Feasibility Study of Native Seaweed Aquaculture in Washington State

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Abstract

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Worldwide, the cultivation of seaweed (marine macroalgae) is growing rapidly. While the majority of this growth is in east Asia, seaweed cultivation is also increasing in North America. Washington state currently has two active in-water seaweed farms growing sugar kelp (*Saccharina latissima*) and one small, land-based farm growing Turkish towel (*Chondracanthus exasperatus*). Recently, there has been a growing, local interest in new seaweed farms. Two more in-water farms are set to start growing sugar kelp within the year (2024). In this analysis, I ask what is the feasibility of cultivating other seaweed species native to Washington, and how do they compare to the feasibility of cultivating sugar kelp? I chose nine species to evaluate: *Pyropia abbottiae, Devaleraea mollis, Gracilariopsis andersonii, Ulva* spp., *Acrosiphonia coalita, Codium fragile, Nereocystis luetkeana, Alaria marginata, and Saccharina latissima*. The feasibility of these species was evaluated and scored on a 4-point scale using five criteria: existing knowledge, global cultivation production, known temperature tolerances, future temperature tolerances, and amenability to land-based aquaculture. Three species tied for the lowest score - *P. abbottiae*, *N. luetkeana*, and *A. coalita* - but they had different causes for their low scores. *Alaria marginata* scored the next lowest due to an absence of information concerning

its amenability to land-based aquaculture. All other species scored equally high, except for sugar kelp which scored highest. The results indicate that (1) sugar kelp is a good choice for an aquaculture crop in Washington regarding the chosen criteria, (2) there are other native seaweed species that are feasible for cultivation in Washington, and (3) some species are currently less feasible for aquaculture.

Introduction

Globally, seaweeds (marine macroalgae) have been used for millennia (FAO, 2018). Much of the cultivation of seaweed has occurred in east Asia as an essential part of the local diet, and east Asia is where the largest producers of cultivated macroalgae are today. Currently, cultivation is increasing globally and is projected to continue to grow while wild collection has remained stagnant (Global Seaweed, 2023). Currently, the top producers of cultivated seaweeds by weight are China, Indonesia, the Philippines, and the Republic of Korea (Global Seaweed, 2023). The top producers by value are China, Indonesia, Japan, and the Republic of Korea (Global Seaweed, 2023). Of all the cultivated seaweeds, 85% is grown for human food (FAO, 2018). Seaweeds are also grown for sources of materials such as carrageenan, agar and for use in biostimulants and fertilizers. Seaweeds are also used as feed for species grown in aquaculture and terrestrial farms. A novel use in this area has been the addition of seaweeds containing bromoform to ruminant feed to reduce ruminant production of methane, a powerful greenhouse gas. As the market for seaweeds has grown, its cultivation has grown in other areas of the globe to meet demand (FAO, 2018; Global Seaweed, 2023). In addition to an increase in cultivation in Asia, seaweed cultivation is increasing in Africa, Europe, Australia, and North America (FAO, 2018; Global Seaweed, 2023). But, these areas outside of Asia, still constitute a very small proportion of global production by volume and value (Nayar & Bott, 2014; Global Seaweed, 2023).

An increase in global demand for seaweeds has added to interest in growing seaweed outside of Asia. The demand for seaweed has likely grown due to seaweed's great nutritional profile, a widening palate for seaweed-based foods, interest in regenerative farming practices, and sources of novel materials for pharmaceuticals, nutraceuticals, animal feed, and

biotechnology. Projections for the market success of seaweed products point to human-food, biostimulants, animal feed, pet-food additives, and methane-reducing additives for ruminant livestock feed as the most economically promising products in the short term (Global Seaweed, 2023).

Along the coast of what is now North America, there has been a long history of using native seaweeds as food, medicine, material, and trade items. For example, many Indigenous groups collect *Pyropia* spp. to eat and trade including the Kwakwaka'wakw, Haida, Heiltsuk, and Tsimshian (Kuhnlein & Turner, 1991; Turner & Davis, 1993; Pérez-Lloréns, 2019). Other groups, like the Nuu-chah-nulth, historically did not often eat *Pyropia* spp. but would collect and sell it to Asian immigrants once they settled near Nuu-chah-nulth villages (Little). Herring spawn on kelp is also a popular traditional food along the northwest coast (Little; The Herring Protectors, 2024). Larger kelps (*Nereocystis* spp. and *Laminaria* spp.) were used as storage vessels and materials to help in steaming foods or softening timber to ease its manipulation (Turner, 2014).

Interest in seaweed cultivation is growing in North America, and US imports of seaweed products have been steady between 30,000 - 40,000 tonnes for the past decade and a half (Nayar & Bott, 2014; FAO, 2018). While the collection of wild seaweeds has occurred on the North American continent for millennia (Kuhnlein & Turner, 1991; Turner & Davis, 1993; Pérez-Lloréns, 2019), there have been few historical attempts to cultivate seaweeds here (Kim et al., 2019). Currently, the states that produce the most seaweed in the US are Alaska and Maine, but interest in growing seaweed is also increasing in other states (Kim et al., 2019).

California and Alaska have recently gained significant funding to enhance investment and research in their seaweed aquaculture industry (Kübler, 2021; *State of Alaska Aquaculture*

Report, 2024). Comparatively, Washington's seaweed industry is growing more slowly and with less investment (Kübler, 2021; Robidoux & Good, 2023). Currently, two companies, Blue Dot Sea Farm and Lummi Island SeaGreens are the only companies growing seaweeds for human consumption in the state (*Blue Dot Sea Farm*; *Lummi Island SeaGreens*). Sol-Sea, Ltd. is a Washington-based company that grows seaweeds in tanks on land. The Sol-Sea company focuses on growing Turkish towel (*Chondracanthus exasperatus*) as an ingredient for skin-care products (Bryant & Aristu, 2023). Two more in-water facilities are planning to start growing seaweed in 2024: Vashon Kelp Forest and Pacific Sea Farms (*Vashon Kelp Forest*; *Pacific Sea Farms*). Besides Sol-Sea, Ltd., all the current and planned farms are growing sugar kelp (*Saccharina latissima*). Vashon Kelp Forest is planning to grow bull kelp (*Nereocystis luetkeana*) along with sugar kelp (*Vashon Kelp Forest*; *Pacific Sea Farms*; Bryant & Aristu, 2023).

While interest in seaweed farms is growing in Washington state, there are many steps and considerations for potential seaweed farmers. One obstacle is a rigorous regulatory and proprietary system through Washington's Department of Natural Resources for the use of state-owned aquatic lands. This creates a barrier of time, knowledge, and monetary investment to potential farmers wanting to start in-water facilities (Brown, 2022). In-water seaweed farmers will need to consult with and gain consent from appropriate tribes as well as obtain permits, leases, and permission from several local, state and federal agencies. On-land facilities will also require some permits from local, state and federal agencies, but will most likely not need to consult with tribes nor gain as many federal permits as in-water farms.

