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Can Farmed Seaweed Help Restore Ocean Ecosystems, Increase Resilience, and Reduce Greenhouse Gas Emissions?

The State of the Science of Farmed Seaweed's Potential Benefits and Knowledge Gaps in California

Proceedings from a workshop convened by the California Ocean Science Trust

January 2025

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About California Ocean Science Trust

California Ocean Science Trust (OST) is an independent non-profit organization created by state legislation in 2000 to formally bridge the gap between cutting-edge research and sound ocean management. In service of our mandate to provide independent science advice, OST has been playing a proactive role in bridging the science-policy interface by equipping state decision-makers with the latest seaweed aquaculture science and information. By serving as a trusted science-policy intermediary, our goal is to assist in identifying opportunities where new science and research, as well as existing information, can support the advancement of seaweed aquaculture in California.

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Key Findings and Science Needs

Seaweed farms can produce 10-30 times more biomass per unit area than agriculture using almost no land, water, fertilizer, or pesticides. This is generating increased interest in seaweed as a source of food and as a low-carbon feedstock for industrial manufacturing processes. Seaweed farming is a mature and growing global industry. Production is dominated by Asia and is nascent but growing in U.S. waters. California is the fourth-largest seaweed producing state in the U.S. but only produces 318,000 lbs annually from eight farms, about 6% (138,000 lbs/1000 MT) of U.S. production. While there are some entrepreneurs interested in farming and processing seaweed in California, numerous factors present significant barriers to growth for the industry. This includes time-consuming and costly permitting processes, competition with other coastal uses, and lack of high value markets for seaweed, which can limit the cost-effectiveness of farming in California.

Climate change including warming water also poses a risk to both natural and farmed seaweeds. **Research to identify which seaweed species can be successfully cultivated in California along with growth rates and potential yields would be useful for scoping the potential benefits of expanding the California seaweed farming. A better understanding of how to improve the productivity and resilience of seaweed farms could help California seaweed farmers develop successful businesses. Small scale pilot projects and research parks or incubators (e.g., in port districts) would likely generate data on the feasibility of growing and processing seaweed in California.**

Methane emissions from cattle are an important driver of climate change. Some seaweeds native to California such as Asparagopsis spp. strongly suppress methane emissions from cattle when added to feed in small amounts (i.e. less than 2%). No significant adverse impacts to animal health have been found to date of feeding small amounts of Asparagopsis spp. to livestock. Larger doses could result in toxicity or excessive bromoform or iodine levels. Research on the effects of bromoform and iodine residues in meat and milk on humans is underway but so far indicates that these residues may not pose risks to human health at low inclusion rates of seaweed in cattle feed. **Understanding variability in seaweed composition, particularly of bioactive and nutritive constituents, and how these constituents vary in response to growing conditions could result in progress toward standardizing seaweed supplements for livestock (and humans) to ensure high levels of safety and efficacy. It will also be important to quantify the potential impact of seaweed supplements on methane emissions from cattle in California.**

Over 95% of edible seaweed consumed in the U.S. is imported. Inspection of seaweed imports is limited to less than 2%, raising concerns about the safety of seaweed food products. Seaweeds are rich in complete proteins, fiber, and various minerals. **More studies are needed on the long-term human health effects of consuming seaweed, particularly regarding contaminants absorbed by seaweeds and high levels of iodine in seaweeds. This could result in progress toward adoption of standardized methods for evaluating, monitoring, and mitigating food safety risks associated with seaweed.**

Seaweed can contribute to climate change mitigation via several different pathways, including: natural processes that result in the export of carbon absorbed by seaweed to sediments and deep ocean waters where the carbon is sequestered; making products from seaweed that store carbon, replacing more carbon-intensive products, or suppressing methane emissions (e.g., from cattle); and sinking seaweed biomass to sequester carbon dioxide (CO_2). Making climate-mitigating products from seaweed appears to be much more cost-effective and can even be profitable relative to sinking seaweed (which could cost about $540/ton of CO_2 sequestered) as a climate mitigation strategy. **More research is needed to characterize the dynamics of carbon in seaweed farms, including the proportion of absorbed carbon that is sequestered and the effects of seaweeds on drawdown of atmospheric CO_2. More sophisticated models and pilot projects are needed to project environmental impacts of seaweed farming and various climate mitigation pathways using seaweed. Life Cycle Assessments using context-specific data (i.e. from field trials) are needed to evaluate the net impacts of climate mitigation pathways based on a variety of seaweed products on greenhouse gas emissions. Suitability analysis would be helpful to ascertain the suitability of California for seaweed farming and climate mitigation using seaweed.**

Cultivation of kelp spores and sporelings can support kelp restoration efforts, and new methods for improving these efforts are being developed. However, overgrazing by urchins and other herbivores as well as climate change and other factors remain challenges to restoration success. Advances have occurred in seaweed genetics, including the creation of non-reproductive variants (to minimize risk of genetic introgression), seed banks, genetic tools, and new strains of seaweed. These advances coupled with threat reduction strategies could help overcome some of these challenges. **Research to characterize seaweed genetic variation and strains with desired traits is needed to understand the resilience of natural seaweed populations. A better understanding of the risks of genetic introgression associated with the use of seaweed farming methods to help restore natural seaweed populations is also necessary.**

