Are Ocean-Farmed Sea Greens And Plant And Cell-Based Meats Part Of A Sustainable Solution To Feed The World?

SUMA Integrative Capstone Workshop

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"Where is that sea, that forest, that spot of land; that is not ransacked to gratify our palate? The very earth burdened with our buildings; not a river, not a mountain, escapes us. Oh, that there should be such boundless desires in our little bodies! … A bull contents himself with one meadow, and one forest is enough for a thousand elephants; but the little body of a man devours more than all other living creatures."

-Seneca the Younger (Roman Statesman and Philosopher), Of a Happy Life[1]

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Executive Summary

This project focused on the analysis of meat and seafood alternatives, in particular a study of sea greens, cell-based meats, and plant-based meats as three sustainable food alternatives.

The client was the New York Seascape Program of the Wildlife Conservation Society. The Seascape program focuses on the New York Bight, a region that extends from the waters of Montauk to the southern tip of the New Jersey shore. The client's objective was to be equipped with enough research and documentation on these solutions to be able to advocate (or not advocate) for each, particularly with regards to their impact on the marine region under their stewardship. The primary concern for this region is the blend of commercial, human, and natural activities occurring in the local marine environment. This area is critical to commercial activities and shipping while also being an important habitat for a wide variety of sea and land-based animals, which rely on it year-round as a primary habitat or as a critical route for seasonal migration patterns.

To understand the full implications of the solutions researched, the team primarily focused on analyzing them through a life cycle assessment perspective. However, the team also ensured that the recommendations and conclusions would be related to the specific region and context in which the client operates, therefore providing actionable and comprehensive suggestions.

The underlying desktop research covered six main themes for each of the three solutions, including: scientific background, environment, policy landscape, economics, health, and marketing. The extensive desktop research amounted to over 300 sources. This was also combined with 16 interviews with subject matter experts identified from the research.

This analysis yielded the following conclusions:

- **Sea greens**: The team recommends that NY Seascape incorporate messaging and educational content for seaweed as a healthy, highly functional food source. Significant environmental benefits include reduced ocean acidification, as sea greens can absorb significantly more CO_2 than land-based plants. Challenges include seaweed being mainly used as an ingredient and not as a full meal. Moreover, rising sea temperatures present a clear threat to the variety and resilience of growing certain species worldwide.
- **Cell-based Meats**: The team's findings concluded that cell-based meats cannot be fully recommended at this time given their experimental stage. However, some findings propose this as the most viable solution in the most extreme climate change scenarios, leading the team to suggest that WCS advocate for more robust studies as commercialization gets closer.
- **Plant-based Meats**: Lastly, the team recommends that NY Seascape support messaging for plant-based meats given their significant environmental benefits in comparison to conventional beef. Select studies showed that carbon and water footprints are reduced by up to 90%, and energy usage up to 50%. The success of this solution in fast food restaurants also suggests that the scale of impact could be impressive globally.

Methods & Project Scope

The team was divided into two sub-groups. The first sub-group focused on ocean farmed sea greens research, and the second sub-group focused on cell- and plant-based meats. The two sub-groups then united as a full team to compare the findings of the research and formulate conclusions based on the analysis of all the data and information collected.

Before commencing the research phase, the team wanted to ensure that the approach would be consistent and exhaustive, in order to grasp the most important aspects of each alternative food solution. Given the focus currently placed on the broader impacts of these solutions on natural and human systems, the team identified six key themes to investigate for each solution. This would ensure that once the team analyzed and compared findings, there would be consistent and balanced sources in each theme. This process was facilitated by the creation of a virtual, searchable literature database, which included the source, title, author, summary, and key words from each of the sources identified.

The six main themes on which the research focused were:

- Scientific Background - growing methods and technologies
- Environment - long vs. short term impacts, including carbon cycling, marine biodiversity, ocean acidification, and marine biochemistry
- Health - nutritional benefits, health risks of consumption
- Economics - supply, demand, pricing, production costs, economic returns, US and global market
- Policy Landscape - regulations and funding mechanisms (government grants)
- Marketing, Products, Producers and Key Players - list in appendix

The research included both desktop literary research as well as phone and in-person interviews with subject matter experts. The desktop research mainly focused on peer-reviewed literature, select articles from popular and reputable media sources, as well as broader internet and general market research both online and in supermarkets and local food and beverage outlets.

Throughout the desktop research process, the variety of sources yielded an extensive list of industry experts. The team then assembled a preliminary list of individuals to interview and submitted it to the client for approval. At this point the team reached out to individuals through email and conducted interviews over the course of two months. These were valuable points of contact, as some of the research topics are relatively novel in the scientific and economic landscape. The team was able to receive insightful information from both sides (sea greens and plant/cell-based meat) in order to have a more concrete overview of the state of the solutions.

Introduction

The world's land and water resources are currently being exploited at unprecedented rates and, when combined with the impacts of anthropogenic climate change, this is putting dire pressure on global food systems. Food is a major contributor to climate change, as agriculture alone contributes to approximately 18% to 51% of humanity's greenhouse gas emissions (see Appendix 1 for more information). The global food system, when taken as a whole, produces over a third of the world's greenhouse-gas emissions.[2]

Modern farming and fishing practices have come under scrutiny due to the substantial greenhouse gas emissions associated with cattle ranching specifically and the depletion of wild fish stocks. Meat production has an outsize impact on the environment, particularly beef with a climate footprint that is about five times as large as chicken, pork, or farmed fish (Appendix 2). Raising animals tends to utilize more land than growing crops, even without considering the land required to grow crops for feedstocks.[3] Cow stomachs contain bacteria that helps to digest their plant-based diet but also produces methane, a potent contributor to climate change. Considering global fish stocks, the World Economic Forum reported that almost 90% of the Earth's fish reserves were fully exploited, overexploited, or depleted.[4] US annual per capita consumption of beef is approximately 55 pounds, dairy products 600 pounds, and seafood 15 pounds.[5] Meat-based diets require a significantly larger amount of resources per calorie than vegetarian options, as approximately 2-15 kg of plants are required to produce 1 kg of meat.[6] Therefore, switching to a more plant-based diet can have a significant impact.

There are many important nuances that must be studied and accounted for to understand the impact of meat on climate change and to develop solutions. Agricultural production systems vary substantially globally, feedstocks differ, and impacts of shifting diets must be calculated. For example, if rainforests are cleared for cattle ranching, it is much worse for climate change than farming on existing plains and pastureland. However, arriving at exact numbers for emissions calculations is difficult, as food systems are globalized with a range of stakeholders and linkages.[7]

Through this report, the team sought to study three unique alternatives to current food systems: sea greens, cell-based meats, and plant-based meats.

Sea Greens

1. *Background & Context*

Sea greens (defined below) have been utilized throughout history for a variety of applications including food consumption, in areas with substantial human development along coastal areas. Sea greens are beneficial across multiple industries and their nutritional value is particularly high.

There are three major types of seaweed (red, green, and brown), with over 221 species that currently bring commercial value to the global market.[8] Today, the overall sea green industry is worth more than $6 billion USD, with about 85% of this made up of food products developed for human consumption.[9] There are also other aspects of sea greens that are utilized in other parts of society. For example, the common red seaweed extract carrageenan is used in the pet food, dairy, meat, and pharmaceutical industries.[10] Sea greens offer benefits to society, whether it be with jobs to harvest them or nutritional value for human consumption.

a. Definitions

Sea greens, also referred to as sea vegetables or seaweeds, are plant and plant-like organisms that grow in ocean waters with the end goal of human consumption. Almost all sea greens consumed from the wild and farmed as vegetables by humans are seaweed, which consist of green (*Chlorophyta*), red (*Rhodophyta*), and brown (*Phaeophyceae*) marine macroalgae.[11]

Macroalgae are multicellular, plant-like organisms that live attached to substrata such as rock or other hard surfaces in coastal areas, preferring shallower waters in intertidal to subtidal zones.[12, 13] Some do live in deeper waters, including species of red macroalgae. Phycoerythrin, a pigment that gives them their red color, aids in photosynthesis in poorly lit environments.[14, 15]

Blue-green algae (*Cyanophyta*) are also referred to as seaweed, but are microalgae and usually consumed as supplements rather than as sea vegetables.[16] There are examples of microalgae being added to smoothies and soups,[17] such as spirulina (*Spirulina spp.*) in powdered form, showing an upward trend in consumption in the US.[18] There is one example of a sea green consumed that is not seaweed (seen on many websites as the literature review was conducted), which are the large seeds of tape seagrass (*Desmarestia ligulata*) commonly eaten in Asia and Australia.[19, 20] Seaweed is also used as a colloquial term referring to a wide range of marine plants and algae that grow in the ocean.[21]

This report will mainly discuss green, red, and brown species of macroalgae as sea vegetables for human consumption. Prominent uses include consumption as dried sheets, wrapping for sushi, raw and picked, and ingredients in salads, soups, and smoothies.

b. *Growing Methods & Production*

Much literature out of the US covers the cultivation of kelp, a variety of brown macroalgae native to the US East and West coasts. This is due to the presence of cool, nutrient-rich, and shallow waters ideal for their growth.[22] Certain species of red macroalgae (*Pyropia* and *Gracilaria*) are also native to the US and are grown on small scales for commercial purposes in states such as California.[23,24] Algae have different reproductive cycles across species including sexual reproduction, asexual reproduction, or alternating, and can be grown vegetatively where a new plant grows from a fragment of the parent plant.[25]

i. *Kelp farming in the US*

The following describes the most common methods for farming kelp in the US, which has been well documented by states like Maine, the largest producer of seaweed in the country. In summary, reproductive tissue are collected from wild populations of seaweed in the ocean, reproductive cells are extracted from tissue and fertilized in a laboratory (sexual reproduction), then those cells (sporophytes) are settled on strings and placed in the ocean to continue growing. Eventually, adult seaweed is harvested and processed depending on the method of consumption (dry or raw).

In the New England region, the farming of kelp requires bringing fertilized cells from the lab (also referred to as sporophytes or seeds) into the ocean from late October to November, with harvesting of adult seaweed occurring from March to May.[26] It is important to note that kelp's natural life cycle produces one harvestable adult population per year,[27] affecting when and how much seaweed can be harvested in regions such as the Northeast and Northwest coasts of the US. Kelp prefers cooler waters, and they begin to deteriorate in the summer months.[28] See Appendix 3 for more detailed information about growing methods and production.

The adult kelp have reproductive tissue that are collected in the ocean and brought to a laboratory for their reproductive cells to be extracted.[29] A phycology expert interviewed from the Philippines discussed how collecting spores from wild populations promotes resilience to diseases and improved growth of farmed crops when compared to the use of vegetative cuttings, which eliminates the introduction of genetic variation that is essential to adaptation of changing environmental conditions.[30]

After reproductive tissue are collected from the ocean, it is recommended to keep them cool (50° F), with processing occurring within hours of collection or else health and viability diminish.[31] The tissue is processed and then placed in a saltwater tank under ideal conditions where spores can release spontaneously and look to settle on a surface such as nylon twine.[32] In nature, this is typically rocks and cobble on the ocean floor. After fertilization occurs, they become sporophytes, and the twine is brought out to sea (under ideal conditions).[33] Then, the nylon twine is wrapped around a line and sailed out to the appropriate depth where it is submerged and can continue to grow. Adult kelp grows blades up to 10 m or larger.[34]

While it is not necessary to monitor water conditions throughout the kelp growing season, the data can be useful for future decision-making in regard to farming. The parameters that affect the growth of seaweed include salinity, water temperature, nitrogen levels, and turbidity. Monitoring mostly focuses on the buoyancy of lines, since the stipe (stem) fills with air as it grows causing the lines to float, when they should be below water.[35]

ii. *Benefits of Seaweed Farming*

No fertilizers or irrigation systems are needed to grow seaweed. Since they are photosynthetic, they utilize the carbon dioxide in ocean water to synthesize foods for growth, while absorbing nutrients such as phosphorus and nitrogen.[36] Traditional land farming of vegetables requires fresh water for irrigation and added fertilizers to meet certain yields, which can run-off into water bodies and degrade ecosystems. Excess nutrients from agricultural processes have resulted in algal blooms and fish die-offs, with increasing examples in the US with the Mississippi Watershed and Gulf of Mexico.[37] Seaweed therefore shows the opportunity to be a resource efficient crop due to its minimal inputs while helping remediate the environment from current agricultural processes that result in consequences such as eutrophication. There is the added benefit that sea greens can also absorb excess carbon in oceans contributing to reduced acidification (elaborated more in the environmental section below). A concern in regard to its ability to absorb these nutrients would be the ingestion of elements harmful to human health such as heavy metals through consumption of seaweed (elaborated on more in health section).

iii. Methods of Ocean Cultivation

Once the sporophytes are settled on lines and ready to be set out into the ocean, they can be arranged in several formations, which are outlined in this section. Common methods of seaweed cultivation in the US are long-line and vertical methods. The long-line method consists of long, horizontal ropes suspended by buoys while anchored by moorings to the sea floor.[38] This technique is used in water at depths of 4-10m, which requires the use of a boat for setting and harvesting.[39]

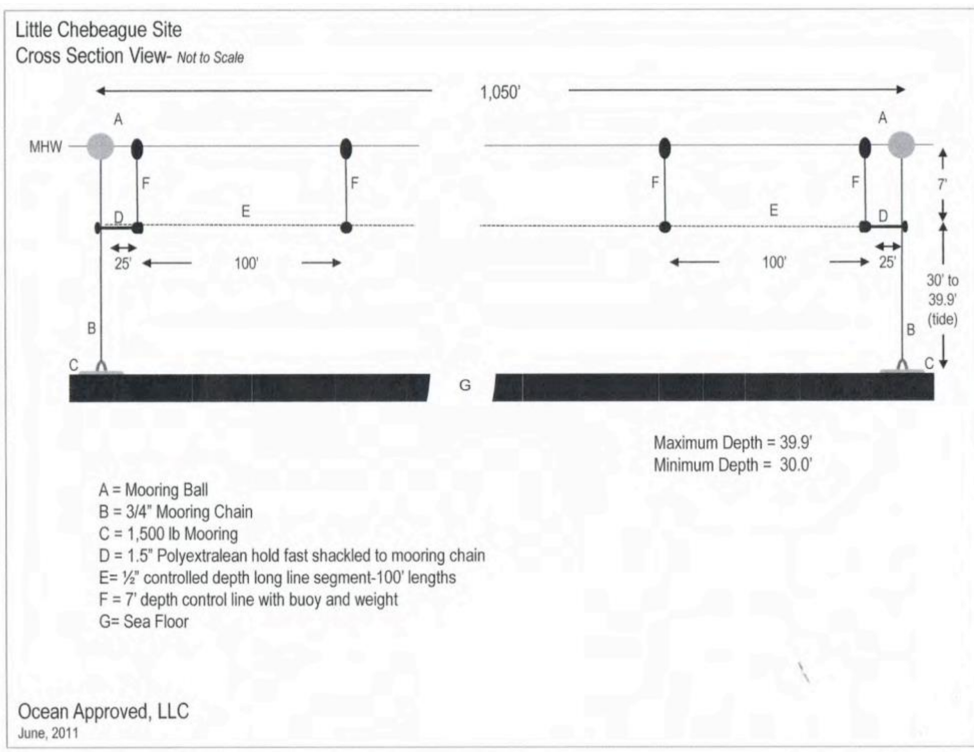


Figure 1: Long-line method[40]

