SEAWEED

How seaweed and polyculture farming can bring innovation to the aquaculture industry

Abstract

Seaweed has been harvested by humans since the Neolithic period for food and medicine. In the current global climate and environmental crises, seaweed could provide alternative and cumulative uses. Growing seaweed alongside shellfish allows them to feed off each other's waste products, processing nutrients and bi-products. Ocean farming in this manner is called integrated multi-trophic aquaculture (IMTA), and was used as early as 2200 BC but never at scale. 3D ocean farming is an innovative method of scaling IMTA. Seaweed remove excess nitrates from the ocean, clearing up dead zones. It also absorbs large quantities of carbon dioxide, which reduces ocean acidification and sequesters carbon as much as 3 times faster than fast growing trees, and can sequester it for over 1000 years. 3D ocean farming can grow seaweed at scales and speeds that far exceed the growth rate of trees, and over much larger areas. Further research and trials are needed to safely develop this innovative ocean farming method so that it can provide genuinely sustainaible environmental, economic, social, and cultural outcomes.

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Introduction

The global seafood industry is increasingly at risk from overfishing, pollution, trophic collapses that have led to large scale dead zones (Figure 3), and potential abrupt ecological community shifts (Beaugrand, Conversi, & Atkinson, 2019), (Petrou & Baker, 2019). The industry is increasingly vulnerable to intensifying marine heatwaves and ocean acidification due to climate change (Bednarsek, et al., 2012), (IAEA, 2018), leading to concurrent negative ecological, economic, social and cultural impacts.

Seaweed is a diverse group of marine macroalgae that, like all plants, uses photosynthesis and carbon dioxide to grow. As a resource, it's used in multiple ways including as food and fertilizer, in pharmaceutical, health, beauty products, and as biofuels and biodegradable packaging. Some species are being researched as a potential feed supplement to decrease the amount of methane produced by ruminants (Roque, et al., 2019), (Kinley, et al., 2015), (Machado, et al., 2016). While these uses and benefits are known (World Bank Group, 2016), less commonly considered is the ability of seaweed to absorb carbon dioxide at up to 3 times that of fast-growing trees such as Radiata pine, remove excess nitrates from agricultural runoff into the ocean, and increase the Ph of water in its immediate surroundings (Noisette & Hurd, 2018), (Sondak, et al., 2017), (Jones, 2016).

This report outlines the 3D ocean polyculture industry's use of these three key attributes of seaweed to bring innovation to the aquaculture industry, particularly the shellfish industry with concurrent ecological, economic, social and cultural benefits. It also discusses some of the potential limitations and uncertainties.

Background

Seaweed

Seaweed has been a traditional food crop, gathered wild and also farmed since the Neolithic period (Buschmann, 2017). The processes for farming seaweed have largely remained unchanged, although along with other forms of aquaculture, farming seaweed has rapidly expanded along coastal areas, particularly in China and parts of SE Asia, with global production doubling between 2005-2015 (Ferdouse, et al., 2018). The global production in 2017 of seaweed was 30 million tonnes (Buschmann, 2017). This is both from wild harvests from countries such as Chile, China, and Norway, as well as farmed production.

> *"Seaweed cultivation is the world's fastest growing aquaculture sector, with the global seaweed industry worth more than US$6bn per year. There are many species that have the potential to be transformed into a range of commercial products as well offering environmental benefits to counteract climate change... We believe our seaweed research,*

alongside our other aquaculture research, could significantly contribute to achieving the government's target of aquaculture becoming a $3bn industry by 2035. Last year alone New Zealand's aquaculture sector generated over $600m in revenue, employing over 3000 Kiwis..." – Cawthron Chief Executive Prof. Charles Eason (Eason, 2020).

Like other forms of aquaculture, seaweed is still largely farmed as a monoculture. Seed stock is gathered from wild stocks and the larvae grown in tanks. Red seaweed is grown in small patches of intertidal sand flats. For brown seaweed and kelp, once it has reached optimal size, the larvae are attached through different methods to ropes. These are then sold to farmers or transported to industry-owned farms where the ropes are strung horizontally in shallow waters up to 10 metres. Depending on the growth rate of the species, which can be up to 1 metre per day (Flannery, 2019), it is then harvested anywhere from 2 to 3 months later (World Bank Group, 2016).

Typical monoculture crops including fish farming and farmed seaweed has led to the degradation of some coastal areas (Black, 2016). For example, in the Philippines where seaweed is farmed in intertidal zones between 1 and 3 metres deep (Figure 1), in many places this has come at the cost of sacrificing mangroves and eelgrass, leading to poor water quality (Hatziolos, Hooten, & Fodor, 2013) as well as the loss of important coastal ecosystems and carbon sinks (Sanderman, et al., 2018).

Figure 1: Top Image shows deforestation of mangroves to produce seaweed (Macharia, 2021). Bottom image show inter-tidal seaweed crops (Franz, 2016)

Deeper water farming methods used in China and Indonesia use lines anchored to the bottom in water 10 to 50 metres deep, holding in place horizontal lines that float around a metre beneath the surface. Kelp grows along these horizontal lines, ensuring maximum photosynthesis and growth rates (Tiwari & Troy, 2015).

