermal liquefaction for bio-oil, as these methods each allow for the use of wet seaweed biomass, avoiding the energy intensive seaweed drying process (Marquez *et al*. 2015).

Modelling studies indicate that seaweed biofuels have the potential to be carbon negative energy sources; however, estimates are highly variable (Hughes *et al*. 2012; Alvarado-Morales *et al*. 2013; emLab 2019; Thomsen and Zhang 2020). For example, a life cycle analysis for seaweed bioethanol production indicates a carbon footprint ranging from a carbon sink to a carbon source[14] when used to replace corn grain ethanol, and a carbon sink[15] when used to replace gasoline (emLab 2019). Replacing global gasoline production with seaweed bioethanol would require an annual 6.5 gigatons of seaweed dry weight farmed across 0.6 per cent of the ocean surface, which could reduce global annual carbon emissions by 2.9 per cent (emLab 2019) (Appendix A, Table A2). However, a cost analysis indicates that for seaweed bioethanol to be competitive against corn grain ethanol and gasoline, the cost of seaweed farming would have to decrease by 77 and 69 per cent, respectively (e.g., a liter of seaweed ethanol would sell for approximately USD 3.03) (emLab 2019). Farm infrastructure (e.g., long-lines and support lines) contributed most of the carbon emissions (72–98 per cent) during the cultivation stage (from propagule production to ocean cultivation and harvesting), indicating the potential for materials innovation to improve the carbon footprint of seaweed production (emLab 2019). The development of emissions efficient ships for harvesting and farm maintenance could further reduce the seaweed farming carbon footprint (NASEM 2021).

Thomsen and Zhang (2020) also present a life cycle analysis for seaweed bioethanol production when used to replace gasoline, wherein seaweed proteins are used to replace soy protein and excess carbon is stored in soils through seaweed biofertilizer. This scenario resulted in a net climate change reduction of 10 kilograms of CO_2 equivalent per hectare for a 1 hectare farmed area (Thomsen and Zhang 2020) (Appendix A, Table A2). A seaweed biogas production scenario had an even greater net climate change reduction of 1,870 kilograms of CO_2 equivalent per hectare for the same 1 hectare area, indicating the sensitivity of life cycle analyses to the type of biofuel produced, among other factors (Thomsen and Zhang 2020) (Appendix A, Table A2).

Modelling of methane biogas production by anaerobic digestion indicates that if the digestate (waste) resulting from seaweed biofuel production is used as soil improver, the refractory component of organic carbon (resistant to biological degradation) in the digestate is sequestered in the soil (Hughes *et al*. 2012). Based on an estimated 7 per cent refractory component in kelp, the sequestration potential from seaweed biofuel was estimated as 0.78 tons of carbon per hectare of seaweed farmed[16] (Hughes *et al*. 2012) (Appendix A, Table A2). This value is in the same order of magnitude as the estimated sequestration potential of low-input high-diversity grassland biofuel[17] (Hughes *et al*. 2012).

A life cycle analysis of seaweed anaerobic digestion for biogas also indicates a carbon negative energy source (Alvarado-Morales *et al*. 2013). The seaweed grow-out phase of cultivation was the most energy intensive phase in the analysis (50–57 per cent of total energy demand) due to fossil fuel use for farm maintenance. However, this was offset by the climate benefit of using digestate as biofertilizer to replace synthetic fertilizers with a higher carbon footprint (Alvarado-Morales *et al*. 2013) (Fig. 2).

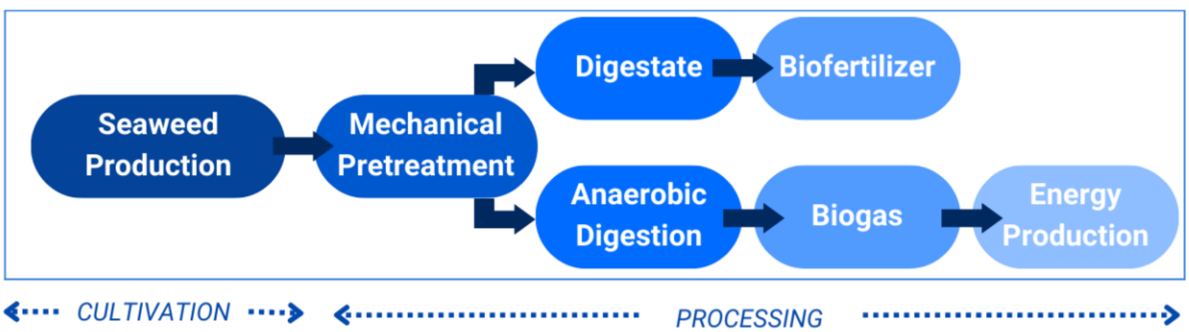


Fig. 2. Biogas production by anaerobic digestion of seaweed can be a carbon negative energy source when the digestate is used as biofertilizer. Two stages in the seaweed farming value chain are shown (cultivation and processing). Based on Alvarado-Morales *et al*. (2013).

[14] -226 to 130 kilograms of net CO_2 per megaton of seaweed dry weight
[15] -239 to -41 kilograms of net CO_2 per megaton of seaweed dry weight
[16] 0.42 tons of carbon per hectare of farm from digestate in soil plus 0.36 tons of carbon per hectare of farm from the release of refractory DOC in the ocean, estimated at 15 per cent of total DOC released
[17] 1.2 tons of carbon per hectare

For seaweed biofuels to be a commercially viable method of BECCS, they must both have a net negative carbon footprint and yield net energy production (Pechsiri *et al*. 2016; Melara *et al*. 2020). A modelling study of methane biogas production by anaerobic digestion with biofertilizer production found that a small-scale farm in Sweden (0.5 hectares) consumed more energy than it produced based on a conservative estimate for biogas yield of 40 per cent, indicating a negative energy return on investment (Pechsiri *et al*. 2016). Upscaling to 10 hectares of farmed area resulted in only a small improvement, with slightly more energy produced than consumed (Pechsiri *et al*. 2016). Similarly, a modelling study in the United States of America, focusing on 3 locations (West Coast, East Coast, and Gulf of Mexico), found a low probability (5 per cent chance) of achieving a combination of both net carbon sequestration and net energy production from seaweed biofuel (Melara *et al*. 2020). There was high carbon output and low energy return on investment from anaerobic digestion, indicating the need for innovation to increase biomass conversion efficiency (Melara *et al*. 2020). Indeed, a more optimistic biogas yield estimate of 90 per cent at the 10 hectare scale in the Swedish study resulted in net energy production that nearly met the energy return on investment required for commercial viability and provided GHG savings of 60 per cent as required by the European Union Renewable Energy Directive (Pechsiri *et al*. 2016). Improvements to anaerobic digestion that increase biogas yield, and economies of scale, particularly during seaweed cultivation, have the potential to make seaweed biofuel a more viable BECCS method (Pechsiri *et al*. 2016; Melara *et al*. 2020).

Calculations indicate the theoretical potential to offset transportation fuel use with seaweed biofuels (Fernand *et al*. 2017). For example, replacing 60 per cent of the transportation fuel needs of France would require seaweed farming over a small fraction (0.5 per cent or 54,795 square kilometers) of the total 11 million square kilometer French exclusive economic zone (EEZ) (Fernand *et al*. 2017).

Similarly, in Israel, the Netherlands, and Norway, farming across 3,250, 17,368, and 1,034 square kilometers of their respective total 27,000, 154,011, and 787,000 square kilometer EEZs would be required for 60 per cent transportation fuel replacement (Fernand *et al*. 2017). By contrast, in Germany, farming across 69,683 square kilometers would be required to replace 60 per cent of transportation fuel use, which is greater than twice the total 33,100 square kilometer German EEZ (Fernand *et al*. 2017). Biofuel obligation targets for transport exist, for example, in Ireland (10 per cent biofuel use by 2020; Bruton *et al*. 2009), indicating the value of such theoretical calculations. Yet, these calculations do not consider the cost and feasibility of large-scale seaweed farming for biofuels (Fernand *et al*. 2017).

As with any commercial use pathway herein, advanced technology and infrastructure will be required for large-scale seaweed biomass production and processing (see section 4.2.3 *Advanced Technology and Infrastructure*). Specific to biofuels, there is a need for identification of locations and seaweed strains with maximal capacity for biofuel production, and technological innovations for high-yield conversion of seaweed biomass to biofuels (Turan and Neori 2010; Kraan 2013; Wei *et al*. 2013; Kerrison *et al*. 2015; Marquez *et al*. 2015). Identification of novel microbes, particularly from the ocean, for use in fermentation of the diverse and unusual carbohydrates found in seaweeds (e.g., galactose, rhamnose and arabinose, and sugar acids), could increase biomass conversion efficiency for biofuel production (Fernand *et al*. 2017).

These advancements will likely require political, private, and public support that may include government regulations, public-private partnerships (PPPs), private investment into research and innovation, and the development of educational infrastructure (Turan and Neori 2010). At the large farming scales required to economically produce seaweeds for commercial uses (including for biofuels), the potential negative effects of seaweed farming on ocean ecosystems must be considered (see section 3.2 *Potential for Environmental Risks*). Finally, accurate accounting of atmospheric CO_2 removal and natural carbon sequestration during seaweed cultivation will be necessary to account for the overall climate benefits of seaweed biofuel production (as with any commercial use pathway; see section 2.1 *Potential for Natural Carbon Sequestration*).

2.2.2 *Reducing Livestock Methane Emissions*

The livestock sector contributes 14.5 per cent of total global anthropogenic GHG emissions, and methane generation by ruminant livestock (e.g., cows and sheep) accounts for 39 per cent of these emissions (Gerber *et al*. 2013). Methane is a short-lived[18] but powerful[19] GHG and is a by-product of the enteric fermentation of plant material by microbes in ruminant livestock (Gerber *et al*. 2013; Vijn *et al*. 2020). Enhancement of livestock feeds with small quantities of some seaweed species can reduce the enteric methane emissions from ruminant livestock (Machado *et al*. 2016; Li *et al*. 2016; Roque *et al*. 2019; Kinley *et al*. 2020), providing a potential pathway for climate mitigation (Duarte *et al*. 2017; emLab 2019). Yet, the use of seaweed feeds to reduce enteric methane emissions has occurred at only experimental scales, and additional research and development are needed for this

[18] Approximately 10 years

[19] 28 times higher global warming potential than CO_2

pathway to reach commercial scale (Vijn *et al*. 2020; Wasson *et al*. 2022).

Including as little as 2 per cent organic matter of the seaweed *Asparagopsis taxiformis* in livestock feed reduced methane production in steers (*Bos indicus*) *in vitro* by 99 per cent (Machado *et al*. 2016) (Appendix A, Table A2). The 2 per cent dose had minimal effect on the ruminant fermentation process, suggesting a suitable feed additive with the potential to reduce methane emissions (Machado *et al*. 2016). These results were supported *in vivo* for sheep, and dairy and beef cattle (Li *et al*. 2016; Roque *et al*. 2019; Kinley *et al*. 2020). *Asparagopsis taxiformis* added to the feed of sheep fed a high-fiber diet reduced methane production in a dosage-dependent manner, with an *in vivo* 80 per cent reduction in methane production in the highest addition treatment (3 per cent seaweed in feed), and with no change in live weight gain (Li *et al*. 2016) (Appendix A, Table A2). A congeneric seaweed species, *Asparagopsis armata*, added to the feed of lactating cows at a rate of 0.5 and 1 per cent reduced methane emissions *in vivo* by 26 and 67 per cent, respectively, with a modest decrease in milk production in the latter treatment (Roque *et al*. 2019) (Appendix A, Table A2). The study did not document an increase in bromoform (a chemical potentially hazardous to humans) in milk and there was no decrease in the nutrient quality of the feed. However, the authors cautioned that mineral concentrations (e.g., iodine) in milk from seaweed-fed cows should be monitored to ensure that they remain within recommended daily allowances (Roque *et al*. 2019).

In beef cattle fed a high-grain diet, addition of *Asparagopsis taxiformis* at a rate of 0.1 and 0.2 per cent reduced methane production *in vivo* by 40 and 98 per cent, respectively, and increased weight gain over 90 days by 53 and 42 per cent, respectively (Kinley *et al*. 2020) (Appendix A, Table A2). Kinley *et al*. (2020) found no negative effects on meat quality, and bromoform was not detected in the meat. These authors concluded that seaweed addition to beef cattle feed had potential to both help mitigate climate change and benefit the livestock sector through increased meat production (Kinley *et al*. 2020). Other seaweed species, including *Bonnemaisonia hamifera*, *Euptilota formisissima*, *Plocamium cirrhosum*, *Vidalia colensoi*, and *Ecklonia radiata* also have been shown to reduce enteric methane emissions *in vitro* at inclusion rates of up to 10 per cent of feed organic matter, indicating the need for follow up studies *in vivo* (Mihaila *et al*. 2022).

A life cycle analysis of enteric methane reduction via the seaweed feed pathway found a carbon footprint ranging from a major carbon sink to a carbon source[20], indicating a potentially potent climate mitigation strategy (emLab 2019). Though the maximum climate benefit of this pathway is constrained by the number of fed livestock on the planet (i.e., excluding free-ranging livestock), if select seaweed species were added to the feed of all cows around the world, global annual carbon-equivalent emissions could be reduced by 2.3 per cent (emLab 2019) (Appendix A, Table A2). This would require farming 33 million megatons of seaweed dry weight across 0.003 per cent of the ocean surface (emLab 2019). Removal of 1 megaton of CO_2 equivalent through addition of seaweed to livestock feed was estimated to be less expensive than other climate mitigation pathways of solar energy, wind energy, land reforestation, and land afforestation (emLab 2019). However, the cost of seaweed farming would have to decrease by 77 per cent to be competitive as a replacement for current feed additives (i.e., corn–the likely feed ingredient to be replaced) (emLab 2019). Thus, innovation to improve the cost efficiency of seaweed farming would be needed to realize the seaweed feed pathway for climate benefits (emLab 2019).

Research into the seaweed feed pathway indicates potential for climate mitigation (Vijn *et al*. 2020; Wasson *et al*. 2022). However, this pathway has been tested for limited seaweed species and under limited livestock production systems and scales. Additional research is therefore needed to identify a variety of seaweed species for cultivation and conduct animal trials in a variety of contexts to further assess the safety and efficacy of the pathway and build the regulatory, industry, and consumer confidence needed for large-scale implementation (Vijn *et al*. 2020; Wasson *et al*. 2022) (Fig. 3). Inclusion of enteric methane emissions in national emissions credit schemes could provide a financial route for the seaweed feed pathway (Vincent *et al*. 2020). Moreover, the cost efficiency of this pathway could be improved when waste from other seaweed products is used as feed (Wan *et al*. 2019) (e.g., in a seaweed biorefinery system wherein additional high value products are produced) (see section 4.2.5 *Market and Product Development*).

[20] -36,774 to 3,160 kilograms of net CO_2 equivalent per megaton seaweed dry weight

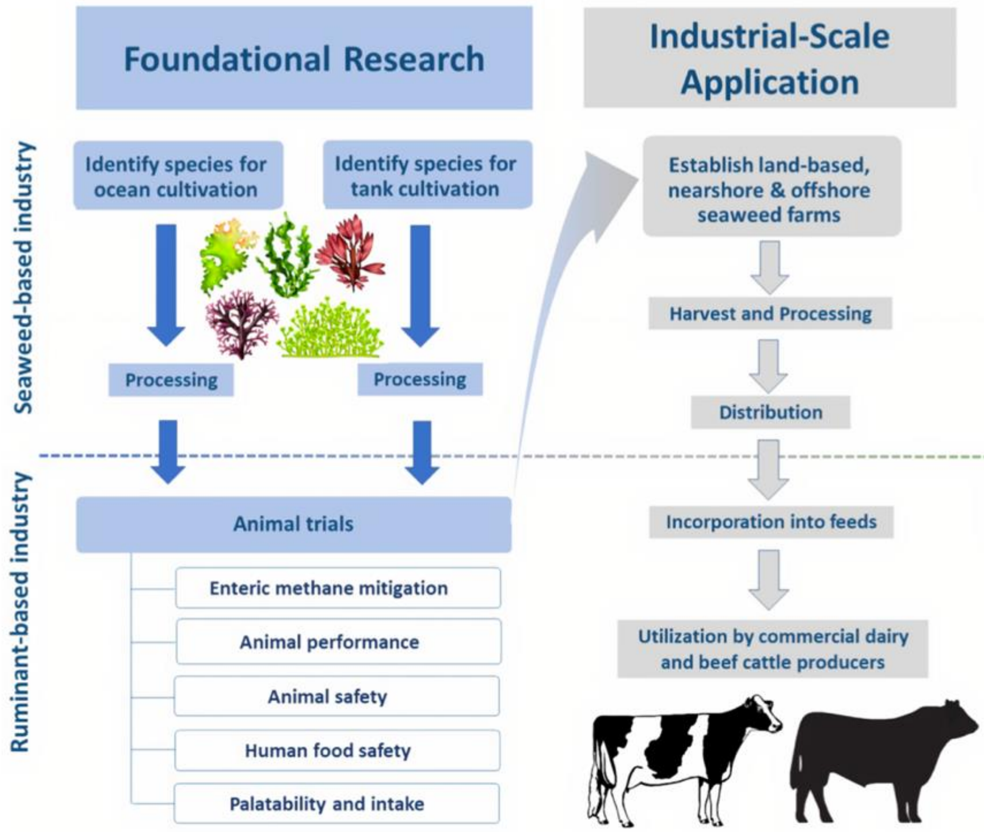


Fig. 3. A commercial scale seaweed feed pathway will require expanded research to identify additional seaweed species for cultivation and examine the enteric methane mitigation, animal performance, and animal safety, etc. in animal trials. Collaboration will be required across the seaweed and livestock industries. Adapted from Vijn *et al*. (2020), distributed under a CC BY license.

2.2.3 *Displacing Carbon-Intensive Food Production*

Expansion of land-based agricultural food production to support the growing human population is constrained by arable land and freshwater (Duarte *et al*. 2009; Falkenmark *et al*. 2009). Moreover, land-based agriculture currently accounts for 70 per cent of global freshwater usage and 30 per cent of global GHG emissions (Vermeulen *et al*. 2012; Steffen *et al*. 2015). In combination, this information provides a strong impetus to find alternative pathways for human food production that require limited or no land, freshwater, or fertilizer, and that have a lower carbon footprint than land-based agriculture (Duarte *et al*. 2022a).

Seaweeds have, in some cases, been deemed a suitable replacement for land-based agricultural crops (Radulovich *et al*. 2015a). For example, in Costa Rica, crude protein from native seaweed farming[21] was similar to that of grain crops, and it was estimated that tropical seaweed farming[22] could replace up to 15 per cent of national food production in terms of dry weight (Radulovich *et al*. 2015a). Similarly, a green seaweed[23] in the Arctic was found to have a similar nutritional profile to select fruits, vegetables, nuts, and grains, contained sufficient dietary minerals, and contained iodine and heavy metals within safe limits (Roleda *et al*. 2021). In China, the largest seaweed producer in the world, cultivation of approximately 2 million tons of seaweed in 2015 is estimated to have saved the equivalent of 62,492 hectares of land resources (Zheng *et al*. 2019) (Appendix A, Table A2). Yet, the risk of heavy metal exposure in seaweeds and their variation in dietary value, must not be overlooked (for further discussion see section 3.4.1 *Adverse Health Effects*).

Seaweeds can also be suitable as a primary feed in aquaculture[24] (Bolton *et al*. 2009) or feed additive in aquaculture (Hua *et al*. 2019) and agriculture (FAO 2018), when included at modest rates[25] (Hua *et al*. 2019). Use of seaweeds in animal feed can indirectly support human food production, while offsetting the pressure on arable land, freshwater, fertilizer, and wild fish stocks (Wan *et al*.

[21] 0.91 tons per hectare per year
[22] *Codium*, *Gracilaria*, *Sargassum*, and *Ulva*
[23] *Ulva lactuca*
[24] For example, abalone
[25] For example, less than 10 per cent in commercial finfish feed

2019; Cottrell *et al*. 2021). Moreover, seaweed addition to animal feed can enhance animal growth rates and provide immune system stimulant effects that reduce the need for antibiotics (e.g., in finfish) (Hoseinifar *et al*. 2018; Mohan *et al*. 2019; Wan *et al*. 2019). Optimizing these benefits will likely require farming a broader diversity of seaweed species, processing seaweeds to increase protein content and reduce indigestible polysaccharides, and conducting additional research to test for bioactives in seaweeds that enhance animal health and production (Øverland *et al*. 2019; Hua *et al*. 2019; Wan *et al*. 2019). It is worth noting that for some seaweed species, growth in nitrogen-enriched (i.e., eutrophic) waters can yield increased protein content (Gordillo *et al*. 2006).

Producing 1 kilogram of grain or beef for food requires between 1000–2000 and 15,000–200,000 liters of freshwater, respectively (Forster and Radulovich 2015). At a rate of 1 liter of freshwater per kilocalorie of food, human food consumption currently requires an average of 2000 liters of freshwater per person per day (Forster and Radulovich 2015). For every ton of food produced at sea, 4 million liters of freshwater can be saved (Radulovich 2011) (Appendix A, Table A2). Additionally, producing grain for biofuels competes with human food and requires 1000s of liters of freshwater, which could be avoided by substituting grain with seaweed as a biofuel feedstock (Forster and Radulovich 2015). Bioplastics made from corn, vegetables, or starch also require arable land, freshwater, and fertilizer, making seaweed bioplastics a viable substitute to reserve these resources for global food production (Mouritsen *et al*. 2021).

Proteins extracted from seaweeds could replace carbon-intensive land-based meat, egg, soy, and milk proteins (Sadhukhan *et al*. 2019). For example, a life cycle analysis indicates that production of seaweed protein yields a climate change savings of 12 kilograms of CO_2 equivalent per kilogram of seaweed protein produced (Sadhukhan *et al*. 2019) (Appendix A, Table A2). Yet, when produced as a single-stream product, seaweed protein is not able to compete with the cost of soy protein[26] (Emblemsvåg *et al*. 2020). Replacement of lower-cost land-based proteins with seaweed proteins could be made economically feasible through a seaweed biorefinery system with limited or zero waste (Sadhukhan *et al*. 2019) (see section 4.2.5 *Market and Product Development*).

Fertilizers used in agriculture are a major contributor to global emissions of nitrous oxide, a powerful GHG, due to soil microbial processes (Gerber *et al*. 2013). Replacement of land-based crops with farmed seaweeds, which do not necessarily require fertilization, could therefore reduce nitrous oxide emissions (Duarte *et al*. 2017). For example, Zheng *et al*. (2019) found that in Chinese coastal waters, the cultivation of approximately 2 million tons of seaweed in 2015 had the potential to save 16,554 tons of nitrogen, 5,503 tons of phosphorous pentoxide, and 7,255 tons of potassium oxide fertilizers, as well as 1,873 tons of pesticides (Appendix A, Table A2). Moreover, given that inorganic fertilizers are sourced primarily from fossil resources, replacing these fertilizers with seaweed-derived nutrients (e.g., through a biorefinery system) could reduce the carbon footprint of land-based agriculture (Sadhukhan *et al*. 2019). A life cycle analysis indicates that biorefining seaweed into inorganics (including for fertilizer) has a climate change savings of 1 kilogram of CO_2 equivalent per kilogram of inorganics produced (Sadhukhan *et al*. 2019) (Appendix A, Table A2). Use of seaweed biofertilizer also has the potential co-benefits of biostimulant effects (e.g., seed germination), controlling plant pathogens, and remediating pollution in contaminated soils (Nabti *et al*. 2017; Ali *et al*. 2021).

While there is potential for seaweeds to displace carbon-intensive land crop production (Cai *et al*. 2013; Mahadevan 2015; Mouritsen *et al*. 2021), as with other seaweed commercial use pathways, additional research and development are needed, particularly towards increased cost efficiency (see sections 4.2.3 *Advanced Technology and Infrastructure* and 4.2.5 *Market and Product Development*). Hoegh-Guldberg *et al*. (2019) suggest that within the current decade, policy decisions could incentivize a shift to seaweed foods, and this may include exploring the impact of a carbon tax on more carbon-intensive foods.

Establishing inclusive policies which incorporate participation of women and men farmers would further guide the sustainable growth and development of the sector (Cottier-Cook *et al*. 2021). To help protect vulnerable groups, seaweed farming expansion strategies can be developed in line with an inclusive policy environment (Cottier-Cook *et al*. 2021). Some policy recommendations emphasize the need to develop assessment tools that balance environmental and economic risks with the potential benefits of seaweed production (Cottier-Cook *et al*. 2021). This should be done while channeling support for long-term investments to promote the beneficial aspects of the industry such as alternative livelihoods for women in coastal communities (see section 3.3.2 *Gender Equity*).

2.2.4 *Intentional Deep Ocean Sinking*

The intentional sinking of seaweed biomass into the deep ocean has been discussed as a potentially scalable carbon sequestration strategy (emLab 2019; Froehlich *et al*. 2019; NASEM 2021; Wu *et al*. 2022a). In concept, seaweed biomass farmed in surface waters would absorb CO_2 and, when intentionally subducted into the deep ocean,

[26] For example, a current primary finfish feed

sequester carbon over climate relevant timescales (greater than 100 years) (emLab 2019; NASEM 2021; Troell *et al*. 2022; Wu *et al*. 2022a). Yet, the feasibility of this pathway as a climate mitigation strategy remains under investigation (Bach *et al.* 2021; Ricart *et al*. 2022).

A target depth for deposition of greater than 2000 meters has been suggested to accomplish maximal sequestration potential (NASEM 2021). Accordingly, a modelling study showed that when delivered to greater than 3000 meters, more than half of the seaweed carbon remained sequestered at year 3000 (Wu *et al*. 2022a). In concept, the rates of seaweed degradation and sedimentation on the seafloor would determine the proportion of the deposited biomass that is sequestered as respired CO_2 versus POC in sediments (NASEM 2021). Timescales for release of respired CO_2 from the deep ocean may depend on ocean circulation and mixing, which vary regionally and across ocean basins (NASEM 2021).

It has been suggested that deep ocean sinking of seaweed has limited economic viability, as there would be greater economic gain from harvesting and processing seaweeds into commercial products[27] (emLab 2019; Chopin and Tacon 2021; Ricart *et al*. 2022; Troell *et al*. 2022). Moreover, authors have raised ethical questions regarding the sinking of seaweed biomass that could be used for food, feed, or fuel, with the potential to address multiple UN SDGs[28] (Ricart *et al*. 2022) (Fig. 4). Troell *et al*. (2022) and Ricarte *et al*. (2022) each conclude that rapid investment in deep ocean sinking as a carbon sequestration strategy should not deflect resources away from research to assess the economic and environmental sustainability of this pathway.

