Great Expectations:
Can Seaweed Aquaculture Be Scaled Up For Climate Mitigation?

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Introduction

It is no secret that climate change is already affecting every corner of the planet, with some regions and people more vulnerable than others. Southeast Asia is particularly vulnerable to rising sea levels, heat waves, floods, droughts, and increasingly severe and frequent weather events. The challenge is crafting a strategy for how this region should respond to mitigate the effects of climate change from a policy and technological standpoint. Macroalgae (i.e. seaweed) represents a new frontier for climate mitigation that may have the potential to sustainably promote opportunities in Southeast Asia.

Background

Kappaphycus and *Eucheuma* are red macroalgae cultivated in Southeast Asia by small family farmers. Seaweed is an important industry in the region due to the numerous products that can be extracted from its biomass, which are used in food, fertilizer, livestock feed, biomedical, pharmaceutical, cosmetic, medicinal, and energy industries. Seaweeds possess many medicinal properties, and they may be used as a bioremediation tool by removing nitrogen and phosphorus from wastewater.

The majority of the present focus on macroalgae comes as a result of its role as a rich source of biomass that can be used to address global challenges when cultivated with sustainable methods. Progress beyond laboratory scale is slow, but many are looking to seaweed for its ability to generate a diversity of biofuel types and sequester carbon dioxide (Griffiths et al. 711).

Biofuel

The most promising processes for biofuel are anaerobic digestion (AD) for biomethane production and fermentation for bioethanol (Griffiths et al. 736). One advantage of bioethanol is that it can be incorporated into existing energy infrastructure (Álvarez-Viñas et al. 4). For example, seaweeds may be cultivated to completely replace fossil fuels for transportation (Farghali et al. 108). For seaweed-derived biofuel to take hold, it must be at least as cheap as petroleum (Chopin and Tacon, 144). This profitability may be achieved through the usage of Integrated Multi-Trophic Aquaculture (IMTA), farming seaweeds in proximity to several species at different trophic levels, and/or a biorefinery approach during processing, to maximize biomass use by sequentially extracting different seaweed constituents of high and low value (Buschmann et al. 394; Griffiths et al. 734). Both methods seek to ensure efficiency by reducing aquaculture wastes. Such approaches comply with the United Nations' Sustainable Development Goals and key bioeconomy principles–particularly in terms of enhancing food security, economic growth, clean energy and technologies, sustainable use of resources, responsible consumption and production, reduced climate impact, and job generation and competitiveness (Álvarez-Viñas et al. 3).

Carbon Sequestration

Macroalgal communities produce more biomass than other coastal vegetation (Bellgrove et al. 2). As photosynthesizing plants, seaweeds absorb considerable amounts of carbon. Their cell wall structure and composition aid in the long-term preservation of macroalgal carbon in marine sediments. As a result, macroalgae can potentially store carbon, but the long-term sequestration capacity is currently unknown. Carbon is only successfully sequestered when macroalgae is dislodged from its benthic habitat, dispersed, and disposed of in coastal sediments or the deep ocean.

Most carbon fixed by seaweeds is only transiently stored as biomass before being consumed or decomposed, entering the fast carbon cycle (not achieving long-term sequestration). Compared to terrestrial forests where carbon is stored for centuries, seaweed farms and wild seaweed are subject to environmental and human dynamics and disturbances that can result in the instant loss of biomass production via damage, consumption, or harvest. Radical suggestions of deliberately sinking seaweeds in the deep ocean are gaining momentum but come with a potentially great and uncertain ecological impact (Troell et al. 291). Seaweed utilization is driven toward the most lucrative applications in the absence of incentives in the form of consequential financial and regulatory tools, meaning that sinking seaweed biomass in this way may be an inefficient use of otherwise value-added and less-carbon-intensive biomass (for fertilizers, feed, food, cosmetics, medicines, etc.) (Troell et al. 291).

While there is the potential to use seaweed for carbon sequestration, in-depth assessments are required to determine the amount of carbon that can be sequestered, the time scale of this carbon storage (short-term or long-term), and the environmental, economic, and social ramifications. It is important to be clear on how and how much seaweeds could contribute to decarbonization and how realistic potential strategies are. Unscrutinized investments in large-scale seaweed present seaweed farming as a “quick fix” for the climate, but such claims risk jeopardizing the future growth of the industry (Troell et al. 288).

