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Blue Farming Potentials: Sustainable Ocean Farming Strategies in the Light of Climate Change Adaptation and Mitigation

Michael Bennett[1], Antaya March[1,*] and Pierre Failler[1]

[1]*Centre for Blue Governance, University of Portsmouth, UK*

Abstract: Modern aquaculture technologies can contribute to both climate change mitigation and adaptation strategies while simultaneously contributing toward food security. Various aquaculture strategies have been reviewed elsewhere but omit a few key strategies worthy of inclusion. This paper reviews various regenerative aquaculture strategies that stimulate habitat creation, biodiversity and capture fisheries stimulation, and increasing resilience to climate change effects. The climate change adaptation strategies discussed include integrated multi-trophic aquaculture (IMTA) and aquaponics, recirculation systems for the control of environmental conditions in a changing climate, habitat restoration through coral aquaculture, the capacity for selective breeding as adaptation mechanism to expected environmental changes, and continuous environmental monitoring programs. Blue farming strategies for climate change mitigation are largely focused on greenhouse gas reduction, carbon capture, and carbon sequestration. The Western hemisphere has recently been enthused by the development of seaweed aquaculture, and the implications of seaweed aquaculture and seaweed products are discussed, as well as the potential of seaweed to contribute to blue carbon stocks. The potential of microalgal bloom stimulation and open ocean fertilization are explored as methods of intensifying natural biogeochemical cycles involved in carbon sequestration. Best aquaculture practices and certifications are also discussed as a potential mechanism to align current farms with climate change and blue carbon objectives. The review concludes that regenerative aquaculture strategies have the potential to change public perception of aquaculture as holding largely negative consequences for the environment and encourage the development of other applications of aquaculture as novel methods of sustainable blue ocean farming.

Keywords: adaptation, blue farming, mitigation, regenerative aquaculture, seaweed farming

1. Introduction

Modern aquaculture is suited to addressing both of the problems of ensuring food security and addressing climate change simultaneously, especially when aquaculture is considered to encompass the production of living materials beyond just food products. Mizuta et al. (2022) recently examined the four uses of aquaculture, namely "commercial aquaculture, conservation aquaculture, restorative aquaculture, and regenerative aquaculture," and go on to define the differences and similarities in each such as to avoid confusion for policy and regulation makers. Notwithstanding, traditional aquaculture (for food production) has been criticized for its negative impact on the environment and unsustainable resource use (Primavera, 2005). This is due to poorly managed systems, the inefficient use of fishmeal to produce high-value species, the large nutrient inputs into farming systems, which then leak out into the surrounding environment, escapes of selectively bred species disrupting the neighboring environment, the introduction of foreign species to the natural environment during these escape events, and being energy intensive (pump-ashore systems). Most of these criticisms of the practice are largely on older and unsustainable systems of food production.

However, more sustainable aquaculture (or "blue farming") strategies and methodologies, such as regenerative aquaculture, have since been developed and are aimed at creating more sustainable methods of food production with added benefits. "Regenerative aquaculture" involves the aquaculture of species that are habitat producing, thereby increasing biodiversity, while at the same time "cleaning the environment" in ways such as water filtration and/or carbon capture. The primary species is then intermittently harvested such that enough is still left over to serve as a habitat for other species. An example of regenerative aquaculture is the current prioritization of seaweed production (marine micro- and macroalgae) in the western hemisphere (dubbed the "seaweed revolution," Global Seaweed Coalition, 2022), despite the East having cultivated seaweed for years to the scale where it is now a major sector of the food industry in eastern countries. The environmental motivation for this enthusiasm is vast and includes benefits such as food security, enhancing biodiversity, stimulating fisheries, and resilience to the effects of climate change. The use of more sustainable food production systems through methods described as regenerative

*Corresponding author: Antaya March, Centre for Blue Governance, University of Portsmouth, UK. Email: antaya.march@port.ac.uk

aquaculture can thus sway public opinion (and investor interest) from disinterest in aquaculture and instead encourage the establishment of such nature-based solutions to addressing climate change challenges.

Many blue economy (BE) strategies and policy documents prioritize aquaculture development primarily for either large-scale economic gain and job creation or to alleviate poverty and hunger in response to declining capture fisheries stocks, despite the challenges of climate change for the aquaculture sector (such as UNECA, 2016). Froehlich et al. (2022) discussed the emerging developments of climate change threats to aquaculture and the climate adaptation thereof. The authors state that temperature and sea level rise were of the main topics discussed by news and scientific articles and concluded that articles cited technology as primary adaptation solution at the global scale, whereas improved governance at the regional scale was cited as the adaptation solution to prioritize (Froehlich et al., 2022).

However, Free et al. (2022) investigated whether coordinated reforms in fisheries and mariculture could increase seafood production per capita under various climate change scenarios (Free et al., 2022). The authors found that although climate-adaptive reforms will be necessary, they will not be enough to maintain global seafood per capita (even with aggressive greenhouse gas emission reductions). The authors state that sustainable marine aquaculture (or "mariculture") has vast potential but that the impact on global seafood production is dependent on (among others) advancements in feed technologies, and the establishment of effective marine aquaculture governance and best practices (Free et al., 2022). The authors ultimately concluded that although climate change will challenge the ocean's ability to meet our growing food demands, the ocean has the potential to meet these demands, through actions associated with greenhouse gas emission reductions, reforming of capture fisheries, and expanding sustainable mariculture operations (Free et al., 2022).

Few BE strategies prioritize converting their established aquaculture sectors to adapt or mitigate the effects of climate change, despite the technologies and knowledge base for more sustainable food production being available (FAO Technical Paper 627, 2018; Reid et al., 2019a; Reid et al., 2019b), instead generally encouraging the establishment of new, more sustainable aquaculture developments. The effects of climate change as environmental stressors on the aquaculture industry as well as the required resources needed to inform responsible decision making (such as vulnerability assessments and strategic research development) have been reviewed in various works, specifically the FAO Technical Paper 627 (2018) and Reid et al. (2019a). Furthermore, these works also include a detailed review of various aquaculture strategies that have the potential to address climate change mitigation and adaptation. However, these works omit a few key aquaculture strategies that need to be discussed and considered, to be incorporated into national aquaculture and BE development programs.

This paper thus aims to discuss the various aquaculture techniques and methods available to address climate change and its consequences, which have not been included in previous reviews surrounding this topic, i.e., FAO Technical Paper 627 (2018) and Reid et al. (2019a). This paper aims to re-contextualize the aquaculture strategies discussed in these previous reviews with the new information that had since been published, providing the reader with an up-to-date synthesis of information. Ultimately, this paper aims to highlight various ways in which modern aquaculture techniques and strategies can be used as a method of production, while simultaneously contributing to different climate change adaptation and mitigation strategies, the most notable of which are reducing atmospheric greenhouse gases and stimulating habitat biodiversity. Ultimately, this paper aims to inform policy makers and BE program developers, on the various options for sustainable ocean farming that are available.

Section 2 of this paper briefly explains the methodology and approach used in the synthesis of this review. Section 3 discusses methods of aquaculture with potential in addressing climate change adaptation. The methods discussed in Section 3 can be classified into "regenerative aquaculture," where the production techniques entail positive consequences for the surrounding environment (contrary to the traditional notion of aquaculture that has large negative consequences for the surrounding environment), by phenomena such as habitat creation, water filtration, or carbon capture with minimal extra inputs beyond what is required for primary production. Section 4 covers aquaculture methods with the benefit of climate change mitigation while simultaneously fulfilling their production expectations. Ethical considerations with the use of these approaches for incorporation into national BE (BE) and development programs are discussed in Section 5. This paper concludes with the identification of future research needs to facilitate the potential impact aquaculture has in addressing climate change mitigation and adaptation, as a nature-based solution.

