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U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Marine Fisheries Service

NOAA Technical Memorandum NMFS-F/SPO-195
July 2019

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July 2019

U.S. Department of Commerce
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National Marine Fisheries Service
Chris Oliver, Assistant Administrator for Fisheries

Recommended citation:

Richard Langton, Simona Augyte, Nichole Price, John Forster, Thomas Noji, Gretchen Grebe, Adam St. Gelais, and Carrie J. Byron. 2019. An Ecosystem Approach to the Culture of Seaweed. NOAA Tech. Memo. NMFS-F/SPO-195, 24 p.

Copies of this report may be obtained from:

Northeast Fisheries Science Center
Ecosystem and Aquaculture Division
James J. Howard Marine Science Laboratory
Highland, NJ 07732

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ABSTRACT

Seaweeds are a significant component of current marine aquaculture production and will play an increasing role in global food security as the human population increases rapidly over the next 30 years. Seaweed farming is analogous to plant-based agriculture except that the crop is cultured in a marine environment. It also differs from agriculture in that seaweeds do not require tillable land, fertilization, or freshwater, which are resources that may ultimately constrain the expansion of agriculture. Seaweeds are converted into a variety of goods, such as food and nutritional supplements for humans and livestock, fertilizer, unique biochemicals, and biofuels. Wild and cultured seaweed also offer multiple ecosystem services, such as bioremediation for coastal pollution, localized control of ocean acidification, mitigation of climate change, and habitat for other marine organisms. Incorporation of seaweeds into marine aquaculture farms in the United States is, however, not without its challenges. Seaweed is an unconventional food which necessitates establishing product acceptability, creating a sustained market, and then balancing demand with a consistent supply for long term economic profitability. Seaweed farms also need to be developed in a manner that is compatible with wild capture fisheries, marine mammal migrations, and other users of the marine environment. A comprehensive understanding of the role that cultured seaweeds play in the marine ecosystem is necessary in order to determine not only the economic value of the goods produced but also the ecosystem services offered by marine farming activities. This will result in a better understanding of how an ecosystem approach to aquaculture incorporates the role and need for both the goods and services these macroalgae will provide.

INTRODUCTION

Seaweeds, or marine macroalgae, are ubiquitous members of the community of organisms found where sunlight penetrates the surface of the world's oceans. They are a diverse group of primary producers that reportedly includes 8,000 to 10,500 species representing 3 different phyla that are commonly referred to as green, red, or brown algae (Lüning 1990, Thomas 2002, Hurd et al. 2014). Historically, humans have utilized seaweeds as food, both for themselves and for livestock, and as medicine. Seaweeds have also been used as fertilizer and soil conditioners, and are a source of unique chemical extracts. In more recent times, the traditional wild harvesting of seaweeds has been augmented by cultivation, utilizing a select number of species that are well adapted to their locality and for their intended use.

Farming seaweeds is becoming an increasingly important aspect of aquaculture, experiencing exponential growth during the last 50 years (Loureiro et al. 2015), and reaching production levels of 27.3 million tons wet weight in 2014 (FAO 2016). This sector of the global marine aquaculture industry has seen an annual growth rate of 8%, accounting for 27% of total reported aquaculture production. However, seaweeds' economic contribution to 2014 aquaculture revenue was disproportionality low, primarily because of its high water content of 80 to 90%, accounting for only 5% of aquaculture's total value that year (FAO 2016).

The use of seaweeds has expanded over time to include such things as bio-based fuels and new specialty biochemicals. The potential scale of production is also changing, particularly as governments and entrepreneurs contemplate the large-scale farms required for biofuel production.[1, 2] In addition to these industrial uses, seaweeds are increasingly being recognized for their ecosystem services. They have been promoted as a means of mitigating climate change, acting as a sponge for carbon dioxide and reducing ocean acidification (Duarte et al. 2017). Furthermore, they may be used as tools for remediating both coastal eutrophication and pollution because of their ability to extract nutrients and "scrub" some toxic chemicals from the water (Kim et al. 2014, Marinho et al. 2015, Rose et al. 2015). Consequently, these features may also afford some protection against harmful algal blooms (Imai et al. 2006).

Seaweed aquaculture has been proposed as a compliment to land-based agriculture by the United Nations Food and Agriculture Organization (FAO 2009) due to its large potential for crop production. Utilizing just 2% of the world's oceans could double the tonnage of food produced

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[1] Roesijadi, G., A. M. Coleman, C. Judd, F. B. Van Cleve, R. M. Thom, K. E. Buenau, J. D. Tagestad, M. S. Wigmosta, and J. A. Ward. 2011. Macroalgae Analysis A National GIS-based Analysis of Macroalgae Production Potential Summary Report and Project Plan No. PNNL-21087. Pacific Northwest National Lab. (PNNL), Richland, WA (United States).

[2] See also. http://www.greencarcongress.com/2017/09/20170919-arpae.html

and substantially contribute to a 70% increase in the estimated food demand by 2050, according to the FAO. Unlike agricultural crops that require irrigation, fertilization, and tillable land, seaweed production does not put demand on freshwater, land, or nutrient resources, and therefore facilitates the conservation of these valuable resources.

An ecosystem approach to aquaculture has a parallel definition to the National Oceanic Atmospheric Administration's (NOAA's) ecosystem approach to wild capture fisheries (McGraw and Rust 2019). In short, it is a systematic approach to managing aquaculture that: 1) occurs in a geographically specified area, 2) contributes to the resilience and sustainability of the ecosystem, 3) recognizes the physical, biological, economic, and social interactions that relate to the aquaculture activity, 4) optimizes benefits among a diverse set of societal goals, and 5) is adaptive over time. When this definition is applied to seaweed there are numerous aspects of seaweed culture and production that need to be considered relative to their influence and role in an ecosystem context. Increasing the production of seaweed for biofuels, human food, animal feed, and sustainable fertilizers could represent an important rethinking of global food security and the utilization of coastal oceans (World Bank 2016). Seaweed aquaculture is currently a rapidly growing component of the world food production systems with a large potential for expansion in the U.S. (Roesijadi et al. 2011, Mazarrasa et al. 2014, Callaway 2015). The purpose of this document is to briefly review some of the different uses of seaweeds and the application of ecosystem principles to seaweed farming, as well as to discuss the expanding role of ecosystem goods and services these primary producers provide as a component of farming the world's oceans.