Seaweed farming has the potential to be regenerative, in that it could enhance ecosystem health or recovery from disturbances. However, the term "regenerative" lacks a clear definition. If defined as seaweed farming that regenerates ecosystem structures and functions, regenerative potential will depend on many factors including location, scale, and species selection. Ecosystem services generated by seaweed farms could be increased by siting seaweed farms in areas with high nutrient loads and low oxygen levels (e.g., upwelling zones), degraded native kelp ecosystems, and areas in need of bioremediation. **Research is needed to understand how seaweed farming might regenerate marine ecosystems based on the**

ecosystem services it can provide such as carbon sequestration, water quality improvements, and habitat provisioning. It will also be important to characterize how seaweed farming interacts with surrounding communities and ecosystems. New metrics based on a clear definition of "regenerative" are needed. Research on the potential for seaweed to remediate areas damaged by high levels of nutrient input (e.g., the Tijuana River Estuary) would be valuable.

Background and Workshop Overview

California's kelp forests and other native seaweeds support healthy fisheries, biodiversity, water quality, and coastal protection, while providing cultural and recreational value. Seaweeds have been shown to locally reduce ocean acidification and eutrophication through absorbing carbon dioxide and excess nutrients, respectively. Seaweeds also contribute to mitigating climate change. When seaweed biomass sinks to the deep sea, some of that carbon is sequestered long-term, although the magnitude, duration, and conditions under which sequestration occurs are uncertain. Seaweeds could also serve as alternative raw materials for diverse industrial uses and processes that help lower greenhouse gas emissions, such as biofuels, bioplastics, and construction materials.

A growing body of evidence is showing that seaweed farming has the potential to maintain these benefits of native seaweeds to ocean ecosystems and the climate, and even enhance them, through smart siting and strain selection, and other management practices. This is important within the context of California's ambitious climate, biodiversity, and restoration plans, which aim to achieve net carbon neutrality by 2045, and conserve 30% of the state's land and coastal waters for biodiversity, climate, and access by 2030. Further, California is working to restore and adaptively manage its native bull kelp and giant kelp forests, including through developing a Kelp Restoration and Management Plan - the state's first ecosystem-based management plan.

Many uncertainties remain about how to optimize the benefits of seaweed farming while mitigating risks, the technoeconomic readiness of new seaweed use cases, and the potential for seaweed farming to generate benefits for California. California Ocean Science Trust (OST) hosted an in-person workshop on November 1, 2024 in Sacramento, California to explore the state of the science of farmed seaweed's potential to improve the status of impaired ocean ecosystems, enhance the resilience of healthy ones, and reduce greenhouse gas emissions in California. The workshop convened representatives of California agencies with mandates concerning ocean conservation, resource use, and climate change mitigation and resilience and scientific experts to co-create an understanding of the potential for farmed seaweed to contribute to California's ocean management and climate goals.

The agenda was formatted into short "state of the science" talks by experts from academic research labs and seaweed farming operations, followed by interactive group discussions facilitated by OST to identify the major science needs from the perspectives of those in the room. Other knowledge gaps that impede decision-making for exploring seaweed farming in California, such as regulatory, policy, economic, and social considerations, naturally came up during discussions and were captured in this report (as "Other Needs & Considerations").

This report provides a summary of information shared at the workshop on the state of the science, science needs, and other needs and considerations for understanding the potential role of farmed seaweed in California. It does not represent the entirety of scientific evidence available on seaweed farming.

Seaweed Farming in California

Presenter: Rafael Cuevas Uribe

Seaweed production has become a major component of global aquaculture, with farmed seaweed accounting for 97% of total production, while wild harvests contribute just 3%. In 2022, aquaculture yielded 36.4 million metric tons (MMT) of seaweed, valued at $16.8 billion. China leads the world in seaweed production, generating 61.5% (22.4 MMT) of the total. In contrast, the United States (U.S.) ranks 19th, producing 0.001 MMT (0.002% of global production). However,seaweed farming is emerging as a growth area in U.S. aquaculture, with production increasing fourteen-fold from 2018 to 2022. Yet, farmed seaweed comprises only 10% of U.S. seaweed production, with the remainder sourced from wild harvest.

According to new research presented by Dr. Rafael Cuevas Uribe at the workshop, California is the fourth-largest seaweed-producing state in the U.S., producing 318,000 lbs annually from eight farms. In comparison, Maine leads U.S. production with 1.5 million lbs from 40 farms. Wild seaweed harvesting in California has declined significantly since 2005 due to kelp forest degradation. California farms cultivate ten seaweed species, including Nori, Giant Kelp, Ribbon Kelp, and Pacific Dulse. The state's farms employ a mix of open-water, land-based, and hybrid systems, with an average age of ten years, reflecting an early-stage but established industry. Most farms sell directly to consumers, restaurants, and distributors, though local production remains insufficient to meet in-state demand.