2. Methods

While this paper does review various methods of aquaculture for sustainable, regenerative production, many of the topics were derived from the author's own experience and conception, as well as identifying certain aspects of these topics as being missing from the discourse in other well-known formal reviews. The content originated from a review of well-known and well-cited publications that reviewed aquaculture strategies and technologies in the context of climate change, specifically the FAO Technical Paper 627 (2018) and Reid et al. (2019a). These texts have 454 and 78 citations, respectively (Google Scholar citation data). The authors identified aquaculture strategies from these reviews that had not been included in these texts, as well as topics where new information had since been published, thus requiring re-contextualization. While these texts primarily refer to aquaculture in reference to food production, the current authors identified topics with the definition of aquaculture as a practice for production not limited to only foodstuffs. Aquaculture strategies were identified and categorized as having potential for addressing either climate change adaptation or climate change mitigation. Thereafter, the topics that were identified were thoroughly investigated and are discussed under unique headings. Topics on which new information had since been published have been re-contextualized, with the inclusion of relevant and recent up to date publications and sources. Supporting literature was sourced using Google Scholar, using keywords relevant to each of the aquaculture topics below.

3. Blue Farming for Climate Change Adaptation

Climate change adaptation involves establishing systems that are able to tolerate or cope with the conditions of a changed environment and altered weather patterns. Furthermore, the distribution ranges of organisms are likely to shift with changing environmental conditions and climate (Williams & Blois, 2018). The distribution of pathogens associated with the introduction of an aquacultured species to a new environment need to be carefully assessed, as this will factor into the risk assessment of the future success of the undertaking. Changing environmental conditions presents a serious challenge to any producer and their future plans in terms of the viability of culturing a species in a specific location. Careful site selection is crucial to the future prospects of the aquaculture operation. However, the capacity to produce different species in changing environmental conditions can also be considered as an adaptive response to environmental changes has been done commonly throughout history (Reid et al., 2019a). Climate change thus presents challenges and opportunities for sustained aquaculture production as well as other stakeholders throughout value chains (FAO Technical Paper 627, 2018).

Maulu et al. (2021) explore the consequences of climate change effects such as changes in salinity and sea-level rise. Although there may be positive consequences for aquaculture production, the majority of the consequences are negative. Aquaculture systems are usually infrastructure intensive and present one of the major investment costs to aquaculture farms. Aquaculture systems (perhaps even more so than most terrestrial agricultural systems) are thus susceptible to extreme weather events. Adverse weather phenomena present high risks due to the potential damage in infrastructure that usually ensues and results in major expenses to correct or rebuild. However, with the advent of new technology the damage and risk these weather events pose can be greatly reduced or avoided completely. For example, ocean cages that can be withdrawn below the surface of the ocean avoid the harshest of waves and forces generated by storms (like those produced by the Badinotti Group Ltd. 2023). The development of increasingly accurate weather prediction models and early warning systems should be prioritized as well, for limiting the potential infrastructure destruction caused by weather phenomena. These technologies could allow for timeous management decisions in the face of changing climates, potentially saving large production volumes and costs in the process. Notwithstanding, careful site selection using risk assessment analysis (Cattermoul et al., 2014) could arguably be the one of the most important factors contributing to the success of an aquaculture operation in terms of coping with climate change effects by reducing the exposure of the aquaculture site to potential negative climate change effects (FAO Technical Paper 627, 2018).

3.1. IMTA and aquaponics

Large commercial terrestrial farms are inclined to monoculture, yielding greater returns for effort spent. From a farmer's perspective, it is easier to manage the needs of one crop than multiple. However, monoculture has several drawbacks: soil degradation, reduced biodiversity, and increased stock vulnerability to disease and pests. All of these factors compound and result in greater risk in the face of catastrophe (like severe weather phenomena). Integrated multitrophic aquaculture (IMTA) is a solution to the problem of monocultures, and there has not yet been a large-scale (commercial) terrestrial technology similar to it (barring aquaponics).

IMTA is a method whereby multiple species (of different trophic levels, such as primary producers and primary consumers) are cultured together, in the same culture site or system. The waste products of one species become the resources of the next, and nutrients that would otherwise be wasted are recycled and result in otherwise increased growth. There is also the potential of having increased system health with otherwise cleaner water circulating among cultured species and cleaner discharge being released back into the environment resulting in a reduced agricultural footprint (depending on the system). An example of an IMTA system would be growing filter feeding bivalves and seaweeds downstream of a finfish culture cage. The finfish would (traditionally) be fed high-protein formulated feeds, all of which would not be completely consumed. The filter feeders would be able to consume the particulate matter from the fish feed and fish feces for their own growth, cleaning up the surrounding water as a result. The seaweeds absorb the surplus nutrients present in the water due to the high-protein formulated feed, thus reducing the net nutrient load in the surrounding environment. The seaweeds would also experience increased growth and production due to the fertilization action of the greater nutrient load in the water.

Aquaponics is a type of IMTA, usually involving freshwater species, whereby circular resource use between multiple species results in enhanced production. It is the result of combining hydroponics (the production of crops using water as media instead of soil) with aquaculture and often uses recirculating systems' approaches. For example, the water from a finfish culture system is used to irrigate terrestrial crops, with the benefit of presenting nutrient-loaded media to those crops. The water, now having been stripped of nutrients by plants, can now be cycled back into the fish culture system, ensuring that the finfish have a clean environment for growing in, better facilitating growth. Integrated Aquaculture Ltd, (2023) in South Africa, presents a working business model and example for just such a system. Systems such as these require careful monitoring of water quality parameters and nutrient loads to ensure that the culture media do not become unfavorable for growth. IMTA systems are inclined to be intensive culture systems (with the use of recirculating systems approaches), which allow for the control of environmental variables. This means that even in an environment likely to alter from normal (due to climate change), this method is likely to provide more consistent growth conditions for food production.

Employing IMTA systems innately facilitates greater biodiversity than most traditional aquaculture methods, due to cultivating multiple species in the same area. In the case of seaweeds and bivalves, there are often various epifauna present with these organisms, such as various marine arthropods. This is the case for other ecosystem engineers or habitat forming organisms, included in an IMTA system (otherwise known as "regenerative aquaculture"). IMTA systems further allow for diversified income streams and increased resilience against severe weather events destroying standing crop monocultures and potential income. Thus, IMTA systems provide a method of increasing food security by adapting to a changing climate.

3.2. Recirculation systems

Recirculating aquaculture technology comprises tank culture in a semi-closed to fully closed system, where water gets filtered and cleaned (in various ways) after passing through the culture stage. Where recirculation technology used to have expensive artificial water treatment stages, some of these functions can be performed by using IMTA and co-culturing different species together, reducing overall running costs (see aquaponics example above). A key benefit of recirculation systems is that water temperature is inclined to increase, due to growing organisms in the "same" circulating body of water. The elevated temperature usually accelerates metabolic processes and often results in faster growing stock, depending on the temperature increase and species. Moreover, the ability of recirculating systems to maintain, and facilitate the control of environmental conditions to optimize crop production, should advocate for the use of these systems where the surrounding environmental conditions are liable to change frequently, such as in a changing climate. However, such systems usually require intensive monitoring and often require high amounts of capital investment, due to the significant water treatment involved.

3.3. Coral aquaculture

Modern aquaculture may also play a significant role in improving coastal systems through habitat restoration. The restoration of high-value habitats, such as coral systems, through regenerative aquaculture offers substantial capacity for the improvement of coastal communities, and as such are a source of food supply, tourism, social, and economic development. Aquaculture technologies that stimulate biodiversity development through habitat restoration are also worthy of attention, because such food production systems offer increased resilience to surrounding ecosystems that are susceptible to the effects of future climate change.

Corals exist as a symbiosis of both coral polyps and microscopic photosynthetic organisms (known as "zooxanthellae"). The persistence of coral habitats is threatened by increasing ocean temperatures and ocean acidification, usually presented in the form of coral bleaching events where the zooxanthellae that inhabit coral polyps are ejected from the polyps themselves. Such disruption in the symbiosis often means that the polyps expire, leaving only the white calcified coral skeleton remaining. The loss of corals through bleaching events coincides with severe reduction in biodiversity (Pratchett et al., 2011; Pratchett et al., 2018), as corals are ecosystem engineers and form habitats that support immense endemic biodiversity. The loss of corals has also been shown to coincide with severe economic losses, e.g., the economic loss of coral reefs in Thailand, Malaysia, and Indonesia due to a 2010 bleaching event was estimated to be 50–60 million US dollars (Doshi et al., 2012). Coral reefs are high-value systems and ensuring the continued survival of corals thus facilitates the improvement (or maintenance) of biodiversity as well as preventing the loss of significant economic potential.

