Analysis of Farmed Seaweed Carbon Crediting and Novel Markets to Help Decarbonize Supply Chains

The Nature Conservancy | BAIN & COMPANY

Scope of Analysis

Interest in seaweed as a potential nature-based solution to climate change has skyrocketed in recent years. There is significant energy among NGOs, corporations, startups, governments, and others to explore how seaweed can play a role in sequestering carbon and reducing greenhouse gas (GHG) emissions in supply chains by substituting seaweed for other products, bring us closer to a net-zero emissions future.

In partnership with Bain & Company, The Nature Conservancy (TNC) examined the potential to support significant near-term growth over the next five to ten years in seaweed farming through two analyses:

1. Assessing the creation of a carbon crediting program to provide supplemental income to existing seaweed farmers who adopt practices to increase carbon sequestration and/or new seaweed farmers who are interested in obtaining carbon financing; and
2. Stimulating demand for sustainably grown seaweed by supporting the growth of new end markets for seaweed products that could replace higher-emissions products.

Through this assessment, TNC's goals were to inform next steps for its own Restorative Seaweed Initiative, and to provide clear guidance to seaweed farmers, research partners, governments, fellow NGOs, and foundations.

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KEY RESULTS & TAKEAWAYS

Novel seaweed markets show potential to drive growth while mitigating GHG emissions. Seaweed carbon crediting likely not viable to drive growth at this time.

The value of carbon sequestration from seaweed farms

- Recent analyses have found seaweed farms sequester carbon in marine sediment in quantities ranging from 0 to 8.1 tons of carbon dioxide equivalent per hectare (CO_2e/ha), with a median net sequestration of approximately 0.5 tons of CO_2e/ha.
- Given carbon crediting requirements for additionality (e.g. behavior change) and discounts (e.g. uncertainty), current blue carbon prices at approximately USD$30/ton would not provide significant supplementary income for existing farmers or create economic incentives to establish new seaweed farms, even when using much larger than the median rates for sequestration.
- In order for supplemental income from a carbon crediting program to contribute more than 10% incremental revenue to farmers (an example threshold at which the carbon income could be likely to incent a behavior change) at 5 tons of CO_2e/ha/year—10 times the median sequestration rate—voluntary carbon prices would need to approach $300-500 per ton or additional scientific data or new farming practices would need to be identified that significantly increase carbon sequestration of farms and/or reduce uncertainties.
- Seaweed aquaculture carbon sequestration research is an emerging space and there is a lack of robust datasets. Further research is required to increase current datasets and quantify further sequestration pathways beyond under farm sequestration, which could contribute to overall higher sequestration levels from seaweed farming and reduce uncertainties.

Critical carbon reduction products

- Biostimulants and bioplastics are two of the most promising growth markets for seaweed over the next five to ten years that have the cobenefits of serving as alternatives to more carbon intensive products.
- Seaweed biostimulants, which have been shown to provide numerous benefits such as improved nutrient uptake, plant stress tolerance, and soil quality are a market that is expected to grow approximately 13% per year. Seaweed biostimulants have been found in initial agricultural trials to generate about 50% fewer CO_2e emissions per application than chemical fertilizers.
- Seaweed bioplastics are significantly lower emissions than traditional plastics and, as a "third generation" bioplastic feedstock, are currently one of the feedstocks being explored to replace "first generation" plastic feedstocks (typically food-grade agricultural products) that compete with food supplies and can have less favorable ecological and social impacts.
- Growth in biostimulants and bioplastic markets have potential to drive significant demand for seaweed—up to 1 million tons of seaweed for each by 2027. However, inferred seaweed prices based on biostimulant and bioplastics costs (about 0.10-0.30 USD per lb wet weight of seaweed) may be currently too low to be attractive to farmers and requires intervention for seaweed farmers to access these markets.
- If cost gaps are closed, a significant amount of carbon emissions could be avoided. 1 million tons of seaweed used for biostimulants could lead to 0.1 – 0.4 megatons of avoided CO_2e emissions per year. If additional interventions are made or incentives created to grow seaweed biostimulant demand further to 3 million tons wherein 3% of global cropland used seaweed biostimulants, this could lead to 0.3 – 1.2 megatons of CO_2e emissions avoided per year.
- Given that the current carbon sequestration potential from all seaweed farms globally is estimated to be 0.4M of CO_2 e/ha per year (Duarte et al., 2023), emissions avoided via seaweed products should be given as much, if not more, attention for its role as a climate change mitigation solution.