The US treats marine space as a public good, so any project that alters the public's access to certain areas of the marine environment, even in state waters will require federal review and authorization. In Washington state, specifically, aspiring farmers are required to consult with and

obtain consent from appropriate tribal nations whose usual and accustomed areas the farmers are planning to operate. Access for tribes to fishing areas and co-management of the state's marine resources are protected by the Stevens Treaties and upheld by the Boldt and Rafeedie decisions (Northwest Indian Fisheries Commission). State law also mandates that marine planning and management "continue[s] to recognize the rights of Native American tribes regarding marine natural resources" (RCW Chapter 43.372). Three of the in-water seaweed farms in the state, Lummi Island Sea Greens, Vashon Kelp Forest, and Pacific Sea Farms, have all indicated that they first consulted and planned with appropriate tribes before progressing with their seaweed aquaculture plans (*Lummi Island SeaGreens*; *Vashon Kelp Forest*; *Pacific Sea Farms*). Currently, the state's expectations for consultation with tribes are lower for on-land facilities. However, this does not prevent on-land seaweed farmers from consulting with tribes nor does it prevent land-based aquaculture facilities from impacting inherent or treaty rights of tribes in Washington state. Prior consultation and consent might therefore be a consideration for land-based seaweed aquaculture facilities as well as those in the water.

In-water farms will need to obtain several permits from various local, state, and federal agencies. Washington, through its Department of Natural Resources (DNR), authorizes uses of marine space through leases of state-owned aquatic lands (SOALs). For any new projects on SOALs, a farmer will have to complete the "Joint Aquatic Resources Permit Application" (JARPA) and Application E (*ORIA - JARPA Form*). Washington DNR is required by statute to manage SOALs to encourage direct public access, foster water-dependent uses, ensure environmental protection, take advantage of opportunities for the utilization of renewable resources, and generate income from the use of SOALs when it does not interfere with the previous goals (RCW 79.105.030). New in-water projects would require use-authorization from

Washington DNR after the agency considers the potential impacts of the in-water seaweed farm on all mandated goals for SOALs. New projects will also need appropriate permits from Washington Department of Fish and Wildlife, Washington Department of Ecology, the US Army Corps of Engineers, the US Coast Guard, as well as from appropriate regional authorities depending on the county in which the aquaculture facility will be located (*ORIA - JARPA Form*). In contrast, land-based operations will avoid having to obtain some of these permits like a Section 404 of the Clean Water Act or a Essential Fish Habitat consultation. Land-based aquaculture projects will still be required to obtain some permits, though. Most seaweed farms are likely to be sited on or near the shore for easy access to saltwater. If the seaweed farm is built on shoreline property, the state's Shoreline Management Act (SMA) will require the producer to obtain a Substantial Development Permit or the appropriate version for agricultural use. There will be other requirements based on local land-use and zoning requirements, but land-based projects avoid most to all of the federal permitting requirements needed for in-water projects. One obstacle that will be greater for land-based seaweed farms will be pollution discharge permits for effluent discharged into the sea. This will require National Pollutant Discharge Elimination System (NPDES) and State Waste Discharge permits.

Another obstacle to creating seaweed farms is social license. Two in-water seaweed farms attempting to open off the coast of Vashon Island are still prevented from putting material in the water because of litigation from local groups who are opposing the seaweed farms in county court (Denkmann, 2023). Social license was also a problem in the 1980's when an effort to start in-water farms of *Pyropia* species was attempted (Kim et al., 2019).

A third large obstacle to successful seaweed cultivation is the impacts of climate change. Any native seaweed species in Washington today will have to face increasing water temperatures

in the coming decades (Khangaonkar 2019; Walker 2022). Knowing which species will be able to grow successfully in a warmer Washington will be important for potential farmers as well as cultivators who want to use their seaweed cultivation facilities to assist in seaweed restoration.

I surveyed a selection of native seaweed species that could be feasible for seaweed cultivation in Washington state. The species will be ranked based on their ability to survive in current climate conditions as well as a warmer climate to measure whether they will be a successful choice for seaweed farms today and in the future. They will also be ranked based on whether there is enough current knowledge on their life cycle to support cultivation and will be ranked based on the feasibility of growing them in on land tank facilities. This will allow for the option of potential farmers to circumvent more rigorous marine area-use regulations in the state. The species will also be ranked based on the global production of the species or related species. Since all products need a market, carving out a space in a market niche that already exists may be more accessible to potential farmers than convincing customers to try a brand-new, unheard of product. This study will also rank sugar kelp (*Saccharina latissima*) in regards to the same criteria. *S. latissima* is the only seaweed currently grown in-water in Washington for a food product. This survey of possible native seaweed candidates for cultivation will show the relative feasibility of cultivating each species in the face of current and future obstacles to commercial seaweed farms in the state.

Table 1: Criteria for relative scores given to each of the categories used to determine feasibility of future cultivation of macroalgae species in Washington state.

	0	**1**	**2**	**3**
Knowledge	No info. found	No information on spp. of interest/ or only life cycle or cultivation but not both for closely related spp. found	Life cycle or cultivation info. but not both/ or both life cycle and cultivated info. of a closely related spp. found	Life cycle and cultivation information found
Global Cultivation Production[a]	In lowest quartile	In 2nd lowest quartile	In 2nd highest quartile	In highest quartile
Known Temperature Tolerances	Upper temp. limit < min. SST for hottest month of the year	Upper temp. limit < avg. SST for hottest month of the year	Upper temp. limit < max. SST for hottest month of the year	Upper temp. limit for spp. > max. SST. for hottest month of the year
Tolerances to Future Temperatures	Upper temp. limit < min. SST for hottest month of the year +1.51°C	Upper temp. limit < avg. SST for hottest month of the year +1.51°C	Upper temp. limit < max. SST for hottest month of the year +1.51°C	Upper temp. limit for spp. > max. Sea surface temp. for hottest month of the year +1.51°C
Amenable to Land-based Aquaculture	No known plans for research into tank-based aquaculture found	No tank-based operations, but current research into spp. or related spp. found	Successful tank-based aquaculture for related spp. found	Successful tank-based aquaculture for this spp. found

a.) Nayar, S., & Bott, K. (2014). Current Status of Global Cultivated Seaweed Production and Markets. *Journal of the World Aquaculture Society*, 32–37.

Methodology

The goal of this analysis is to assess the relative feasibility of cultivating certain native seaweed species in the Pacific Northwest, specifically Washington state. All of the current in-water macroalgae aquaculture projects in Washington state grow *Saccharina latissima* (sugar kelp). Two other farms that are expected to begin operating in 2024, are also planning to grow kelp species, *S. latissima* and *Nereocystis luetkeana* (bull kelp). This analysis focuses on species from all three groups of seaweeds: red (Rhodophyta), green (Chlorophyta), and brown (Phaeophyta), and compares their relative feasibility to kelp species that are commonly cultivated for aquaculture or are commonly wild harvested in North America. Species were scored according to five criteria considered important to current and future success of aquaculture projects: state of existing knowledge, global cultivation popularity, known temperature tolerances, future temperature tolerances, and amenability to land-based aquaculture. All evaluation criteria were scored on a 4-point scale from 0 to 3, where 0 represents a low score (limited knowledge or low feasibility) and 3 indicates a high score (sufficient knowledge or promise of feasibility; Table 1).

Species Selection - I selected nine seaweed species to investigate. The majority of the selected species were not kelps; aquaculture of kelp species is already increasing along the west coast of North America and of all the current in-water seaweed aquaculture projects in Washington state, all are focusing on growing kelp species. Kelp species also currently make up the majority, by weight, of all macroalgae cultivation globally (Valgorize, 2019). Despite interest and activity around kelp cultivation along the west coast of North America, there is concern over the steep decline of native kelp species in this same region. While there are several factors that are potentially contributing to this decline, increasing sea surface temperatures may be the

primary cause. Rising sea surface temperatures in the Pacific Northwest could have an adverse effect on both current and future kelp aquaculture projects.