Coral reef restoration involves complex processes involving coral aquaculture. The establishment of coral reefs requires pioneer species of coral to lay down the base substrate on which other corals can grow (usually corals from the Mussidae and Merulinidae families). These pioneer species are often slow-growing, taking many years to form a reef, and are thus vulnerable and susceptible to climate change effects. Traditionally, coral restoration has taken the form of protected coral nurseries in the open ocean, providing a relatively undisturbed environment for coral fragments to grow in (Dry Tortugas National Park and Fort Lauderdale in Florida, Reef Resilience Network, 2022; Bahamas, UNESCO, 2022), but the number of suitable sites for such nurseries is limited.

However, new aquaculture technologies are able to reduce the growth period required for these corals to grow large enough to start forming reef substrata (UNESCO, 2022). It involves collection of natural coral, precise splitting and separation of coral fragments (micro-fragmentation), intensified land-based growth and laboratory culture of the coral fragments, and outplanting of fragments onto predetermined sites and substratum (UNESCO, 2022). This process allows for far greater numbers of coral fragments to be introduced to a site than was previously possible, increasing the likelihood that a reef system will develop from these outplanted segments (UNESCO, 2022).

Coral polyps are also known to re-colonize existing substrata in the ocean (Chen et al., 2018; Loch et al., 2002) and continue to lay down new substrata eventually culminating in a coral reef. Providing such substrata on the ocean floor will allow for greater numbers of attachment sites for coral polyps and thus facilitate the establishment of reefs naturally. This has been proposed with the design of 3D-printed artificial substrates specifically to facilitate optimal polyp attachment (Leonard et al., 2022; Ruhl & Dixson, 2019). Both methods result in coral habitat formation and eventual carbon sequestration due to the formation of calcium carbonate coral skeletons as long as the corals remain intact and alive.

The controlled laboratory culture of corals allows for the ability to select for traits such as improved heat stress tolerance and water acidity tolerance in specific reef forming coral fragments (UNESCO, 2022). Greater resilience of future coral systems to the effects of climate change is thus possible, if outplanted fragments develop into coral reef systems. Where previously one would have observed the entire coral system decimated by the effects of climate change (increasing ocean temperature and ocean acidification), whole reefs formed from selected coral species are better able to survive such altered environmental conditions. Coral reefs that persist/tolerate the consequences of climate change would eventually reproduce and result in future reef systems with even greater capacity to tolerate environmental pressures, through natural selection.

Theoretically, one would be able to select for coral polyps with the specific combinations of zooxanthellae that facilitate increased heat tolerance (of the corals) (Berkelmans & van Oppen, 2006). Better understanding of the nutrient fluxes of coral systems and how they affect the coral-zooxanthellae symbiosis would lead to options in selective breeding for phenotypic traits that allow for increased carbon sequestration in the coral skeleton as well as heat and light tolerance in changing climate conditions (Dubinsky & Jokiel, 1994; Jones & Yellowlees, 1997; Smith et al., 2004). Furthermore, the increased reduction of ambient dissolved carbon dioxide in the surrounding waters would reduce the likelihood of corals experiencing the negative effects of local coastal acidification. To this point, the potential of seaweed farming operations neighboring coral reefs should be investigated further to determine the potential benefits of local ocean acidification remediation by the presence of seaweeds, and the benefits this may hold for the survival of coral reefs. However, this needs to be approached with caution as seaweeds (by virtue of their relatively faster growth and reproduction rates) can outcompete corals and potentially smother them.

The ultimate benefit of coral aquaculture and coral reef restoration (beyond the preservation of biodiversity) is that this form of regenerative aquaculture can supplement coral reef capture fisheries, through the establishment of new or more resilient reef habitats that support immense biodiversity and various desired fish species, thus contributing to increased food security in the light of changing environmental conditions including those associated with climate change. Coral reefs are important to the livelihoods of local fishers as they contribute to the artisanal fisheries, as well as forming an essential part of the cultural identity of the people and societies that are reliant on them.

3.4. Selective breeding and epigenetics

Artificial selection (via selective breeding) of traits in farmed species may be another way to approach adaptation aquaculture in a changing climate. Selecting for traits that match expected environmental conditions, such as elevated heat tolerance, will allow species to persist despite changing local environmental conditions. This may lead to the domestication of crops and livestock, producing yields that far exceed their wild counterparts, and would likely be suitable for isolated aquacultured species and systems. When applied to habitat forming or "umbrella" species (such as blue carbon organisms like mangroves), the persistence of entire habitats, trophic networks, and ecosystems in a changing climate can be expected. However, artificially selecting for specific phenotypes and introducing them into wild natural populations in such a way as it alters natural genetic variation are ethically gray (see Section 5).

Notwithstanding, there is great value in the maintenance of genetic variability in high-value aquaculture animals such as broodstock, serving as genetic repositories of specific alleles that may offer resistance to future disease and environmental stressors (such as has been investigated in farmed *Mytilus edulis* in Canada, Gurney-Smith et al., 2017; Reid et al., 2019a; Reid et al., 2019b). Furthermore, the influence of study areas such as gene editing and epigenetics may also offer adaptive capacity (Roy et al., 2021). Environmental conditions can influence epigenetic changes (selectively activating and/or deactivating genes in the natural genome by influencing the behavior of an organism) to alter the phenotype's adaptive capacity. This adaptive capacity is heritable and creates the possibility of epigenetic programming in aquaculture for the selection of favorable traits for climate change adaptation and production (Roy et al., 2021). Examples of this already exist for terrestrial crops (such as Pairwise Ltd.'s Conscious™ Foods). Eirin-Lopez and Putnam (2019) provide a comprehensive review of environmental epigenetics in a marine context. Although epigenetics has great potential to improve the resilience of aquaculture operations (from production to bioremediation capacity), the study of economically important aquaculture species is still in its early stages and several unanswered questions remain (Roy et al., 2021).

3.5. Continuous environmental monitoring systems and programs

Environmental monitoring systems and programs involve the continuous monitoring and measuring of key (usually abiotic) variables in strategic locations in the ecosystem surrounding an aquaculture farm. This information usually gets integrated into a database, which is analyzed periodically with the goal of providing actionable measures and advice to farmers. Such continuous environmental monitoring can be developed into early warning systems for detecting phenomena such as incoming severe weather events, harmful microalgal blooms (HABs), and changes in environmental conditions key to the culture of the target species on the farm. In the context of changing environmental conditions, knowledge of such events in advance is key to informing time sensitive management decisions, which may reduce the losses incurred to such phenomena, unless otherwise informed or having been informed too late (FAO Technical Paper 627, 2018). Monitoring the surrounding waters that directly influence the aquaculture crop may allow for appropriate remediation such that the aquacultured crop is not adversely affected, by allowing for the opportunity at remediating or adjusting the qualities of the incoming water (such as increasing the dissolved oxygen). Continuous monitoring of the influence of aquaculture effluent on the external environment may also be used to assess the environmental sustainability of that operation and what can be done to improve this (in more of an attempt at climate change mitigation). An example of this would be monitoring the water nutrients such as ammonia of the effluent for ensuring that the concentration of ammonia is within acceptable limits, which would not negatively impact the surrounding environment (and potentially ensuring compliance with sustainability certifications, as discussed in Section 4.5 below).

Measurements in the field can be done by technicians and experts as well as remote sensing, but farmers themselves are also able to provide reliable, cost-effective reporting of environmental variables (as they are in the field frequently to oversee farming activities). Importantly, incorporating farmer inputs can encourage trust in the feedback received from the monitoring programs because there is now increased ownership and investment on the results of the monitoring from the farmer's perspective. Environmental monitoring schemes also allow for collaboration between industries and industry stakeholders (such as an agriculture co-op), fostering stronger relationships and benefit for all parties involved (e.g., through the establishment of early warning of farms downstream of an environmental phenomena already affecting a farm further upstream). Despite the potential benefits of such collaborative efforts, monitoring and reporting on any environmental variable require standardization for the information to be useful and trustworthy (FAO Technical Paper 627, 2018). Although a number of global environmental early warning monitoring programs exist (such as WISPWeb (2012), FAO Technical Paper 627, 2018), emphasis should be placed on the development of early monitoring programs of the local surrounding environment, as these are more likely to be of (immediate) direct benefit to farmers in that locale or region (Froehlich et al., 2022). To be effective, environmental monitoring should occur at the appropriate resolution, such that the data are applicable and usable to farmers (the benefit of global monitoring programs to site specific farmers may be limited). Continuous environmental monitoring programs present an ideal area for government involvement and contribution.