Shellfish

Shellfish have been gathered for food for over 160,000 years (Minkel, 2007), and farmed by indigenous cultures for several thousand years (Smith, et al., 2019). Today, like seaweed, they are also grown from a larval state either in the wild or in hatcheries until they mature into seed or juvenile animals, at which point they are sold to farmers. Mussels are suspended vertically in deep water mesh socks until maturity. Oysters are grown in floating containers that allow water to circulate through them. Once larger, they are moved to intertidal cages or semi submersed rafts, which are extremely susceptible to hurricanes and tropical storms (SeaWestNews, 2017).

Integrated multi-trophic aquaculture

Integrated multi-trophic aquaculture (IMTA) is the process of farming multiple species that exist on different levels of the food chain, feeding off each other's waste products, processing nutrients and by-products (Hickson, 2018). The concept itself is not innovative insofar as permaculture on the land has been used for thousands of years. In aquaculture, China began integrating fish with marine plants as early as 2200-2100 BC. However, with the advent of industrialisation, monoculture crops both on the land and in aquaculture became more cost-effective to grow, maintain, and harvest at scale. While IMTA made an appearance in the 1970s where it was applied to farm kelp, muscles and salmon, it was, for the most part too complex, and not scalable (Chopin, 2013).

Concept & Implementation

Greenwave's innovative IMTA concept and implementation

Driven by the collapse of the cod-fishing industry and disillusioned by the destructive technologies used by Canadian salmon farming, life-long professional fisherman Bren Smith explains his motivation for turning to IMTA and creating Greenwave, in this 2013 TED[X] talk:

> "*I ended up in Long Island Sound with this new programme to attract young fishermen back into the fishery, by leasing shell-fishing grounds for the first time in 150 years. So, I became an oysterman. Then the storms hit. Hurricane Irene buried all my oysters. Hurricane Sandy: 80% crop loss and most of my gear washed out to sea two years in a row. Ocean acidification killing literally billions of shellfish-seed up and down our coast. Rising water temperatures spreading disease. And this isn't just in Long Island Sound. This is happening globally… My oysters were canaries in the coal mine for a climate crisis that's arrived 100 years earlier than expected*." – Smith on 3D ocean (Smith B. , 2013)

Smith goes on to explain how it was not just the economy, but entire communities where generations of fishermen had lived, whose livelihoods and lifestyles were under threat. After ten years of experimentation, trial and error, Smith developed an innovative form of IMTA using the entire water column, which he refers to as 3D farming.

How 3D farming works

The system uses lines and buoys that act as a support framework, with bottom anchors tethering the system in place. In an area of ocean off Long Island Sound on the east coast of the United States, kelp is grown from the horizontal lines close to the surface, similar to seaweed farming elsewhere. Mussels and/or scallops are grow from vertical lines coming off the buoys, and oysters and clams are grown on the sea floor (Figure 2). The Long Island Sound farm produces 10 to 30 tonnes of seaweed and 250,000 shellfish per acre per year (Bioneers, 2016).

Monoculture kelp and shellfish farming methods need fertilisers and pesticides. 3D ocean farming, which works best in industrialised waters, for example, near rivers that discharge high levels of nitrates from farm runoff, uses a multi-trophic system instead. Aside from ocean space, it doesn't require any external inputs including chemicals, freshwater, fencing, pest or predator control. It helps to improve water quality, creates new habitats for other species (Butfield, 2019), and in the industry, from growing juveniles in tanks to processing seafood, creates jobs (Smith, 2013).