A life cycle analysis of intentional deep ocean sinking indicates the potential to sequester 787–945 kilograms of CO_2 per megaton of seaweed dry weight (emLab 2019). Sequestering 2017 global emissions would require 57 gigatons of seaweed dry weight farmed across approximately 5 per cent of the ocean surface (emLab 2019). Given the size of the global carbon market, deep ocean sinking currently could accomplish removal of at most approximately 0.43 per cent of total global emissions (Appendix A, Table A2), and authors have concluded that the cost of this pathway[29] would have to be significantly reduced[30] to be feasibly funded through carbon offset markets (emLab 2019).

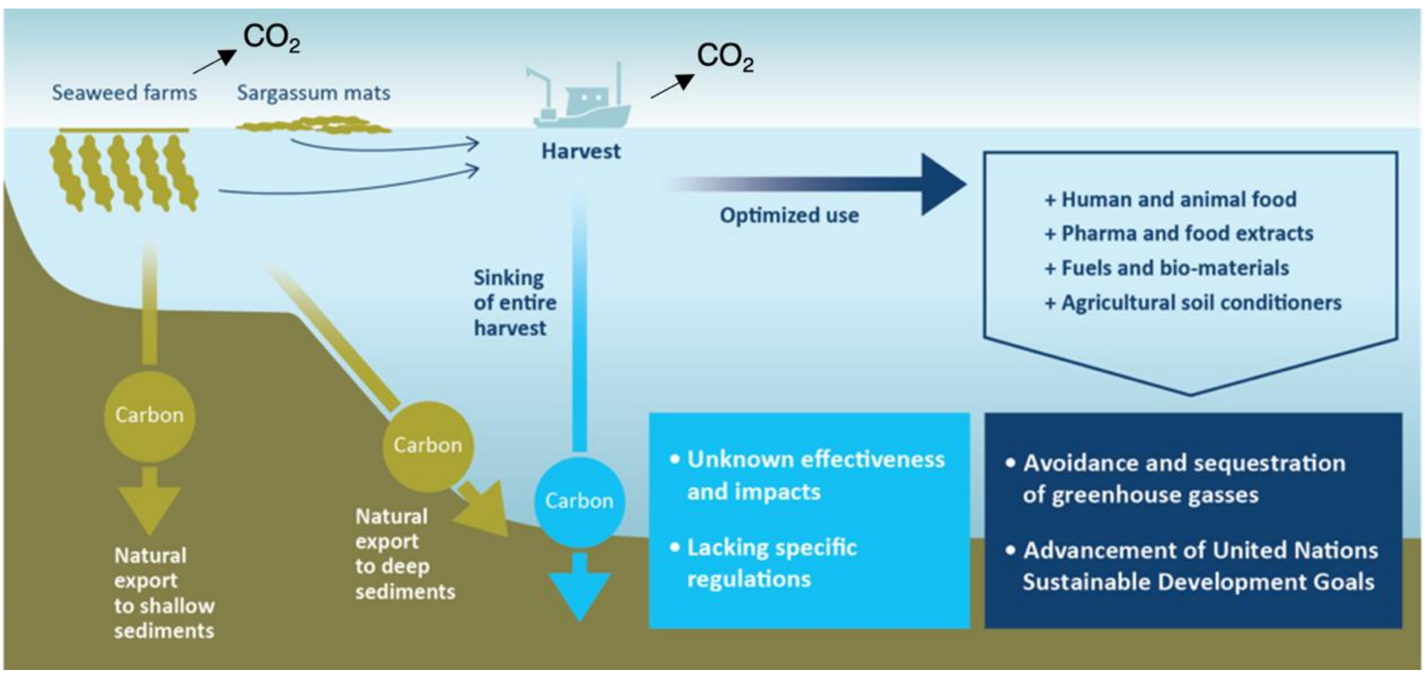


Fig. 4. Carbon sequestration through intentional deep ocean sinking (light blue) and alternatives that are considered optimal to accomplish multiple UN SDGs (dark blue). Release of CO_2 will occur during the seaweed cultivation and harvesting/transport phases. Adapted from Ricart *et al.* (2022), distributed under a CC BY 3.0 license.

[27] For example, food and pharmaceuticals
[28] SDG2: zero hunger and SDG7: affordable and clean energy
[29] USD 709 per megaton of CO_2
[30] 88–99 per cent

The efficient transfer with minimal loss of seaweed biomass to deep ocean sinks would likely require specialized equipment (NASEM 2021). New technology would be required to confirm the veracity of the carbon storage (NASEM 2021; Ricart *et al*. 2022). As with any seaweed commercial use pathway discussed herein, there may be environmental risks of upscaled seaweed farming for this pathway (see section 3.2 *Potential for Environmental Risks*). Risks specific to deep ocean sinking include acidification, deoxygenation, and eutrophication of the deep ocean due to enhanced respiration of deposited biomass (emLab 2019; NASEM 2021; Wu *et al*. 2022a). Finally, as with any atmospheric CO_2 removal and sequestration strategy, intentional deep ocean sinking must consider the residence time of surface waters relative to the air-sea CO_2 equilibrium timescale to ensure an effective carbon sink (Bach *et al*. 2021; Hurd *et al*. 2022).

2.2.5 *Land-Based Carbon Sequestration*

While research into seaweed carbon sequestration on land is limited, it is expected that carbon in seaweed biochar and biofertilizer in soils will persist for months to years (Clark *et al*. 2021). Yet, estimates vary, and the refractory component of seaweed carbon could persist in soils for timescales of decades to centuries (Hughes *et al*. 2012; Troell *et al*. 2022). This is in contrast to the seaweeds consumed as food or feed that should result in the release of carbon in a matter of days to weeks (Clark *et al*. 2021). The carbon stored in seaweed bioplastics is expected to persist for years to decades (Clark *et al*. 2021). Seaweed bioplastics can be used to produce materials such as films for food packaging, edible containers, and biodegradable drinking straws (Mouritsen *et al*. 2021). Seaweed bioplastics are produced from the polysaccharides in seaweeds, including carrageenan, alginate, and agar, and tend to be highly durable and heat resistant (Mouritsen *et al*. 2021). However, single-use bioplastics that are highly biodegradable may have shorter lifespans. The use of seaweeds to produce bioplastics currently occurs at experimental and pilot scales (FAO 2020).

2.2.6 *Summary of Potential Commercial Use Pathways for Climate Mitigation*

Seaweed commercial use pathways have been proposed for carbon sequestration and GHG emissions reduction, with varying levels of progress towards implementation. These pathways include displacing carbon-intensive energy with seaweed biofuels, reducing livestock methane emissions with seaweed feed, displacing land-based crops with seaweed foods, providing ocean carbon sequestration through intentional sinking of seaweeds, and providing land carbon sequestration in seaweed products (Marquez *et al*. 2015; Sadhukhan *et al*. 2019; Vijn *et al*. 2020; Clark *et al*. 2021; NASEM 2021). Each of these pathways would require robust and cost-efficient seaweed supply and production chains and the social license to operate. Regarding supply and production, economies of scale and a seaweed biorefinery concept wherein multiple high and low value seaweed-based products are co-produced, with limited or no waste, have potential to increase cost efficiency (Marquez *et al*. 2015). Regarding social license, additional research is needed to further assess the environmental and socioeconomic benefits and risks of each pathway.

The evidence reviewed here on the potential seaweed commercial use pathways for climate mitigation indicates several ***strengths*** and ***weaknesses*** of seaweed farming and ***opportunities*** and ***threats*** that could be planned for under future expansion.

STRENGTHS

- Select cultivated seaweeds are candidates for processing into carbon negative biofuels that do not compete with land-based food crops
- Select cultivated seaweeds are candidates to reduce enteric methane emissions when added to ruminant livestock feed
- Select cultivated seaweeds can contribute some human food in place of carbon-intensive land-based crops
- Seaweed products, such as biofertilizers and bioplastics, can sequester some carbon on land or displace more carbon-intensive products

WEAKNESSES

- Energy return on investment for seaweed biofuel is limited by various factors including the efficiency of seaweed biomass conversion to energy
- The potential of seaweed feed methane mitigation is limited by various factors including the number of ruminant livestock nourished by feeds
- High production costs for seaweeds create a barrier to replacing low-cost carbon-intensive commodities
- The potential of intentional deep ocean sinking of seaweed is constrained by various factors including economic viability and uncertainties in the veracity of long-term carbon storage and the environmental ramifications

OPPORTUNITIES

- Seaweed farming could provide carbon sequestration and GHG emissions reduction through commercial use pathways that is proportional to industry scale
- Technological improvements to energy conversion could increase the energy return on investment for seaweed biofuels and their commercial feasibility
- Innovation towards a biorefinery concept, wherein multiple seaweed products are co-produced with zero waste, could increase the cost efficiency of various seaweed use pathways and their commercial feasibility
- Policy interventions could incentivize a shift from consumption of low-cost carbon-intensive commodities to seaweed-based commodities
- Improved understanding of the cycling of seaweed carbon in the ocean and land-based products could improve accounting of the climate benefits of various commercial use pathways

THREATS

Rapid upscaling of seaweed commercial use pathways for carbon sequestration and GHG emissions reduction could pose environmental and social risks where rigorous research has not yet been conducted

PART 3: REVIEW OF EVIDENCE FOR POTENTIAL ENVIRONMENTAL AND SOCIOECONOMIC CO-BENEFITS AND RISKS

3.1 Potential for Environmental Co-Benefits

Various environmental co-benefits may be associated with seaweed farming. In this section, information relating to these potential co-benefits is reviewed and contextualized, and knowledge gaps are identified.

3.1.1 *Marine Biodiversity*

Climate change is driving the rapid loss of biodiversity on land and in the sea (IPCC 2019a; IPCC 2019b), and there is great interest to determine whether seaweed farming can support biodiversity (Duarte *et al*. 2017). Yet, studies examining the biodiversity effects of seaweed farming are rare, and results thus far are mixed (Forbes *et al*. 2022). While a global meta-analysis found an overall positive effect of seaweed farms on tropical fishes and mobile macroinvertebrates (Theuerkauf *et al*. 2022), the effects of seaweed farms on biodiversity can be highly context dependent (Kelly *et al*. 2020) and some authors have concluded that seaweed farms do not provide the same biodiversity benefits as wild seaweed forests (Forbes *et al*. 2022). The identity of the habitat superseded by a seaweed farm may be highly relevant. This section reviews recent progress on understanding the biodiversity effects of seaweed farms.

Farming of kelp in temperate waters tends to attract biodiversity (Kerrison *et al*. 2015; Walls *et al*. 2016; Walls *et al*. 2017; Wood *et al*. 2017; Visch *et al*. 2020; Hancke *et al*. 2021). At an experimental kelp farm over sandy bottom in the west of Ireland, holdfasts of farmed kelp[31] provided a biogenic habitat for native macroinvertebrates[32], fostering higher species diversity and a "novel" species assemblage as compared to wild holdfasts (Walls *et al*. 2016) (Appendix A, Table A3). The authors suggested that kelp harvesting approaches could be employed that retain the holdfast and associated biodiversity (Walls *et al*. 2016). Also, in the west of Ireland, an 18-hectare kelp farm[33] grown above a seagrass bed[34] had no significant negative effect on seagrass biomass over a two-year period as compared to reference sites (Walls *et al*. 2017). However, there was lower sediment total organic matter and smaller grain size beneath the farm likely due to consumption of detritus by fouling organisms and physical baffling of water currents by the farm (Walls *et al*. 2017). In Northern Ireland, benthic marine organisms[35] colonized the anchoring structures of an experimental kelp farm on sandy bottom (Wood *et al*. 2017). On the west coast of Sweden, kelp farming[36] had no effect on benthic mobile fauna but increased the abundance and diversity of benthic infauna as compared to sandy bottom reference sites (Visch *et al*. 2020). Kerrison *et al*. (2015) reported grazing by snails on farmed kelp[37] in the United Kingdom. In Norway, Hancke *et al*. (2021) determined that while small (0.4–4 hectare) kelp farms act as artificial habitats for marine species, they support lower species abundance and diversity than wild kelp forests. This is likely because farmed kelp is harvested seasonally and does not reach a mature kelp forest state, and when placed over sandy bottom, lacks the extensive rocky habitat of a wild kelp forest (Wood *et al*. 2017). The kelp detritus released by farms[38] may stimulate biodiversity through subsidies to benthic food webs (Zhang *et al*. 2012; Wu *et al*. 2016; Fieler *et al*. 2021), but may conversely negatively affect benthic fauna due to biogeochemical changes to the seafloor (Zhou 2012; Hancke *et al*. 2021) (see section 3.2.4 *Organic Matter Over-Deposition*).

In Zanzibar, United Republic of Tanzania, seaweed farming occurs primarily in shallow water that is accessible from shore at low tide, and 92 per cent of seaweed farms are at least partly located on seagrass habitat (Hedberg *et al*. 2018). Small-scale seaweed farming is considered to have a limited impact on seagrass ecosystems, as extensive seagrass beds remain in between farms (Eklöf *et al*. 2012). However, negative effects of seaweed farms on seagrass beds have been documented, likely due to competition for light and nutrients, and upscaling of seaweed farming could have greater impacts (Eklöf *et al*. 2005; Eklöf *et al*. 2006a; Eklöf *et al*. 2012; Lyimo *et al*. 2006; see section 3.2.1 *Habitat Competition*). For example, Eklöf *et al*. (2005) found that seagrass beds beneath seaweed farms[39] had less seagrass and wild seaweeds and finer sediment with less organic matter than reference sites. Similarly, a manipulative study in Zanzibar found that experimental seaweed farm plots had lower abundance of seagrasses[40] as compared to control plots (Eklöf *et al*. 2006a). The effects of seaweed farming on seagrasses in Zanzibar can be species-specific, with a study documenting a negative effect on the abundance of *Enhalus acoroides* but not *Thalassia hemprichii* (Eklöf *et al*. 2006a) and another study documenting the reverse pattern (Lyimo *et al*. 2006). Given recorded reductions in sediment organic matter at seaweed farms placed over seagrass beds (e.g., Eklöf *et al*. 2005), it is worth considering how seaweed farms at large scales could affect regional seagrass carbon sequestration.

[31] *Laminaria digitata*
[32] 42 species total
[33] *Alaria esculenta* and *Saccharina latissima*
[34] *Zostera marina*
[35] Seaweeds, tunicates, razor clams, and crabs
[36] *Saccharina latissima*
[37] *Saccharina latissima*
[38] Up to 49–58 per cent of productivity in some studies (Appendix A, Table A3)
[39] *Eucheuma* and *Kappaphycus*
[40] 40 per cent lower biomass

The effects of seaweed farming on benthic fauna in tropical seagrass beds have generally been negative, likely due to the loss of seagrass habitat (Eklöf *et al*. 2005; Eklöf *et al*. 2006b; Ólafsson *et al*. 1995; Eklöf *et al*. 2012). For example, in Zanzibar, seagrass beds beneath seaweed farms[41] had less benthic macrofauna[42] than reference seagrass sites (Eklöf *et al*. 2005). Experimental farm plots in Zanzibar also had lower abundance of associated benthic epifauna[43] as compared to control plots (Eklöf *et al*. 2006b). Furthermore, all major benthic meiofauna taxa were less abundant within seaweed farms[44] in Zanzibar as compared to reference sites (Ólafsson *et al*. 1995). It has also been noted that tropical seaweed farming requires mangrove poles as part of the farm infrastructure, and this may contribute to unsustainable mangrove harvesting (Sievanen *et al*. 2005; Msuya *et al*. 2007). However, this risk has not been quantified and was not discussed in a recent review on the environmental effects of tropical seaweed farming (Kelly *et al*. 2020).

While tropical seaweed farms are associated with enhanced local abundance of herbivorous fishes (likely due to provisioning of food), the abundance of carnivorous fishes[45] tends to decrease when seaweed farms supersede seagrass beds. This is likely due to losses of benthic invertebrates that are dependent on seagrass habitat (Eklöf *et al*. 2012). For example, in Kenya, the relative abundance of herbivorous and carnivorous fishes increased and decreased, respectively, following development of seaweed farms on patchy seagrass habitat (Mirera *et al.* 2020). Similarly, in Zanzibar, herbivorous fishes were more abundant at seaweed farms, while carnivorous fishes were more abundant at seagrass habitats (Eklöf *et al*. 2006b). At a national scale, Hehre and Meeuwig (2016) found a positive correlation between landings of herbivorous reef fishes[46] and seaweed production in Indonesia, Malaysia, and the Philippines. However, this pattern did not hold for the United Republic of Tanzania and Fiji, possibly due to their sporadic/lower seaweed production (Hehre and Meeuwig 2016). On the south coast of Kenya, non-native farmed seaweed was found in the guts of fish at a reference site nearby the seaweed farm, indicating a pathway for farmed seaweed into local food webs (Anyango *et al*. 2017).

In general, seaweed farming is associated with increased fish abundance when farms supersede a lower complexity habitat (e.g., sandy bottom), but lower fish abundance when farms supersede a higher complexity habitat (e.g., seagrass bed or coral reef) (Hehre and Meeuwig 2015; Kelly *et al*. 2020). For example, in Zanzibar, seaweed farms had similar fish abundance as nearby seagrass beds, but fish abundance was 3–7 times higher at the farm than at a nearby sandy bottom site (Eklöf *et al*. 2006b). In Costa Rica, greater fish counts[47] and species diversity[48] were observed within a farm plot of mixed seaweed species as compared to two sandy bottom reference areas, and invertebrates including gastropods and crabs were seen grazing on farmed seaweeds (Radulovich *et al*. 2015a) (Appendix A, Table A3). In the Philippines, a negative association was found between fish biomass and seaweed farming at healthy coral reefs in a marine protected area (MPA), but there was no effect of seaweed farming on fish biomass at degraded coral reefs impacted by blast fishing outside the MPA (Hehre and Meeuwig 2015). At a seaweed farm[49] in Belize, there was no difference in fish diversity or abundance as compared to reference areas dominated by a mixed seaweed and coral habitat (de Carvalho *et al*. 2015).

It is unknown to what extent enhanced abundance and diversity of species at seaweed farms is due to additional production supported by the farm or attraction of species away from nearby wild habitats (Eklöf *et al*. 2012; Gentry *et al*. 2020; van den Burg *et al*. 2020). Unlike mature seaweed forests, seaweed farms provide a temporary habitat, given that seaweed biomass is harvested (Skjermo *et al*. 2014). Seaweed farming may therefore be particularly beneficial when cultivation coincides with the spawning or early life-history stages of marine species, given that availability of seaweed habitat is particularly critical during these stages (Skjermo *et al*. 2014). Yet, harvesting of farmed seaweeds during critical stages could have negative effects on populations, and these ecological dynamics require further examination (Forbes *et al*. 2022). Seaweed farms also may harbor pests or invasive species that pose a threat to nearby ecosystems (see section 3.2.2 *Spillover of Pathogens and Invasive Species*). Additional research is needed to quantify the biodiversity effects of seaweed farming over large spatial (e.g., entire habitats and ecosystems) and temporal (e.g., before, during, and after cultivation and harvesting) scales. Given that seaweed farming represents seaweed afforestation rather than protection or restoration of an existing ecosystem, biodiversity changes should be carefully scrutinized for their positive versus negative effects on marine ecosystems.

[41] *Eucheuma denticulatum* and *Kappaphycus alvarezii*
[42] Primarily suspension-feeding bivalves
[43] Sea urchins and sponges
[44] *Eucheuma spiniosum*
[45] For example, those that eat invertebrates
[46] Siganids
[47] Approximately 100 versus 5
[48] 14 versus 3
[49] *Kappaphycus alvarezii*

3.1.2 *Water Quality*

Ocean acidification, deoxygenation, and coastal pollution[50] are major coastal water quality issues that can have negative knock-on effects for marine biodiversity (Beman *et al*. 2005; Howarth *et al*. 2011; IPCC 2019b). Through the uptake of CO_2 and nutrients and release of oxygen during photosynthesis, wild seaweed forests increase ocean pH, reduce nutrient levels, and oxygenate the water column, respectively (Krause-Jensen *et al*. 2015).

Moreover, seaweeds passively absorb heavy metal ions (e.g., arsenic, cadmium, and lead), providing heavy metal bioextraction (Zeraatkar *et al*. 2016). Like wild seaweed forests, seaweed farms may have the potential to improve water quality through the mitigation of ocean acidification, deoxygenation, and coastal pollution (Duarte *et al*. 2017; Langton *et al*. 2019) (Fig. 5).

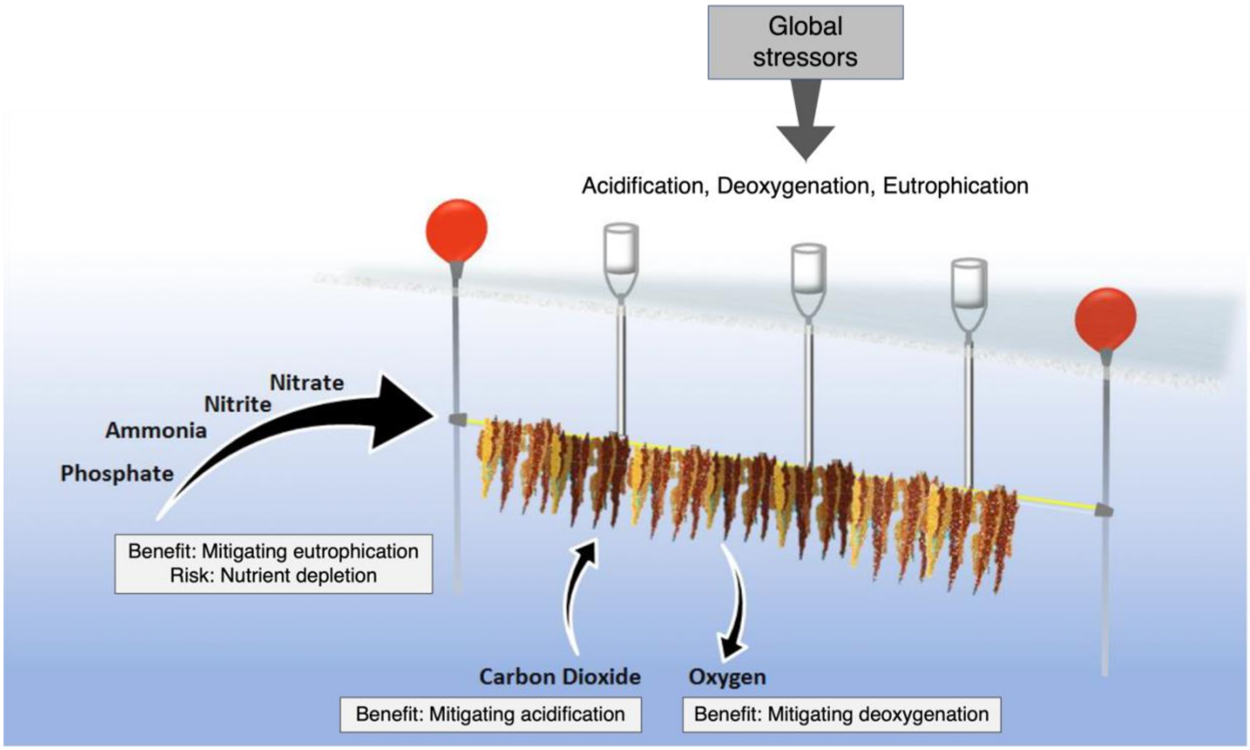


Fig. 5. Potential for mitigation of ocean acidification, deoxygenation, and coastal eutrophication by seaweed farms due to the absorption of CO_2, production of oxygen, and removal of nitrogen and phosphorus, respectively, by seaweeds. Nutrient depletion is a related environmental risk. Adapted from Langton *et al*. (2019) with permission.

Ocean acidification is caused by increased anthropogenic CO_2 concentrations in the ocean and leads to low aragonite saturation states that can impact the growth, development, and survival of calcifying organisms (IPCC 2019b). While direct measurements of aragonite saturation states at seaweed farms are limited (Gentry *et al*. 2020), Xiao *et al*. (2021) found generally higher aragonite saturation[51], higher pH[52], and lower dissolved CO_2[53] at seaweed farms[54] as compared to reference areas in China (Appendix A, Table A3). Jiang *et al*. (2020) also observed higher pH in the vicinity of a seaweed farm[55] as compared to a reference area in China. Mongin *et al*. (2016) used a numerical model to assess the potential for seaweed farms to buffer the impacts of ocean acidification on coral reefs at the Great Barrier Reef through removal of dissolved CO_2. They found that an optimally located, approximately 2 square kilometer seaweed farm[56] increased aragonite saturation by 0.1 units over a 24 square kilometer area (Mongin *et al*. 2016) (Appendix A, Table A3). The theoretical farm had the potential to buffer

[50] For example, eutrophication
[51] 0–0.29-unit increase
[52] 0.03–0.1-unit increase
[53] 27.3–113.9 micro atmosphere decrease
[54] *Saccharina japonica*, *Gracilariopsis lemaneiformis*, and *Porphyra haitanensis*
[55] *Saccharina japonica*, *Gracilariopsis lemaneiformis*, and *Porphyra haitanensis*
[56] With seaweed harvested at a rate of 42 grams of nitrogen per square meter per week (equivalent of 6.6 tons of carbon per hectare per week)

the coral reef from ocean acidification for approximately 7–21 years of projected future conditions (IPCC RCP 8.5–2.6) (Mongin *et al*. 2016).

The combination of land-based nutrient inputs and climate change-induced ocean surface warming are causing ocean deoxygenation due to the associated increase in oxygen demand by marine life and decrease in ocean mixing, respectively, and this can compress suitable marine habitats and cause mortality of marine organisms (IPCC 2019b). Enhanced dissolved oxygen has been measured in the vicinity of seaweed farms in China as compared to reference areas (Zheng *et al*. 2019; Jiang *et al*. 2020; Xiao *et al*. 2021; Gao *et al*. 2022). Zheng *et al*. (2019) determined that seaweed farming in Chinese waters produces a total of 1,440,612 tons of oxygen per year in a region with high chemical oxygen demand (Appendix A, Table A3). Gao *et al*. (2022) found a higher estimate of 2,533,221 tons of oxygen per year generated by seaweed farming across China and determined that this is sufficient to counteract deoxygenation in surface waters (Appendix A, Table A3). Xiao *et al.* (2021) also observed enhanced dissolved oxygen[57] at seaweed farms as compared to reference areas in China (Appendix A, Table A3).

Some farmed seaweeds are very efficient at removing nitrogen and phosphorus (Kim *et al*. 2014; Kim *et al*. 2015; Kim *et al*. 2017; Wu *et al*. 2017; Xiao *et al*. 2017; Zheng *et al*. 2019; Gao *et al*. 2022) and heavy metals (Zeraatkar *et al*. 2016) from polluted waters. Regarding the latter, seaweeds can be used in environmental heavy metal remediation and water treatment (Zeraatkar *et al*. 2016). However, where farmed seaweeds are harvested for human food or food production[58], heavy metals, such as inorganic arsenic and cadmium, pose a risk to human health (Besada *et al*. 2009) (see section 3.4.1 *Adverse Health Effects*). As with all food products, monitoring for harmful elements in farmed seaweeds is required, and contaminated seaweeds should be considered for use in non-food related products (Duarte *et al*. 2022a).