4. Blue Farming for Climate Change Mitigation

Mitigation measures are primarily concerned with reducing atmospheric greenhouse gases, carbon (CO_2) capture, and carbon sequestration. Aquaculture, if implemented with mitigative activities in mind, can contribute significantly to climate change strategies and targets. Mitigation strategies (such as the reduction of greenhouse gases) are as of yet the only solution to climate change (Reid et al., 2019a; Reid et al., 2019b).

4.1. Seaweed farming

Seaweed farming has largely been concentrated in Asia (99.9% of the global production, FAO, 2018a), where the aquaculture of macroalgae has been established as a commercial industry for centuries. It is only recently that seaweed aquaculture has captured the interest of the Western hemisphere, as evidenced by several news headlines and articles in popular media, in what has been referred to as the "Seaweed Revolution" (Global Seaweed Coalition, 2022).

The most commercially valuable seaweeds are red seaweeds (Rhodophyta, specifically "carrageenophytes"). These seaweeds are used for the production of gelling agents such as carrageenans and agars (Campbell et al., 2022), and their production is taking place mostly in Tanzania, Indonesia, and Malaysia (Campbell et al., 2022, Msuya et al., 2022). However, the bulk of global seaweed farming (by volume) comprises of what is known as "kombu" (*Saccharina japonica*, with global production at 11,448.3 thousand tons wet weight) and *Eucheuma* spp. (global production at 9412.4 thousand tons wet weight) (Chopin & Tacon, 2021; FAO, 2020). The majority of global seaweed aquaculture is thus based on kelps and brown seaweeds (Phaeophyceae) with several organizations funding kelp research (e.g., ASTRAL IMTA project (2020); South African kelp aquaculture pre-feasibility report – Brown-Webb et al., 2022; Kelp Crofting Ltd. (2020); and several projects funded through the Global Seaweed Coalition, Oceans 2050 Seaweed project), in the hopes of realizing the benefits of seaweed farming.

Seaweed aquaculture holds many potential benefits due to the ability of seaweeds to support biodiversity through habitat creation (open ocean culture or raft/rope culture, see also Theuerkauf et al., 2021), the nutritional benefits of seaweeds (as superfoods), the biorefinery capabilities of seaweeds, the bioremediation capabilities of seaweeds, the opportunity of sustainable food (and fodder) production, and utilizing a previously unused space for food production (in light of the limited and dwindling available arable land with an increasing global populace), job creation, as well as contributing to several of the UN sustainable development goals (SDGs).

Duarte et al. (2017) detail the specific climate mitigation benefits seaweed aquaculture may provide (Table 1). These include carbon removal, food production, future bioenergy production, ruminant methane emission reduction, stimulating terrestrial agriculture, and benefits of circular resource management. The social and economic benefits of an increase in global seaweed production should not be ignored either, as the scales and volumes at which seaweed production is expected to increase would have significant positive effects for human livelihoods (FAO, 2013; Larson et al., 2021; Valderrama, 2012); however, additional policy development and technical support have been encouraged (Rimmer et al., 2020).

Table 1
The mitigation services provided by seaweed aquaculture with respect to climate change

Mitigation via	Adaptation to
Ongoing processes: • Carbon removal • Food production	Increased storm frequency and intensity • Shoreline protection via dissipation of wave energy
Future potential measures: • Bioenergy production • Reduction of methane emission • Stimulation of land-based production • Climate benefit of circular nutrient management	Ocean acidification • High daytime pH in seaweed to the benefit of calcifiers Oxygen inputs to coastal waters • Avoiding deoxygenation with warming

With the increasing attention on seaweed farming and all the potential benefits it holds, the number of seaweed (harvesting) projects and aquaculture operations is expected to increase in the coming future. It has been projected that in 2050 the kelp production industry in Norway alone, may have an annual turnover of 4 billion Euros, with a production volume of 20 million tons per year (Olafsen et al., 2012). Previous global production projections for seaweed farming have been estimated at 1–100 billion tons dry weight (Lehahn et al., 2016). While seaweeds have a variety of uses, the majority of seaweeds are used for human consumption (85%) with the remainder being reserved for fertilizers, animal feeds, pharmaceuticals, cosmetics, and biofuels (15%, FAO, 2018). However, Chopin and Tacon (2021) have estimated the economic value of the bioremediation potential of the global seaweed stock (32.4 million MT, at the time) to be between 1.2 and 3.5 billion USD, which was an estimated 26% of its commercial value (of 13.3 billion USD). Furthermore, there is also potential for seaweed farmers to trade in nutrient credits. While the trading of carbon credits as a way to offset CO_2 emissions has been discussed as an additional way for seaweed farmers to make an income from their enterprise, there is potentially more to be gained from trading in nitrogen and phosphorous credits (Chopin & Tacon, 2021). The value of the nitrogen credit market was 1.1–3.4 billion USD, and the value of the phosphorus credit market was estimated at 51.8 million USD, whereas the carbon credit market was estimated at only 29.1 million USD (Chopin & Tacon, 2021). The recognition and the implementation of the nutrient trading market further incentivize prospective entrepreneurs to pursue seaweed farming from an economic perspective, as well as encouraging current aquaculture operations to transition to more sustainable IMTA incorporating seaweeds. However, what has not yet been quantified is the extent to which seaweed farming can stimulate local capture fisheries through habitat and nursery ground provisioning. Theuerkauf et al. (2021) have already commenced research in this direction, but this area is still a nascent area of research, presenting an exciting new avenue of research that may further encourage the development of seaweed farming in the western hemisphere, as well as the potential of regenerative seaweed farming as a conservation measure.

The sustainable harvesting (farming) of seaweeds as blue carbon systems may be one of the most promising blue ocean farming strategies for addressing climate change. This is because of the wide variety of end-products that can be derived from seaweed biomass (see below) as well as the potential of seaweed ecosystems to contribute to blue carbon stocks and carbon removal (Section 4.2), while stimulating biodiversity through habitat development. Seaweed farming, as an example of restorative aquaculture, presents the opportunity for countries to develop their coastlines and capacity to address climate change challenges through nature-based solutions.

Seaweed farming has the further benefit of having a low fiscal barrier to entry and is relatively inexpensive to get started (Duarte et al., 2017). For example, in Mexico it costs an investment of less than US $ 15,000 to plant a 1ha seaweed farm (Robledo et al., 2013), whereas the cost of installing a renewable energy wind farm is upwards of US $ 1.5 million per turbine (Duarte et al., 2017). Many developing countries can thus not afford to address climate change through costly solutions but are instead able to develop seaweed farming as a viable alternative (Duarte et al., 2017). Indeed, any of the above methods of aquaculture needs to be observed in the light of entrepreneurship and financial gain/sustainability. Projects such as these would likely only garner interest and investment if the projects are able to eventually fund themselves and contribute to the immediate society, otherwise potential investors or shareholders and communities would become un-incentivized by these “fiscal sinks,” despite the fact that they contribute to combatting the effects of climate change in the light of a growing global populace.

The benefits of seaweed farming have been investigated and discussed for a long time, yet it remains a mystery as to why large-scale seaweed aquaculture has not been seen as an impactful tool to combat the effects of climate change. A shift in thinking of climate change remediation is required, where moving the focus from minimizing the environmental impacts of terrestrial agriculture should be paired simultaneously with the benefits of developing sustainable seaweed aquaculture systems. Several key knowledge gaps and a lack of clear incentive for investors (such as leveraging carbon credits) are hypothesized to hinder the development of seaweed aquaculture. Recent global events (such as the COVID-19 pandemic and the destabilization of Eastern Europe) further dissuade potential investors from knowledge-lacking industries or ventures, such as large-scale seaweed farming. Addressing critical knowledge gaps such as the need for mapping of carbon storage potentials of seaweed systems is hypothesized to encourage investment for the protection and development of such systems.