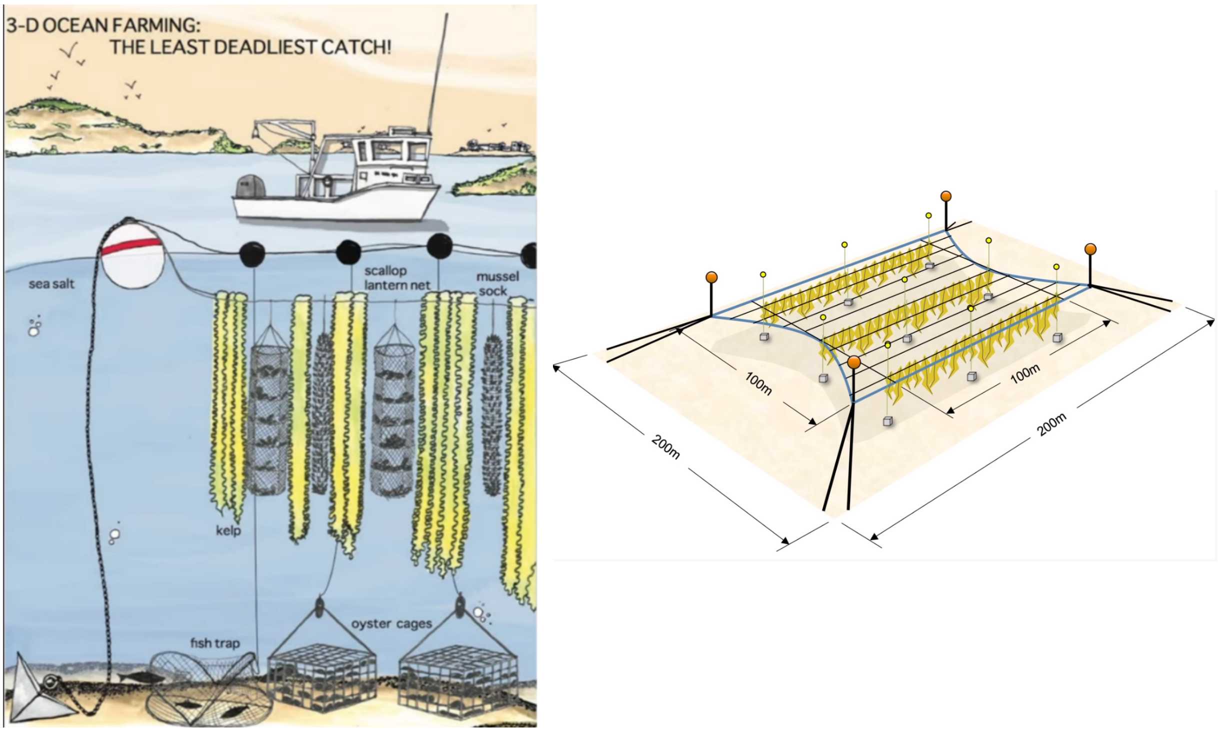

Figure 2: Greenwave 3D farming ocean cross-section and diagram (Greenwave, 2021)

Environmental impact

Climate change impacts on shellfish aquaculture

The ocean has absorbed roughly one quarter of carbon emissions released into the atmosphere to date. This has increased ocean acidity by 30% since the pre-Industrial era, reducing carbonate, which shellfish need to grow their shells. This rapid change on oceanic Ph makes it very difficult for larvae and for young shellfish to grow to maturity, it increases their susceptibility to disease and predation, and inhibits reproduction (Bennett, 2018). For example, oyster larvae production in the US dropped by up to 80% between 2005 and 2009 because of ocean acidification (Melker & Campbell, 2012). Mature oysters were also lost due to storm surges Hurricane Katrina, for example, attributed on part to sea-level rise (Irish, et al., 2014) caused an estimated loss of over $1.3 billion in US seafood production, predominately in lost oyster production (Buck, 2005).

The Halo Effect

In order to combat the impacts of ocean acidification, in some locations conventional aquaculture introduced eelgrass and added sodium carbonate to the waters around their stock, mitigating the corrosive effects. However, this is not a permanent fix as ocean acidity is increasing, with the IPCC estimating it could be 100-150% higher by the end of the century (IPCC, 2019). Kelp absorbs carbon dioxide from the surrounding water, reducing its acidity, creating a halo effect that provides a safe environment for shellfish to grow with minimal energy requirements (Bigelow, 2018). The kelp is also able to provide primary and secondary nutrients for shellfish. 3D farming has also created an artificial reef system which help to protect juvenile fish, some 150 different species of fish have been recorded returning to what was previously a barren patch of seafloor in Long Island Sound (Smith B. , 2013). The kelp also acts as a wave buffer, absorbing energy and protecting shellfish during hurricanes (Hickson, 2018).

Preventing eutrophication

Eutrophication or oceanic dead zones occur near highly populated areas when nitrate and phosphate runoff in freshwater sits on top of the denser saltwater (Figure 3). In developed countries, such as the US and New Zealand, this is predominantly due to agricultural runoff from manure and fertilizers. In developing countries such as Asia and Africa this is from untreated wastewater dumped directly into the ocean. In both instances, the excess nitrates and phosphates lead to an out of control increase in cyanobacteria (blue-green algae) on the surface. These blooms prevent light from reaching primary producers—oxygen producing kelp, seagrasses, and phytoplankton. When the cyanobacteria die, their decomposition uses up what's left of the dissolved oxygen, creating a hypoxic environment, with a negative cascade effect through the entire food chain (Rutledge, 2011).