Uptake by seaweeds of nitrogen and phosphorus does not impact palatability to humans and can mitigate coastal eutrophication by removing excess nutrients that may otherwise lead to harmful algal blooms (Yang *et al*. 2015; Duarte *et al*. 2017). In Long Island Sound and Bronx River Estuary, seaweed farming[59] resulted in nitrogen removal of up to 28–180 kilograms of nitrogen per hectare (Kim *et al*. 2014; Kim *et al.* 2015). In Jiangsu Province, China, seaweed farms[60] removed 3,765 tons of nitrogen and 103 tons of phosphorus in a harvest season (Wu *et al*. 2017).

Farming of various seaweed species across China removes an estimated annual 70,000–75,000 tons of nitrogen[61] and 8,500–9,500 tons of phosphorus[62] (Xiao *et al*. 2017; Zheng *et al*. 2019; Gao *et al*. 2022) (Appendix A, Table A3). Based on industry growth trajectories, seaweed farming has the potential to remove 100 per cent of phosphorus inputs to Chinese waters by 2026 (Xiao *et al*. 2017). By contrast, complete removal of land-based nitrogen inputs from Chinese waters would require an estimated 17 times greater area of seaweed farming, necessitating substantial expansion (Xiao *et al*. 2017). It is, however, unclear where the excess phosphorus would come from to support the seaweed productivity required to absorb total nitrogen inputs. Gao *et al*. (2022) calculated that the nitrogen and phosphorus pollution produced by fish farms in China could be mitigated by a seaweed farming area 2 and 3 times larger, respectively, than the current scale. Farmed kelp[63] currently removes the most nitrogen and phosphorus from Chinese waters due to a combination of total harvest yield and tissue nutrient content (Zheng *et al*. 2019; Gao *et al*. 2022). Under an upscaling scenario, a red seaweed[64] had the greatest nitrogen removal capacity (Gao *et al*. 2022).

A life cycle analysis of seaweed farming for biofertilizer production in Denmark indicated that biofertilizer from seaweeds grown offshore provided a sustainable circular nutrient management approach with a net decrease in coastal eutrophication (Seghetta *et al*. 2016). The use of farmed seaweeds as biofertilizer could also assist in addressing the growing global shortage of phosphorus for fertilization of land crops, given that seaweeds are very efficient at absorbing, and therefore recycling, excess phosphorus released into the ocean (Bjerregaard *et al*. 2016).

The estimated annual nitrogen removal by seaweed farming in coastal China[65] is similar to the total global nitrogen removal[66] estimated by Kim *et al*. (2017) for 5 primary farmed seaweed taxa[67] (Appendix A, Table 3A). Given that China accounts for approximately 2/3 of global seaweed farming production (FAO 2020), this global value is likely still correct within an order of magnitude, meaning that current upper estimates of nitrogen removal represent a small fraction of the total global fertilizer use estimated

[57] 0.02–0.35 milligram per liter increase
[58] For example, feed or fertilizer
[59] *Gracilaria tikvahiae* and *Saccharina latissima*
[60] *Pyropia yezoensis* (formerly *Porphyra yezoensis*) also containing *Ulva*
[61] Up to 59.07 tons of nitrogen per square kilometer per year
[62] Up to 7.50 tons of phosphorus per square kilometer per year
[63] *Saccharina japonica*
[64] *Gracilariopsis lemaneiformis*
[65] 70,000–75,000 tons of nitrogen per year
[66] 65,000 tons of nitrogen per year
[67] *Saccharina/Undaria*, *Pyropia/Porphyra*, *Gracilaria*, *Kappaphycus/Eucheuma*, and *Sargassum*

for the year 2022[68] (FAO 2019), up to 30 per cent of which may end up in the ocean (Kim *et al*. 2017; González-Rivas *et al*. 2020). Hence, while there may be strong local benefits of seaweed farms for nutrient mitigation, substantial upscaling would be required to accomplish globally relevant remediation.

Current estimates of nutrient removal by seaweed farms assume that all nutrients stored in seaweed biomass are removed from the ocean during harvesting and the nutrients are not released into the ocean later in the value chain. Yet, some of the nutrients fixed by farmed seaweeds will be exported into the marine environment during cultivation as seaweed detritus (Zhang *et al*. 2012). For example, in Sungo Bay, China, Zhang *et al*. (2012) found that 54 per cent of nitrogen gross production from seaweed farming[69] was released through detrital export (Appendix A, Table A3) and the fate of the nitrogen remains unexplored (Zhang *et al*. 2012). Data on nutrient mitigation by tropical seaweed farms is also lacking (Kelly *et al*. 2020). Future research should examine the fate of farmed seaweed nutrients in the environment throughout the value chain and assess the effects of tropical seaweed farming on water quality, particularly near seagrass beds and coral reefs that are highly vulnerable to coastal eutrophication (Kelly *et al*. 2020). The potential for depletion of nutrients upon which native ecosystems depend is also an important consideration for seaweed farming (see section 3.2.1 *Habitat Competition*).

3.1.3 *Coastal Protection*

Climate change-induced sea level rise and increased storm activity threaten vulnerable coastlines with wave inundation and erosion (IPCC 2019b), and there is evidence that wild seaweed forests provide coastal protection by mitigating surface waves (Mork 1996; Gaylord *et al*. 2007). It is therefore theorized that seaweed farms may similarly dampen coastal waves, providing a climate change adaptation benefit (Duarte *et al*. 2017).

While studies on coastal protection by seaweed farms are limited (Gentry *et al*. 2020), a modelling study for the northeastern United States of America showed the potential for suspended shellfish and seaweed farms to reduce wave energy during a storm event (Zhu *et al*. 2020). The study indicated that the effectiveness of a suspended farm in mitigating waves was less impacted by sea level rise than that of submerged aquatic vegetation, given that there was less bottom baffling by vegetation at higher sea levels (Zhu *et al*. 2020). There was a strong benefit for wave mitigation of offshore suspended farms in combination with inshore submerged aquatic vegetation (Zhu *et al*. 2020).

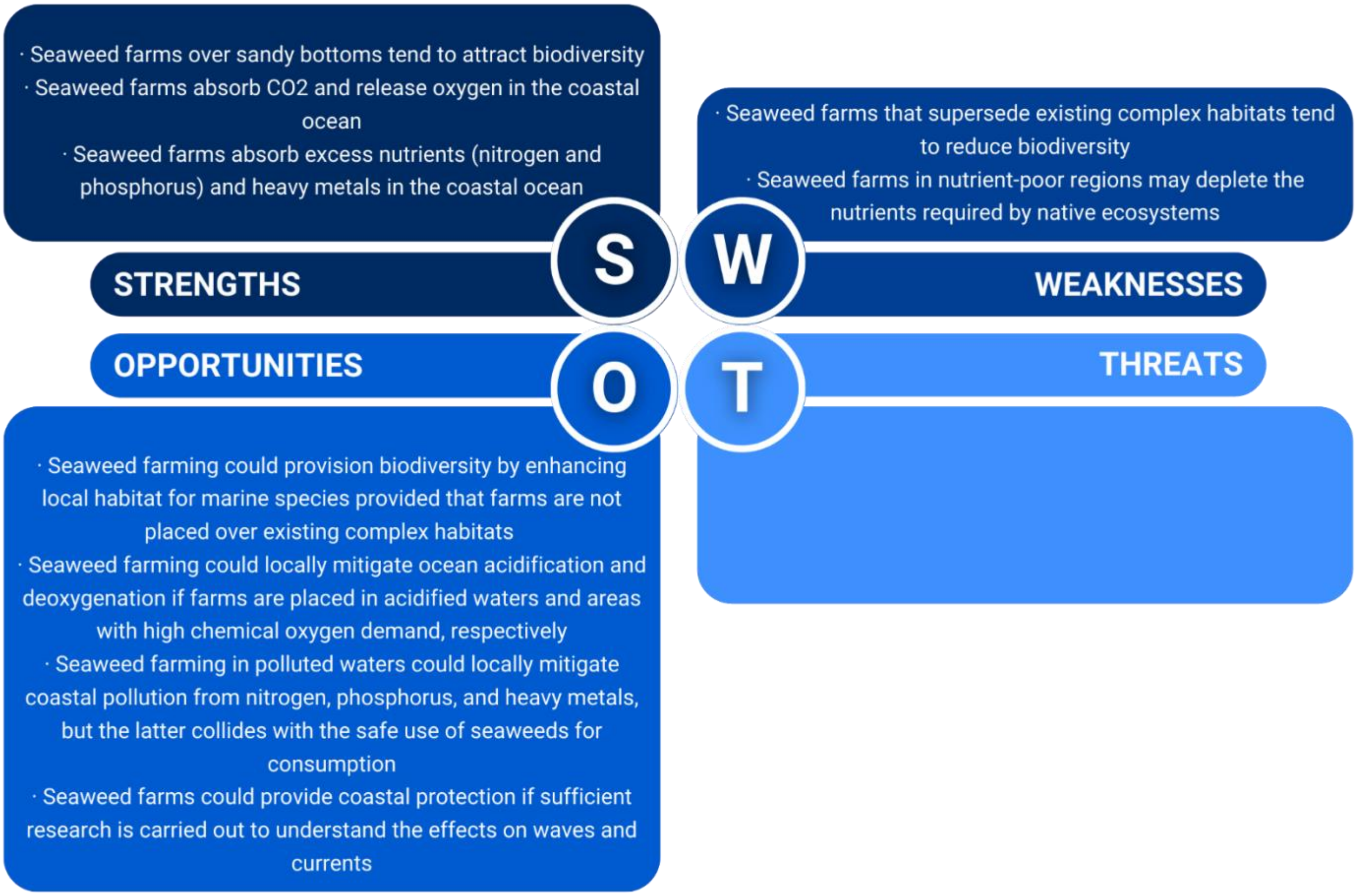
The potential for seaweed farms to provide coastal protection may depend on several variables, including farming method, species farmed, timing of harvest, and location and orientation of the farm (Clark *et al*. 2021). Thus, additional site-specific research is needed to assess the universality of this potential co-benefit (Clark *et al*. 2021). Moreover, seaweed farms have the potential to alter ocean currents, and therefore nutrient flows, presenting a potential risk to natural ecosystem functioning (see section 3.2.1 *Habitat Competition*). The risk–benefit profile of alterations to waves and currents by seaweed farms requires further research.

3.1.4 *Summary of Potential for Environmental Co-Benefits*

Seaweed farms have the potential to provide environmental co-benefits, including altering/enhancing biodiversity, improving water quality, and protecting coastlines (Kim *et al*. 2014; Kim *et al*. 2015; Walls *et al*. 2016; Walls *et al*. 2017; Zhu *et al*. 2020). However, these benefits can be highly context dependent, with evidence for some neutral or negative effects of seaweed farming on biodiversity, and limited research on coastal protection benefits. While the local environmental benefits of seaweed farming can be strong (as is the case for coastal nutrient mitigation), the global scale benefits likely remain small at current farming scales. In areas where seaweed farming is expected to expand, there is great need for additional research on the environmental effects, particularly to biodiversity and nutrient cycling.

The evidence reviewed here on the potential for environmental co-benefits of seaweed farming indicates various inherent ***strengths*** and ***weaknesses*** of seaweed farming as well as ***opportunities*** for the future.

[68] 111,591,000 tons of nitrogen
[69] *Saccharina japonica*



3.2 Potential for Environmental Risks

Various environmental risks may be associated with seaweed farming, and these risks should be weighed when considering the sustainability of expanded seaweed farming. In this section, information on these potential risks is reviewed and contextualized, and the possible mitigation measures are discussed.

3.2.1 *Habitat Competition*

Seaweed farms may compete with wild habitats for resources such as sunlight and nutrients (Campbell *et al*. 2019). While data are generally limited on the effects of seaweed farms on light and nutrients, depletion of these resources is considered a medium- to high-risk impact driver of environment change as seaweed farming expands (Campbell *et al*. 2019).

Field observations of light and nutrient competition between seaweed farms and wild ecosystems indicate mixed results (Johnstone and Ólafsson 1995; Jiang *et al*. 2020; Visch *et al*. 2020; Hancke *et al*. 2021). On the west coast of Sweden, a maximum of 40 per cent light attenuation occurred at 5 m depth under a 2-hectare seaweed farm[70], but there were no negative effects on dissolved nutrients or biodiversity (Visch *et al*. 2020) (Appendix A, Table A4). A study of open water seaweed farming in Norway found no effects of small farms (0.4–4 hectares) on the growth of phytoplankton or the local availability of nutrients (Hancke *et al*. 2021). In Zanzibar, there were no significant reductions in bacterial production, bacterial abundance, or primary productivity in the water column beneath seaweed farms in a region with greater than 100 hectares of farms (Johnstone and Ólafsson 1995). In a study in China, seaweed farming[71] yielded increased phytoplankton diversity due to increased water clarity in the vicinity of the farm (Jiang *et al*. 2020).

Modelling studies of ocean nutrients indicate the potential for nutrient competition between seaweed farms and wild

[70] *Saccharina latissima*

[71] *Saccharina japonica*

ecosystems (Shi *et al*. 2011; Aldridge *et al*. 2012; Stephens *et al*. 2014). For example, a modelling study in China indicated competition between farmed kelp and phytoplankton for dissolved inorganic nitrogen at a typical farm site (Shi *et al*. 2011). The seaweed farm also decreased water flow from the open ocean[72], which could further affect nutrient supplies (Shi *et al*. 2011) (Appendix A, Table A4). A modelling study of an approximately 20 square kilometer seaweed farm in Scotland showed a significant reduction in phytoplankton productivity, indicating the potential for nutrient competition between farmed seaweed and phytoplankton in nutrient-limited waters (Aldridge *et al*. 2012). Reduced phytoplankton productivity could alter natural carbon flux to deep waters and energy flow to higher trophic levels[73] (Bach *et al*. 2021; NASEM 2021). Modelling also indicated the potential for kelp farms in Scotland to compete with wild kelp forests for nutrients at a site level (Stephens *et al*. 2014).

Benthic organisms such as seagrasses may be more affected than phytoplankton by light and nutrient competition at seaweed farms, as phytoplankton drifts through the farm and is exposed to farm conditions only temporarily while seagrasses are continuously exposed to farm conditions (Campbell *et al*. 2019). Decreased seagrass biomass under seaweed farms in Zanzibar has been linked to shading and nutrient competition in multiple studies (Eklöf *et al*. 2005; Eklöf *et al*. 2006a). Yet, one study found no difference in seagrass growth or photosynthetic performance under farms versus at reference sites, and it is possible that mechanical abrasion or deliberate removal of seagrasses by farmers were the cause of reduced seagrass abundance in this case (Lyimo *et al*. 2006). Removal of seagrasses to initiate seaweed farming has, for instance, been documented in Zanzibar (Trono 1992; Eklöf *et al*. 2012; Kelly *et al*. 2020). Additional research should act to clarify the primary driver(s) of negative habitat effects of seaweed farming on seagrass ecosystems.

Site-specific field studies and additional modelling of nutrient budgets and hydrodynamical-biological coupling are needed to clarify the nutrient relationship between seaweed farms and wild ecosystems (Campbell *et al*. 2019). Such information could aid in siting seaweed farms to avoid the depletion of nutrients and to mitigate nutrients from aquaculture, agriculture, or urban wastewater (Campbell *et al*. 2019). The effects of habitat competition also should be quantified at levels of entire marine populations, communities, and ecosystems. In the meantime, researchers recommend that seaweed farming employ a precautionary approach of not placing farms over habitats dominated by native primary producers[74] (Campbell *et al*. 2019; Kelly *et al*. 2020; Eggertsen and Halling 2021) and establishing focused ecosystem monitoring programs, including for phytoplankton (Campbell *et al*. 2019).

3.2.2 *Spillover of Pathogens and Invasive Species*

Seaweed farming often involves the transfer of non-native seaweed species or strains to new farming areas. With this transfer, there is the potential for pathogens and invasive species to spread and impact wild ecosystems, particularly given the high rates of dispersal of biological material in the ocean (Valero *et al*. 2017; Wood *et al*. 2017; Campbell *et al*. 2019; Clark *et al*. 2021).

Although there are no known reports of pathogen spread from seaweed farms to the environment, facilitation of seaweed pathogens is nonetheless considered a high-risk impact driver of environmental change as seaweed farming expands (Campbell *et al*. 2019) and diseases are a primary cause of crop loss at seaweed farms (see section 4.1.2 *Crop Diseases and Pests*). Quarantine of seaweed seed prior to cultivation could prevent pathogen introduction (Kelly *et al*. 2020); however, the risk of disease spread is generally considered difficult to mitigate (Loureiro *et al*. 2015; Campbell *et al*. 2019; Msuya *et al*. 2022) (see section 4.2.4 *Global Biosecurity*).

The spread of invasive species from seaweed farms to the environment has been documented and represents a high-risk impact driver of environmental change as seaweed farming expands (Campbell *et al*. 2019). Farmed seaweed species/strains are often selected for their tolerance to local conditions and fast growth, and these are traits that increase their invasive risk (Valero *et al*. 2017). For example, in Hawaii, United States of America, a non-native seaweed[75] farmed for agar production in the 1970s escaped cultivation and now competes with local flora and fauna on coral reefs (Smith *et al*. 2004). In Panama, a non-native seaweed[76] was introduced for farming and now has high coverage[77] in seagrass, mangrove, and coral patch habitats where it smothers the native flora and fauna (Sellers *et al*. 2015) (Appendix A, Table A4). A non-native seaweed[78] has similarly overgrown and smothered reef-building corals in India (Chandrasekaran *et al*. 2008). As a result, farming of non-native carrageenophytes is banned in various countries, including Cuba, Columbia, and the Marshall Islands (Kelly *et al*. 2020). Non-native species also cannot be farmed in Europe or New Zealand, unless the invasive species is already present in the environment (Campbell *et al*. 2019; Cunningham *et al*. 2020).

[72] Surface currents decreased by 40 per cent
[73] For example, fisheries
[74] For example, seagrasses
[75] *Gracilaria salicornia*
[76] *Kappaphycus alvarezii*
[77] Greater than 30 per cent
[78] *Kappaphycus alvarezii*

Abandonment of seaweed biomass at decommissioned farms can increase the risk of species invasions (Campbell *et al*. 2019; Kelly *et al*. 2020). Yet, even if non-native seaweeds do not escape cultivation, they can still alter local ecosystems through indirect effects on species interactions (Stimson *et al*. 2001). For example, in Hawaii, farmed non-native seaweed[79] attracts herbivorous fishes away from coral reefs, reducing the grazing pressure on other invasive seaweeds that compete with corals (Stimson *et al*. 2001). Moreover, native seaweed species that escape from cultivation and colonize local wild habitats, such as coral reefs, can also pose a problem where nutrient loading facilitates fast seaweed growth or native herbivores that control seaweed growth are patchily distributed or have declined[80] (Kelly *et al*. 2020).

Recurrent large-scale[81] green tides have occurred in the Yellow Sea since 2007, partially attributed to intensive seaweed farming[82] and the release of epiphytes[83] into the ocean as a byproduct during harvesting (Liu *et al*. 2009; Hu *et al*. 2010; Xing *et al*. 2019, but see Pang *et al*. 2010; Duan *et al*. 2012). Ocean disposal of epiphytes from seaweed farms also occurs in the tropics, but the environmental risks there have not been assessed (Mariño *et al*. 2019). The cost to remediate a 2008 green tide in China[84] was almost twice the annual value of the seaweed farming[85] industry (USD 53 million) (Hu *et al*. 2010). Research indicates that green tides can be minimized through improved seaweed farming management practices, including harvesting rather than discarding epiphytes (Xing *et al*. 2019).

In China, a non-native kelp[86] escaped from cultivation and is now considered to play an important ecological role on shallow rocky reefs as a habitat former (Shan *et al*. 2019). By contrast, a kelp[87] native to Asia and intensively farmed in China, Japan, and Korea, is considered a major nuisance invasive species globally (Epstein and Smale 2017). The primary modes of introduction are believed to have been on ship hulls and by shellfish aquaculture, aside from a single known introduction event through seaweed farming in Brittany, France (Epstein and Smale 2017). Following its colonization of habitats, the non-native kelp[88] has been considered as a possible option for seaweed farming (e.g., in New Zealand) (Cunningham *et al*. 2020). Yet, farming of established invasive species could still be problematic when it undermines attempts to curb regional spread (Campbell *et al*. 2019).

Additional research is needed to determine the frequency of spillover of pathogens and invasive species from seaweed farms to the environment (Campbell *et al*. 2019; Kelly *et al*. 2020). The risk of these events could in the meantime be reduced by limiting farming to native seaweed species/strains, and this will require identification of new seaweeds for commercial production (Campbell *et al*. 2019). Strategic siting of seaweed farms and preventative ecosystem management practices also could act to mitigate these risks (Kelly *et al*. 2020).

3.2.3 *Genetic Pollution*

The high rate of dispersal of material in the ocean could facilitate gene flow from farmed to wild seaweed populations, leading to maladaptation (Valero *et al*. 2017; Wood *et al*. 2017; Campbell *et al*. 2019; Clark *et al*. 2021). Moreover, farmed seaweeds that have undergone artificial selection could escape from farms and colonize local habitats, outcompeting wild seaweeds (Valero *et al*. 2017). As a result, the release of reproductive materials from seaweed farms is considered a high-risk impact driver of environmental change as seaweed farming expands (Campbell *et al*. 2019).

Genetic pollution from farms to the wild is poorly studied and limited data exist (Loureiro *et al*. 2015; Valero *et al*. 2017; Campbell *et al*. 2019). In China, a study of an extensively farmed kelp[89] found no marked effect in terms of gene flow of the farmed population on a historically introduced wild population (Zhang *et al*. 2017). This was similarly true for another kelp[90] farmed in China, where a wild population had nearly no genetic membership from farmed populations (Li *et al*. 2020). By contrast, kelp farming[91] in China has been negatively affected by gene flow from wild to farmed populations, as wild phenotypes are considered less desirable for farming (Shan *et al*. 2018).

The potential to mitigate genetic pollution is considered limited (Campbell *et al*. 2019). Thus, various researchers advocate for using locally sourced ecoregion-specific seaweed seed for farming (Campbell *et al*. 2019; Evankow *et al*. 2019; Clark *et al*. 2021; Hancke *et al*. 2021). The use of sterile seaweed strains should also be technologically feasible and could prevent genetic pollution if developed for widespread use (Campbell *et al*. 2019). The risk of genetic pollution also could be reduced by differences in

[79] *Kappaphycus*
[80] For example, due to overfishing
[81] Greater than 1000 square kilometers
[82] *Porphyra yezoensis*
[83] *Ulva*
[84] USD 100 million
[85] *Porphyra yezoensis*
[86] *Saccharina japonica*
[87] *Undaria pinnatifida*
[88] *Undaria pinnatifida*
[89] *Saccharina japonica*
[90] *Undaria pinnatifida*
[91] *Undaria* strains

the reproductive timing of wild and farmed populations through selective breeding of farmed strains (Shan *et al*. 2019) or harvesting of farmed seaweeds before they reach reproductive maturity (Clark *et al*. 2021). Yet, risks likely still exist under these circumstances (Campbell *et al*. 2019).

3.2.4 *Organic Matter Over-Deposition*

Over-deposition of seaweed organic matter on the seafloor has the potential to cause oxygen deficiency, toxic sulfide production, and the loss of seafloor fauna (Campbell *et al*. 2019; Clark *et al*. 2021; Hancke *et al*. 2021). Although studies of these effects are limited, over-deposition of organic matter is considered a low-risk impact driver of environmental change as seaweed farming expands given the incentive to minimize crop biomass loss at farms (Campbell *et al*. 2019).

A case study in Norway indicated that greater than 90 per cent of released kelp detritus[92] ended up on the seafloor within 4 kilometers of the seaweed farm but did not affect seafloor biodiversity (Hancke *et al*. 2021). However, a field experiment in the same region showed that the release of large quantities of kelp detritus onto the seafloor, simulating a predicted upper limit of export from kelp farms[93], led to a decrease in animal biodiversity likely due to oxygen depletion and toxic sulfide production (Hancke *et al*. 2021). Similarly, a study in Sandu Bay, China showed higher sedimentary acid volatile sulfide content[94] beneath a kelp farm[95] versus a control area, but the study found little effect of kelp farming on the benthic community, with stronger effects observed at fish farming locations (Zhou 2012) (Appendix A, Table A4). Beneath intensive kelp farms[96] in Sungo Bay, China, the effect on the benthic community was low and sediment oxygen conditions appeared unaffected (Zhang *et al*. 2009). A modelling study in China showed a strong stimulating influence of kelp farming on some benthic organisms (e.g., sea cucumbers), likely explained by energy subsidies to benthic communities in the form of kelp detritus (Wu *et al*. 2016). On the west coast of Sweden, no change in benthic oxygen flux was observed beneath a 2-hectare kelp farm[97] (Visch *et al*. 2020). Buschmann *et al*. (2014) also found no significant trend in organic matter over 3 years under a 21-hectare kelp farm[98] in Chile, and few kelp fronds were observed on the ocean bottom.

Dispersal of seaweed fragments away from farms by currents may act to dissipate the effects of organic matter over-deposition (Clark *et al*. 2021). Thus, differences in ocean currents across farming sites could lead to differences in the effects of seaweed farms on the benthos. There is a need for additional research to assess the environmental effects of organic deposition as a function of farm location and size (Wood *et al*. 2017; Campbell *et al*. 2019). It is expected that these effects will be mitigated in part by industry practices that limit the loss of harvestable biomass, such as strategic farm siting and harvest timing (Campbell *et al*. 2019). The co-culture of seaweeds with shellfish and sea cucumbers, which consume seaweed fragments, could also act to reduce seaweed deposition on sediments (Cottier-Cook *et al*. 2016).

3.2.5 *Marine Megafauna Entanglement*

Seaweed farming infrastructure may risk entangling marine megafauna[99], which can lead to drownings, and this is considered a high-risk impact driver of environmental change as seaweed farming expands (Campbell *et al*. 2019). The attraction of megafauna to seaweed farms also may increase negative human-wildlife interactions, for example with green turtles[100] that are considered a nuisance grazer in tropical carageenophyte farming (Kelly *et al*. 2020). Reports of entanglement events at seaweed farms are rare[101] but this could be due to a lack of reporting (Campbell *et al*. 2019). Risk of entanglement could be mitigated through proper farm planning and management, including siting farms away from foraging, reproduction, and migration areas and using infrastructure that minimizes entanglement risk (Campbell *et al*. 2019). Regulations should require that infrastructure is well maintained and fit for purpose to avoid accidental damage or loss that increases risks to marine megafauna (Campbell *et al*. 2019).

