Carbon Sequestration by Seaweed:

Background paper for the Bezos Earth Fund EDF workshop on seaweed carbon sequestration

Environmental Defense Fund
Natural Climate Solutions

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Authors

Rod Fujita
Jamie Collins
Kristin Kleisner
Douglas Rader
Annie Mejaes
Simona Augyte
Poppy Brittingham
Environmental Defense Fund

Contact

Rod Fujita - *rfujita@edf.org*

Acknowledgments

The authors acknowledge contributions that helped build a foundation for this work, including the work of Laura Chavez Anderson and Aukai Manson. We also appreciate discussions with Kristin Kleisner, Camrin Braun, Sarah Cooley, Doria Gordon and the many scientists and experts who participated in the EDF/Bezos Earth Fund consensus workshop on natural climate solutions in the open ocean.

How to cite this report

Fujita, R. M., Collins, J. R., Kleisner, K. M., Rader, D. N., Augyte, S., and Brittingham, P. A., 2022. Carbon sequestration by seaweed: background paper for the Bezos Earth Fund - EDF workshop on seaweed carbon sequestration. Environmental Defense Fund, New York, NY. URL

Version 2, 3/28/22

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About this report

This is one of three reports produced by the Environmental Defense Fund (EDF) ocean science team as part of a two-year EDF project on natural climate solutions (NCS). With financial support from the Bezos Earth Fund, EDF seeks to build consensus around the scientific readiness, market suitability, socioeconomic dimensions and pathways to large-scale uptake of NCS within four major parts of the earth system – tropical forests, temperate forests, working (agricultural) lands and the oceans. The ultimate objective of EDF's work is to identify scalable interventions that could preserve or magnify NCS pathways and that are ready to implement – i.e., interventions that are likely to result in durable carbon sequestration via a NCS pathway, are likely to generate co-benefits and that present low risk of adverse social, economic or ecological adverse impacts. We also identify where further scientific and policy research is needed to result in NCS that meet these criteria.

Within the ocean system specifically, EDF is examining three sets of potential NCS interventions:

- Interventions in the open ocean, including carbon sequestration via the rebuilding of biomass in large marine mammals and epipelagic fishes, and the potential for avoided emissions by restricting or limiting new fishing in the mesopelagic ocean or benthic trawling,
- various interventions to conserve, restore and increase the productivity of macroalgal (seaweed) systems (natural beds and farms) to avoid GHG emissions and sequester more carbon (C) and
- interventions to conserve, restore and manage vegetated, coastal blue carbon ecosystems such as mangroves, marshes and seagrasses to avoid GHG emissions and increase C sequestration.

The present report attempts to describe the state of the science, including key uncertainties, surrounding the second set of pathways – those based on macroalgal ecosystems and aquaculture. EDF has prepared companion reports on the state of the science surrounding the open ocean and coastal blue carbon pathways. Together, these ocean system reports served as inputs for a series of complex systems mapping workshops in which EDF engaged more than 60 outside experts to critically evaluate our initial findings; to identify co-benefits, risks, tradeoffs and equity concerns associated with the various pathways; and identify any promising additional pathways for carbon sequestration or avoided emissions. As such, the present report is just a starting point for discussion and exploration of the scientific and socioeconomic dimensions surrounding macroalgal NCS pathways, and does not necessarily reflect the consensus of EDF's macroalgal workshop participants. EDF is separately investigating the market readiness of pathways associated with forest and agricultural systems.

Executive Summary

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The purpose of this paper is to provide a review of the literature on what is both known and unknown about seaweed as a Natural Climate Solution (NCS), with respect to the need to characterize current and potential future carbon sequestration by seaweeds. We first summarize the existing literature on carbon sequestration by seaweeds. We then propose three "interventions" aimed at increasing seaweed-based carbon sequestration, and evaluate the potential of each intervention for enhancing carbon sequestration by seaweed and for generating co-benefits (such as habitat provisioning and the alleviation of ocean acidification), social impacts and ecological impacts. Finally, we describe the degree to which each intervention may be ready for implementation by evaluating them against criteria defining a high quality carbon credit (i.e., how credible carbon removal would be) (EDF et al., 2020 and 2021).

Definitions:

Carbon market: A market in which units — allowances or credits — are traded between entities. When units are used for voluntary purposes or where carbon credits are certified solely by voluntary programs or standards, the market is often referred to as a "voluntary" carbon market. Where units are used to satisfy legal compliance obligations, this is often referred to as a "compliance" market.

Nature-based solutions (NBS): The full range of values humans derive from natural systems, defined by IUCN (2020) as "actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits".

Natural climate solutions (NCS): A subset of NBS that directly addresses the GHG reduction benefits (i.e., increase carbon storage and/or avoid greenhouse gas emissions) that humans derive from natural systems via conservation, restoration, and/or improved management actions.

Carbon Dioxide Removal: process in which carbon dioxide gas (CO_2) is removed from the atmosphere and sequestered for long periods of time.

Monitoring, Reporting and Verification: A system or protocol for tracking specific methods and outcomes, transparently communicating specific information, and validating that the information is accurate and complete. Often abbreviated as MRV.

Carbon capture and storage: the process of trapping carbon dioxide produced by burning fossil fuels or any other chemical or biological process and storing it in such a way that it is unable to affect the atmosphere.

Blue Carbon: carbon sequestered mangrove forests, seagrass beds and tidal marshes (Mcleod et al., 2011). More recently, some have broadened the definition to include all carbon "captured by the world's ocean and coastal ecosystems" (NOAA NOS, 2021).


UNSPLASH | BENJAMIN JONES

Introduction

In this paper, we review existing literature on carbon sequestration by natural seaweed stands and seaweed farms, the co-benefits that are associated with seaweed, and risks that could be associated with seaweed as a NCS. We also evaluate three proposed interventions aimed at expanding carbon sequestration by seaweed against criteria for a high quality carbon credit (as defined by EDF et al., 2021) in order to describe the degree to which each intervention may be ready for implementation and what activities may be required to develop high quality carbon credits based on seaweed.

In a recent workshop, NCSs based on marine ecosystems – namely mangroves, marshes, seagrasses, epipelagic fishes, mesopelagic communities, large marine mammals, and seaweed – were compared with respect to carbon sequestration potential, co-benefits, risks, and the degree to which interventions comport with the attributes of a high quality carbon credit. We anticipate that the outputs of this exercise will inform the development of policies, blue carbon markets/offsets, research programs, and other activities aimed at implementing ocean-based NCSs, including those based on seaweed. We also hope to identify activities that may be necessary to develop high quality carbon reduction projects based on seaweed.

Additionally, we convened a separate working group and models for workshop participants who wished to work together to improve estimates of carbon sequestration by seaweeds in different types of seaweed farms. To facilitate this, we have developed seaweed farm archetypes (see Appendix – Seaweed Farm Archetypes for Data and Models Working Group) to account for context-dependent factors that strongly influence carbon sequestration such as nutrient availability, strength of advection to sediments and deep water, harvest cycle, products and uses of the seaweed, etc. The outputs of this working group would ideally serve as an input to the development of a robust protocol for monitoring and verifying carbon sequestration by seaweeds.

Carbon sequestration by natural seaweed stands

Seaweeds take up dissolved carbon (C) from seawater and convert it to organic compounds and biomass (Paine et al., 2021) via photosynthesis at rates that are among the highest on the planet (Packer 2009). The dissolved C removed by seaweed is slowly replaced by atmospheric CO_2 (NASEM 2021 report and references therein), resulting in a flux of CO_2 from the atmosphere into the ocean.

While seaweeds fix C rapidly, and store it for a time in biomass, only a portion of this C is sequestered on a timescale of centuries or millennia. Some of the fixed C is grazed, then remineralized to CO_2. In some cases, grazing can remove a large fraction of the seaweed biomass. For example, Krumhansl and Scheibling (2012) estimate that 82% of kelp productivity is removed by grazing. Some of the carbon fixed by seaweeds is exuded as dissolved organic C (DOC), a portion of which is also remineralized to CO_2 in surface waters. The total quantity of C sequestered by seaweeds is thus affected by many factors, including the gradient in CO_2 concentration between the ocean and the atmosphere, the amount of loss to grazing and DOC remineralized in surface waters, the amount of seaweed C that is transported to sediments or deep waters as fragments and C adsorbed onto particles or as DOC (Krause-Jensen and Duarte 2016). Krause-Jensen and Duarte (2016) present a useful diagram depicting flows of C through a generalized seaweed stand:

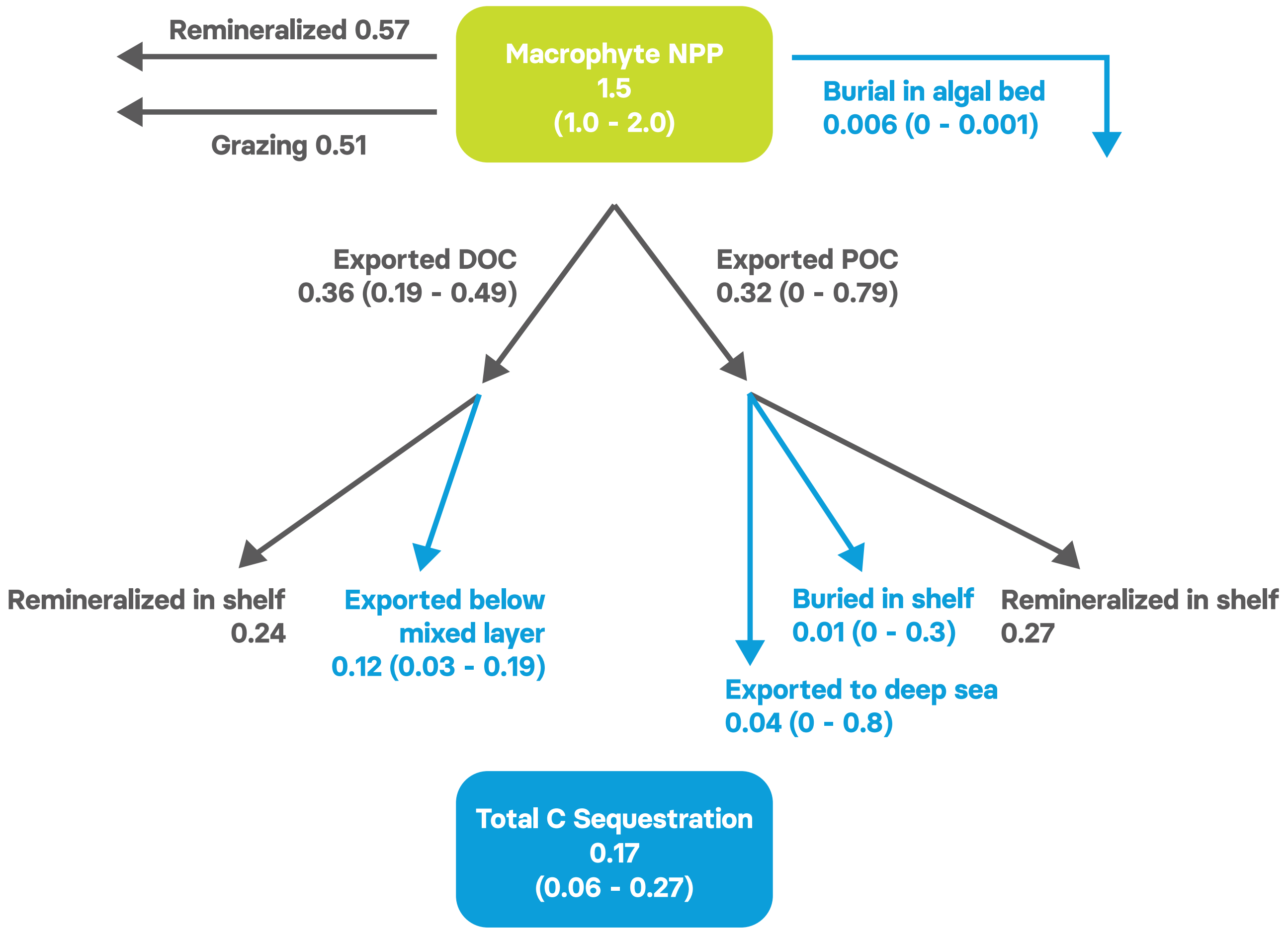

FIGURE 1.
Synthesized pathways of carbon export and sequestration by natural macrophytes if these seaweed popilations could be grown to their maximal extent (values in Pg C/yr). The blue text represents exported carbon that is thought to be sequestered for long times; black text is rapidly remineralized and exchanged with the atomosphere. Values in parentheses represent 25 percent and 75 percent quartile uncertainty levels.
Source: Redrawn from Krause-Jensen and Duarte (2016).
From NASEM 2021.

The rate at which DOC is exuded from seaweeds and the degree to which it is remineralized strongly influence how fast and how much C is sequestered. It is estimated that 30% – 50% of the net primary production of seaweeds is released as DOC. Some of the DOC exuded by seaweed is considered labile and has a short lifespan of days to weeks as it is consumed by microbes and remineralized as CO_2. Some of the DOC can be refractory – i.e., resistant to rapid microbial degradation – and can be exported to the deep sea via advection (flow) (Carlson et al., 1994, Hansell 2013). In this paper, we take "refractory" to mean resistant to degradation and release of C on a timescale of hundreds of years, given our focus on carbon sequestration. The proportion of labile to refractory DOC exuded by seaweeds remains uncertain and probably depends on species and environmental conditions. Watanabe et al. (2020) estimated that 56% - 78% of the DOC released by temperate *Sargassum* stands is refractory after 150 days. However, the relevant timescale for carbon sequestration is >100 years, so more studies will be necessary to ascertain the fraction of refractory DOC on this timescale.

The rate of C sequestration by seaweeds remains uncertain but it is estimated that if all the suitable habitats for seaweed were actually inhabited by seaweed (e.g., if large-scale seaweed afforestation were to occur), these ecosystems would sequester about 0.173 Pg C yr^{-1} (equivalent to 0.635 Pg CO_2 yr^{-1}) – about 11% of their net productivity (Krause-Jensen and Duarte 2016). This estimate of potential carbon sequestration via seaweed afforestation was reported with extraordinarily high uncertainty; the authors estimated the sequestration rate could be as high as 0.268 Pg C yr^{-1} (0.98 Pg CO_2 yr^{-1}), or as low as 0.061 Pg C yr^{-1} (0.22 Pg CO_2 yr^{-1}). Nevertheless, seaweeds may be sequestering more carbon than some other ocean-based biological pathways; the seaweed sequestration rate and associated uncertainty are of the same magnitude as the 0.077 – 0.204 Pg C yr^{-1} (0.28 – 0.75 Pg CO_2 yr^{-1}) estimated to be sequestered by all coastal blue C ecosystems (mangroves, tidal marshes and seagrass stands) combined (Howard et al., 2017). Various methods have placed the extent of natural seaweed stands, including kelp forests, at between 1.4×10^6 ha (minimum estimated extent) (Duarte et al., 2013) and 5.7×10^6 ha (maximum possible extent, based on modeled habitat) (Gattuso et al., 2006). The 3,500,000 km^2 reported by Krause-Jensen and Duarte (2016) is based on a Monte Carlo bootstrap simulation that combined all available literature values. The amount of "additional" C sequestered via restoration of seaweed stands will depend on the amount of initial standing stock, the area reforested, the degree to which standing biomass can be maintained and other factors.

Different types of seaweed process C differently, with implications for the overall rate of sequestration by different macroalgal ecosystems. For example, calcifying algae assimilate C via both photosynthesis and calcification; the latter process releases one molecule of CO_2 for every molecule of calcium carbonate that is produced, offsetting at least some of the C sequestration benefit attributable to photosynthesis alone. The carbonate minerals fixed in this way are an important component of carbonate sands, which eventually become consolidated into carbonate rocks. Calcifying algae can also grow on seaweed, complicating the estimation of carbon sequestration by a seaweed bed. Depending on the ratio of calcification to photosynthetic C fixation, this could even result in a net flux of CO_2 into the water under certain conditions for species such as *Sargassum* (Bach et al., 2021). Gallagher et al. (2022) noted that the net C budget of a given naturally occuring seaweed ecosystem – i.e.,, whether the system ultimately serves as a net sink or source of C to the atmosphere – is determined by the balance between a number of different, simultaneous biogeochemical processes that include photosynthesis, calcification, microalgal uptake of DOC exuded by seaweeds and export of both dissolved and particulate C. Importantly, Gallagher et al. (2022) also found that the net contribution of a seaweed bed to the global C cycle depends heavily on the way ecosystem boundaries are defined; some systems that exchange C heavily with other parts of the ocean, or in which rates of heterotrophic respiration are substantial, may serve as net sources of C rather than sinks.

The role of pelagic seaweed in C sequestration is less well understood. Accumulations of pelagic seaweeds can become quite large due to ocean gyres and eddies that concentrate floating species like *Sargassum*. These seaweeds can form very large floating masses (Davis et al., 2021). It has been estimated that about 10% of the production of *Sargassum* in the Atlantic sinks to the seafloor in deep water as fragments, and there are also massive episodic injections of pelagic seaweed biomass into deep water during storms (Krause-Jensen and Duarte 2016). Both the chronic and episodic advection of this biomass presumably result in the sequestration of at least some of the C in that biomass. There is considerable uncertainty over the amount of C stored in pelagic seaweed aggregations, with Hu et al. (2021) suggesting that Sargassum in the North Atlantic could potentially store up to 3.61 x 10-3 Pg C. Pelagic seaweed aggregations can sometimes have adverse impacts as the biomass starts to decompose after reaching shallow waters and beaches (Davis et al., 2021), resulting in damage to coastal ecosystems, undesirable odors and other nuisance factors, as well as some release of C to the atmosphere. To sequester the carbon stored in this seaweed biomass, it would be necessary to harvest the seaweed and direct the biomass into a sequestration pathway. However, this may pose ecological risks as pelagic seaweeds are important habitats for many species, both at sea and after the biomass strands on beaches (Piñeiro-Corbiera et al., 2021; Bustamante et al., 2017). These seaweeds are also an important source of fixed carbon and nutrients to coastal ecosystems, including beaches (SAFMC 2002).