Seaweed is a versatile resource with applications ranging from human consumption to industrial uses like cosmetics, ice cream, and toothpaste. It is cost-effective to grow, requiring almost no freshwater, pesticides, fertilizers, or land. Additionally, seaweed farms can produce 10–30 times more biomass per hectare annually than traditional agriculture.

There are a number of potential "ecosystem services," or benefits, that seaweed offers. Seaweed potentially contributes to carbon sequestration, reduces ocean acidification, removes excess nutrients, produces oxygen, and enhances marine biodiversity. Some species, when added to livestock feed, also reduce methane emissions. However, large-scale production in the ocean poses risks such as nutrient competition, marine mammal entanglement, and habitat disturbance.

Globally, 95% of seaweed is cultivated using open-water long-line systems. Land-based tank culture, such as recirculating or flow-through systems, offers an alternative with advantages like better quality control, higher market prices, and easier permitting. These systems can also integrate with other aquaculture species, such as using nutrient-rich effluent from farmed fish to support seaweed growth.

California seaweed farming faces several challenges, including:

- **Regulatory and Financial Barriers:** Lengthy and expensive permitting processes, costing up to $550 per month per acre, alongside restrictions in certain areas due to seagrass protections.
- **High Costs of Production:** Elevated expenses compared to other regions hinder scalability.
- **Coastal Conflicts:** Competition with other coastal uses limits expansion opportunities.
- **Market Development:** Marketing and selling seaweed profitably remain a hurdle, especially for open-water systems.
- **Climate Change:** Impacts on ocean ecosystems and infrastructure pose long-term risks.

Can Farmed Seaweed Be a Regenerative Livestock Feed?

Presenter: Luke Gardner

Seaweed has drawn significant interest as a sustainable addition to livestock diets due to its potential to reduce methane emissions from ruminants, a major contributor to agricultural greenhouse gas emissions. While certain species, like *Asparagopsis taxiformis*, have demonstrated effectiveness in reducing methane production during digestion, seaweed has not yet been approved as a feed specifically for this purpose. However, kelp is already approved by the California Department of Food and Agriculture (CDFA) for use in livestock diets. Regulatory distinctions categorize ingredients used in quantities above 1% of the diet as feed, while those below 1% are classified as supplements. These distinctions are crucial for determining how seaweed might be integrated into feeding practices. Seaweed's dual role as a nutritional resource and an environmental tool underscores its potential to contribute to sustainable agriculture once regulatory and implementation challenges are addressed.

State of the Science

- **Mechanisms of Methane Reduction:** Certain seaweeds, particularly Asparagopsis spp., contain bioactive compounds like bromoform that inhibit rumen methanogenesis.
- **Seaweed Species Studied:** *Asparagopsis spp*. have been shown to be the most effective at reducing methane emissions, by up to 80% in vivo. The primary active compound, bromoform, has a potent antimethanogenic effect at low inclusion rates (<2% of feed dry matter). *Ascophyllum nodosum* is a widely used supplement in the organic dairy industry (>50%) for its perceived health benefits; however, the literature shows inconsistent effects on methane emissions, likely due to variability in composition and insufficient control in dosing. Other species (e.g., kelp, *Sargassum*) have been studied for their potential but are generally less effective than *Asparagopsis*.
- **Efficacy and Limitations:** Low levels of *Asparagopsis* (<2%) can achieve methane reductions without significant adverse effects. Over-supplementation may lead to toxicity due to bromoform or excessive iodine. For species other than *Asparagopsis*, outcomes vary widely due to differences in seaweed composition, seasonal variation, and experimental conditions.
- **Health and Safety**: Research suggests low inclusion rates of *Asparagopsis spp*. can affect methane reductions without appreciable effects on livestock, human, or environmental health. However, bromoform can be toxic at higher doses. In the marine environment, high levels of bromoform are toxic to marine life. Residues of bromoform and iodine in milk and meat are under investigation, with preliminary results indicating that low doses may not pose risks.
- **Stability and Storage:** Bromoform is volatile and can degrade over time, reducing efficacy. Studies are exploring ways to stabilize it, such as freezing or encapsulation, to maintain potency during storage and feeding.

Science Needs

- **Understanding Variability in Seaweed Composition:** Better characterization of bioactive and nutritive compositions of different seaweeds and how they vary based on different growing conditions. This could lead to developing methods to standardize the composition of seaweed supplements for efficacy.
- **Safety and Health:** More risk assessments of the potential toxic effects of bromoform, iodine, and other potentially toxic compounds on animal health, and potential human health effects of bioactive compound residues in meat and milk. Long-term studies to determine effects of seaweed

supplementation on livestock, human, and environmental health. Research into whether potentially harmful levels of bromoform, iodine, ash, or other compounds could be removed from the seaweed before it is fed to livestock.