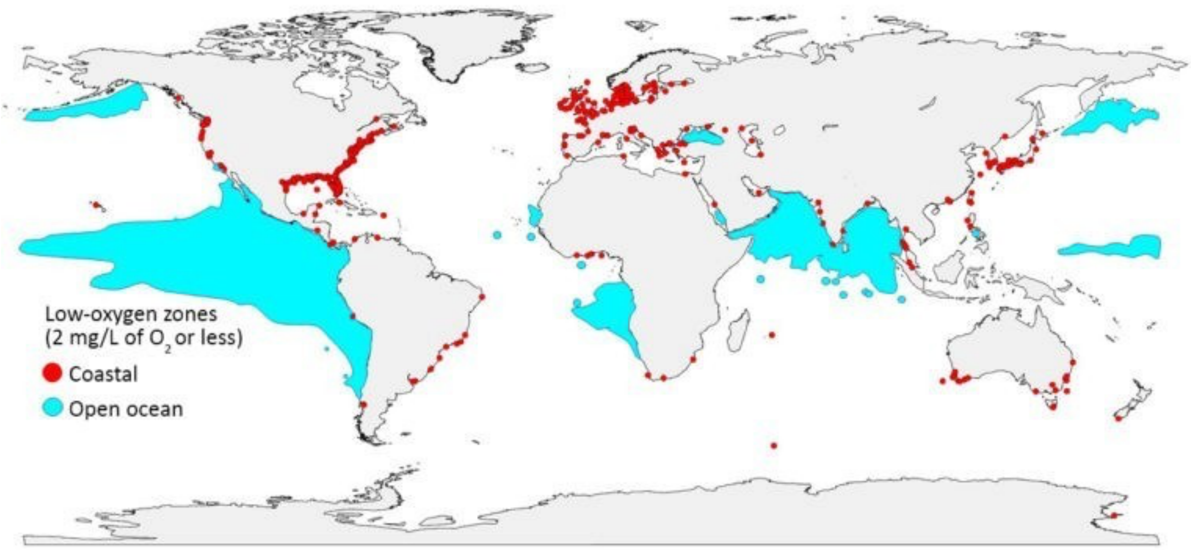

Figure 3: Dead zone locations globally (McKenna, 2018)

In the summer of 1999, high nitrates from agricultural activity created a 530km^2 dead zone in Long Island Sound off New York. By 2014, using waste water management and a nitrogen trading scheme, costing a total of $2.5 billion USD, the amount of nitrates entering the water was reduced by 55%. This reduced the dead zone to 230km^2 (University of Connecticut, 2019). Kim, Kraemer, & Tarish (2015) studied multiple kelp species in Long Island Sound and found that over the course of a year, cultivating both winter and summer species of kelp would remove 320 to 430kg of nitrogen per hectare, while shellfish could remove between 77 to 556kg of nitrogen per hectare (Kim, Kraemer, & Tarish, 2015). Using 3D aquaculture, coving only 1.5% of Long Island Sound, kelp and shellfish would be able to remove a further 9% to 23% of the nitrates entering the water (Mixon, 2020), with marginal maintenance, minimal effect on recreational boat activities, provide a net income of roughly $63 million USD, and up to 1200 full time jobs and 3100 seasonal jobs, (Bioneers, 2016).

Carbon sequestration

One of the strategies to keep global temperatures under 1.5°C require drawing down and sequestering large volumes of excess carbon dioxide from the atmosphere (Coninck, et al., 2018). The technologies to do this through engineering are limited and not yet cost-effective (Harper, et al., 2018) Replanting forests is also part of the strategy. However, forests grow slowly. In New Zealand, for example, under the current Emissions Trading Scheme, Radiata pine is considered to be the most efficient form of terrestrial carbon sequestration, absorbing up to (depending on where in New Zealand it's planted) 1.74kg of CO2-e (carbon dioxide equivalent) per metre squared, per year (Hickson, 2018). Pine, however, is considered to have a 30 year turnover from sequestration to release back into the atmosphere, due to harvesting, transport, and manufacturing (Rassweiler, Reed, Harrer, & Nelson, 2018). These carbon calculations don't include the loss of carbon from lost soil biodiversity or the ongoing problem of wilding pines, which currently cover more than 1.8 million ha of land, causing billions in economic losses (Ministry for Primary Industries, 2020). Nor do the calculations factor in lost ecosystem services, problems that collectively put the climate at risk (Waller, et al., 2020), (Lewis, Wheeler, Mitchard, & Koch, 2019). Forests and other terrestrial forms of carbon sequestration are also at risk of climate change effects such as flooding and fires. For example, the Australian government estimated that the 2020 bush fire season released 830 million tonnes of CO2-e back into the atmosphere (Australian Government, 2020).

Blue carbon – oceanic sequestration and storage

In contrast to terrestrial carbon storage, kelp has an extremely high growth rate and can be grown over much larger areas than on land. In the right conditions it can grow 60-100cm per day. Over the course of a year, it's able to sequester up to 5.25kg of CO2-e, per metre squared. This calculation is based on the growth of natural kelp forests sequestered and lasting over a 30 year-period where carbon is then released due to decomposition (Rassweiler, Reed, Harrer, & Nelson, 2018). Using 3D ocean farming, kelp could be grown and deposited over ocean trenches deeper than 1,000m, where the carbon is considered sequestered for an average of 1000 years. The Kermadec Trench off New Zealand, for example, is 8000m deep (Hickson, 2018). Sequestering for 1000 years makes kelp 33 times more effective than growing kelp forests, and up to 100 times more effective than growing Radiata pine, as shown in Figure 4.