The vertical method utilizes submerged vertical ropes tied to a long horizontal line, with parallel lines alternating between seaweed. It also goes by other names such as the "3D method" and "integrated aquaculture," since most literature describes this seaweed farming method being paired with growing mollusks such as mussels and scallops, with options such as oyster cages anchoring ropes at the bottom.[41, 42]

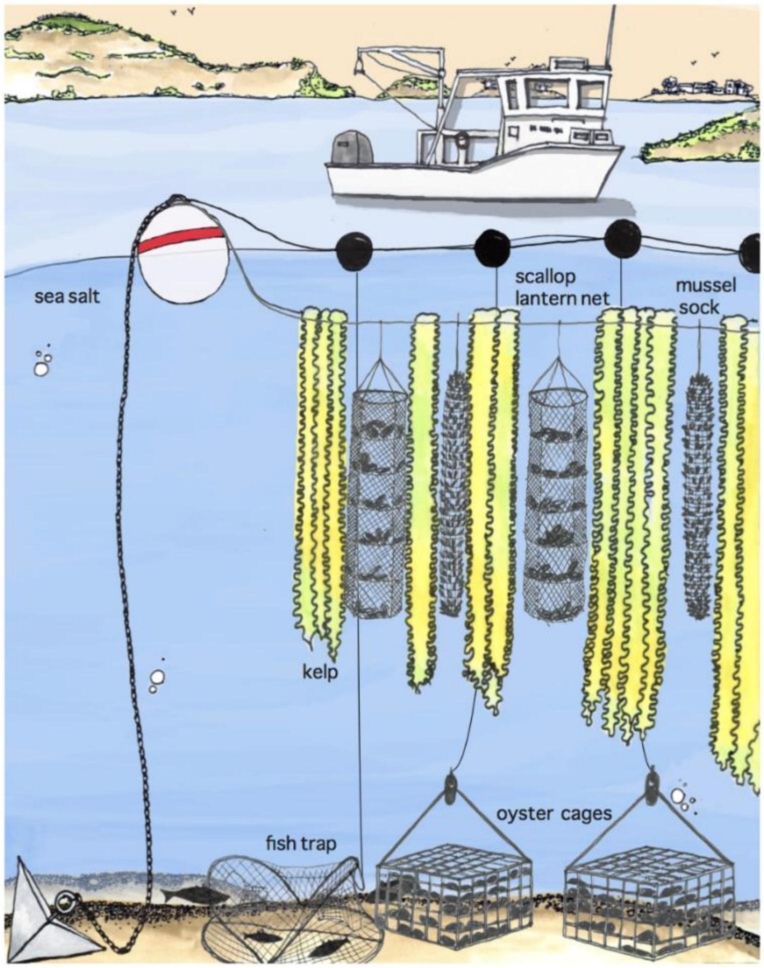


Figure 2: Vertical method with integrated aquaculture[43]

Other methods used in Asia and East Africa include "rock-based" growing, which ties the sporophyte to a rock at the bottom of the shore and "off-bottom," which ties lines between posts (usually bamboo) closer to the sea bed and is ideal for lagoons.[44] There is also the "raft method," which starts from making a square frame out of bamboo or mangrove wood and stretching ropes inside the frame to which the seaweed is tied.[45] It is anchored in about two places to the sea floor and more bamboo is tied to the frame to keep it from sinking.[46] This particular technique is easier to implement at increased depths, which might see an increase in frequency in the near future as seaweed farms move further from the shore. The reason for this is to avoid diseases associated with warmer waters such as "ice-ice," a bleaching of the seaweed due to physiological stresses related to fluctuations in temperature and salinity.[47] Coastal waters have experienced warming due to climate change.[48,49]


Figure 3: Raft method of seaweed farming[50]

These methods can be manually intensive, unlike the vertical and long-line methods which instead rely more heavily on the use of boats to place the lines. The intensity of manual labor for seaweed farming in South Asia is why sizes of farms are limited to 0.25 - 0.5 hectares in the Philippines for example, and have not been successful on larger commercial scales since it becomes expensive due to increased employment requirements.[51] The topography of the environment is what ultimately influences the farming method, with shallower waters leading to the use of the off-bottom method for example, and the raft or long-line method used for deeper waters.[52]

Best practices dictate that the length, width, and spacing between plots should not get too large or too close together. This is to prevent the seaweed from competing over nutrients with each other and other local species.[53] While interviewing the sea corporation Atlantic Sea Farms, the first commercial seaweed farm in the US, they noted that the area of their multiple farms totaled 50 acres, with limited demand of kelp products restricting the amount of farmed area.[54] There is currently a farm on the Connecticut side of the Long Island sound (part of East Coast Kelp Farms) that is as large as 50 acres, but the 12 lines present have spaces of 50 feet between them.[55] Alaska, the second largest producer of seaweed has plots ranging from 0.2 acres to about 300 acres.[56] The Catalina Sea Ranch, the first federal water kelp farm (also a polyculture farm using shellfish as food but algae as biofuel) off California's coast is 100 acres.[57] Overall, there are a large variety of plot sizes and it is clear that attempts are being made to increase plot size for commercial purposes whether it is for food or reasons such as biofuel, while space between lines is kept far enough to ensure successful yields.

iv. Seaweed Farming in New York Waters

In New York, ideal farming methods would most likely be those heavily practiced in the New England region already, including long-line and vertical methods with integrated aquaculture. Even though there are a wide variety of seaweeds in the region (for example, the Long Island sound has about 250 alone),[58] the most commonly farmed for human consumption are kelp species.

There have been attempts In New York to farm red seaweed such as *Gracilaria tikvahiae*, which has shown to be successful in the North Atlantic. However, it grows during summer months when farmers are prioritizing their other main businesses such as shellfish farming. It also conflicts with recreational boating and fishing in the summer. This species experiences heavy biofouling, or the build-up of microorganisms on a host. [59] In the case of seaweed, this typically happens if the harvest period is too long. When it occurs, it results in seaweed not fit for human consumption.[60]

The Cornell Cooperative Extension of Suffolk County in collaboration with the University of Connecticut recently conducted a study in Long Island waters called the "Peconic Estuary Seaweed Aquaculture Feasibility Study," assessing the viability of seaweed farming and gauging consumer interest in kelp.[61] Six test sites were set up and it was determined that sites in Gardiner's Bay and Long Beach were successful at producing impressive yields, while sites in Great Peconic Bay were not due to water temperature and quality that was not favorable (not similar to that of the Long Island sound where these species grow naturally).[62] A research-based pilot project by Stony Brook University also started a kelp farm in Moriches Bay, NY, showing the excitement around pairing oyster farms with kelp to promote crop diversification, since yields were successful in shallow waters where oysters are farmed.[63] Two other sites were set up in Great South Bay and outside of Mount Sinai Harbor on Long Island to continue data collection in deeper waters.[64]

In summary, it seems that certain locations around Long Island are favorable to farming sea greens and can serve populations in multiple ways aside from environmental remediation. Farming sea greens can also provide a food source and offer an opportunity for shellfish farmers and fishermen to make a supplementary income. Moving forward, it would be interesting to see the effects of scaled-up farms, especially if trends move towards deep-sea farming, and how that would change opportunities available to individuals, corporations, and the environment in and around the New York region.

c. Market Size & Industry Trends

When looking at the economic impact of the seaweed industry, there is a large global market growing 8% annually with good economic returns, although this may be inflated in developing markets by depressed wages. The supply is largely driven by small farmers, which is attractive for economic development in developing markets. Small-scale farmers have sustained a competitive advantage over large-scale commercial farms in most markets as the labor for seaweed cultivation must be highly flexible to work on the cyclical time-scale of tides, making it difficult to pay workers stable wages. Seaweed farming historically has also had a low capital and minimal technology requirements.[65] Since much of the supply is produced in the winter months, it is complementary work for the fishing community, which is busier in the summer.[66]

Current seaweed supply is concentrated in Asia. Globally, supply may be susceptible to negative impacts from climate change such as warmer sea temperatures or increased disease. Also, from a demand perspective, seaweed is highly dependent on Asian cuisine demand growth. The global market appears to be evolving, experimenting with larger-scale production and deep-sea cultivation instead of coastal, small lots. Demand is also slowly evolving as surveys show young consumers appreciate the health benefits of seaweed,[67] but culinary experts are still looking for the right form to incorporate seaweed as a consistent part of western diets. Dried seaweed and fermented products appear to be a priority for commercial producers as they have a longer shelf life. A further analysis of the macroeconomics of seaweed can be found in Appendix 4.

Food represents 46% of current seaweed demand on a volume basis, and seaweed extracts for food additives, cosmetics, and pharmaceuticals represents close to another 40% of demand.[68] The largest non-food incremental demand potential is the use of seaweed as a biofuel. This is due to its estimated 100x higher productivity of gallons per acre than corn or soy biodiesel, and carbon-neutral potential as a transportation fuel. The US Department of Energy invested close to $50M in 2009 in the National Alliance for Advanced Biofuels and Bio-products (NAABB) to do over 100 peer-reviewed studies over 5 years. The goal was to develop a roadmap to take the cost of algae based biofuel from $33 per gallon to $7.50 per gallon, which would support the DOE's goal of reaching $3 per gallon by 2030.[69] This price would need to reach approximately $1.50 per gallon to be cost competitive with gasoline.[70] 2019 academic research estimates the current production cost of algae biodiesel at $5 to $16 per gallon (depending on the lipid content), so it is a long way from being economically viable.[71] The costs of drying and finding a commercial use for the 70% of biomass byproducts that are proteins and carbohydrates represent the biggest economic impediments.

i. *US Market*

The US market for seaweed production remains small. Of the 10 states producing seaweed, the largest are producing hundreds of tons versus the 3.6M dry weight ton global market. These states include Maine, New York, Alaska, Connecticut, Washington, Oregon, New Hampshire, Massachusetts, Rhode Island, and California. Like developing countries, the economics look promising, but the volume of demand is small for the native seaweed species cultivated in the US so far.[72]

Maine has among the most diversity of seaweed in the country with 12 species, but rockweed historically has dominated volume and sugar kelp has recently also become significant. Laver/nori, (*Pyropia spp.*) which is consumed in higher volumes in Asian cuisine, does not grow well in the region.[73] Alaria (*Alaria esculenta*), Rockweed/bladder wrack (*Fucus vesiculosus*), Rugosa (*Galaxaura rugosa*), and kelp (various genus and species in the order *Laminariales*) have also been wild harvested in Maine for some time.[74] Sugar kelp (*Saccharina latissima*) is the predominant species farmed, with fewer biofouling problems than cultivating red seaweed such as *Gracilaria*. Successful production is thought to be very site-specific, with nutrient waters and appropriate temperatures the starting-point variables.

New York State has the potential to be a top five market in the US, which can be concluded based on the team's interviews with commercial participants in the shellfish market in New York and seaweed farmers in Connecticut.[75] Connecticut seaweed farmers have already seen success in the Long Island Sound, and a recent academic study at Stony Brook illustrated impressive growth rates that were better than expected on the Long Island coast. New York City provides a large, high-demand market, and the New York government has been supportive of growing the localized food producer industry, so New York State grown seaweed would be advantaged. The growth of the seaweed industry would also provide augmented income for the shellfish fishermen on Long Island, as they are harvested in separate seasons using some of the same equipment.

2. *Impacts*

a. *Environment*

i. *Positive Environmental Impacts*

Seaweed cultivation provides various positive environmental impacts. The chart below provides World Bank Group's data on how expanding seaweed cultivation would benefit the broader ecosystem in several ways: reducing ocean area and land usage, offering a new source of protein and oil, containing high biomass energy, removing phosphorus (P) and nitrogen (N), capturing carbon, and filtrating local water.[76]

Table 1: Environmental Impacts of Seaweed[77]

TABLE 1. Extrapolated ecosystem services from 500 million tons (dry weight) of seaweeds.

Ocean area required	500,000 km^2	Based on average annual yield of 1,000 dry tons/km^2 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 km^2	Assumes 5 tons/ha average farm yield. Equals 6% of global cropland.
Freshwater sparing	500 km^3	Assumes agricultural use averages 1 m^3 water/kg biomass. Equals 14% of annual global freshwater withdrawals.

Eutrophication is the excessive growth of algae when a body of water is overly enriched with nutrients, resulting in oxygen depletion and deteriorating water quality. When eutrophication-induced algae blooms occur near coastal areas, the microscopic algae produce toxins that kill fish, poison shellfish, and can even make the surrounding air difficult to breathe. Since algae blooms typically turn the water red, they are also known as "red tide."[78] Large scale seaweed cultivation can play a role in solving the coastal eutrophication problem. Two studies in China and Sweden show that cultivated seaweeds have a great potential to absorb Nitrogen (N), Phosphorous (P), and Carbon Dioxide (CO_2), effectively mitigating eutrophication as well as preventing "red tide" microalgae in coastal areas.[79,80]

As cultivated seaweeds absorb CO_2 through photosynthesis, they are also considered a carbon sink and can help to mitigate global climate change. One study noted that when calculating the potential CO_2 removal of seaweed, consideration of seaweed farming's energy consumption is also needed. Therefore, these researchers divide the CO_2 avoidance of wind farms by occupied seaweed farming areas, "corrected for 2% lifecycle CO_2 emissions over a nominal 20 year life span of the turbines."[81] The results show that a seaweed farm's potential CO_2 sequestration (with about 1,500 tons CO_2 per square km of the farm per year) is slightly higher than CO_2 emissions avoided by offshore wind farms (with about 12,500 tons CO_2 per square km of the wind farm per year).[82] However, while the overall impact seaweed has on CO_2 absorption is positive, another study suggests that the CO_2 absorption by cultivated seaweed will only reach 6% of the global wild seaweed's CO_2 sequestration by 2050, which equals less than 40 million tons of CO_2.[83]

Seaweeds absorb dissolved CO_2 (which elevates pH) and produce oxygen. Researchers estimate that the acidity of the ocean has increased 30% since the beginning of the Industrial Revolution and will increase 100-150% by the end of the century.[84] Shellfish, in particular, are extremely sensitive to the pH level of coastal waters. Studies show that cultivated seaweeds have the potential to reduce ocean acidification and protect shellfish and local coral reefs. For example, one of the few corals still found in Florida, Cheeca Rocks, has seagrass beds nearby that lower the surrounding water's acidity. Nevertheless, the impact of seaweed farming at a commercial scale still requires more study.