- **Economic Analysis:** Studies on the economic viability of integrating seaweed supplements into livestock systems; feasibility of scaling production for the livestock industry.

Other Needs & Considerations

- **Approval Pathways:** FDA approval is required for seaweed or its compounds to be marketed as feed additives with methane reduction claims. FDA bases approval on U.S.-based studies demonstrating scientific validity of the claim. Early engagement with FDA during study design is highly recommended. Following FDA approval, the California Department of Food and Agriculture (CDFA) must approve the product, focusing on ingredient consistency and safety for animals and humans.
- **Claims and Climate Goals:** Methane reduction claims are assessed by California Air Resources Board (CARB), which evaluates the role of such claims in achieving climate goals.
- **Consistency:** Regulatory bodies require consistent product composition, a challenge for seaweed grown in open oceans due to environmental variability. Tank-grown seaweed offers better consistency. Ensuring uniform feeding levels is essential for methane mitigation claims to be viable at scale.
- **Testing Framework:** A clear framework is needed to determine whether testing costs for seaweed safety and efficacy should fall on producers, researchers, or other stakeholders.

Can Farmed Seaweed Be a Regenerative Food for Humans?

Presenter: Torre Polizzi

Seaweed has been a staple in East Asian cuisines (e.g., nori, kombu, wakame) for centuries, with increasing popularity worldwide. Seaweed is being used in innovative applications such as plant-based products, functional foods, and as a natural additive for its gelling, thickening, and stabilizing properties. Over 95% of edible seaweed consumed domestically in the U.S. is imported. The limited inspection of imports—less than 2%—raises concerns about food safety and national security, underscoring the need to expand domestic production.

State of the Science

- **Nutritional Benefits:** Seaweeds are rich in complete proteins (especially green and red seaweeds); contain high dietary fiber (primarily in the form of polysaccharides), which supports gut health; are high in iodine, addressing deficiencies common in many populations; and contain various vitamins and minerals.
- **Food Safety and Risk Considerations:** Seaweed can bioaccumulate heavy metals (e.g., cadmium, mercury) and other contaminants if grown in polluted waters, raising food safety concerns. Overconsumption of iodine-rich seaweed can lead to thyroid dysfunction.

Science Needs

- **Toxicology and Bioavailability Studies:** More studies are needed on the long-term effects of consuming seaweed, particularly regarding contaminants and high iodine intake. Research on how seaweed nutrients are absorbed and utilized by the body is limited.

- **Standardization:** Developing global standards for seaweed safety and quality is crucial for its widespread adoption as a food source, as well as standardized methods to evaluate and monitor potentially harmful toxin and contaminant levels in seaweed to ensure safety for consumption.

Other Needs & Considerations

- **Regulatory Landscape:** No federal food safety regulations exist for farmed seaweed, leaving testing responsibilities to farmers, which is costly and risky. Some states, like Maine and Connecticut, have developed regulatory guidelines where state agencies take responsibility for sampling and testing.
- **Testing Protocols:** Testing responsibilities on farmers discourage investment and expansion in seaweed farming. The lack of streamlined, consistent protocols across states creates challenges for industry standardization.
- **Testing Cost Challenges:** Minimized testing costs for California seaweed farms are critical to support industry growth. Questions remain on how costs should be shared between farmers, government, and industry stakeholders.
- **Market Competition:** Competing with lower-cost Asian seaweed imports is a significant challenge for U.S. seaweed farmers, highlighting the need for efficiencies and support in production, certification, and marketing.

Can Farming and Sinking Seaweed Enhance Climate Mitigation?

Presenter: Kristen Davis

Seaweed is being considered as a strategy for marine carbon dioxide removal (mCDR) through cultivating seaweed in open-ocean farms and sinking the biomass into the deep ocean for long-term sequestration (100+ years). When seaweed is harvested or naturally deposited in deep ocean sediments, it can lock away carbon for extended periods, reducing atmospheric CO_2 levels; however, significant uncertainties remain.

State of the Science

- **Global Potential:** A modeling study estimates it is possible to farm over 1 gigaton (GT) of carbon annually through seaweed cultivation, but it requires utilizing over 1 million km² of the most productive Exclusive Economic Zones (EEZs). Harvest efficiency declines steeply with expanded farmed areas. Nutrient availability and uptake assumptions introduce uncertainty in biomass production estimates.
- **Environmental Effects:** Cultivating and sinking large quantities of seaweed may affect ocean ecosystems in various ways. Potential positive impacts include bioremediation of excess nutrients, habitat creation, and ocean acidification mitigation. Potential negative impacts include alteration of ocean ecosystems, nutrient depletion, carbon leakage, and disrupted sedimentation patterns. Sinking seaweed may affect benthic ecosystems.
- **Costs and Economics:** Sinking seaweed for carbon sequestration costs approximately $540 per tCO_2, with profitability challenges due to high farming and transport costs. Using farmed seaweed to replace high-emission products could yield a profit of $50 per tCO_2-eq, making it a more cost-effective climate mitigation strategy than sinking. Carbon sequestration was found to be most viable in areas like some parts of the equatorial Pacific, where transport costs back to ports were high.