3.2.6 *Marine Pollution*

Synthetic polymer ropes, plastic ties, and other materials used in seaweed farming are designed to withstand degradation in the environment, and therefore have the potential to contribute to marine plastic pollution when discarded or lost (Campbell *et al*. 2019; Hurtado *et al*. 2019). Anecdotal reports indicate that some tropical seaweed farmers use empty plastic bottles as floats on seaweed lines, where lost/discarded materials may enter marine food webs (Campbell *et al*. 2019; Duarte *et al.* 2022a). However, plastic pollution is considered a low-risk impact driver of environmental change as seaweed farming expands that could be mitigated through mandatory reporting of infrastructure losses and the

[92] *Alaria esculenta* and *Saccharina latissima*
[93] More than 8 kilograms of fresh kelp per square meter
[94] 1.22 versus 0.14 milligram per gram dry weight
[95] *Saccharina japonica*
[96] *Saccharina japonica*
[97] *Saccharina latissima*
[98] *Macrocystis pyrifera*
[99] Such as marine mammals and turtles
[100] *Chelonia mydas*
[101] See Poonian and Lopez (2016) for an incident with a dugong

development of innovative material substitutes such as seaweed polymers (Campbell *et al*. 2019; Duarte *et al*. 2022a).

Noise pollution from machinery and increased vessel traffic is also considered a low-risk impact driver of environmental change as seaweed farming expands and can similarly be avoided by placing seaweed farms away from sensitive locations, such as marine mammal colonies (Campbell *et al*. 2019).

3.2.7 *Short-Lived Halocarbon Emissions*

Short-lived halocarbons deplete ozone in the troposphere and stratosphere, increasing harmful ultraviolet (UV) irradiance on the earth's surface. Seaweeds commonly farmed in the tropics emit high levels of bromocarbons, a type of halocarbon (Leedham *et al*. 2013). The risk level (high/medium/low) of halocarbon emissions as seaweed farming expands was not formally assessed in a recent review (Campbell *et al*. 2019).

At current farming scales in Malaysia and Southeast Asia, short-lived halocarbon emissions are considered small (Leedham *et al*. 2013). For bromoform, seaweed farming at current scales contributes only approximately 2 per cent of the estimated regional wild seaweed emissions (Appendix A, Table A4). Yet, upscaled seaweed farming could contribute a substantial proportion of regional wild seaweed emissions (up to 20 per cent), particularly if the primary farmed species are rhodophytes (Leedham *et al*. 2013) (Appendix A, Table A4). Placed in a global context, it is estimated that wild seaweeds in the tropics contribute only 2–9 per cent of the global short-lived halocarbon budget, suggesting a more substantial contribution by the open ocean, including phytoplankton (Leedham *et al*. 2013). Consistent with this, it has been argued that if seaweed farming were increased to 50 times the current area, overall short-lived halocarbon emissions would increase by only 1 per cent and are therefore of low concern (Duarte *et al*. 2022a) (Appendix A, Table A4). This may be a conservative estimate, as it assumes that farmed seaweeds emit similar levels of halocarbons as wild seaweeds, which is true only if a representative group of taxa are farmed (Duarte *et al*. 2022a).

Emissions of volatile gases such as iodine should also be considered as seaweed farming expands, specifically kelp farming. Large quantities of these may lead to the formation of cloud nuclei that affect climate and radiative forcing (Wood *et al*. 2017).

3.2.8 *Summary of Potential for Environmental Risks*

Various environmental risks are associated with seaweed farming, and although variation exists among farm sites, the greatest risks are likely nutrient depletion, spillover of pathogens and invasive species, genetic pollution, and entanglement of marine megafauna (Campbell *et al*. 2019; Clark *et al*. 2021) (Fig. 6). Aside from the spillover of pathogens and genetic pollution, the risks of seaweed farming could be lessened with currently available mitigation measures (Campbell *et al*. 2019). Following a review of literature focused on the European Union, Wood *et al*. (2017) recommended against the term environmental "impact" when referring to seaweed farming given the paucity of data for negative changes to marine populations in that region. They instead suggest the term environmental "effect", meaning a change in the environment, until further data on population level effects are collected (Wood *et al*. 2017). In accordance, Hoegh-Guldberg *et al*. (2019) state with "high confidence" that small-scale seaweed farming has low levels of environmental risks. However, environmental risks should be carefully assessed as seaweed farming scales expand. The extent of negative environmental effects are likely both site and scale dependent, and additional research is needed, particularly in data poor regions such as the tropics.

The evidence reviewed here on the potential for environmental risks of seaweed farming indicates various ***weaknesses*** of seaweed farming and ***threats*** for the future that should be protected against as seaweed farming expands.

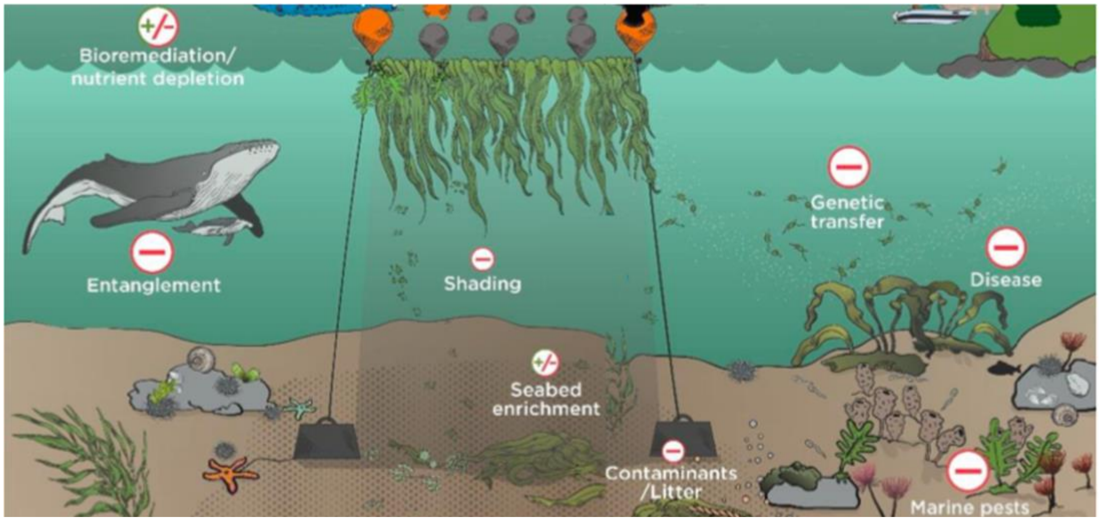


Fig. 6. Summary of the potential for environmental risks of seaweed farming, including nutrient and light depletion, spillover of pathogens and invasive species, genetic pollution, over-deposition of the seabed, marine megafauna entanglement, and marine pollution. Adapted from Clark *et al*. (2021) with permission.

3.3 Potential for Socioeconomic Co-Benefits

Various socioeconomic co-benefits may be associated with seaweed farming. In this section, information on these potential co-benefits is reviewed and contextualized, and knowledge gaps are identified.

3.3.1 *Income Generation and Diversification of Livelihoods*

Seaweed farming has provided a source of income that has diversified the livelihoods of coastal people in developing countries, including India, Indonesia, Kenya, Malaysia, the Philippines, the Solomon Islands, and the United Republic of Tanzania (Msuya *et al*. 2007; Krishnan and Kumar 2010; Msuya 2011a; Zamroni *et al*. 2011; Valderrama 2012; Cai *et al*. 2013; Nor *et al*. 2017; Steenbergen *et al*. 2017; Mirera *et al*. 2020). In Indonesia, the seaweed farming industry supports at least 267,000 households (Langford *et al*. 2021), in the Philippines at least 100,000–150,000 people (Hurtado 2013), in the United Republic of Tanzania at least 30,000 people (Msuya *et al*. 2022), and in India the industry is expected to support up to 200,000 households in the near-future (Krishnan and Kumar 2010) (Appendix A, Table A5). Overall, the global seaweed farming industry is estimated to support 6 million small-scale farmers and processors (Cottier-Cook *et al*. 2021) and creates employment opportunities across the value chain, including for local consolidators, small traders, and administrators[102] (Cai *et al*. 2013).

In coastal communities with high rates of poverty, the establishment of seaweed farming has been shown to increase standards of living and food security (Valderrama 2012; Cai *et al*. 2013). In particular, seaweed farming can provide supplemental income or an alternative and more stable livelihood to fishing where capture fisheries are overexploited (Smith and Pestano-Smith 1980; Padilla and Lampe 1989; Crawford 2002; Msuya 2011a; Zamroni *et al*. 2011; Valderrama 2012; Eklöf *et al*. 2012; Cai *et al*. 2013). Although labor-intensive, seaweed farming in developing countries has short production cycles with a relatively fast return on investment[103] and a low barrier to entry based on low capital costs and material requirements (Cai *et al*. 2013; Piconi *et al*. 2020; Neish 2021). This simple method practice is known as "adaptive phyconomy" (Neish 2021).

Establishment of seaweed farming may also reduce pressure on local fish stocks in areas of overexploited fisheries (Smith and Pestano-Smith 1980). However, due to continued fishing efforts made possible by differences in the timing of seaweed farming versus fishing and the recruitment of women into the seaweed farming workforce, several examples indicate that seaweed farming does not always lead to decreased fishing pressure (Crawford 2002; Sievanen *et al*. 2005; Hill *et al*. 2012). Seaweed farming has benefited women in coastal developing countries by providing an employment opportunity where income opportunities for women are otherwise limited (Sievanen *et al*. 2005; Msuya 2011a; Valderrama 2012) (see section 3.3.2 *Gender Equity*).

Nonetheless, seaweed farming is considered a low-income livelihood, and farmers in coastal developing regions can be at risk of poverty or extreme poverty when the industry is not appropriately managed (Krishnan and Kumar 2010; Fröcklin *et al*. 2012; La Ode *et al*. 2018; Mariño *et al*. 2019). Measures to mitigate such risks and protect farmers against low income exist, and when in place, can enhance the socioeconomic sustainability of seaweed farming (see section 3.4.2 *Low Income*).

3.3.2 *Gender Equity*

Seaweed farming contributes to gender equity by providing women with an accessible employment opportunity (Msuya 2011a). Employment as seaweed farmers has reportedly given women recognition and power within society and their families in various coastal developing countries, including India, Indonesia, Kenya, and the United Republic of Tanzania (Msuya 2011a; Zamroni *et al*. 2011; Periyasamy *et al*. 2014; Mirera *et al*. 2020; Larson *et al*. 2021).

Establishment of seaweed farming industries dominated by women in Zanzibar and Kenya (75.2–90 per cent women) has generated training opportunities for women to develop entrepreneurial and business skills and create value-added products[104] that can substantially increase income (Msuya 2011a; Eklöf *et al*. 2012; Mirera *et al*. 2020) (Appendix A, Table A5). Shallow water seaweed farming in India is also dominated by women and provides an opportunity for income in what is considered a generally safe environment (Cai *et al*. 2013). Membership of women in India in so-called "self-help groups" has led to the implementation of best practices that substantially increase seaweed farming income (Periyasamy *et al*. 2014). However, as women farmers are often limited to shallow water due to a lack of training on boats or swimming skills, their crops may be at particularly high risk from diseases and pests that are linked to warming sea temperatures (UNEP 2022) (see sections 4.1.2 *Crop Diseases and Pests* and 4.1.4 *Climate Change*).

A study in Indonesia indicates that the equity effects brought about by seaweed farming have improved the life satisfaction of both seaweed farmer and non-farmer

[102] At laboratories and government offices
[103] Within months

[104] Such as seaweed soaps and lotions

women (Larson *et al*. 2021). Children also tend to have roles on small-scale seaweed farms alongside their mothers or family members (Cai *et al*. 2013). While this does not appear to lead to exploitation or abuse, time spent working on the seaweed farm may detract from the children's education (Cai *et al*. 2013). Alternatively, children from families that enter into seaweed farming may be more likely to continue with their secondary and tertiary education due to an increase in household income that enables families to pay school fees (Steenbergen *et al*. 2017; Mirera *et al*. 2020; Larson *et al*. 2021).

Given the generally positive effects of small-scale seaweed farming on women in coastal developing countries, it is important that upscaling of seaweed farming does not displace existing farmers (Larson *et al*. 2021). For example, an unmanaged offshore expansion of seaweed farming in coastal developing regions could exclude many women who are untrained to handle boats or swim (UNEP 2022).

Although research is limited, there is evidence that seaweed farming also can enhance gender equity in developed countries, such as the United States of America (McClenachan and Moulton 2022). In the state of Maine, there was at least 4 times greater participation by women in seaweed farming than in wild-caught fisheries due to factors including flexible working hours (McClenachan and Moulton 2022). Gender equity may be enhanced as seaweed farming replaces the declining wild-caught fisheries that are male dominated (McClenachan and Moulton 2022).

To ensure development of an equitable seaweed farming industry, it is important to recognize the relevance of gender and social inclusion and address the different needs of women and men seaweed farmers by using gender disaggregated data in decisions (Asri *et al*. 2022). This will help develop understanding of how different farmers respond to different economic, environmental, and health risks (Asri *et al*. 2022).

3.3.3 *Nutrition and Global Food Security*

Seaweed farming can deliver indirect and direct benefits for nutrition (Cai *et al*. 2013). In impoverished regions, the establishment of a small-scale seaweed farming industry can improve nutrition indirectly by providing income that increases food security (see section 3.3.1 *Income Generation and Diversification of Livelihoods*). In regions where seaweeds are broadly consumed by humans[105], seaweeds provide high-quality food that is rich in nutrients and contains the only non-fish source of natural omega-3 long-chain fatty acids (Radulovich *et al*. 2015b; Wells *et al*. 2017; FAO 2020; Mouritsen *et al*. 2021). Yet, while seaweeds are rich in calcium, iodine, iron, magnesium, phosphorus, potassium, selenium, and zinc (Forster and Radulovich 2015), they can also contain dangerous levels of heavy metals that must be carefully monitored and regulated (see section 3.4.1 *Adverse Health Effects*).

Importantly, seaweeds concentrate iodine, which is an essential micronutrient for healthy pregnancy, childhood development, and thyroid function (WHO 2004). In 54 countries around the world, the population is considered iodine deficient (WHO 2004). Zheng *et al*. (2019) found that seaweed farming in China produced a total of 4,954 kilograms of iodine per square kilometer farmed per year (Appendix A, Table A5). Based on the dietary recommendations for iodine, this production is sufficient to support approximately 100 billion people for a year, meaning that only a small amount of seaweed production needs to be allocated to iodine to support human health (Zheng *et al*. 2019). A modelling study in the Netherlands and Portugal recorded a near doubling of iodine intake when seaweeds replaced 10 per cent of the human diet, and this increase was considered beneficial to the populations (Vellinga *et al*. 2022) (Appendix A, Table A5). However, excessive intake of iodine from a seaweed rich diet has the potential for adverse health effects and should therefore be monitored alongside heavy metals, and guidance and recommendations for intake are needed (Banach *et al*. 2020).

Future global expansion of seaweed farming has the potential to assist in meeting the nutritional requirements of the growing human population for complex carbohydrates, proteins, fats, and other organic nutrients (Forster and Radulovich 2015). Seaweed farming could become particularly relevant for global food security as resources for land-based agriculture become increasingly limited and global requirements for food continue to expand (Forster and Radulovich 2015). Currently, aquaculture is focused on growing marine animals for human consumption and these animals are in at least the second trophic level of the food chain, while seaweed is in the first trophic level (Forster and Radulovich 2015). Given that approximately 90 per cent of energy from primary producers is lost with each step up the food chain (Fig. 7), shifting from animal to seaweed-based aquaculture food production has the potential to provide significant increases in food energy (Forster and Radulovich 2015).

[105] For example, China and Japan

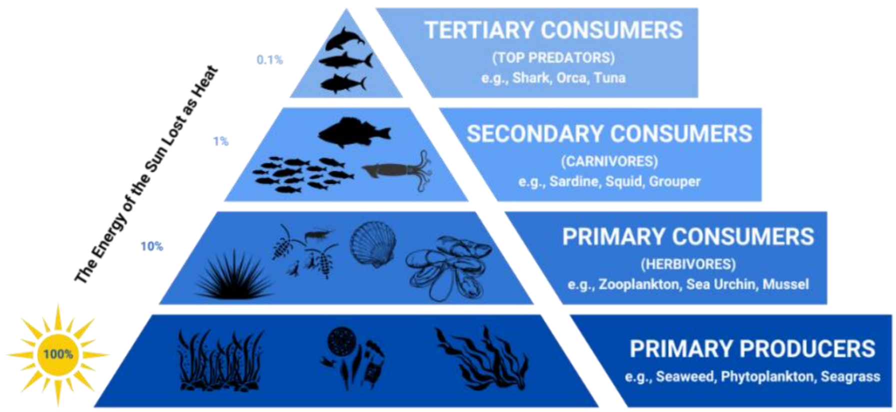


Fig. 7. Trophic levels. Illustration of the loss in energy from producers to primary consumers where 90 per cent is lost in 1 step. Credit: UNEP

The potential health benefits of consuming seaweeds range from regulation of blood sugar and cholesterol levels to promotion of intestinal health and gut microbiota (Jaspars and Folmer 2013; Cherry *et al*. 2019). Yet, based on the mechanisms by which some of these benefits occur[106], the benefits may be disproportionately felt by well or overfed populations rather than those that are undernourished. As a result, the bioavailability of nutrients in seaweeds should be closely examined when evaluating their nutritional value to various populations, and when considering seaweeds as a food to address global food security (Forster and Radulovich 2015; Wells *et al*. 2017; FAO and WHO 2022). The nutritional composition of seaweeds varies with species, region, and season, as well as the method of harvesting, holding, and processing, and therefore, research is needed to assess the dietary value of seaweeds across a range of factors (Wells *et al*. 2017; FAO and WHO 2022). Moreover, consumer willingness to eat seaweeds must be considered, particularly in western societies that do not currently have high intake rates (see section 4.2.5 *Market and Product Development*). Thus, work remains underway to fully establish the potential for seaweeds as a global food source (FAO and WHO 2022).

3.3.4 *Cultural Services*

The cultural services provided by coasts can include recreation, aesthetic value, science and education, cultural heritage, inspiration, and natural heritage (TEEB 2010). Seaweed farming may contribute to cultural services when it reinvigorates coastal villages that were in decline due to a shift in fisheries from small to large scale (Hasselström *et al*. 2018). An example is in Sweden, where seaweed farming has inspired research, business ideas, and sustainability innovations (Hasselström *et al*. 2018). Seaweed farming may also provide non-use cultural services when the perception of farming is that it contributes positively to the local environment and economy (Hasselström *et al*. 2018).

In coastal developing countries, small-scale seaweed farming is reported to increase social cohesion through cooperation among seaweed farming families (Cai *et al*. 2013; Hurtado 2013; Kronen 2013). Seaweed farming can also lead to collaboration at a global scale (Hwang *et al*. 2020). For example, a global demand for agar from farmed seaweeds prompted collaboration among 14 countries on research towards the seaweed *Gelidium*, a primary agar-producing taxon (Hwang *et al*. 2020). The project involved Belgium, Canada, Chile, China, Germany, India, Japan, the Netherlands, the Democratic People's Republic of Korea, the Russian Federation, the Republic of Korea, Spain, the United Kingdom of Great Britain and Northern Ireland, and the United States of America (Hwang *et al*. 2020). The seaweed farming industry can, however, be considered a nuisance to other coastal industries and activities (e.g., due to aesthetic changes to the seascape), and therefore resistance from local stakeholders can present a major obstacle to seaweed farm development that requires careful consideration (see section 3.4.3 *Spatial Use Conflicts*).

To ensure the broadest socioeconomic benefits of seaweed farming, the industry should be developed in a manner that is gender-sensitive and inclusive, supporting farmers' diverse needs (Ramirez *et al*. 2020). This will ensure that both women and men seaweed farmers have equitable access to seaweed farming resources and markets (Ramirez *et al*. 2020). The differing benefits, risks, and vulnerabilities of women and men in seaweed farming

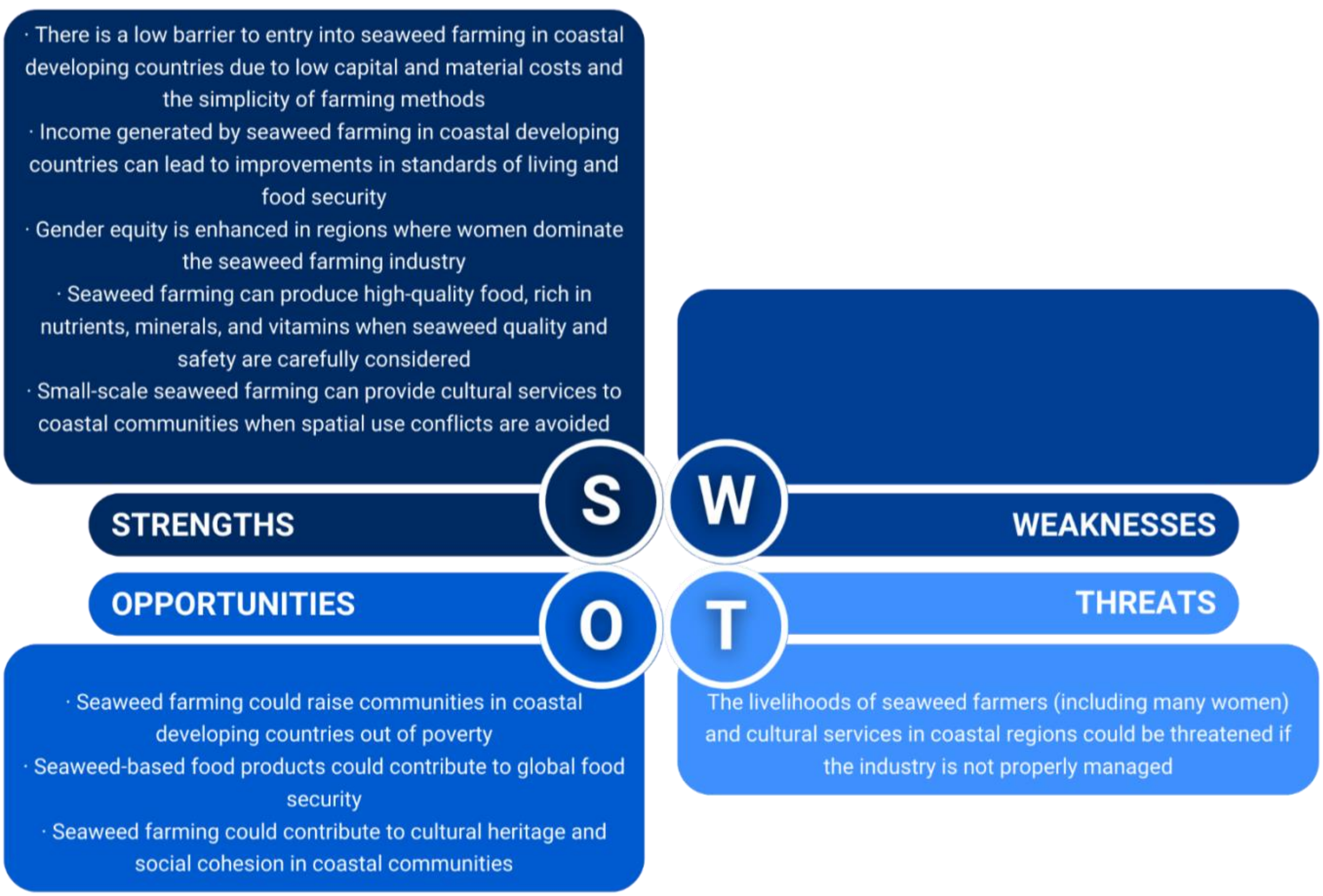
[106] For example, low protein digestibility and high soluble dietary fiber

is crucial (Asri *et al*. 2022). A better understanding of the benefits and risks seaweed farmers face could help in determining their constraints and identifying coping strategies to increase benefits and reduce risks (Asri *et al*. 2022). This could further inform policies and development programs to achieve the UN SDGs and Agenda 2030 (Asri *et al*. 2022).

3.3.5 *Summary of the Potential for Socioeconomic Co-Benefits*

Most studies of the socioeconomic benefits of seaweed farming have occurred in coastal developing countries and focus on small-scale community-based seaweed farming. These studies indicate generally positive outcomes for income and the diversification of livelihoods, which lead to increased standards of living, food security, and gender equity (Msuya *et al*. 2007; Krishnan and Kumar 2010; Msuya 2011a; Zamroni *et al*. 2011; Valderrama 2012; Cai *et al*. 2013; Periyasamy *et al*. 2014; Nor *et al*. 2017; Steenbergen *et al*. 2017; Mirera *et al*. 2020; Larson *et al*. 2021). Yet, low income can remain a risk for seaweed farmers (Eklöf *et al*. 2012). While seaweeds provide a source of food with the potential to contribute to global food security, limitations to the nutritional quality of some seaweeds and the presence of contaminants must be considered (Cai *et al*. 2013; FAO and WHO 2022). Seaweed farming may also provide cultural services to humans, including enhanced cultural heritage and social cohesion but risks such as spatial use conflicts must be avoided (Cai *et al*. 2013; Hurtado 2013; Kronen 2013; Hasselström *et al*. 2018; Hwang *et al*. 2020; Clark *et al*. 2021).

The evidence reviewed here on the potential for socioeconomic benefits of seaweed farming indicates several ***strengths*** of seaweed farming and ***opportunities*** that can be taken advantage of in the future. Additionally, a ***threat*** has been identified that if protected against in the future could maximize the socioeconomic benefits of seaweed farming expansion.



3.4 Potential for Socioeconomic Risks

Various socioeconomic risks may be associated with seaweed farming, and these risks should be weighed when considering the sustainability of expanded seaweed farming. In this section, information on these potential risks is reviewed and contextualized, and the possible mitigation measures are discussed.

3.4.1 *Adverse Health Effects*

Human health risks have been reported in relation to seaweed farming and seaweed foods (Fröcklin *et al*. 2012; Cai *et al*. 2013; Bruhn *et al*. 2016; Banach *et al*. 2020; Vellinga *et al*. 2022). For example, in Zanzibar, various health conditions occurred at a higher incidence in women seaweed farmers than non-farmers, including fatigue, respiratory problems, general eye problems due to exposure to sun and glint, parasites, and injuries from animal hazards in the water such as sea urchins (Fröcklin *et al*. 2012). Children were also reported to show adverse health responses when seaweeds were stored in the home, potentially due to toxic vapors from hydrogen peroxide and halogenated compounds produced while seaweeds dry (Fröcklin *et al*. 2012). In general, there are limited studies on the health effects of the seaweed farming livelihood, indicating an area of future research need (Fröcklin *et al*. 2012; Cai *et al*. 2013).