Ocean scientists call kelp farming a zero-input food source as it does not require arable land. Cultivating seaweeds could further reduce GHG emissions by reducing arable land use.[85, 86]

ii. Negative Environmental Impacts

The scale of seaweed cultivation is important to consider when discussing environmental impacts. On the positive side, one study calculates that one km^2 of a seaweed farm can remove the annual Nitrogen inputs received by 17.8 km^2 of Chinese coastal waters and the annual Phosphorus inputs received by 126.7 km^2 of Chinese coastal waters. Figure 4 shows that Chinese seaweed aquaculture production, contributing over 2/3rd of global production, has already risen 7.7-fold from 1978 to 2014 with a growth rate of about 8% per year.[87]

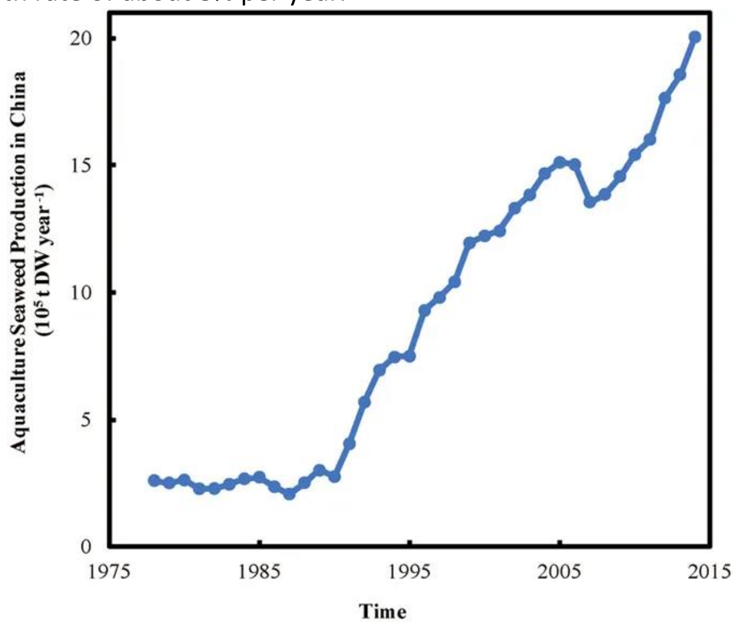


Figure 4: Timeline of aquaculture seaweed production in China (1978–2014)[88]

However, removing the total Nitrogen inputs to Chinese coastal waters would require a seaweed farming area 17 times larger than the current area, and removing the total Phosphorus inputs to Chinese coastal waters would require a seaweed farming area 1.5 times larger than the current area.[89] The environmental impacts of such large-scale ecosystem change are unknown. It is also not clear how industrial-scale production of seaweed would alter nutrients in coastal regions and affect local ecosystems. It is possible that commercial-scale seaweed production could negatively impact the ecosystems by consuming nutrients used by existing plants and animals.

Seaweeds tend to be an introduced species in many countries, which can then become invasive. For example, Japanese kelp (*Undaria pinnatifida)* is on the list of "100 of the World's Worst Invasive Alien Species."[90] The primary long-distance dispersion and introduction of *Undaria* were via accidental import with shellfish and on commercial vessels' hulls. Once established in artificial substrates within anthropogenic habitats such as harbors, marinas, canals, or modified embayments, *Undaria* then spread into natural habitats.

Seaweeds can also have negative physical effects on corals such as shading and abrasion. They can also release allelochemicals, which can alter the chemical environment to suppress beneficial or enhance detrimental microbes on coral surfaces and may enhance the coral's susceptibility to pathogens. One study found that reefs are less diverse and more prone to decline when grown with abundant macroalgae, but this varies depending on the type of reef.[91]

Commercial-scale seaweed production of one species could lower overall biodiversity of algae, which can allow parasites and pests to become more common. The use of stakes or anchors and pollution and debris from abandoned equipment when cultivating seaweeds also have detrimental impacts on the ecosystem, and mammal entanglement is a concern.[92,93]

As seaweeds are farmed in cooler waters, they are also becoming more susceptible to rising temperatures due to climate change. Under the RCP 2.6 climate model, which is the most optimistic scenario created by the IPCC, there is a 78% average loss of species, and projections for 2100 predict major poleward shifts for 13 of the 15 species of seaweed investigated.[94]

b. Health

i. Nutrition

There are over 10,000 types of edible seaweed, but currently, nutritional analysis is only available on the most common varieties (a small subsection of this number). A more robust nutritional analysis of a wider variety of seaweed types is needed as seaweed consumption gains popularity.[95] See Appendix 5 for more detailed nutritional information on six popular edible varieties.

The nutritional human health impacts of seaweeds are diverse. They are often called a "superfood" because they contain high levels of nutrients and minerals for which deficiencies are common.[96] For example, some varieties of seaweeds have more calcium than milk, more iron than red meat, more protein than soy, and are often better sources of minerals than meat, milk, eggs, and land plants.[97] They are also low in calories,[98] sodium,[99] and contain high levels of fiber and protein[100] (protein alone can account for up to 47% of the dry weight of macroalgae).[101] The figure and table below display the percentage of the recommended daily value per person that one serving of seaweed provides for a variety of key nutrients.[102]

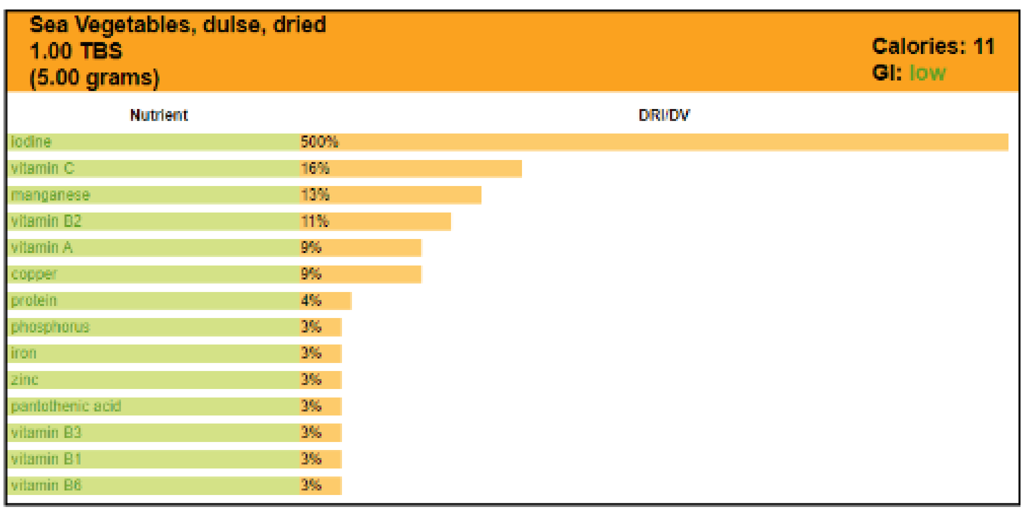


Figure 5: Percentage of the recommended daily value of nutrients per person that one serving of dried dulse, a specific sea green, provides[103]

Table 2: Amount of nutrients that one serving of dried dulse provides[104]

Sea Vegetables, dulse, dried 1.00 TBS 5.00 grams				Calories: 11 GI: low
Nutrient	**Amount**	**DRI/DV (%)**	**Nutrient Density**	**World's Healthiest Foods Rating**
iodine	750.00 mcg	500	829.5	excellent
vitamin C	12.16 mg	16	26.9	excellent
manganese	0.31 mg	13	22.4	excellent
vitamin B2	0.14 mg	11	17.9	excellent
vitamin A	81.05 mcg RAE	9	14.9	very good
copper	0.08 mg	9	14.7	very good
protein	1.81 g	4	6.0	good
pantothenic acid	0.16 mg	3	5.3	good
iron	0.56 mg	3	5.2	good
zinc	0.33 mg	3	5.0	good
vitamin B6	0.05 mg	3	4.9	good
vitamin B3	0.46 mg	3	4.8	good
phosphorus	18.05 mg	3	4.3	good
vitamin B1	0.03 mg	3	4.1	good

Primarily, seaweeds are one of the best natural sources of iodine. Iodine is critically important for making thyroid hormones, which control the body's metabolism and supports proper bone and brain development.[105] Brown algae (which includes kombu, kelp, wakame, and arame) in particular have high iodine content. Some species, such as in the genus *Laminaria*, can accumulate iodine at levels up to 30,000 times more concentrated than sea water.[106]

Seaweeds also have high iron and vitamin C content. One tablespoon of dried seaweed can contain between 0.5 and 35 milligrams of iron depending on the variety, which is ten times the levels found in many land vegetables.[107] Seaweeds also have high levels of vitamin C, which can increase the bioavailability of plant iron. Therefore, this combination is particularly beneficial for health.[108]

Seaweeds are excellent sources of minerals such as potassium, sodium, calcium, magnesium, sulfur, nitrogen, zinc, boron, copper, manganese, molybdenum, chromium, selenium, bromine, vanadium, phosphorus, and nickel.[109] They also provide high levels of fatty acids (such as long-chain omega-3 fatty acids comparable to those in fish oil) and vitamins such as A (in the form of carotenoids), B's (especially B12), C, D, E, and K.[110] These can increase the antioxidant capacity of the bloodstream.[111] Seaweeds are particularly popular among vegetarians and vegans due to the range of B vitamins that they contain, which are challenging to find in plant-based diets.[112]

Seaweeds contain several things necessary for proper brain functioning. These include taurine, decosahexaenoic acid, alpha-linolenic acid, and eicosapentaenoic acid (along with zinc, magnesium, vitamin B12, and iodine mentioned previously).[113] They also have a high glutamate content, which is an amino acid. In addition to being necessary for normal brain function, research suggests that the glutamate content provides the umami flavoring revered by chefs.[114] Umami is known as the "fifth taste" (after salty, sour, sweet, and bitter), and is found in foods such as mushrooms, soy sauce, and parmesan cheese.[115]

Seaweeds also have a variety of unique phytonutrients such as fucoidans, which are believed to be responsible for many of their health benefits.[116] Fucoidans are similar to starches (polysaccharide molecules) but are unique because they have a very complicated structure with a high degree of branching, and also contain sulfur.[117] Studies have linked fucoidans with anti-inflammatory properties, immunity, cardiovascular function, and even life expectancy.[118]

ii. Medical Benefits

While not a focus of this investigation, it is also interesting to note that seaweeds are used for a variety of medicinal and therapeutic applications around the world. For example, they have been used to fight cancer as well as to help with obesity, hair regrowth, skin problems, gut health, depression, inflammation, lower respiratory problems, and thyroid problems.[119] They have also been studied by researchers at The Agriculture and Food Development Authority in Ireland for their ability to help treat cardiovascular diseases and hypertension, and lower blood pressure.[120]

iii. Warnings

While consuming seaweeds can have a variety of human health benefits, there are also risks for some populations. High concentrations of some nutrients found in seaweeds may be problematic for certain individuals. For example, iodine-sensitive individuals should avoid the consumption of brown algae,[121] individuals taking blood thinning medications should avoid overconsumption of vitamin K, and those with kidney problems should avoid high levels of potassium.[122]

Seaweeds grown in polluted waters are also unsafe to eat as they can absorb unwanted contaminants. For example, the consumption of seaweed grown in water contaminated with heavy metals like arsenic, lead, and cadmium from sewage, industrial activities, mining, agricultural activities, and radioactive waste disposal can cause health concerns.[123] Arsenic in particular is problematic, and almost all varieties of seaweed have been found to contain trace amounts. High risk varieties for arsenic contamination include arame, kombu, nori, wakame, and hijiki with the highest risk. Between 2000-2005, England, New Zealand, and Canada issued public health recommendations advising against the consumption of hijiki unless it was verified as containing very low levels of arsenic.[124] In the 1980's, Australia and New Zealand also banned the importation of seaweed from Japan due to high levels of lead, cadmium, and arsenic.[125]

Seaweeds grown in warm tropical waters are also typically riskier to consume than those grown in cold northern waters. Tropical seaweeds are susceptible to transmitting infectious microbes, such as Cholera (which cannot survive in cold northern waters), when seaweed becomes contaminated by human feces. A few individuals died in the 1990's after eating Cholera-contaminated raw tropical seaweed in salads. Seaweed can also become contaminated during harvesting if it comes in contact with *Palythoa* (genus) sea anemones (marine predatory animals of the order *Actiniaria*) found in tropical waters. These anemones produce Palytoxin, one of the deadliest marine neurotoxins, which can be passed on to the seaweed. Several consumers have also died after eating seaweed contaminated with Palytoxin.[126]

Regulations for seaweeds are in a state of partial review at the National Organics Program within the US Department of Agriculture. There are also two types of certified organic seaweed currently available. These certified organic seaweeds are produced in a more closely monitored environment in regions where waters are better protected against contaminants and may provide a safer choice for consumers.[127]

c. Social & Policy

Sea green farming and cultivation is intertwined with current policy regulations. As the industry continues to grow (aided by research explaining the benefits surrounding sea greens), countries must strive to cultivate seaweeds in a sustainable manner. Regulations and directives that protect the exploitation of natural resources must be brought to a national or international political agenda.[128]

The majority of the sea green farming companies starting up in the United States are infantile, which means "best practices" for sea green harvesting, management, and cultivation have not yet been established. This is critical, considering that the worldwide sea green industry accounts for US $10 billion per year.[129] With the growth of sea green farming in new areas there will also be new job opportunities.[130]

Policy needs to ensure a sustainable future for sea green harvesting. The National Oceanic and Atmospheric Administration (NOAA) has funding options to back grants in pursuit of best practices in cultivating sea greens. The Sea Grants offered by NOAA provide a variety of funding opportunities based on four focus areas: Healthy Coastal Ecosystems, Sustainable Fisheries & Aquaculture, Resilient Coastal Communities & Economies, and Environmental Literacy & Workforce Development.[131] The Stony Brook sea green cultivation project mentioned later in this analysis was approved on the basis of being an academic study, and not a commercial project.