Furthermore, Washington state specifically has robust permitting laws regulating the use of marine areas for aquaculture through the Joint Aquatic Resources Permit Application (JARPA) process (*ORIA - JARPA Form*). The aquaculture permitting process in the state of Washington is expensive, time-consuming, and difficult to navigate (Brown, 2022). This is not necessarily a negative thing. All in-water farm operators in Washington must consult and obtain consent from appropriate tribal nations to ensure co-management agreements between Washington and tribal nations are followed. This required consultation process also works to prevent infringement of inherent and treaty rights of tribal nations in the state. In comparison, the increased popularity of seaweed farms in Alaska combined with their less rigorous permitting system may result in seaweed farms preventing coastal tribes in Alaska from accessing traditional fishing and foraging areas (*State of Alaska Aquaculture Report*, 2024; The Herring Protectors, 2024). For this reason, I focused on macroalgal species that could potentially be grown in land-based facilities in order to allow for the option to circumvent many of the permitting obstacles and conflicts with other marine space users. While operational obstacles to growing native seaweeds at in-water facilities typically can be overcome, there can often be technological or methodological barriers to cultivation of seaweeds in land-based facilities. Therefore, knowing current research into growing native seaweed species in land-based facilities can indicate whether there exists a land-based option for cultivation of those species.

I focused my research on three red and three green algal species (Rhodophyta and Chlorophyta, respectively) plus three native kelp species (Laminariales; Phaeophyta). *Pyropia abbottiae* (Rhodophyta) (“black seaweed”) has a long history as a source of food and medicine

for Indigenous Peoples of the west coast and has been a source of trade and economy among Indigenous Peoples and between Indigenous Peoples and Asian immigrants to the west coast. *Devaleraea mollis* (Rhodophyta) is related to one of the most commonly consumed seaweed species globally, *Palmaria palmata*, commonly known as dulse (Dumay et al., 2022). Additionally, *Devaleraea mollis* from Puget Sound is already grown in tanks as food for abalone restoration projects in Washington and is grown commercially in tanks in Oregon (Considine et al., 2023). *Gracilariopsis andersonii* (Rhodophyta) is edible and its relatives are commonly used in dishes across the Pacific (e.g., as ogonori). Moreover, this genus is the source for the industrial compound, agar, and makes up a large portion of global seaweed production (~16%) (FAO, 2022). *Ulva* spp. (Chlorophyta) can grow prolifically, are being successfully grown in tanks, and have promising applications as a food additive, pharmaceutical ingredient, and for excess environmental nutrient extraction. *Ulva* spp. can be difficult to distinguish without molecular methods; I used published information for *Ulva lactuca, Ulva prolifera*, and *Ulva fenestrata* as representatives of the genus in Washington. *Acrosiphonia coalita* (Chlorophyta) is of interest because of its potential to serve the Korean-American community in Washington. At a meeting convened by the Washington state legislature with Washington Sea Grant, state representatives, who are members of the Korean-American community, commented that a certain seaweed (*Capsosiphon fulvescens*) from the Republic of Korea is commonly eaten within the community but is expensive to import (Washington Sea Grant, 2022). Community members have seen the same or a similar species growing in Washington waters and asked whether it could be grown in Washington state for food production (Washington Sea Grant, 2022). *Acrosiphonia coalita* is a native species of green seaweed that is related to *Capsosiphon fulvescens* and was chosen to evaluate as a possible replacement for *C. fulvescens*. *Codium fragile* (Chlorophyta) grows

prolifically in many habitats. Although native to Washington and the west coast, this genus has become a troublesome, invasive species around the world in areas where it is not native. It has already been grown successfully in tanks, is edible, has a history of being a food and medicinal source, and has potential as a source for pharmaceutical compounds (*Monterey Bay Seaweeds*; Meinita et al., 2022). *C. fragile* could also possibly serve as potential bioremediator due to its propensity to absorb large amounts of ammonia (Kang et al., 2007).

I compared these species with three kelp species (Laminariales; Phaeophyta). I chose *Saccharina latissima* as one comparator because it is currently the most commonly grown seaweed in the US and is the species cultivated by the two active open-water seaweed farms in Washington: Blue Dot Sea Farms and Lummi Island Sea Greens (*Blue Dot Sea Farm*; *Lummi Island SeaGreens*). *Saccharina latissima* will also be the primary species grown in the two open-water farms that will start production in 2024: Pacific Sea Farms and Vashon Kelp Forest (*Pacific Sea Farms*; *Vashon Kelp Forest*). I chose *Nereocystis luetkeana*, bull kelp, as a second comparator because it is a foundation species in the coastal waters of the Pacific Northwest, but has declined sharply in the past few decades. Moreover, there is a growing wild harvest and an expansion in open-water cultivation of *Nereocystis luetkeana* in Alaska, suggesting its potential for cultivation in Washington state. I chose *Alaria marginata* as a third comparator because it is currently being grown commercially in Alaska and is being marketed as a North American version of wakame, the ingredient for the popular Japanese dish, seaweed salad. It is also collected wild in Washington and elsewhere on the west coast of North America as an ingredient for wakame.

Knowledge - I reviewed research performed on individual species. I focused on information pertaining to reproduction and life history and whether there had been attempts to

cultivate the species in laboratory and/or aquaculture settings. Where information on the species of interest was limited, I used information from close relatives that grow outside Washington state waters. The scoring criteria are expressed in Table 1.

Global Cultivation Production - While aquaculture of macroalgae is relatively new and still fairly limited in the US, it has been cultivated for decades to centuries in other parts of the world, particularly in Asia. A look at the current global production of cultivated seaweed, especially in the current climate of rapid global growth of seaweed aquaculture, suggests a high market demand for seaweed raw materials. While seaweeds produced in the US may not be able to easily compete with close relatives produced more cheaply abroad, US producers could carve out a niche in these already established markets with a focus on locavore trends, higher quality products, or more sustainable methods of production (Besada et al., 2009; Filippini et al., 2020).

Known Temperature Tolerances - I considered whether the species of interest could tolerate current maximum sea surface temperatures in Washington waters. Climate change is increasing sea surface temperatures in Washington waters (Walker et al., 2022). I inspected temperature data from buoys located in Washington waters during the warmest month of the year. These temperatures were compared to research that reports maximum temperature tolerances and optimal growing temperatures for each species or closely related species. The criteria for scoring in this category are described in Table 1.

Future Temperature Tolerances - Climate change is projected to impact the Washington marine and coastal environment through increased water temperatures, decreased pH, increased occurrence of storms, and sea level rise (Khangaonkar et al., 2019; Walker et al., 2022). Predictions indicate that the sea surface temperature in Pacific Northwest waters will increase an average of 1.51°C before 2095 (Khangaonpar et al., 2019). New aquaculture ventures must be

robust to these changes. This category was scored by adding 1.51°C to the average maximum temperature for the hottest month of the year (Table 1).

Amenability to Land-based Aquaculture - A major obstacle hindering the growth of seaweed aquaculture projects in Washington state is the regulations and proprietary issues surrounding new uses for marine space. One way to circumvent this obstacle is to grow seaweed in tanks on land. Such tanks typically are located close to the shore to allow reasonable access to seawater, and consequently, shoreline, agriculture, and water discharge regulations will apply, but land-based operations can avoid many other permitting obstacles that in-water operations face. While there are fewer regulatory obstacles to cultivation of seaweeds in tanks, there are still monetary and technological considerations that would have to be taken into account as well.