Growing market demand

- Across both biostimulants and bioplastics markets, the highest intervention needs are to either differentiate seaweed as a premium product worthy of a higher price or bring down the cost of seaweed products via increased efficiencies or establishment of long-term incentives or subsidies for seaweed farming.
- All stakeholders in the seaweed ecosystem have a role to play in in working together to build cohesion throughout the supply chain to help enable efficiencies, encourage sustainable practices, provide stability in market access, and increase attention on seaweeds as a viable and important lower GHG emissions alternative at a global scale and across markets.

Background and Context

Seaweed has been farmed for thousands of years and is well established as a source of food in several world cultures. Today, more than 80% of farmed seaweed is produced in China and Indonesia with approximately 40% of farmed seaweed directly consumed by humans, and another 40% consumed by humans as an additive used in a variety of food products and consumer goods.

By and large, seaweed is grown in nearshore environments. While farming in offshore environments provides an opportunity to expand the industry in new marine areas, continued development and expansion of nearshore farming is currently more economically feasible and attractive for a variety of reasons:

- Water quality improvements, which are well documented and established through the scientific literature. Seaweed can remove excess nitrogen from coastal waterways that contributes to eutrophication in coastal waterways and nearly 500 "dead zones" in the world's oceans.
- Biodiversity benefits in the surrounding nearshore ecosystems, providing forage, shelter and spawning refuge for fish and invertebrates (Theuerkauf et. al 2022).
- Localized ocean acidification buffering by increasing the aragonite saturation levels, which can provide benefits to nearby calcifying organisms (Mongin et al., 2016).
- Low resource requirements for farming when compared to terrestrial farming, including but not limited to fertilizers, freshwater use, and land use.
- Few barriers to entry, low capital and operational expenditure costs to get started, and less specialized knowledge, which all contribute to making seaweed farming an accessible and important economic activity for many coastal communities around the world.

In addition to these benefits, emerging science indicates that nearshore farming can sequester small amounts of carbon in the sediment beneath the farms (Duarte et al. 2023). Given the positive environmental and social benefits and limited drawbacks of seaweed aquaculture, when farmed well, TNC is working to catalyze the growth of "restorative" seaweed farming. TNC has been working on the ground with farmers in Indonesia, North America, East Africa and Central America since 2016 to promote restorative farming practices and enhance livelihood outcomes for farmers.

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Carbon Financing as a Mechanism to Provide Supplementary Income to Farmers and Increase Seaweed Farming

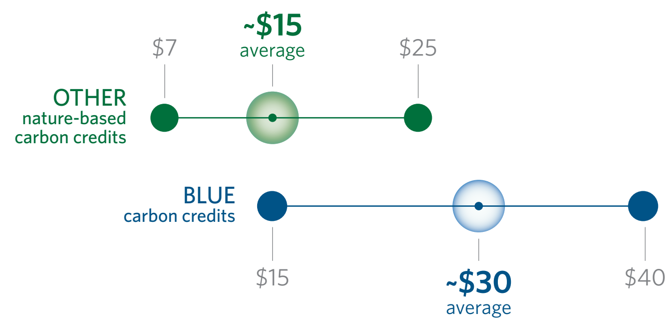
It has long been hypothesized that nearshore seaweed farming could be a carbon sequestration vehicle, given the known mechanisms by which seaweed contributes to ocean carbon. In 2023, Duarte et al. released a pre-print reporting the results of a global study that directly measured the amount of carbon buried and subsequently sequestered in the sediment beneath 20 seaweed farms across 11 countries. None of the sampled seaweed farms were intentionally designed to sequester carbon.

The farms sampled varied in farm age (2 to 300 years), farm size (1 to 15,000 ha), species grown (12 different species across red and brown varieties), yield (1 to 150 tons per ha per year), climate (one tropical and many temperate farms), current and wave exposure, and depth (including intertidal farms and farms located over 30 meters of water). Methods included obtaining and conducting chemical analysis on sediment cores from both farm and reference sites that ranged in depth from 60 centimeters to 1 meter and were obtained prior to seaweed crop harvest. Results showed a range of net sequestration (i.e., the difference between the sequestration of farm and reference sites sampled) from 0 to 8.1 tons of CO_2e/ha, with a median net sequestration of approximately 0.5 tons of CO_2e/ha. Nine of eleven farms (about 80%) with measurements for both farm and reference site sequestration demonstrated the ability to sequester carbon in sediment underneath the farms.