Also applicable to seaweed-based products (below):

- **Sequestration Rates:** Studies show that seaweeds sequester a variable amount of atmospheric carbon dioxide under some conditions, while the rest is remineralized back to carbon dioxide via the marine food web.

Science Needs

- **Carbon Pathways and Dynamics:** Investigate fundamental carbon pathways of seaweed farming and sinking, including the proportion of carbon that reaches below the mixed layer. Assess the long-term atmospheric carbon drawdown from seaweed cultivation.
- **Modeling and Experimentation:** Develop fully-coupled global models to predict near- and long-term environmental effects of large-scale seaweed farming and sinking. Perform field-scale experiments to measure carbon fluxes, inform models, and support development of robust monitoring, reporting, and verification (MRV) methodologies.
- **Environmental Interactions:** Examine the release, composition, and reactivity of dissolved organic matter (DOM) from seaweed farming and sinking of biomass. Study potential impacts of large-scale seaweed farming for mCDR on nutrient availability (e.g., "nutrient robbing") and highly productive fisheries.
- **Suitability and Location Analysis:** Analyze the suitability of locations, including California, for seaweed farming and sinking for mCDR based on site-specific data on the marine environment, nutrient availability, and other relevant factors. Consider regional variability in seaweed bioremediation capacity and its environmental implications.

Also applicable to seaweed-based products (below):

- **Carbon Sequestration and Enabling Conditions:** Quantify the additional carbon sequestration of seaweed farms ("additionality"). Identify and characterize enabling conditions for effective carbon sequestration.
- **Quantification of Carbon Benefits:** Develop methodologies to quantify year-to-year carbon benefits and establish clear metrics for the atmospheric carbon drawdown achieved by seaweed farming.
- **Environmental Impacts of Large-Scale Farming:** Use small-scale field experiments to study environmental effects at the scale required for large-scale seaweed farming. Investigate potential nutrient modifications at scale and downstream effects on fisheries.

Other Needs & Considerations

- **Cost-Effectiveness:** Seaweed may have higher economic value in applications like replacing liquid biofuels for transportation compared to sinking.
- **Diminishing Returns:** Seaweed farming for mCDR in highly productive ocean areas provides initial gains but achieving the next GT of seaweed carbon requires significantly larger areas to farm.
- **Cost Factors to Assess:** Other factors that influence production costs should be included in assessments of sinking farmed seaweed biomass including leasing, permitting, and insurance costs; capital farm costs, influenced by water depth and ocean region; and transportation costs to sinking sites.
- **Assessment Tools:** Available tools for assessing the potential and impacts of seaweed farming and sinking include Ocean Visions' framework for assessing environmental effects of seaweed cultivation and sinking and CarbonPlan's online seaweed farming potential mapping tool.

Also applicable to seaweed-based products (below):

- **Siting and Local Contexts:** Proper siting of seaweed farms is critical for addressing nutrient modification concerns and conflicts with EEZ/fisheries. Modeling tools like Macroalgal Cultivation Modeling System (MACMODS) can assess local contexts and trade-offs for optimal site selection. The National Oceanic and Atmospheric Administration's Aquaculture Opportunity Areas (AOAs) provide suitability analysis processes that could be used for state waters, such as in California.
- **Carbon Accounting:** Including seaweed in CARB's carbon accounting requires climate-scale data. Further research is needed to quantify the atmospheric carbon dioxide drawdown of seaweed-based climate mitigation pathways.

Can Farmed Seaweed Products Enhance Climate Mitigation?

Presenter: Rod Fujita

The climate and economic benefits of farmed seaweed could be enhanced by developing products that store carbon, replace carbon-intensive materials, or suppress greenhouse gas (GHG) emissions. Some industrial processes and markets for seaweed-based products, such as construction materials and biodegradable plastics, are already established, while others require further research and development. Seaweed can reduce the use of GHG-intensive fertilizers as biostimulants in agriculture, displace higher-emission foods when used as a food product, and lower methane emissions from livestock when added to animal feed. Its versatility also extends to replacing petrochemicals in producing sustainable materials.

State of the Science

- **Carbon Accounting:** Carbon storage from seaweed-based products (e.g., construction materials) occurs on a decadal time scale but there are uncertainties on the impact to climate mitigation because of long-term carbon accounting challenges.
- **Research and Development:** Some industrial applications of seaweed are more mature, such as biofuels, biostimulants, while some are pre-commercial (e.g., bioplastics).