AN ECOSYSTEM APPROACH TO SEAWEED FARMING

An ecosystem approach to aquaculture accounts for more than the marketable products and byproducts that result from farming the sea. Although a narrowly defined return on investment is a logical starting point for aquaculture and has traditionally been the primary focus of aquaculture entrepreneurship, other factors are gradually being recognized that can increase profitability, while also paying ecological dividends. This is primarily because, for both wild and cultured fisheries, monitoring and management have increased our understanding of the ecological relationships that exist between species and there is the real possibility of applying many of those findings directly to aquaculture. Indeed, aquaculture, like wild caught fisheries, has evolved from targeting a single species to multiple species and is now focusing on an ecosystem approach similar to that of wild capture fisheries. This ecosystem evolution in aquaculture was first explored in multi-species cultivation systems, referred to as polyculture, and more recently as integrated multi-trophic aquaculture. This progression started by simply appreciating that trophic levels could be combined, (e.g. Ryther et al. 1975, Haines 1976, Langton et al. 1977) and developed to include an understanding of the ecological role of extractive and fed species (Neori et al. 2004). This has led to an appreciation of how different trophic levels can be combined at a farm and then integrated at the estuary or basin scale to maintain not only the water quality but the overall environment in a near "pre-farm" condition, while still producing an aquacultural crop. In other words, this includes understanding not only the individual species requirements but the ecological effect each species has on the natural system and each other and how these ecological relationships can be integrated into multi-trophic aquaculture in a positive way.

The ecological consequences of an aquaculture system can be considered in terms of the ecosystem goods and services that derive from the sea farming activities. The obvious "goods" are the cash crop itself, but there can also be several other goods and services that are generally ancillary to the primary goal of food production or food-related byproducts. Because seaweeds are primary producers, there are a number of services they supply which can make them an extremely attractive crop. These ancillary goods and services have not traditionally been expressed in terms of their monetary value, but that does not make them less important, and if (when) a dollar value is determined, it may be a compelling reason to consider seaweeds as part of any aquaculture venture. For example, algae can extract excess nutrients, perhaps from the farm itself, or even reduce the impacts of land-based run off or sewage outfalls, and thus maintain the water quality. The seaweed could save the farmer costs related to pollution remediation, or perhaps result in a pollution credit as we develop a blue carbon-based economy.

SEAWEED AS FOOD

In a 2009 report, the United Nations Food and Agriculture Organization (FAO) hosted a forum titled "Feeding the World in 2050". The outcome of this meeting included predictions of an increasing world population, upwards of 9.7 billion people (FAO 2016), and a concomitant increase in the food requirements. They speculated that the majority of humans would be living in an urban setting and the larger human population would increase the current global food demand by ~70%. Because wild capture fisheries reached their peak landings in the later 1980s (FAO 2016), we cannot anticipate an increasing yield from expanding wild fisheries to meet this food demand, although as fish stocks recover from overfishing there may be a modest rebound. Nor can we rely on agriculture to grow significantly because of potential limits on land, water, and essential chemicals like phosphorous (Cordell et al. 2011). Currently, for example, approximately 50% of the land area of the U.S. is dedicated to agriculture (Pimentel and Pimentel 2003) while more than 70% of the freshwater in the U.S. is utilized to irrigate crops (Madramootoo and Fyles 2010). Turning to the ocean to augment the human food supply and expanding production through farming the sea is a logical alternative, and seaweeds offer an option from the base of the food web that has a number of ecological benefits, which include food for human and animal consumption.

Much has been written about the potential growth of aquaculture in the U.S., but the focus has been primarily on animal rather than algal culture (Kite-Powell et al. 2013). The contribution that seaweed has already made, and has the potential to make, to an expanding industry has been described both in terms of it food value and biomass production (Tiwari and Troy 2015, Wells et al. 2017). There is little doubt that seaweeds can positively contribute to the human diet, especially since they have been part of the human diet for thousands of years, and the demand for some seaweed products is currently increasing because of an emphasis on health and the broader use of food supplements (Wells et al. 2017). Depending on the species, seaweeds are usually low in fat and high in carbohydrates, vitamins, minerals, antioxidants, and protein. In western nations like the U.S., however, culinary habits are slow to change and American's seaweed consumption lags well behind many Asian nations, particularly China (FAO 2016). Nevertheless, dietary habits can and do change, and more health-conscious Americans are turning to an increased consumption of plant and algal proteins, produced both on land and in the sea.

Approximately 145 species of seaweed are utilized directly as human food, but only 34 are reported to be cultured worldwide to any substantial degree and only about 6 species make up close to 90% of the total farmed biomass (Buschmann et al. 2017). Nevertheless, there are reports of smaller scale or experimental work that may rapidly expand these numbers if the species being investigated prove to be a satisfactory candidates for culture (Radulovich et al. 2015).

Seaweeds for human consumption are either eaten directly as a vegetable or processed to create food additives that may or may not change the flavor profile. The most notable of these are the hydrocolloids agar, alginate, and carrageenan that come from cultured red and brown seaweeds. These products are widely utilized to add texture, emulsify and stabilize foods like ice cream, sauces, and yoghurt (Bixler and Porse 2011). These extracts are also important components of the cosmetic, textile, pharmaceutical, and nutraceutical industries. Because of their high protein content, some seaweeds have also been used as animal feed and included as a cost-effective addition to compound feeds or silage.