Maulu et al. (2021) elaborate on this topic in a review of the consequences of climate change effects on aquaculture production sustainability. The negative consequences of climate change outweigh the potential positive ones. There is thus a need for developing successful adaptation strategies to cope with predicted environmental changes in the short term, while considering climate change mitigation strategies over the long-term (Maulu et al., 2021). Seaweed aquaculture has the capacity to address both short- and long-term climate change goals, while also stimulating socio-economic development over these time scales.

4.2. Blue carbon

This concept has taken shape in the form of "blue carbon" ecosystems. The proposal behind "blue carbon" ecosystems is to protect the coastal habitats and ecosystems, which sequester carbon to great degrees. The term is used to describe the carbon that is contained in or by marine systems as opposed to those from terrestrial "green carbon" systems (Macreadie et al., 2019, and see Mcleod et al. (2011)).

Several countries (China, Australia, UK, EU) are drawing up blue carbon strategies involving coastal habitat restoration, thereby enhancing their blue carbon stocks to assist in carbon removal from the atmosphere (Bertram et al., 2021; Frigstad et al., 2021; Wu et al., 2020). A blue carbon program in Korea provides the first step in combining both seaweed aquacultures as a blue carbon strategy for climate change mitigation and adaptation (Chung et al., 2013; Sondak & Chung, 2015). The development of seaweed farming as a strategy for climate change would only be effective at large scales, emphasizing the need for major seaweed producers (like China) to adopt their own aquaculture sectors to align with blue carbon goals (Duarte et al., 2017). Korea has subsequently developed into one of the world's largest producers of seaweeds, producing 1,812,765 tons in 2019 (Park & Hwang, 2022).

Blue carbon habitats are often classified as marine protected areas (MPAs) and have the benefits of not only biodiversity conservation and fish stock protection (and thus fishery stimulation) as regular MPAs do but also offer carbon sequestration as an ecosystem service. The persistence of these systems is necessary for the carbon sequestration to work, otherwise the carbon fixed in the tissues and soils of these habitats will be released back into the atmosphere once they degrade and cycle back into the atmosphere, hence the importance of conservation. Howard et al. (2017) elaborate on the potential to integrate blue carbon into MPA design and management as well as detailing the blue carbon finance mechanisms with which to fund such endeavors.

Blue carbon habitats include mangrove forests, seagrass meadows, and salt marshes (Oceans 2050, 2022). Kelp forests are also largely known as blue carbon systems but differ from other blue carbon systems in distinctive ways. Where most blue carbon systems are able to concentrate carbon in their soils via their roots, kelps do not have such abilities. Seaweeds do not have woody structures and most kelps attach to rock substrate with a holdfast and are unable to sequester carbon in soils (Duarte et al., 2013; Hill et al., 2015). Indeed, many seaweeds (particularly "*kombu"* and *Eucheuma*) when grown in aquaculture are attached to raft and rope infrastructure. The classification of blue carbon systems would have to be adapted to include seaweeds that fix carbon in their cell tissues as opposed to the underlying soils or sediments of known blue carbon habitats.

Many seaweed ecosystems experience a high annual rate of biomass turnover (<0.5–7 years depending on species and location, Howard et al., 2017; Muraoka, 2004), casting doubts as to their effectiveness as blue carbon ecosystems and as carbon removal mechanisms. Kelp forests do form large swathes of photosynthetic biomass, estimated at 1, 469, 900 m^2 globally (Jayathilake & Costello, 2020); however, the variability in annual kelp biomass may indicate that this estimate is subject to change (Buschmann et al., 2006; Pedersen et al., 2021; Queirós et al., 2019).

The only way kelp forest ecosystems could be classified as blue carbon systems is if they are classified as MPA. This classification would ensure that these habitats are not (over-) harvested and remain as undisturbed as possible to facilitate their growth and production and thus maintain their ability to sequester carbon in their cell tissues. If seaweed farming were to be incorporated into a blue carbon strategy, specific legislation would have to be produced allowing farmers to harvest the protected habitat (or sites) that would not have existed without its aquaculture, for food security and the potential of carbon sequestration with the proposed sinking of seaweed biomass into the deep ocean.

The use of seaweeds as a carbon sequestration mechanism is contentious and debated (Duarte et al., 2017; Hurd et al., 2022). Some of these reasons include the traceability of stored carbon in seaweed biomass, the volatile nature of seaweed forest standing stock, and knowledge gaps in the carbon-energy fluxes surrounding seaweed systems (Hurd et al., 2022). Furthermore, seaweed forests support invertebrates, which respire and release CO_2 (Bué et al., 2020; Hepburn & Hurd, 2005; Poore et al., 2012; Suárez-Jiménez et al., 2017; Taylor & Cole, 1994). The effect of cumulative respiration is that in some instances, seaweed beds release more CO_2 than they remove from the atmosphere (Gallagher et al., 2022). A more comprehensive understanding of the energy and nutrient fluxes in seaweed systems is thus required (Smith & Fox, 2022) to further elucidate the effectiveness of seaweeds as blue carbon systems, as many systems are poorly quantified (Hurd et al., 2022). While the effectiveness of global seaweed forests for carbon removal from the atmosphere is not at the scales of terrestrial systems (Hurd et al., 2022), estimates of global kelp biomass are becoming more accurate with recent discoveries of previously unknown seaweed refugia (Duarte & Bruhn, 2022), particularly in the Arctic, which holds significant portions of rocky substrata for seaweed attachment (Duarte & Bruhn, 2022). This contributes to and motivates for the development of seaweed aquaculture as global seaweed carbon stocks contribute to blue carbon inventory and the potential for seaweed biomass harvesting and sinking, and as blue carbon systems appear to be increasingly viable with more accurate global estimates (Duarte & Bruhn, 2022).

The economic and environmental potential of seaweed production and seaweed habitat development specifically for carbon sequestration and associated biodiversity improvement needs to be quantified/estimated to incentivize investors for such projects. Addressing this knowledge gap should be prioritized as it limits the development of seaweed aquaculture, by disincentivizing potential investors. It is hypothesized that development in the accurate mapping of global carbon stores and their nutrient fluxes is necessary for establishing the impact of seaweed as blue carbon systems (Oceans 2050 project), in contributing to mitigate the effects of climate change and legacy carbon.

Swaile et al. (2022) have attempted to estimate the blue carbon storage potential of kelp forests (and other blue carbon habitats) in English waters. The carbon storage potential of a habitat of 131.4 km^2 was estimated at between 0.026 and 0.039 million tons of carbon, at a carbon stock range of 0.2–0.3 kg C m^{-2} (Swale et al., 2022). It was reported that the confidence of this measure was low, likely due to the volatile nature of kelp biomass in forests. The extent of blue carbon systems using the most up to date layers in Natural England's Marine Evidence Geodatabase (which contains data from various sources) was mapped. However, these estimates are likely underestimated, as they were based on areas of coastline that have been extensively mapped through comprehensive intertidal or shallow subtidal surveys. The need for further mapping to quantify the extent of kelp habitat would allow for more accurate estimates of blue carbon storage capacity (Swale et al., 2022). The above methodologies could be replicated to other coastlines, which would contribute to better estimation of the global blue carbon inventory.

Kelp forests aside, the protection and conservation of blue carbon habitats, often known as MPAs, allow for important ecosystem services provisioning, which can be commercialized through "payment for ecosystem services" schemes, the potential of trading on the nutrient credit markets and sustainable harvesting (such as harvesting mangroves for necessary lumber). These coastal systems also offer key benefits such as coastal storm surge and tidal buffering and protection, such that these systems offer a potentially important resilience measure against tropical storms, which may increase with the onset of climate change. The potential economic benefits of blue carbon systems once realized incentivize their propagation (such as the outplanting of mangrove saplings) as a method of regenerative aquaculture.

4.2.1. Sinking kelp biomass

Fixing carbon in cell tissues (such as seaweed material) only reduces the atmospheric carbon for the long term when the material remains intact. This means that seaweed that is harvested for consumption (by humans or livestock) or processing does not sequester atmospheric carbon. It only acts as a vessel for carbon to cycle through.