The context-specific factors that influence C fluxes through seaweed stands must be better understood to accurately quantify C sequestration. Rates that determine C sequestration by seaweeds – including CO_2 flux from the atmosphere to the ocean, C fixation into biomass, labile and refractory DOC exudation rates, fragmentation rates and rates of advection – are all likely to vary with dominant species, bed density, harvest intensity, nutrient availability, grazing intensity, season and other factors. They will also likely vary with environmental conditions, such as whether the seaweed is subjected to high current and wave energy, steepness of the gradation of the bottom to depth, etc. (NASEM 2021).

While standing stocks of natural seaweed stands have been widely studied, the amount of C present within seaweed stands is highly uncertain. We could not find estimates of total seaweed biomass that take into account pelagic seaweed biomass. Calcifying algae and the sediments derived from them may represent a significant pool of biologically sequestered C – some portion of which could be stored for millennia as carbonate minerals – but the magnitude of C stored in this pool is unknown (NASEM 2021). We have developed a preliminary estimate of the total amount of C present in natural seaweed stands (1.3 – 9.5 Pg C) by combining data reported in several sources on the potential coastal area seaweeds may occupy based on their light requirements and light availability on the seafloor (Duarte et al., 2017; Gattuso et al., 2006; Graham et al., 2007; Muraoka 2004), and by assuming that elemental composition and areal density can be estimated by a representative species, the kelp *Laminaria* spp. Seaweed species vary markedly in C content and areal density; however, additional data and models accounting for these differences are needed for a more accurate estimate of C stocks in natural seaweed stands.

Natural seaweed stands probably sequester relatively small amounts of C relative to other NCS pathways for several reasons. While seaweeds take up C rapidly and may represent a fairly large (but highly variable) stock of C, turnover rates are high relative to other C stocks such as forests, or even large fish and whales (compare 1 – 2 years for some kelp forests with 50 – 100 years for the woody biomass in some tropical forests).

Natural seaweed populations have declined very steeply in certain regions due to climate change, fishing pressure, excessive sedimentation and other factors (e.g., a 93% decline in kelp cover was observed off California from 2008–2014), with global kelp forest declines occurring two and four times faster than coral reefs and tropical forests, respectively (Feehan et al., 2021). These declines may be offset by increases in other areas, resulting in a relatively small global average decline rate of 1% or 2% (Krumhansl et al., 2016). If the average decline rate is indeed small, this might equate to low C sequestration potential via seaweed stand conservation and restoration since restoration potential, on average, would also be low. On the other hand, the potential for additional C sequestration via seaweed stand restoration would be high for specific stands, depending on the availability of suitable habitat and the extent of seaweed biomass loss. Restoration of seaweed stands that have been lost offers an opportunity to store a one-time pulse of "new" or "additional" C into seaweed biomass for as long as the biomass can be maintained. However, because many factors affect biomass levels in seaweed stands they can be highly variable, increasing the vulnerability of the C stored in the biomass to remineralization. Ultimately C sequestration by seaweed on timescales that influence atmospheric CO_2 concentrations depends on the fate of the biomass and of the dissolved carbon that seaweeds exude.

Carbon stored in standing biomass via restoration of natural seaweed stands may prove to be easier to monitor and verify than C stored via exudation of refractory DOC or fragments to deep waters or sediments, as the seaweed biomass would occur in relatively shallow nearshore waters, making remote sensing or even field surveys feasible.

Conservation, restoration and afforestation efforts aimed at increasing C storage and sequestration by natural seaweed stands could be challenging because of context-specific differences in the factors that limit seaweed productivity and longevity of storage, including climate change, depletion of predators of grazing species, sediment input, disease, etc. A recent meta-analysis of seaweed restoration studies suggests a relatively high rate of success (Eger et al., 2022); however, many of these have been small in scale, and the results perhaps do not reflect failures that are unreported in the literature. Eger et al. (2022) report on some large-scale restoration successes as well. The Nature Conservancy offers useful guidance on how to develop kelp forest restoration plans (Gleason et al., 2021). Based on these considerations, we conclude that conservation of seaweed stands will be essential to prevent further C loss from marine systems, and that there is potential to store "additional" C via seaweed bed restoration. Seaweed conservation and restoration would also generate many co-benefits and relatively few social or ecological risks. Emerging restoration models may be capable of delivering social and economic benefits to small-scale fishers (e.g., the Urchinomics model, in which fishers are paid to harvest "empty" urchins from urchin barrens, which are then fed in cultivation systems to be sold into premium markets) (UN The Ocean Decade 2022; Verbeek et al., 2021).

The following questions remain regarding carbon sequestration by natural macroalgae stands:

- Which of the carbon fluxes relevant to C sequestration by seaweeds (atmosphere to ocean, ocean to seaweed, seaweed to microbial and other food webs, seaweed to deep water) are well quantified and which are not?
- What is the best way to measure carbon sequestration rates by natural seaweed stands?
- How might the potential C sequestration by natural seaweed stands compare with other ocean-based C sequestration pathways?
- Is it feasible to sequester C via restoration of natural seaweed stands for long enough to help stabilize the climate?

Carbon sequestration via seaweed farming

Carbon sequestration by natural seaweed stands is constrained by productivity, areal extent, high turnover rate of seaweed biomass, losses of C to DOC exudation and grazing, and the rate of natural advection of refractory DOC and fragments to sediments and deep waters. Seaweed farming can, in concept at least, reduce each of these constraints, thereby dramatically increasing carbon sequestration.

Seaweeds are already highly productive, but productivity can be increased by farming practices that optimize spacing, choice of species or cultivars, timing of seeding and harvesting, and other operational aspects. Some seaweeds, such as the kelps Macrocystis and Laminaria, have very high rates of productivity on the order of ≥3000 g C m^{-2} $year^{-1}$ or $30x10^6$ g ha^{-1} $year^{-1}$. A number of other species have productivity rates per unit area of 1,000 g C m^{-2} $year^{-1}$ (Chung et al., 2011). Selective breeding and farming practices can make them even more productive (Umanzor et al., 2020; Wade et al., 2020). Several breeding programs are ongoing with the kelp Saccharina and Macrocystis, with the goal of enhancing productivity by 20% - 30% (MARINER), while ranges of 30% - 131% have been reported for species cultivated in Asia (Patwary and van de Meer 1992).

Farming seaweeds can also be used to overcome limitations on production imposed by the need for suitable habitat by providing artificial habitat for spore settlement and grow-out. In theory, seaweed can be grown anywhere in the ocean where sufficient light and nutrients are available. Froehlich et al. (2019) estimate that about 48 million km^2 may be suitable for seaweed farming, based on suitable temperature and nutrient availability. However, the extent of potential farmable ocean area remains poorly understood (e.g., there are many potential user conflicts including vessel traffic, fishing, military operations, etc.).

Moreover, we still do not have a full understanding of relevant biogeochemical processes or the possible ecological consequences of seaweed farming conducted at a scale that could remove a significant amount of atmospheric CO_2. However, despite high uncertainty, it seems clear that because less than 0.01% of the suitable ocean area estimated by Froehlich et al. (2019) is currently being used for farming seaweed, all in nearshore waters (Duarte et al., 2017; Froehlich et al., 2019), carbon fixation by seaweeds could be greatly expanded. The quantity of C sequestered by new seaweed farms is likely to vary dramatically depending on siting, operations and the ways in which the yield is used (see Appendix: Seaweed Farm Archetypes for Data and Models Working Group). Hence, the range of C sequestration that may be possible as a result of expanded seaweed farming will likely be very large, even once sufficient data are available on rates of C absorption, remineralization and storage to estimate C sequestration from seaweed farms. At very large scales, nutrient availability and conflicts with other claims on marine space could constrain offshore seaweed farming. Nutrient availability constraints could be overcome via artificial upwelling; however, this could entail added expense and energy inputs (NASEM 2021).

Limitations to carbon sequestration resulting from rapid biomass turnover and natural advection rates in natural seaweed stands can also be overcome in seaweed farms. Seaweed farms can be monitored and regularly harvested, which could result in the conversion of seaweed biomass into refractory products with long lifetimes, such as bioplastics (Sudhakar et al., 2020; Lim et al., 2021), products that result in avoided greenhouse gas emissions, such as biofuels, and to products that may result in some C sequestration in soils, such as soil amendments (Ramya et al., 2015; Wang et al., 2018). A comprehensive database of seaweed products (Phyconomy 2022) has been assembled, and researchers are evaluating the climate and ecological impacts of sinking seaweed, converting it to biofuel, or making food and animal feed products (Davis 2022). Seaweed biomass can also potentially be sunk to the ocean bottom or injected into deep water or stable geological formations to dramatically increase C storage duration (Wu et al., 2021; Sandalow et al., 2021; Zhang et al., 2020; Chopin 2021).

The amount of C stored and the duration of C storage in products currently made from seaweed is probably fairly small, as 40% of seaweed was used as food for direct consumption in 2012 (Bjerregaard et al., 2016). Consumption of seaweed results in rapid return of the C sequestered in seaweed biomass to the atmosphere. Another 40% of seaweed production in 2012 was used to make agar, carrageenan and other hydrocolloid products that are used in processed foods and other products (Bjerregaard et al., 2016). These products also have relatively short lifespans, resulting in limited C sequestration and effects on atmospheric C concentrations. During the extraction of hydrocolloids, the majority of the seaweed biomass goes unused, and thus only a negligible amount of C is expected to be sequestered. However, markets for direct consumption are growing as demand for substitutes for high-impact foods (e.g., meat substitutes) grows; this creates some scope for reducing future GHG emissions.