ENVIRONMENTAL ROLE OF SEAWEED

HABITAT

As primary producers, seaweeds assimilate inorganic nutrients and carbon dioxide and, through photosynthesis, convert these nutrients into organic matter. This organic matter is then available to organisms at higher trophic levels (or further up the food chain), as a source of energy for metabolism and growth. Additionally, the growth of seaweeds, either directly on the seafloor or on rope culture suspended off the bottom, adds complexity to the environment, creating three-dimensional habitat. This habitat offers refuge (see Figure 1) as well as a surface for settlement of other organisms. For instance, seaweed-type habitat is preferred by Caribbean spiny lobster (*Panuliris argus)* pueruli post-larvae so they can settle out of the water column and safely complete metamorphosis into their substrate associated forms (Acosta and Butler 1999). Similarly, but on a finer scale, seaweed can provide a surface for algicidal bacteria that might serve to mitigate the impacts of harmful algal blooms (Imai et al. 2006).

Figure 1. Juvenile fish seeking refuge amongst heads of farmed *Eucheuma*. (photo: A. St. Gelais)

When seaweeds are farmed in the coastal zone, rather than as an add-on to a land-based aquaculture system, there is an additional environmental role that these plant-like organisms can play. That is, to what extent do seaweeds augment coastal habitats and enrich biodiversity? Recently Radulovich et al. (2015) investigated the potential for some tropical seaweed species to serve as a human food source and, at the same time, examined the impacts the cultured seaweed had on biodiversity. Working on both the Caribbean and Pacific coasts of Costa Rica they found that the ecosystem service of "biodiversity enrichment" extended to both fish and invertebrates. The increased abundance of herbivorous fish compromised the experiments in some locations due to their consumption of the seaweed, and for some species of fish their behavior was also observed to change when compared to control plots that lacked floating longlines. Sardines and grunts, for example, moved up into the water column instead of showing their more typical cryptic behavior of swimming close to the seafloor or hiding in crevices. Additionally, finfish species richness increased; a barracuda took up residence in the cultivated plots, and sharks were observed frequenting the site. The overall invertebrate species richness also increased as gastropods and crabs were observed feeding on the seaweed. Additionally, the seaweed served as settlement substrata for epiphytic weed species of filamentous algae, thus enhancing the environmental complexity further. Interestingly, in one experiment shrimp were used for "weed control" by cultivating the desired seaweed in shrimp cages where the epiphytic seaweed was a source of food for the shrimp.

In temperate waters, seaweed such as *Saccharina latissima* and other kelp species are also likely to provide habitat augmentation and biodiversity enrichment because of the large surface area provided by the kelp blades themselves. However, much of the biodiversity increase associated with farming of seaweed, specifically kelp, is associated with epiphytic organisms that are not only a nuisance to the farmer but are potentially ecologically disruptive. Native hyrdozoans (*Obelia sp*.) and harpacticoid copepods are some of the most common colonizers of farmed kelp in the spring (Peteiro & Freire, 2013) and negatively impact crop quality. More concerning however, especially in the Gulf of Maine, are the invasive bryozoan (*Membranipora mebranacea)* and invasive colonial ascidians (*Botryllus*, *Diplosoma* and *Didemnum spp*.) (Fig. 2).

These species can not only render an entire crop valueless but their presence is responsible for wide spread degradation of wild kelp populations (Saunders and Metaxas 2008).

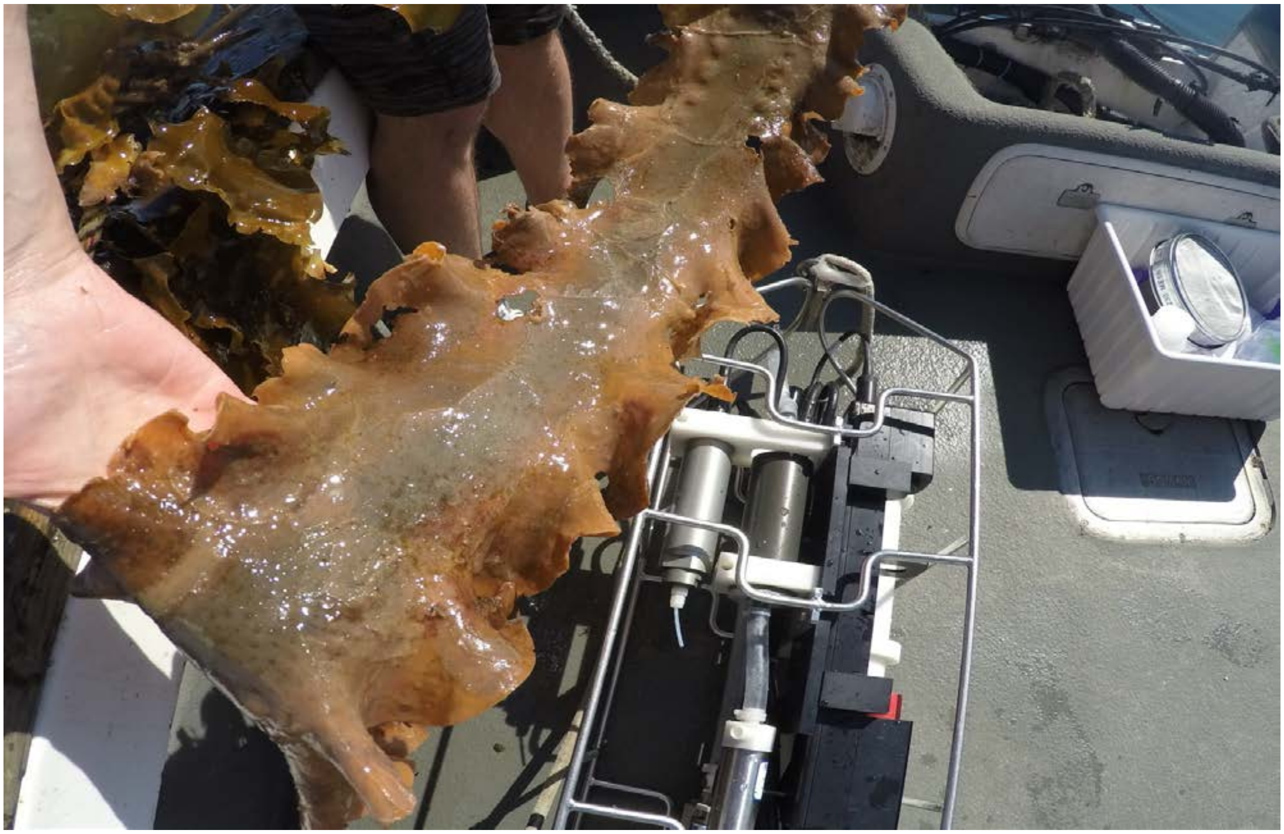

Figure 2. Example of extensive bryozoan fouling of farmed kelp blade in late spring, Gulf of Maine. (photo: A. St. Gelais)