True carbon sequestration occurs in the form of protected habitats that remain undamaged or the deposition of carbon into the Earth's crust sealing it away from the biosphere. Sinking seaweeds to the bottom of the ocean for carbon sequestration has merit as the deep ocean is a non-volatile, high-pressure environment, which allows for biotic material to remain intact (undecomposed) on the scale of multiple 100s of years. The attributes of the deep ocean increase the likelihood that this carbon-rich material will be subducted or buried by sediment, removing the biogenic material from the biosphere and locking it away in the Earth's crust. Site selection and manipulating the precise location of seaweed sequestration may increase the likelihood that carbon-rich material gets subducted under the Earth's crust. However, the way in which this endeavor is undertaken is of principal importance in its efficacy as a carbon sequestration mechanism, as other factors such as burning ship fuel may contribute to inefficiencies in this approach.

A recent modeling study demonstrates the potential of seaweed biomass sinking if practized for 80 years (Wu et al., 2022). It was estimated that global carbon export to the deep ocean equates to 270 PgC, which is scaled up to 447 PgC when stimulated by artificial upwelling (Wu et al., 2022) as totals over 80 years, with more than half of the sequestered carbon remaining in the ocean until year 3000. However, the potential side effects that are associated with this method of carbon capture include a reduction of phytoplankton net primary production due to open ocean macroalgal mariculture, as well as changing the distribution of oxygen minimum zones in the oceans (Wu et al., 2022). Such effects are reversible after cessation of open ocean macroalgal mariculture, but that oceans will not recover until after the year 3000. This method of carbon sequestration has great potential despite the side effects, and continued evaluations beyond this first modeling study are necessary to quantify the extent of consequences (Wu et al., 2022).

The efficacy of carbon sequestration by seaweed is largely contentious despite great potential, with several knowledge gaps contributing to the lack of consensus on the supposed sequestration thereof (Duarte et al., 2017; Duarte & Bruhn, 2022; Hurd et al., 2022).

4.2.2. Microalgal bloom stimulation

Another approach to carbon capture at a scale required to reduce atmospheric carbon dioxide is planktonic microalgal bloom stimulation. It is ironic that phytoplanktonic microalgal bloom stimulation may be a possible solution to address carbon capture and promote biodiversity as such blooms are usually considered unfavorable events for aquaculturists, particularly for the instance of "red tides" whose microalgae are known to produce toxins which get concentrated in filter feeders such as bivalves and crustaceans (Brandenburg et al., 2020). However, it is in the open ocean (far from the coastline where most aquaculture infrastructure and easily accessible bivalve fisheries are located) where this solution may be viable.

Phytoplankton blooms are a known occurrence in nature and are at the scales (not only geographic but of time as well) where they can be viewed via satellite images from outer-space. These blooms are a product of natural deep ocean circulation, where the upwelling of deep-sea nutrient rich water, together with light availability at the surface of the ocean, stimulate prolific microalgal production and reproduction. The rampant microalgal production requires significant amounts of carbon, resulting in carbon being absorbed and fixed in the cells of microalgae. The hope for this strategy to work is that these kinds of blooms can be artificially stimulated and that the phytoplankton biomass that gets produced sinks to the deep ocean, locking away all the carbon that was absorbed from the atmosphere. These blooms occur at scales, which effect mass-scale carbon capture and hold potential for carbon sequestration via biomass sinking or as resources for liquid carbon injection.

Phytoplankton blooms usually occur with microscopic diatomaceous species, species with elaborate (and often beautiful) silica-based shells/tests. An example of such a group of organisms is coccolithophores, who have predominantly calcium-carbonate tests. The type of dominating microalgal species is usually dependent on aspects like ocean current dynamics, geographical location, nutrient dynamics (e.g., ratios of nitrogen to phosphorus), seasonality, light regimes, as well as characteristics like water pH. Phytoplankton blooms are usually the primary source of production for open ocean trophic chains, meaning that they promote biodiversity development via zooplankton proliferation (as primary consumers), which, in turn, support (usually teleost) fishes and fisheries (up various trophic levels) that can be exploited for human benefit (secondary, tertiary, quaternary, etc., consumers).

Phytoplankton blooms form part of natural biogeochemical systems, namely the "biological pump." This means that the idea of artificial phytoplankton bloom stimulation is limited by processes such as remineralization (caused by the phytoplankton themselves and by heterotrophic bacteria (Passow & Carlson, 2012) as well as surface predation (grazing) by zooplankton. Indeed, very low amounts of natural phytoplankton biomass gets sequestered into the deep ocean (Passow & Carlson, 2012). The slow sinking rate of individual cells (caused by increased drag from the silica frustules that form part of their tests) contributes to this phenomenon (remineralization prior to sequestration).

One solution to this would be to introduce or manipulate the phytoplankton such as to create hypothetical "super-heavy" cells that would sink rapidly, reducing the amount of remineralization taking place and thus allowing greater amounts of carbon to be sequestered in the deep ocean. One approach to creating 'super-heavy' phytoplankton cells, is to genetically engineer (or selectively breed) phytoplankton to have larger vacuoles (storage organs), which facilitates greater carbon storage, and thereby produces heavier cells with lower surface-area to volume ratios, ultimately contributing to a faster sinking rate. Another option would be to integrate artificially selected phytoplankton cells into natural populations with characteristics such as smaller and shorter silica frustules, which would contribute to faster sinking cells, specific secondary metabolites (compounds) that deter grazing and heterotrophic bacteria (reduced self-remineralization capacity). These radical options require a far greater understanding of bloom dynamics (likely through modeling) and specific bloom mechanisms to be attempted in the first place.

4.2.3. Fertilizing the open ocean

Bloom formation can be facilitated by "fertilizing" the open ocean. The global ocean production is limited in certain areas due to inherent limitations of micronutrients required for photosynthesis. An example of this is the Southern Ocean, which is constrained by iron limitation (Andrew et al., 2019; de Baar et al., 1990). Previous work has shown that blooms can be stimulated in this area with direct iron enrichment (Tripathy & Jena, 2019), otherwise known as the "iron hypothesis" (Boyd et al., 2000). Iron enrichment can come from terrestrial dust inputs (continental dust advection), Antarctic sea-ice melting, and shallow bathymetric weathering (Tripathy & Jena, 2019). Phytoplankton blooms have even been shown to be stimulated by whale excrement (Lavery et al., 2014; Roman et al., 2014). Whale conservation thus has the potential to contribute to carbon sequestration via microalgal bloom stimulation.

Phytoplankton bloom stimulation via nutrient input to the open ocean could also be accomplished with the advent of nutrient input downstream of open ocean aquaculture infrastructure. This would be done through careful and precise understanding of ocean current dynamics, allowing for positioning of aquaculture infrastructure "upstream" from environmental conditions that are favorable for phytoplankton bloom formation. For example, remotely controlled robots could dispense feed at the amounts/times favorable for stimulating phytoplankton blooms downstream of the aquaculture cages. Uneaten feed and fecal inputs are then transported downstream, fertilizing the seawater in the process facilitating bloom formation. In this way, harmful effects to the aquacultured products contained within the aquaculture infrastructure are limited and the consequences of phytoplankton bloom formation realized.

Phytoplankton bloom formation specifically for carbon sequestration is being undertaken by the company Brilliant Planet Ltd., which went public in 2022. The South African startup uses pump-ashore raceway culture to create the conditions for controlled phytoplankton bloom formation, in a controlled and isolated system on shore (removing the risk of leaking into the surrounding ocean environment), and facilitating the proliferation of specific microalgae for the purposes of carbon capture and removal from the atmosphere. The mass of the stimulated phytoplankton bloom is then dried and buried in desert locales, sealing the carbon away, effectively sequestering it at gigaton scales (Brilliant Planet Ltd.). Burying dried phytoplankton in desert environments specifically is particularly important to the success of the carbon sequestration, as the conditions are arid enough to ensure long-term storage and prevent any degeneration of dried phytoplankton (which would return carbon back to the biosphere). Furthermore, this method is an ironic example of using barren desert environments (or environments destined to be desertified) for carbon sequestration, with the aim of reducing climate change and thus reducing the associated desertification of future environments in the process.