Methods

I conducted a literature review during the summer of 2023 investigating the sociopolitical and technological potential and obstacles of using macroalgae for biofuel and carbon emissions sequestration in the Philippines. I studied issues, such as seaweed and marine ecology, seaweed production, the political ecology of the seaweed trade and climate solutions, the sociology of expectations and hype, microbiology, deep learning, and remote sensing. Perhaps the most central question to any study of the potential use of seaweed for climate mitigation is whether or not cultivation can be scaled up feasibly and safely. Much of the literature shied away from directly addressing the potential to scale up production as many of the technological proposals that are described are still in their infancy in a laboratory setting or as thought experiments.

Researchers used a diversity of methods. These included approaches like interviews, surveys, quantitative analyses, laboratory experiments, algorithmic modeling, deep learning, remote sensing, literature reviews, and meta-literature reviews. Throughout much of the literature, there is a limited focus on the social, environmental, and economic limitations, costs, and processes at work. There is a heavy emphasis on the technical aspects of seaweed cultivation for environmental mitigation and scaling up production. This may lead to outsized expectations for seaweed without a positive chance of follow-through.

For instance, the various development proposals outlined by Buschmann et al. (2017) rarely mention even the potential of social and ecological costs or the absence of present technological feasibility. One proposal details a large-scale algal culture in a coastal desert. This is also known as the Green Sahara Concept, having millions of cubic meters per year of relatively nutrient-rich deep Atlantic seawater gravity fed into IMTA-farming operations based in the Sahara's shebkhas (salty flatlands). This scenario would allow producers to sustainably and simultaneously produce fish, crustaceans, mollusks, seaweeds, additional aquatic crops, aquaponic crops, biogas, and hydroelectric power. This may be a theoretically promising way to produce seaweed and various fauna, siting aquaculture where there are fewer claims to marine space. The World Bank plans to fund a water conduit from the Red Sea to the Dead Sea to support such a plan. However, it is dangerous to move forward with such a strategy until the social and environmental effects are understood (Buschmann et al. 399-400).

Considerations For Scale

These social ramifications are important as it would be wholly irresponsible to assume that such developments will go unimpeded and be immediately accepted by locals. Local support is required for any of these proposals to be successful as they will likely require significant areas in the ocean and the coast, altering cultural practices and shifting livelihoods. A lack of local support and sensitivity to local needs may be socially dangerous and a terminal sentence for seaweed innovation. Thus, more work needs to be done to understand the social ramifications of these ecological and technological proposals.

Any consideration of scale elicits subsequent questions—including,

- What would it take for seaweed cultivation to be scaled up?
- What part of the industry would be the focus of such efforts (i.e. smallholders or industrial-scale aquaculture)?
- For what purpose(s) will the industry be scaled up (e.g. for carbon sequestration or biofuel production)?
- What are the potential social, economic, environmental, and geopolitical limitations and effects?

To address these latter questions, we must tease out the system of processes behind mitigation innovations in the seaweed industry. Additionally, we must be able to assess whether there is sufficient, multi-scalar support and infrastructure (vertical and/or horizontal) in place for long-term seaweed harvesting amid the threat of volatile environmental and market conditions as well as the consequences of inflated expectations and hype.

Hype occurs when areas of technological innovation become saturated with stratospherically high expectations of imminent and revolutionary change (Brown, 4). Within the cycle of innovation, a narrative of the future is constructed and exaggerated to command sufficient interest within the competitive arena where rival expectations vie for ascendancy to enroll allies and secure investment (Brown, 6). Such early ambitions often give way to disillusionment as time passes, circumstances change, and problems emerge. As doubts increase the need to reinforce a positive future, the outlook increases until the effort to maintain expectations is too high, triggering an abrupt collapse, scapegoating, and victim blaming for the researchers, developers, and even the industry as a whole (Brown, 7). While shared expectations act as a coordinating device for innovation activities, outsized expectations of hypothetical future benefits may be used to legitimate costs in the present that may turn out unjustifiable in the future, weakening the trust between consumers, governments, industries, scientists (Ruef and Markard, 320). To avoid these negative effects of the disappointment period, we must learn to recognize and classify hype when it occurs.