In Europe, Portugal requires an appraisal of seaweed management plans, while Norway and Canada develop and execute coastal management plans, which include sustainable farming of sea greens.[132] Chile, a leader in sea green farming practices, has succeeded in establishing a sustainable seaweed farming program for the majority of seaweed grown there.[133]

The US has recently seen significant momentum surrounding policy on sea green cultivation. For instance, on August 2nd, 2018, US Senator Sheldon Whitehouse (D-RI) announced that the Senate had passed a bipartisan amendment designed to encourage job growth in the emerging kelp farming industry.[134] Sheldon said, "kelp is good for human health and good for our environment and oceans. [The] bipartisan amendment will help the promising ocean-growth kelp industry, which is just getting started in Rhode Island."[135]

The amendment, co-sponsored by Senators Lisa Murkowski (R-AK) and Chris Murphy (D-CT), would direct the National Oceanic & Atmospheric Administration and the US Department of Agriculture to begin research and pilot programs supporting this newer farming practice, while applying other scalable commercial applications for these crops.[136] This amendment, passed in August 2018, was later followed up with the success of the Farm Bill approved by the US Senate in December 2018.[137] This bill dramatically expands the support for algae agriculture on the federal level. Guaranteed funding through 2023, alongside research and programs established in this market, increases the potential to expand US sea green production, with advanced technology to accompany it.[138]

The people involved in the sea green cultivation community are taking note of the changes being made in their field. For example, Capt. David Blaney, MMS, of Point Judith Kelp Company, has jumped on the opportunity presented by this progressive legislation with his company. Point Judith Kelp Company, Rhode Island's first dedicated farm, received permits in 2016 from Rhode Island agencies to further explore the possibilities with kelp. Some of the products made by this company include cosmetics, fresh seaweed for consumption, and plant food.[139]

In New York and New Jersey there are active areas where farmers are beginning to capitalize on introducing kelp farming. A collaborative team including scientists at Stony Brook University, 3D ocean farming innovators at the non-profit organization GreenWave, local seafood industry pioneers from Dock to Dish and Haskell Seafood, and several Long Island oyster farmers worked together on a grant to Stony Brook from the New York Farm Viability Institute to bring sugar kelp to Long Island.[140]

A key takeaway from this Stony Brook research on Long Island sea greens farming was around growing depths of kelp. Previous wisdom dictated that the depth be at least 20 feet for optimal growing. However, the majority of oyster farms on Long Island are located within shallow water estuaries, specifically on Long Island's south shore, where farmers began to grow kelp. The best growth was seen in Moriches Bay, where low-tide water depths dropped as low as a foot. Even with the shallow water, the kelp continued to grow over four feet in length.[141] Due to this realization, sea green farming in the shallower waters of New York and New Jersey may be even more viable.

3. Messaging

For those who want to address global overfishing issues, climate change, and marine contamination problems, seaweeds can be an alternative "seafood" that provide high nutritional value and environmental benefits. Seaweed products can be promoted as a healthy and environmentally friendly "superfood." For example, Atlantic Sea Farms advertises its products as "delicious, fresh and sustainable kelp."[142]

From a health perspective, promoting seaweed as a food source is beneficial because of their substantial nutritional value. In an interview with Atlantic Sea Farms, they noted that a priority was making their product taste good,[143] revealing that perhaps for the seaweed industry in the US, advertising sea vegetables for their taste alone might not be enough to get people in western cultures to eat them. In another interview with a seaweed expert, it was mentioned that taking a nutritional angle to messaging seaweed products can be an effective way to encourage consumption in Europe and the US.[144]

From an environmental perspective, seaweed aquaculture is beneficial because of its ability to mitigate acidification, purify water, and sequester carbon. In an interview with the former CEO of Catalina Sea Ranch, he mentions that seaweed would have a negative carbon footprint (using the method California has adopted to measure carbon intensity).[145] In another interview with Scott Schmidt, the CEO of Primary Ocean, he mentions other secondary environmental benefits to be considered from seaweed: when seaweed is used in the agricultural end market, there is a 20% reduction in pesticide usage, 30% reduction in water usage, and 30 to 80% increase in crop yields, which are productive and sustainable.[146]

4. Recommendations & Key Findings

A summary of the team's synthesis of insightful findings across the impact categories for sea greens is illustrated in the table below, followed by highlights of our key findings for each of the four life cycle impacts.

Table 3: Summarization of Key Findings

Sea Greens Life Cycle Assessment Matrix				
Environment	CO2 emissions	Water quality, usage	Climate Change Resilience	Contaminants
Health	Calories	Nutrients	Protein	Processed
Economics	Commercial Scalability	Macro Demand	US Supply	Technology Uncertainty
Social / Policy	Labor Impact: # of workers	Poverty Impact: Fair wages	Regulation well defined	Food Safety

LEGEND:	Strong Solution	Requires more study	Weakness / Threat

a. Environment

Seaweed is an excellent CO_2 and nutrient sink. On an individual plant basis, kelp takes in five times more CO_2 than land-based plants on average, and per acre, these "blue carbon" ecosystems can take up to 20 times more CO_2 from the atmosphere than land-based forests.[147] However, it is unclear what the environmental impact will be if production is scaled up. Also, if sea temperatures keep rising, there is recent modelling research that shows that 80% of the biodiversity of seaweed in Australia will be gone by 2100.[148] Given that seaweed has been moving poleward as the sea temperature rises, if sea greens in Australia are challenged, the rest of the world likely will be too.

b. Health

Seaweed deserves the classification as a "superfood." It has many healthy attributes including one of the highest natural sources of iodine, and high levels of a variety of other nutrients and protein. Seaweeds are also used for medical applications. As a food ingredient, seaweed does not have a high calorie content and does not require much processing to be sold.

c. Economics

Asia dominates current supply and demand, and that is unlikely to change although the US and Europe are investing in growing and cultivation. At the small-scale farmer level, the economics are very attractive, and US seaweed farming can serve as complementary income for fishermen as it is planted in the winter. As sea temperatures rise, cultivation will need to move from coastal areas to deeper seas to regulate temperature, and the economics for deep sea cultivation are still unproven.

d. Social & Policy

It is clear that the US is looking to seaweed farming. On a global scale, economic return on capital can be attractive for small farmers, but still represents a low absolute income. A number of the developing countries that produce seaweed pay their seaweed farmers close to a $1 per day,[149] and the grower may only be making $2,000 to $15,000 per year.[150]

5. Conclusion & Discussion

While seaweed is shown to be nutritionally dense and economically attractive (especially for those in fishing, shellfish, and lobster industries in the US that are supplementing their incomes during the off seasons), there is still a need for more data collection on the ecological impacts of large and small-scale seaweed farming, specifically in US waters. Literature shows that seaweed has been useful in absorbing N, P and CO_2 and deterring eutrophication on large[151,152] and small scales,[153] but there is uncertainty around where the threshold is for excess absorption that can adversely affect marine environments. While large-scale farming studies referenced above discuss positive remediation effects with most data coming from China, one cannot compare their quality of ocean water to New England waters and assume the same outcomes if large-scale farming were brought to the North Atlantic region. Since water quality is better to a certain degree in this region, industrial-scale seaweed farming might have the negative effect of excessive nutrient absorption. NY waters do have excess nutrients from sewage pollution, however.[154]

In the South Pacific seaweed farms are creating havens for juvenile fish, epiphytes, and other grazers (fish and turtles), some of which are consuming the product.[155] Integrated multi-trophic aquaculture has been successful in China, Canada, Europe[156] and the US,[157] with salmon and shellfish for example, removing excess nutrients that would otherwise be harmful. Sea corporations such as Atlantic Sea Farms are currently in the process of collecting data in collaboration with Bigelow Laboratory for Ocean Sciences on nutrient and carbon absorption but have yet to collect data on biodiversity impacts from seaweed farming on the shorelines on Maine.[158]

The future of seaweed farming is uncertain due to climate change impacts. More data is needed to understand the reaction and resilience of seaweed in response to temperature increases and extreme weather events. Increased global temperatures would not be ideal for species such as kelp, pushing the geographic boundary towards the poles for their cultivation. This could also mean that other species that were not able to grow in cooler regions can expand into spaces that were not possible before. Deep-sea cultivation can be an option in dealing with temperature, which is already being seen in places such as the Philippines to avoid diseases such as “ice-ice.”[159] Increased extreme weather events have been decimating seaweed farms in the South Pacific, specifically typhoons that are category 2 or higher, destroying farming structures and propagules.[160,161] Deep-sea farming can have other consequences such as increased marine mammal entanglement[162] and there is also a lack of data on deep-sea impacts of farming since, up until now, it has been mostly practiced in coastal areas.

As this industry continues to grow, more regulations need to form around it. Currently, New York State does not allow for commercial farming of seaweed, but does on a pilot basis.[163] Topics related to health and biosecurity arise, meaning that standards must be set for the quality of seaweed for consumption and the types of species that will be cultivated in waters (native, introduced, monoculture, polyculture).

Alternative Meats

1. *Introduction*

Viable meat substitutes, such as cell- and plant-based meats, are currently being researched and commercialized. This paper will analyze the background and context, production methods, industry trends, and impacts of these two options. Cell-based meats utilize stem cells from an animal and fetal bovine serum to grow animal cells in a lab, at this time rendering them still made from 'animal products.' Plant-based meats mimic the properties of burgers and other meat products and are strictly vegetarian. Due to this distinction in characteristics, the target audience and marketing practices will differ for cell- and plant-based meats.

Cell-Based Meats

1. *Background & Context*

Although the technology behind growing cell-based meat is new, this solution has been expected for quite some time. In 1931, Winston Churchill proclaimed, "we shall escape the absurdity of growing a whole chicken in order to eat the breast or wing, by growing these parts separately under a suitable medium."[164] With growing global populations and an increase in meat-heavy diets, new solutions are required. Alongside improved agricultural practices, reducing food waste, and altering other consumer habits, new technologies and practices to deliver meat substitutes are increasingly feasible.[165]

One report foresees the demand for cow products falling by 70% by the year 2030 due to the cost of various non-animal protein dropping substantially from scientific advancements, economics, knowledge of the perils of cows, and health impacts.[166] The alternative meat industry is relatively new and is witnessing substantial growth. Investments in alternative meat and seafood collected $192 million in investments in 2018 alone.[167]

a. *Definitions*

Cell-based meat refers to animal cells grown outside of an animal's body for the purpose of human consumption.[168] It can also be referred to as cultured meat, cell-cultured meat, in vitro meat, lab-grown meat, and clean meat.

b. *Growing Methods & Production*

Cell-based meats were first patented in 1999 by a Dutch scientist named Willem van Eelen.[169] In 2001, bioengineer Morris Benjaminson and colleagues took muscle tissue from a goldfish and introduced fetal bovine serum (FBS) to produce more muscle cells.[170]

Even after years of careful study and scientific advancement, cell-based meats are not scalable at the current time. To create cell-based meats, 'satellite' or stem cells from the muscle tissue of a live animal are fed a nutrient-rich serum, the most popular being fetal bovine serum, or FBS.[171] When fed the serum, the cells proliferate. The first product of cell-based meats will inevitably take the form of processed meats such as burgers, because unprocessed meat has a complex structure of bone, blood vessels, connective tissue, and fat that is much harder to replicate.[172] Since cell-based meats utilize animal cells and fetal bovine serum for growth, they are not technically meat alternatives and still require animal products for production.

c. *Market Size & Industry Trends*

The potential market size for cell-based meats could be comparable to a major fraction of the entire current meat industry, as cell-based meats act as a direct replacement for "real" meat. However, as stated in the previous section, the replication of unprocessed meat is harder than processed meats. Therefore, this is the sector of the meat industry with which cell-based technology will compete first.

Some projections estimate that the cell-based meat industry will have a total worldwide value of $214 million USD in 2025 and a value of $593 million in 2032, a 15.7% growth per year for that period.[173] That growth is projected to be highly influenced by the North American market (US and Canada) due to a higher amount of flexitarian consumers in the main metropolitan areas of those countries.[174] It is also likely that this technology in the future will be cost competitive against traditional meat.[175] This is because the price of the major raw material of this technology (cell culture medium components and serum) will decrease.[176]

When thinking about scaling the technology, there are challenges in some key processes and materials. The most relevant are the ones described in relation to the high nutrient serum, which allows the cells to grow and reproduce. However, these will likely be overcome by innovation, given the rate of improvement in the technology.[177] As an example, though most of the major players in the industry are still using fetal blood for their nutrient serum,[178] a Dutch startup called Meatable is creating a synthetic nutrient serum for the growth process while also reducing their costs.[179]

There are also concerns over potential changes in the supply chain concentration of power.[180] This means that only a few companies, given their potential oligopoly and oligopsony power, could shift the entire market and control the food value chain with vertical and horizontal integration. The current market is already facing high concentration, as few companies dominate the industry at the moment.

Cost competition becomes even more likely when considering the externalities of the current meat industry. Greenhouse gas (GHG) emissions, land use, and water use need to be considered too from a cost benefit analysis perspective. With that in mind, future regulations might directly or indirectly influence this competition. Subsidies, carbon pricing, and energy prices are some of the components that can affect both the "regular" meat price as well as the cell-based meat price. Regarding subsidies, the US government provides over $38.4 billion USD per year directly to US animal producers.[181] A reduction on that subsidy would push meat prices to rise. Another element is the social price for carbon. Some academics estimate that a 40% price increase can be expected for beef if a carbon tax is applied.[182] Another component that affects the potential price of cell-based meat is energy price. By following the U.S. Energy Information Administration projections for 2050, the price of energy will remain stable in the US. However, there are some scenarios such as low fossil fuel prices and technological improvement that would reduce the cost of electricity.[183]

2. *Impacts*

a. *Environment*

Cell-based meats have a comparatively shorter track record when compared to ocean farmed sea greens and plant-based meats. Since the technology is still in the developmental phase, there are a limited number of calculations that can be made to determine the environmental footprint of this solution. Therefore, the models and prediction tools used to forecast future impacts can yield differing points of view. As cell-based meat operations have not yet been scaled, multiple assumptions and projections were made for life cycle analysis (LCA) studies. The variables in these studies are climate change potential, land use, water use, and energy use.

Some LCAs conclude optimistically, others are favorable but uncertain, and some are pessimistic regarding this technology. While the methods employed by the studies presented in the optimistic and pessimistic views are not directly comparable, the key takeaway is that the variety of methods and models currently being used to estimate the environmental impacts of this solution can yield very different results. Increased attention on this solution will generate further studies where accuracy will improve. This will also ideally be matched by a scale-up of the technology worldwide and real-life data from commercial activities once the solution is cleared for market.[184]

i. Optimistic View

An LCA approach and research method was employed to estimate the large-scale impacts of a fully established cell-based meat industry. One study took Cyanobacteria hydrolysate as the primary nutrient and energy source to enable the growth of the muscle cell. The results of this study indicated that ~2.6 GJ, 367.5 m3 of water, ~190 m2 of land were required to produce 1 kg of cultured meat. Further calculations showed that the equivalent emissions of this unit of meat were of approximately 19,000 kg CO2-eq.