4.3. Seaweeds in terrestrial livestock feeds (ruminants)

While seaweeds have previously been cultured mostly for carrageenan production and human food consumption, seaweeds may now be cultured specifically as fodder for terrestrial livestock (specifically ruminants). Research has shown that incorporating seaweeds into the diet of cattle (through specific feed formulations) reduced the methane emissions associated with their production (*Asparagopsis armata*, Roque et al., 2019). This is accomplished by an active compound "bromoform," which halts specific gut bacteria metabolism and prevents methane from being produced in ruminants (Roque et al., 2019). Methane emissions can be reduced by up to 99% with only a 2% addition of seaweeds in their diet (Machado et al., 2016; Maia et al., 2016; Kinley et al., 2020). This exceptional reduction in methane emissions is particularly noteworthy due to methane's greater potency as a greenhouse gas when compared with carbon dioxide. Methane is 25 times more potent than carbon dioxide (EPA, 2022), so being able to reduce methane emissions from one of the largest methane contributors to the global budget is extremely beneficial in mitigating excessive global warming and climate change. However, the challenge of producing enough seaweed at the scales required for supplementing terrestrial livestock remains. However, organizations like Future Feeds Ltd. and the Fonterra Cooperative Group, in Australia and New Zealand, have already undertaken this endeavor with the national cattle production industry. Duarte et al. (2017) elaborate on the benefits of seaweed for terrestrial agriculture, including the use of seaweeds as soil supplements and fertilizers, therewith avoiding the greenhouse gas emissions involved with the deploy of synthetically produced fertilizers (Cole et al., 2016; Roberts et al., 2015; Smith, 2002; Zacharia et al., 2015).

4.4. Replacing conventional fuels and plastics

Seaweeds are able to be used as raw ingredients for "blue" biofuels and have the benefits of not competing for resources such as arable land, freshwater, fertilizer, and pesticides (Duarte et al., 2017). Blue biofuels can thus be regarded as more sustainable and environmentally friendly alternatives to those biofuels produced from terrestrial crops (Duarte et al., 2013). However, the area for seaweed aquaculture that is required to supply 60% of transportation fuels varies, from $< 1\%$ of the economic exclusive zone (EEZ) for Norway to 10% of the Dutch EEZ, and about twice of the German EEZ (Fernand et al., 2017). Regardless, these scales allow for the culture of seaweeds with different product or processing outcomes without impeding on the development of other seaweed farms destined for other uses (such as carbon sinking). The use of biofuels facilitates emissions reductions, by reducing reliance on fossil fuels, and that carbon in the global geosphere is cycled rather than having sequestered carbon (fossil fuels) brought up from within the Earth's crust.

Seaweeds may also be essential in the production of biodegradable plastics from renewable sources (Rajendran et al., 2012). Conventional bioplastics have limitations such as the requirements of large amounts of biomass for their feasible production. Furthermore, seaweeds as raw material for bioplastics have the benefits of being cost effective while minimizing impact on the food chain and are chemically insensitive (Rajendran et al., 2012). Bioplastics produced from seaweeds are reported to be less brittle, more durable, and better resistant to microwave radiation (Rajendran et al., 2012).

Using seaweeds for the production of biofuels and bioplastics holds great potential for a more sustainable society. These methods reduce the emissions associated with the conventional production of such products, through avoiding the burning of fossil fuels, which contributes to the global greenhouse gas budget. However, due to the multiple potential uses of seaweeds, there is cause for concern as to how much seaweed biomass the different strategies should be allocated, as production is currently limited. The future development of seaweed aquaculture will resolve this conundrum with the development of improved distribution and value chain networks.

4.5. Good practices and technology development

Aquaculture sustainability certifications such as Friends of the Sea or Best Aquaculture Practices (BAPs) certification are necessary methods of verifying an aquaculture organization's sustainable operation. The concept of BAPs is the practices that can be adopted to limit the negative effects of poor aquaculture production techniques and system, and can be adopted to assist in the mitigation of climate change by creating more sustainable production systems. BAP certification is the only third-party aquaculture certification program that covers the entire production chain (including processing), and as such is ideally suited to ensuring more sustainable systems. These certifications can be adopted to include carbon accounting to promote carbon neutral and carbon negative production systems, which may incentivize climate change mitigation.

BAP is one of the easier strategies already-existing organizations can use to contribute to developing sustainable production systems, without having to build new infrastructure. Existing infrastructure or systems can be modified to adhere to BAP and as such would be far less costly in terms of capital investment, as opposed to the construction of newer production infrastructure. However, BAP requires consensus on standards/ limits for specific aspects of aquaculture production (such as the concentration of heavy metals in aquaculture discharge), for it to be useful as a standard of aquaculture operation. This is no simple task and is further complicated by the production of different species, each with unique characteristics and requirements for different production systems. The Global Seafood Alliance (in which the BAP organization is nested) is developing such standards for the myriad types of aquaculture species and systems combination that have been developed.

Although expensive, the advent of robotics, renewable energy and battery technology, and ideas like rolling sea cages may also contribute to the mitigation of climate change effects, reducing the emitted greenhouse gases involved when using transport to travel to open ocean aquaculture infrastructure. Remotely operated machines/drones could be placed inside aquaculture cages for performing various tasks instead of human resources, thus eliminating the need for frequent traveling to off-shore locations for activities like administering feed. Alternatively, rolling sea cages are based on the idea that a self-contained aquaculture cage can be placed in an ocean current and cast adrift for the duration of the species' growth to market size, and then be collected at a known location downstream ("at the end of the ocean current"). This may be beneficial as the growth conditions of specific ocean currents may align with the nutritional and water quality requirements of certain aquacultured species. Governance and specific legislation may be developed to incentivize the use of such eco-friendly technologies, to promote the transition to more sustainable methods of aquaculture production and businesses.

5. Ethical Considerations

As with terrestrial agriculture, the potential impact and consequences of intensified aquaculture production in an otherwise previously pristine environment should be accounted for. Ideally, one would operate aquaculture production systems in such a way as to have as little impact on the surrounding environment as was possible. The notion of sustainability and sustainable food production systems has become increasingly significant with the rising susceptibility of the natural environment to undue change from increasing human activities (climate change). It is thus necessary for agricultural systems to stimulate biodiversity development and reduce potential negative impacts associated with poor management and operations, altogether ensuring more sustainable ways of food production and security.

Site selection of aquaculture production operations should be carefully planned. Degraded or altered locations can be considered from the perspective of limiting potential negative influence to one area and not spreading potential negative effects to other pristine environments. However, degraded sites should be selected more preferably with the justification of regenerative aquaculture practices (such as coral outplanting or kelp forest creation).

The question of whether it is moral or ethical to **influence a pristine desert ecosystem** (such as the open ocean) to an intensive production system needs to be weighed. The effects of doing so likely affects the biota that has adapted to survive in those environments, to the extent that altering the pristine environment in question may decrease their survival (such as via displacement, predator introduction) without any compensatory habitat creation of the sort that was adapted to by the biota in question. Are the potential influences of a production system (even a sustainable one that is regarded as beneficial to the environment, such as developing biodiversity) justified, at the expense of what is currently living in those environments? How does one compare the value of one species to the next? The extent of practices such as "de-desertification" (restoring previously naturally barren environments) should be viewed from a conservation perspective – it is surely worth conserving that specific habitat and its evolved biodiversity for future prosperity, despite the fact that the space could be a more productive area with countless benefits.

A blue accounting approach is proposed to assess site suitability, to compare costs and benefits of conserving a specific site (keeping it pristine) or using it for aquaculture production. It should be questioned whether it would be more ethical (or beneficial) that "sustainable" aquaculture production systems focus on limiting their influence on the surrounding environment, as opposed to changing the environment according to what is viewed as "favorable or better" at the time. This has relevance to the designation of areas such as MPAs or fisheries management, and protected species conservation.

When considering what to invest in, the choice between seaweed farming and coral aquaculture for reef restoration presents a complicated one. This is primarily due to habitat phase-shifts that occur when coral reefs are stressed and overfished, where coral mortality and an absence of herbivorous fish may lead to an abundance of seaweed (Hughes et al., 2007; McManus & Polsenberg, 2004). This leads to somewhat of a dichotomy in the literature (Tano, 2016) where seaweeds are concurrently presented as saviors providing future generations with food while reducing nutrient inputs from other forms of agriculture (e.g. Huo et al., 2012; Løvstad-Holdt & Kraan, 2011; Radulovich et al., 2015), while at the same time being the "villains" where they threaten the biodiversity and persistence of coral reefs (e.g. Diaz-Pulido et al., 2011; Jessen & Wild, 2013; Rasher & Hay, 2010). However, this dichotomy is contextual and with appropriate structure in place and tools such as MSP and MPA management unwanted phase-shifts can be ensured.

