Riplee Mercer

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Thesis Literature Review Synthesis Paper

**General Seaweed Aquaculture:**

History

The aquaculture of macroalgae has roots in Asia dating back centuries (Yang et al. 2017). Over time, technology and methods have spread across countries as interest in the industry has increased. The aquaculture of macroalgae began as wild harvest, but as understanding of different macroalgae life history expanded, cultivation methods were adopted (Yang et al. 2017). The macroalgae industry has taken off since the 1950s, with cultivation representing 97 percent of the industry, while wild collection has slowly begun to decline (Mancini). This fast-growing industry went from 4.2 million tonnes of macroalgae yield in 1990 to 34.7 million tonnes in 2019. In nearly three decades, the industry has greatly expanded and went from predominantly brown macroalgae to predominantly red macroalgae (Mancini).

Uses

Macroalgae has a wide range of uses in the food, medical, and biotechnical industries. Besides having everyday uses, such as food for humans and animals, macroalgae has derived compounds that can be seen in everyday life—shampoo, cosmetics, toothpaste, cosmetics, textiles, gelling agents, agar, and even implications in biofuels (Green 2014, Sahoo & Yarish 2005, Thomas et al. 2021).

Integrated multi-trophic aquaculture is a newly up and coming system, of pairing finfish aquaculture, responsible for large inputs of inorganic waste into the environment, with an economically valuable macroalgae and/or shellfish. Finfish aquaculture is responsible for nitrogen, carbon, and phosphorous (Araújo et al 2021, Chopin et al. 1999, Green 2014, Kim, J.-H. et al 2019, Knoop et al. 2020, Thomas et al. 2021) augmentation of the surrounding environment, which can result in harmful algal blooms. To bioremediate such eutrophication, shellfish or macroalgae can be co-cultured to extract excess nutrients (Chopin et al. 1999, Kim, J. K. et al. 2007, Kucera et al. 2012).

US

The US macroalgal aquaculture industry is relatively small compared to global production. Out of the 35,762,504 tonnes of macroalgae cultivation and wild collection in 2019, the US only contributed 3,394 tonnes (Mancini). Of that 3,394 tonnes, 247 tonnes came from brown macroalgae, and 3,125 tonnes came from green macroalgae (Mancini).

The value of the global macroalgae industry was $11.7 billion in 2020 (). The total US coastline is 95,471 miles (US Department of Commerce). There is high potential for the US macroalgae industry, but lack of knowledge on macroalgae life history. With the immense range use that macroalgae possesses, the US is severely underusing this resource, and thus limiting their expansion into this multibillion-dollar industry.

New England

Kelp aquaculture in New England began in 2010, with the first kelp farm being developed in Casco Bay, ME (Grebe et al. 2019). The macroalgae industry has since budded into over 100 kelp farms in Maine alone in the last 13 years (Planet 2022). There are also kelp farms in Maine, New Hampshire, Massachusetts, Connecticut, and Rhode Island (Grebe et al. 2019). Growing interest in seaweed aquaculture has fueled the desire for expansion, through the introduction of a new macroalgal species.

**Kelp:**

Background

Kelp is a temperate to cold-water brown macroalgae that has increased popularity as human food in Europe and North America (Grebe et al. 2019). Kelp has value beyond its range of economic purposes. This macroalgae is known for waste sequestration (nitrogen, carbon), bioremediation, nutrient cycling, and fisheries production (Grebe et al. 2019). Kelp forests are incredibly important to juvenile fish populations, by providing food, shelter, and protection from ocean currents and predators (Eger et al. 2023, NOAA).

The aquaculture of kelp began in the US through the introduction and adaptation of Asian methods, with the first US kelp farm being established in Casco Bay, ME in 2010 (Grebe et al. 2019). In the US today, kelp aquaculture farms can be found across seven states—Maine, New Hampshire, Massachusetts, Connecticut, Rhode Island, Washington, and Alaska. Within Maine alone, there are 100+ kelp farms, with two species of kelp being the most extensively cultivated—sugar kelp (Saccharina latissimi) and winged kelp (*Alaria esculenta*) (Grebe et al. 2019).

Methodology/Technology

Kelp has a heteromorphic life history, alternating between a diploid sporophyte stage (blade) and a haploid gametophyte stage (microscopic). In the US, as in Asia, kelp is grown on longlines suspended just below the sea surface (Flavin et al. 2013, Planet 2022). With various methods used for structuring longline grow out, including submerged parallel lines or buoy suspension of lines, methods are dependent on locality conditions. Longlines are outplanted in late fall with seed strings of kelp sporlings that are produced in kelp nurseries. The objective of a nursery is to provide a mimicked version of the location’s environment conditions for the sporophytic kelp, allowing for optimal growth and higher survival. In kelp nurseries, nylon twine wrapped on short PVC pipes provide the substrate necessary for kelp spore attachment. Spores on the twine germinate to produce microscopic male and female gametophyte. Through changes in temperature, light level, and daylength, fertilization occurs. The resulting zygotes remain attached to the twine and begin to grow into new sporophyte blades. The process usually takes four to six weeks. These spools are then transferred to grow out locations, where the spools are unwrapped onto the longlines and monitored for growth rate and fouling until it is time to harvest (Flavin et al. 2013).