This study also compared the obtained results with "conventionally produced European meat." The calculated factors for cell-based meat approximately corresponded to a 7-45% lower energy use (with the only exception being chicken and poultry), 78-96% lower GHG emissions, 99% lower land use, and 82-96% lower water use. While the comparative data does include a high level of uncertainty, the initial comparison does point to an advantage in the cultured meat field when compared to conventional animal-based meat.[185]

ii. Favorable but Uncertain View

Some preliminary LCAs found that there is a potential 95% reduction in GHG emissions associated with the production of cell-based meat compared to more conventional meat production.[186] However, sensitivity analysis also shows that the uncertainty is high. Taking the worst case scenario, the reduction of GHG emissions of this technology would be of only of 16.7% (25 kg CO_2eq per kg of product vs. 30 kg CO_2eq per kg of regular meat).[187] Other environmental comparisons can be made in eutrophication potential (7.9 gPO_4eq for cell based meat vs. 214 gPO_4eq for regular meat), land use (5.5 m^2 for cell based meat vs. 92 m^2 for regular meat), and industrial energy use (106 MJ for cell based meat vs. 78.6 MJ for regular meat).[188]

iii. Pessimistic View

Another study presented a different set of findings when estimating the impact of cell-based meats as an alternative to conventional meats. It found that the GHG emissions of cell-based meats are between 23.9 - 24.64 kg CO_2e per kg of product compared to 1.8-2.3 kg CO_2e for conventional meat. They also found land use is between 0.39 and 0.77 m^2 per kg of cell-based meats compared to 0.18-0.23 m^2 for conventional meat.

b. Health

Since cell-based meat has yet to reach the market, there is a lack of information available on the health impacts of these products. Most companies in the US are still in the research and development stage, and several with whom we spoke estimated they would have a consumer product available within 2 to 3 years.

However, there are a few assumptions that can be made that point to cell-based meat as a potentially attractive alternative to conventional meat and fish in the future specifically around health impacts. The general health impacts would likely be similar, since the inputs for these products (animal cells, growth media to feed the cells) would be the exact same for meat. In addition to theoretically having the same nutritional profile as their conventional counterparts (since it is still meat on a cellular level)[189] cell-based meat could provide advantageous benefits. Bluefin tuna, for example, contains elevated levels of mercury and polychlorinated biphenyls (PCBs) according to the Monterey Bay Aquarium's Seafood Watch report on the species. San Francisco-based startup Finless Foods is creating a cell-based Bluefin tuna that, due to its lab-grown nature, would be free of the toxins and contaminants such as micro-plastics that can affect conventional fisheries. Growing cell-based meats such as beef and pork in a sterile environment would also eliminate both the need for antibiotics and the risk of bacterial contaminants such as salmonella. According to the CDC, antibiotics can cause antibiotic-resistant bacteria to thrive and can result in infections that are hard for consumers to fend off.[190]

c. Social & Policy

Even with cell-based meats not having yet hit the market, there have already been several laws passed in US state courts that regulate the labeling that would be used on these products. In Missouri in 2018, the United States Cattlemen Association (USCA) claimed that the broader definition of "meat" must be limited to the tissue or flesh of animals that have been harvested in the traditional manner, which would prohibit product grown in labs from animal cells from being labeled as "meat." [191] Another similar lawsuit was filed in Mississippi that is currently being appealed by the Good Food Institute.[192] These two laws, among others, typically include rules surrounding labeling for cell-based meat products.

3. Messaging

In the team's survey of cell-based meat products that are currently being developed, most boast the benefit of creating actual meat products that do not involve animal slaughter.[193] They also mention that their technologies play a part in improving animal welfare, have a smaller impact on the environment, and will increase food security for the future because they use fewer natural resources than conventional meat products.[194]

The terminology that companies use around this technology will be immensely important to industry success. There has been considerable debate between marketers and scientists about how to describe meat that is grown in labs. What was called 'in-vitro' meat in the early 2000s changed to 'cultured' or cell-based meat in recent years.[195] Perhaps because of the negative perceptions of the term 'cultured meat' detected by a survey of consumer perceptions, a new term – 'clean' meat – emerged to describe both plant-based and cell-based cultured meat.[196] In this projects' literature, "cell-based" is the most common term found in research since 2018.

According to John Pattison, the Director of Operations of cell-based meat startup New Age Meats, a major hurdle in the success of this technology will be educating customers adequately about cell-based meat products, and marketing primarily toward meat eaters instead of vegetarians and vegans. He believes that this group would be more receptive to this technology but would still need to be convinced there would be no sacrifice to the taste, texture, price or nutrition.[197] Arye Elfenbein from The Wild Type, which is currently developing a cell-based salmon, plans to market this product as being mercury and microplastic free, concerns top-of-mind for consumers.[198]

It is also important for cell-based meat producers to understand the values, customs, and religious traditions of a targeted group. Dietary considerations, likes and dislikes, and rules for meat consumption are very emotionally charged and indoctrinated into cultural traditions and cuisines, sacred texts, and traditions that guide many of the world's largest religious groups. With the recent emergence of modern food technologies, religious leaders have been challenged with reinterpreting their respective texts to guide their faith communities.[199] All cultural and religious groups that have rules governing meat consumption would likely require specially targeted marketing and labeling to address their respective concerns.

Looking at Islamic doctrine, the animals to be eaten must be of acceptable species and must be slaughtered according to traditional halal methods.[200] Halal labeling for cell-based meat products could be obtained through identifying the source cell and culture medium, which can be deemed acceptable if the stem cell is extracted from a halal-slaughtered animal, and no blood or serum is used.[201] Islamic law forbids Muslims from eating or using any product derived from pigs, therefore, a cell-based development method for pork would still not be acceptable for consumption.[202]

Since cell-based meat products are not on the market yet, there is still a lack of information regarding acceptance of cell-based meat consumption for most cultural and religious groups.

4. *Recommendations & Key Findings*

Table 4: Summarization of Key Findings

Cell-based Meats Life Cycle Assessment Matrix				
Environment	CO2 emissions	Water quality, usage	Climate Change Resilience	Contaminants
Health	Calories	Nutrients	Protein	Processed
Economics	Commercial Scalability	Macro Demand	US Supply	Technology Uncertainty
Social / Policy	Labor Impact: # of workers	Poverty Impact: Fair wages	Regulation well defined	Food Safety

LEGEND: Strong Solution | Requires more study | Weakness / Threat

Our food choices have an impact on the environment around us. From a study compiling lifecycle analysis data from 570 published papers, the environmental impacts of the lowest-impact animal products typically exceed those of vegetable substitutes.[203] This, alongside the data provided throughout this document, provides substantial evidence that a dietary shift away from animal products is crucial to sustainable agricultural and food systems. Cell-based meats, although not currently commercially viable or scalable, offer a unique solution to this necessary shift away from large-scale factory farming and animal agriculture since a single animal cell is needed to replicate meat in a lab.

5. *Conclusion & Discussion*

Demand for alternatives to conventional meat are growing significantly. Although cell-based meat production does present a significant opportunity to alleviate environmental harm by conventional meat production and factory farming and to eliminate animal slaughter, the viability of this technology as a sustainable solution is uncertain. Benefits for the environment would largely depend on what a scaled-up production model of cell-based meats would look like and the associated impacts, as well as what is done with land and resources left over from conventional meat production. Because current production is too small to facilitate controlled studies on human consumption of these products, there is little known information about the health benefits or risks from cell-based meats. When they do come to market, it is highly likely that there will be considerable regulation about their production processes and marketing claims, and companies will need to invest heavily in educating customers about the production, human health impacts, and environmental impacts of their products.

Plant-Based Meats

1. *Background & Context*

Plant-based meats are a relatively established industry, as veggie burgers have been on grocery store shelves for decades. In 1995, Turtle Island Foods released 'Tofurky,' catapulting vegetarian "meat" into mainstream discourse.[204] However, the meatless "meat" products on the market today are similar in composition to veggie patties but drastically different in taste, marketing strategy, and consumer. Impossible Foods and Beyond Meat, two of the largest players in the space, are creating products that are meant as a replacement to meat, marketed to meat-eaters who want a product that still tastes like meat.[205]

a. *Definitions*

Plant-based meat refers to a new generation of vegetable-based "meats" (such as burgers and sausages) that aim to replace real meat but contain no animal protein or products. These high-tech assemblages are made possible by technological advancements such as the whipping of vegetable oils to mimic the fatty appearance of marbled beef. They are meatier, juicier, and crustier than the previous frozen veggie burgers.[206]

b. *Growing Methods & Production*

As its name indicates, this protein alternative is made of plants and components derived from plants. Beyond Meat discloses its five categories of ingredients: proteins, fats, minerals, flavors and colors, and carbohydrates. Impossible Foods uses different ingredients for their products and does not disclose the functionality of each. Their most unique ingredient is heme, an iron component that is part of hemoglobin. Impossible Foods has developed a technique for growing heme through yeast so as to recreate the 'bloodiness' of meat.[207] This ingredient is relevant for the company's final products as they have found it to be the ingredient that provides a meat-like flavor. The following tables provide more detail on the ingredients both Beyond and Impossible use for their products.

Table 5. Beyond Burger ingredients[208]

Use	Plant ingredient
Proteins	Peas, mung beans, fava beans, brown rice, sunflower
Fats	Cocoa butter, coconut oil, sunflower oil, canola oil
Minerals	Not disclosed
Flavors	Beets, apples
Colors	Beets, apples
Carbohydrates	Potatoes

Table 6. Impossible Foods ingredients[209]

Use	Plant ingredient
Proteins	Soy, potatoes
Fats	Coconut oil, sunflower oil
Flavor	Heme
Not disclosed	Food starch
Not disclosed	Methylcellulose (chemical compound derived from cellulose, natural fiber that comes from plants)

c. Market Size & Industry Trends

According to research firm Euromonitor, the current market size for plant based meat is estimated to be around $1.4 billion USD per year.[210] According to market players such as Conagra, the potential US market size alone is around $30 billion USD per year.[211] Major players from the 'traditional' food supply are starting to enter this market.[212] In 2018, Conagra purchased the brand Gardein, and since then, they have launched new products and are studying the expansion of their vegan products. Kellogg's is revamping its Morningstar brand through a new vegan cheeseburger and imitation chorizo tacos, Nestlé is entering the market with a plant-based burger, and Tyson Foods will launch its own line of alternative proteins.[213]

In addition, restaurants and fast food chains have started to incorporate this type of alternative protein into their menus, such as Carl's Jr and Burger King.[214] Burger King had a comparable growth of sales of 5% (Q3 2019 vs Q3 2018), mostly driven by their adoption of the 'Impossible Whopper' plant-based burger.[215] The growth of this market can also be seen with the recent IPO of Beyond Meat. The initial offer in May 2019 was $25 per stock, and now (December 2019) the price is around $80. Beyond Meat's full year sales guidance has moved from $210 million to $270 million, showing a growth trend beyond their own estimations.[216]

However, as happens with every new industry, there are potential downsides with the expansion of this market. In the US, according to lobbyist group Meat Fuels America, the meat industry generates approximately 1.8 million jobs. The characteristics of those jobs can be seen in Table 7.

Table 7. US Economic Impact of Meat Industry[217]

Direct Economic Impact	Jobs	Wages	Output
Slaughter	104,378	$4,574,303,700	$50,302,152,800
Meat	142,632	$7,813,668,800	$70,754,334,500
Poultry	274,523	$11,223,765,000	$81,820,021,500
Hides, Skins and Offal	5,486	$384,563,000	$3,371,997,700
Wholesaling and Distribution	232,418	$20,346,335,200	$57,429,093,400
Retail Sales	1,112,550	$27,287,687,000	$84,514,089,500
Total	1,871,987	$71,630,322,700	$348,191,689,400

As plant-based meat can be seen as a substitute for regular meat products, a diminishment in total sales volume would not be expected for the US market. On the other hand, the current meat industry provides substantial jobs and approximately 527,000 jobs are at risk with the growth of the plant-based meat industry.

2. Impacts

a. Environment

When it comes to environmental impacts, there are estimations that suggest that omnivores (people that consume both animal- and plant-derived food) have a 52% greater emissions footprint than vegetarians. In addition, an omnivorous diet has a 35.6% greater water footprint and a 61.5% higher ecological footprint (including land use) than a vegetarian diet.[218] Given these differences, a reduction in meat consumption generates positive environmental impacts. Plant-based meat is a viable option to reduce meat consumption while decreasing dietary environmental impacts. In addition, vegetarianism represents a large food security opportunity. If the US would convert to a vegetarian diet, it would have the capacity to feed 350 million people in addition to its current productive capacity.[219]

Beyond Meat conducted a cradle-to-gate LCA of their product with the University of Michigan, comparing a regular beef burger patty to a Beyond Meat burger patty. This study showed that overall, the Beyond Burger has a lower carbon footprint (0.4 kg CO_2eq vs. 3.7 kg CO_2eq of a regular beef patty). The same can be said when comparing energy use (6.1 MJ vs. 11.4 MJ for a regular patty), land use (0.3m^2 vs. 3.8 m^2 for a regular patty), and water use (1.1 liters vs. 218.4 liters for a regular patty).[220]

Impossible Foods also conducted an LCA of their burger compared to a "regular" beef burger. However, the study is not public, and they only disclosed some of the results. Their burger has a carbon footprint 89% below a regular patty, a reduction in land use of 96%, and a reduction in water consumption of 87%.[221]

b. Health

Compared to a beef burger, plant-based burgers (such as those from Beyond Meat and Impossible Foods) have similar profiles in terms of calories, fat, and protein (Appendix 6). One significant advantage of plant-based meats is that they have lower levels of cholesterol and fat than their traditional meat counterparts. Having high cholesterol can lead to an increased risk of heart attack, stroke, or heart disease. Meat has been shown to increase cholesterol levels, while plant-based protein sources can lower them.[222]

While lower in overall fat, both the Impossible and Beyond burgers contain high levels of saturated fat. This mainly comes from the vegetable oils used in the patties. In the Beyond burger, coconut oil adds the appealing marbling effect found in conventional beef. In addition, the plant-based burgers contain higher levels of sodium, which when consumed in excess can increase risk of high blood pressure, stroke, and cardiovascular disease. As a growing number of restaurant chains add plant-based versions of their classic menu items, it is unclear if the new additions are marketed as being healthier, or rather an imitation that can entice consumers to swap meat for a plant-based alternative. Health is not at the core of these products, which is showcased in Business Insider's comparison of popular meat and plant-based burgers and their similar levels of saturated fat and higher levels of sodium.[223] While cholesterol itself is only found in animal products, according to the American Heart Association, coconut oil is 82% saturated fat and can raise levels of 'bad' cholesterol in a similar way that butter and beef fat do.[224]

Plant-based meats are also highly processed. This poses an issue of public perception, as whole foods are generally more nutritious than processed foods, but also raises concern since highly processed foods are very altered and contain additives. According to dietician Sharon Palmer, processing often results in a reduction of the important nutrients such as fiber, vitamins, minerals, and phytochemicals.[225]

While ground beef contains mainly just animal meat, Beyond burgers contain 22 ingredients,[226] while Impossible burgers contain 21.[227]

In the case of Impossible "meat," one ingredient in particular took substantial time to be approved by the FDA. Heme is the ingredient responsible for the burger's coloring, 'bleeding' properties, and meaty iron-rich flavor. While it is a naturally occurring compound in beef and soybean roots, Impossible Foods sources theirs from a genetically engineered yeast. The company faced hurdles with getting the ingredient approved as an additive by the FDA, but after a years-long battle, the FDA deemed their 'secret sauce' safe for human consumption.[228] For vegans and vegetarians who might already rely on processed meat alternatives (such as faux bacon or 'chicken' patties), these newer products likely won't be healthier, but, due to their processing, will not be as healthy as a handmade (whether at home or in-house at a restaurant) veggie burger that uses whole foods such as fresh vegetables, grains, and beans[229].