The remaining 20% of global seaweed yield was used in other nonfood related seaweed products, such as pharmaceuticals, cosmetics and animal feed. Like the food products, these products are also not expected to provide much direct C sequestration due to their relatively short life cycles. Hence, we omit the C stored in seaweed products from our estimate of total C storage in seaweed (Bjerregaard et al., 2016).

Because sinking seaweed grown in farms may result in a C sequestration pathway that is easier to measure than other ocean-based pathways, there has been considerable interest in this pathway by scientists, entrepreneurs and investors (Duarte et al., 2017; Bever 2021; Froehlich et al., 2019). The 2021 study board on ocean carbon dioxide removal (CDR) convened by the U.S. National Academies of Science, Engineering and Medicine (NASEM) estimated that farming a 100 m wide continuous belt of ocean along 63% of global coastline (about 72,900 km^2) could sequester 0.1 Gt CO_2/yr if all the biomass were sunk directly into the deep ocean. This would represent a 45-fold increase from current areal extent of seaweed farming to about 0.2% of the total suitable farmable area estimated by Froehlich et al. (2019). This estimate rests on several simplifying assumptions: (1) 8% of DOC exuded by the seaweed is refractory (undefined in the NASEM 2021 report) and becomes sequestered (low contribution of refractory DOC to sequestration results from harvesting and sinking the biomass); (2) 20% of the biomass is lost to breakage, grazing and other factors; (3) yield will approximate that of a natural kelp forest (1 kg dry weight m^{-2}); and (4) 1.5 harvests will be completed each year. Nutrient availability may constrain the expansion of large-scale seaweed farming. To illustrate the potential scale of nutrient uptake by large-scale seaweed farming: a recent study estimates that by 2026, seaweed farms will use *all* of the anthropogenic nutrient runoff in China (Xiao et al., 2017). There is concern that shading and the highly efficient uptake of nutrients by large-scale seaweed farming could reduce phytoplankton productivity in some areas, with adverse impacts on marine food webs (Campbell et al., 2019; Wu et al., 2022).

Seaweed farming currently involves some fossil fuel use, resulting in GHG emissions. Operating processes (e.g., harvesting) and value-add processes (e.g., drying) could be optimized to reduce or prevent emissions; for example, via conversion to fuel efficient or zero emission boats, changes in flushing rates, the use of low energy intensive drying methods, etc. (Kim et al., 2017, Stévant and Rebous 2021). GHG emissions could also be reduced by altering the mix of products that are made from seaweed, since different product supply chains have very different emissions profiles and store the C absorbed by the seaweed for different lengths of time. Many of these changes could probably be applied to existing seaweed aquaculture operations or incorporated at baseline into new farming activities.

Carbon sequestration is not the only way seaweed farms could help avert catastrophic climate change. In fact, uses of seaweed that result in avoided emissions of CO_2 and other more powerful greenhouse gasses may present options for slowing climate change that are easier to document and verify than carbon sequestration. Application of seaweed-based soil conditioners or biochar may result in some carbon sequestration in soils and perhaps spare the release of GHGs associated with chemical fertilizer production (Smith 2002). Use of seaweed-based soil conditioners may indirectly influence N20 production by changing soil chemistry, especially in slightly acid soils, although more research is needed (Thomson et al., 2012). There is some evidence that the addition of seaweed to soil can also improve crop yields (Roberts et al., 2015; Zacharia et al., 2015; Cole et al., 2015) and crop quality (El-Salhy et al., 2017), which would reduce GHG emissions associated with fertilizer production (Smith 2002) to the extent seaweed-based amendments can replace chemical fertilizers. This application, however, may be limited by the relatively small concentrations of macronutrients present in seaweed biomass (Roleda and Hurd 2019).

Use of seaweed as a biofuel could reduce GHG emissions to the extent it is substituted for fossil fuel or as a feedstock in a bioenergy with C capture and storage (BECCS) system (Hughes et al., 2012). Consumption of seaweed as food could also reduce GHG emissions, to the extent that seaweed replaces other foods that have higher GHG footprints. Several studies suggest that inclusion of small amounts of seaweed in ruminant feeds can result in substantial reductions in methane emissions (Kinley et al., 2016; Maia et al., 2016); the safety and efficacy of this pathway are under active investigation.

There are trade-offs involved with the generation of many of the benefits of seaweed farming. For example, managing a seaweed farm to maximize carbon sequestration by sinking seaweed biomass into deep ocean waters would be expected to reduce the generation of other benefits such as food production, and may pose ecological risks to deep sea ecosystems (NASEM 2021). Conversely, producing food, hydrocolloids and other valuable products from seaweed would likely result in less carbon sequestration, due to the short life cycle of the C in these products. Farms that grow and harvest seaweeds seasonally will likely reduce in situ benefits of seaweed farming, such as amelioration of ocean acidity (Campbell et al., 2019), habitat provisioning (Langton et al., 2019; Campbell et al., 2019) and fishery enhancement (Bertocci et al., 2015).

The following questions remain regarding the effects of seaweed farms on carbon sequestration and GHG emissions avoidance:

- Are there estimates of GHG emissions and C sequestration associated with seaweed farms?
- Do seaweed farms differ significantly in their ability to sequester carbon?
- If so, what are the factors that influence carbon sequestration in seaweed farms?
- Which of these factors are well documented and which remain uncertain?
- Which carbon flows relevant to quantifying C sequestration by seaweed farms are well documented and which remain uncertain?

Co-benefits associated with carbon sequestration by seaweed

Seaweed can generate a number of benefits for marine ecosystems, which are regarded in this paper as co-benefits to the main benefit of carbon sequestration. However, it is important to note that some of these benefits are so significant (while the carbon sequestration benefits are still so uncertain) that they could rightly constitute the main benefits of seaweed farming, with carbon sequestration as a co-benefit. We summarize some of the co-benefits that could be generated by natural seaweed stands and different types of seaweed farms that we believe are either quite common or may become common in the near future.

Seaweed farms and natural seaweed stands have the capacity to ameliorate ocean acidification somewhat (at least locally) as a result of rapid uptake of CO_2, which increases seawater pH (Mongin 2016). They can also contribute to biodiversity (Theuerkauf et al., 2021), habitat provisioning (Langton et al., 2019), heavy metal and nutrient pollution removal (Zheng et al, 2019; Jiang et al., 2020), and fishery enhancement (Rimmer et al., 2021; Theuerkauf et al., 2021). Seaweeds may also improve water clarity by facilitating the settlement of fine sediments originating from soil erosion (Jiang et al., 2020).

In addition to these ecological benefits, seaweed can generate several social and economic co-benefits. These include job creation, which can be especially important in coastal communities that are highly dependent on fisheries and need to reduce harvests temporarily in order to allow fish stocks to recover to sustainable levels. Seaweeds may also enhance fisheries production under certain conditions (e.g., where habitat is limiting fish productivity or habitat connectivity) by improving habitat conditions and by attracting aggregations of target species (Theuerkauf et al., 2021). Seaweeds can be the basis for circular marine bioeconomies, which recycle waste products and generate multiple benefits (Zhang and Thomsen 2019).

Clearly, seaweeds are capable of generating many co-benefits, but the degree to which they generate them depends on the harvesting intensity, as well as siting and other factors. Natural seaweed stands that are not harvested can provide consistent biodiversity and habitat provisioning co-benefits year-round but of course generate fewer social and economic benefits than harvested stands. Annual harvests or trimming to increase social and economic benefits would be expected to reduce the ecosystem benefits somewhat, while frequent harvests could dramatically reduce them. Natural seaweed stands can also remove nutrient and heavy metal pollution and consistently ameliorate ocean acidification.

Tropical seaweed farming typically involves a long growing season, with multiple harvests each year. A tropical seaweed farm that is trimmed, rather than completely harvested, during multiple annual harvests may provide more stable, continuous habitat provisioning. Water clarity and nutrient extraction benefits could also be consistent and especially important in tropical waters, where seagrass meadows and coral reefs depend on high water quality.

Temperate seaweed farming typically has shorter growing seasons, with a single annual harvest; however, diversifying cultivated species may allow for extended farming periods. Typically, the single annual harvest of temperate seaweed farms would remove any habitat available for fish species, so any in situ co-benefits would be temporary or seasonal.

See the Appendix (Seaweed Farm Archetypes for Data and Models Working Group) for more details on how growing season, harvest cycle, nutrient availability and other factors could impact carbon sequestration and the generation of co-benefits in different kinds of seaweed farms.

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Interventions to increase carbon sequestration by seaweed, and their potential social and economic effects

To compare NCS and develop guidance for investors, entrepreneurs and policymakers, it is useful to describe the interventions that would be required to protect or enhance each pathway so GHG emissions are avoided, or that more atmospheric carbon is sequestered. In this section we describe three interventions for implementing seaweed-based carbon sequestration or GHG avoidance. We attempt to characterize the potential to contribute to climate stabilization, co-benefits, social and economic effects and ecological risks that could be associated with each intervention.

Intervention 1: Conserve existing seaweed stands and restore stands that have declined.