In evaluating the potential for carbon crediting, it is important to consider the price at which carbon credits could be sold. Carbon prices vary across markets and project types, but blue carbon projects for carbon sequestration in aquatic environments typically trade on voluntary markets at about $30/ton of CO_2e.

While providing carbon credits may be of interest to seaweed farmers, there are some unique requirements that must be accounted for. Projects are typically eligible for carbon credits based on the premise of additionality: that is, projects must show that a specific behavior or the project itself would not have been undertaken without the carbon financing. Emissions associated with the project or specific behavior are typically subtracted from the sequestration value for

FIGURE 1. Range of carbon credit prices, by type



crediting purposes. Finally, the number of credits a project ultimately receives is typically discounted based on levels of uncertainty about the permanence of the sequestration as well as the net amount of sequestration.

This means that seaweed farmers would need to prove that specific choices were made to create the right farming environment to be eligible for credits. Given the requirement for additionality (e.g. behavior change) and discounts (e.g. uncertainty) associated with seaweed farming, current blue carbon prices imply there is little economic incentive for either existing farmers to expand their farms or new seaweed farmers to establish new farms specifically for the purpose of carbon crediting.

For example, if a small, 0.5-hectare farm could earn 1 credit per year, this would translate to about $30 in credits annually, which is about a 1% increase even for farms in lower income regions, where average annual incomes average between $2,000 and $5,000. This assumes baseline sequestration at the site of 5 tons of CO_2e/ha/ year (10 times the median rate found in the paper), identification of an additional behavior that could increase gross sequestration by 50%, emissions of about 0.5 ton CO_2e/ha/year associated with the additional behavior (assuming additional activity is as emissions intensive as standard seaweed farming), and about 50% reduction in credits for permanence and uncertainty discounts.

In addition to analyzing potential carbon crediting income for existing farms in lower income areas, analysis was also conducted on a theoretical new and significantly larger

1,000-hectare farm in a higher income temperate area. In this scenario where the environment has lower capacity for sequestration, but the farm could theoretically sequester 50% additional carbon per year through behavior change, this would translate to about $8,000 in credit income annually, which is also about a 1% increase in farm income for a large farm in a higher-income region (estimated against a $1 million operating income farm). This assumes baseline sequestration at the farm of about 1 ton of CO_2e/ha/ year (which is double the median sequestration rate observed in the recent study), identification of an additional behavior that could increase sequestration by 50%, minimal incremental emissions associated with the behavior, and approximately a 50% reduction in credits for permanence and uncertainty discounts.

Under these assumptions, in order for the potential supplemental income from a carbon crediting program to contribute more than 10% incremental revenue to farmers (an example threshold at which the carbon income could be likely to incent a behavior change), carbon prices would need to approach a range of $300 to $500 or practices that can much more dramatically increase carbon sequestration must be identified, submitted to a standards agency for approval, and verified for each project. It's important to note that this space is novel and emerging and further research is required to quantify further sequestration pathways beyond under farm sequestration that could contribute to overall higher sequestration levels from seaweed farming.

Sensitivity analysis for % increase in farmer income

Beyond the limited impact to farmer income, there are significant costs to establishing a project; a 20-year program covering multiple seaweed farming communities at 350 hectares in a tropical Asian nation would likely cost $2 million to $3 million to administer over the course of the program, which even if funded entirely philanthropically, would imply a per-credit administration cost upwards of approximately $170. Administration costs include activities like conducting a feasibility assessment; setting up, validating, and developing the project; and monitoring and verifying the credit. Some individual players may be willing to pay prices of $300 to $500 per ton CO_2e for carbon credits from seaweed farming if they are interested in other co-benefits of the project (e.g., social value, water quality value), but it is unlikely that the market appetite for credits so far above typical blue carbon projects would fund enough new seaweed farms to drive notable growth in the overall seaweed market.