Another nutritional challenge is that many products are made from ingredients that are known to be common allergens: soy, wheat, gluten, and peanuts. Beyond burgers, while they do not contain peanuts, should be treated with caution by consumers with such allergies. Peanuts and peas are both legumes, so a person with a severe peanut allergy might also be sensitive to the pea protein used.[230] In August 2019, Kentucky Fried Chicken's Atlanta test kitchen debuted a Beyond Fried Chicken made of non-GMO wheat protein (also known as gluten).[231] While it has not been named as a permanent menu item yet, it would not be suitable for consumers who are gluten intolerant.

Despite not making for a particularly healthier product due to their higher levels of processing, sodium, and saturated fat, and the barrier some allergen-sensitive consumers face, some nutritionists, such as Cynthia Sass, say that plant-based meats are fine to eat in moderation. Sass says that given that red meat is linked to some of the most prevalent chronic diseases such as heart disease, "plant options that displace red meat are a step in the right direction."[232]

c. Social & Policy

The emergence of alternative food products on the market has been met with considerable resistance from industry groups and local governments that advocate for agricultural products, and governments have responded by creating laws aimed to protect traditional agricultural products against these newcomers. At least twelve US states have already passed laws that restrict the words that can be used on food packaging for cell-based meat, plant-based meat, riced vegetables, and dairy products, claiming that words typically associated with conventional meat products intentionally mislead consumers.[233]

According to the Good Food Institute, "authoritarian" labeling restrictions are a violation of the U.S. Constitution's First Amendment, and challenges to these laws have been filed in several states.[234] In Louisiana, the "Truth in Labeling" law bans the use of the terms "meat," "rice," or "sugar" on food products derived from non-traditional sources, such as plant-based or cell-derived meats and riced vegetables. A product must meet a strict, prescribed definition in order to include those words on product packaging.[235] A similar law in the state of Missouri was challenged by plant-based meat producer Tofurkey, the American Civil Liberties Union, and The Good Food Institute, citing a violation of first amendment rights, and the court declined to issue an injunction of enforcing the law.[236]

The outcome of labeling laws is uncertain at this time, but lawsuits will likely continue as the popularity of these products continue to rise.

3. *Messaging*

Beyond Meat and Impossible Foods are the faces of the plant-based meat movement because of their impressive products and ability to change public perception of what a plant-based lifestyle can look like since they introduced their signature burgers in 2014 and 2016, respectively.[237, 238] Both companies have the same mission of getting the masses to eat less meat and to inform people about conventional meat's impact on the environment, but have taken slightly different approaches to this. Impossible, until recently, was marketed only toward restaurants and chefs,[239] while Beyond sells to restaurants and directly to customers in grocery stores.[240]

According to Beyond Meat's website, two of four top components of Beyond Meats' "Future of Protein" mission are related to the environment; their products "positively impact climate change" and "alleviate global resource constraints." A Beyond burger will use 99% less water, 46% less energy, 90% reduction in GHG, and 93% less land than conventional beef burgers.[241] Their other top two claims concern animal welfare and human health, although they disclose no information about the former. For nutrition, grams of protein and non-GMO certification labels are most prominently labeled on packaging for all products. They also highlight that their products are soy-free and gluten-free.[242]

Beyond wants to "deliver the meaty experience you crave without the compromise." They won't have customers miss out on their favorite meals or events by switching to plant-based food. Accordingly, Beyond's advertisement and social media campaigns have worked to change the public's perception of a plant-based lifestyle. The company's Instagram account is flooded with picture-perfect hamburgers, creative recipes, chef testimonials, and light-hearted publicity stunts,[243] one of which puts brand ambassador and rapper Snoop Dogg working the cash register at Dunkin' Donuts, pushing "that plant-based great taste" of Beyond's sausage sandwich.[244] At the center of Beyond's "Go Beyond" campaign is basketball all-star Kyrie Irving, whose photo appears alongside boldface text "Break Barriers. Defy Convention. Shatter Expectations." This campaign reinforces that meat-free products can be fun, flavorful, masculine, and can even fuel elite athletes. Brand ambassadors also include rock climber Alex Honnold and basketball player Chris Paul, among others.[245]

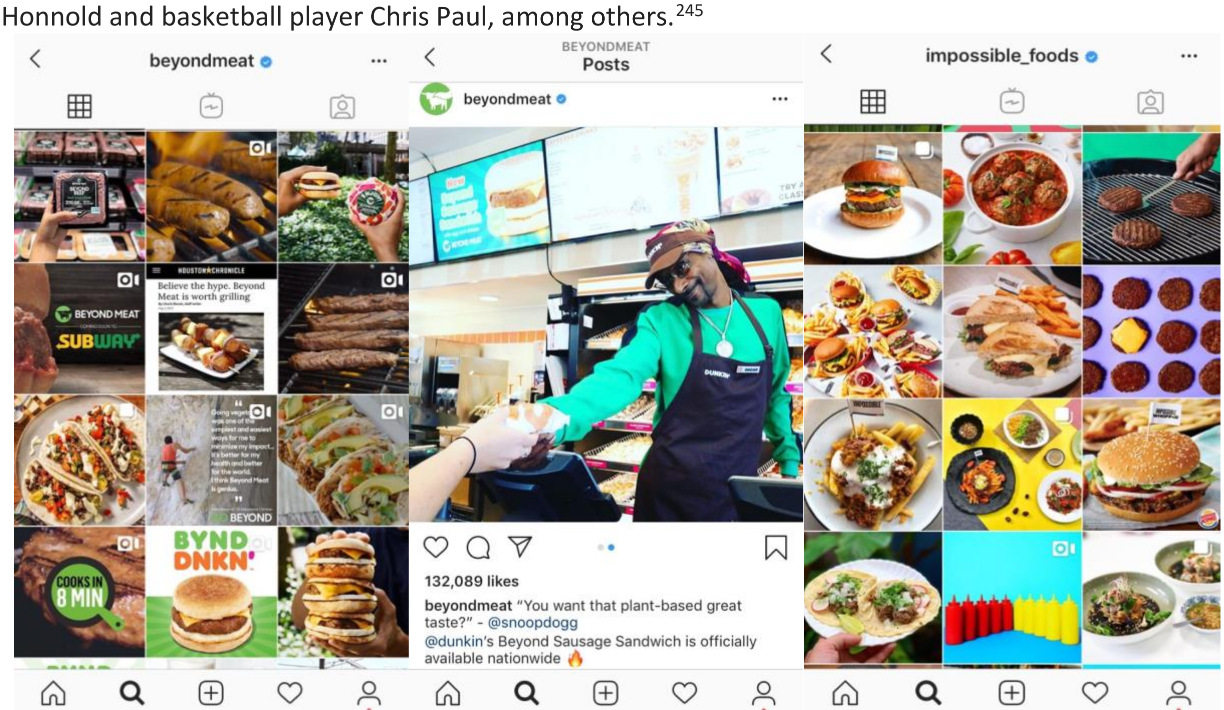


Figure 6. Examples of plant-based messaging on social media[246]

Impossible Foods has taken a slightly different messaging approach than Beyond on their website and social media. Impossible has released annual impact reports since 2017, which contain sprawling information about land use, carbon capturing maps, scaling up their product, and water use.[247] They aim to educate about the perils of beef on the environment and advocate for urgent change. In terms of nutrition, they highlight that one burger has the same amount of protein as a beef burger, no cholesterol, and is a good source of iron, fiber and calcium.[248]

Impossible's social media focuses primarily on restaurant partnerships and creative culinary recipes that can be made with Impossible meat, which is not just a burger, but can also become a taco, a pizza topping, poutine, breakfast burrito, or Swedish meatballs.[249] Their website imagery is full of whimsical drawings, blocks of bright color, and exploded words. [250]

4. *Recommendations & Key Findings*

Table 8: Summarization of Key Findings

Plant-based Meats Life Cycle Assessment Matrix				
Environment	CO2 emissions	Water quality, usage	Climate Change Resilience	Contaminants
Health	Calories	Nutrients	Protein	Processed
Economics	Commercial Scalability	Macro Demand	US Supply	Technology Uncertainty
Social / Policy	Labor Impact: # of workers	Poverty Impact: Fair wages	Regulation well defined	Food Safety

LEGEND: Strong Solution | Requires more study | Weakness / Threat

Plant-based meats are a necessary alternative to current reliance on animal agriculture and factory farming. Jonathan Safran Foer, author of *We Are the Weather*, argues that the easiest sustainable transition for individuals in developed countries is to not eat animal products for breakfast or lunch. "Choosing to eat fewer animal products is probably the most important action an individual can take to reverse global warming - it has a known and significant effect on the environment, and, done collectively, would push the culture and the marketplace with more force than any march. The average US and UK citizen must consume 90% less beef and 60% less dairy."[251] To make a transition away from animal products even easier, these plant-based 'mimics' can be a viable solution.

5. *Conclusion & Discussion*

There is an increased demand for protein alternatives in diets worldwide, as certain environmental pressures impact the planet. One of the immediate consequences of this phenomenon is a naturally forced behavioral and consumption shift. Climate change, water use, and land use, among others, are impacted by global meat production, and a transition to vegetarian and vegan diets would inherently help the planet. In addition, developed countries are starting to look into 'healthier' options and trying to reduce their meat intake based on health concerns. For many, plant-based meat represents a viable solution.

The commercial success of plant-based meats when taste is the focus may pave a path to greater adoption of plant-based seafood alternatives. When looking at seafood alternatives currently in the market, most of these products are built with seaweed as a core ingredient. They also have lower sodium and cholesterol, and some such as New Wave shrimp and Sophie's Kitchen Crab Cakes have positive reviews on taste profile. New Wave shrimp is currently only in small foodservice facilities while they perfect the taste, so it could become a more important alternative as it scales in the market. Sophie's Kitchen launched its crab cakes in 2013 and has reached 1,000 supermarkets but lacked capital to grow beyond $1 million USD in sales until recently.[252] The company most recently saw sales accelerate, as Chipotle and PepsiCo recently invested in Sophie's Kitchen in 2019[253,254] This should help them reach a larger consumer audience, as to date they have only been in supermarkets.

Conclusion

Every individual must take action to prevent further climate change. One of the easiest and most impactful changes one can make is conscious consumerism around food. The food system is a major contributor to climate change, as agriculture contributes to an estimated 51% of humanity's greenhouse gas emissions.[255] Switching to a 'meat-mindful' or reduced meat diet reduces the greenhouse gas emissions associated with current animal agriculture, clear-cutting of Amazon forests for ranching, the inhumane treatment of animals in factory farming, and the depletion of wild fish stocks. Switching to a more plant-based diet has a significant impact. In the words of Yvon Chouinard, founder of Patagonia, "People need a new jacket every five or ten years, but they eat three times a day. If we really want to protect our planet, it starts with food."[256]

Appendices

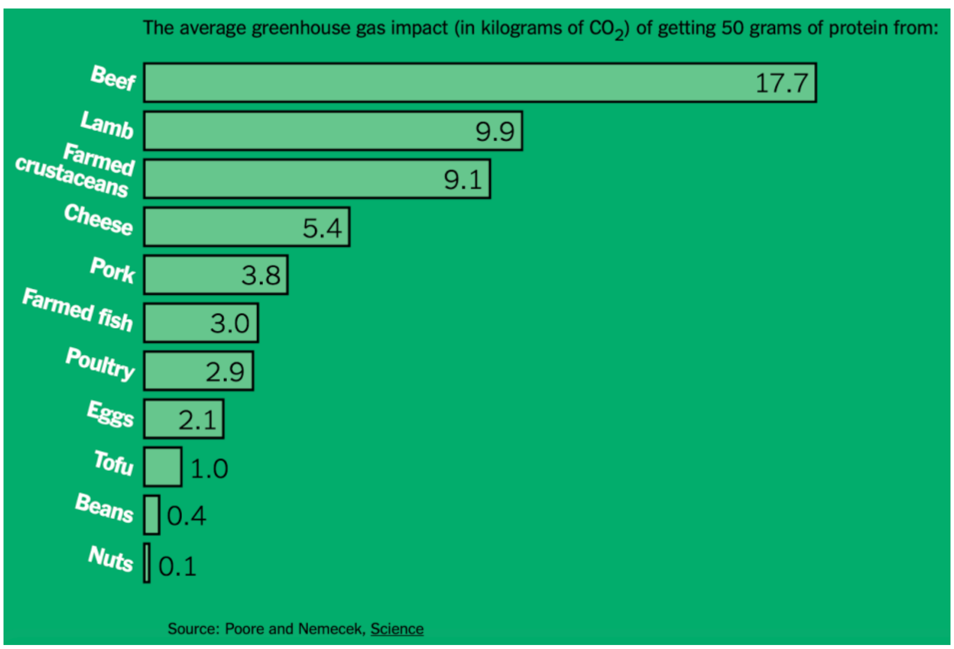
Appendix 1: Agriculture's GHG Emissions

The two most frequently cited reports on greenhouse gas emissions from animal agriculture are *Livestock's Long Shadow* from the Food and Agriculture Organization (FAO) of the United Nations and *Livestock and Climate Change* from the WorldWatch Institute.[257] Each provide two distinct numbers for the amount of greenhouse gas emissions. The FAO report concludes that 18% of global GHG emissions are claimed by animal agriculture, whereas the WorldWatch Institute deduced that it is in fact at least 51%.[258]

"The key difference between the 18% and the 51% figures is that the latter accounts for how exponential growth in livestock production (now more than 60 billion land animals per year) accompanied by large scale deforestation and forest-burning, have caused a dramatic decline in the Earth's photosynthetic capacity, along with large and accelerating increases in volatilization of soil carbon."[259] The FAO report also does not consider refrigeration of livestock products (which requires fluorocarbons that have substantial GWP over that of CO_2), GHGs from cooking animal products, and livestock respiration.[260]

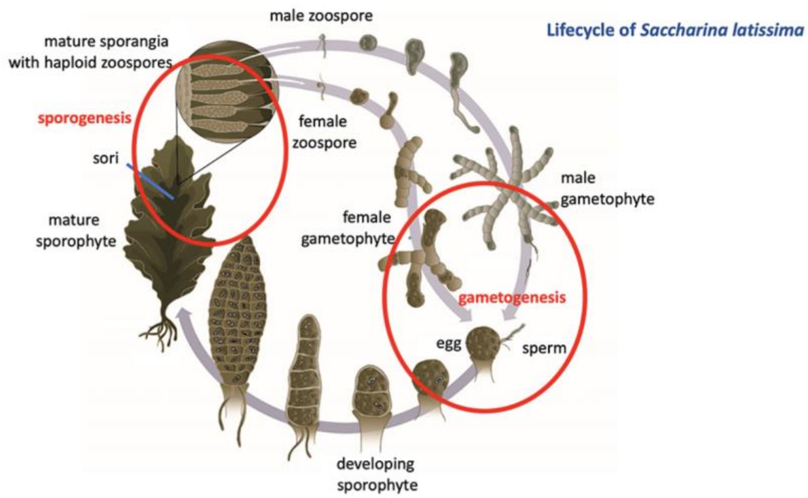
Appendix 2: GHG Emissions from Food Products

This chart shows the average GHG emissions of 50 grams of protein from specific animal products.[261]



Appendix 3: Growing Methods and Production

This image shows the life cycle of *Saccharina latissima,* or sugar kelp,[262] a common species grown in the North Atlantic US.