Tanks, pumps, and other necessary equipment require large upfront investment. In many instances, growing seaweeds in tanks is technically more difficult than growing in open-water due to constraints on biomass (size, density), the need to control physical and chemical conditions (light, nutrients, etc.) and biofouling. At the same time, land-based aquaculture can allow for greater control of growing conditions, which can ensure consistently favorable growing conditions and higher quality products. Such control of growing conditions does come with higher energy use and possibly increased greenhouse gas emissions (GHG). There are no studies that compare GHG emissions produced by macroalgae grown at in-water aquaculture facilities to those at land-based facilities. Research has shown, though, that the majority of GHG emissions from on-farm processes in seaweed aquaculture comes from fuel, energy use, and infrastructure maintenance. At many in-water seaweed farms in tropical and subtropical regions of the world, harvesters can collect cultivated seaweed by wading at lower tides and using small human-powered rafts. In Washington, in-water projects will be accessed

and harvested by gasoline or diesel powered boat, to safely harvest in the cold and heavily currented waters. Hence, boat use is likely to be the largest GHG emission source for on-farm processes for in-water seaweed aquaculture in the state, when compared to farms in warmer climes. In comparison, land-based facilities will generate most of their GHG emissions from electricity use and infrastructure maintenance. Currently, 60% of electricity production in the state comes from renewable sources. Therefore, if land-based farms are located in Washington, they will most likely have lower GHG emissions than farms based elsewhere since the farms will fulfill their electricity needs from the state's renewable-dominated energy production portfolio (*Washington State Profile and Energy Estimates*, 2024). Another source of GHG emissions from land-based facilities could come from land-use changes associated with converting undeveloped land to open-air tanks or tanks enclosed in a building. If the facility is built on land that is forested or otherwise supporting coastal ecosystems, this will add to the farm's total GHG emissions by disturbing or eliminating those ecosystems that are acting as carbon sinks (Jones et al., 2022) Other studies have shown that the majority of the GHG emissions from seaweed aquaculture products come from downstream or post-harvest activities such as drying and transportation (Ghosh et al., 2015; Jones et al., 2022). The GHG emissions from transportation of seaweed aquaculture products can quickly eclipse the emissions produced from the energy use at farms. To score this category of amenability to land-based aquaculture, I reviewed research that reported success with growing the focus species or their close relatives in tanks and I also considered current aquaculture facilities globally that already are growing the focus species or their close relatives in tanks (Table 1).

After a search of the available literature, individual species were scored based on the available information. A majority of the species considered in this study have been the subject of research focused on their life history, reproduction or cultivation in a laboratory setting. I found information on six of the nine species that described life-history and cultivation techniques. For the other three species, I found information on either cultivation or life history, or information on both for a closely related species (Table 1).

I reviewed current aquaculture production information for seaweeds globally. I obtained information on global seaweed production from Nayar & Bott (2014). These authors used data from a 2012 FAO report to calculate the global seaweed aquaculture production for different types of seaweeds (Nayar & Bott, 2014) (Supplementary Figure 3). I broke these data into quartiles and matched each species in this study with their closest relative that is globally cultivated. I then analyzed each species based on which quartile they would fall into. Since most of the species that are commonly grown globally are not native to Washington, I placed each of the native species within the group that their species was the most closely related. For example, I place *Saccharina latissima* in the *Saccharina japonica* group.

I used sea surface temperature (SST) data from two locations, Westport, WA and central Puget Sound near Seattle, WA to ascertain the scope of likely increases to current surface seawater temperatures in Washington. I used temperature data from NOAA's 1/4° daily Optimum Interpolation Sea Surface Temperature (SST), which combines data from ships, buoys, satellites, and Argo floats. I compared these data with data from two NOAA stations in Washington. One station was the Westport station, WPTW1 (46°54'16"N 124°6'18"W), which is located in the south bay on the inside of Point Chehalis. The other station was EBSW1, which is located on the

coast of Elliott Bay near Seattle, WA (47°36'6"N 122°20'18"W). For both data sources I used the average SST from the month that showed the highest temperatures for each location. Based on this comparison, I chose to use the data from NOAA's 1/4° daily Optimum Interpolation Sea Surface Temperature program because it reported higher average temperatures and could be more representative of overall warmer conditions. SSTs were highest in July in Westport and in August in Elliott Bay. For both data sources the higher temperatures were observed at the Westport location, perhaps because the sensor was located in a shallow, protected site, since I would expect the outer coast to have cooler surface water, since this is the case even during marine heatwaves (Starko et al., 2022). To adequately capture high temperatures as they now occur, I used the higher maximum temperatures from the Westport location in the analysis. I then searched the published literature for information on each species' latitudinal range, optimal temperatures for growth, upper growth temperature thresholds, and upper lethal temperature limits (Table 2). I used thermal tolerance information (Table 2) in combination with reported SST values (Table 3) to assign each species a score indicating their ability to tolerate current observed temperatures in Washington waters based on the evaluation criteria outlined in Table 1. Macroalgae usually have multiple phases in their life cycles, and I searched the literature for studies that studied the effects of temperature on each life stage of each of the nine species reviewed in this study. The temperatures of upper thermal growth limits, upper lethal temperature limits, and optimal temperature windows were recorded when available. Since each species will have to survive in each life stage, the lowest maximum temperature where growth occurs that was found for each species was entered into Table 2 and used for analysis. The temperature limits for each life stage are recorded in Supplementary Tables 5-9.

Given that all the species that I considered for this analysis currently are found in Washington waters, it is unsurprising to see that almost all of their scores were high in the current temperature tolerance category. The lone exception was *Pyropia abbottiae* whose reported temperature threshold was below the current observed maximum SST in Washington. Even so, the upper temperature threshold for this species is still above the mean SST for the hottest month in Westport, WA.

I used the published projected increase in average SST for the Pacific Northwest of 1.51°C by 2095 to project future maximum SSTs in the hottest months of the year (Khangaonpar et al., 2019). Sources for all species but *Pyropia abbottiae* indicated reasonable tolerance to forecasted elevated temperatures.

A review of published research and of companies advertising their land-based tank-cultured seaweeds on their websites were used to assess each species' amenability to tank-based aquaculture. I included information from current or past projects that successfully cultivated each species in land-based systems. Much of this information came from companies that currently are growing these species in land-based systems (Supplementary Table 2).

Table 2: Northern and southern limits of the nine selected macroalgae species and the species' optimal growing temperatures and upper temperature threshold for growth collected from literature sources.

Species	**Southern limit**	**Northern limit**	**Optimal Growth**	**Upper Temp. Threshold**
Pyropia abbottiae	Monterey Peninsula, Monterey Co., CA[k]	Sanak Island, AK[d]	11°C[l]	15°C[l]
Devaleraea mollis	Goleta, Santa Barbara Co., CA[k]	Aleutian Islands, AK[d]	14-18°C[b]	20°C[b]
Gracilariopsis andersonii	Northern Sinaloa, Mexico[d]	Southern Haida Gwaii, British Columbia, CAN[d]	20°C[p*]	30°C[p*]
Ulva spp.	Baja California, Mexico[d]	Alaska[d]	16-17°C[c]	25°C[q]
Acrosiphonia coalita	San Luis Obispo Co., CA[k]	Gulf of Alaska[i]	10°C[m]	20°C[m]
Codium fragile	Baja California, Mexico[f]	Prince William Sound, AK[f]	24°C[f]	30°C[f]
Nereocystis luetkeana	Diablo Cove, SLO Co., CA[k]	Umnak Is., AK[g]	10-16°C[o]	18°C[o]
Alaria marginata	Diablo Cove, SLO Co., CA[k]	Kodiak Is., AK[g]	12°C[e]	18°C[e]
Saccharina latissima	Sta. Catalina Is., CA[d]	Aleutian Is., AK[g]	13.39°C[n]	20°C[n]