Moreover, it is likely that coral reef restoration would have a greater societal impact than seaweed farming due to the importance of the coral habitat to native people reliant on them for livelihoods as well as the cultural significance attached to coral reefs. Coral habitats are arguably more economically important as they support established industries such as local fisheries and tourism, as well as being important loci for research, conservation, and genetic biodiversity repositories.

However, in tropical settings native red seaweed farming could be practiced and could be effective in appropriate locations that would otherwise be minimally invasive and minimally negatively impactful to coral systems in the surrounding area. Mangrove estuaries and bays are proposed locations and seem like the obvious choice for seaweed farming (a priori to any ecological impact assessments). However considering the intermittent presence of tropical storms in the area (such as cyclone Idai), regular monsoons, and because seaweeds can also outcompete corals and smother coral reefs, it may be more beneficial to focus attention on coral reef restoration instead of seaweed farming as the damage to seaweed farming infrastructure during such storms may lead to the release of farmed seaweed into the surrounding waters (similar to the mass seaweed influx that wash up on beaches), which may then have severe ecological and economical (tourism) impacts.

The effects of climate change come with the possibility of **introducing species to habitats** or areas that cannot support their growth, and with that, their associated parasites. Introducing new species to an area also increases the possibility that species-specific pathogens/diseases may be present, and thus the risk of species to species transmission of pathogens is possible, where previously this would not have been the case due to hosts not sharing the same geographic environment. For this reason controlling pathogen/disease outbreaks in an aquaculture system is emphasized, particularly for an *IMTA system or one that is in direct contact with the external environment and is liable to be the source of potential pathogens or species introductions to the surrounding environment.* Seaweed aquaculture is seen as one of the greatest vectors of unintentional species introductions globally (Schaffelke & Hewitt, 2007) and such introductions have been described as major threats to local marine biodiversity (Bax et al., 2003; Courchamp et al., 2017). The negative effects of such an event are further exacerbated when considering the opportunity of a species to rapidly proliferate in an area due to absence of a natural (present) control or limiting mechanism (such as natural predators). The increased likelihood of certain environmental conditions to change (due to climate change) increases the risk of negative effects to natural populations in the environment surrounding aquaculture infrastructure.

As with pathogens, the **consequences of "escapes" (of non-indigenous species)** from a controlled aquaculture system or infrastructure into a new area should also be examined. An escape event is further complicated by the associated subsequent introduction of a selectively bred species, potentially integrating with natural populations of the same species. Another view of this is introducing new genetic combinations into the natural world without knowing how this would affect the natural population (potentially negatively). The production of sterile species is one solution to this problem.

The problem escalates in the light of ecosystem engineering species or umbrella species. The subsequent associated biodiversity changes with the escape of umbrella species risks severe natural habitat augmentation. Mitigation measures would need to be considered, which are likely to be monetarily expensive (due to the increased possibility that the biodiversity alterations are at a large-scale) and would likely not restore the habitat to its initial state (before escape) as the damage may already have been done. Improved biosecurity measures have been emphasized in response to the increasing likelihood of escapes with the variable increase in severe weather events under climate change (Bondad-Reantaso et al., 2018).

However, from a conservation perspective, selective breeding of certain organisms such as umbrella species or habitat forming species, if aligned to future environmental projections, may be beneficial upon introduction to previous habitable ranges (as is being done by Coral Vita – see above). The alternative risks having species (genetic combinations) and potentially entire ecosystem types being vulnerable to extinction (due to intolerable environmental conditions) and being lost forever. Seaweed farming has been shown to lead to the unintentional selection of traits leading to the domestication of such crops (Guillemin et al., 2008; Valero et al., 2017; Zohary, 2004) and has been previously observed in the red alga *Agarophyton chilensis*, where farmed specimens were more tolerant to temperature fluctuations than their wild counterparts (Usandizaga et al., 2019). Vegetative propagation favors traits for high growth under a variety of stressful conditions, leading to increased resilience to environmental change. This comes at the cost of genetic diversity (Guillemin et al., 2008), but not in productivity (Usandizaga et al., 2019). However, such resilience and ability to tolerate wide-ranging environmental conditions is characteristic of species or strains (haplotypes) being invasive (Richards et al., 2006), potentially easing the integration of escapees into new environments

The biosecurity implications of potential species introduction via seaweed aquaculture in new sites, an occurrence that will become more likely with the prevalence of exacerbated climate change (Duarte et al., 2017), should be carefully evaluated before the implementation of any new ventures. Campbell et al. (2022) present a review of biosecurity implications for the current carrageenan seaweed industry.

6. Conclusion

The regenerative farming strategies discussed in this paper should be assessed for incorporation into the BE strategies and action plans of countries who have prioritized aquaculture for BE development (like Madagascar, Failler & Andriamahefazafy, 2022), alongside those that have previously been discussed in works such as the FAO Technical Paper 627 (2018), Reid et al. (2019a) and Reid et al. (2019b). Furthermore, regional structures could incorporate the specifics of implementing these strategies into their aquaculture development advisory documents and governance initiatives when offering support to their member states.

Current aquaculture operations and organisations should be encouraged to adopt strategies to develop and transition to more sustainable food production systems using their current infrastructure (such as the incorporation of seaweeds as part of IMTA into current operations); as opposed to destroying and rebuilding new infrastructure for the sake of developing sustainable systems from the ground up. Transitioning to more sustainable production systems using already established infrastructure, incurs a lower cost to aquaculture producers as farm-wide infrastructure alterations changes are costly and expensive, potentially affecting the continued commercial viability of the aquaculture business. However new aquaculture businesses, infrastructure, and frameworks are encouraged to be as sustainable as possible, producing goods and services with as little negative environmental impact as possible.

Future avenues of research should pursue the investigation of the carbon sequestration capacity of coral reefs (and the subsequent consideration of coral reefs as blue carbon habitats), potential (feasibility) of seaweed farming as bioremediation services in polluted areas, degree to which regenerative aquaculture supplements existing capture fisheries (through habitat creation), and the effects of seaweed farming next to coral habitat (restoration) needs to be investigated to improve our understanding of the dynamics at play between these ecosystems. Future research can be directed towards any projects that assess the efficacy of regenerative aquaculture as well as the co-benefits these practices provide, as this will only improve and advance the development of more sustainable methods of production in the context of climate change. An analysis of the economic implications (such as Qi, 2022) and the contextualization of the methodologies included in this review and Reid et al. (2019a) and the FAO Technical Paper 627 in the broader scope of "blue growth" (see Ertör and Hadjimichael (2020)) would constitute meaningful avenues of future research. For example, Le Gouvello et al. (2022) made a first attempt to contextualize aquaculture systems within the recent framework of the IUCN Global Standard for nature-based solutions. Contextualization of the presented aquaculture strategies under the UN SDGs in the context of the BE may help define the BE under the SDG framework as previously suggested (Lee et al., 2020). As has been suggested elsewhere (Qi, 2022), contextualizing the marine products derived from the methodologies herein presented in how they align with the sustainability and economic interests of private companies and national governments presents avenues for further work.

The current review is limited in that it did not discuss methods of adaptation such as aquaculture insurance and other fiscal mechanisms as climate change adaptation options, pertaining to risk management. However, the topic has been extensively covered elsewhere (Theodorou & Tzovenis, 2014; van Anrooy et al., 2022). Other limitations include that the paper largely discussed strategies relating to marine aquaculture and not freshwater aquaculture; however, the strategies discussed herein can still be considered for their potential in adaptive capacity building and increasing resilience as examples of climate change responses, as has been encouraged in the FAO Technical Paper 627 (2018, p. 466).

In conclusion, this paper hopes to emphasize that aquaculture has the potential to be a solution to climate change stressors and increasing food security, as research into the field has already yielded numerous adaptation solutions to changing environmental conditions (FAO Technical Paper 627, 2018; Reid et al., 2019a; Reid et al., 2019b). Regenerative aquaculture practices such as discussed in this review have the potential to change public perception of aquaculture as holding largely negative consequences for the environment and thus encourage the development of other applications of aquaculture as novel methods of blue ocean farming.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

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