Science Needs

- **Research & Development (R&D):** Advance R&D for seaweed-based products like construction materials.
- **Climate Mitigation Potential:** Assess the magnitude and durability of carbon storage in seaweed products. Conduct Life Cycle Assessments (LCAs) to evaluate life cycle GHG impacts. Perform comparative LCAs using primary data from pilot projects to address knowledge gaps on the relative climate mitigation benefits of different seaweed products. Investigate substitution rates for products replacing carbon-intensive alternatives.
- **Economic Viability:** Study the economic feasibility of cascading biorefinery approaches versus single-product refining. Explore market dynamics for high-value and low-value seaweed products. Conduct biorefinery and market simulations.
- **Production Efficiency:** Develop methods to improve the efficiency of seaweed product manufacturing.

Other Needs & Considerations

- **Market Expansion and Economic Viability:** Strategic investments and new business models are needed to expand seaweed-based markets and stabilize production volume and pricing. Cascading biorefinery approaches should be compared to single-product refining for economic feasibility.
- **Profitability and Scaling Potential:** Farmed seaweed has high scalability potential compared to other nature-based climate mitigation approaches if economic profitability is achieved.

Can Farmed Seaweed Help Restore Ocean Ecosystems?

Presenters: Scott Hamilton, Sergey Nuzhdin

Over 96% of the kelp canopy in Northern California has been lost in the past decade due to marine heatwaves, the loss of sunflower sea stars from a wasting disease, and a surge in the purple urchin population. Solutions to kelp deforestation include suppressing purple urchins and enhancing kelp growth through field outplanting methods like green gravel, spore bags, seeded line cultures, and ARKEV (Array to Recover Kelp Ecosystem Vegetation) modules. Lab culturing of baby kelp spores from reproductive tissue can support various kelp outplanting efforts, though challenges such as predation by urchins and snails persist. Advances in seaweed genetics, including seed banks and genetic tools, aim to improve kelp restoration strategies. Of the >700 seaweed species in California, only two (the most abundant canopy forming species) have been the subject of restoration efforts. Many other native seaweed species are also being lost at the same time as kelp forests are lost to urchin barrens. Thus, future efforts may also focus on other seaweed species in need of restoration.

State of the Science

- **Lab Culturing for Kelp Enhancement:** Scientists have successfully “closed the loop” on culturing kelps in the lab for later outplanting in the field. Kelps are maintained in tumble culture until spores are released; gametophytes are incubated and baby kelps are grown in tumble culture until reaching juvenile stage.
- **Some Restoration Methods Demonstrate Success:** Techniques like spore bags have shown success, with more baby kelps in plots supplemented with soral blades. Suspended lines and spliced juvenile kelps demonstrated high survivorship and strong growth. A pilot deployment of ARKEVs in Northern California showed early success toward kelp survival and growth.
- **Genetic Insights into Wild Kelp Populations:** Wild kelp populations have significant genetic variation, with over 1 million genetic variants identified. Many kelp genotypes exhibit temperature resilience. Non-reproductive (“sporeless”) kelp strains have been developed, aimed to support the safe scaling of restoration or aquaculture by minimizing ecological risks to wild populations.

Science Needs

- **Seed Banks and Genetic Resources:** Develop seed banks to store gametophytes for long-term use in seaweed restoration and farming. Use genotyping to select strains with desired traits (e.g., low-iodine). Develop sporeless strains of giant kelp (already achieved for sugar kelp).
- **Genetic Studies and Mapping:** Conduct genetic mapping of wild kelps and other seaweeds in California. Study the impacts of using different seaweed strains for restoration or aquaculture on wild populations to assess risks or benefits of genetic introgression (gene flow between cultivated and wild populations).

Other Needs & Considerations

- **Restrictions on Seed Bank Applications:** Commercial operations cannot grow or sell kelp from seed banks due to scientific collection permit regulations in California.
- **Regulatory Uncertainty:** Unclear regulations on the use of different seaweed strains for commercial and restoration purposes. Climate-resilient strains of kelp cannot currently be outplanted for restoration under California regulations. Need to address regulatory concerns and questions regarding the genetic aspects of seaweed cultivation and restoration.
- **Genetic Source Limitations:** California currently takes a precautionary approach, prohibiting use of genetically selected strains in seaweed farming until more information on potential effects is available. Alaskan regulations require kelp restoration projects to use genetic source material from within 50 miles of the study site; California regulators have not issued such guidelines.
- **Precedents and Frameworks:** High selection criteria for genetics exist in restoration efforts, such as with native salmon populations. Frameworks for assessing genetic introgression risks for other species could inform seaweed restoration.

Can Seaweed Farming Be “Regenerative”?

Presenter: Janet Kubler

Historically, aquaculture has been associated with ecosystem damages, but aquaculture has the potential to accrue ecological benefits. Ecosystem services from seaweed aquaculture include provisioning (food, materials, organic carbon), regulating (bioremediation, wave attenuation, nutrient and carbon uptake), supporting (habitat, biodiversity, resilience), and cultural benefits (employment, recreation). Inspired by regenerative agriculture, regenerative *aquaculture* aims to enhance ecosystem health, but lacks a clear definition. Potential metrics for regeneration could include nutrient retention, enhancement of biodiversity, and carbon sequestration. The regenerative potential of seaweed farming depends on factors like location, farm scale, and species selection. To maximize ecosystem services, seaweed farming could target areas with high nutrients and low oxygen (e.g., upwelling zones), degraded native kelp ecosystems, and locations where bioremediation is beneficial and farming increases ecosystem resilience. The current regulatory system for aquaculture minimizes or mitigates negative impacts, without fully accounting for these potential ecological benefits.