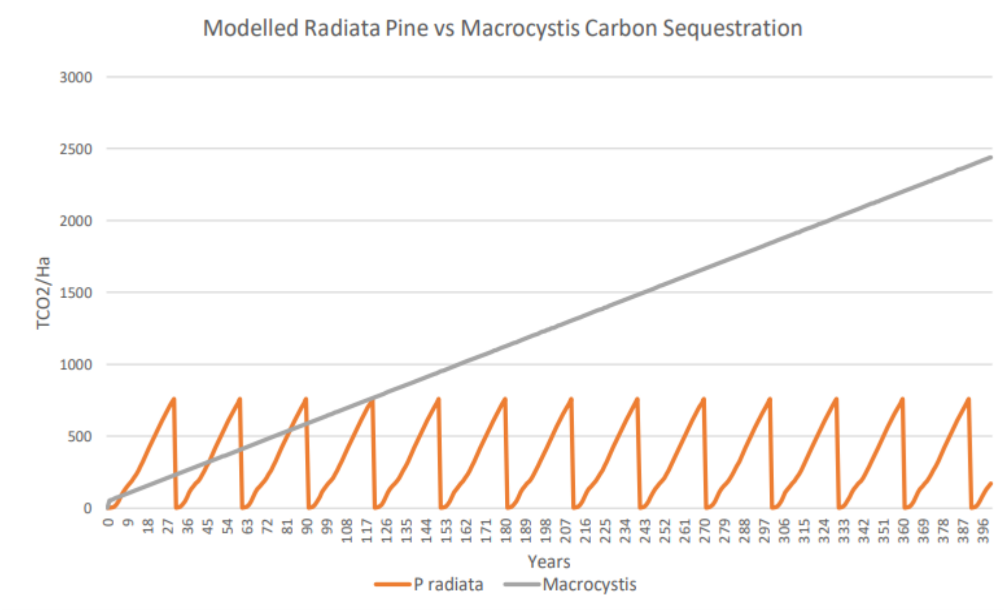

Figure 4: Effect of carbon sequestration over a 1000 year period compared with Macrocystis (Kelp) to the 30 year period of Radiata pine (Hickson, 2018)

Socio-economic Impact

Increase in demand for seaweed production

Currently, livestock and agriculture produce 14.5% of the world's greenhouse gas emissions (Temple, 2018). In New Zealand, livestock and agriculture produces 47.8%, with 22.9% from dairy cattle alone (Ministry for the Environment, 2020). Recent studies have found that depending on the kelp species (primarily the red seaweed, *Asparagopsis*) and the concentration, when added to the diets of ruminant animals, it can decrease their methane production by 50% to 80% (Roque, et al., 2019)

The ability to reduce agricultural emissions while still growing the same amount of food, would be hugely beneficial economically. In 2020, New Zealand dairy exports were valued at 20.1 billion NZD, an increase from 2019 and following an ongoing upwards trend (Granwal, 2021). The dairy sector will be required to begin offsetting emissions by 2025 and farmers are already feeling like their way of life is under threat, with concurrent economic and social impacts to farmers and rural communities (Mackle, 2021). While *Asparagopsis* is currently difficult to grow in larger scales (Kart, 2019), research is underway in Australia and New Zealand to adapt the red seaweed to 3D ocean farming (Macdonald, 2020).

Seaweed has also been applied as a sustainable agricultural alternative to pesticides and fertilizers, helping to enhance nutritional composition of soils, improve soil texture, aeration and drainage (Pulidindi & Prakash, 2020). Other recent studies have shown that non-food grade seaweed could be powdered or fermented, producing lactic acid, and used to make bio-plastics.

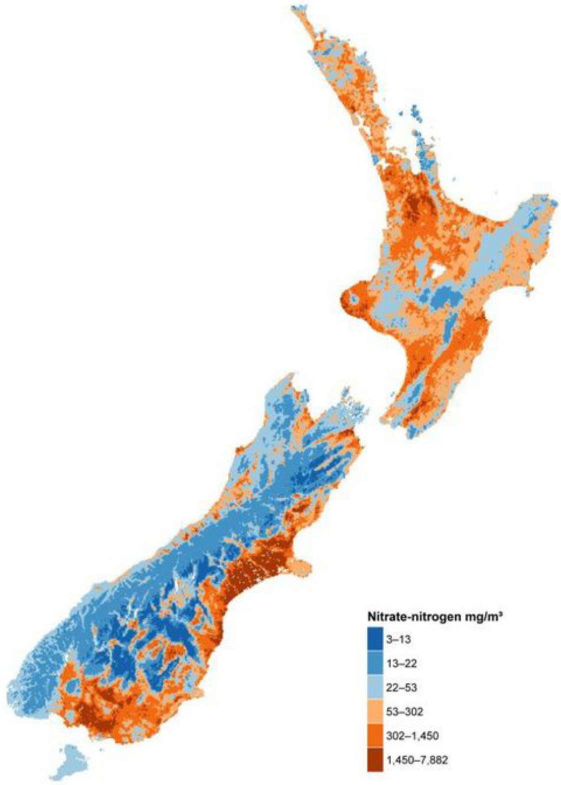

Figure 5: Intensity of nitrate prolusion due to agriculture, across New Zealand (Ministry for the Environment, 2017)