FIGURE 2. Seaweed carbon credit sequestration *(tCO_2 per half hectare farm)*

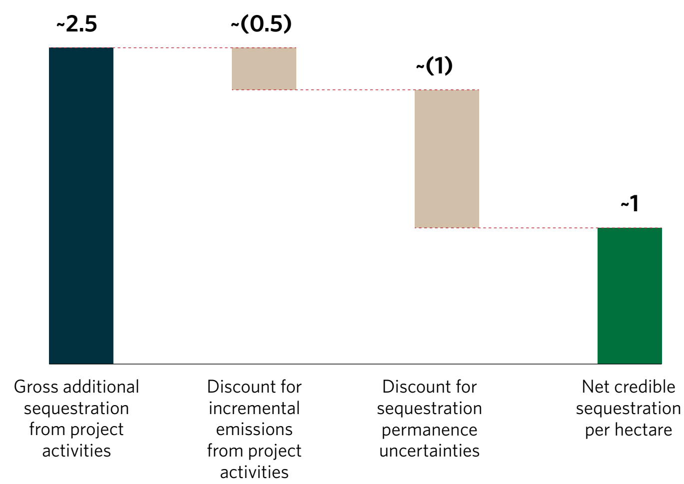


FIGURE 3. Sensitivity analysis for % increase in farmer income

Net carbon credit multiplier vx. baseline

Carbon credit sale price	0.25x	0.50x	1x	2x	3x
$15	<1%	<1%	<1%	~1%	1%
$30	<1%	<1%	~1%	2%	3%
$50	<1%	<1%	1%	3%	4%
$100	<1%	1%	3%	6%	9%
$150	1%	2%	4%	9%	13%
$250	2%	4%	7%	15%	22%
$500	4%	7%	15%	29%	44%

Baseline; < 10% incremental income; 10-20% incremental income; > 20% incremental income

In conclusion, carbon crediting programs are unlikely to provide a significant economic driver to grow nearshore seaweed farming and contribute significantly to farmer incomes unless practices are identified that increase sequestration dramatically more than currently hypothesized, additional data and evidence identifies higher rates of carbon sequestration than those initially identified in the Duarte et al 2023 study, and/or carbon market prices are orders of magnitude higher than they are today.

Driving End Market Demand for Seaweed Farming

Numerous novel use cases for seaweed as direct alternative to more carbon intensive products have been contemplated, but many have yet to be proven at scale (e.g. biofuels). Two of the most promising use cases in the near-term (5 to 10 years) were determined to be biostimulants and bioplastics.

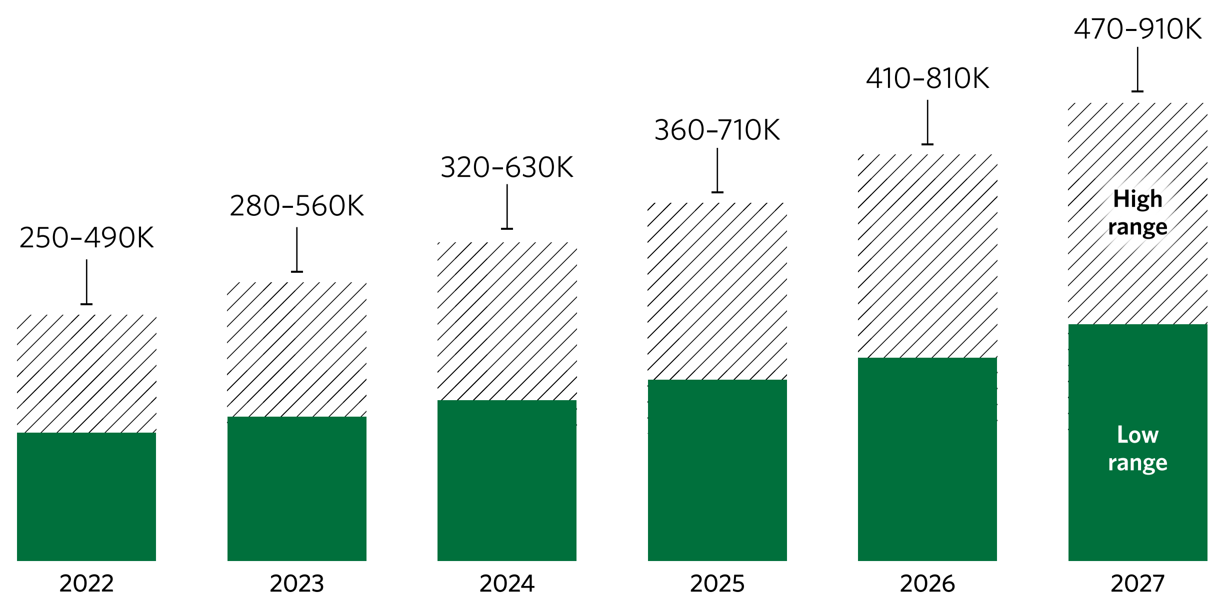
Biostimulants

Seaweed biostimulants have shown numerous benefits when used in addition to nitrogen, phosphorous, and potassium (NPK fertilizers), such as improved nutrient uptake, plant stress tolerance, and soil quality (Boukhari et al., 2020; Illera-Vives et al., 2020; Ali et al., 2021). They make up a meaningful portion of the biostimulants segment of the crop nutrition market today but have yet to gain a meaningful foothold across larger-scale crops. We conservatively estimate seaweed biostimulants are used on less than 0.5% of global farmland today.