In theorizing an energy transition, we also must recognize that there is no way to be ethically or politically neutral. Certain vulnerable groups—including host communities or households, farmers, rural poor, occupational workers or wage laborers, indigenous groups or ethnic minorities, future generations, fishers, and water resource users—and non-human species tend to emerge as active victims in their experience of climate mitigation (Sovacool, 7). A low-carbon world can only become more pluralistic, democratic, and just with proactive governance as low-carbon transitions are sites of power struggles (Sovacool, 14).

Climate mitigation impacts are not distributed evenly across beings, scales (local-community divides, urban-rural locations, or global actors), and time (present or future). Climate mitigation creates the opportunity for elitism, discrimination, and consolidation of wealth as historical trajectories shape current circumstances and management practices (Sovacool, 13). We must design a framework to proactively overcome such issues through participatory processes and benefit-sharing mechanisms during coastal development.

The Experience of the Seaweed Value Chain

Understanding the upstream and downstream dynamics of the value chain across geographic boundaries will enable us to begin to analyze the ways in which our efforts perpetuate enclosure (capture of resources), exclusion (unfair planning), encroachment (destruction of the environment), and entrenchment (worsening of inequality or vulnerability) (Sovacool, 2). Rather than blinding ourselves with a fetishization of technical solutions (in line with the Western Enlightenment tradition), we need to understand how the justice impacts of climate mitigation unfold across different contexts and at different spatial scales.

Most studies only focus on a few, if any, of these contexts. By paying attention to the macro-, meso-, and micro-interactions, we can observe how individual farmers and the local scale are influenced by social, political, and economic trends or shocks occurring at regional, national, and global levels (Bennett, 74). Such macro-scale changes can undermine local property rights, institutions, and resilience in coastal communities in Southeast Asia. For example, formal institutions can determine the nature of smallholders' insertion in value chains and livelihood outcomes. This begs the question: who has claim over the resources, area, people, materials, etc. required for seaweed cultivation?

Additionally, agrarian value chains assume a continuous flow of raw and intermediate produce from dispersed rural areas to urban centers. Seaweed growers occupy a marginal position in the agrarian political economy, disconnected from national rural struggles and other smallholders. Nevertheless, seaweed can work as a positive livelihood strategy to promote resilience by providing a fall-back option during times of vulnerability (Andréfouët et al. 6; Rimmer et al. 2). Seasonal biomass production is high during the wet season when tourism happens to be low and vice versa, allowing farmers to achieve livelihood diversification and lifting rural households above the poverty line (Chopin and Tacon, 144; Moreno et al. 11). Seaweed farmer wellbeing may increase due to improved housing, fulfillment of basic needs, establishment and strengthening of social networks and access to motorbike transportation, markets, education, etc. However, seaweed farmers are still vulnerable to market fluctuations, adverse environmental conditions (high ocean temperatures and inadequate nutrients), a lack of seeds, and coastal squeeze from development (Fabinyi et al. 191). Social calamities and natural hazards may disrupt supply and alter value chain configurations and access, the behavior of dominant intermediaries, horizontal and vertical coordination, and the socio-economic vulnerability of smallholders and rural communities.

In the face of such pressures, smallholders must remain resilient. Many NGOs and development groups claim that the key will be to facilitate vertical coordination between seaweed farmers and institutions at greater scales. Vertical coordination entails forming closer relationships between actors at different functional nodes of a value chain. Seaweed farmers tend to be isolated geographically in small coastal communities and within the value chain, lacking full market integration and relying on intermediaries, leaving them with limited bargaining power.

However, smallholders have had much better luck in systems of horizontal coordination within their communities. Horizontal coordination describes processes of forming closer relationships (formal or informal) within the same functional node of the value chain. Long-lasting fisherfolk associations and cooperatives may collect association dues for community savings and emergencies foster agreements with collectors to protect sellers, pool harvest resources to sell collectively, and use a family-style approach by sharing evenly what is given and exhibiting strong social bonds, a sense of place, and attachment to marine lifestyle (Andriesse and Lee, "Viable insertion," 37).