This would likely involve research to ascertain context-specific factors causing declines or limiting restoration potential, followed by context-specific threat reduction activities (e.g., harvesting grazing organisms whose populations have exploded due to lack of predation; regulations to reduce fishing pressure on predators of grazing species; reduction of pollution, etc.).

These activities would require policy and regulatory reform in some cases, increased funding or pressure in other cases and new policies and regulations in other cases. There is also an intriguing business model developed by the for-profit company Urchinomics for restoring kelp stands that have declined due to overgrazing by urchins, a common driver of kelp decline (UN The Ocean Decade 2022). The urchins, which are low quality due to lack of sufficient food, are harvested and then fed to produce very high quality urchin roe, which is then sold into high-end markets for premium prices (Verbeek et al., 2021). The next phase of this business model will depend on the development of markets for C sequestration and nutrient removal by the restored kelp stands to finance the removal of more urchins, resulting in more kelp restoration (UN The Ocean Decade 2022; Verbeek et al., 2021).

Implementing entities and specific restoration actions would vary depending on the nature of the threats. For example, if overfishing of predators of herbivores is a major factor limiting seaweed restoration at a site, fishery management agencies could reduce fishing pressure on the predatory species which are often valued fishery targets. On the other hand if excessive turbidity related to deforestation or agricultural practices were determined to be major factors limiting seaweed restoration, entities with jurisdiction over these practices would be engaged, affecting different sets of stakeholders. Programs to build capacity among small-scale seaweed harvesters and connect harvest operations with markets could result in a more equitable distribution of the benefits of conservation and restoration of seaweed stands. Specific interventions would occur in nearshore tropical and temperate waters with sufficient light, nutrients, and substrate availability to support seaweed growth. Carbon reduction via seaweed bed restoration within exclusive economic zones (EEZs) that are sufficiently well documented could be credited in Nationally Determined Contribution accounts.

Potential for C sequestration:

Conservation of existing seaweed stands would not result in additional C sequestration, unlike afforestation of seaweed stands. This remains highly uncertain, but it has been estimated that if large-scale seaweed afforestation were to occur, these ecosystems might sequester about 0.173 Pg C yr^{-1} (equivalent to 0.635 Pg CO_2 yr^{-1}) (Krause-Jensen and Duarte 2016). Currently, most of the yield from seaweed harvesting is used for food and colloid production, limiting the amount of C that is sequestered by natural seaweed stands to the C that is advected to sediments or deep water. Use of larger fractions of harvest from natural seaweed stands to make refractory products or products such as bioplastics, biofuels or fertilizers that result in avoided GHG emissions would enhance the role of natural seaweed stands in climate stabilization, but the potential would likely be low relative to other NCSs.

Co-benefits:

High levels of habitat and biodiversity provisioning, local amelioration of ocean acidification, water quality improvement and fishery enhancement.

Social and economic effects:

This intervention could benefit fisheries and ecotourism, as seaweed stands can be important nurseries for sport and commercial target species and many are attractive dive tourism locations. However, it could also have negative impacts on short-term fishery revenues in contexts which require reductions in fishing pressure to restore predator populations capable of regulating grazing pressure, if that is what is needed to restore a seaweed stand.

Ecological risks:

We do not anticipate large adverse ecological impacts from the conservation and restoration of natural seaweed stands. There may be a risk of genetic bottlenecks if restoration is based on a highly inbred strain, or on only a few such strains.

Intervention 2: Increase productivity and carbon sequestration performance of existing seaweed farms

by identifying and addressing factors that constrain productivity, such as disease, strain selection, pollution, capacity and financing, and address constraints to the development of farms that optimize for carbon sequestration, such as the quantification of carbon sequestration, research to address other aspects of a high quality carbon credit (EDF et al., 2020) and the enhancement of markets for refractory seaweed products and uses. It could be undertaken largely by seaweed farmers, processors, blue carbon accrediting entities and buyers, supported by NGOs and government agencies which could provide extension services and oversight to ensure that efforts to increase productivity do not harm public trust resources or the interests of other stakeholders. In the near term, this intervention would be largely limited to farms located in nearshore tropical and temperate waters, as that is where the vast majority of seaweed farms are currently sited.

Potential for C sequestration:

Potential productivity increases in current seaweed farms would vary depending on local conditions, including nutrient availability, water flow, temperature and other factors. They would also likely depend on local technical capacity. Duarte et al. (2021) assume an average yield of 16t DW ha^{-1} when estimating potential C sequestration by seaweed, and note that this is nearly 10-fold lower than maximum productivity reached under intensified farming conditions. Froelich et al. (2019) use an estimate of 2000t DW km^{-2} (20t DW ha^{-1}) and also note that this is uncertain due to variability in productivity at the farm level. These considerations suggest that potential productivity increases could be large. This in turn could result in proportionally larger amounts of C storage in farmed seaweed biomass; however, the rates of several processes that influence C sequestration could change with increasing productivity, including DOC exudation rate, the fraction of the DOC that is refractory and fragmentation rate. We could find no empirical data on how C sequestration rate scales with increased seaweed productivity.

Co-benefits:

Relatively low levels of additional seaweed habitat and biodiversity, with some enhanced amelioration of ocean acidification and habitat/biodiversity provisioning depending on siting and operations.

Social and economic effects:

Increased productivity of seaweed farms could benefit smallholders who currently dominate seaweed farming operations, as well as operators of offshore farms. This intervention, if highly successful, could also reduce seaweed prices by increasing supply, impacting mostly smallholders who currently dominate production.

Ecological risks:

Higher productivity seaweed farms located in nutrient-poor water could reduce phytoplankton production. Sequestering C by sinking seaweed into deep waters would increase the advection of organic C into deep water which could alter food webs, species composition and oxygen levels via microbial decomposition and respiration.

Intervention 3: Expand seaweed farming.

Most of the expansion of seaweed farming is expected to occur in offshore waters both within and beyond national jurisdictions. Some nations are developing governance systems for offshore aquaculture (e.g., the U.S.), but governance is largely absent as very few commercial ventures currently exist. Research into the social and ecological risks that could be associated with offshore seaweed farms would be required to set performance standards, accountability measures and other elements of an effective offshore governance system. Any governance system would also have to reduce barriers to expansion without compromising social and economic goals. For example, the complexity and cost of aquaculture permitting in U.S. waters is widely recognized as a significant barrier to industry expansion. Solutions may include the establishment of aquaculture enterprise zones where farmers could take advantage of government-subsidized research to prepare permit applications, or operate under an umbrella permit supported by several farms, performance standards and accountability measures to mitigate risks of adverse social, economic and ecological impacts. National plans of action and the incorporation of seaweed C sequestration into Nationally Determined Contribution accounts could also be elements of this intervention that incentivize the expansion of types of seaweed farming that sequester more C than other types.

This intervention would also include an effort to remove barriers to the development of seaweed farms that sequester more C than others, e.g., by quantifying carbon sequestration by different types of seaweed farms, doing research to address other aspects of a high quality carbon credit (EDF et al. 2020) and enhancing markets for products and uses of seaweed that sequester carbon and result in avoided GHG emissions.

Sites and therefore jurisdictions are uncertain and would depend on many factors, including light and nutrient availability, proximity to shoreside support facilities and markets, areas where risk of interactions with marine wildlife is high and others. Siting will also depend on existing claims on marine space and the need to minimize adverse ecological impacts, e.g., reductions in phytoplankton production resulting from nutrient uptake by farms. While these considerations will limit the potential farmable area of the ocean, this is still likely to be quite large. For example, in the U.S. Caribbean and Florida, 80% of the total area within 10–100 m depth is potentially available for seaweed farming or has no conflicts with navigation, natural resources, oceanographic conditions, etc. (NOAA OceanReports 2022). For sugar kelp, *Saccharina latissima*, in Alaska and New England, that number drops to around 20% of the total area available. But for Alaska in particular, a considerable amount of farmable area remains (over 3.5 million ha) (NOAA OceanReports 2022). The large and fragmentary nature of these areas (or intentional siting for this purpose) could mitigate adverse impacts caused by nutrient uptake by the farms.

Potential for C sequestration:

NASEM (2021) estimate that farming about 72,900 km^2 of seaweed and injecting the biomass into the deep ocean could sequester 0.1 Pg CO_2/yr. This could scale dramatically with increasing use of the suitable farming area of the ocean, barring other limiting factors, such as negative impact on phytoplankton productivity, congestion at sea, etc.

Co-benefits:

Most of this expansion would probably occur offshore due to existing claims on nearshore marine space, pollution and other factors. Because floating debris and seaweed are known to attract marine life, it seems likely that this intervention could result in substantial amounts of habitat and biodiversity provisioning. Large-scale seaweed farming could also result in larger-scale amelioration of ocean acidification.

Social and economic effects:

This intervention may primarily benefit entrepreneurs with access to capital and technical expertise, perhaps to the detriment of smallholders, as a result of competition in some markets. To the extent different products are produced offshore, this competition would be reduced. Larger-scale seaweed farming could also pose hazards to navigation, fishing and other uses of offshore waters. This intervention, if highly successful, could also reduce seaweed prices by increasing supply, impacting mostly smallholders who currently dominate production.