The seaweed biostimulants market is about $1 billion today, requires about 250,000 to 500,000 tons of seaweed per year, is expected to grow at a robust 13% per year, and could demand 500,000 to 1 million tons by 2027. Today, the majority of seaweed used in biostimulant production is wild harvested (including *Ascophyllum nodosum*, *Ecklonia maxima*, and *Laminaria digitata*) which could pose problems for ecosystems as the demand for seaweed grows. The price that biostimulant producers are willing to pay for seaweed feedstock is driven by the availability of wild harvested seaweed, making it difficult for farmed seaweed to compete on a cost basis. There is a need to begin to shift this market so that the expected growth can be met by farmed seaweed, thus preserving wild seaweed populations that contribute significantly to ecosystem function.

Even at 13% annual growth, the biostimulant market would contribute only a small incremental increase in the global farmed seaweed market (about 35M tons today), but could contribute significantly to geographies that have emerging seaweed farming industries and produce much smaller amounts (e.g. Europe produces about 11,000 tons and the Americas produce about 23,000 tons). The seaweed volume required to fulfill expected seaweed biostimulant growth could help seed nascent seaweed markets in these areas, if farmed native or naturalized species are used and mechanisms are in place to enable seaweed for biostimulants to be bought at an attractive price for seaweed farmers. The overall seaweed volume required for biostimulants could be higher if adoption became widespread (e.g. about 3 million tons of seaweed would be required if 3% of global farmland used seaweed biostimulants).

FIGURE 4. Estimated range of seaweed used in seaweed biostimulant production *(K, wet tons)*



Bioplastics

Traditional plastics have negative ecological impacts across the lifecycle including carbon emissions created during extraction of the feedstock, processing to make plastic, and waste impacts at the end of life. Bioplastics—moldable plastic materials derived from renewable resources rather than petroleum and often biodegradable—are increasing in market share due to their lower emissions profile. Seaweed bioplastics are lower emissions than traditional plastics through the extraction and processing phases; even the additional energy that may be required to dry seaweed during processing is more than offset by the lower emissions associated with using seaweed as a feedstock. End of life is slightly more complex; most seaweed bioplastics degrade more quickly than traditional plastics after use, which can be a benefit (many seaweed bioplastics are industrially compostable, and a few are home compostable) or a concern (if disposed of in a landfill, seaweed and other biodegradable bioplastics often emit methane as they decompose, similar to foods and other organic matter).

In the bioplastics segment, seaweed competes against other feedstocks (raw materials for an industrial process), many of which are cheaper. Bioplastic from "first generation" feedstocks (typically food-grade agricultural products) are about 2 to 5 times less expensive than seaweed bioplastics, though there are several concerns about using these feedstocks for bioplastics, such as competition with food supplies and fertilizer and freshwater requirements. Newer "second generation" feedstocks (typically agricultural and forestry waste) and "third generation" (other novel feedstocks, including microalgae and seaweed) are being explored as a replacement for