a.) *AlgaeBase :: Listing the world's algae*. (n.d.). https://www.algaebase.org/

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i.) *Seaweeds of Alaska*. (n.d.-c). https://www.seaweedsofalaska.com/
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Table 3: Low, mean, and high sea surface temperatures of the hottest month of the year for sea surface temperatures compiled for Westport, WA (on the outer coast) and central Puget Sound along with their predicted increase in temperature using the standard +1.51°C before 2095 under CMIP5 projections and RCP8.5 emissions scenario (Khangaonpar et al., 2019).
Data are from seatemperatures.net and "Raw data for the calculations made to find the sea surface temperature in Westport (Puget Sound) comes from the National Oceanic and Atmospheric Administration (NOAA) and their 1/4° daily Optimum Interpolation Sea Surface Temperature. The water temperature data is constructed by combining observations from different platforms (satellites, ships, buoys, and Argo floats) on a regular global grid. A spatially complete sea surface temperature map is then built by interpolating to fill in gaps in the data."

	Westport (July)[b]	+1.51°C	Puget Sound (August)[a]	+1.51°C
Low	9.82°C	11.33°C	9.8°C	11.31°C
Mean	13.83°C	15.34°C	11.4°C	12.91°C
High	**18.08C**	**19.59°C**	**15.79°C**	**17.3°C**

a.) "Puget Sound Sea Temperature". *SeaTemperatures.net, http://seatemperatures.net/north-america/united-states/puget-sound/. Accessed 13 February, 2024*
b.) "Westport Sea Temperature in July". *SeaTemperatures.net, http://seatemperatures.net/north-america/united-states/westport-july-temperature/. Accessed 13 February, 2024*

Table 4: Scoring (0-3) of nine selected macroalgae species based on aquaculture feasibility chosen criteria along with their calculated total score.

Species	**Common name(s)**	**Knowledge**	**Global Cultivation Production**	**Known Temp. Tolerances**	**Future Temp. Tolerances**	**Amenable to Land-based Aquaculture**	**Sum**
Pyropia abbotiae	black weed, nori	2	2	2	1	2	9
Devaleraea mollis	Pacific dulse	3	0	3	3	3	12
Gracilariopsis andersonii	red spaghetti, ogonori	2	2	3	3	2	12
Ulva spp.	sea lettuce	3	0	3	3	3	12
Acrosiphonia coalita	green rope, maesaengi	2	0	3	3	1	9
Codium fragile	sea staghorn	3	0	3	3	3	12
Nereocystis luetkeana	bull kelp	3	1	2	2	1	9
Alaria marginata	winged kelp	3	3	2	2	0	10
Saccharina latissima	sugar kelp	3	3	3	3	1	13

Discussion

My analysis shows that the majority of the seaweed species considered here are candidates for cultivation in Washington both now and in the future (Table 4). For each of these species, there exists at least some knowledge regarding their life cycles or the life cycles of close relatives (Supplementary Table 1). However, this does not suggest that there is sufficient information to make cultivation successful or economically feasible. The reviewed literature

provides a base of reproduction and life cycle information for all the species surveyed or their close relatives, but cultivation of native seaweeds in Washington can only be successful if more research is completed on life cycles. Even more than information on each species life cycle, the creation of nurseries to produce seedstock would be needed to support any expansion of the diversity of seaweed species in cultivation. Existing knowledge of species' life cycles and thermal tolerances indicates a knowledge base that could be used as a starting point for the creation of successful cultivation processes and seedstock in the state. There are funded projects on the east coast of the US to develop new nursery and seedstock capacity (University of New Hampshire, 2022; SARE; Lawrence, 2023). These projects also aim to build new technologies for kelp species, native dulse (*Palmaria palmata*) and nori (*Wildemania amplissima*) cultivation in order to support the seaweed aquaculture industry in New England (University of New Hampshire, 2022; SARE; Lawrence, 2023). There are currently no similar programs on the west coast. There are a few hatcheries and seed banks on the west coast, and these are all focused on kelp species (GreenWave, 2024; Cascadia Seaweed). There is a hatchery in Washington state run by Puget Sound Restoration Fund, but its purpose is to support the restoration of bull kelp not commercial aquaculture (PSRF, 2022). More investment and research into seed banks, and hatcheries for potential commercial seaweed species in Washington would greatly benefit the growth of the nascent seaweed aquaculture industry in the state.

Of the nine species considered, there were four species that scored lower with respect to the overall promise for feasibility: *Pyropia abbottiae*, *Nereocystis luetkeana*, *Alaria marginata*, and *Acrosiphonia coalita*. The first two species scored lower based on their temperature tolerances now and in the future. *Pyropia abbottiae* scored lowest of all, in regards to temperature tolerance, and this could indicate that it would have low feasibility under future

climatic conditions. There already are temperature-related problems affecting this species along the west coast in British Columbia and Alaska (Dye, 2023; Denning, 2023). The decrease in abundance and quality of the wild *P. abbottiae* in British Columbia and Alaska have raised concerns for Indigenous and western researchers alike (Dye, 2023; Denning, 2023). This decrease in abundance and quality followed the marine heatwave event that affected the west coast of North America in 2014-2015, and its effects on *Pyropia* species still linger (Dye 2023; Denning, 2023). This decline following the marine heat wave may not be solely due to the species' low tolerance to high water temperatures. Following the heat wave, an epiphytic diatom in the genus *Licmophora* was observed covering *Pyropia* spp. on the coast of Alaska (Dye, 2023). This diatom, which discolors the *Pyropia* and gives it an unpleasant taste, is not a new phenomenon, but is being observed more frequently as coastal waters warm (Dye, 2023). Novel or more frequent growth of epiphytes may affect seaweed growth and survival as rising temperatures favor epiphytic species or negatively influence the condition of host species. Seaweed farmers will be faced with such considerations as they choose species and locations that will be least affected by the impacts of climate change. Lack of high temperature tolerance in *P. abbottiae* could lead researchers to consider other native *Pyropia* species to see whether their temperature tolerances are similar, lower, or higher. On *Pyropia* farms in east Asia, higher temperatures are negatively impacting production. *Pyropia yezoensis*, *Pyropia tenera*, and *P. haitensis*, which are grown in east Asia as sources for nori, are experiencing negative effects from warming waters (Shin et al., 2018; Wang et al., 2018; Lee & Choi, 2019; Ding et al., 2020). The detrimental effects of warming waters on these *Pyropia* species are motivating research to find wild genotypes with higher temperature tolerances or to perform intraspecific crossings of different strains in an attempt to grow more high-temperature tolerant cultivars (Dong et al.,

2024). Intraspecific crossbreeding could be a technique to enhance the tolerance of *P. abbottiae* to higher temperatures in Washington, although more research would be required to achieve this. Moreover, state agencies are currently wary of taking any action or allowing any project that might cause changes in the existing genetic diversity of native species. A search of the literature shows that information regarding temperature tolerance is sparse for *Pyropia* species native to Washington, and is complicated by the realization that the taxon now recognized as *Pyropia abbottiae* may in fact be comprised of more than one species (Mumford, personal communication, 2024). As a first approximation and in lieu of laboratory experiments, researchers could use southernmost observations of *Pyropia* species. For example, there has been research into cultivation techniques of *Pyropia perforata* which ranges further south into the Gulf of California in Mexico, compared to *P. abbottiae* which only reaches Monterey Bay, California (Swezey, 2020; AlgaeBase).