**Nori:**

History

The aquaculture of nori began in Asia centuries ago. This once solely wild harvest industry developed over time with the expansion of knowledge. Before the life history of nori was understood, methods for wild harvest were developed in China and Japan (Sahoo & Yarish 2005, Yang et al. 2017). Early techniques for cultivation of nori species focused on “planting” sticks or lime washing rocks where nori was known to grow to allow new plants to colonize them. The method used until the early 1950s. This technique ensured an open substrate for the macroalgae to attach and grow on (Yang et al. 2017, Green 2014). The nori aquaculture industry was revolutionized after British scientist Kathleen Drew-Baker discovered the conchocelis stage of nori life history. Japanese scientists were able to build on this discovery to develop nursery methods to seed nets with nori sporlings. From that point on, larger scale aquaculture of nori species was accomplished, and the industry was able to expand and spread (Yang et al. 2017).

Economics

The red alga within the foliose Bangiales order have become one of the most economically important seaweeds worldwide (Yang et al. 2017). They were responsible for 2,984,573 tonnes of cultivated and wild collection in 2019 globally, with 450 tonnes being from wild collection (Mancini). In Asia, China is responsible for 2,123,040 tonnes of cultivated or wild collected nori, with the Republic of Korea (606,913 tonnes), Japan (251,200 tonnes), and the Democratic People’s Republic of Korea (3,000) producing the rest (Mancini). The America’s are responsible for 294 tonnes, which is solely produced through wild collection in Chile (Mancini). Europe is responsible for 8 tonnes of nori harvest, solely from wild collection (Mancini).

Uses

Nori has been a staple in Asian diets for centuries (Kim, J.K. et al. 2019; Moreira et al. 2021); being a well-known source of the wrapper to sushi. This macroalgae contains high amounts of vitamins, minerals, and proteins (Chopin et al. 1999, Kim et al. 2007), can even stand as an alternative substitute in fishmeal (Redmond et al. 2014, Walker et al. 2009). *Wildemania amplissima* is also a source of taurine and r-phycoerythrin (Kim et al. 2007).

Foliose species within the Bangiales have also been under review as the seaweed of choice for integrated multi-tropic aquaculture systems. Finfish aquaculture is a significant source of phosphorus and nitrogen in ecosystems, which can result in phytoplankton and harmful algal blooms (Kim et al. 2007). The development of polyculture systems would counteract the ecological downside of finfish monoculture, as well as provide other sources of revenue. Effective bioremediation would require finding native macroalgae that can uptake the large inorganic waste outputs from finfish farms, as well as having economic value (Kim et al. 2007). Nori species are fast growing, economically valuable, and can thrive in high levels of nutrients (Kim et al. 2009). Depending on the species, nori blades are one or two cell layers thick—meaning they have higher surface to volume ratio, making species capable of high nutrient absorption (Kim et al. 2007, Kim et al. 2009).

Taxonomy

Historically, the order Bangiales was divided into 2 genera. Those with filamentous gametophytes were assigned to the genus Bangia, those with blade-like morphologies were placed in the genus Porphyra. Dating back to the 1700’s, dozens of species of Porphyra were described. Due to the very simple morphology, there are few characteristics upon which to distinguish species. As a result, the number of foliose species in the order had been greatly underestimated and the relationships among the species was largely unknownThe advent of easy, reliable, inexpensive DNA sequencing has revolutionized taxonomy. Beginning in the 1990’s algal taxonomists began looking at *Porphyra* (sensu lato) using molecular tools. What at first appeared to be high levels of genetic diversity within species was later realized to represent numerous cryptic species (Neefus et al. 2000). Over the next decade, a concerted effort by an international group of scientists led to the discovery of new species and eventually a major revision in the Bangiales from molecularly based phylogeny (Sutherland et. al 2011).

The genus *Wildemania* was named by G.B. De Toni in 1897 and *Diploderma* by Kjellman in 1883, due to its distromatic thalli. These synonymous genera were later combined under the name *Diploderma*, and united by Rosenvinge in 1893 within the genus *Porphyra* due to discrepancies in consistent thalli stromatic layers. The genus *Porphyra* was named by C. Agardh in 1824, that incorporated distromatic and monostromatic thalli (Krishnamurthy 1972).