Collective action in support of seaweed-growing communities to move up the value chain does not guarantee success, especially in the long term. Cooperatives are currently a "bridge too far" in most seaweed-growing areas due to a lack of economies of scale, local managerial and financial capacity, and high required start-up capital (Andriesse and Lee, "Resisting the coastal squeeze," 500). The lack of appropriate government assistance is compensated for by international civil society and horizontal coordination, but such coordination is insufficient without vertical integration as smallholders remain marginalized and isolated within the value chain (Andriesse and Lee, "Viable insertion," 38).

These scalar impacts and struggle for vertical integration should make us consider whether there is any tension between the promotion of seaweed cultivation as a smallholder livelihood strategy that promotes community cohesion and wellbeing and large-scale industrial cultivation. Many mitigation proposals—including offshore aquaculture, the IMTA, the biorefinery, etc.—seem to be geared toward larger industrial outfits with greater capital to invest in such innovations. How do smallholders factor into these strategies especially as cultivation is scaled up?

The fast livelihood shifts of smallholders remain likely in Indonesia. They are triggered by climate change, natural hazards, policy and planning, the market, tourism, development opportunities, pandemics, or a combination of these (Andréfouët et al. 109). This precarity leads many in the field to prioritize monitoring for coastal zone management within or outside marine reserves, contributing to the greater emphasis on deep learning algorithms and remote sensing to make coastal environments increasingly legible. We must look past the expectations surrounding these methodologies to interrogate the different kinds of costs and consequences of this kind of monitoring and surveillance.

For instance, do these practices threaten a community's agency as they are primarily heralded by the West? Improved surveillance and detection especially with unbiased molecular methods like metagenomics on inflected tissues could facilitate the discovery and characterization of viruses and their influence on seaweed aquaculture (Ward et al. 824). But, who are these surveillance methods serving as a result of cost barriers, smallholders, or industrial scale outfits? If the initial target customers for innovations in the field of seaweed cultivation tend to be wealthy industrial sectors then there is a disconnect between which innovations garner the most hype and which are most impactful for the majority of farmers (Milne, 20).

Moving Forward

Even though many of the climate mitigation strategies and methodologies detailed in the literature are still in the stage of laboratory development, we have to be critical of our methods for assessing hype, interest, possibility, and ramifications (Dedehayir et al. 29). We need a better understanding of which seaweed uses may provide the highest values for various stakeholders and have the best chance of increasing environmental sustainability because even though seaweeds can be used in many different ways for many different purposes, certain destinies may foreclose others. For instance, we can not use seaweed as both a bioremediation strategy and for biochar because seaweeds from water contaminated with heavy metals can have adverse effects on crops/plants grown in different environments (Farghali et al. 109).

The promise of technology is that it will continue to offer possibilities for progress (Borup et al. 291). This concept of progress is rooted in Enlightenment ideology. We have to define exactly what we mean by "progress" by asking: whose progress, what do we value in progress and the future, and what and who are we willing to risk to achieve such a future? Progress is a cultural phenomenon, entailing values, assumptions, and the identities of groups and communities. If seaweed is included in our understanding of progress, we must recognize that cultural changes will be necessary to carry forth this vision. Innovation is a future-oriented business that emphasizes the creation of new opportunities and capabilities. Expectations are generative. By performing such futures to meet expectations we make them real.

Too much emphasis on the technical aspects of progress may result in a lack of true multi-disciplinary approaches that consider the connections between disciplines and phenomena. For instance, we may be blind to the way that hype is involved in conversations around an energy transition that scales up seaweed cultivation, coastal monitoring, and blue carbon, in turn affecting smallholders and industry stakeholders. This hype cycle triggers investment from governments and development groups that results in the economic support of smallholders to begin seaweed farming or expand their existing farms. This institutional support leads to greater crop output, allowing for well-being improvements and industry growth. However, the vulnerability of seaweed cultivation and smallholders to environmental conditions and markets may reduce expectations and contribute to a lack of long-standing vertical integration and support, triggering a greater emphasis on horizontal cooperation or the end of farming in certain communities. Further, more recent hype for technological monitoring and modeling of seaweed biomass and potential has begun to alter management strategies and cultivation by turning the focus toward offshore cultivation, IMTAs, and a greater understanding of crop diseases, potentially favoring larger industrial farms.