Nereocystis luetkeana and *A. marginata* also seem less well adapted to warming ocean temperatures. Concerns around the decline of *N. luetkeana* (bull kelp) in Washington have already been raised due to the precipitous loss of bull kelp in the state's inland waters and elsewhere along the west coast. Washington has made wild bull kelp recovery a priority through legislation, and bull kelp protection and restoration is occurring through a partnership of local organizations, tribes, state agencies, and federal agencies through the Puget Sound Kelp Restoration and Recovery Plan (Calloway et al., 2020). The Washington state legislature passed Senate Bill 5619 in June 2022 requiring the state to recover and conserve *N. luetkeana* (RCW 79.135.440). One of the approved, but not yet active farms, Vashon Kelp Forest, is planning to grow sugar kelp as a commercial product intended for harvest and bull kelp as a restorative measure, presumably leaving the bull kelp in the water to provide habitat and a source of bull

kelp spores (*Vashon Kelp Forest*). However, the inability of bull kelp to grow well at higher temperatures could dissuade potential seaweed aquaculturists from attempting to cultivate them, and could drive more interest in local research in support of restoration efforts for this species. It would be interesting though, if more in-water farms attempt to provide restoration support for native species, but it is still unknown if these attempts would be successful.

More research on the effects of temperature on all phases of each seaweed species will provide more clarity on the future feasibility of seaweed aquaculture in Washington. Species response to short-term events such as marine heatwaves may differ from response to gradually increasing temperatures. Moreover, some phases in the life cycle of certain seaweed species (e.g. *Pyropia* spp.) require cold temperatures in the cooler months in order to complete the life cycle. Warmer winter water temperatures could, in the future, limit production, even if the macroscopic life stages can survive higher, summer temperatures.

Another consideration is that temperature increases can be highly variable in coastal ecosystems over small distances (mm - km) and short time periods (min - hr; Bates et al., 2018; Harley, 2011; Helmuth et al., 2014). Impacts from increasing SSTs and future marine heat waves will most likely be irregular along Washington's coast. During recent marine heatwaves in the Pacific Northwest, the temperature in the inland marine areas on nearby Vancouver Island (British Columbia, Canada) were 3°C higher than they were offshore (Starko et al., 2022). Local marine organisms will experience different levels and durations of stress brought on by higher temperatures depending on where they are located (Bates et al., 2018). This also indicates that careful site selection will be necessary to maximize the likelihood that the cultivated species will grow in local climatic conditions now and in the future. Land-based aquaculture projects presumably would have the ability to chill incoming water, but that would require large amounts

of energy and impose higher costs. Farmers and researchers may also want to carefully consider the effects of increasing ocean temperatures because such environmental shifts can affect the nutritional quality of seaweeds and cause species-specific increases or decreases in metabolite production. The impacts of a warmer and more acidified ocean on seaweed metabolite concentrations are not well studied (Park et al., 2023). In some species, rising temperatures are resulting in increased uptake and concentration of nutrients and increased production of carbohydrates and proteins. (Gao et al., 2018; Park et al., 2023; Rizzo, 2023). It cannot be expected though, that all seaweed species will respond similarly. Giant kelp (*Macrocystis pyrifera*), a seaweed native to the west coast of North America, has shown declines in tissue nitrogen content associated with increasing sea surface temperatures (Lowman et al., 2021).

Aside from temperature tolerance, suitability for land-based aquaculture (or lack thereof) contributed to low scores in *A. marginata*. *Alaria marginata* is cultivated at in-water farms in Alaska, but through my literature review I did not find any projects or experiments that grew *A. marginata* in land-based systems. This could be because there has been little need to, or the fact that it may be difficult since this kelp species can grow to large sizes around 3 meters in length (Druehl & Clarkston, 2016).

Acrosiphonia coalita also scored lower than others, but this was not because of temperature tolerances — the species has an upper temperature threshold of 20°C (Table 2) (Sussmann & DeWreede, 2001). This species is of interest because a related seaweed, *Capsosiphon fulvescens*, is used in Korean cuisine. However, there has been limited research into cultivation of *Acrosiphonia coalita*, since there has been little use of it or any closely related native species in North America. *Capsosiphon fulvescens* has only recently been cultivated in the Republic of Korea and I could find no information about in-tank cultivation attempts (Sohn,

2003; Hwang & Park, 2020). The lack of information on cultivating *A. coalita* or *C. fulvescens* in tanks led to a lower total score for *A. coalita*. The interest in *C. fulvescens* and its native relative, *A. coalita*, emerged from members of the Korean-American community at a seaweed informational meeting in King County, WA, indicating that *A. coalita* may be able find a market in the Korean-American community on the west coast of North America (Washington Sea Grant, 2022). More market research showing local interest from consumers may be required to convince seaweed farmers to invest in this species.

Lack of market research on edible seaweeds in the US may be an obstacle for more rapid growth in the domestic seaweed aquaculture industry. Farmers are more likely to invest in growing more seaweed and a larger diversity of seaweeds if they have an idea of what will sell. The US imports, on average, around 36,000 tonnes of seaweed annually, and in 2022, the US cultivated around 979 tonnes of seaweed (FAO, 2018; NOAA Fisheries; Robidoux & Good, 2023). Most of the seaweed imported to the US is non-edible and is used for industrial purposes (mostly textile and paper production) or in the form of carrageenan which is used as a thickening agent in the dairy and meat industries (FAO, 2018). In contrast, almost 100% of the seaweed produced in the US is edible and is destined for groceries or restaurants (Robidoux & Good, 2023). While the US has records on how much seaweed is imported annually and how much seaweed is being produced domestically, I was unable to find substantial market research for different seaweed species in the US. Some market studies have been performed asking whether Americans would favor seaweed in their foods or groceries, mainly to ascertain if they would accept seaweed additives to foods other than in the form of agar or carrageenan (Li et al., 2021; Zheng et al., 2024). The literature does suggest that there is some growing interest in the seaweed food market, although it depends on how the product and its features are framed and

marketed (Li et al., 2021). One study asked if Americans could identify different common edible seaweeds, but so far no studies have ascertained American consumers' willingness to pay for different edible seaweed species or seaweed products (Zheng et al., 2024). Studies that seek to determine which species of seaweed consumers are interested in buying have been performed in other regions with emerging seaweed markets such as western Europe, but to date North America lags behind in this endeavor (Valgorize, 2019). More market fit studies of seaweed products in the US as well as studies on how long it would take for different cultivated species to generate a profit in an aquaculture setting would benefit seaweed farmers and may promote the diversification of seaweed species that are cultivated in the US.

Conclusions

The cultivated seaweed industry and market is growing globally and locally on the US west coast. If the nascent seaweed aquaculture industry in Washington continues its growth, there are both opportunities and challenges. This study shows that there are opportunities for a more diversified suite of species to be considered by the Washington seaweed aquaculture industry beyond the current focus on sugar kelp. This study also shows that there are some species that may be less amenable to cultivation under future climate conditions. Species that show less potential feasibility are characterized by lower temperature tolerances or lower levels of prior research concerning cultivation.

This study, along with others, shows that care should be taken with regard to the impacts of climate change on cultivated seaweeds (Kübler et al., 2021; Alaska Fisheries Science Center, 2022). Adaptation to the impacts of climate change on growing conditions is necessary for

current and future seaweed aquaculture endeavors anywhere on the globe, including in Washington state. New seaweed farms in the US would benefit from the use of model projections and experimental research to prepare for the impacts of climate change to protect their investments, site future farms, and select species for cultivation.

