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10 November 2023

Thesis Literature Review Synthesis Paper

**General Seaweed Aquaculture:**

History

The aquaculture of macroalgae has roots in Asia dating back centuries (Yang et al. 2016). 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 (source). 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).

Uses

Macroalgae has a wide range of uses in food, medical, X, and X industry. Besides having everyday uses, such as food—for humans and animals—shampoo, toothpaste, cosmetics, textiles, there are 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 (Thomas et al. 2021, sources) to enter the surrounding environment, which can result in harmful algal blooms. In an attempt to bioremediate these inorganic compounds, shellfish or macroalgae can be added to the system for sequestration efforts (source).

US

The US macroalgae industry is relatively small compared to the global scale. 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 current value of the global macroalgae industry is $XX (source). The total US coastline is 95,471 miles (source). 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

Aquaculture in New England began in 2010, with the first kelp farm being developed in Casco Bay, ME (Grebe). The macroalgae industry has since budded into over 100 kelp farms in Maine alone in the last 13 years (Planet 2022).

Growing interest in this field has fueled the desire for expansion, through the introduction of a new macroalgae.

**Kelp:**

Background

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

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). Of the 100+ kelp farms in the US today, located across seven states (Maine, New Hampshire, Massachusetts, Connecticut, Rhode Island, Washington, and Alaska), only two species of kelp are grown—sugar kelp (Saccharina latissimi) and winged kelp (*Alaria esculenta*) (Grebe) out of the 30+ species (source).

Methodology/Technology

Kelp has a heteromorphic life history, transitioning between a sporophyte stage (blade) and a gametophyte stage (microscopic). Kelp is grown on longlines suspended just below the sea surface (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. Nylon twine wrapped PVC pipes provide the substrate necessary for kelp spore attachment on growth, usually a four-to-six-week process. 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 (source). Early techniques for cultivation of nori species focused on lime washing rocks where nori was known to grow that was used until the early 1950s (Yang et al. 2017, Green 2014). This technique ensured an open substrate for the macroalgae to attach and grow on (source). Once British scientist Kathleen Drew-Baker discovered the conchocelis stage of nori, Japanese scientists were able to understand nori’s life history and build on this discovery. From that point on, larger scale aquaculture of nori species was accomplished, and the industry was able to expand and spread (source).

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). 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

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, Kim et al. 2007), can even stand as an alternative substitute in fishmeal (Redmond et al. 2014). Compounds derived from red macroalgae can be used as gelling agents, such as agar which can have a use in the food or science industry (Green 2014). Other uses in everyday life; shampoo, cosmetics; as well as in the biotechnological industry; with *Wildemania amplissima* being a source of taurine and r-phycoerythrin (Kim et al. 2007); have been identified for this macroalgae.

Species within the foliose Bangiales order have also been under review as the seaweed of choice for integrated multi-tropic aquaculture systems. Finfish aquaculture is a significant offloading source of phosphorus and nitrogen into an ecosystem, which can result in phytoplankton and harmful algal blooms (Kim et al. 2007). The development of polyculture systems would combat the ecological downsides of monocultured finfish, as well as provide other sources of revenue. Actions for bioremediation would mean finding native macroalgae that can manage the large inorganic waste outputs from these finfish farms, as well as having economic value (Kim et al. 2007). The foliose species within the Bangiales order are fast growing, economically valuable, needing constant high levels of nutrients in the water (Kim et al. 2009). Many foliose species within the order Bangiales are distromatic—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

The order Bangiales has been under constant taxonomic review. The constant review within the foliose species of the Bangiales has been due to misidentification, discovery of new species, and revisions of relationships between species (sources). Misidentification among the bladed Bangiales is considerably common due to extreme morphological similarities (sources), which has led to incorrect identifications and underrepresentation of the order (sources). With the development and use of molecular analysis, misidentifications have become less common (source). Even without misidentifications, revision of the foliose Bangiales species remains constant, with reworking relationships between genera and species.

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. This taxonomic revision by Sutherland et al. resurrected two genera and named five new genera within the foliose species of the Bangiales order (Sutherland et al. 2011). 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 between genera (Yang et al. 2020).

Habitat/Morphology

Nori species have a wide distribution worldwide (source), with seven species being distributed throughout the Gulf of Maine (source). Beyond global distribution, nori species can vary in tidal zone location shoreline (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 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 (sources, 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). These blades generally have ruffled edges and grow in an oblong shape. Species can be monecious (containing both female and male portion) or dioecious (separate blades for female and male). While most species of nori are monostromatic (one cell layer thick), *W. amplissima* is one of several distromatic species. Blades are monoecious (Sutherland et al. 2011) with male gametangi 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 to shells, rocks, or epiphytically on other macroalgae.

Biology/ Life History

Nori has a heteromorphic life cycle, alternating between a gametophyte blade and microscopic filamentous sporophytes. 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 spores. 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, other source).

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 (source).

Modern methods for nori aquaculture entail four main parts, the conchocelis culturation stage, seeding of nets with conchospores, initial growth of blades on netting, and the 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 around life history of other native macroalgae species limits expansion of this industry. To begin expansion, the life history of a native species must be known along with methods and technology necessary for the aquaculture of that species. *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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