Figure 6: Shellfish farming locations across New Zealand (Environment Foundation, 2018)

This massive growth in demand for seaweed has shown an increase in production from 14.5 million tonnes in 2005 to 30 million tonnes in 2017 (CORDIS, 2015). The world needs 50% to 70% more food by 2050, and only 2% of global food production comes from oceans, of that 45% comes from aquaculture production (Butfield, 2019). The majority of seaweed and shellfish are grown as monoculture. In New Zealand, 600 monoculture mussel farms covering thousands of hectares exporting 33,000 tonnes, worth $337 million NZD annually and are in danger from ocean acidification. These mussel farms are currently being cultivated in a similar process to those produced from 3D farming, but have the potential to simultaneously grow seaweed, complimenting the growth of mussels, and bringing in multiple income streams for fishers (Science Learning Hub, 2015). Given the amount of nitrate pollution currently besetting New Zealand's rivers (Figure 5), and the current shellfish farming locations (Figure 6), there should be considerable potential for 3D ocean farming, while creating a closed nitrogen loop by providing seaweed fertilisers to farms.

Jobs

Fishermen in early 2000s Western culture considered kelp farming a failed form of fishing, as the fishing industry was predominately male, and kelp farming was regarded as a mundane form of ocean harvesting (Bioneers, 2016). As global fish stocks decreased, due to overfishing and other environmental factors like the Blob, an oceanic heatwave over the Alaskan gulf that caused the 2017 cod crash, sustainable fishing stocks fell to 60% in 2017 compared to 90% in 1970 (Ritchie & Roser, 2019). In the United States, federal officials cut the allowable cod catch by 80% to help mitigate the impacts (Cornwall, 2019).

In the UK, the total number of employed fishers dropped from 21,000 in 1970 to 12,000 in 2019 (Uberoi, 2020). The oyster industry was also failing as ocean acidification caused a massive reduction in oyster farming. The US oyster larvae production dropped by up to 80% between 2005 and 2009 because of ocean acidification (Melker & Campbell, 2012). A clear example of this is in Maryland and Virginia, where oysters contributed over $200 million USD to GDP in 1980, with over 136 shucking houses, providing jobs for coastal locals and seasonal workers. By 2008 this had dropped to $13 million and 12 shucking houses (Chesapeake Bay Foundation, 2010).

For many cultures across the world, fishing is not just about jobs. It's been a way of life for hundreds, even thousands of years; their economies, societies, and cultural identities integral to their ability to harvest seafood. This is now being threatened by collapsing fish stocks, pollution, climate change-induced warming and acidification, and for those selling their catch, an increasing demand for consumers that their catch be sustainable. 3D regenerative ocean farming offers a practical alternative for fishermen to apply their skills in a sustainable and productive industry. Greenwave have made their innovative 3D farming processes open source, provided guidelines and resources to help reduce the barriers to entry for prospective 3D farmers. Their goal is to support the transition of fishers and local fishing communities to a sustainable way of life that aims to meets current and future challenges.

In the US, farmers can start up with a license to farm a minimum 8 hectares of ocean, a boat, and an investment of $20,000-$50,000 USD (Greenwave, 2021). This model aims to increase the supply to match the increase in demand for seaweed. Production of seaweed also increases land based jobs in the form of hatcheries, where seaweed is grown from spores and added onto ropes. The combined work on the ocean and land adds roughly 10 jobs for every 8 hectares of ocean used for 3D farming (Mixon, 2020). Projected to a global scale, seaweed as of 2017 was 30 million tonnes. **Error! Not a**

valid bookmark self-reference. shows a possible future with seaweed production up to 500 million tonnes, taking up only 0.03% of the ocean surface area while providing multiple ecological and economic benefits (World Bank Group, 2016).

Table 1: What we would need and provide with 500 million (dry weight) tonnes of seaweed (World Bank Group, 2016)

Ocean area required	500,000 km²	Based on average annual yield of 1,000 dry tons/km² undert current best practice. Equals 0.03% of the ocean surface area.
Protein for people and animals	50,000,000 tons	Assumes average protein content of 10% dry weight. Estimated value $28 billion. Could completely replace fishmeal in animal feeds.
Algal oil for people and animals	15,000,000 tons	Assumes average lipid content of 3% dry weight. Estimated value $23 billion. Could completely replace fish oil in animal feeds.
Nitrogen removal	10,000,000 tons	Assumes nitrogen content 2% of dry weight. Equals 18% of the nitrogen added to oceans through fertilizer.
Phosphorous removal	1,000,000 tons	Assumes phosphorous content 0.2% of dry weight. Represents 61% of the phosphorous input as fertilizer.
Carbon assimilation	135,000,000 tons	Assumes carbon content 27% of dry weight. Equals 6% of the carbon added annually to oceans from greenhouse gas emissions.
Bioenergy potential	1,250,000,000 MWH	Assumes 50% carbohydrate content, converted to energy. Equals 1% of annual global energy use.
Land sparing	1,000,000 km²	Assumes 5 tons/ha average farm yield. Equals 6% of global cropland.
Freshwater sparing	500 km³	Assumes agricultural use averages 1 m³ water/kg biomass. Equals 14% of annual global freshwater withdrawals.