State of the Science

- **Regenerative Potential:** Research seeks to understand how seaweed farming might regenerate ecosystems, considering the ecosystem services it can provide, such as carbon sequestration, water quality improvement, and habitat provision.
- **Potential Risks:** Seaweed farming may lead to changes in local ecosystems, including the introduction of non-native species, which could disrupt existing marine communities.
- **Seaweed Interactions:** There is a lot of research on the relationships between ecosystem properties (e.g., water quality and external environmental factors), organismal properties (e.g., growth, productivity, and metabolism of a seaweed species), and population properties (e.g., overall production (gross and net) within aquaculture systems).

Science Needs

- **Interactions with Surrounding Environment:** Investigate how seaweed aquaculture interacts directly and indirectly with surrounding communities and ecosystems. In particular, interactions of seaweed farms with microscopic organisms (bacteria and microplankton) that support healthy marine ecosystems are unstudied. Study how interactions are affected by changing environmental conditions, such as climate change, and their impact on biotic or community properties.
- **Development of Science-Based Metrics:** Create standardized metrics to assess and quantify regenerative aquaculture practices.
- **Bioremediation Potential:** Explore the bioremediation capabilities of seaweed farms in improving water quality. In California, investigate the potential application of seaweed farming for bioremediation near the Tijuana watershed and other eutrophic areas.
- **Designing for Resilience:** Explore application of the extensive ecological literature on ecological community resilience to the design and implementation of mariculture systems for aquaculture system resilience.

Other Needs & Considerations

- **Lack of Regulatory Framework:** Current regulations are designed for commercial aquaculture, leaving many ecosystem services unaccounted for or undervalued in a commercial context.
- **Funding Ecosystem Services:** There is uncertainty around who should fund ecosystem services, with potential roles for government and private sectors. There is a need to explore the potential economic drivers that could support the funding of ecosystem services and to account for ecological benefits as commercial benefits.
- **Public Interests:** Developing metrics for regeneration that align with public interests could help incentivize public support and funding for ecosystem services of seaweed farming.
- **Ecosystem Services Markets:** Development of markets for ecosystem services, such as remediation trading or cap-and-trade systems, would require strong policy frameworks and well-regulated systems to ensure effectiveness and sustainability.

Conclusion

The previous sections highlight the science needs and other policy, regulatory, economic, and social needs and considerations of exploring farmed seaweed's potential to improve the status of impaired ocean ecosystems, enhance the resilience of healthy ones, and reduce greenhouse gas emissions in California. In addition, there were a number of holistic science needs and knowledge gaps that came up repeatedly throughout workshop discussions. The following cross-cutting science and other needs would help improve our overall understanding of seaweed farming benefits, risks, and opportunities in California, regardless of the specific goals or objectives of a single seaweed farming operation.

Cross-Cutting Science Needs

- **Production in California:** Given there are hundreds of native seaweed species in California but less than a dozen are cultivated, research could identify which seaweed species can be successfully cultivated in California, along with growth timelines and expected yields.
- **Climate Change Impacts and Resilience:** Further research is needed to improve the productivity and resilience of seaweed farms.

- **Small-Scale Field Experiments:** Small-scale field experiments and pilot studies are essential, requiring collaboration across academia, NGOs, and the public and private sectors.
- **Impact of Growing Conditions:** Investigate how different growing conditions (ocean, nearshore, tank environments) influence the quality of seaweed.
- **Life Cycle Assessments:** Conduct Life Cycle Assessments (LCAs) to evaluate the environmental impact and sustainability of different seaweed uses.

Other Cross-Cutting Needs & Considerations

- **Scaling Potential and Environmental Impacts:** Need to evaluate the scaling potential for seaweed farming for diverse uses (food, feed, etc.) and the potential environmental impacts of large-scale harvesting operations.
- **Siting and Location:** Proper siting is essential, especially for CDR, which requires farms near biomass sinking sites. Mapping tools and California's ocean observing systems can provide important information to guide siting decisions. The Aquaculture Opportunity Area process could be leveraged for suitability analysis.
- **Research Collaborations:** Small-scale field experiments and pilot projects require collaboration among public and private groups, NGOs, academics, and funding sources. Experimental farms or research parks (e.g., near port districts) could be established to foster collaboration between developers, scientists, and entrepreneurs.
- **Balancing Risks and Benefits:** Agencies have mandates/statutorial roles to protect, regulate, and manage ocean resources; however, potential benefits of seaweed farming for providing ecosystem services, including resilience to climate change and enhancing or protecting ocean resources are not always explicitly considered in policy/regulation.
- **Infrastructure and Co-activities:** Develop processing infrastructure and identify compatible activities that can co-occur with seaweed farming to optimize resource use.
- **Regulatory Gaps:** While there are established regulations for the collection of wild broodstock in fish farming (e.g., sturgeon), there is a lack of clear guidelines or regulations for the ownership and management of seaweed broodstocks that may be vegetatively reproduced.
- **Aligning Science Needs with CEQA:** Environmental impact analyses (e.g: CEQA or NEPA) may benefit from additional science to help inform regulatory decision making.
- **Policy Needs:** Consideration of seaweed farming in the U.S. Farm Bill could support infrastructure and incentives for sustainable seaweed production.