The accumulation in seaweeds of heavy metals, such as cadmium and inorganic arsenic, presents a health risk when seaweeds are grown in contaminated waters and should be closely monitored and regulated for human consumption (Forster and Radulovich 2015; Duarte *et al*. 2017; Banach *et al*. 2020). While studies of heavy metal concentrations in seaweeds farmed for human consumption are limited, a study in Spain found that cadmium concentrations in most of the 9 seaweed species regionally commercialized for consumption[107] exceeded the safety standards stipulated in legislation in France– one of the few European countries with legislation specific to seaweed consumption (Besada *et al*. 2009) (Appendix A, Table A6). Inorganic arsenic levels were also above the limit for one species[108] (Besada *et al*. 2009) (Appendix A, Table A6). A study of seaweed food products[109] imported to the United Kingdom of Great Britain and Northern Ireland showed high levels of inorganic arsenic in samples of hijiki seaweed[110], particularly when the preparation instructions on the packaging were not followed, such as soaking the seaweed prior to consumption (Rose *et al*. 2007) (Appendix A, Table A6). A modelling study in the Netherlands and Portugal examined the effects on food safety of a 10 per cent replacement of the human diet with seaweed and found no effects on sodium intake or cadmium, lead, and mercury exposure, but recorded an increase in arsenic exposure that exceeded the benchmark dose lower confidence limit (Vellinga *et al*. 2022) (Appendix A, Table A6). Farm location is likely an important consideration for heavy metal exposure, and location-appropriate safety standards should be implemented to mitigate the risk of human exposure to toxic substances (Bruhn *et al*. 2016; Banach *et al*. 2020).

Exposure to excess iodine from consumption of seaweeds is also a concern, particularly for high-risk groups such as pregnant and breastfeeding women (FAO and WHO 2022). Moreover, seaweeds consumed in uncooked raw form, for example in salads, may pose a health risk due to microbiological hazards (FAO and WHO 2022).

3.4.2 *Low Income*

As a natural resource and commodity traded on the global market, seaweed production and prices can be volatile, affecting the economic well-being of seaweed farmers (Valderrama 2012; Valderrama *et al*. 2013). Accordingly, income below the poverty and extreme poverty line has been reported by seaweed farmers in Indonesia (La Ode *et al*. 2018; Mariño *et al*. 2019) and the United Republic of Tanzania (Fröcklin *et al*. 2012).

Low income has been linked to the low value placed on seaweeds caused in part by monopolistic buyers who reduce the power of farmers to negotiate prices (Cai *et al*. 2013). Low income is further exacerbated by low farm productivity caused by crop diseases and pests and a lack of informational and material resources for farmers (Eklöf *et al*. 2012; Cai *et al*. 2013; La Ode *et al*. 2018; Mariño *et al*. 2019; Msuya *et al*. 2022; UNEP 2022) (see section 4.1.2 *Crop Diseases and Pests*). Farmers may lack information on appropriate site selection, cultivation techniques, and harvest/post-harvest practices (UNEP 2022). Farmers can be heavily dependent on the farming materials provided by buyers, which compromises the capacity of farmers to negotiate seaweed prices (Msuya *et al*. 2007; Zamroni *et al*. 2011). Profit maximization by global companies can also decrease farmer income indirectly by lowering pay to exporters who then pay less to farmers and provide fewer free materials which is a tactic initially used as an incentive for coastal communities to start farming seaweeds (Eklöf *et al*. 2012).

Under poor management, small-scale seaweed farming can have transitory socioeconomic benefits, displaying a boom-and-bust pattern (Smith and Pestano-Smith 1980; Steenbergen *et al*. 2017). This occurs when rapid

[107] Likely sourced from both farming and wild harvest
[108] *Hizikia fusiforme*
[109] Likely sourced from both farming and wild harvest
[110] Scientific name not given

expansion of farming leads to seaweed overproduction and a concomitant price drop (Smith and Pestano-Smith 1980). It can also occur when farming overwhelms the carrying capacity of the local environment such that production declines (Steenbergen *et al*. 2017). For example, in Hingotanan, Philippines, the establishment of a seaweed farming industry increased the number of middle-class households in the community within a year but the benefits to seaweed farmers collapsed when high seaweed production drove down prices (Smith and Pestano-Smith 1980). Given the cultural changes that occur following the establishment of a seaweed farming industry, such as greater reliance on a cash economy for food, it can be difficult for households to shift back to less reliable, alternative livelihoods[111] (Steenbergen *et al*. 2017).

When seaweed farming income is low, feedback mechanisms may lock seaweed farming into a "low-income state" (Eklöf *et al*. 2012) (Fig. 8). For example, low farmer income can drive farmers to increase seaweed stocking densities, increasing the incidence of diseases that decimate the crop, further driving down income (Eklöf *et al*. 2012). Additionally, low farmer income can disincentivize farming as a livelihood, leading farmers to produce less seaweed and increasing the costs to export companies, which respond by paying farmers less for their product and further disincentivizing farming (Eklöf *et al*. 2012) (Fig. 8).

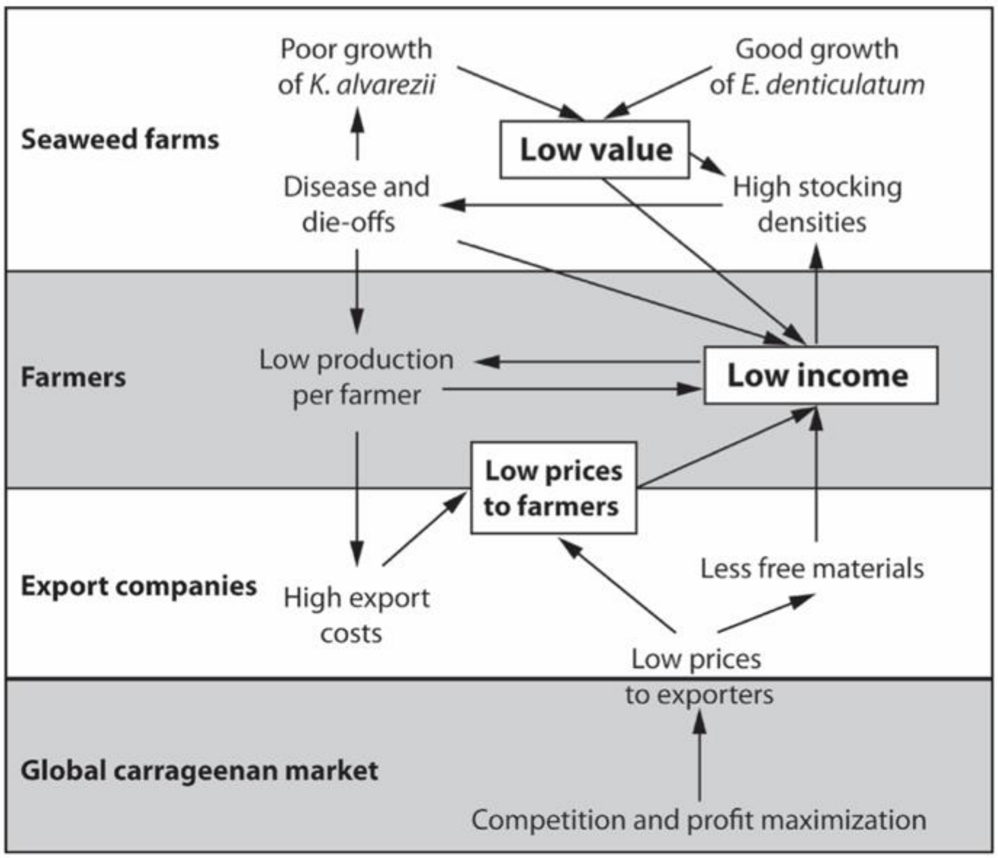


Fig. 8. Feedback mechanisms resulting from interactions between environmental and economic factors that may lock seaweed farming into a "low-income state". Reproduced from Eklöf *et al*. (2012) with permission.

[111] Such as capture fisheries

Low income may be mitigated in part through product diversification that adds value to seaweeds, or small government loans to seaweed farmers, provided that the loan payment schedule is consistent with the production and sale cycle of seaweeds (Msuya *et al*. 2007). Notably, production of seaweeds for direct consumption commands greater prices than processing for carrageenan, but currently the latter dominates the industry in poor rural areas of developing countries (Buschmann *et al*. 2017). Over 80 per cent of carrageenan produced globally is used in only 3 types of products: processed meats, dairy, and desserts and jellies, and approximately 50 per cent of seaweed dry matter from single-stream carrageenan production is wasted (Hurtado *et al*. 2019). Diversification with high value products via a biorefinery concept has the potential to increase the income of thousands of small-scale farmers in poor rural areas (Fernand *et al*. 2017) (Appendix A, Table A5). For example, in the United Republic of Tanzania, only approximately 1 per cent of seaweed production is used in value-added products, including cosmetics and food, but where present, this activity has substantially increased the economic viability of seaweed farming (Msuya *et al*. 2022) (see section 4.2.5 *Market and Product Development*).

Community or government management may increase the economic viability of the seaweed farming industry (Smith and Pestano-Smith 1980; Nor *et al*. 2017; Msuya *et al*. 2022). For example, in Zanzibar, establishment of a farming cooperative enhanced the sales and profits from seaweeds and seaweed-based products for some farmers (Msuya 2011a). By contrast, in Malaysia, an attempt by the government to establish a seaweed cooperative was viewed as generally unsuccessful due to the exclusion of indigenous seaweed farmers, a lack of acceptance of new technology by farmers, and a lack of participation by farmers in decision making (Nor *et al*. 2017). However, the program had the benefits of increasing the social status of farmers and reducing operating costs (Nor *et al*. 2017). Full integration of local indigenous seaweed farmers into the conception and implementation of community and government programs will be crucial for such programs to be successful (Nor *et al*. 2017).

Training programs intended to transfer technical knowledge to seaweed farmers should provide flexible training schedules that accommodate the domestic duties of women given their large role in the industry (UNEP 2022). Programs for job skills training should specifically target local women's groups to prepare women seaweed farmers to respond to environmental change[112] and build capacity[113] (Brugere *et al*. 2020). Priority should be placed on effectively training women in novel seaweed farming techniques to overcome crop losses in order to empower women seaweed farmers and secure their livelihoods (Brugere *et al*. 2020).

3.4.3 *Spatial Use Conflicts*

Spatial use conflicts are an important socioeconomic risk factor when considering the placement of seaweed farms (Cabral *et al*. 2016). Indeed, there is evidence that the positive effects of seaweed farms on ecosystem services tend to occur at regional scales, while negative effects tend to occur at local scales (Hasselström *et al*. 2018). This has the potential to negatively affect the well-being of coastal communities and drive local resistance to seaweed farming (Hasselström *et al*. 2018). Accordingly, a 300-hectare seaweed farming project in the Normand-Breton Gulf region of France was put on hold, despite administrative approval, due to resistance from the local community (Cabral *et al*. 2016). Similarly, in the United States of America, resistance to seaweed farming has occurred due to the so-called "NIMBY" (Not in My Backyard) phenomenon, wherein farms lack the social license to operate (Kim *et al*. 2019). A study in Scotland showed that local stakeholders are more amenable to the development of seaweed farming when it focuses on a small-scale approach that provides local benefits, such as job creation, rather than a large-scale multi-nationally owned seaweed farming industry (Bjørkan and Billing 2022).

Spatial use conflicts can arise due to negative effects of seaweed farming on cultural services, such as recreation, tourism, and the aesthetic value of the coastline, due to physical changes or noise pollution from farms (Wood *et al*. 2017; Hasselström *et al*. 2018). For example, beach cast seaweed may impact tourism due to the appearance and smell (Wood *et al*. 2017), and buoys may cause undesirable visual changes to the seascape (Hasselström *et al*. 2018). To avoid conflict with local stakeholders, evidence-based decision making should be supplemented with informed discussions with local stakeholders at an early stage and throughout the farm development process (Cabral *et al*. 2016). Some negative effects can be mitigated. For example, white or gray, rather than brightly colored buoys, can diminish the visual footprint of a farm (Hasselström *et al*. 2018). A marine spatial planning (MSP) approach also can be used to identify the development sites least likely to conflict with other human uses (Cabral *et al*. 2016) (see section 4.2.1 *Marine Spatial Planning*).

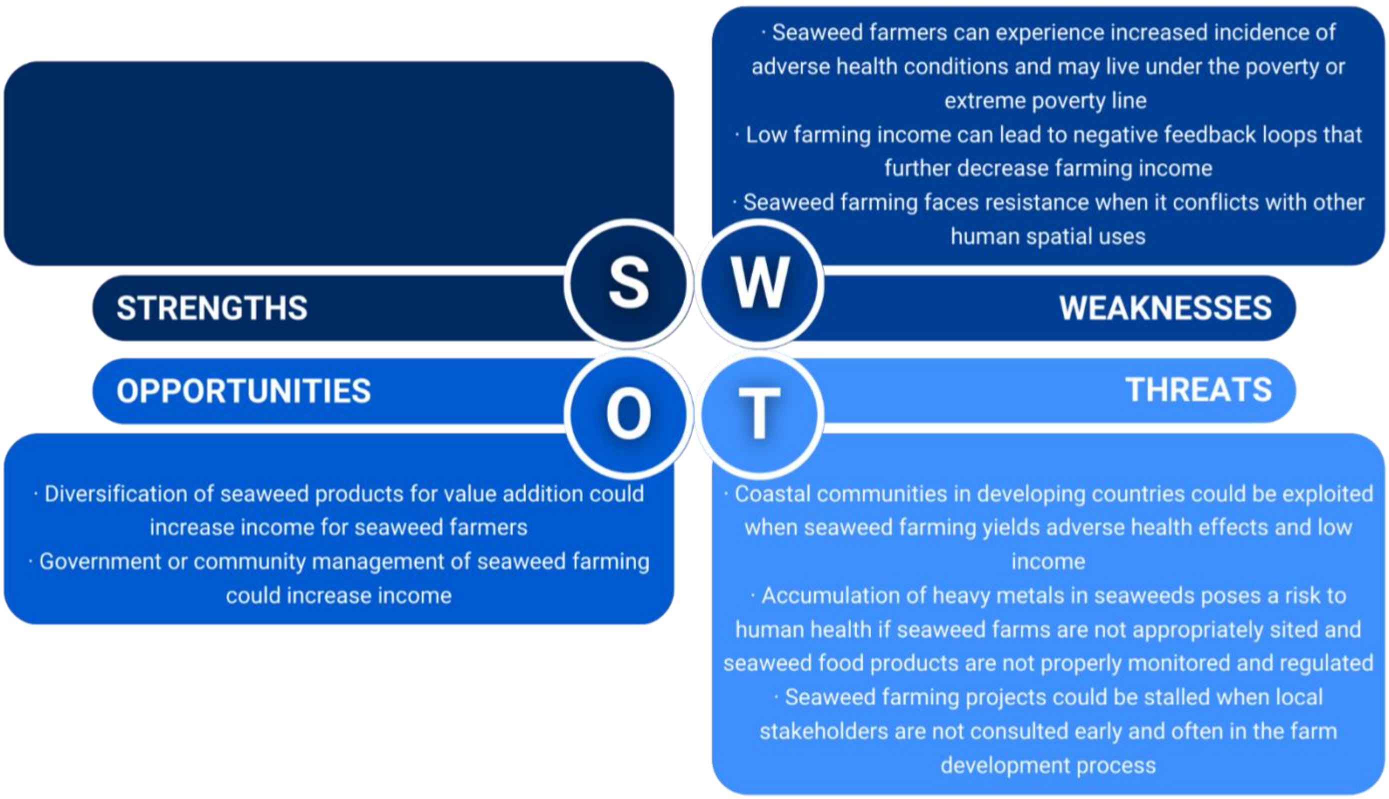
[112] For example, training in basic sea survival for offshore seaweed farming

[113] For example, on seaweed health and farming techniques

3.4.4 Summary of Potential for Socioeconomic Risks

The socioeconomic risks of seaweed farming include adverse health effects, low income, and human use conflicts. Some of these risks could be mitigated through community and government interventions, such as cooperatives, training programs, and regulations that fully integrate local stakeholders, including women seaweed farmers (Smith and Pestano-Smith 1980; Msuya 2011a; Forster and Radulovich 2015; Cabral *et al*. 2016; Nor *et al*. 2017; Banach *et al*. 2020; UNEP 2022). The health impacts of the seaweed farming livelihood remain poorly understood and further research is needed to determine how best to mitigate risks to workers (Fröcklin *et al*. 2012).

The evidence reviewed here on the potential for socioeconomic risks of seaweed farming indicates several ***weaknesses*** of seaweed farming and ***threats*** for the future that should be protected against. Additionally, several ***opportunities*** have been identified that if taken advantage of could increase the socioeconomic sustainability of expanded seaweed farming.



PART 4: FEASIBILITY OF UPSCALING GLOBAL SEAWEED FARMING PRODUCTION

4.1 Biophysical Factors that Limit Seaweed Farming Production

In addition to the environmental and socioeconomic risks of seaweed farming that may present barriers to sustainable farming (see sections 3.2 *Potential for Environmental Risks* and 3.4 *Potential for Socioeconomic Risks*), various biophysical factors can be major determinants of the production capacity of seaweed farming. In this section, information on these factors is reviewed to provide context for the potential limits to future upscaling.

4.1.1 *Conditions Required by Seaweed Crops*

The environmental conditions required by seaweed species for growth vary greatly (Campbell *et al*. 2019). As a result, the global ocean contains many locations from the tropics to the poles that are suitable for seaweed growth (Duarte *et al*. 2022b) and potentially, seaweed farming (Froehlich *et al*. 2019).

Based on the availability of adequate nutrients and temperature as the only constraints, it is estimated that 48 million square kilometers of the ocean could theoretically support seaweed farming (Froehlich *et al*. 2019). This area estimate does not consider ocean currents and waves that can affect seaweed growth, or environmental and socioeconomic risk factors such as the displacement of marine habitats and spatial use conflicts (Froehlich *et al*. 2019). Moreover, it is likely considered undesirable to alter such large swaths of ocean area, as has occurred in agriculture on land (Froehlich *et al*. 2019). At the current industry growth rate[114], it would take approximately 2 centuries to reach a 48 million square kilometer farmed area, an area 10-fold greater than the estimated distribution of wild seaweed habitats (Duarte *et al*. 2022a). This is also considerably larger than the estimated 220,000 square kilometers required to produce 440 megatons of seaweeds[115] and contribute significantly to global food security (Forster and Radulovich 2015).

Variability in environmental conditions can have a large effect on farmed seaweed productivity (Bruhn *et al*. 2016; Forbord *et al*. 2020; Largo *et al*. 2020). For example, a study in Denmark showed a 10-fold difference in the biomass yield of farmed kelp[116] across sites that varied in light and nutrients (Bruhn *et al*. 2016). A study in Norway also found substantial differences in growth rates of kelp[117] across sites of varying salinity (Forbord *et al*. 2020). These studies indicate the importance of careful site selection to increase farmed seaweed production (Bruhn *et al*. 2016; Forbord *et al*. 2020). Environmental conditions can also moderate the occurrence of seaweed crop diseases and pests (Largo *et al*. 2020). For example, in Zanzibar, a bacterial disease[118] and epiphytes[119] cause outbreaks during the hot-dry season but almost disappear during the wet season, likely due to variations in local sea temperatures (Largo *et al*. 2020) (see sections 4.1.2 *Crop Diseases and Pests* and 4.1.4 *Climate Change*).

While more refined estimates of the ocean area available for seaweed farming are needed, it is nonetheless a unique trait of seaweed farming that expansion of the industry is not limited by arable land or freshwater, as is the case for land-based agriculture (Froehlich *et al*. 2019; Duarte *et al*. 2022a). Yet, the capacity of marine environments to sustain seaweed farms is not limitless and understanding ecosystem carrying capacities is an area of great research need.

4.1.2 *Crop Diseases and Pests*

Diseases and pests have caused substantial losses to seaweed crops, with particularly detrimental economic effects on seaweed farmers in poor rural areas of coastal developing countries, including Indonesia, the Philippines, and the United Republic of Tanzania (Msuya 2011b; Valderrama 2012; Radulovich *et al*. 2015b). Pathogens of concern include bacteria and water molds[120] (Hurtado *et al*. 2019; Ward *et al*. 2020), and problematic pests include epiphytes, biofouling organisms, and herbivores (Radulovich *et al*. 2015a; Bannister *et al*. 2019; Hurtado *et al*. 2019). It is difficult to control seaweed crop diseases and pests and illegal use of algicides and pesticides may present a growing concern (Cottier-Cook *et al*. 2016) (see section 4.2.4 *Global Biosecurity*).

Seaweed farm production losses of 15–30 per cent have been recorded in China, the Republic of Korea, and the Philippines due to disease outbreaks (Ward *et al*. 2020). In China alone, over 30 diseases have been identified across 8 farmed seaweed species[121] (Ward *et al*. 2020). In the Philippines, a bacterial disease[122] and epiphytes[123] have significantly impacted farming of carrageenophytes[124] (Largo *et al*. 1995a; Largo *et al.* 1995b; Hurtado *et al*. 2019). For example, the combined effects of disease and epiphytism led to a decrease in the number of seaweed

[114] 6.2 per cent per year
[115] Adding 5 per cent to overall global food production
[116] *Saccharina latissima*
[117] *Saccharina latissima*
[118] Ice-ice disease
[119] *Polysiphonia-Neosiphonia* complex
[120] Oomycetes

[121] Particularly problematic are the oomycete pathogens *Pythium porphyrae* and *Olpidiopsis porphyrae* that cause red rot disease in the seaweed *Pyropia yezoensis*
[122] Ice-ice disease (bacterial complex *Vibrio-Aeromonas* and *Cytophaga-Flavobacterium*)
[123] *Polysiphonia-Neosiphonia* complex
[124] *Kappaphycus* and *Eucheuma*

farmers at Calaguas Island, Camarines Norte, Philippines from approximately 300 to less than 15 over 4 years (Hurtado *et al*. 2006). Across the Philippines, there was an overall 15 per cent loss of seaweed production[125] due to disease and epiphytism between 2011 and 2013 (Cottier-Cook *et al*. 2016).

Disease[126] and epiphytism also impact seaweed farms in Indonesia, Malaysia, and Zanzibar (Vairappan *et al*. 2009; Largo *et al*. 2020), with spread from the Philippines likely caused by the transfer of infected seedlings between farms (Hurtado *et al*. 2019). Epiphyte infection across all regions alters the physical structure of the seaweed causing secondary infections with opportunistic bacteria (Vairappan *et al*. 2009). To reduce the impacts on seaweed farming and limit the spread of crop diseases and pests, farmers may need to farm in deeper waters and adopt strict biosecurity measures (Msuya *et al*. 2007; Hurtado *et al*. 2019) (see section 4.2.4 *Global Biosecurity*). Treatment of seaweed with a biostimulant/bioeffector or nitrogen can elicit a natural defense response to epiphytes (Loureiro *et al*. 2017; Hurtado *et al*. 2019). Treatment of tropical seaweed seed[127] with Acadian Marine Plant Extract Powder (AMPEP), produced from a temperate seaweed[128], has been shown to experimentally reduce epiphyte infestation (Loureiro *et al*. 2017; Hurtado *et al*. 2019).

Biofouling organisms reduce seaweed farm production through light, space, and nutrient competition, or through physical damage to seaweeds and farm infrastructure (Bannister *et al*. 2019). For example, suspension feeders, including bryozoans, ascidians, and juvenile mussels can coat the surface of farmed kelps, increasing their susceptibility to breakage by ocean waves (Skjermo *et al*. 2014; Bruhn *et al*. 2016). To mitigate these effects, farmed kelps can be harvested in the spring prior to summer outbreaks of biofouling organisms (Skjermo *et al*. 2014; Bruhn *et al*. 2016). Given that kelps store carbohydrates over the summer and autumn months, early harvesting can affect the biochemical content of the harvested kelp (Skjermo *et al*. 2014). Biofouling by nuisance seaweeds occur on seaweed farms in various locations[129] and has caused farmers to abandon seaweed farming sites or resulted in high costs for remediation (Hu *et al*. 2010; Msuya 2011b). These seaweed blooms may be linked to warming ocean temperatures and coastal pollution (Hu *et al*. 2010; Msuya 2011b).

Herbivory during seaweed cultivation can decimate select seaweed crop species (Radulovich *et al*. 2015a). For example, in Costa Rica, Radulovich *et al*. (2015a) found that herbivory was extreme on 3 of at least 6 seaweed species[130] in newly established seaweed farms, limiting the usefulness of some species for farming.

4.1.3 *Crop Genetic Erosion*

Genetic erosion, or the loss of genetic diversity, in farmed seaweed populations can increase the risk of crop failure due to outbreaks of diseases and pests or environmental change (Hurtado *et al*. 2019). Genetic erosion has been documented in various farmed seaweeds[131] (Huh *et al*. 2004; Voisin *et al*. 2005; Niwa and Aruga 2006; Zhang *et al*. 2017; Hurtado *et al*. 2019). For example, Zhang *et al*. (2017) found that the genetic diversity of non-native farmed kelp[132] populations in China was lower than wild populations in Japan, likely due to selective breeding and genetic drift. The authors suggest that genetically distinct or geographically isolated populations can be used to enhance genetic diversity and increase productivity (Zhang *et al*. 2017). In tropical carrageenophytes[133], repeated vegetative propagation from a limited genetic pool has resulted in populations with desirable traits regarding size and coloration but very low genetic diversity (Hurtado *et al*. 2019; Ward *et al*. 2020). This has led to devastating outbreaks of diseases and pests (Hurtado *et al*. 2019; Ward *et al*. 2020). Limited genetic background of other farmed seaweeds[134] has also increased their susceptibility to diseases and pests (Valero *et al*. 2017; Hurtado *et al*. 2019; Largo *et al*. 2020) (see section 4.1.2 *Crop Diseases and Pests*).

4.1.4 *Climate Change*

Climate change is driving major shifts in the distribution of the world's wild seaweed forests (e.g., Filbee-Dexter and Wernberg 2018; Assis *et al*. 2022). An increase in the frequency or severity of thermally mediated crop diseases and pests could pose a threat to seaweed farming, particularly in shallow warm waters (Largo *et al*. 2017; Largo *et al*. 2020; Ward *et al*. 2020) (see also section 4.1.2 *Crop Diseases and Pests*). Women seaweed farmers may be at the greatest risk from climate change, particularly in regions where women farmers are limited to warmer shallow waters due to a lack of access to offshore cooler deep waters (Asri *et al*. 2022).