Seaweed drying and processing facilities are able to replace dying land-based industries such as tobacco farming. In New York, tobacco drying facilities are being converted to seaweed drying facilities. Staff need little training as the process for drying tobacco is very similar to seaweed. This helps retain jobs and keep communities intact (Smith, 2021).

Economic benefits of carbon sequestration

Carbon emissions from the Emissions Trading Scheme (ETS) are currently sold at varying prices depending on country, from $1USD per tonne in lower socio-economic countries to $28USD in European countries (ICAP, 2021). The average seaweed price is $250USD per ton, which makes farming seaweed for carbon credit currently uneconomic. However, the price of carbon is expected, to increase, with some countries, such as Canada, increasing the price up to $170CAD ($127USD) per tonne by 2030. Moreover, rather than working to reduce and eliminate emissions by 2050, some large multi-national carbon emitters are planning or already are buying up large tracts of land for forests to offset their emissions:

> *"Eni and International Airlines Group each anticipate using forests to offset 30 Mt/ year of CO2 by 2050: just these two companies could thus exhaust up to 12% of the available total. About 500 Mha of previously-forested and currently unused land could be available for reforestation i.e. without necessarily impacting food or biodiversity. This could remove 3,700 Mt/year of CO2.To put this in perspective, Shell has proposed planting 50Mha of forest to*

> *offset its own emissions: doing so could thus effectively claim one tenth of the sustainably available total for just one company."* (Greenpeace UK, 2021)

This is likely to place upwards pressure on the value of carbon credits, as the available space on land declines and the time frame to meet the Paris Accords' emissions' targets grows shorter.

Growing seaweed solely for carbon sequestration may become viable economically, if the costs of growing it can be brought down by removing costs from drying and packaging, which can be done if seaweed is grown near or directly over deep ocean trenches. Seaweed prices also have the potential to decrease as the supply of seaweed increases due to economies of scale. China's increase in production of temperate seaweed has already started a downward pressure on pricing (World Bank Group, 2016).

Cultural impact

In New Zealand, Ngati Kuia, the iwi in the Tasman District, once enjoyed the kaitiaki principle 'when the tide goes out, the table is laid'. They harvested fish, shellfish, and seaweeds. However, parasites that infected farmed salmon in the area killed the wild fish, while nitrates from the salmon farms caused algal blooms that removed the oxygen, and with that, the table once replete with kai was laid bare (Watson, 2020). The New Zealand government has begun to recognize the rights of local iwi, through the marine customary title that gives local iwi, hapū or whānau the ability to veto activities that require resource consents, such as aquaculture (Ministry of Justice, 2014). The New Zealand government plans to work with Māori to build community knowledge of sustainable aquaculture practices by developing aquaculture training programmes, which will increase the workforce to meet the coming industry demands (New Zealand Government, 2019).

The practice of 3D ocean farming fits very well with the Māori concept of kaitiakitanga: the circulatory nature of providing food for local iwi, helping to restore native wildlife by providing natural protection for wild fish species, helping to remove nitrogen from salmon farming and forestry runoff, promoting growth of shellfish through the halo effect, and restoring the mauri of environment (EnviroStrat, 2020).

Discussion

Globally, overfishing, pollution, trophic collapses, and the multiple impacts of climate change are devastating the environment and the livelihoods of entire communities, most notably indigenous peoples and those in developing nations. Integrated multi-trophic aquaculture or 3D ocean farming is an innovative form of aquaculture that seeks to address these multi-layered problems.

The managing director of Greenwave, Bren Smith, has stated that his primary motivation is to support local economies by creating a new way of farming the ocean that provides jobs and retains a way of life, and creates a genuinely sustainable industry that helps restore and support oceanic ecosystems and could become a game-change in terms of carbon sequestration.

Like all newly evolving innovative projects, several aspects remain uncertain. One report states that 10 acres of 3D farming can produce 20 tonnes of seaweed and 250,000 shellfish (Greenwave, 2021). Others state this can be achieved in one acre (Bioneers, 2016), (Mixon, 2020), and yet others claim only 4 tonnes per acre can be produced (World Bank Group, 2016).

Based on the outcomes to date, 3D ocean farming seems to work well in polluted areas, like Long Island Sound. However, the claim that it doesn't require anything but seawater does not factor in the inputs from pollution and acidic waters due to the carbon dioxide. So, while the kelp farmers themselves are not providing any external inputs, they are being provided these inputs in the form of run-off from agriculture and decreasing oceanic Ph. To that end, if 1.5% of Long Island Sound were indeed given over to 3D ocean farming, it may not remove equal, scalable quantities of nitrogen and carbon dioxide. Farms closer to the run-off sites may be more prosperous compared to those further away, which could lead to value differences within the Sound, when leasing different areas. This is very difficult to estimate as these farms need to exist first before accurate testing can be accomplished (Kim, Kraemer, & Tarish, 2015). Extremely polluted areas may produce seaweed, while mussels may not be a viable human food source due to the pollutants they've absorbed, decreasing their value. However, seaweed may make them more economically suitable for permanent carbon sequestration.