Appendix A: Agenda

9:30 AM	**Coffee and light breakfast in East Meeting Room (Library Galleria)**
10:00 AM	**Welcome, Charge, and Introductions** Ocean Science Trust
10:15 AM	**Policymaker/Regulator Table Setting** One representative from each agency shares role and current perspectives (if any) in seaweed farming/resilience/restoration/climate mitigation, science-based questions and concerns to inform workshop discussions (~3 min each) **Audience Q&A**
10:45 AM	**Overview Talk: Knowns and Unknowns About Seaweed Farming** Rafael Cuevas Uribe, Cal Poly Humboldt **Audience Q&A**
11:15 AM	**Science Talks: Can Farmed Seaweed Be a Regenerative Food?** Torre Polizzi, Sunken Seaweed (remote talk) Luke Gardner, Moss Landing Marine Labs/CA Sea Grant
11:30 AM	**Roundtable Discussion: Information/Science Needs on Regenerative Food Potential** Facilitated group discussion to understand science needs/priorities about farmed seaweed as a regenerative food (for humans and livestock)
12:15 PM	**Lunch (catered at workshop location)**
1:00 PM	**Science Talks: Can Farmed Seaweed Help to Mitigate Climate Change?** Kristen Davis, Stanford University Rod Fujita, Ocean Innovations
1:15 PM	**Roundtable Discussion: Information/Science Needs on Climate Mitigation Potential** Facilitated group discussion to understand science needs/priorities about farmed seaweed for climate mitigation
2:00 PM	**Science Talks: Can Farmed Seaweed Help Restore Ocean Ecosystems?** Scott Hamilton, San Jose State University Sergey Nuzhdin, University of Southern California
2:15 PM	**Roundtable Discussion: Information/Science Needs on Restoration Potential** Facilitated group discussion to understand science needs/priorities about farming seaweed for ecosystem restoration
3:00 PM	**Break**

3:15 PM	**Science Talks: Other Ecosystem Services and How (and Where) Do We Grow Seaweed Responsibly to Balance Benefits and Risks?** Janet Kubler, California State University Northridge Monica Moritsch, Silvestrum Climate Associates
3:30 PM	**Roundtable Discussion: Assessing Trade-Offs of Seaweed Farming in California** Facilitated group discussion on approaches to assessing trade-offs of seaweed farming in California, existing data, and data gaps for evaluating benefits/risks
4:00 PM	**Synthesis of Workshop Takeaways and Next Steps** Ocean Science Trust
4:30 PM	**Optional Happy Hour**

Appendix B: Participants

Organizers:

Dr. Lauren Linsmayer, OST
Anthony Rogers, OST
Kevin Travis, OST

Participants:

Government:

Katie Cieri, California Ocean Protection Council
Randy Lovell, California Department of Fish and Wildlife
Kimberly Rogers, California Fish and Game Commission
Edie Marshall, California Department of Food and Agriculture
Rachelle Kennedy, California Department of Food and Agriculture
Dr. Kyle Lunneberg, California Air Resources Board
Dr. Jules Kelly, California Coastal Commission
Katie Robinson-Flipp, California State Lands Commission
Paula Sylvia, Port of San Diego
Renee Angwin, Port of San Diego
Sarah Donald, Port of San Diego
Stephanie Gordon, U.S. Environmental Protection Agency

Academic / Research Institution:

Dr. Luke Gardner, Moss Landing Marine Labs / California Sea Grant
Dr. Rafael Cuevas Uribe, Cal Poly Humboldt
Brian Donovan, Cal Poly Humboldt
Dr. Kristen Davis, Stanford University
Dr. Jennifer Smith, Scripps Institution of Oceanography
Dr. Janet Kubler, CSU Northridge
Dr. Sergey Nuzhdin, University of Southern California
Dr. Scott Hamilton, San Jose State University
Dr. David Siegel, UC Santa Barbara

Science Consulting:

Dr. Rod Fujita, Ocean Innovations
Dr. Melissa Ward, Silvestrum Climate Associates
Dr. Monica Moritsch, Silvestrum Climate Associates

Industry:

Javier Infante, Ocean Rainforest
Gabie Carne, Rootless
Torre Polizzi, Sunken Seaweed (remote)

Nonprofit:

Jade Clemons, AltaSea at the Port of Los Angeles