Ecological risks:

More seaweed farms could translate into higher risk of wildlife entanglement. Sequestering 0.1 Pg CO_2/yr via sinking seaweed into deep waters would increase the injection of organic C into deep water by about 25%, a very significant increase (NASEM 2021) that could alter food webs, species composition and oxygen levels via microbial decomposition and respiration.

Readiness for implementation

We propose using criteria defining high-integrity carbon credits (EDF et al., 2020) to evaluate which, if any, of the proposed interventions could generate high-integrity carbon credits, and to identify appropriate actions for getting interventions ready for implementation.

The criteria are:

- **Additionality (carbon reduction would not have happened without the project)**
- **Vulnerability of the carbon sequestration pathway**
- **Robust quantification of emission reductions and removals**
- **Significance of risks to permanence of carbon sequestration**
- **Robustness of approaches to achieve permanent carbon sequestration**
- **Adoption of low, zero or negative emissions technology**
- **Contribution to adaptation and resilience including support of poorest and most vulnerable people affected by climate change**
- **Social and economic impacts**
- Avoidance of double issuance, use, claims against domestic and international targets, double counting in carbon markets
- Demonstration of host country commitment to global carbon reduction goals
- Program governance
- Third-party auditing
- Transparency and stakeholder consultation

The following evaluation is based on the criteria from EDF et al. (2020) that seem amenable to scientific analysis (bolded in the list above). The remaining criteria relate to governance and accountability, which we did not explore as part of this report.

Additionality

Intervention 1: Conserve and restore natural seaweed stands. Additionality for restoration, but not for conservation. While conserving existing seaweeds would not result in additional carbon sequestration, unlike restoring seaweed stands that have declined relative to a recent historical baseline. The amount of additional carbon sequestered via seaweed bed restoration would depend on a number of context-specific factors, including the ability to maintain seaweed biomass over time, proximity to deep water, rate of advection of fragments and refractory DOC to deep water, and factors that affect losses of C absorbed by seaweed such as grazing and exudation of labile DOC, and reduced phytoplankton production (with reduced C sequestration) resulting from competition for macronutrients.

Intervention 2: Increase productivity of seaweed farms. High additionality if operations leave seaweed in the water or products and uses are refractory. Increased productivity would increase yield but would only increase C sequestration if biomass is left in the water long enough for fragmentation and advection to occur. If the increased yields are used to produce food, hydrocolloids or other products with short life cycles, additional carbon sequestration via increased productivity would be minimal. On the other hand, if increased yields are sunk, buried or incorporated into soils (i.e., products and uses are refractory) resulting in long-term C storage, additionality would be high.

Intervention 3: Expand seaweed farming. High additionality if operations leave seaweed in the water or products and uses are refractory. Increased seaweed production associated with the expansion of seaweed farming would increase yield but would only increase C sequestration if biomass was left in the water long enough for fragmentation and advection to occur, or if products and uses were refractory.

Vulnerability of the carbon sequestration pathway

Intervention 1: Conserve and restore natural seaweed stands. High vulnerability. Because many factors can influence natural seaweed productivity, C loss and C sequestration, this pathway seems quite vulnerable. Climate change can result in dramatic declines in seaweed productivity (Bennett et al., 2015) and hence in C sequestration (Krause-Jensen and Duarte 2016). Increased grazing pressure resulting from overfishing of predators or other factors can also result in natural seaweed bed decline, which could also reduce C sequestration via DOC and seaweed fragment advection. Some of the C fixed by the seaweed will be stored in grazers and microbes, but on short timescales.

Intervention 2: Increase productivity of seaweed farms. Moderate vulnerability. Because many factors (including climate change) can influence C loss and C sequestration by farms, this pathway could be vulnerable. Vulnerability could be reduced to some extent via strain selection, changes in farming practices,and changes in product disposition.

Harvesting frequently and using the yield to make refractory products, sinking the yield, burying the yield or using the yield to make soil conditioners to incorporate C into soil would reduce vulnerability.

Intervention 3: Expand seaweed farming. Moderate vulnerability. Because many factors (including climate change) can influence C loss and C sequestration by farms, this pathway could be vulnerable. Vulnerability could be reduced to some extent via strain selection, changes in farming practices and changes in product disposition. Harvesting frequently and using the yield to make refractory products, sinking the yield, burying the yield or using the yield to make soil conditioners to incorporate C into soil would reduce vulnerability.

Robust quantification of emission reductions and removals

Intervention 1: Conserve and restore natural seaweed stands. No robust quantifications yet. Estimates of carbon removal by natural seaweed stands are highly uncertain currently. Context-specific research on C flow from the atmosphere through seaweed stands that differ in conditions hypothesized to affect C sequestration (e.g., with differing nutrient availability, delta pCO_2, advection to deep water, proximity to sediments, grazing pressure, fragmentation frequency, etc.) will be required to quantify carbon sequestration by seaweed bed restoration projects.

Intervention 2: Increase seaweed farm productivity. No robust quantification yet.

Intervention 3: Expand seaweed farms. No robust quantification yet. However, Oceans 2050 and other groups of researchers are conducting studies designed to quantify C sequestration by seaweed farms (Froehlich et al., 2019; Duarte et al., 2017; GSP 2022).

Significance of risks to permanence of carbon sequestration

Intervention 1: Conserve and restore natural seaweed stands. High risk. Declines in biomass after restoration, reduced fragmentation rate, reduced fraction of refractory DOC exudation and reduced advection rates to sediments and deep water can all reduce the duration of carbon sequestered by natural seaweed stands.

Intervention 2: Increased seaweed farm productivity. Moderate risk. The duration of carbon sequestration resulting from increased farm productivity would be vulnerable to the extent that sequestration depends on natural processes (production of refractory DOC and advection of seaweed fragments to sediments or deep waters). Currently, reliance on these processes is high. However, reliance and therefore risk to the duration of C sequestration could be greatly reduced by shifting to the production of refractory products and uses. Purposeful sinking of all or most of the seaweed yield from a farm could reduce risks to the permanence of C sequestration, but could pose risks to deep ocean ecosystems. Storage of seaweed biomass into geological formations or applying seaweed to soils would also reduce risks to permanence.

Intervention 3: Expand seaweed farming. Moderate risk. The duration of carbon sequestration resulting from increased farm productivity would be vulnerable to the extent that sequestration depends on natural processes (production of refractory DOC and advection of seaweed fragments to sediments or deep waters). Currently, reliance on these processes is high. However, reliance and therefore risk to the duration of C sequestration could be greatly reduced by shifting to the production of refractory products and uses. Purposeful sinking of all or most of the seaweed yield from a farm could reduce risks to the permanence of C sequestration, but could pose risks to deep ocean ecosystems. Storage of seaweed biomass into geological formations or applying seaweed to soils would also reduce risks to permanence.

Robustness of approaches to achieve permanent carbon sequestration

Intervention 1: Conserve and restore natural seaweed stands. Moderately robust. Natural seaweed stands, both existing and restored, sequester carbon by exporting refractory DOC and biomass fragments to deep water. In addition, restored seaweed stands would store the C absorbed during growth following restoration as long as this biomass is maintained. Bundles of kelp degrade fairly rapidly even at 1700 m depth, but this results in very little change in sediment C concentration, suggesting that most of the seaweed carbon is converted to DIC and DOC (Bernardino et al., 2010 – cited in a NASEM 2021 report). Ocean circulation plays an important role in determining how long seaweed carbon would remain in deep water. Most of the C is expected to stay in the deep ocean for more than 100 years, except perhaps in the western north Atlantic. The Pacific and Indian ocean basins are likely to sequester this carbon for longer periods of time than the Atlantic and Southern ocean basins (NAS 2021).

Intervention 2: Increase productivity of seaweed farms. Highly robust. This could result in robust C sequestration if products and uses are refractory (i.e., have long lifetimes or do not result in the remineralization of C back into CO_2).

Intervention 3: Expand seaweed farming. Highly robust. This could result in robust C sequestration if products and uses are refractory (i.e., have long lifetimes or do not result in the remineralization of C back into CO_2).

Adoption of low, zero or negative emissions technology

Intervention 1: Conserve and restore natural seaweed stands. Low emissions. To the extent that vessels would be necessary to restore seaweed stands, low or zero emissions engines could be used to minimize GHG emissions.

Intervention 2: Increase productivity of seaweed farms. Moderate emissions. Compared with conservation and restoration of natural seaweed stands, farming – even with increased productivity – would be expected to release more GHG emissions. Vessels and other machinery associated with seaweed farms could use low or zero emission engines to minimize GHG emissions. Drying seaweed prior to shipping or processing is the most energy intensive process in most seaweed farm operations. Drying technology can also be converted to use low or zero emission fuels. Transport of the seaweed to markets or sequestration locations may also result in GHG emissions.

Intervention 3: Expand seaweed farming. Moderate emissions. It seems likely that expansion of seaweed farming into offshore waters would entail higher GHG emissions relative to nearshore farming or conservation/restoration of natural seaweed stands. However, vessels and other machinery associated with seaweed farms could use low or zero emission engines to minimize GHG emissions. Drying seaweed prior to shipping or processing is the most energy-intensive process in most seaweed farm operations. Drying technology can also be converted to use low or zero emission fuels. Transport of the seaweed to markets or sequestration locations may also result in GHG emissions.