Increases in the frequency or severity of climate driven natural disasters, such as tropical cyclones, may also negatively affect seaweed farming (Largo *et al*. 2017). For

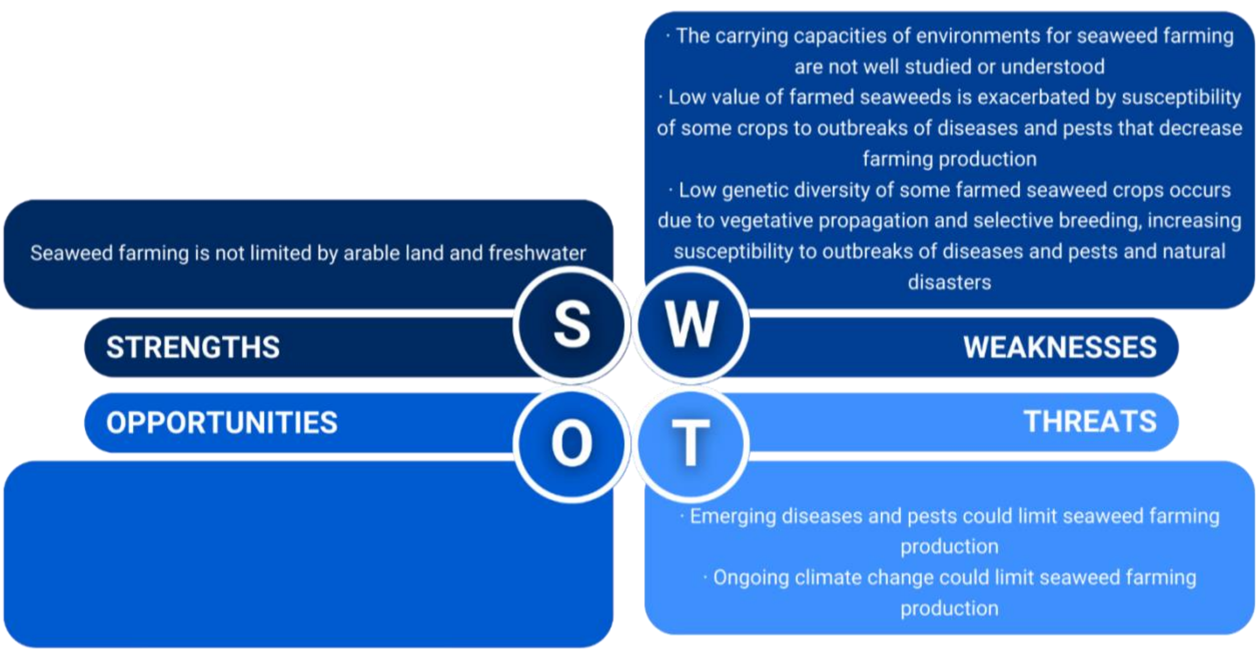
[125] 268,000 ton reduction of *Kappaphycus*
[126] Ice-ice disease
[127] *Kappaphycus*
[128] *Ascophyllum nodosum*
[129] For example, *Cladophora* in the United Republic of Tanzania and *Ulva* in China
[130] *Eucheuma isiforme*, *Gracilaria cervicornis*, and *Caulerpa racemose*
[131] *Undaria*, *Ulva*, *Porphyra*, *Saccharina*, *Kappaphycus*, and *Eucheuma*
[132] *Saccharina japonica*
[133] *Kappaphycus* and *Eucheuma*
[134] For example, *Gracilaria* and *Pyropia*

example, in the Philippines, a strong tropical cyclone destroyed an entire seaweed stock[135] 5 years after farm establishment, requiring complete replanting (Hurtado *et al*. 2006). In China, ocean warming and acidification under climate change are considered major risks to seaweed farming, and it has been recommended that efforts are made to preserve existing wild and domestic seaweed genetic diversity, establish stress-resistant seaweed strains, develop novel cultivation methods, and identify suitable sites for seaweed farming under changing environmental conditions (Hu *et al*. 2021). It is possible that ocean warming could increase the number of subtropical regions suitable for tropical seaweed farming (Largo *et al*. 2017), yet the area suitable for tropical seaweed farming may correspondingly decrease. Finally, farmed seaweed productivity in some regions could theoretically increase under increased CO_2 concentrations, which have yielded increased seaweed growth rates and nutrient assimilation in laboratory experiments[136] (Zou 2005).

4.1.5 *Summary of Biophysical Factors that Limit Seaweed Farming Production*

The primary biophysical factors limiting the production capacity of seaweed farming include ocean conditions required by seaweed crops, outbreaks of diseases and pests, genetic erosion of farmed seaweeds, and climate change. While large swaths of the ocean could in theory support seaweed farming (Froehlich *et al*. 2019), careful site selection is important to minimize environmental risks and maximize seaweed productivity (Bruhn *et al*. 2016; Froehlich *et al*. 2019; Forbord *et al*. 2020). Outbreaks of crop diseases and pests have substantially impacted seaweed farm production, particularly in coastal developing countries (Msuya 2011b; Valderrama 2012; Radulovich *et al*. 2015b; Bannister *et al*. 2019). Genetic erosion has occurred in various farmed seaweeds, yielding decreased genetic diversity, increased susceptibility to outbreaks of diseases and pests, and decreased productivity (Hurtado *et al*. 2019; Ward *et al*. 2020). Finally, climate change poses a risk to seaweed farming due to reductions in native seaweed populations as genetic sources, alteration of environmental conditions at farming sites, and intensifying outbreaks of diseases and pests and natural disasters, such as tropical cyclones (Largo *et al*. 2017; Hu *et al*. 2021).

The biophysical factors limiting seaweed farming production reviewed here indicate a ***strength*** and several ***weaknesses*** of seaweed farming and ***threats*** that should be protected against for future sustainable expansion.



[135] *Kappaphycus alvarezii*

[136] For example, in *Hizikia fusiforme*

4.2 Potential Approaches for Upscaled Production

Various approaches are discussed in the literature as having the potential to overcome the broad range of environmental, social, and economic factors that limit global seaweed farming production. In this section, information on these approaches is reviewed and contextualized, and knowledge gaps are identified.

4.2.1 *Marine Spatial Planning*

An MSP approach could be useful in determining the best locations for seaweed farms (Cabral *et al*. 2016). These locations may maximize production while minimizing human use conflicts and negative effects on ecosystems (Cabral *et al*. 2016). Available quantitative biophysical (e.g., salinity, nutrients, and temperature), ecological (e.g., eutrophication and species richness), and socioeconomic (e.g., cultural activities and other human uses) indicators can be combined to identify appropriate locations (Fig. 9). In addition, methods such as the Habitat Equivalency Analysis (HEA) can be used to assess the cost required to compensate for the ecosystem services impacted by seaweed farm development (Cabral *et al*. 2016). This method uses expert knowledge to assess the presence of ecosystem services within the farm area and calculate the cost of damage[137] (Cabral *et al*. 2016). Direct engagement with local stakeholders will remain important, as the various ecological and socioeconomic indicators may have different value to local people and should be weighted accordingly (Cabral *et al*. 2016).

Stakeholder-based MSP could also yield synergies across marine sectors through ocean multi-use (Msuya *et al*. 2007; Cottier-Cook *et al*. 2016; Gimpel *et al*. 2016; Eggertsen and Halling 2021; NASEM 2021). Ocean multi-use could include the expansion of seaweed farming into wind farms (Gimpel *et al*. 2015; Buck *et al*. 2018), MPAs (Le Gouvello *et al*. 2017), and Integrated Multi-Trophic Aquaculture (IMTA) systems (Troell *et al*. 2009; Buck *et al*. 2018). Developing and piloting offshore multi-use areas for seaweed farming is considered by Hoegh-Guldberg *et al*. (2019) as a short-term high priority by 2025 for ocean-based climate mitigation.

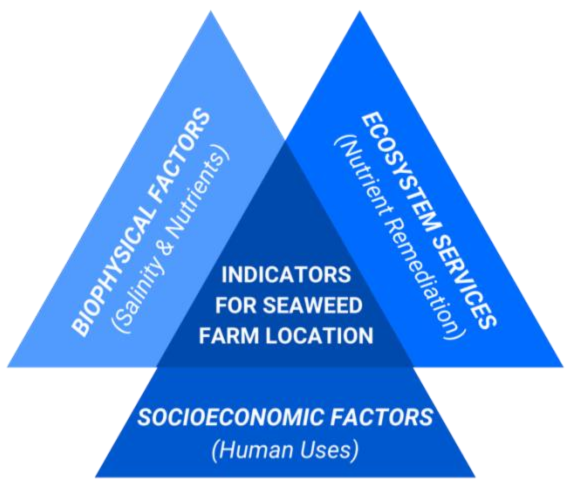


Fig. 9. MSP approach to identifying appropriate seaweed farm locations based on the biophysical limitations to farming (such as salinity, nutrients, and temperature), the potential for a farm to provide ecosystem services to humans (such as nutrient remediation and biodiversity), and socioeconomic factors that may determine tolerance to farm development (such as existing human uses). Based on Cabral *et al*. (2016).

Given the strong competition for inshore space, offshore expansion may be necessary for upscaled seaweed farming to meet a significant portion of global resource needs (Forster and Radulovich 2015; Stévant *et al*. 2017; Buck *et al*. 2018). Potential challenges to offshore seaweed farming include the need for robust infrastructure in deep water with strong waves and currents, and the high cost of operating offshore (Troell *et al*. 2009; Eklöf *et al*. 2012; Forster and Radulovich 2015). It may therefore be strategic to leverage wind farm infrastructure and resources such as labor and equipment (Buck *et al*. 2018).

[137] For example, USD 24,700–123,548 per hectare for maerl beds in Normand-Breton Gulf, France

Biophysical criteria should be evaluated offshore, including temperature, salinity, nutrient, and flow requirements for seaweeds (Gimpel *et al*. 2015; Azevedo *et al*. 2019). For example, a modelling study along the Norwegian coast indicates strong potential for kelp farming in offshore areas with high and consistent nutrient supplies (Hancke *et al*. 2021). High offshore currents could enhance seaweed productivity through increased nutrient cycling and by limiting outbreaks of diseases and pests (Eklöf *et al*. 2012; Peteiro and Freire 2013; Kerrison *et al*. 2015; Bannister *et al*. 2019).

Where governments wish to facilitate seaweed farming expansion offshore, full integration of stakeholders, including indigenous farmers, will be necessary (Nor *et al*. 2017). For example, an attempt in Malaysia to transition seaweed farming to deeper water was met with resistance from women farmers who lacked seafaring skills (Nor *et al*. 2017). Research will be needed to identify and mitigate spatial use conflicts and environmental effects and to identify cultivation methods and seaweed species best suited for offshore farming (Roesijadi *et al*. 2008).

Co-location of seaweed farms within MPAs has been suggested as an approach to improve the use of coastal space while enhancing biodiversity (Le Gouvello *et al*. 2017). However, few studies exist on the effects of seaweed farms on biodiversity within MPAs, and negative effects of seaweed farms have been documented for coral reef fishes in MPAs in the Philippines (Hehre and Meeuwig 2015) (see section 3.2.1 *Habitat Competition*). In countries such as Germany, expansion of aquaculture is limited by regulations related in part to MPAs, which may make offshore seaweed farming a more feasible option (Fernand *et al*. 2017).

Nutrient limitation on seaweed growth may be addressed through cultivation of seaweeds as part of an IMTA system (Neori *et al*. 2004). IMTA is an aquaculture system wherein extractive species, such as seaweeds, are grown alongside fed species, such as finfish (Troell *et al*. 1997; Neori *et al*. 2004; Kim *et al*. 2017; Buschmann *et al*. 2017). IMTA may decrease pollution from aquaculture, as most of the feed provided to fed species becomes waste and some of this waste could be converted by seaweeds into biomass (Troell *et al*. 1997; Neori *et al*. 2004; Sanderson *et al*. 2012; Buschmann *et al*. 2017). For example, farming of seaweed[138] in open water in the state of Maine initially failed due to insufficient nutrients for seaweed growth, but later succeeded following co-location near an Atlantic salmon farm[139] (Kim *et al*. 2017). Nutrient limitation on seaweed productivity has also been observed in Denmark, even in eutrophic waters (Bruhn *et al*. 2016). In Scotland, farming of seaweeds[140] near a salmon farm increased seaweed growth by 48–61 per cent and seaweed biomass yields were 27–63 per cent higher (Sanderson *et al*. 2012). Similarly, in Chile, seaweed[141] farmed alongside salmon had a 40 per cent greater growth rate (Troell *et al*. 1997). IMTA may present an environmentally sustainable method to manage pollution from fed aquaculture and avoid the use of fertilizers on seaweed farms. Fertilizers could contribute to eutrophication and are currently not permitted by law for seaweed farming in some regions[142] (Campbell *et al*. 2019).

IMTA is already practiced on a commercial scale in China and the Republic of Korea, resulting in the efficient production of large quantities of food, with the co-benefit of improving coastal water quality (Cottier-Cook *et al*. 2016). Although there are experimental-scale offshore IMTA systems under evaluation, only a single commercial-scale system exists[143] (Buck *et al*. 2018). While IMTA provides a potentially promising approach for seaweed farming expansion, potential differences in the timing of peak production of wastes from fed aquaculture and peak growth of seaweeds must be considered, particularly when background nutrient levels are limiting for seaweed growth (Park *et al*. 2018).

4.2.2 *Polyculture, Crop Rotation, and Selective Breeding*

Innovations in seaweed cultivation could enhance farm production and may include seaweed polyculture, crop rotation, and selective breeding (Jiang *et al*. 2013; Park and Hwang 2014; Roleda and Hurd 2019).

Polyculture is the synchronous cultivation of multiple crop species to maximize resource use and farm production (Roleda and Hurd 2019). Roleda and Hurd (2019) reviewed the nutrient physiology of seaweeds and argued that polyculture of seaweeds that have differing nitrogen physiologies[144] could increase seaweed farming production through niche partitioning that optimizes nitrogen use and limits competition. Further studies are needed to identify candidate species for seaweed polyculture, and seaweeds[145] with high nitrogen demand may be more appropriately farmed as monocultures (Roleda and Hurd 2019).

Seaweed farm production could be facilitated by seasonal crop rotation (Jiang *et al*. 2013). Some seaweed species undergo sexual reproduction that is seasonal and have strict seasonal environmental conditions required for growth, both of which constrain the period over which

[138] *Pyropia yezoensis*
[139] *Salmo salar*
[140] *Palmaria palmata* and *Saccharina latissima*
[141] *Gracilaria chilensis*
[142] For example, Europe
[143] In the Yellow Sea
[144] Preference for ammonium versus nitrate
[145] For example, *Porphyra* and *Ulva*

seaweed farming can occur (Charrier *et al*. 2017). To optimize farm yield, farmers can rotate seaweed species with different life histories and environmental tolerances throughout the year. For example, in Lidao town, China, to optimize yield, kelp[146] is farmed from November to May, while a red seaweed[147] is farmed from June to October (Jiang *et al*. 2013). Biotechnological innovations that target the reproductive cycles of seaweeds could also remove constraints on seasonal cultivation to increase annual production (Charrier *et al*. 2017).

A primary goal of the seaweed farming industry is to establish strains with combinations of fast growth, high yield, consistency and stability of chemical composition, and disease and pest resistance, which may be accomplished through selective breeding (FAO 2018; Wang *et al*. 2018). For example, selective breeding has led to improvements in disease tolerance in various farmed seaweed species (Park and Hwang 2014; Cottier-Cook *et al*. 2016; Hwang *et al*. 2019). Two strains of a red seaweed[148] have been developed in the Asia-Pacific region that are partially resistant to red rot disease[149] (Park and Hwang 2014). Disease resistant strains of kelp[150] have also been developed in China, prompted by the disease-induced reduction in yield (Cottier-Cook *et al*. 2016). Chen *et al*. (2015a) developed a protocol for transferring foreign genes into seaweeds[151] as a step towards transgenic disease resistance.

Selective breeding for seaweed productivity, and more recently quality, is commonly practiced in the Republic of Korea, Japan, and China (Hwang *et al*. 2019) but is generally absent in tropical developing countries, which may in part explain a recent decline in seaweed production in those countries (Hurtado *et al*. 2019; FAO 2020). In regions of low surface nutrients, seaweed strains could in theory be developed that grow well under low nutrient conditions (NASEM 2021). Selective breeding is, however, limited in countries such as Norway where regulations prevent the use of hybridized or bred strains (Skjermo *et al*. 2014).

In general, to accomplish polyculture, crop rotation, and selective breeding, additional fundamental research will be needed on the biology of seaweeds, including nutrient physiologies, life cycles, environmental tolerances, growth strategies, and disease resistance (Charrier *et al*. 2017; Fernand *et al*. 2017; Roleda and Hurd 2019). These innovations should occur with careful consideration for the potential environmental risks, including genetic pollution from farms to wild ecosystems (Campbell *et al*. 2019) (see section 3.2.3 *Genetic Pollution*).

4.2.3 *Advanced Technology and Infrastructure*

Seaweed farming is centuries behind land-based agriculture, and extensive investment in technology and infrastructure is likely needed for upscaling (Forster and Radulovich 2015; NASEM 2021). To achieve economies of scale and support large production volumes of seaweed, efficient farm engineering and operation[152] and robust farm infrastructure are likely required (Campbell *et al*. 2019; NASEM 2021). Where surface nutrients are limited, farms could be engineered to move seaweeds into deeper waters at night for nutrient absorption and shallower waters during the day for light absorption (NASEM 2021). Alternatively, technology could be developed to artificially upwell deep nutrient rich seawater to the surface (NASEM 2021). This in principle could substantially increase seaweed production (Wu *et al*. 2022a) but could also bring CO_2 enriched seawater in contact with the atmosphere, compromising the climate (NASEM 2021). Some technology and infrastructure needs could be met through ocean multi-use (see section 4.2.1 *Marine Spatial Planning*).

Given the low cost of labor in countries where the seaweed farming industry has matured, for instance in China and other parts of Asia, emphasis on technology and infrastructure to mechanize farming has been low (Campbell *et al*. 2019). For example, transporting wet seaweed biomass to drying sites in countries such as the United Republic of Tanzania occurs by human power and has been identified as a major challenge for seaweed farmers (Msuya 2013). Air drying of seaweeds has been noted as particularly problematic during the wet season in the tropics and can decrease the quality and market value of seaweeds (Ali *et al*. 2017; Largo *et al*. 2020). Given that seaweed farming is currently a seasonal activity, there is a need for methods to preserve biomass following harvesting to provide a continous annual supply for commerical applications such as food, feed, and fuel (Skjermo *et al*. 2014). Vacuum packaged blanching prior to freezing has been found to maintain the quality of kelp for consumption for up to at least 6 months (Akomea-Frempong *et al*. 2022).

There is a geographical disconnect between rapid seaweed farming scientific advancement in developed countries and rapid seaweed farming industry expansion in developing countries (Mazarrasa *et al*. 2013; Mazarrasa *et al*. 2014). The countries with fast expansion but low rates of scientific advancement are experiencing concomitant declines in production (Mazarrasa *et al*. 2014;

[146] *Saccharina japonica*
[147] *Gracilaria lemaneiformis*
[148] *Pyropia yezoensis*
[149] *Pythium porphyrae*
[150] *Saccharina japonica*
[151] *Pyropia*
[152] Including mechanization of seeding and harvesting

FAO 2020). This indicates the need for global scientific collaboration to grow the industry.

Furthermore, women need more access to new knowledge in seaweed production, including the use of digital technologies (Ramirez *et al*. 2020). Enhanced gender equity and social inclusion that includes the full participation of women in seaweed farming development could act to strengthen traceability for seaweed quality and improve production sustainability (Ramirez *et al*. 2020).

4.2.4 *Global Biosecurity*

Biosecurity planning can be used to prepare for outbreaks of crop diseases and pests and environmental changes that can be devastating to seaweed farms, and to protect wild ecosystems from pathogens and invasive species (Cottier-Cook *et al*. 2016; Campbell *et al*. 2019; Cottier-Cook *et al*. 2021).

Examples of biosecurity measures to protect seaweed farms include training in quarantine procedures and farm management practices to prevent the introduction and spread of diseases and pests, development and implementation of diagnostic tools for early detection, and breeding to maintain genetic diversity and resistance to diseases and pests and environmental change (Cottier-Cook *et al*. 2016; Campbell *et al*. 2019; Ward *et al*. 2020). Biosecurity planning can also include capacity building for the control of outbreaks of disease and pests when they occur (Cottier-Cook *et al*. 2016). This may include access to government-funded regional facilities for quarantine (Kambey *et al*. 2020).

National and international seed banks can be used to preserve and maintain the genetic diversity of farmed and wild seaweeds (Buschmann *et al*. 2017; Campbell *et al*. 2019; Barbier *et al*. 2020; Wade *et al*. 2020). Moreover, government insurance schemes can provide farmers with the opportunity to rebuild or treat farms following outbreaks of disease and pests or natural disasters, rather than abandoning the farm which can lead to environmental problems (Cottier-Cook *et al*. 2016). Insurance schemes can also encourage seaweed farming as a livelihood by reducing the investment risk for farmers (Cottier-Cook *et al*. 2016).

Currently, European legislation requires biosecurity measures for seaweed farming that prevent the spread of pathogens and invasive species (Campbell *et al*. 2019). In Madagascar, farmers receive biosecurity training from the private sector (Msuya *et al*. 2022). However, in some countries, biosecurity measures are generally lacking (Kambey *et al*. 2020; Rusekwa *et al*. 2020) and this has been linked to limits in legislative recognition, up-to-date scientific evidence, and recognition of the biosecurity hazards related to seaweed farming (Kambey *et al*. 2020; Rusekwa *et al*. 2020).

Biosecurity measures specific to farming established invasive species include farming only in regions of heavy infestation, careful containment of stock during land transportation, decontamination of land-based water intakes and outflows, standardized monitoring of associated non-native diseases and pests for early detection, and continuous monitoring for negative effects of farming on the environment (Cunningham *et al*. 2020).

While global safeguards exist for terrestrial agricultural crops and animal aquacultural species, global coordination for the protection of seaweed crops is yet to occur (Cottier-Cook *et al*. 2021). For global seaweed farming biosecurity implementation, future research needs include continued development of diagnostic tests for diseases and pests of concern, capacity building to manage outbreaks when they occur, identification of local seaweed species/strains for cultivation, and developing breeding and cultivation technologies for those species (Cottier-Cook *et al*. 2016). While some biosecurity protocols have been developed for regional seaweed farming, broader implementation of those protocols through training, reporting systems, and incentives is needed (Cottier-Cook *et al*. 2021).

4.2.5 *Market and Product Development*

The development of new markets for seaweeds and diversification of seaweed products could drive the expansion of the seaweed farming industry (Forster and Radulovich 2015). Market and product development may include the expansion of seaweeds in diets around the world and the development of novel high value products and biorefinery processes for value addition (Palmieri and Forleo 2020; Duarte *et al*. 2022a; Msuya *et al*. 2022).

Seaweeds have been consumed for centuries in China, Japan, and the Republic of Korea, and popularity is growing in western diets following an increased interest in plant-based diets and environmentally sustainable food (Forster and Radulovich 2015; FAO 2018; FAO 2020; Palmieri and Forleo 2020; Vincent *et al*. 2020). Yet, many countries with coastlines potentially suitable for seaweed farming lack a strong market for seaweed products (Barbier *et al*. 2020; Lähteenmäki-Uutela *et al*. 2021). In these areas, a complete list of seaweed species that are authorized as food could be useful to grow public confidence in seaweed consumption (Barbier *et al*. 2020). Including seaweeds as part of recommended daily dietary guidelines could also increase consumer acceptance of seaweeds as a food source (Palmieri and Forleo 2020). Broad regulatory guidelines for allowable levels of heavy metals in seaweeds are needed but currently exist for only a small subset of countries[153] (Hayes 2015). Product safety and consumer protection must be a priority, and legislation on limits of contaminants in seaweeds is needed for public confidence (Barbier *et al*. 2020; Lähteenmäki-Uutela *et al*. 2021; FAO and WHO 2022). In terms of the various purported health benefits of seaweeds (see section 3.3.3 *Nutrition and Global Food Security*), research is needed to establish the intake amounts and frequencies required to realize those benefits for various products (Barbier *et al*. 2020; Lähteenmäki-Uutela *et al*. 2021).

Though research on consumer behavior regarding seaweeds is generally sparse, a case study in Australia indicated that the odds of eating seaweeds were associated with familiarity with seaweed products, having a university degree, and health-conscious eating behaviors (Birch *et al*. 2019). Neophobia, or the fear of new things, can contribute to a lack of interest in consuming seaweeds (Losada-Lopez *et al*. 2021). Other considerations among consumers are the way in which seaweed food products are packaged and promoted, including their environmental sustainability (Young *et al*. 2022).

Forster and Radulovich (2015) cite 3 potential pathways for market development of seaweed as food: 1) wealthy consumers in developed countries, recognizing the health and environmental benefits of seaweeds, pay a premium for seaweed-based foods, supporting the seaweed food industry despite its early stage of development; 2) seaweeds are farmed and used directly for food in developing countries where seaweed consumption is currently limited or absent; and 3) global seaweed farming production is upscaled to the extent that costs are reduced and seaweeds are globally processed into low cost ingredients. According to the authors, the first scenario may hold the most promise to rapidly accelerate global seaweed production and processing in the short-term given that capital and infrastructure are already in place in developed countries (Forster and Radulovich 2015). Establishment of domestic processing infrastructure, distribution networks, and consumer demand would be needed for this pathway (Piconi *et al*. 2020). Yet, the potential to increase food security in developing countries through local seaweed farming and consumption (second scenario) should not be overlooked (Forster and Radulovich 2015). Finally, substantial research and development would be required for economies of scale to be realized in the third scenario (Forster and Radulovich 2015).

Diversification of seaweed products also could act to grow the seaweed farming industry (Piconi *et al*. 2020). This would likely require a societal shift from a simple linear one-species one-process product model to a several-species several-processes biorefinery model within a circular bioeconomy, where wastes and by-products are utilized as commercial products (Chopin and Tacon 2021; Duarte *et al*. 2022a). For example, the value chain for carrageenan production is typically single stream, and carrageenan competes on an existing global hydrocolloid market rather than opening new market space with diversified products (Neish and Suryanarayan 2017). The waste products of seaweed hydrocolloid production are high in protein, fat, and minerals that could be extracted for food or feed (Forster and Radulovich 2015). The chemical diversity of seaweeds indicates opportunities for the production of multiple high value products with collaboration across broad economic sectors (Hafting *et al*. 2015; Chopin and Tacon 2021). Bioactives could be used in functional foods, cosmeceuticals, nutraceuticals, and pharmaceuticals but this would require greater standardization of seaweed quality than is currently required by the industries driving seaweed farming (Hafting *et al*. 2015). A biorefinery system could include the production of biofuels through multiple processes (Wei *et al*. 2013; Chen *et al*. 2015b; Marquez *et al*. 2015). Residual seaweed biochar can be used as soil conditioner for a zero-waste production process (Sadhukhan *et al*. 2019). A study in the state of Maine indicated a net revenue of USD 0.72 per cubic meter wastewater treated when seaweed farming (for human consumption) replaced a water resource recovery facility upgrade (Wu *et al*. 2022b).

To accomplish ocean-based climate mitigation, the establishment of biorefining techniques to sequentially extract seaweed products is considered a high priority by 2023 (Hoegh-Guldberg *et al*. 2019). Seaweed biorefinery systems may be more cost effective than terrestrial lignocellulosic biorefinery systems (Sadhukhan *et al*. 2019) but research and development towards seaweed biorefineries are in infancy (Kostas *et al*. 2021). Government support for the development of domestic processing plants in regions with high seaweed production and export could enhance opportunities for seaweed products (FAO 2018; Msuya *et al*. 2022).