The biodiversity and habitat ecosystem services of kelp forests and, even more so, farmed kelp communities in the northeast Atlantic, are poorly studied (Smale et al. 2013). Given the continued climate related degradation of kelp ecosystems in the region (Merzouk and Johnson 2011, Filbee-Dexter et al. 2016), further research in the area of habitat related ecosystem services of kelp farming is imperative.

NUTRIENT BIOREMEDIATION

Seaweed farms can help to maintain or improve water quality through a process referred to as bioremediation or bioextraction (Fig. 3). Utilizing this management approach, seaweed farms are strategically sited in impaired coastal waters often in tandem with land-based culture systems. As the seaweed grows it can serve to reduce the excess nitrogen and phosphorous, while at the same time, producing and releasing oxygen through photosynthesis (Rose et al.

2015). The rate at which nutrients are removed is a function of the species, seaweed biomass present, the nutrient load itself, water movement and clarity, and light availability (Hurd et al. 2014).

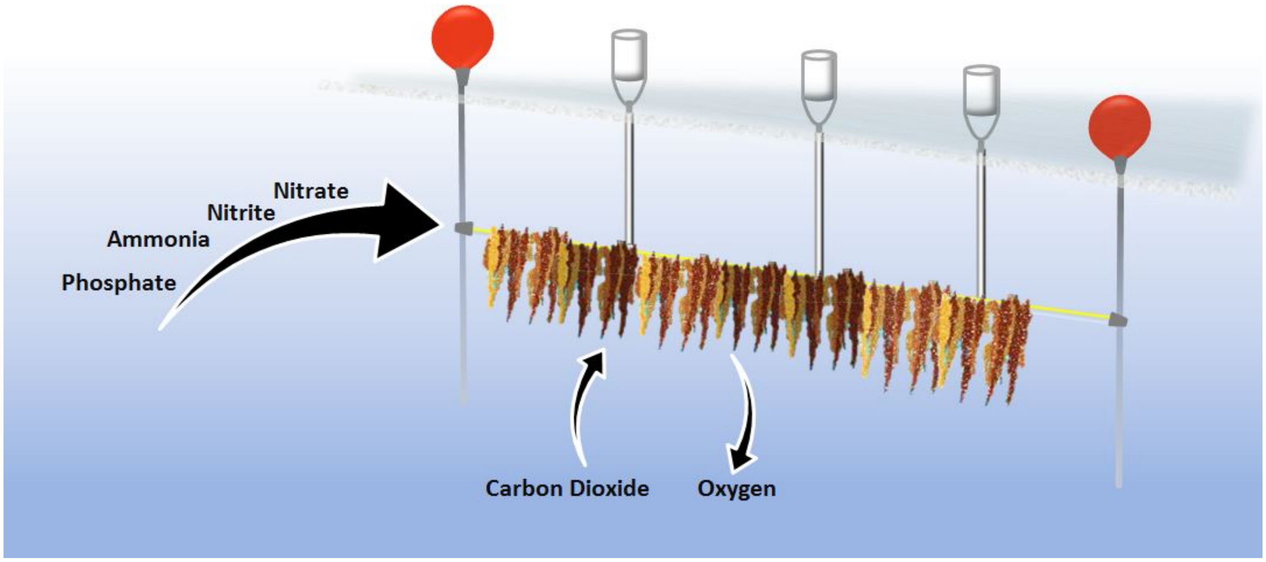

Figure 3. Nutrient bioremediation, demonstrating the uptake of nutrients and carbon dioxide by seaweed and the production of oxygen as a function of photosynthesis. (Figure by G. Grebe)

Numerous studies have documented the potential for bioremediation in different locations around the world and using different species of seaweed, e.g. (Chopin et al. 2012, Wang et al. 2012, Al-Hafedh et al. 2015). In Long Island Sound and the Bronx River Estuary of New York, for example, both the opportunistic red seaweed, *Gracilaria tikvahiae,* and the fast-growing brown seaweed, *Saccharina latissima,* have been shown to rapidly assimilate nitrogen and carbon (Kim et al. 2014, 2015). By removing the excess dissolved inorganic nitrogen from the water column, seaweed farms can also reduce the incidence of harmful algal blooms like red tides. On large-scale *Porphyra yezoensis* farms on the sandbanks of the Jiangsu Province in China, for example, it was found that the richness index of the red tide species *Skeleton emacostatum* declined from 0.32 to 0.05 during the growing season (Wu et al. 2015).

Nutrient bioremediation is an important ecosystem service offered by seaweed farms, yet seaweed farmers do not currently receive economic compensation for this service. There is a need for recognition of seaweed bioremediation in existing or future emissions trading. Kim et al. (2014, 2015) suggest that seaweed aquaculture could profitably contribute to and should therefore be included in the state of Connecticut’s Nitrogen Trading Program and other states bordering Long Island Sound. Emerging regulations in the U.S. that seek greater control of nutrients in effluent discharge will require costly infrastructure upgrades with diminishing environmental returns. Nitrogen bioextraction using strategically-sited farmed seaweed may serve as a cost-effective and complementary strategy for reducing the impact of wastewater effluent on receiving waterbodies.