The following methodology is based on kelp farming in New England waters.[263] When fertilization of the seaweed spores occur in the lab, the essential capabilities needed are control over water temperature, light, seawater, aquaria and pH. Kelp grows best between 41 and 59 degrees Fahrenheit (5 to 15 degrees Celsius). Light intensity, wavelength and light hours per day (12 hours/day) must be controlled. Contaminants must be removed from seawater and nutrients must be added to help in the growth of sporophytes. Aquaria used can be from 5 to 50 gallons (or larger). Kelp spores and plants must be grown between a pH of 7.0 and 9.0, with the pH monitored regularly and carbon dioxide added to adjust.

The adult sporophyte (full-grown kelp) has reproductive sorus tissue (sori, plural) containing sporangia, which are cells that produce and house zoospores in quantity only a few months out of the year. Spores are collected from seaweed in the ocean. Favorable sorus tissue from the wild that is brought into the lab begins to release spores into the water and does not show any evidence of contamination such as biofouling, bacteria, or viruses. Biofouling is the accumulation or deposition of macro and microorganisms on seaweed, leading to decreases in health and productivity. Depending on state regulations, the quantity of tissue collected must be reported and cannot exceed certain limits to preserve the integrity of native populations. [264]

Processing in the laboratory of reproductive tissue includes cutting out sori from the blade (leaf), cleaning, disinfecting, drying, and then refrigerating it until it is placed in settling tubes (can be PVC pipes with chilled, filtered seawater).[265] The diagram below shows a step by step summary of the process just described.[266]

The following diagram shows how sori are placed in conditions promoting the fertilization of kelp spores.[267]

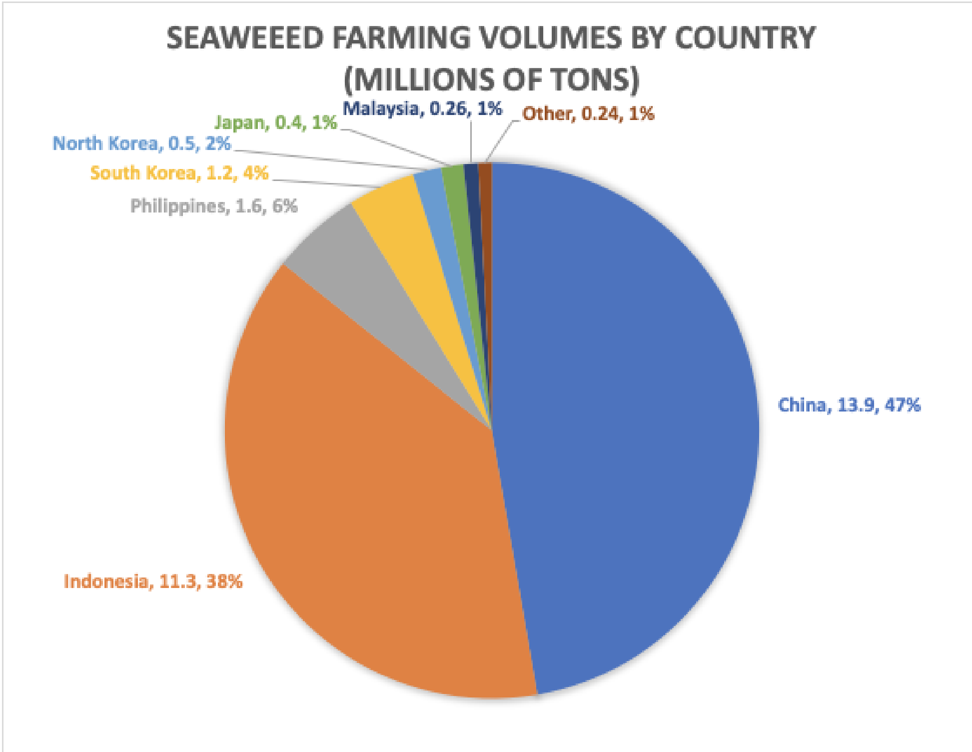
The following diagram shows how the spools with kelp spores are transferred into an aquarium.[268]

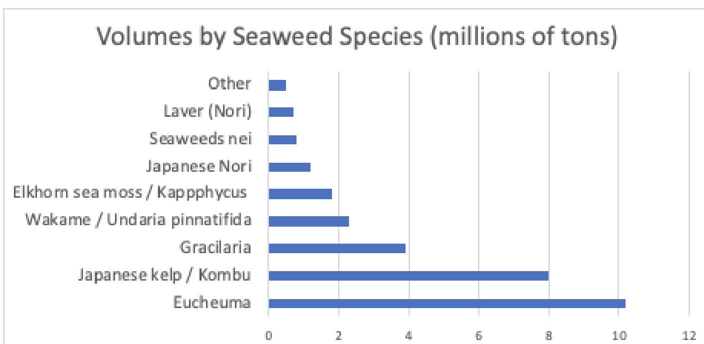
Appendix 4: Macroeconomic Analysis of Sea Greens

1. *Supply*

The global sea greens industry produces 30.4M wet weight tons annually, with 29.4M farmed and 1.1M harvested from the wild.[269] Wild harvest production has been flat to declining since the 1990s,[270271] but seaweed farming has been growing 8% annually. Allied Market Research anticipates supply and demand growth will accelerate to a 12% compounded annual growth rate through 2024. The team does not have full disclosure as to the assumptions driving the acceleration in the forecast. *Eucheuma* (common name is guso) and *Laminaria* (common name is kelp, same as *Saccharina japonica*) have seen the greatest growth over the last 50 years due to the increased use in food additives, and sea green production increased most significantly over the last 25 years.[272] Wild harvest production has been flat likely due to the peak of harvesting productivity in the early 1990s from the introduction of mechanical equipment.[273]

Food production has been the primary use for sea greens, accounting for 46% of the volume of product sold.[274] Food products are sold fresh, dried, powdered, as flakes, salted, canned, as liquid extracts, or as prepared foods. Finished product volumes are reported in dry weight tons, which is 12% of wet weight tons. Another 39% of global sea green use comes from food additives that provide thickening or stabilizing texture. These high value food additive products are typically created from extracting the water-soluble polysaccharides out of the seaweed known as hydrocolloids, with carrageenan, alginate, and agar being the most common. Brown seaweeds contain alginate. Red seaweeds contain carrageenan (commonly derived from *Eucheuma*) and agar (commonly derived from *Gracilaria*). The remaining 15% is used for animal feed, fertilizer, nutraceuticals, cosmetics, and industrial applications.[275] The geographic split, species production split, and species pricing are found in the charts below from the FAO.[276] [277]





Asia currently dominates the global market, and China alone accounts for about 47% for volume of sea greens farmed. China produced 2.25M dry weight tons, with 68% kelp, 13% *Gracilaria*, 9% wakame, and 6% nori. 60% of China's production is for food, and is the largest producer of kelp and nori globally. Indonesia is among the fastest-growing sea green-producing countries, accounting for 38% of global production.[278]

Most of the world supply of sea greens is grown by small farmers. China is one of the few countries with commercial scale production, but their largest producer generates 25,000 tons per year.[279] There are 221 species of commercial value, and 10 varieties are intensely cultivated globally.[280] For brown seaweed, this includes Japanese kombu (kelp, also known as *Saccharina japonica*), wakame (*Undaria pinnatifida*), and hijiki (*Sargassum fusiforme*). For red seaweed, the most notable are *Gracilaria* (used as a food additive), and *Euchema* and *Kappaphycus* (both are high in carrageenan content which has industrial, cosmetic, and nutraceutical applications). The most notable green seaweed is *Ulva spp.* In the northeast US, sugar kelp (*Laminaria saccharina*) is the most commonly produced seaweed, and much of the production is exported to Asia.[281] The table below sums the seaweed imports into the top 35 countries from 2013-2016 in weight (tonnes) and value (USD).[282]

Table 21. Seaweed imports into the top thirty-five countries, 2013–2016

	Weight in tonnes; value in USD thousands					
	2014		2015		2016	
	Weight	Value	Weight	Value	Weight	Value
Edible seaweed	247 527	692 978	251 709	633 915	250 735	648 719
Non-edible seaweed	244 514	348 059	244 777	271 209	245 381	269 473
Carrageenan	115 467	913 486	111 852	891 776	110 555	759 844
Agar agar	11 738	243 316	11 771	231 958	12 052	225 624
Total	**619 246**	**2 197 839**	**620 109**	**2 028 858**	**618 723**	**1 903 660**

Source: Various sources of sources of national statistics.

2. Demand

Japan is the best market to understand peak sea green demand potential. 20% of meals in Japan include seaweed, and the average Japanese person eats 4 kg of seaweed per year.[283] For context, that would be the equivalent of each person eating one small 4 g small seaweed snack box each day.

Extrapolated to the US, this would imply a $1B+ market potential. The team does not have end market data for the US, but future research could look at the growth of Asian cuisine in the US, particularly sushi, ramen, and miso soup to determine an estimate of growth rate. However, using Europe as a proxy, in 2013, 61% of seaweed was sold to foodservice and restaurants, 21% was sold to food processors, and 18% was sold to retail (grocery).[284]

Empirically from interviews, the team believes that almost all of the demand is driven by Asian cuisine and dried seaweed snacks. New applications such as seaweed pasta have been introduced but are still small in terms of volume.

3. Pricing

The table below shows the pricing per kg trend by species. Japanese kelp and Nori/*Porphyra* are a good proxy for trends in seaweed used for human food, and pricing has come down as cultivation volumes have grown significantly. At the same time, *Kappaphycus* and *Eucheuma* are good proxies for seaweed extracts used for food additives, and these species have seen significant price increases in spite of dramatic increases in production volumes. In aggregate, the second chart below shows that the commercial value of global cultivated seaweed is only up 20% from 2006 to 2015 despite production volume more than doubling over that time period.

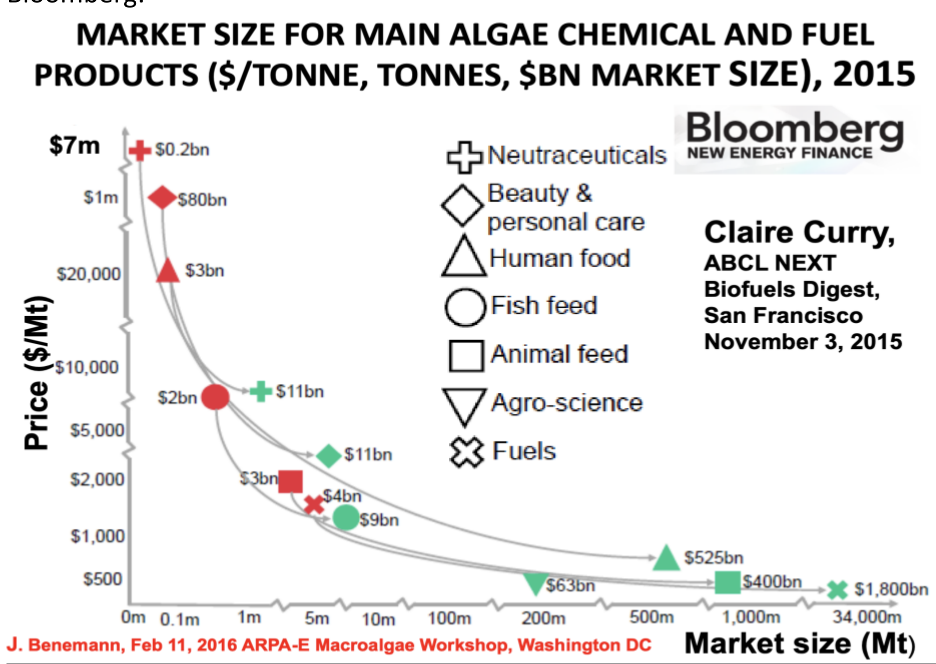
Commercial value of all seaweed farmed products 2006 - 2015 ($ Billions): [285]

2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
4	4.2	4.3	4.9	5.6	5.4	6.3	6.5	5.8	4.8

Pricing per kg of wet seaweed species: [286]

Pricing per kg	2000	2012
Japanese kelp	$ 0.10	$ 0.06
Elkhorn sea moss / Kappaphycus	$ 0.07	$ 0.18
Eucheuma	$ 0.09	$ 0.21
Nori / Porphyra	$ 2.03	$ 1.86
Wakame / Undaria pinnatifida	$ 0.40	$ 0.45
Gracilaria	$ 0.59	$ 0.04

The chart below shows the demand for sea greens at lower prices across a number of industries.[287] Keep in mind the industry is currently producing close to 30M tons. Within the food application, it is estimated that this could be a $525 billion industry if pricing approaches $750 / ton. The price of sea greens would need to be close to $200 per ton to be mainstream as a biofuel feedstock according to Bloomberg.



4. *Production Costs & Economic Returns*

The table below shows the production cost and economic returns for *Kappaphycus* seaweed farming in six developing countries as of 2009 using a variety of farming methods. In this example, production costs were \$0.27 to \$0.70 per dry weight kg. Economic returns of income to total costs range from 20% to 200%.[288] (*Kappaphycus* is typically using as a food thickener.)

TABLE 5. Comparative enterprise budgets for *Kappaphycus* seaweed farming systems in 6 developing countries, 2009 (Valderrama *et al.* 2015).