If no changes are made to Washington's state regulations regarding marine spatial uses, seaweed aquaculture may lag behind that in other states, or drive potential farmers to consider land-based infrastructure. Lack of research on land-based cultivation for seaweed species could limit the growth and diversification of land-based seaweed aquaculture in Washington state.

Interest in seaweed aquaculture in Washington is growing and the market for cultivated seaweed is projected to grow globally for the foreseeable future. If Washington state or the US chooses to successfully grow their seaweed aquaculture industry, there will need to be more market studies to show where consumer's interest in seaweed products lies. This could give confidence to farmers to grow more and different species of seaweeds. After conversations with seaweed farmers in the state, this seems to be a key to the future success of seaweed farming in the region. If there are no markets for seaweeds grown in Washington, then there will be no profitable farms. While research has been done on the life cycles of local seaweeds, additional research could increase the success of future cultivation, and is needed to create successful nurseries and a stable supply of seedstock. Also, more research is needed on land-based cultivation for many native species if land-based cultivation is to become a viable option.

This study ignored the question of social license of seaweed farms, whether in water or on land. This large and multifaceted question will need to be explored throughout coastal Washington before any major growth of this industry can occur in the state.

This evaluation shows that there are native species other than sugar kelp (*S. latissima*) that can be explored for cultivation, and that sugar kelp is currently a feasible choice for seaweed aquaculture in Washington. Species that scored low in this study did so for different reasons, indicating that careful research should be undertaken before choosing or eliminating a native seaweed species for cultivation in Washington. Finally, the list of species that was evaluated in this study is not exhaustive and there are many native species in Washington's waters that may also be prime candidates for seaweed cultivation.

Supplementary Table 1: Sources and details on the state of existing knowledge of reproduction and life-histories of seaweed species

Species	Common name(s)	Paper or company	Info	Score
Pyropia abbottiae	black weed (nori)	García‐Jiménez & Robaina (2015); Mikami et al. (2019); Mikami & Takahashi (2023)	Extensive research into life cycles and reproduction in *P. yezonensis* and other *Pyropia* species	2
Devaleraea mollis	Pacific dulse	Umezaki (1989); Van der Meer & Bird (1985)	Description of *P. mollis* species. Description of types of life-histories in red seaweeds and listed which one *P. mollis* belongs to	3
Gracilariopsis andersonii	red spaghetti (ogonori)	Wehrenberg (2010); Engel et al. (2001); Capillo et al. (2017)	Population dynamics and reproduction processes in *G. andersonii;* Description of reproduction in related *G. gracilis*	2
Ulva spp.	sea lettuce	Bonneau (1978); Chávez-Sánchez et al. (2018); Liu et al. (2015); Niesenbau (1988)	Much information on life histories and reproductive strategies for *U. lactuca*, *U prolifera*, and other *Ulva* spp.	3
Acrosiphonia coalita	green rope (maesaengi)	Sussmann & DeWreede (2001)	Description of life history of *A. coalita*, but little information on reproduction	2
Codium fragile	sea staghorn	Drouin et al. (2016); Bulleri et al. (2007); Prince & Trowbridge (2004)	Much information on life histories and reproductive strategies for *C. fragile*, because it is a problematic invasive species elsewhere	3
Nereocystis luetkeana	Bull kelp	Vadas (1972); Dobkowski et al. (2018); Korabik et al. (2019); Merrill & Gillingham (1991)	Much information on life history and reproduction due to this species importance to ecosystems and recent declines	3
Alaria marginata	Winged kelp	McConnico & Foster (2005); Raymond (2020); Raymond & Stekoll (2021)	Information on both life history and reproduction	3
Saccharina latissima	Sugar kelp	Raymond (2020); Raymond & Stekoll (2021); Ebbing et al. (2021); Andersen (2013); Forbord et al. (2018)	Information on both life history and reproduction	3

Supplementary Table 2: Sources and details on seaweed species' amenability to land-based aquaculture

Species	Common Name(s)	Paper or company	Information	Score
Pyropia abbottiae	black weed, (nori)	Israel et al. (2006)	Successful experimental tank cultivation and harvest of *P. yezoensis*, *P. linearis*, and *P. tenera*	2
Devaleraea mollis	Pacific dulse	Oregon Dulse	farm growing *P. mollis* in tanks in Oregon	3
Gracilariopsis andersonii	red spaghetti, (ogonori)	Monterey Bay Seaweeds	Monterey Bay Seaweeds grows related species *G. parvispora* in tanks	2
Ulva spp.	sea lettuce	Blue Evolution	farm growing *Ulva* spp. in Baja California	3
Acrosiphonia coalita	green rope, (maesaengi)	Rorrer (1995)	tests to propagate and start growing *A. coalita* in bioreactors	1
Codium fragile	sea staghorn	Monterey Bay Seaweeds.	farm growing *C. fragile* in tanks in California	3
Nereocystis luetkeana	bull kelp	Supratya & Martone (2023)	Successful experiment to grow *N. luetkeana* in tanks	1
Alaria marginata	winged kelp	None found	N/A	0
Saccharina latissima	sugar kelp	Azevedo et al. (2016)	Pilot-scale project to grow *S. latissima* in tanks in southern Europe	1

Supplementary Table 3: Data from Nayar & Bott (2014) showing global production of seaweeds by types in million tonnes.

Species Name	**Common Name(s)**	**Type**	**Weight (million t)**	**Percentage**	**Score**
Ulva clathrata	Bright green nori	green	0.011	0.07	0
Ulva prolifera & others *Ulva* spp.	Green laver, aonori	green	0.005	0.03	1
Caulerpa spp.	*Caulerpa* seaweeds	green	0.004	0.03	2
Codium fragile	*Codium fragile*	green	0.001	0.01	3
Gelidiae	Japanese isinglass	red	0.001	0.01	
Pyropia yezoensis, tenera, etc.	Nori nei	red	1.072	6.79	
North Atlantic *Pyropia* sp.	Laver, nori	red	0.564	3.57	
other *Gracilaria*	*Gracilaria* seaweeds	red	0.565	3.58	
Gracilaria gracilis	Warty *gracilaria*	red	1.152	7.30	
other *Eucheuma*	*Eucheuma* seaweeds nei	red	3.489	22.11	
Eucheuma denticulatum	Spiny eucheuma	red	0.259	1.64	
Kappaphycus alvarezii	Elkhorn sea moss	red	1.875	11.88	
Undaria pinnatifida	Wakame	brown	1.537	9.74	
Sargassum fusiforme	*Sargassum fusiforme*	brown	0.078	0.49	
Saccharina japonica	Japanese kelp, kombu	brown	5.147	32.61	
Other brown seaweeds	Other brown seaweeds	brown	0.022	0.14	
SUMS			**15.782**	**100.00**	

Supplementary Table 4: Mean, upper standard deviation, and lower standard deviation from historic averaged sea surface temperatures along with their predicted increase in temperature using the standard +1.51°C before 2095 under CMIP5 projections and RCP8.5 emissions scenario (Khangaonpar et al., 2019). Data were collected at NOAA stations in Westport, WA (on the outer coast) and Elliott Bay (near Seattle, WA) in Puget Sound from the National Data Buoy Center Mean and Standard Deviation Climatic Summary Plots for sea temperature. Westport data from 6/2008 - 12/2012. Elliot Bay data from 4/2005 - 12/2012.