4.2.6 *Economic Incentives and Regulatory Support*

Expansion of the seaweed farming industry may be facilitated by financial incentives or tax deductions for farmers that consider the environmental benefits of seaweed farming, such as nutrient and carbon removal (Duarte *et al*. 2022a). If the ecosystem services contributed by seaweed farming were monetized, this could increase the value of the seaweed aquaculture sector (Chopin and Tacon 2021). Assuming a nitrogen, phosphorus, and carbon content of seaweeds of 0.35 per cent, 0.04 per cent,

[153] For example, Australia and France

and 3 per cent, respectively, the value from bioremediation of wastewater is USD 10–30 per kilogram of nitrogen and USD 4 per kilogram of phosphorus, and the carbon tax value is USD 30 per ton of carbon (Chopin and Tacon 2021). This yields an additional global value from seaweed farming of between USD 1.214 and 3.482 billion, which represents 26 per cent of the current global seaweed farming industry[154] (Chopin and Tacon 2021). The establishment of nutrient trading credits (NTCs) could lead to a fairer price for seaweeds that incentivizes production (Chopin and Tacon 2021). The biodiversity benefits of seaweed farming, if appropriately quantified (see section 3.1.1 *Marine Biodiversity*), could also be incorporated into markets for biodiversity and nature credits, which are currently emerging for blue carbon ecosystems (Macreadie *et al*. 2022).

Voluntary carbon markets could provide economic incentives for seaweed farming in lieu of domestic regulated seaweed carbon trading markets[155] (Clark *et al*. 2021). A benefit of seaweed farming for carbon crediting is that there should be little debate over who owns the carbon since the carbon can be harvested directly from a farm lease. This is unlike wild blue carbon ecosystems, where the right to transact carbon credits can be contested when the habitat traverses private and public coastal lands or extends beyond the EEZ, or if the carbon sink occurs at distance from the source of production, as in the case of exported coastal detritus (Macreadie *et al*. 2022). A necessary step for successful development of seaweed farming carbon credits will be to accurately account for natural carbon sequestration by farms, which remains an area of ongoing research (see section 2.1 *Potential for Natural Carbon Sequestration*).

As markets for seaweed products grow, seaweed farming may expand as a direct response to overexploitation of wild seaweed populations and regulatory restrictions on their harvest (Duarte *et al*. 2007; Buschmann *et al*. 2014). This has been observed for carrageenophyte farming in the tropics, kelp farming in Norway, and red seaweed farming in Chile (Valderrama *et al*. 2013; Buschmann *et al*. 2017). For example, carrageenan was sourced from wild seaweed harvest in temperate and tropical waters until demand outpaced supply from wild stocks, at which point tropical farming met the demand (Valderrama *et al*. 2013).

In developed countries, regulatory pathways to establish a seaweed farming industry are often lacking, limiting the expansion of the industry (Wood *et al*. 2017; Barbier *et al*. 2020). For example, throughout Europe, there is no regulatory process specific to seaweed farming, as marine leasing and licensing are directed towards shellfish and finfish farming (Wood *et al*. 2017; Barbier *et al*. 2020). There is a need to update current marine activities guidance to consider seaweed farming, taking into consideration risks for farmers and regulators (Wood *et al*. 2017; Barbier *et al*. 2020). Of particular interest is to determine the circumstances under which an environmental impact assessment (EIA) is required, as this can be a costly process (Wood *et al*. 2017). Exemption of seaweed farms from the marine licensing process in the United Kingdom of Great Britain and Northern Ireland, as is the case for shellfish farming, has been proposed (Wood *et al*. 2017). Given the limited evidence available for negative environmental effects of seaweed farming in the United Kingdom of Great Britain and Northern Ireland, Wood *et al*. (2017) suggest a "survey, deploy and monitor" approach to assess environmental effects while avoiding an expensive regulatory process, as is used for offshore wind development.

4.2.7 *Summary of Potential Approaches for Upscaled Production*

Various approaches have been proposed to overcome limitations on seaweed farming production. An MSP approach has the potential to avoid spatial use conflicts and lead to synergies across marine sectors (Msuya *et al*. 2007; Cottier-Cook *et al*. 2016; Gimpel *et al*. 2016). Innovations in polyculture, crop rotation, and selective breeding have the potential to increase seaweed farming production (Jiang *et al*. 2013; Park and Hwang 2014; Roleda and Hurd 2019). Technological and infrastructural breakthroughs could increase the efficiency of seaweed farming (NASEM 2021). Global biosecurity could prevent and mitigate hazards to seaweed farming and the environment (Cottier-Cook *et al*. 2016; Campbell *et al*. 2019; Ward *et al*. 2020; Cottier-Cook *et al*. 2021). Development of new markets for seaweeds and diversified products could increase seaweed demand and value (Forster and Radulovich 2015; Palmieri and Forleo 2020; Msuya *et al*. 2022). Finally, economic incentives and regulations, such as nutrient trading schemes and streamlined marine licensing processes, have the potential to support the seaweed farming industry (Chopin and Tacon 2021; Duarte *et al*. 2022a).

The approaches to upscale seaweed farming production reviewed here indicate several ***opportunities*** that can be taken advantage of in the future under seaweed farming expansion.

[154] USD 13.3 billion

[155] Selling seaweed farming carbon credits is not currently permitted in some countries, such as New Zealand

STRENGTHS S

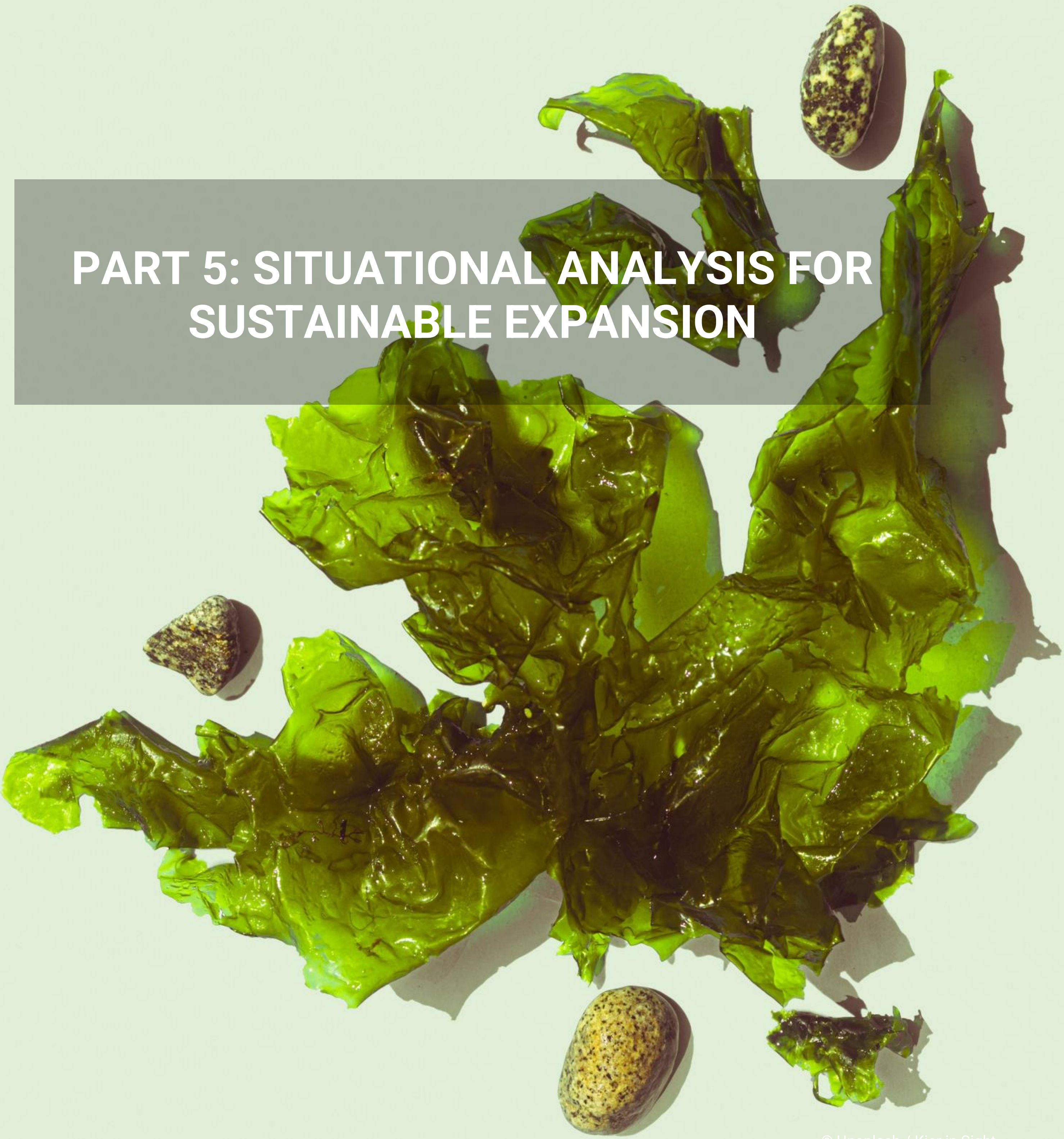
W **WEAKNESSES**

OPPORTUNITIES O

T **THREATS**

- Seaweed farms could be co-located with offshore wind or as part of IMTA to share space and resources
- Crop innovations in polyculture, crop rotation and selective breeding could increase production
- Enhancement of global biosecurity, including control of diseases and pests, could protect against crop losses
- Collaboration between developed countries, with high rates of scientific innovation, and developing countries, with high rates of seaweed farming, could increase production
- Technological advancements (e.g., automation) could increase cost efficiency
- Exposure of new markets to seaweed-based foods could increase demand for seaweed products
- Development of national regulations to support a seaweed farming industry could increase production
- Establishment of nutrient trading credits and expansion of the carbon market could increase production

PART 5: SITUATIONAL ANALYSIS FOR SUSTAINABLE EXPANSION



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A situational analysis was performed to assess the potential for expansion of seaweed farming to deliver climate benefits and other co-benefits while avoiding environmental and socioeconomic risks. The situational analysis considers how factors both internal and external to seaweed farming affect the potential for sustainable industry expansion. The format used is that of a SWOT analysis of global seaweed farming expansion. Based on the evidence reviewed in this report, the analysis focuses on climate benefits, environmental co-benefits and risks, socioeconomic co-benefits and risks, and production upscaling aspects of seaweed farming. Strengths and opportunities are factors considered helpful to the sustainable expansion of seaweed farming, while weaknesses and risks are considered harmful. Strengths and weaknesses are internal factors inherent to seaweed farming, while opportunities and threats are external factors that can either be taken advantage of (opportunities) or protected against (threats) in the future.

5.1 Strengths

Several strengths of seaweed farming have been identified (Fig. 10). From a climate perspective, seaweed farms have several strengths, including their capacity to absorb CO_2 and build it into seaweed biomass, the potential for select cultivated seaweeds to be processed into carbon negative biofuels that do not compete with land-based food crops, and the potential for select seaweeds to reduce enteric emissions of methane as ruminant livestock feed. Select cultivated seaweeds can also contribute to human food intake in place of more carbon-intensive land-based crops. Moreover, seaweed products such as biofertilizers and biochar can sequester some carbon on land and can displace more carbon-intensive products. From an environment perspective, seaweed farms over sandy bottoms tend to attract marine biodiversity, and seaweed farms release oxygen and absorb excess nutrients and heavy metals. From a socioeconomic perspective, there can be a low barrier to entry into seaweed farming in developing countries due to low capital and material costs and the simplicity of methods, and income generated by seaweed farming can lead to improvements in standards of living and food security. Moreover, gender equity is enhanced in regions where women dominate the seaweed farming industry. Seaweed farming can also produce high-quality food, rich in nutrients, minerals, and vitamins, when seaweed quality and safety are carefully considered. Moreover, seaweed farming can provide cultural services to coastal communities. Finally, in terms of upscaling production, seaweed farming has the strength of not being limited by the availability of arable land and freshwater, unlike land-based agriculture.

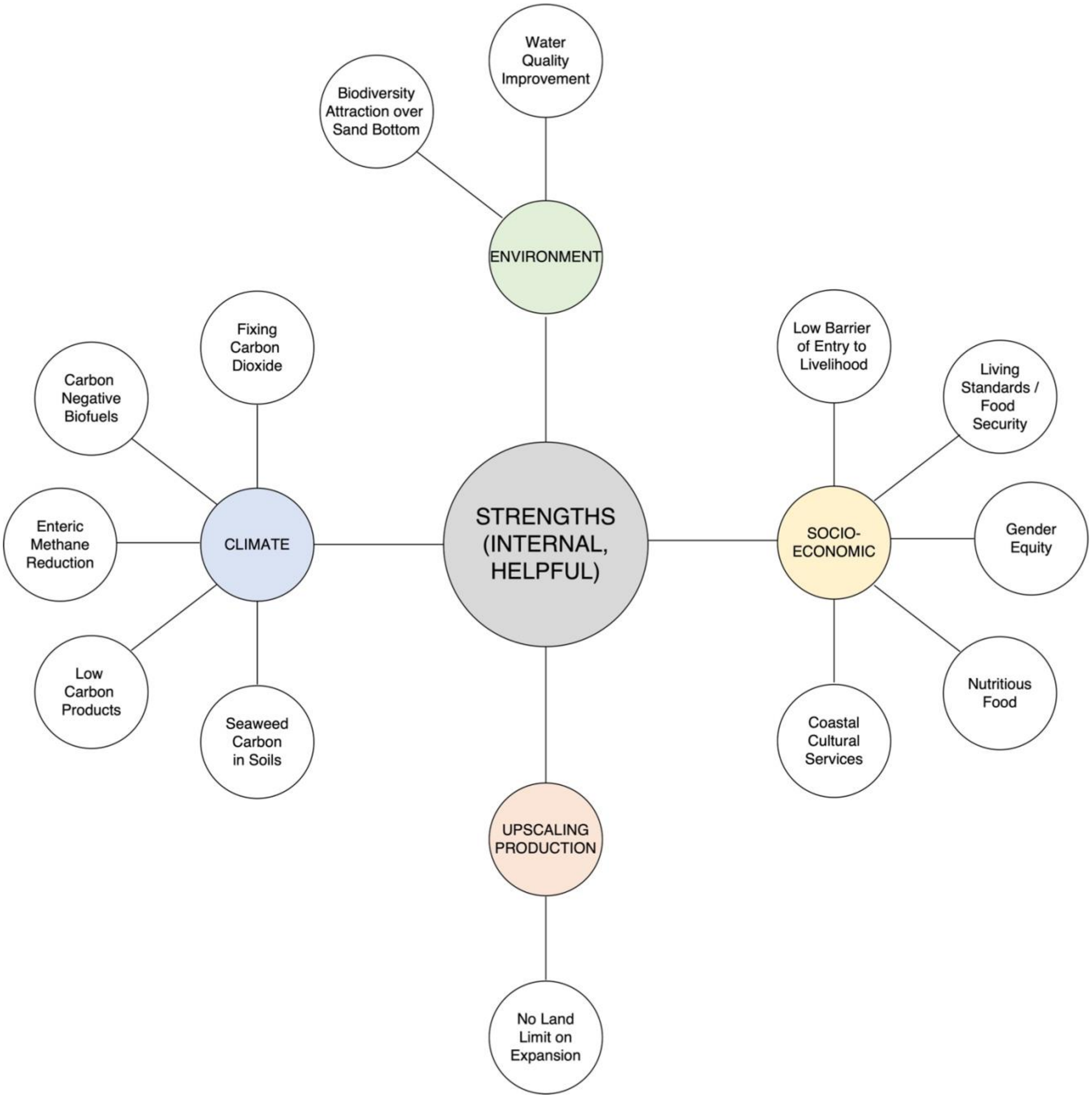


Fig. 10. Major strengths (internal and helpful factors) for seaweed farming relating to the potential for climate benefits, environmental co-benefits and risks, socioeconomic co-benefits and risks, and upscaling production.

5.2 Weaknesses

Several weaknesses of seaweed farming have been identified (Fig. 11). Regarding the climate, the fraction of the carbon built into seaweed biomass that is exported to long-term oceanic carbon sinks is unknown, and this information will be needed to quantify the climate benefits of seaweed farming through natural carbon sequestration. Moreover, commercial scale implementation of various seaweed end-uses for climate mitigation, such as seaweed biofuels, are limited by the high cost of seaweed production, which cannot currently compete with low-cost carbon-intensive commodities. Biofuel production is also limited by the efficiency of seaweed biomass conversion to energy, and the seaweed feed pathway for methane mitigation is limited by the number of ruminant livestock nourished by feeds. Moreover, the viability of intentional deep ocean sinking of seaweed is constrained by the size of carbon markets, uncertainty in the veracity of long-term carbon storage, and the unknown environmental ramifications.

Regarding the environment, seaweed farms that supersede existing complex habitats tend to reduce biodiversity, and farmed seaweeds use sunlight and nutrients for growth, which may displace native photosynthetic organisms. Moreover, the effects of seaweed farms on ocean waves and currents are not well understood. There is also a lack of understanding on the risks of pathogen spillover and genetic pollution from seaweed farms to the environment. The high environmental tolerance and fast growth of farmed seaweeds can facilitate species invasions when non-native seaweeds species/strains are farmed, and the infrastructure needed for seaweed farming can entangle marine megafauna or be a source of plastic pollution. The environmental risks of seaweed farming may be most pronounced in the tropics but are poorly studied in those regions.

Regarding socioeconomic weaknesses, seaweed farmers can experience increased incidence of adverse health conditions and may live under the poverty or extreme poverty line. Moreover, low farming income can lead to negative feedback loops that further decrease farming income. In addition, seaweed farming faces resistance when it conflicts with other spatial uses by humans.

Finally, regarding upscaling, weaknesses of seaweed farming include a lack of research and understanding on the carrying capacity of environments for seaweed farming. Additionally, the low production value of some farmed seaweeds is exacerbated by the susceptibility of crops to outbreaks of diseases and pests; and low genetic diversity of some farmed seaweed crops, due to vegetative propagation and selective breeding, can increase susceptibility to diseases and pests.

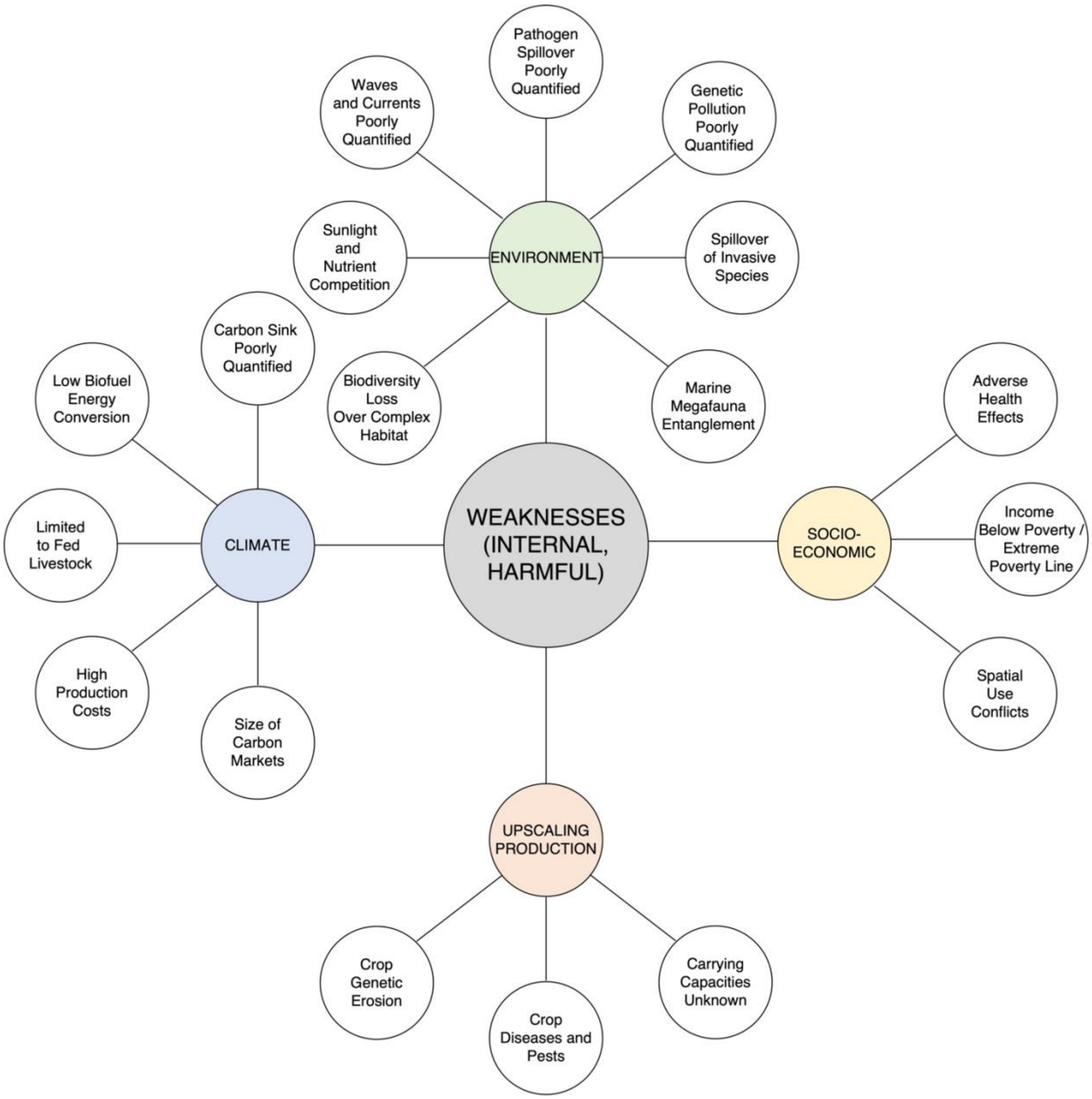


Fig. 11. Major weaknesses (internal and harmful factors) for seaweed farming relating to the potential for climate benefits, environmental co-benefits and risks, socioeconomic co-benefits and risks, and upscaling production.

5.3 Opportunities

Several opportunities have been identified for seaweed farming (Fig. 12). In terms of the climate, seaweed farming could provide carbon sequestration and GHG emissions reduction that is proportional to industry scale, although some of these benefits are likely to be spatially and temporally limited. Technological improvements could increase the energy return on investment for seaweed biofuels. Innovation towards a biorefinery concept, wherein multiple seaweed products are co-produced with zero waste, could increase the cost efficiency of various seaweed commercial use pathways. Additionally, policy interventions could incentivize a shift from consumption of low-cost carbon-intensive commodities to seaweed-based commodities. Finally, improved understanding of the cycling of seaweed carbon could improve accounting of the climate benefits.

Regarding the environment, seaweed farming could enhance local habitats for marine species if farms are not placed over existing complex habitats, such as seagrass beds or coral reefs. Seaweed farming could locally mitigate ocean acidification and deoxygenation when farms are placed in acidified waters and areas with high chemical oxygen demand, respectively. Seaweed farming in polluted waters could locally mitigate coastal pollution from nitrogen, phosphorus, and heavy metals, but the latter collides with the safe use of seaweeds for consumption. There is also potential for seaweed farms to provide coastal protection if sufficient research is carried out to understand effects of farms on waves and currents.

Regarding socioeconomic opportunities, seaweed farming could contribute to raising communities in coastal developing countries out of poverty. Seaweed-based food products could contribute to global food security, and seaweed farming could contribute to cultural heritage and social cohesion in coastal communities. Diversification of seaweed products through value addition could increase income for seaweed farmers, and government or community management of seaweed farming could increase incomes.

Regarding upscaling, seaweed farms could be co-located with offshore wind or as part of IMTA to share space and resources. Crop innovations and enhancement of global biosecurity, including control of diseases and pests, also could increase production. Collaboration between developed countries, with high rates of scientific innovation, and developing countries, with high rates of seaweed farming, can help facilitate seaweed farming expansion. In addition, technological and infrastructural improvements have the potential to increase cost efficiency of seaweed production. There are also opportunities for exposure of new markets to seaweed-based foods and for national regulations to support the seaweed farming industry. Establishment of nutrient trading credits and expansion of the carbon market also represent opportunities to upscale seaweed farming.

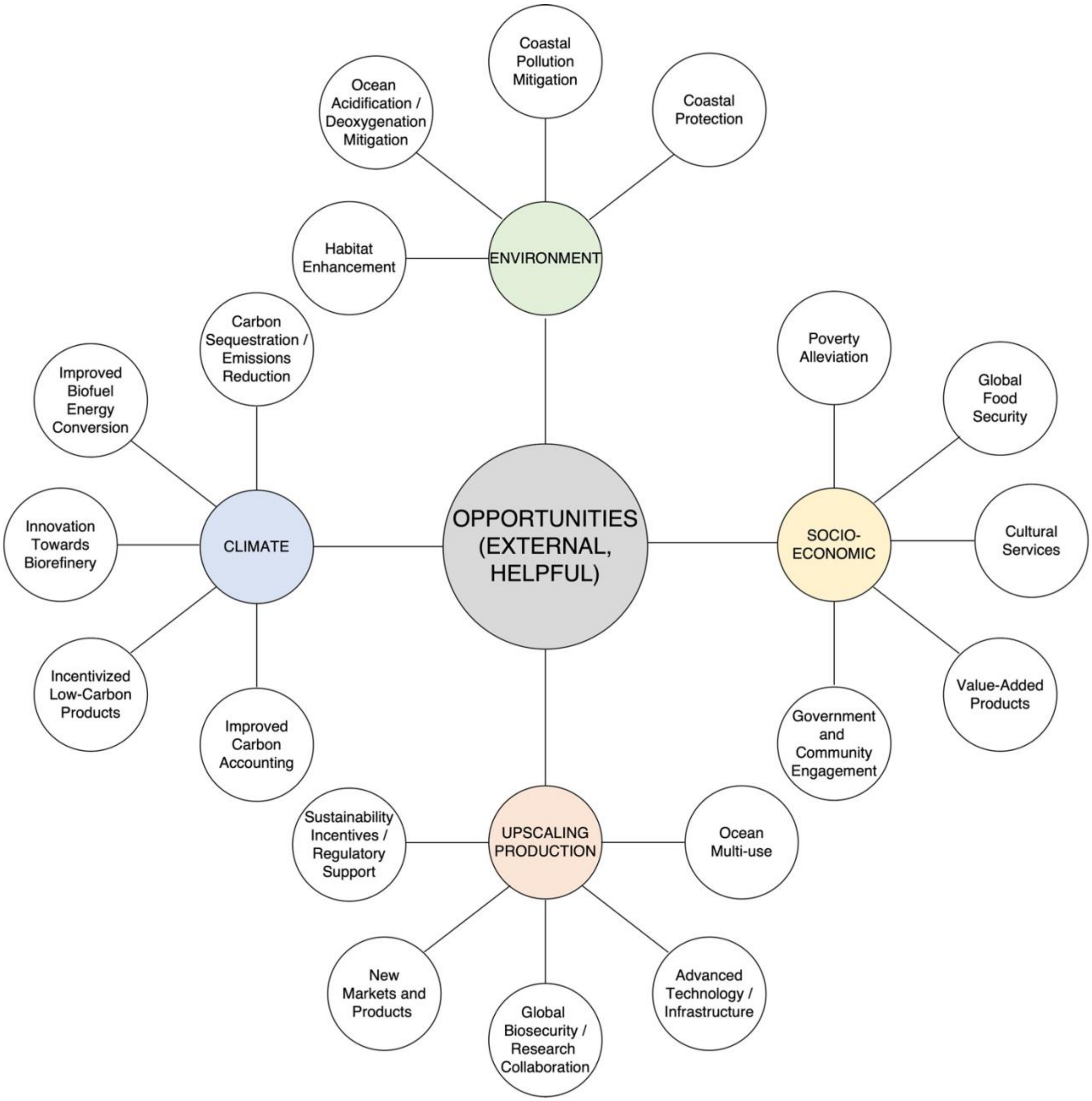


Fig. 12. Major opportunities (external and helpful factors) for seaweed farming relating to the potential for climate benefits, environmental co-benefits and risks, socioeconomic co-benefits and risks, and upscaling production.