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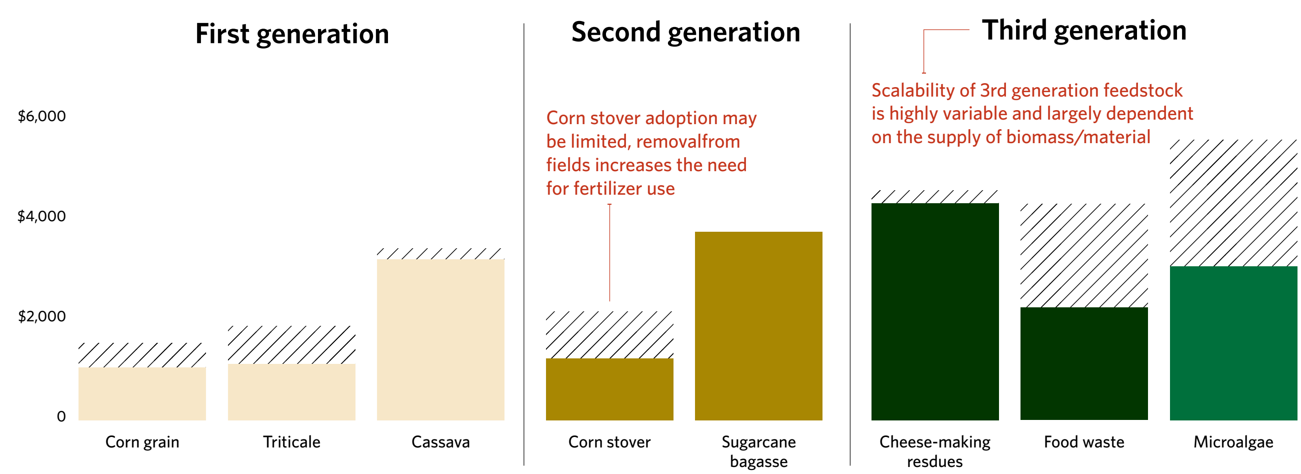
first generation feedstocks, generally with fewer ecological downsides, though some second-generation feedstocks (e.g. corn stover) have alternative uses in regenerative agriculture, generating questions as to whether these feedstocks would serve more ecological benefits in regenerative agriculture than as a bioplastic feedstock. Seaweed is currently more expensive to produce than many of these feedstocks, especially the waste feedstocks being considered.

For seaweed to make meaningful in-roads as a feedstock into the bioplastics market there would need to be a structural change in the cost relative to other feedstocks, such as a large premium market that specifically values seaweed bioplastics higher than other bioplastics, subsidizing seaweed as a feedstock for bioplastics due to the added ecological benefits it has over many other feedstocks, or a dramatic development in processing technology that would enable seaweed bioplastics to be produced at a lower cost than other bioplastics.

FIGURE 5. Production of bioplastics by feedstock source *($/ton, inflation adjusted costs)*



End market implications

Given the obstacles both seaweed biostimulants and bioplastics are facing, growth is likely to be limited to about 1 million tons of seaweed in each market in the near-term without targeted investments from governments, NGOs, and industry. Across both markets, the highest needs would be to either differentiate farmed seaweed as a premium product worthy of a higher price or bring down the cost of farmed seaweed production. The latter could be advanced in multiple ways, including research to bring down processing and drying costs, the development of more efficient methods of farming, and/or activities to establish long-term incentives or subsidies. As seaweed farming is often disincentivized in many newer geographies with farmers facing difficulty in obtaining permits, incentives or subsidies would need to be part of a multi-step process for regulators with the first step being the creation of a clear and transparent permitting framework.

In the biostimulants market, there is an additional need to ensure that growth in production is realized from farming rather than further use of natural resources (i.e., wild harvesting) and support the research needed to increase adoption and prove efficacy of seaweed biostimulants across more crops and nutrient schemes. In the bioplastics market, a focus on cost reductions that could bring seaweed bioplastics into closer competition with alternative feedstocks would be a particularly impactful way to improve the odds of seaweed bioplastics taking a meaningful share in the market.

Several geographies have expressed a particular interest in developing seaweed markets given the ecological and economic benefits of seaweed farming to local communities. Both the biostimulants and bioplastics market could result in sufficient volume demand to seed these industries – though inferred seaweed prices based on biostimulant and bioplastics costs (about 0.10 to 0.30 USD per lb wet seaweed) may be too low to be attractive to farmers in these geographies without some form of intervention, incentive, and/or subsidy.

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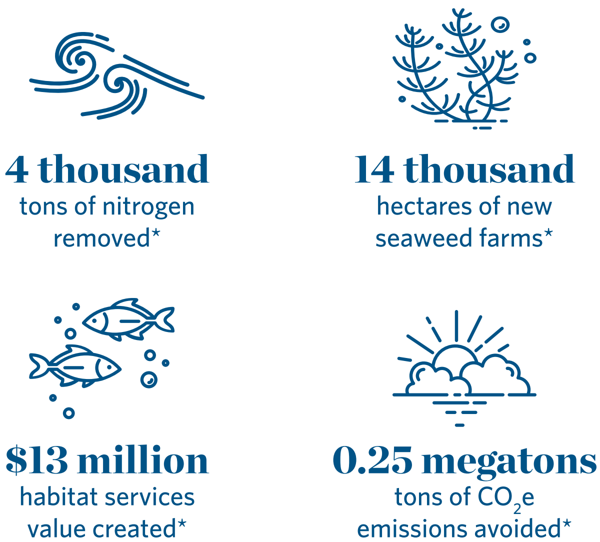
TNC's Priorities for Seaweed Market Development

FIGURE 6.