Species within *Wildemania* continued to stay within the genus *Porphyra* until *Wildemania* was resurrected in 2011 as part of the Sutherland et al. (2011) revision. The order Bangiales has continued to be revised, with the discovery of new species (Hasan et al. 2022), the resurrection of old genera (Sutherland et al. 2011, Yang et al. 2020), creation of new genera (Sutherland et al. 2011, Yang et al. 2020), and reorganization of relationships among genera (Yang et al. 2020).

Habitat/Morphology

Nori species have a wide distribution worldwide (Krishnamurthy 1969), with nineteen species being distributed throughout the Northwest Atlantic (Mathieson & Dawes, 2017). Beyond geographic distribution, nori species distribution can vary with habitat (coastal vs estuarine), season, and elevation in tidal or subtidal zones (Krishnamurthy 1972). With this zonal distribution, specific species receive varying environmental conditions, such as light levels, wave exposure, and exposure to air—desiccation. *Wildemania amplissima* specifically is a cold-water species, found in the low intertidal and shallow subtidal region. This species is not adapted to desiccation events due to its location in the tidal region, but can be exposed to rare desiccation events during extreme low tides (Redmond et al. 2014).

Coloration of the foliose Bangiales species can range on a scale of pale pink to dark red, and olive yellow to brown (Sutherland et al. 2011) due to the ratio of phycobilins in the blades (Redmond et al. 2014). *Wildemania amplissima* is a spring annual species. Its blades are generally pinkish red early in the spring and pale pink later. The blades generally have ruffled edges and grow in an oblong to lanceolate shape. While most species of nori are monostromatic (one cell layer thick), *W. amplissima* is one of several distromatic species (Mathieson and Dawes, 2011). Blades are monoecious (Sutherland et al. 2011) with male gametangia developing along the edges of the blade and female carpogonia in the middle (or represented by the reddest portion of the blade). The blades of the species are commonly found attached by a small discoid holdfast to shells, rocks, or epiphytically on other macroalgae (Mathieson and Dawes, 2011).

Biology/ Life History

Nori has a heteromorphic life cycle, alternating between a gametophyte blade and microscopic filamentous sporophyte (conchocelis). Sexual reproduction occurs when male gametes are released from the male thalli section of the blade and fertilize the egg in the female carpogonia. Once fertilized, mitosis occurs resulting in production of zygotospores which are then released into the environment. Once the zygotospores settle onto a substrate, typically shells, they germinate into microscopic filaments that bore into the shell surface and enter the conchocelis stage. The conchocelis grows in its vegetative form as ‘red fuzz’ on and in the shell surface. Under the right conditions, conchosporangial filaments form and meiosis occurs resulting in mature conchosporangia and forming four identical haploid conchospores. Conchospores are released and settled onto suitable substrate, typically shells, rocks, or other macroalgae, and grow into macroscopic haploid gametophyte blades (Redmond et al. 2014).

Aquaculture

After the discovery by Kathleen Drew-Baker, Japanese scientists were able to expand the macroalgae industry based on their newfound understanding of nori’s life history. This change in cultivation methods began with new technology being developed in the early 1950s. Nori used to be solely wild collection, but once the life history of nori was understood, expansion and scaling up of the industry was possible (Yang et al. 2017).

Nori aquaulcutre in Asia is based on several species of *Neopyropia*. Modern methods entail four main parts, the conchocelis culture stage, seeding of nets with conchospores, initial growth of blades on netting, and the growout and harvesting of full-grown blades (Redmond et al. 2014, Sahoo & Yarish 2005). Traditional methods trigger zygotospore release from fertile blades by temperature shocking and rehydration of the blades in a tank. The tank also contains shells, so when the rehydrated blades release zygotospore they settle onto the available shell substrate. The conchocelis then persist and grow on the shells until the environmental conditions change from fall to winter, where conchospores are released through increased water agitation and decreasing of temperatures. There are many ways to seed nets with conchospores, the first entails rotating a wheel of netting over the water where the buoyant conchospores are. The second common method entails spraying netting suspended over water with water containing conchospores. Once the nets are seeded, they can be moved out into open systems and harvested around day 50; nets can be re-harvested several more times every 15-30 days. At the point of harvest, blades are typically between 15 and 30 cm in length (Remond et al. 2014).

The US macroalgae aquaculture is centered around kelp species, and the lack of knowledge of nursery conditions required to trigger life history stages of other native macroalgae species limits expansion of this industry. *Wildemania amplissima* is a native species of nori in New England, but cannot be found on the coastlines in Asia. With species specific environmental conditions (Krishnamurthy 1972), cultivation methods have yet to be developed for this species. Additionally, traditionally nori is grown on netting, but with the interest of incorporating this new macroalgae quickly and efficiently into the US industry, similarities between this new species and the already developed methods of kelp must be made.

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