Control of nutrients to maintain ecosystem structure and function is, however, not without its challenges. In the Seto Inland Sea of Japan, for example, which receives runoff from ~24% of the country's population, eutrophication and the resulting harmful algal blooms were controlled via legislation restricting land-based runoff. Enforcement of these regulations converted the sea from eutrophic (nutrient replete) to oligotrophic (nutrient deplete), altering the composition of the primary producers and negatively affecting fishery production (Yamamoto 2003, Imai et al. 2006), and also included a significant reduction in the production of the seaweed *Porphyra* (nori) (Tada et al. 2010).

INTEGRATED MULTI-TROPHIC AQUACULTURE (IMTA)

A discussion of seaweed aquaculture cannot be presented without recognizing the developing concept of Integrated Multi-Trophic Aquaculture (IMTA) (Fig. 4). This approach to aquaculture applies ecosystem thinking at the farm scale because it integrates primary producers with higher trophic-level organisms (shellfish, finfish etc.); using the primary producers (seaweeds) as a mechanism to recycle the waste nutrients (e.g., nitrogen) generated by the primary consumers. Documenting that such linkages exist in an aquaculture setting is not new (Ryther et al. 1975, Haines 1976, Langton et al. 1977) but the application at a farm scale has been more recently recognized, developed, and widely promoted as ecosystem thinking for aquaculture which takes into account the ecological footprint and/or nutrient halo that results from farming activities in coastal areas (Neori et al. 2004, Neori et al. 2007, Chopin et al. 2012).

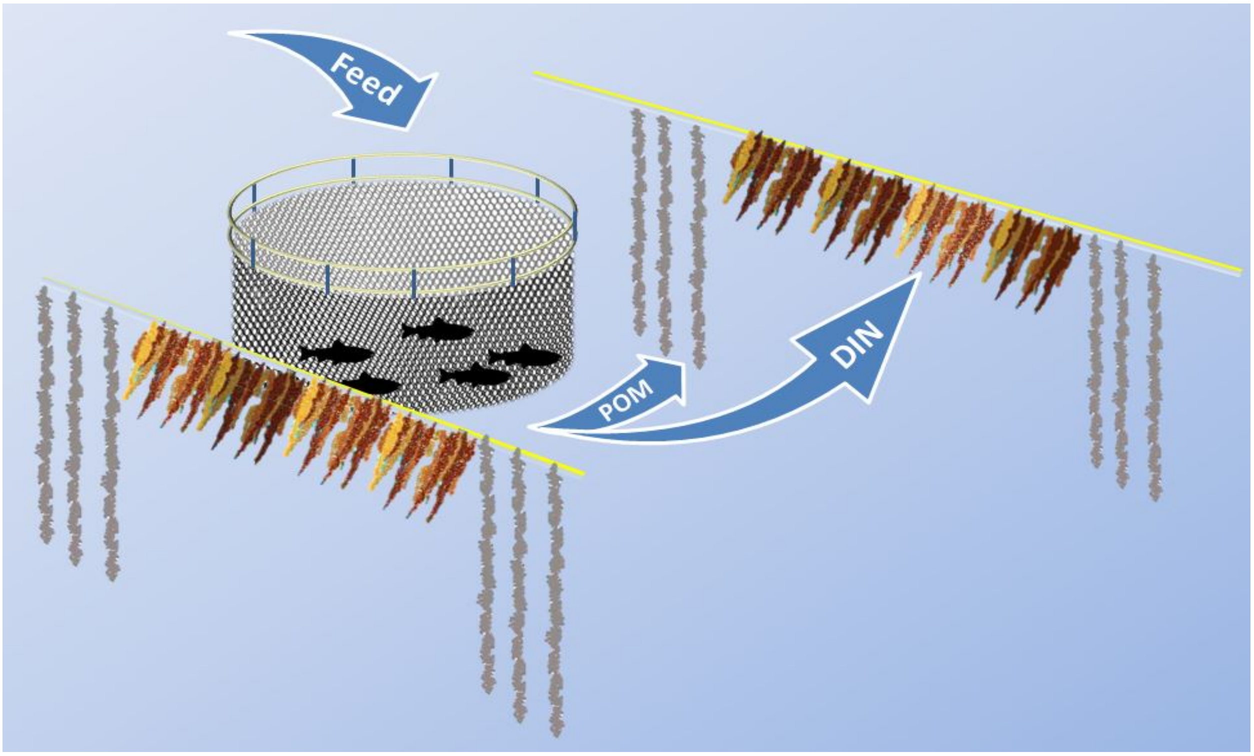

Figure 4. Conceptual diagram of an integrated multi-trophic aquaculture (IMTA) system demonstrating the downstream reduction of the nutrient loading from farming fish, with strings of mussels consuming particulate organic matter (POM) and seaweeds utilizing the dissolved inorganic nutrients (DIN) which enhance their growth and help maintain water quality. (Figure by G. Grebe)

One of the objections to aquaculture in the past has been the environmental impact that maximizing production of a single trophic level can have (Goldberg and Triplett 1997). Wild capture fisheries that focus on a single species, or species complex, have also been documented as having an extensive environmental footprint (e.g. Auster and Langton 1999), but more recently there is a clear move towards an ecosystem approach for both capture and culture fisheries. When combining trophic levels using "fed organisms," like fish and shrimp, in tandem with "extractive organisms," such as seaweed (Neori et al. 2004) it may be possible to enhance profitability of the activities, while minimizing ancillary environmental impacts that could result from the farming activities. Most of the fish and shrimp species that are candidates for marine aquaculture in the U.S. will require a formulated diet to meet their nutritional needs. The cost of these diets can account for one half the cost of the entire operation (Neori et al., 2004), and the associated waste products can have negative environmental effects. Integrating different trophic level species and increasing the number of products that can be sold may result in an economic gain to the farmer and an ecological gain for the environment. With only a 10%

conversion efficiency from food into flesh in natural systems (Lindeman 1942), environmental waste management is an issue, although for aquaculture and agricultural systems conversion efficiencies are often higher (Forster 1999). In either case, balancing inputs and outputs at each trophic level, with conditions ranging from nutrient depleted to nutrient laden waters, is a challenge. In aquaculture settings gross growth efficiency is well researched as a measure of the ratio of growth to ingestion and is optimized to the extent possible. Still, it can never approach 100% efficiency, especially when trying to maximize growth. As in nature, this presents a challenge in balancing outputs in the context of waste management, which are reflected in economic costs.