Contribution to adaptation and resilience

Intervention 1: Conserve and restore natural seaweed stands. High contribution. Restoration of natural seaweed stands will likely enhance biodiversity, functional redundancy and other attributes of resilient ecological systems. To the extent that restoration also results in larger fish populations and ecotourism opportunities, seaweed bed restoration could also increase social and economic resilience by diversifying livelihood opportunities and revenue streams.

Intervention 2: Increase productivity of seaweed farms. High contribution. Habitat provisioning with resulting biodiversity enhancement and increased resilience could result from this intervention to the extent that biomass is left in the water (e.g., via less frequent harvesting or year-round production).

Intervention 3: Expand seaweed farming. High contribution. Habitat provisioning with resulting biodiversity enhancement and increased resilience could result from this intervention to the extent that biomass is left in the water (e.g., via less frequent harvesting or year-round production).

Support of poorest and most vulnerable people affected by climate change

Intervention 1: Conserve and restore natural seaweed stands. High support. Some of the poorest and most vulnerable people affected by climate change live in tropical coastal communities. Many are highly dependent on fishing, which in turn depends on the maintenance of high quality spawning, rearing and grow-out habitats, including seaweed stands. Natural seaweed stands also allow for seaweed gathering, which is an important source of income in some coastal communities.

Intervention 2: Increase productivity of seaweed farms. High support. Almost all seaweed farms are currently located in nearshore waters and operated by smallholders, including some fishers, many of whom are poor and quite vulnerable to climate change due to the lack of economic opportunities in their communities and declines in fish stock abundance due to climate change, particularly in the tropics.

As a result, increased seaweed farm productivity would therefore likely benefit these groups, unless these improvements result in the displacement of smallholders by individuals or firms with greater access to capital and technical expertise.

Intervention 3: Expand seaweed farming. Low support. While some expansion could occur in nearshore waters, potentially benefiting smallholders and fishing-dependent communities, most expansion is likely to occur in offshore waters. This will likely benefit those with access to sufficient capital and technical expertise to carry out offshore operations, rather than smallholders. In addition, a major increase in seaweed supply could disrupt existing markets dominated by smallholders to the extent the products compete in the same markets.

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Conclusions

Seaweeds are, in concept, capable of sequestering significant amounts of atmospheric carbon dioxide. However, the amount of carbon sequestered depends on a number of variables, many of which are context-dependent.

The literature seems to indicate that the major processes that influence carbon sequestration by seaweeds are fairly well understood conceptually, but significant data gaps exist. Estimates of the amount of carbon being sequestered by seaweeds currently depend on extrapolations of the rates of C uptake, C pool size in seaweed biomass, DOC exudation, microbial mineralization, losses to grazing and senescence and advection of C fixed by seaweeds to sediments or deep waters from limited studies for only a few species in a few locations; moreover, data on these fluxes are not often collected simultaneously. However, these rates and pools vary widely, depending on context and species. More empirical, parallel studies of these rates and pools with more species under different environmental conditions would be needed to improve global estimates of seaweed carbon sequestration. It seems likely that the rate of CO_2 drawdown resulting from C uptake by seaweeds will also vary due to variation in CO_2 concentration differentials between the ocean and the atmosphere in different parts of the ocean and at different times of the year.

Quantifying carbon sequestration by specific seaweed farms with respect to the creation of high quality credits (EDF et al. 2020, 2021) requires these data gaps be filled, plus some additional data streams will be required, many of which are also context-specific. These include data on harvest frequency, fraction of biomass harvested, seaweed density, product disposition, GHG emissions associated with seaweed production and processing, and impacts of the farm on other sources and sinks of GHGs. Such data are largely lacking; however, several research efforts are underway to fill these data gaps.

Seaweed stands and seaweed farms already produce many social, economic and ecological benefits, including food and hydrocolloids, livelihoods for smallholders who dominate the seaweed farming industry, alternative livelihoods and supplemental incomes for people and communities with limited economic opportunities, biodiversity provisioning, local amelioration of ocean acidification and some carbon sequestration. However, there are tradeoffs inherent in the generation of these benefits. For example, farms that use seaweed to make food products or hydrocolloids would be expected to sequester less carbon than farms that sequester seaweed biomass in the sea or on land. On the other hand, farms that maximize carbon sequestration would probably generate less food and other valuable products, and co-benefits. A portfolio of farms producing different types of products and uses with different harvest cycles would probably be required to realize all the benefits that seaweeds are capable of providing.

There are several ways in which carbon sequestration by seaweeds could be enhanced: Conservation and restoration of existing seaweed stands, increasing productivity of seaweed farms and expansion of seaweed farming to offshore waters with the creation of enabling conditions that incentivize more C sequestration.

Conservation of existing seaweed stands will be important to avoid C loss from the ocean to the atmosphere and to conserve the many benefits that seaweed generates, but would not result in additional carbon sequestration. Restoration of depleted stands would result in additional C absorption and storage as long as the seaweed biomass is maintained, which may prove challenging given that many factors influence seaweed standing stock. Some of the C fixed by current and restored seaweed stands would be sequestered via advection of fragments and refractory DOC to sediments and deep waters.

This intervention would not likely result in a large increase in additional carbon sequestration because the areal extent of such efforts is constrained by available nearshore habitat. However, it would likely result in a large number of substantial co-benefits, including food production, fishery enhancement, biodiversity provisioning and increased socio-ecological resilience with very low risk of adverse social, economic or ecological impact. This intervention is already underway. Acceleration of C sequestration by seaweeds via this intervention would require research to identify context-specific threats to natural seaweed stands and specific areas where threats are amenable to threat reduction actions such as the reduction of fishing pressure or pollution (rather than threats that require international action) and appropriate substrate (Fredriksen et al., 2020), coupled with enhanced efforts to counter those threats. This can also be expanded to areas that have not traditionally had seaweed farms or have not had natural stands for >20 years (e.g., TBF 2022).

There is also scope for increasing carbon sequestration by increasing the productivity of seaweed farms through improved strain selection and other practices, although it is not known how much additional C sequestration would result. This intervention would result in additionality for existing farms, but carbon sequestration would be constrained by the relatively small area that is currently farmed. Additional productivity in the near term would likely drive the production of carbon labile products such as food and hydrocolloids, given current market structure. This would also constrain the amount of additional carbon that could be sequestered. This intervention is also currently underway. Enhancement of carbon sequestration via this intervention would require more research on high-yield strains for many more species, as well as research on how to improve cultivation methods and remove constraints on productivity such as disease. Capacity building would also be required to mainstream practices that improve farm productivity, particularly in tropical regions where temperatures are already high. New policies and a robust C offset market would probably be necessary to encourage the development of refractory products and uses (e.g., sinking, storage in geological formations, or use as soil amendments) that could leverage increased seaweed productivity to result in increased C sequestration or avoid GHG emissions (e.g., biofuels, bioplastics and use as feed additives to reduce ruminant methane emissions if further research indicates that this is a safe and effective pathway).

Expansion of seaweed farming into offshore waters is perhaps the most promising way to increase C sequestration by seaweeds at a scale that could significantly contribute to climate stabilization. Offshore seaweed farming is becoming feasible given rapid advances in infrastructure, farm operations and monitoring. Farmable area is constrained by rough seas, light and nutrient availability, as well as by proximity to shore-side support infrastructure, claims on marine space, and the need to avoid negative social and ecological impacts. While estimates of farmable area are uncertain, recent exercises that take some of these factors into account suggest that farmable area would be very large relative to the area currently farmed. Further advances in how to safely sequester seaweed carbon, in offshore farming infrastructure and in understanding the fate of carbon absorbed by seaweed grown in different types of farms will likely be necessary to make this NCS viable (NASEM 2021). Significant data gaps must also be filled, and while it may be possible to improve estimates of the C sequestration potential of different types of farms (see Appendix – Seaweed Farm Archetypes for Data and Models Working Group), many of these uncertainties can only be reduced by building highly monitored farms in diverse ocean settings that are optimized for carbon sequestration (NASEM 2021).

As is the case for nearshore seaweed farming, there will be tradeoffs between benefits that offshore seaweed farms could generate. In the near-term, seaweed yield from offshore farms would likely flow into food production, hydrocolloid production and perhaps into some newer high-value products such as nutraceuticals given current markets. This would constrain carbon sequestration in the absence of interventions to incentivize sequestration, such as policy directives, government funding and high integrity markets for carbon offsets based on seaweed carbon sequestration. Collaboration between entities such as Oceans 2050, Ostrom Climate Solutions, Verra, EDF and others working on protocols for quantifying carbon sequestration via seaweed farming would probably be helpful in this respect by reducing uncertainty about what constitutes credible carbon accounting for seaweed farms.

Appendix

Seaweed Farm Archetypes for Data and Models Working Group

At our workshop, we proposed the formation of a seaweed data and models working group for scientists who would like to work together to refine estimates of current levels of C sequestration by seaweed farms and develop monitoring and verification protocols for seaweed-based C sequestration. This group will attempt to agree on which carbon fluxes must be measured in order to quantify carbon sequestration by seaweed stands and seaweed farms, and on how to monitor and verify a seaweed-based carbon offset project based on the criteria for a high quality carbon credit. The group will also strive to create an inventory of existing data streams, identify necessary additional data streams, create an inventory of existing and planned models, and identify ways that we can continue to work together to add value to the global dialogue around carbon sequestration by seaweeds.