5.4 Threats

Several threats have been identified for seaweed farming (Fig. 13). Regarding the climate, rapid upscaling of seaweed commercial use pathways for carbon sequestration and GHG emissions reduction could have unforeseen environmental and social risks. Regarding the environment, habitat competition with seaweed farms may degrade sensitive ecosystems, such as seagrass beds and coral reefs, when farms are placed directly over these habitats. The high dispersal of biological material in the ocean also may lead to the spread of pathogens and invasive species and genetic pollution from seaweed farms to the environment, particularly when appropriate mitigation measures are not in place. Infrastructure to support seaweed farming may compromise marine megafauna conservation and worsen plastic pollution when farms are not appropriately sited and managed.

Socioeconomic threats of seaweed farming include the loss of seaweed farming livelihoods and degradation of cultural services in coastal regions if the industry is not properly managed. Coastal communities in developing countries could be exploited when seaweed farming yields adverse health effects and low income, and seaweed farming projects could be stalled when local stakeholders are not consulted early and often in the farm development process. Accumulation of heavy metals in seaweeds pose a risk to human health if seaweed farms are not appropriately sited and seaweed food products are not properly monitored and regulated. Finally, emerging diseases and pests and ongoing climate change could threaten the upscaling of seaweed farming production.

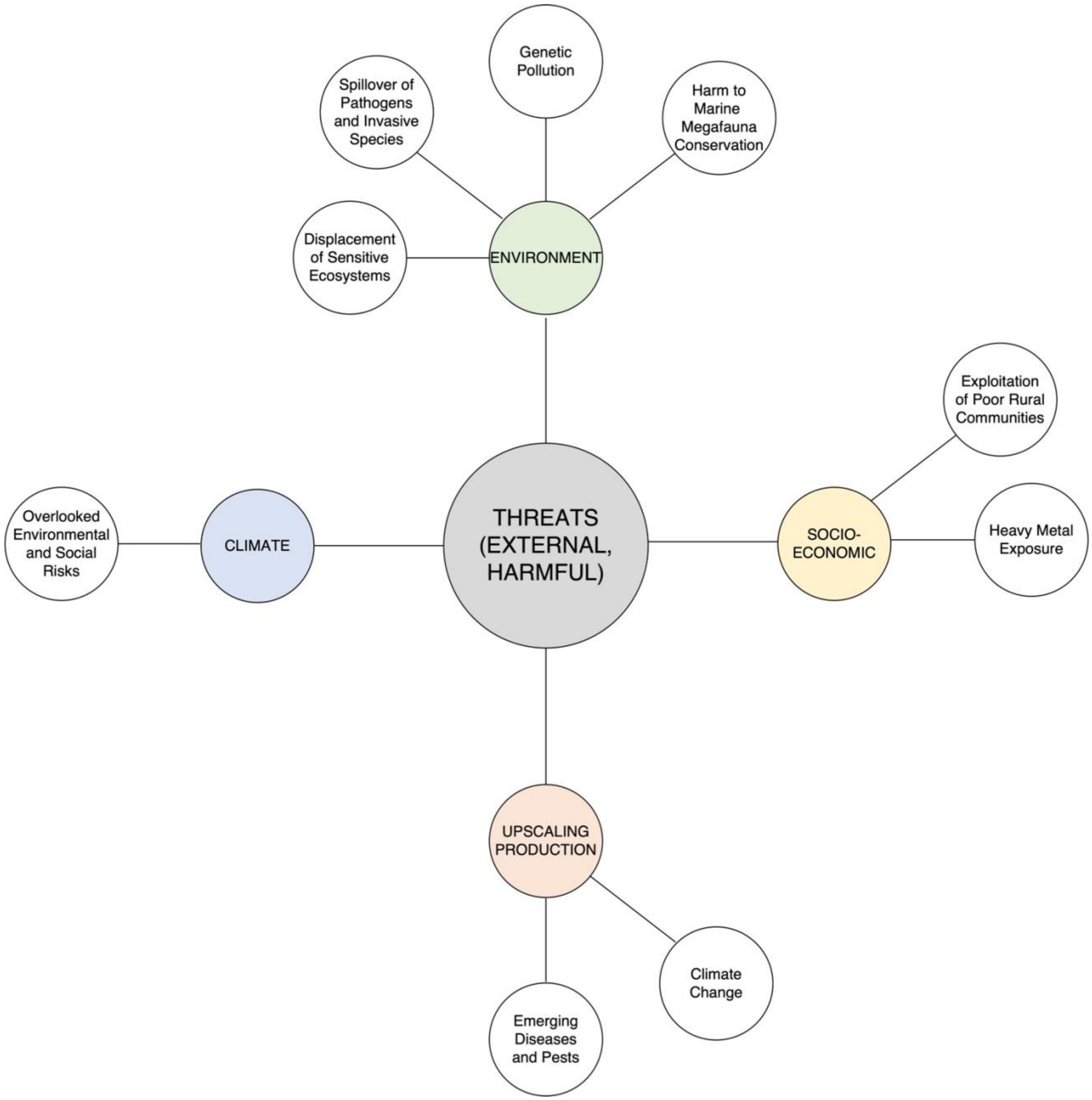
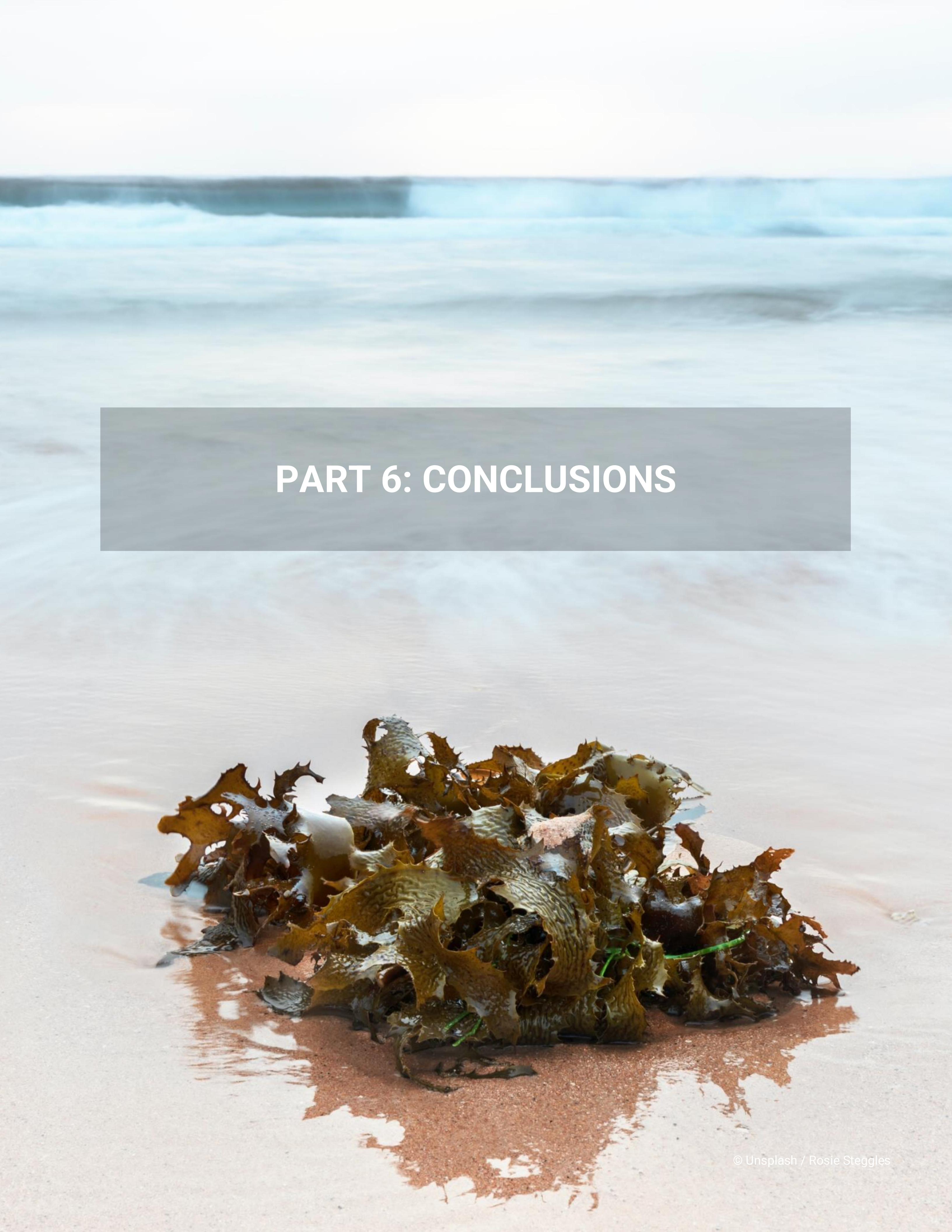


Fig. 13. Major threats (external and harmful factors) for seaweed farming relating to the potential for climate benefits, environmental co-benefits and risks, socioeconomic co-benefits and risks, and upscaling production.

PART 6: CONCLUSIONS



The seaweed farming industry has seen rapid growth in recent decades, and while this growth has been maintained to some degree in top-producing countries with strong biotechnology markets and research outputs, it has slowed in top-producing countries with limited access to and control of these resources by women and men. Research is needed to overcome major environmental and socioeconomic barriers to seaweed farming production, including outbreaks of crop diseases and pests. In countries where seaweed farming is a nascent industry, research and innovation can be strong, yet expansion of the industry is limited by factors such as social license to operate and a lack of regulatory support.

Various approaches have been identified in the literature to overcome the limitations to global seaweed farming production, including an MSP approach, crop innovations, advanced technology and infrastructure, global biosecurity, market and product development, and new economic incentives and regulatory support. It is important to note that the adoption of such measures should occur only under careful consideration for the environmental and socioeconomic benefits and risks of an upscaled seaweed farming industry. By proceeding carefully and taking swift action to fill the gaps that exist in scientific understanding across many environmental and socioeconomic benefits and risks, as identified in this report, it may be possible to open a sustainable pathway for the expansion of seaweed farming. Additionally, interactive participatory engagement and collaboration on gender, social inclusion, and adoption of gender responsive laws and policies will be important in contributing to the development of a sustainable and equitable seaweed farming industry.

Seaweed farming has the potential to advance many (13 of 18) of the beneficial contributions of nature to people identified by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, as part of a circular bioeconomy, if the risks are appropriately mitigated (Fig. 14). These benefits encompass: habitat creation and maintenance, regulation of climate, regulation of ocean acidification, regulation of freshwater and coastal water quality, regulation of hazards and extreme events, energy, food and feed, materials and assistance, learning and inspiration, physical and psychological experiences, supporting identities, and maintenance of options (IPBES 2019) (Appendix A, Table A1–A3, A5). Dedicated research towards identifying the contexts wherein sustainable expansion of seaweed farming can contribute to society, particularly towards solutions to the urgent climate crisis, is strongly warranted.

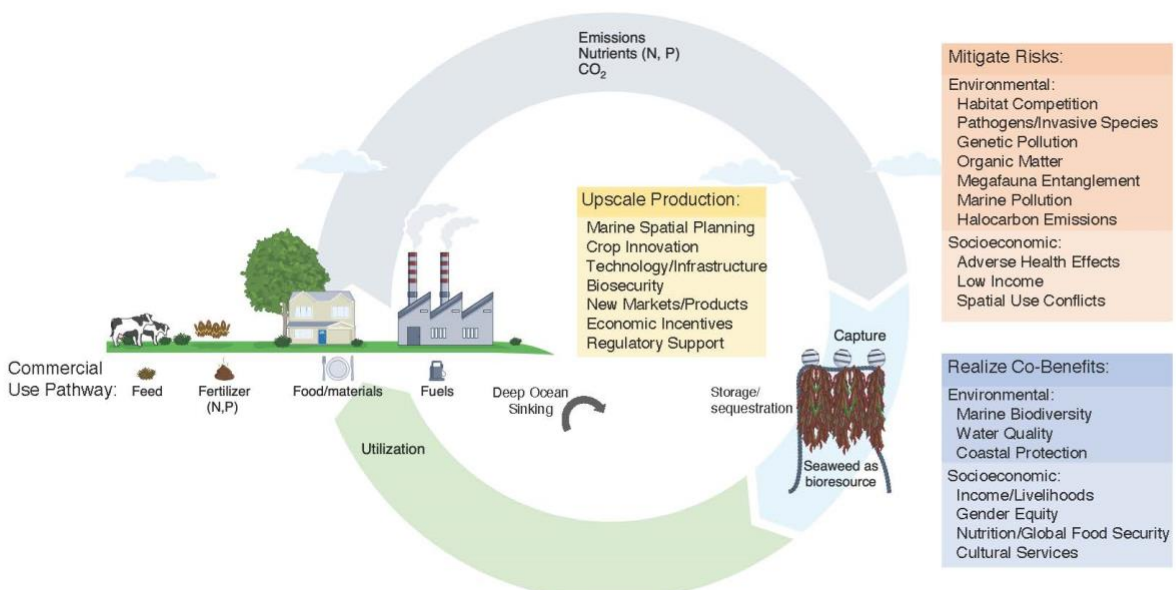


Fig. 14. Seaweed farming as part of a circular bioeconomy (wherein carbon and nutrients are recycled through seaweed commercial uses such as feed, fertilizer, food, and fuels) could yield carbon sequestration and GHG emissions reduction. The potential climate benefits of seaweed farming and associated environmental and socioeconomic co-benefits and risks require further research, but where the benefits are deemed to outweigh the risks, approaches exist to upscale production. Based on Duarte *et al*. (2022a).

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APPENDIX A: Tables

Table A1. Quantitative data relating to the potential for natural carbon sequestration as a climate benefit of seaweed farming.

Location	Farmed Species	Climate Benefit	Metric 1	Metric 2	Source
Lidao town, China	*Saccharina japonica* and *Gracilaria lemaneiformis*	Carbon dioxide absorption / flux of CO_2 into sea from air	286.44 vs. 307.25 µmol L^{-1} aqueous pCO_2 at seaweed farms vs. reference area	−34.85 vs. −24.17 mmol m^{-2} d^{-1} sea-air CO_2 flux in seaweed farms vs. reference area	Jiang *et al*. 2013
Long Island Sound/ Bronx River Estuary, USA	*Gracilaria tikvahiae*	Carbon built into biomass	Up to 300–727 kg C ha^{-1} held		Kim *et al*. 2014
Long Island Sound/ Bronx River Estuary, USA	*Saccharina latissima*	Carbon built into biomass	Up to 1,200–1,800 kg C ha^{-1} held		Kim *et al*. 2015
Republic of Korea	*Ecklonia cava* and *Ecklonia stolonifera*	Carbon built into biomass	~10 t CO_2 ha^{-1} y^{-1} held		Chung *et al*. 2013
China	Various species	Carbon built into biomass	421.78 t C km^{-2} y^{-1} held		Zheng *et al*. 2019
Global	Global	Refractory component of DOC	0.36t C ha^{-1} seaweed farm		Hughes *et al*. 2012
Sungo Bay, China	*Saccharina japonica*	POC export	58 per cent ww seaweed released	61 per cent gross C production released	Zhang *et al*. 2012
Norway	*Saccharina latissima*	POC export	8–49 per cent dw seaweed released	63–88 g C m^{-2} y^{-1} released	Fieler *et al*. 2021
Global	Global	Upper-bound carbon sequestration	0.67 Tg C y^{-1} removed		Turan and Neori 2010
Global	Global	Upper-bound carbon sequestration	0.68 Tg C y^{-1} removed		Duarte *et al*. 2017
Global	Global	Upper-bound carbon sequestration	0.76 Tg C y^{-1} removed		Kim *et al*. 2017
Global	Global	Upper-bound carbon sequestration	0.78 Tg C y^{-1} removed		Sondak *et al*. 2017
Across China	Various species	Carbon built into biomass and natural sequestration	605,830 t C y^{-1} held	344,128 t C y^{-1} sequestered	Gao *et al*. 2022
Global	Global	Natural carbon sequestration	0–205 kg CO_2 Mt^{-1} dw seaweed y^{-1} sequestered		emLab 2019
Global	Global	Seaweed farming carbon footprint (pre-processing)	-62–287 kg CO_2 Mt^{-1} dw seaweed		emLab 2019

Table A2. Quantitative data on the potential commercial use pathways for climate mitigation.

Location	Farmed Species	Commercial Pathway	Metric 1	Metric 2	Metric 3	Source
Global	Various	Seaweed biofuels	1,500 t CO_2 km^{-2} y^{-1} in potential avoidance of fossil fuel emissions			Duarte *et al.* 2017
Global	Various	Seaweed biogas	0.78 t C ha^{-1} in potential sequestration			Hughes *et al.* 2012
Global	Various	Seaweed ethanol	Up to 2.9 per cent global emissions reduced compared to gasoline			emLab 2019
Global	Various	Seaweed bioethanol	10 kg CO_2 eq ha^{-1} in net climate change reduction			Thomsen and Zhang 2020
Global	Various	Seaweed biogas	1870 kg CO_2 eq ha^{-1} in net climate change reduction			Thomsen and Zhang 2020
In vitro	*Asparagopsis taxiformis*	Seaweed in steer feed	99 per cent reduction in methane at 2 per cent addition rate			Machado *et al.* 2016
Australia	*Asparagopsis taxiformis*	Seaweed in sheep feed	80 per cent reduction in methane at 3 per cent addition rate			Li *et al.* 2016
Australia	*Asparagopsis armata*	Seaweed in dairy cattle feed	26 per cent reduction in methane at 0.5 per cent addition rate	67 per cent reduction in methane at 1 per centaddition rate		Roque *et al.* 2019
Australia	*Asparagopsis taxiformis*	Seaweed in beef cattle feed	40 per centreduction in methane at 0.1 per cent addition rate	98 per cent reduction in methane at 0.2 per cent addition rate		Kinley *et al.* 2020
Global	*Asparagopsis*	Seaweed in cow feed	Up to 2.3 per cent of global emissions reduced			emLab 2019
Global	Brown	Land crop displacement	12 kg CO_2 eq kg^{-1} of seaweed protein produced			Sadhukhan *et al.* 2019
Across China	Various	Land crop displacement	62,492 ha saved in land resources			Zheng *et al.* 2019
Global	Various	Land crop displacement	4 million L freshwater saved per ton of food produced at sea			Radulovich 2011
Across China	Various	Land crop displacement	16,554 t N saved in fertilizer use	5503 t P_2O_5 saved in fertilizer use	7255 t K_2O saved in fertilizer use	Zheng *et al.* 2019
Global	Brown	Land crop displacement	1 kg CO_2 eq kg^{-1} of inorganics produced			Sadhukhan *et al.* 2019
Global	Various	Deep ocean sinking	Up to 0.43 per cent of global emissions reduced considering carbon market			emLab 2019

Table A3. Quantitative data on the potential for environmental co-benefits of seaweed farming.

Location	Farmed Species	Environmental Co-Benefit	Metric 1	Metric 2	Source
West of Ireland	*Laminaria digitata*	Biodiversity provisioning	42 species in farmed holdfasts		Walls *et al.* 2016
Costa Rica	Various species	Biodiversity provisioning	3 vs. 14 fish species in control vs seaweed plot	~5 vs. 100 fish individuals in control vs seaweed plot	Radulovich *et al.* 2015a
China	Various species	Buffering against acidification and oxygenation	0.03–0.1 units higher pH, 27.3–113.9 µatm lower pCO_2, and 0–0.29 units higher Ω_a	0.02–0.35 mg L^{-1} higher dO_2	Xiao *et al.* 2021
Great Barrier Reef	Modelled *Chlorophyta* and *Phaeophyta*	Buffering against ocean acidification	0.1 increase in Ω_a over a 24 km^2 area		Mongin *et al.* 2016
Across China	Various species	Oxygenation and nutrient removal	1,440,612 t O_2 y^{-1} produced	59.07 t N and 7.50 t P km^{-2} y^{-1} removed	Zheng *et al.* 2019
Across China	Various species	Oxygenation and nutrient removal	2,533,221 t O_2 y^{-1} produced	70,615 t N and 8,515 t P y^{-1} removed	Gao *et al.* 2022
Long Island Sound/ Bronx River Estuary, USA	*Gracilaria tikvahiae*	Upper-bound nutrient removal	28–94 kg N ha^{-1} removed		Kim *et al.* 2014
Long Island Sound/ Bronx River Estuary, USA	*Saccharina latissima*	Upper-bound nutrient removal	38–180 kg N ha^{-1} removed		Kim *et al.* 2015
Jiangsu Province, China	*Pyropia yezoensis*	Nutrient removal	3688 t N $season^{-1}$ removed	106 t P $season^{-1}$ removed	Wu *et al.* 2017
Jiangsu Province, China	*Ulva*	Nutrient removal	77 t N $season^{-1}$ removed	3 t P $season^{-1}$ removed	Wu *et al.* 2017
Across China	*Saccharina japonica*, *Gracilariopsis* and others	Nutrient removal	75,000 t N y^{-1} removed	9,500 t P y^{-1} removed	Xiao *et al.* 2017
Across China	Various species	Nutrient removal	75,000 t N y^{-1} removed	9,500 t P y^{-1} removed	Zheng *et al.* 2019
Across China	Various species	Nutrient removal	70,615 t N y^{-1} removed	8,515 t P y^{-1} removed	Gao *et al.* 2022
Global	*Pyropia/Porphyra*, *Gracilaria*, *Kappaphycus/Eucheuma*, kelp, and *Sargassum*	Upper-bound nutrient removal	65,000 t N y^{-1} removed		Kim *et al.* 2017
Sungo Bay, China	*Saccharina japonica*	Nutrient removal	54 per cent gross N production released		Zhang *et al.* 2012

Table A4. Quantitative data on the potential for environmental risks of seaweed farming.

Location	Farmed Species	Environmental Risk	Metric 1	Source
Sweden	*Saccharina latissima*	Light attenuation	40 per cent attenuation at 5 m depth beneath farm	Visch *et al*. 2020
Zanzibar	*Eucheuma* and *Kappaphycus*	Seagrass biomass decrease	40 per cent lower under farm than in control plots	Eklöf *et al*. 2006b
China	*Saccharina japonica*	Reduction in surface currents	Average 40 per cent reduction by farm	Shi *et al*. 2011
Panama	*Kappaphycus alvarezii*	Farmed seaweed species invasion	Up to >30 per cent cover by invasive algae in wild habitats	Sellers *et al*. 2015
China	*Saccharina japonica*	Sedimentary acid volatile sulfide content	1.22 vs. 0.14 mg g^{-1} dw in farm vs. control, respectively	Zhou 2012
Tropics	Various species (primarily rhodophytes)	Current halocarbon emissions	2 per cent of wild macroalgae emissions	Leedham *et al*. 2013
Tropics	Various species (primarily rhodophytes)	Increase in halocarbon emissions	12–20 per cent of wild macroalgae emissions at future farming area	Leedham *et al*. 2013
Global	Global	Increase in halocarbon emissions	1 per cent more global emissions at 50 times greater farming area	Duarte *et al*. 2022a

Table A5. Quantitative data on the potential for socioeconomic co-benefits of seaweed farming.

Location	Farmed Species	Socioeconomic Risk	Metric	Source
Indonesia	Various species	Estimated number of households supported	267,000 households	Langford *et al*. 2021
Philippines	Various species	Estimated number of people supported	100,000–150,000 people	Hurtado 2013
The United Republic of Tanzania	Various species	Minimum number of people supported	30,000 people	Msuya *et al*. 2022
India	Various species	Estimated number of near-future households supported	200,000 households	Krishnan and Kumar 2010
Kenya	*Eucheuma* and *Kappaphycus*	Percentage of women farmers	75.2 per cent	Mirera *et al*. 2020
Zanzibar	*Eucheuma* and *Kappaphycus*	Percentage of women farmers	90 per cent	Eklöf *et al*. 2012
Across China	Various species	Production of iodine	4,954 kg I km^{-2} y^{-1}	Zheng *et al*. 2019
Netherlands	*Saccharina latissima*	Iodine intake	300 µg d^{-1} intake	Vellinga *et al*. 2022
Portugal	*Saccharina latissima*	Iodine intake	208 µg d^{-1} intake	Vellinga *et al*. 2022

Table A6. Quantitative data on the potential for socioeconomic risks of seaweed farming.

Location	Farmed Species	Socioeconomic Risk	Metric	Source
Spain	Various species	Heavy metal exposure	0.025–4.82 mg kg^{-1} dw cadmium concentration	Besada *et al*. 2009
Spain	*Hizikia fusiforme*	Heavy metal exposure	32.1–69.5 mg kg^{-1} dw inorganic arsenic concentration	Besada *et al*. 2009
United Kingdom	Hijiki seaweed (scientific name not given)	Heavy metal exposure	67–96 mg kg^{-1} inorganic arsenic concentration in unprepared seaweed	Rose *et al*. 2007
United Kingdom	Hijiki seaweed (scientific name not given)	Heavy metal exposure	5.1–23 mg kg^{-1} inorganic arsenic concentration in prepared seaweed	Rose *et al*. 2007
Netherlands	*Saccharina latissima*	Heavy metal exposure	1.02 µg kg^{-1} bw d^{-1} total arsenic concentration	Vellinga *et al*. 2022
Portugal	*Saccharina latissima*	Heavy metal exposure	1.67 µg kg^{-1} bw d^{-1} total arsenic concentration	Vellinga *et al*. 2022

UNITS AND SYMBOLS

bw	Body Weight
C	Carbon
CO_2	Carbon Dioxide
d	Day
dO_2	Dissolved Oxygen
DOC	Dissolved Organic Carbon
dw	Dry Weight
eq	Equivalent
g	Gram
Gt	Gigaton
ha	Hectare
I	Iodine
K_2O	Potassium Oxide
kCal	Kilocalorie
kg	Kilogram
km	Kilometer
L	Liter
m	Meter
mg	Milligram
mmol	Millimole
Mt	Megaton
N	Nitrogen
O_2	Oxygen
P	Phosphorus
P_2O_5	Phosphorus Pentoxide
pCO_2	Partial Pressure of Aqueous Carbon Dioxide
POC	Particulate Organic Carbon
s	second
t	Ton
Tg	Terragram
wk	Week
ww	Wet Weight
y	Year
µatm	Microatmosphere
µg	Microgram
µmol	Micromole
Ω_a	Aragonite Saturation State

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