*Per 1M tons of seaweed produced for biostimulants

Due to the numerous water quality, biodiversity, carbon sequestration, and social benefits of seaweed farming and the carbon emissions reductions achieved when swapping out more resource intensive materials for seaweed, TNC will continue to support the general growth of restorative seaweed aquaculture. This will include supporting growth in markets by:

- Continuing the development of restorative seaweed farming through existing TNC programs focused on encouraging better farming practices globally, and expanding this strategy to include species and geographies that will benefit from new end markets. These benefits are an important component of developing climate-smart industries and will increase the resilience of natural environments, primary production, and communities.
- Exploring alternative or multiple modes of financing, including blended financing, to increase restorative seaweed production.
- Partnering and investing in research and policy developments to help expand the use and prove the efficacy of farmed seaweeds as biostimulants and persuade growth in the biostimulants market to be served by farmed rather than wild-harvested species.
- Selectively partnering, particularly in TNC target geographies, with local farmers and other industry partners to explore new farming methods, drying technologies, processing efficiencies such as biorefinery approaches, and other interventions that can reduce the costs of farmed seaweed production and/or increase the market value of seaweed products, including bioplastics, to enable increased cost competitiveness as a feedstock across end uses.

In targeting and supporting a farmed seaweed biostimulants market, TNC seeks to encourage at least 1 million tons of seaweed farming growth in the near-term, which will result in the ecological benefits listed in Figure 6. If other attractive use cases emerge and mature (e.g., biofuels, animal feed additive for animal health or methane reduction), TNC will consider developing additional active partnerships to further support the development of these markets as well.

Accounting for projected sequestration rates, the current prices offered by global carbon markets, current farming revenues, and the costs of administering a program, TNC will not be pursuing the development of a seaweed carbon crediting program for partner farmers at this time. While data indicates that seaweed farms do sequester some carbon in many cases, carbon crediting is unlikely to increase industry development and farmer incomes under current market conditions. That stated, carbon sequestration is one of the many important ecological benefits of seaweed farming and TNC will monitor the development of the emerging science around nearshore farming carbon sequestration and associated carbon crediting methodologies; if future developments improve the carbon quantity or economic viability of a crediting program, TNC will reassess the viability of establishing and/or partnering on a carbon crediting program.

Messages for Seaweed Partners & Stakeholders

All stakeholders in the seaweed ecosystem have a role to play in helping ensure seaweed farming develops sustainably so that the water quality, habitat provisioning, and carbon benefits of seaweed aquaculture can be scaled to help restore ecosystems while providing important livelihoods, food, and products. Working together will help build cohesion throughout the supply chain, enable efficiencies, provide stability for market access, and increase attention on seaweeds as a viable and important lower GHG emissions alternative that can help us support a net-zero emissions future.

Coordinate funding and development efforts across the value chain, with ecosystem partners leveraging core competencies

Government and regulatory bodies	• **Improve accessibility** of restorative seaweed aquaculture • **Provide subsidies** or incentives for restorative seaweed farming **and grants** for R&D on long-term bets • **Regulate wild harvesting** to manage impact
NGOs, coalitions, funders and industry associates	• Focus on i**mproving the cost position of seaweed** across use cases without compromising sustainability • **Continue to build partnerships** with industry, researchers, and government to leverage core competencies • Advocate for policies that **encourage restorative seaweed aquaculture** and **mitigate risk for farmers**
Seaweed farmers	• Seek out novel and emerging markets, but **remain pragmatic about market risks and opportunities** • **Implement high-yield and restorative seaweed farming practices**
Academia and non-corporate researchers	• **Research foundational qualities of seaweed** to identify unique benefits • **Provide pre-commercial proof points for seaweed solutions** across the value chain • Identify and research **novel processing techniques and product applications**
Corporations and start ups *(including seaweed supply chain)*	• **Focus on product and process development** for specific use cases, including premium, and/or scale end markets • **Invest directly in sustainable supply chains** • Work with NGOs and other partners to support restorative practices

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