Future research should be aimed at validating the long-term potential of macroalgae outside of the lab and in the market for harvest, blue carbon sequestration, and/or biofuel as well as its effects on and limitations for the environment, economies, industries, and livelihoods. Part of this investigation of harvest potential requires defining whether we are talking about cultivation in the open ocean or near shore, using IMTAs or non-integrated means, for what uses, etc. We will have to understand the interactions between smallholder communities and industrial aquaculture in terms of their niches, levels of market access, dominance, agency, and economic, environmental, and social benefits. We must integrate political ecology and environmental science insights within transdisciplinary collaborations between scholars, practitioners, managers, and policymakers (Bennett, 79).

For example, by engaging with power and equity considerations, we can devise a framework for proactively overcoming issues through participatory processes and benefit-sharing mechanisms during coastal development. This plays into the five recommendations for future research detailed by Sovacool: 1) the creation of more interdisciplinary teams, 2) more rigorous and comparative research designs, 3) more emphasis on mundane technologies and novel locations, 4) more whole systems and multi-scalar approaches, and 5) more prescriptive recommendations and policy implications (13-14).

Conclusion

We must remember that despite promises in the literature, there is no silver bullet seaweed mitigation strategy. Any approach will have a slew of non-neutral effects, potentially requiring additional fixes. Considering macroalgae for sequestration forecloses uses that allow for carbon to re-enter into the short-term carbon cycle and may put certain areas of the environment at risk like deep ocean ecosystems or other sequestering environments such as seagrasses. Further, throughout the literature, there is a lack of explicit discussion of resiliency. Resiliency will depend on how we decide to value and weigh the environment, economy, and people. Reconciling this issue will be crucial if we wish to scale up seaweed in a way that provides the most significant benefit to communities at all scales.

Modern technology is inherently asymmetrically distributive and reinforces social inequalities (Hornborg, 10). Energy technologies are often fetishized and considered engineering breakthroughs as new politically neutral ways of harnessing natural forces (Hornborg, 8). But, nature and society are intertwined within such technologies, as a product of human inventiveness and contingent on human knowledge about nature. The wealthiest and most technologically advanced parts of the world are net importers of biophysical resources from less affluent sectors of the world. These resource exchanges remain invisible to the economy which is more preoccupied with money flows and market equilibrium, but they are reflected in the ways in which climate change (and its consequences) is intertwined with problems of ecologically unequal exchange and power relations (Hornborg, 12).

To prevent these unequal power relations in the renewable energy sector, we must focus on justice in the global flows of resources embodied in the industrial machine (Hornborg, 13). In the clean energy transition, it is imperative that we understand the requirements of the capital and labor needed to invest in these technologies and their asymmetries (Hornborg, 16).

Further understanding the complex sociocultural, political, ecological, and economic ramifications of scaling up algal mitigation and adaptation strategies will require engaging in empirical research in multiple sites. Much of the literature is based in Indonesia, the largest global producer of seaweed biomass, but there are far fewer studies on seaweed trade based in the Philippines, one of the largest producers and the largest global seaweed processing center. It is crucial that we further understand the specific groups who benefit the most, the government support that is needed, and the impact on traditional human-environmental relationships specific to the Philippines. The next phase of my research is to accompany a multi-disciplinary team in the Philippines to conduct an empirical study. By building community partnerships in the field, we may be able to understand the experience, wants, and needs of the seaweed farmer as well as the impacts of market integration, middlemen, processors, industrial production, and industry innovation. This ability to analyze the ecosystem behind a proposed innovation (the people, communities, industries, costs, and benefits) may also help us gain a window into understanding the expectations and potential hype surrounding seaweed for climate mitigation and the effects of such expectations on the lives of stakeholders (Milne, 76).

It is clear that technological solutions alone can not save us as there are downsides to any proposal. If we are brave enough to revel in the world's complexity, we may get closer to understanding what things don't work, why they don't work, and find ways to fix them, seeking to improve the world without drowning in the sea of hype that surrounds popular ideas.

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