Many context-specific factors influence C sequestration by seaweed farms. These include growing season, nutrient availability, harvest cycle and end uses of the yield. While ultimately it will be necessary to monitor every farm that is being used to offset carbon emissions, it may be helpful to define seaweed farm archetypes that capture variation in the most important factors that influence C sequestration to serve as frameworks that could guide the development of common monitoring and verification protocols for different kinds of farms.

Selected seaweed farm archetypes

Consideration of just a few of the factors that influence carbon sequestration by seaweed farms – proximity to carbon sequestration pathways such as deep water, nutrient availability, duration of growing season, harvest patterns and product disposition – yields dozens of possible seaweed farm archetypes. Since this is far too many to evaluate within the scope of our project, we propose a focus on the archetypes that are now common or seem likely to be implemented and which capture a wide range of variation in these factors. We refer to products and uses in which C turns over on a timescale of months to years (e.g., food and hydrocolloids) as “labile,” and to products and uses in which C turns over on a timescale of hundreds of years (e.g., sinking or the production of very durable products) as “refractory” for brevity.

1. **Tropical (long growing season, multiple annual harvests), nearshore, low nutrient, carbon-labile products and uses.** This type of seaweed farming is very common in countries that produce large amounts of seaweed (e.g., Indonesia and the Philippines) (Rimmer et al., 2021; Trono and Largo 2019). We anticipate that seaweed productivity would be quite high despite low nutrient availability given observed tropical seaweed growth rates under these conditions, with some loss to grazing. Advection of refractory DOC and fragments could be relatively low due to intensive grazing, remineralization and distance to deep water. We anticipate that most nearshore tropical seaweed farms will continue to produce carbon-labile products because they are valuable, and because carbon markets and policies do not yet incentivize practices and products that would result in large amounts of carbon sequestration.
2. **Tropical (long growing season, multiple annual harvests), close to sequestration pathways, low nutrient availability, refractory products and uses.** If carbon markets develop, carbon sequestration and other aspects of a high quality carbon credit can be verified, and policies that encourage seaweed-based carbon sequestration are emplaced, we would anticipate these types of farms to increase in number and scale.
3. **Temperate (short growing season, single annual harvest), close to sequestration pathways, high nutrient availability, labile products and uses.** Longer harvest cycles typical of temperate water seaweed farms could result in more C sequestration via fragmentation and advection, as well as co-benefits such as habitat provisioning, fishery enhancement and amelioration of ocean acidification. However, the production of labile products in response to existing price signals and markets would limit C sequestration benefit.
4. **Temperate (short growing season, single annual harvest), close to sequestration pathways, high nutrient availability, refractory products and uses.** Longer harvest cycles could result in more C sequestration via fragmentation and advection, as

well as co-benefits such as habitat provisioning, fishery enhancement and amelioration of ocean acidification. If carbon markets develop, carbon sequestration and other aspects of a high quality carbon credit can be verified, and policies that encourage seaweed-based carbon sequestration are emplaced, we would anticipate these types of farms to increase in number and scale.

We chose these archetypes to facilitate the development of carbon flow maps for use in developing quantification and monitoring programs for different types of seaweed farms. We eliminated archetypes that seem uncommon, such as tropical, high nutrient and close to deep water. We also eliminated archetypes based on types of products and uses that are not directly related to C sequestration.

For example, seaweed farms that produce biomass for conversion to biofuel can spare CO_2 emissions to the extent that the biofuel is substituted for fossil fuel, but this will not result in net CO_2 sequestration and so are not considered in this analysis. Seaweed farms that produce biomass to be used as a ruminant feed supplement could reduce emissions of methane (Min et al., 2021), a potent greenhouse gas, but this pathway would require a separate system mapping exercise. Similarly, it would be necessary to separately map carbon flow through systems that include seaweed farms that produce biomass to be used as soil amendments. We will discuss with the data and models group whether there is interest in adding archetypes that capture these pathways for avoiding GHG emissions.

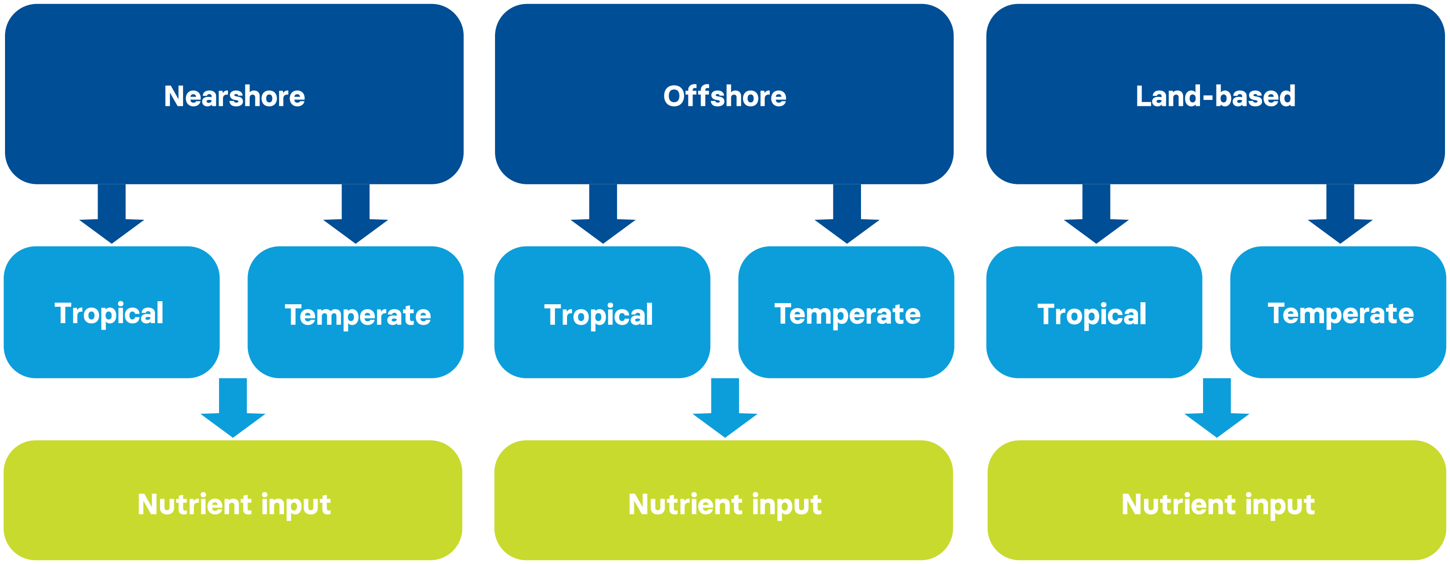
TABLE 1:
Seaweed farm archetypes based on location, climate regime and nutrient availability.

Measure	Type	Definition / Description
Location	**Nearshore**	• Proximate to other nearshore ecosystems • Most versatile regarding farm structure, including bottom, off-bottom, rafting and long-line culture • Close to land • Shallower waters • User conflicts • Proximity to deep water and upwelling • Current movement • Can utilize agricultural runoff as nutrient source • Provide ecosystem services to coastal marine life (enhanced fisheries, biodiversity, ocean acidification remediation)
	Offshore	• Typically stronger currents and rougher conditions • Not able to utilize bottom or off-bottom culture • Can be installed in combination with other structures, such as wind farms and oil rigs • Out-of-state waters – EEZ at three miles from coast • Depth profile is much deeper • Less user conflicts
	Land-based	• This includes the cultivation of seaweed in ponds or tanks, indoors and outdoors, where water is pumped to the algae. • Usually, land-based systems also include a higher control of environmental parameters (including light, water velocity, water residence time, and temperature and nutrient types and amount) when compared to the other types • Control over carbohydrate / protein production • Zero pollution of effluent • May have high costs • Constrained by land, has to be closer to the coast

Measure	Type	Definition / Description
Climate	Tropical	• *Eucheuma, Gracilaria, Hydropuntia, Hypnea, Kappaphycus, Cladosiphon* and *Caulerpa* are primarily cultivated in the tropics and subtropics • Tropical seaweed farms are characterized by year-round growth and multiple harvesting cycles yearly • Oligotrophic waters, low nutrients and low advection to deep water
	Temperate	• *Agardhiella, Gelidium, Gigartina, Porphyra, Saccharina, Laminaria, Undaria, Monostroma* and *Ulva* are primarily cultivated in temperate zones • Temperate seaweed farms are characterized by a limited harvesting cycle • Eutrophic waters and seasonal pulsing of nutrients
Nutrient input	High	• Proximity of the seaweed farm to high-nutrient sources that can be natural (i.e., upwelling) or anthropogenic sourced (i.e., from fish farms, agricultural runoff, sewage, eutrophication and IMTA / co-culture) • Artificial upwelling
	Low	• The absence of nutrient sources proximate to the seaweed farm, resulting in lower nutrient uptake by the seaweed and thus slower growth

It will be important to consider scale for all these farm archetypes, as this will also affect processing capacity and export vs. keeping this in the local areas. Planting density and structure are also important considerations. Scaling up requires strain selection, genetic diversity, as well as diversifying species for cultivation vs. mono-cropping.

Seaweed Typologies Schematic



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