Item	Indonesia	Philippines	Tanzania		India	Solomon Islands	Mexico	
	Floating	Floating	Off-bottom	Floating	Floating	Floating	Off-bottom	Floating
Production Parameters								
Total length of lines (m)	30,000	2,000	270	288	2,565	4,000	10,000	10,000
Number of cycles per year (cycles)	8	5	7	8	6		4	4
Length of a cycle (days)	45	63	45	45	45		60	60
Annual yield of dry seaweed (kg)	33,000	2,850	662	806	5,400	21,700	53,778	53,778
Annual productivity (kg/m/year)	1.10	1.43	2.45	2.80	2.11	5.43	5.38	5.38
Cycle productivity (kg/m/cycle)	0.14	0.29	0.35	0.35	0.35		1.34	1.34
Farm-gate price (USD/kg)	0.85	1.09	0.27	0.27	0.33	0.38	1.00	1.00
Gross Receipts	**28,050**	**3,107**	**179**	**218**	**1,785**	**8,246**	**53,778**	**53,778**
Variable Costs (USD)								
Propagules							13,264	13,264
Labor	4,320	759	26	28	1,041	3,556	8,853	8,853
Fuel	29	332				1,117		
Maintenance and repairs	420							
Sales and marketing	600						7,115	7,115
Total Variable Costs	**5,369**	**1,091**	**26**	**28**	**1,041**	**4,672**	**29,232**	**29,232**
Fixed Costs (USD)								
Depreciation	2,501	906	26	24	432	1,157	2,274	2,934
Administrative costs	900							
Utilities	120							
Fees for coastal land usage							3,109	3,109
Total Fixed Costs (USD)	**3,521**	**906**	**26**	**24**	**432**	**1,157**	**5,383**	**6,043**
Total Costs (USD)	**8,890**	**1,997**	**52**	**52**	**1,473**	**5,829**	**34,615**	**35,275**
Net Returns (USD)	**19,160**	**1,109**	**127**	**166**	**312**	**2,417**	**19,163**	**18,503**
Production Cost (USD/kg)	**0.27**	**0.70**	**0.08**	**0.06**	**0.27**	**0.27**	**0.64**	**0.66**

5. *US Market Production Costs and Economics*

Estimated production cost in the US for dried seaweed is \$0.15 per kg. Vertically integrated processors acting as wholesalers in the northeast purchase seaweed at \$0.45 to \$0.70 per kg, so producer gross margins are comparable to developing markets. While production costs are lower in the US than in developing markets, sugar kelp is easier to grow than *Gracilaria* and nori, for example, but has less demand.[289]

Costco sells Kirkland brand dried seaweed for the equivalent of \$76 per kg, and Korean branded product for \$108. One study estimates that a farmer could generate a \$37,000 profit per year by producing ten tons of kelp and 150,000 shellfish per acre. Atlantic Sea Farms has set a \$0.55 per lb. price it pays for seaweed so big farms with four acres can net \$45,000 income and their investment is \$3,000 to \$20,000 depending on their boats.[290,291] This is a fantastic economic return; however, several experts in the commercial market that the team interviewed (GreenWave and Atlantic Sea Farms) are cautious about the amount of demand in the US market for sea greens.[292]

There are also production challenges with productivity varying between four and seven pounds per foot planted. Crop insurance is too expensive for these small farmers to justify, so weather is a risk for the crop and for the laborers who need to be on the water daily.

From a demand perspective, the table below indicates a 9% CAGR from 2013 to 2016. Allied Markets Research forecasts US demand growth to accelerate to 13% through 2024.

The table below summarizes US imports of seaweed from 2013-2016 in weight (tonnes) and value (USD).[293]

Table 25. United States of America: Imports of seaweed, 2013–2016

	Weight in tonnes; value in USD thousands					
	2014		2015		2016	
	Weight	Value	Weight	Value	Weight	Value
Edible seaweed	7 180	60 670	10 695	72 628	8 560	55 883
Non- edible seaweed	18 030	46 698	14 826	36 400	20 959	38 481
Carrageenan	11 475	114 695	11 192	105 699	9 959	82 830
Agar agar	14 17	34 379	1 565	38 500	1 383	31 949
Total	**38 102**	**256 442**	**38 278**	**253 227**	**40 861**	**209 143**

Sources: U.S. Department of Customs and Border Protection; U.S. Census Bureau.

Below are more informative tables from the FAO reports for easy reference on macroeconomic supply and demand of seaweed by species and geography. [294] [295] [296] [297]

WORLD AQUACULTURE PRODUCTION OF AQUATIC PLANTS (thousand tonnes, live weight)

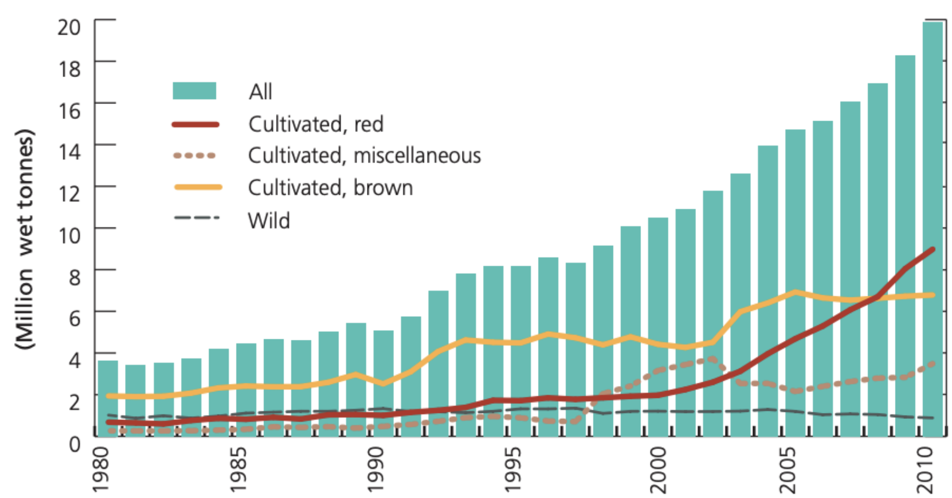
Species item	2005	2010	2011	2012	2013	2014	2015	2016
Eucheuma seaweeds nei, *Eucheuma* spp.	987	3 481	4 616	5 853	8 430	9 034	10 190	10 519
Japanese kelp, *Laminaria japonica*	4 371	5 147	5 257	5 682	5 942	7 699	8 027	8 219
Gracilaria seaweeds, *Gracilaria* spp.	933	1 691	2 171	2 763	3 460	3 751	3 881	4 150
Wakame, *Undaria pinnatifida*	2 440	1 537	1 755	2 139	2 079	2 359	2 297	2 070
Elkhorn sea moss, *Kappaphycus alvarezii*	1 285	1 888	1 957	1 963	1 726	1 711	1 754	1 527
Nori nei, *Porphyra* spp.	703	1 072	1 027	1 123	1 139	1 142	1 159	1 353
Seaweeds nei, Algae	1 844	3 126	2 889	2 815	2 864	449	775	1 049
Laver (nori), *Porphyra tenera*	584	564	609	691	722	674	686	710
Spiny eucheuma, *Eucheuma denticulatum*	172	259	266	288	233	241	274	214
Fusiform sargassum, *Sargassum fusiforme*	86	78	111	112	152	175	189	190
Spirulina nei, *Spirulina* spp.	48	97	73	80	82	86	89	89
Brown seaweeds, Phaeophyceae	30	23	28	17	16	19	30	34
Others	20	28	27	28	18	15	14	17
Total	**13 503**	**18 992**	**20 785**	**23 555**	**26 863**	**27 356**	**29 365**	**30 139**

MAJOR FARMED SEAWEED PRODUCERS (thousand tonnes, live weight)

Country	2005	2010	2011	2012	2013	2014	2015	2016	% of total, 2016
China	9 446	10 995	11 477	12 752	13 479	13 241	13 835	14 387	47.9
Indonesia	911	3 915	5 170	6 515	9 299	10 077	11 269	11 631	38.7
Philippines	1 339	1 801	1 841	1 751	1 558	1 550	1 566	1 405	4.7
Republic of Korea	621	902	992	1 022	1 131	1 087	1 197	1 351	4.5
Democratic People's Republic of Korea	444	444	444	444	444	489	489	489	1.6
Japan	508	433	350	441	418	374	400	391	1.3
Malaysia	40	208	240	332	269	245	261	206	0.7
Tanzania	77	132	137	157	117	140	179	119	0.4
Madagascar	1	4	2	1	4	7	15	17	0.1
Chile	16	12	15	4	13	13	12	15	0
Solomon Islands	3	7	7	7	12	12	12	11	0
Viet Nam	15	18	14	19	14	14	12	10	0
Papua New Guinea	0	0	0	1	3	3	4	4	0
Kiribati	5	5	4	8	2	4	4	4	0
India	1	4	5	5	5	3	3	3	0
Others	25	14	15	16	13	12	16	8	0
Total	**13 450**	**18 895**	**20 712**	**23 475**	**26 780**	**27 270**	**29 275**	**30 050**	

FIGURE 1

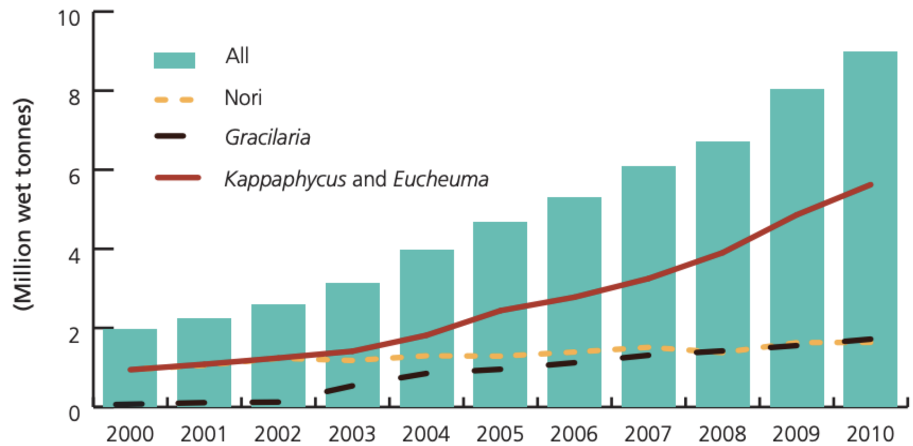
World seaweed production



Note: Red seaweeds include species belonging to Rhodophyceae; brown seaweeds include species belonging to Phaeophyceae; miscellaneous seaweeds include species belonging to Chlorophyceae and Cyanophyceae as well as species unspecified.
Source: FAO Fishstat

FIGURE 2

World red seaweed farming production



Note: Kappaphycus and *Eucheuma* includes species belonging to Solieriaceae. *Gracilaria* includes species belonging to Gracilariaceae; nori includes species belonging to Bangiaceae.
Source: FAO FishStat.

Appendix 5: Sea Green Nutrition Information

The table below contains key facts about nutrition of most common types of sea greens.[298]

Sea Greens Type	Key Nutrition Information
Nori or purple laver (*Porphyra*)	● Protein content of 30-50%, of which 75% is digestible. ● Low in sugars (0.1%) ● Very high vitamin content, with significant amounts of vitamins A, C, niacin, and folic acid ● Sodium content low due to typical processing ● Large amounts of the amino acids alanine, glutamic acid, and glycine
Aonori or green laver (*Monostroma* and *Enteromorpha*)	● Protein content of 20% ● Very low fat and sodium ● High iron and calcium content ● Vitamin B-group content is higher than most land vegetables, and while its ● Relatively high levels of vitamin A (about half of that found in spinach)

Kombu or haidai (*Laminaria japonica*)	● Protein content of 10% ● Only 2% fat ● Relatively high levels of minerals and vitamins, though generally lower than those found in nori (e.g. one-tenth the amounts of vitamins and niacin, half the amount of B1) ● Very high levels of iron (e.g. three times the amount found nori ● High levels of iodine ● Raw contains manganese, copper, cobalt, iron, nickel, and zinc
Wakame or quandai-cai (*Undaria pinnatifida*)	● High total dietary fiber content (higher than nori or kombu) ● Very low fat content ● High levels of the vitamin B group, especially niacin (however, processed products lose most of their vitamins) ● Raw contains manganese, copper, cobalt, iron, nickel, and zinc
Hiziki (*Hizikia fusiforme*)	● Protein content of 10% ● Only 1.5% fat, with 20-25% of the fatty acid as eicosapentaenoic acid ● High levels of the vitamin B group, especially niacin (however, processed products lose most of their vitamins) ● High levels of iron, copper, and manganese, higher than in kombu) ● Raw contains, cobalt, nickel, and zinc
Dulse (*Palmaria palmata*)	● Good source of minerals, with very high levels of iron and trace elements ● Vitamin content much higher than land vegetables such as spinach

Appendix 6: Comparison of Nutrition of Meat vs. Plant-based Burgers

This table compares meat and plant-based burgers.[299]

How popular meat and plant-based burgers compare

Meat burger | Plant-based burger

BURGER	CAL.	FAT (g)	SAT. FAT (g)	CHOL. (mg)	CARB. (g)	SODIUM (mg)	PROTEIN (g)
Burger King beef patty	240	18	8	80	0	230	20
Impossible Burger patty	240	14	8	0	9	370	19
Burger King's Classic Whopper	660	**40**	12	**90**	49	980	28
Impossible Whopper	630	34	11	10	58	1,240	25
Carl's Jr. Famous Star	670	37	**13**	75	57	1,210	28
Beyond Famous Star	**710**	**40**	0	30	**61**	**1,550**	**30**
White Castle's Original Slider	140	7	3	10	16	380	6
White Castle Impossible Slider	210	11	4	0	17	550	9

Source: Barclays research

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Key Players & Producers

Sea Greens

- Premium Oceanic (Blue Evolution brand) - primary buyer for Alaska Seaweed
- Atlantic Sea Farms - largest player in Maine
- Thimble Island Farms - Bren Smith brand in Connecticut
- HMart - key distributor for Asian branded seaweeds
- Asian brand seaweeds sold in HMart:
    - Emerald Cove
    - Pulmuone - market themselves for sustainability, 35-year history
    - Bibigo - brand marketed as one of the largest in Korea
    - Maine Coast Sea Vegetables -- US sourced seaweed
    - Eden
    - ChoripDong
    - SeoulTradingUSA
    - Wang
    - LeeZen
    - Sukina
    - Takaokaya
    - Nico-Nico
    - Ottogi
- Amazon.com listed Seaweed snacks
    - Jayone
    - Kim's
    - GimMe (owned by Annie Chun)
    - Daechun
    - Annie Chun's (CJ Food)
    - SeaSnax
    - KimNori
    - Wel-Pac
    - Myungga
    - Nishimoto
- Jinga
- Industrial seaweed player
    - DowDuPont - alginate, food additives, thickeners
    - Cargill
    - Roullier Group (French) - soil conditioners
    - Biostadt India - farmer focus
    - CP Kelco
    - Acadian Seaplants (Canada)
    - Gleymar (Chile) - 3rd largest carrageenan producer globally
    - Seasol (Australia) - fertilizer
    - Algea (Norway)
    - Aglaia (France)
    - Ceamsa (Spain)
    - Qingdao Seawin Biotech (China) - produces fertilizer from seaweed

Cell-Based Meats

- JUST, Inc.
- Meatable
- Memphis Meats
- New Age Meats

Cell-Based Seafood

- BlueNalu
- Finless Foods
- Prime Roots
- The Wild Type

Plant-Based Meats

- Amy's
- Atlast
- Beyond Meats, Inc
- Boca
- Don Lee Farms
- Dr. Praeger's
- Field Roast
- Gardein
- Hilary's
- Impossible Foods
- Morning Star
- Novameat
- Rilbite
- Sophie's Kitchen
- Sweet Earth
- Tofurkey
- Upton's Naturals

Plant-Based Seafood

- Good Catch
- Loma Linda
- New Wave Foods
- Ocean Hugger Foods
- Sophie's Kitchen
- Vegan Seastar
- Tofuna Fysh
- Gardein

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