In temperate climates, the co-culturing of macroalgae may provide an entry point for many farmers (Granada et al. 2015) and especially bivalve farmers. Current research is examining the nutritional benefit of kelp detritus for bivalves. As kelp degrades, it sheds particles from the blade tips that are an appropriate size for bivalve filtration (Riisgård 1988). These kelp detritus particulates could be a beneficial nutritional supplement for bivalves (Miller and Page 2012). Conveniently, the growing seasons for kelp and bivalves, such as oysters, are offset. Farmers growing and harvesting oysters in the summer could then supplement their income by growing kelp in the winter. With warming water temperatures in the late spring and early summer, kelp starts to degrade as bivalves are filter feeding. Farmers could harvest some of their kelp in early spring before it starts to degrade and leave the remaining kelp in the water near their bivalves as a supplemental natural feed in the early summer (Fig. 5).

Figure 5. Photograph of degrading kelp; note the discoloration in the submerged fronds and ragged edges. (Photo: A. St. Gelais)

OCEAN ACIDIFICATION AND CLIMATE CHANGE

Ocean acidification is a growing threat to the marine ecosystems, with decreasing pH levels interfering with the life processes of many species and ultimately affecting commercially important groups of animals like mollusks and crustaceans. These 2 groups of animals deposit shell material as they grow, and shell formation is greatly hampered at a lower pH, which is a result of increasing concentrations of dissolved CO_2 in seawater, forming carbonic acid that dissociates into bicarbonate and the hydrogen ions, which lowers pH. Installation of a seaweed farm could potentially benefit its immediate environment by stabilizing the pH of the surrounding water and by releasing oxygen during photosynthesis. Photosynthesis, as a light driven process, converts CO_2 into seaweed biomass, while at the same time releases oxygen into the environment. Seaweeds respire at night but the level of oxygen consumption and CO_2 evolution in the dark does not usually offset the daytime O_2 production and CO_2 absorption in the light. Ongoing research suggests that particularly during the exponential growth phase of the seaweed life cycle, seaweed cultivation results in a net positive increase in pH and oxygen in the immediate area of the farm activities. There can be the occasional exception when an aquaculture system becomes unbalanced (Liu et al. 2009), but this phenomenon can be monitored and controlled by understanding the production rate of the seaweed crop and timing seaweed harvest accordingly. Because shellfish constantly respire CO_2 and seaweeds, for the most part, absorb it, this exchange of inorganic carbon could represent yet another mutually beneficial aspect to be considered as an ecosystem management approach with IMTA, and increasingly so as oceans become more acidic.

Seaweed can also help mitigate and adapt to the environmental impacts of climate change (Duarte et al. 2017). Since seaweeds are very efficient at assimilating and retaining carbon during their lifespan, they could help offset the emissions resulting from burning fossil fuel. It has even been postulated that the addition of seaweed to cattle feed could theoretically reduce methane (a greenhouse gas) production in the livestock rumen by up to 99% (Kinley et al. 2016, Machado et al. 2016). It is unknown the degree to which farmed seaweeds might emit halocarbons that could deplete ozone (Carpenter and Liss 2000), a process that likely depends on the seasonal development of the seaweed (Zhou et al. 2005); it is possible that cultivated seaweeds are actually harvested before making an impactful contribution of halocarbons to the atmosphere.

Additionally, the presence, and even strategic location, of large seaweed farms can offer shoreline protection by dampening wave energy, thus reducing the physical damage from increasing storm intensity resulting from climate change.

AGRICULTURE AND ENERGY

AGRICULTURE

Agricultural endeavors produce waste materials that are potentially compostable, and seaweeds are no different. Seaweeds have been used as fertilizer for land-based agriculture for centuries and will continue to be used for this purpose to a limited degree. Seaweed has proven to be a good soil conditioner (Han et al. 2014, Cole et al. 2016) and can play a role in the transfer of ocean-based nutrients to land. Additionally, liquid extracts made from seaweed act as biostimulants of terrestrial plant growth that elevate plants' resistance to pathogens, enhance metabolism, increase photosynthetic efficiency, and stimulate the rhizosphere microbiome (Khan et al. 2009). Furthermore, as more seaweed is grown for biofuel production, there will be an increasing quantity of the by-product, biochar. Biochar is a form of carbon resulting from decomposition of biological material at the high temperatures required to convert biomass into biofuels. Recent reports indicate that kelp biochar has potential as a plant substrate in aquaponics (Chopin and Murray 2016), thus turning a marine derived waste material back into an agriculturally desirable product.

BIOFUELS

Organic materials, like seaweed, can be digested anaerobically or fermented to produce various biofuels such as methane, ethanol, and butanol. The concept of utilizing seaweed for this purpose in the United States is attributed to Howard Wilcox who was somewhat of a visionary in the 1960s when he looked to macroalgae as both a renewable source of fuel and solution for slowing global warming (Wilcox 1975).

In the U.S. the interest in biofuels, as an alternative to fossil fuels, has surged and waned over the past 50 years. In the 1970s and 1980s, the U.S. Department of Energy funded research on macroalgae farms under the Marine Biomass Program with the goal of replacing the entire natural gas supply through the growth, harvest, and anaerobic digestion of giant kelp. That goal was not achieved, but much was learned about cultivating macroalgae in an open ocean environment. The project was abandoned because of political issues, engineering, and resource supply and associated costs.[3] New natural gas resources were also discovered, following natural gas price deregulation, which forced down the prices; out-competing the nascent kelp biomass industry.[4] Notably, if costs of seaweed culture and biofuel production

[3] Ashare, E., D. Augenstein, A. Sharon, R. Wentworth, E. Wilson, and D. Wise. 1978. Cost analysis of algae biomass systems - Final report. Dynatech R/D Company, Cambridge MA. Report to the US Dept of Energy, C00/4000-78-1.
[4] Anonymous. 2012. Topic Paper # 12 Macroalgae (Seaweeds). National Petroleum Council Future Transportation Fuels Study.