Research is currently being conducted into the possibility of producing deep sea 3D ocean farms to expedite the process of carbon sequestration, however this is not yet possible. It may be un-economical to maintain deep sea ocean farms, especially considering the current price of kelp ($250USD/tonne), and the planned future price of carbon credits ($128USD/tonne). It would be hopeful to assume that the price of kelp would decrease as supply increases with new production methods, however kelp prices have remained steady over the last decade, while supply doubled (World Bank Group, 2016).

The IPCC pathways to keep global temperatures under 1.5°C assumes that greenhouse gasses will continue to be emitted, with the pace slowing until we become carbon neutral by 2020. This seems optimistic given that energy demand is set to increase 4.6% in 2021 (IEA, 2021) and the rush of heavy carbon polluting companies to purchase carbon credits rather than working to reduce the amount of carbon they produce and transform their industries. Consequently, the cost of carbon credits will likely increase to a greater price than planned, considering future pricing is based on current emissions trading policies, which give carbon credits to companies that are recycling carbon rather than sequestering it, such as plantation forests for biofuels (Rassweiler, et al., 2018), or direct air capture facilities that capture carbon from the air and then used for enhanced oil recovery or sell it is a fuel alternative (Smolker & Ersting, 2012).

As carbon sequestration through kelp is popularised, it could incentivise large carbon heavy companies to overexploit the capacity to permanently sequester carbon, so they can continue business as usual. If kelp eventually becomes the new carbon-farming gold rush, the kelp farming industry must be careful not to repeat the same mistakes that currently beset emissions trading schemes that favour short term profits over biodiversity, as it would require roughly 4.5 times the surface area of Australia in ocean space to grow enough kelp for the sole purpose of carbon sequestration to offset *current* yearly carbon emissions (Flannery, 2019). Kelp grown specifically for carbon sequestration has the potential to degrade before reaching below 1000m, especially the faster growing varieties, which decompose faster than slower growing seaweed, releasing the carbon dioxide back into the ocean before reaching the seafloor. This could have severe consequences if seaweed is dropped in the gigatonnes as this could produce localized, deep water dead zones potentially killing other marine life (Hickson, 2018). There are also concerns about the potential effect of dumping large quantities of seaweed onto the bottom of the ocean, however once it reaches past 1000m it can no longer decompose and is unlikely to have serious environmental effects over places like deep ocean trenches (Flannery, 2019).

It is difficult to determine actual economic benefits of 3D ocean farming from country to country and even from location to location depending on economies of scale, optimal growing conditions. and job prosperity per country. In New Zealand the bottleneck is not in the ocean farming of shellfish, but the hatcheries, as there are only one each for mussels and oysters (EnviroStrat, 2020). In 2021, Bren Smith stated that the New Zealand government is giving back 12,000ha of ocean area to local iwi for the use of 3D ocean farming (Smith 2021). A search revealed no specific details about this. However, on 09 May 2021, the High Court issued a landmark ruling on Māori customary rights to foreshore and seabed along an area of the Bay of Plenty between Whakatane *and* Ōpōtiki. This may set a precedent for tribes around the country, allowing them rights to refuse marine farming or commercial fishing activities they deem to be adverse to tikanga (In the Matter of an application for an order recognising Customary Marine Title and Protected Customary Rights, 2021). Conversely, this could pave the way for development of 3D farming based on Greenwave's model.

New Zealand has often been at the forefront of innovation. Professor Sir Paul Callaghan's last public talk was about conservation. In it, he introduced an idea so bold and innovative that it took a while for the scale to be realised:

> *"Let's get rid of the lot. Let's get rid of all the damn stoats, all the rats, all the possums, from the mainland islands of New Zealand. "It's crazy and ambitious but I think it might be worth a shot."* – Ballance, 2019

Sir Paul's idea is underway through Predator Free New Zealand. Kiwis have often been at the forefront of innovation, especially in the peculiar. So it seems apt that we should consider Bren Smith's innovative idea for 3D ocean polyculture farming:

> *"Let's reclaim the coal plants that are shutting down near me. Let's re-imagine the fossil fuel industry. Turn them into kelp biofuel and fertiliser plants. We have to act. We've triggered one of the largest marine extinctions in the planet's history and every other breath you breathe comes from marine life. We've screwed things up. We have to innovate. We have to figure out strategies for resiliency. We have to completely change our relationship to the planet and reformat our economy around principles of sustainability. It is a little bit crazy. But to do what we need to do to make it through a climate change and make sure everybody can make a living on a living on the planet, may be exactly what we need right now is a little bit of crazy."* – Smith 2013

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