	Westport WPTW1 (Aug.)	+1.51°C	Elliot Bay EBSW1 (Aug.)	+1.51°C
Std. Dev. -	9.5°C	11.01°C	11.5°C	13.01°C
Mean	14.0°C	15.51°C	13.0°C	14.51°C
Std. Dev. +	**17.0°C**	**18.51°C**	**15.5°C**	**17.01°C**

Supplementary Table 5: Temperature limits and windows for sporophyte phase of brown seaweed species (Phaeophyta) sourced from literature

Species	**Common Name(s)**	Macroscopic Sporophyte Optimum Temp. Window	Macroscopic Sporophyte Upper Temperature Limit for growth	Macroscopic Sporophyte Lethal Temperature Limit
Nereocystis luetkeana	bull kelp	10 - 14°C[b]	15.9°C[d]	18°C[d]
Alaria marginata	winged kelp	-	18 - 20°C[a, e]	18 - 20°C[a, e]
Saccharina latissima	sugar kelp	10 - 15°C[c]	23°C[c]	24°C[f] (90% mortality)

a.) Muth, A. F., Graham, M. H., Lane, C. E., & Harley, C. D. G. (2019). Recruitment tolerance to increased temperature present across multiple kelp clades. *Ecology*, *100*(3). https://doi.org/10.1002/ecy.2594

b.) Weigel, B. L., Small, S. L., Berry, H., & Dethier, M. N. (2023). Effects of temperature and nutrients on microscopic stages of the bull kelp (*Nereocystis luetkeana*, Phaeophyceae). *Journal of Phycology*, *59*(5), 893–907. https://doi.org/10.1111/jpy.13366

c.) Bolton, J. J., & Lüning, K. (1982). Optimal Growth and Maximal Survival Temperatures of Atlantic Laminaria Species (Phaeophyta) in Culture. *Marine Biology*, *66*, 89–94.

d.) Springer, Y., Hays, C., Carr, M., & Mackey, M. (2007). *Ecology and Management of the Bull Kelp, Nereocystis luetkeana: A synthesis with recommendations for future research*. Lenfest Ocean Program.

e.) Lüning, K., & Freshwater, W. (1988). Temperature Tolerance of Northeast Pacific Marine Algae. *Journal of Phycology*, *24*, 310–315.

f.) Nepper-Davidsen, J., Andersen, D. T., & Pedersen, M. F. (2019). Exposure to simulated heatwave scenarios causes long-term reductions in performance in Saccharina latissima. *Marine Ecology. Progress Series*, *630*, 25–39. https://doi.org/10.3354/meps13133

Supplementary Table 6: Temperature limits and windows for gametophyte phase of brown seaweed species (Phaeophyta) sourced from literature

Species	**Common Name(s)**	Microscopic Gametophyte Optimum Temp. Window	Microscopic Gametophyte Upper Temperature Limit for growth	Microscopic Gametophyte Lethal Temperature Limit
Nereocystis luetkeana	bull kelp	10 - 16°C[b]	18°C[a]	20-22°C[b]
Alaria marginata	winged kelp	12°C[e]	18°C[a]	21-22°C ♂, 22 - 23°C ♀[c]
Saccharina latissima	sugar kelp	10 - 15°C[d]	15°C[d]	20°C[d]

a.) Muth, A. F., Graham, M. H., Lane, C. E., & Harley, C. D. G. (2019). Recruitment tolerance to increased temperature present across multiple kelp clades. *Ecology*, *100*(3). https://doi.org/10.1002/ecy.2594
b.) Weigel, B. L., Small, S. L., Berry, H., & Dethier, M. N. (2023). Effects of temperature and nutrients on microscopic stages of the bull kelp (*Nereocystis luetkeana*, Phaeophyceae). *Journal of Phycology*, *59*(5), 893–907. https://doi.org/10.1111/jpy.13366
c.) Dieck, I. (1993). Temperature tolerance and survival in darkness of kelp gametophytes (Laminariales, Phaeophyta): ecological and biogeographical implications. *Marine Ecology Progress Series*, *100*, 253–264.
d.) Park, J., Kim, J. K., Kong, J., Depuydt, S., Brown, M. T., & Han, T. (2017). Implications of rising temperatures for gametophyte performance of two kelp species from Arctic waters. *Botanica Marina*, *60*(1), 39–48. https://doi.org/10.1515/bot-2016-0103
e.) Raymond, A. E. T. (2020). Life Cycles of the kelps Saccharina latissima and Alaraia marginata: Implications for mariculture and ecology in Alaska. *University of Alaska Fairbanks*.

Supplementary Table 7: Temperature limits and windows for conchocelis phase of *Pyropia abbottiae* (Rhodophyta) sourced from literature

Species	**Common Name(s)**	Conchocelis/ sporophyte Optimum Temp. Window	Conchocelis Upper Temperature Limit for growth
Pyropia abbotiae	black weed, nori	11°C (at optimum salinity and irradiance)[a]	15-19°C[a]

a.) Stekoll, M. S., Lin, R., & Lindstrom, S. C. (1999). *Porphyra* cultivation in Alaska: Conchocelis growth of three indigenous species. *Hydrobiologia*, *398/399*, 291–297. https://doi.org/10.1023/a:1017043813609

Supplementary Table 8: Temperature limits and windows for macroscopic phase of red seaweed species (Rhodophyta) sourced from literature

Species	**Common Name(s)**	Macroscopic phase Optimum Temp. Window	Macroscopic phase Upper Temperature Limit for growth
Pyropia abbotiae	black weed, nori	-	-
Devaleraea mollis	Pacific dulse	12°C (Low Light), 14 - 18°C (High Light)[a]	20-22°C[a]
Gracilariopsis andersonii	red spaghetti, ogonori	-	-

a.) Demetropoulos, C. L., & Langdon, C. (2004). Enhanced production of Pacific dulse (*Palmaria mollis*) for co-culture with abalone in a land-based system: effects of stocking density, light, salinity, and temperature. *Aquaculture*, *235*(1–4), 471–488. https://doi.org/10.1016/j.aquaculture.2003.09.012

Supplementary Table 9: Temperature limits and windows for green seaweed species (Chlorophyta) sourced from literature

Species	**Common Name(s)**	Optimum growth window	Upper Temperature Limit for Growth
Ulva spp.	sea lettuce	16-17°C[a]†, 14-27°C[b]†	30°C[a]†, 40°C[b]† 25°C[f]‡
Acrosiphonia coalita	green rope (maesaengi)	10°C[d] 10 - 18°C[c]	20°C[d]
Codium fragile	sea staghorn	24°C[e]	30°C[e]

a.) Bao, M., Xing, Q., Park, J., He, P., Zhang, J., Yarish, C., & Kim, J. K. (2023). Population specific responses to temperature and nutrients in the bloom forming *Ulva prolifera*. *Journal of Applied Phycology*. https://doi.org/10.1007/s10811-023-03143-4
b.) Xiao, J., Zhang, X., Gao, C., Jiang, M., Li, R., Wang, Z., Li, Y., Fan, S., & Zhang, X. (2016). Effect of temperature, salinity and irradiance on growth and photosynthesis of *Ulva prolifera*. *Acta Oceanologica Sinica/Acta Oceanologica Sinica*, *35*(10), 114–121. https://doi.org/10.1007/s13131-016-0891-0
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f.) Lüning, K., & Freshwater, W. (1988). Temperature Tolerance of Northeast Pacific Marine Algae. *Journal of Phycology*, *24*, 310–315.
†.) data from research done on *Ulva prolifera*
‡.) data from research done on *Ulva fenestrata*

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