relative to fossil fuels were to change in favor of the former, then the projected global increase in energy requirements of ~40% by 2035 (Karl et al. 2009) could be offset by a carbon neutral fuel based on seaweeds. Although it is undeniable that there are substantial technological challenges when considering construction and operation of large scale biomass seaweed farms in the open ocean, or at least in exposed nearshore environments (Forster 2013), the winds of change have filled the sails of renewable energy once again. More recently the U.S. Department of Energy has awarded $25M in grants under the Macroalgae Research Inspiring Novel Energy Resources, or MARINER, Program. The expressed aim of this program is "the development of transformational technologies to enable a U.S. based macroalgae industry capable of producing up to 2 Quads of bioenergy by 2050 (= 366 million barrels of oil)."

Research supporting the renewed interest in the large-scale culture of seaweeds for bioenergy and related byproducts was summarized by Roesijadi et al. (2008)[5] and more recently by Montingelli et al. (2015) in comprehensive reports that address both the technological and economic challenges for developing such an industry (see also Huesemann et al. 2010). Various other papers have also described different aspects of algal bioenergy production and discussed both its potential and challenges. Goh and Lee (2010) proposed an approach for generating bioethanol from seaweed for Malaysia, for example, while Wei et al. (2013) reviewed bioethanol production and pointed out that although it is an attractive idea, and has been successful on a limited scale, there are many technical, economic, and ecological hurdles before large-scale industrial scale production is feasible. Likewise, in Ireland and the UK, many of the challenges to the development of this industry were explored, but in this case through the analysis of stakeholder interviews (Roberts and Upham 2012). As pointed out previously, the concept of growing, harvesting, and processing seaweed for biofuel production is alluring and has tremendous potential, but the reality is that it may take some years before it is a practical solution. This will be in a future that balances our utilization of fossil fuels with renewable energy sources to match the needs of a growing world population.

POTENTIAL CONFLICTS AND CHALLENGES FOR A GROWING INDUSTRY

Some potentially negative effects of developing large offshore fields of cultured seaweed must also be considered. Two of the largest and most publicized concerns are the potential impacts on wild capture fisheries and hazards to protected species. The fishing community has already expressed much concern about the gradual loss of fishing grounds due to management restrictions related to essential fish habitat and renewable energy development, specifically

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[5] Roesijadi, G., A. Copping, M. Huesemann, J. Forster, and J. Benemann. 2008. Techno-economic feasibility analysis of offshore seaweed farming for bioenergy and biobased products. Independent research and development report IR# PNWD-3931, Battelle Pacific Northwest Division p. 115.

wind farms. The addition of yet another constraint on the industry in the form of aquaculture will raise more objections and create additional discord between various ocean user groups. Working with the fishing industry to seek agreement on suitable areas for offshore aquaculture, and perhaps creating a secondary stream of income for the fishers, will help to address these concerns. Using existing GIS tools, such as those being developed by NOAA's National Centers for Coastal Ocean Science (NCCOS; https://coastalscience.noaa.gov/research/marine-spatial-ecology/) to define different user areas, is also very helpful in resolving potential conflicts. The dangers presented by large-scale seaweed-farming infrastructure for protected marine megafauna are real and, like fishing, need to be considered in determining the utilization of our offshore waters. In particular, loose ropes and moorings pose a hazard of entanglement for protected species, particularly to marine mammals and sea turtles. Informed engineering and farm design can reduce entanglements, and science can support development of instrumentation (acoustical, other) that would make seaweed farms an unfavorable habitat for some of this fauna. In both cases, regulations will need to be developed to promote success for the entrepreneurial seaweed farmer.

There are also some biologically negative consequences to consider, particularly for large scale offshore farms. With the monoculture of any species, there are inherent risks to the farm and to the ecosystem that must be eliminated or, at the very least, mitigated. If, for example, a non-native or even unique genetic strain of a native species is cultured, there is the possibility of it becoming an invasive species and negatively impacting the environment, as has been documented in Hawai'i resulting from the proliferation of a non-native red alga (Conklin and Smith 2005).

Biosecurity must also be considered, where the introduction of a cultured species brought in from a different locale could harbor seaweed pathogens. Existing knowledge of microbial (bacterial, viral, and fungal) pathogens that cause disease in commercially cultivated seaweeds is fairly sparse and phenomenological in nature; the exact pathogen or treatment thereof is rarely defined (Largo 2002). Diseases like "ice-ice" have the potential to eradicate entire farms and outbreaks may be driven by exposure to combinations of specific bacterial pathogens when the seaweed is already weakened by suboptimal environmental conditions such as warming waters (Msuya and Porter 2014). The infective agents, in many cases, are attracted to the self-same products for which the seaweed is farmed (e.g. agar and carrageenan). Direct contact transmission within a farm and between individuals can be minimized with proper spacing of the moored lines on which the seaweed is cultivated. While it is unknown if vertical transmission – or spread of seaweed pathogens across life stages – is possible, precautions can be taken to limit geographic distribution of "seed" generated from disparate populations, thereby containing a potential outbreak to a single population. Further, treatment of "seed" as it is produced (with iodine, surfactants, or antibiotics) may inhibit vertical transmission;

however not all microbes harm seaweed and a deeper understanding of the algal microbiome and its role in protecting seaweeds from infection is urgent.

Perhaps the greater current challenge to maintaining healthy seaweed cultivars is not the presence of pathogens, but of pests. Epiphytes (e.g., small crustaceans, hydroids, or other filamentous algae) colonize the surface of farmed seaweed fronds, reducing seaweed production rates and degrading the quality of the product. Proper site selection for installation of the seaweed farm in oceanographic conditions unfavorable to epiphyte attachment (Peteiro and Freire 2013) and operating a harvest schedule that minimizes the likelihood of the appearance of epiphytes (Walls et al. 2017) are the best methods to combat these pests.

Finally, some seaweeds used for bioremediation may not be suitable for human consumption because certain species have been shown to accumulate heavy metals in a linear pattern with increasing exposure time (Wang and Dei 1999, Wang et al. 2012) and/or could create conditions favorable for the production of films of bacteria harmful to humans (e.g., *Vibrio*). Establishing and adhering to product standards for a market is imperative for maintaining product acceptability and market share. All these biological concerns can be countered by following good management practices and carefully monitoring for unwanted or unanticipated changes in the environment.

FUTURE OF SEAWEED FARMING IN THE U.S.

As part of an ecosystems approach to fisheries, NOAA has made an extensive effort to identify essential fish habitat, as required by the Magnuson-Stevens Fishery Conservation and Management Act (as amended by the Sustainable Fisheries Act of 1996) and emphasize the importance of habitat for recovering and sustaining wild fisheries. It is not a new observation that fish are attracted to structures, for either refuge or in search of food, and as we discover more about the reliance of all life history stages of fish on different habitat types it is valid to ask if adding structure to the ocean, both on the sea floor or as floating cages or suspended ropes, might enhance the survival of a particular species. Fouling of almost any floating object in the ocean by marine organisms is a common occurrence; so the structures placed in the ocean for sea farming contribute to options for organisms to use for attachment or shelter (Rensel and Forster[6]). Fouling is generally considered a problem, but can also contribute to biodiversity (Radulovich et al. 2015) and is yet another ecosystem service provided by seaweed aquaculture. On the scale of a wild population of fish, it is hard to imagine that seaweed aquaculture could enhance or restore a fishery; but it is also incorrect to dismiss aquaculture-

[6] Rensel, J., and J. Forster. 2007. Beneficial environmental effects of marine finfish mariculture. Final Report to the National Oceanic and Atmospheric Administration, # NA040AR4170130, Washington, DC Available: www.wfga. net/documents/marine_finfish_finalreport. pdf. (April 2014).

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derived habitats as having no contribution to the overall health and well-being of an ecosystem, or components of that system. This is especially true at a point in time when aquaculture is experiencing exponential growth in market share that is dominated by seaweeds (Loureiro et al. 2015, FAO 2016). The latter situation is somewhat analogous to potential recovery of a wild fishery through stock enhancement, where a localized addition of the desired species might increase in numbers to the point where an overexploited or locally extirpated stock is re-established (Langton et al. 2002). As aquaculture increases, localized ecosystem-based monitoring is needed to determine whether there is a correlation with any positive effects on non-aquaculture species or increases in commercially harvested wild species.

There are some challenges with a new fishery, be it a wild fishery or aquaculture, or for that matter any new source of human nutrition. Briefly, these include establishing the acceptability of the new product; creating a market; meeting a growing demand; and finally balancing the demand with a consistent supply for longer term economic profitability. We have seen economic "boom and bust" cycles repeatedly in fisheries, and it is reasonable to assume that seaweed cultivation and harvesting will be no different. However, there are diverse ecosystem goods and services that can accrue from seaweed cultivation, all of which generate value. In the U.S., for example, the current production of food uses approximately 50% of the land, 80% of all freshwater, and 17% of the fossil energy (Pimentel and Pimentel 2003). These demands on land, water, and other resources will only increase over time. This corresponds to increasing costs of using arable land, freshwater, and fossil fuels, which could result in an ecosystem credit system for remediation services, thus stimulating the expansion of marine farming of seaweeds. Similarly, as we look to renewable energy sources to meet rising energy demands, the mass culture of seaweeds in offshore farms and the conversion of the resulting biomass into fuels will yield additional products, such as biochar, which hold promise for use in land-based agriculture. In addition, the more traditional practice of compositing seaweeds or seaweed residue after extraction of commercially valuable biochemical compounds can benefit agriculture. Seaweeds are also a "green" (or perhaps "blue") fuel alternative since burning such fuels does not add to the carbon imbalance created by burning fossil fuels. As seaweeds grow they are a carbon dioxide sink and, to a degree that is proportional to the scale of culture, can mitigate some of the effects of climate change and ocean acidification. Of all the aquaculture crops being considered for large scale culture, seaweeds are the most analogous to plant-based agriculture because both rely on photosynthesis to grow. However, the long list of alternative uses for seaweeds and the derived benefits make them a truly sustainable solution to a world facing a potential food shortage crisis.

The challenge for seaweed farming is not necessarily culturing the organism, or even developing the technological solutions that will enable the inevitable expansion of this form of farming. Rather, the challenge is documenting all the many benefits and uses of seaweeds and determining a monetary value for them so that we have a comparable scale to measure the individual and cumulative values. One such approach, as outlined by Forster (2013), is Life Cycle Assessment (LCA) which has been applied globally to salmon (Ecotrust 2010). By accounting for all resource and service inputs to a seaweed farm, for example, as well as the food and other products derived from the farm, it is possible to make a comparison with other farm-based endeavors and demonstrate the comparative efficiency and profitability. This is not unlike the caloric or net energy approach that was being promoted by Odum and Brown (2007), which essentially required a full accounting of all inputs and outputs in a uniform currency that enables comparisons between different systems. Once the relative value of the ecosystem goods and services inherent in seaweed farming are realized and incorporated into our economic system, seaweed culture will be recognized as a partial solution to many environmental challenges, including a growing world population.

Seaweeds are truly a unique component of marine aquaculture when considered in the context of an ecosystem approach to aquaculture. They not only produce a large variety of goods that are directly marketable but they also provide a diversity of ecosystem services. These ecosystem services help maintain environmental quality and, when accounted for at an individual farm or bay scale, or ecologically defined region or even a larger geographic scale, the result is the production of food for human consumption with virtually no net environmental degradation. Furthermore, strategic placement of seaweed farms can offset the environmental effects of run off from land-based agriculture and other sources of pollution that enter the marine environment. Aquaculture may well be the answer for meeting the food demands of a growing human population, but seaweed offers a solution for both food production and the maintenance of marine environmental quality.

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