National Science Challenges

SUSTAINABLE SEAS

Ko ngā moana whakauka

Stocktake and characterisation of New Zealand's seaweed sector: Species characteristics and Te Tiriti o Waitangi considerations

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Report

Report for Sustainable Seas National Science Challenge project *Building a seaweed sector: developing a seaweed sector framework for Aotearoa New Zealand. (Project code 2.5)*

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For more information on this project, visit:
www.sustainableseaschallenge.co.nz/our-research/building-a-seaweed-economy

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About the Sustainable Seas Challenge

Our vision is for Aotearoa New Zealand to have healthy marine ecosystems that provide value for all New Zealanders. We have 60+ research projects that bring together around 250 scientists, social scientists, economists, and experts in mātauranga Māori and policy from across Aotearoa New Zealand. We are one of 11 National Science Challenges, funded by Ministry of Business, Innovation & Employment.

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Executive summary

This report provides an overview of seaweed species in Aotearoa New Zealand (NZ) that have commercial potential, as well as recognition of their cultural importance and the role of Māori in the emerging seaweed sector. The report is a companion to Bradly et al. (2021), which characterises the Aotearoa New Zealand seaweed sector today and describes the current markets and regulatory environment and to Clark et al. (2021), which describes the ecosystem services provided by seaweed and the environmental impacts of a seaweed sector. Together, these three reports form the background to the development of a Seaweed Sector Framework for Aotearoa New Zealand, and part of the broader Blue Economy workstream of the Sustainable Seas National Science Challenge.

Aotearoa New Zealand has a wealth of diversity amongst the seaweeds growing along our coastlines. Māori have a special whakapapa relationship with native flora and fauna, including our seaweed species. Māori kaitiaki rights and interests in taonga seaweed species and associated mātauranga is important to acknowledge and respect. Our species are generally undeveloped in regard to their commercial potential and there is an opportunity to produce and sell seaweed products that are different from those from other parts of the world. To establish a thriving seaweed sector that is reflective of our values, any research and commercialisation projects for seaweed need to be co-designed and collaborative, meeting the highest ethical standards of informed consent, access protocols and benefit sharing for Māori.

Current knowledge of Aotearoa New Zealand's seaweed species is mostly focused on their ecology, whereas information on the fundamental biology and cultivation of species is either sparse or scattered throughout the scientific literature, making it difficult for the developing seaweed sector to access. Practical experience in growing, processing and marketing seaweeds and seaweed products in Aotearoa New Zealand is limited.

There are six key groups of seaweed species that are presently of commercial interest:

- karengo,
- *Asparagopsis*,
- agarophytes,
- lamanarians,
- fucoids,
- green algae.

Karengo are a group of red seaweeds that are found intertidally and are taonga to Māori. They were a traditional food source and are high in protein as well as omega-3 fatty acids and vitamin B12. They are related to species consumed elsewhere such as nori, and techniques for their cultivation are therefore likely to be similar. There is an opportunity to produce unique Aotearoa New Zealand foods with health benefits from them.

Asparagopsis spp. are another group of red seaweeds that are of interest and the main species that occurs here, *Asparagopsis armata*, has been cultivated vegetatively in France and Ireland for use in cosmetic products. Interest in cultivation of *Asparagopsis* spp. has increased markedly in the last few years following discovery of their ability to reduce methane emissions from livestock when used as a feed supplement. There is an opportunity for Aotearoa New

Zealand to produce *Asparagopsis* for this purpose, but further research is needed to develop large-scale cultivation techniques, ensure product stability and address animal and food safety concerns.

Agarophytes are typically used for food and agar and there are established cultivation methods in Chile and Asia for some species that are also found here. We may be able to adapt overseas cultivation methods to suit our other Aotearoa New Zealand species, but it may be difficult to compete with other agar-producing countries.

Lamanarian kelps are subtidal species that are used to produce a range of products including fertiliser and food both in Aotearoa New Zealand and overseas. Bladder kelp (*Macrocystis pyrifera*) is being farmed in the Marlborough Sounds. Wakame (*Undaria pinnatifida*), which is invasive in Aotearoa New Zealand and naturally seeds itself on to mussel lines, is cultivated elsewhere on suspended long line systems. Other laminarian species would also be well suited to long line cultivation.

Fucoid species have simple lifecycles and are internationally sold as food and food ingredients. Though Aotearoa New Zealand species have not been farmed, there is widespread cultivation elsewhere of related species that would be a good starting point to base cultivation systems on.

Green algae are typically grown for bioremediation in land-based systems overseas and can be used to produce products such as biostimulants and fertilisers and these techniques could be applied to species found in Aotearoa New Zealand.

No matter what species are chosen, the development of commercially viable farming systems is probably the most pressing hurdle to overcome. This can be best achieved through leveraging overseas expertise where appropriate, and by ensuring that knowledge generated through Aotearoa New Zealand research is publicly accessible and enables farmers to 'give it a go' using approaches that are appropriate for the Aotearoa New Zealand situation. This would reduce the cost of entry for innovators and first movers.

Aotearoa New Zealand requires specific information on its species to target higher value markets. This may be challenging to establish from the outset for an emerging industry in terms of the investment and research required. One approach may therefore be to build from our already existing biostimulant and fertiliser markets. In doing so, these markets could be used as a platform to build towards higher value products; for example, extracts from karengo, kelps or fucoid species as functional foods, food ingredients and health supplements or cosmeceuticals and extracts from kelp or fucoid species.

Introduction

Sustainable Seas National Science Challenge

This report contributes to the Sustainable Seas National Science Challenge; Theme 2: Creating value from a blue economy. Sustainable Seas' (2021a) objective is "to enhance utilisation of our marine resources within environmental and biological constraints" and its mission is:

> Transformation of Aotearoa New Zealand's ability to enhance our marine economy, and to improve decision-making and the health of our seas through ecosystem-based management.

Sustainable Seas (2021b) defines the blue economy as "marine activities that generate economic value and contribute positively to social, cultural and ecological well-being."

"Fostering and growing the blue economy is crucial to meeting the Challenge objectives."

Background

Seaweed is a natural contributor to blue economies. Aside from commodities and products, seaweed farming has the capacity to provide a range of ecosystem services including nutrient removal, shoreline protection, regenerative opportunities, and the potential for carbon sequestration (Gentry et al. 2020; Clark et al. 2021). Such services are particularly relevant to the sustainability principle of ecosystem-based management (EBM) and the blue economy more broadly, but they will depend on the scale of operations, the species being farmed, and industry drivers such as regulatory frameworks and markets. For example, nutrient removal/bioremediation operations would target fast growing species such as *Ulva* spp. and *Agarophyton chilense* that have been shown to be effective biofilters in polyculture enterprises in other parts of the world, whereas a requirement for shoreline protection would more likely be reflected in choice of growing structures (e.g., backbone lines), rather than the crop species itself (Neori et al. 2014). Aotearoa New Zealand is naturally well positioned to take advantage of this growing industry and expand upon our nascent seaweed sector, by using the ecological suitability of our environment for seaweed aquaculture (Figure 1).

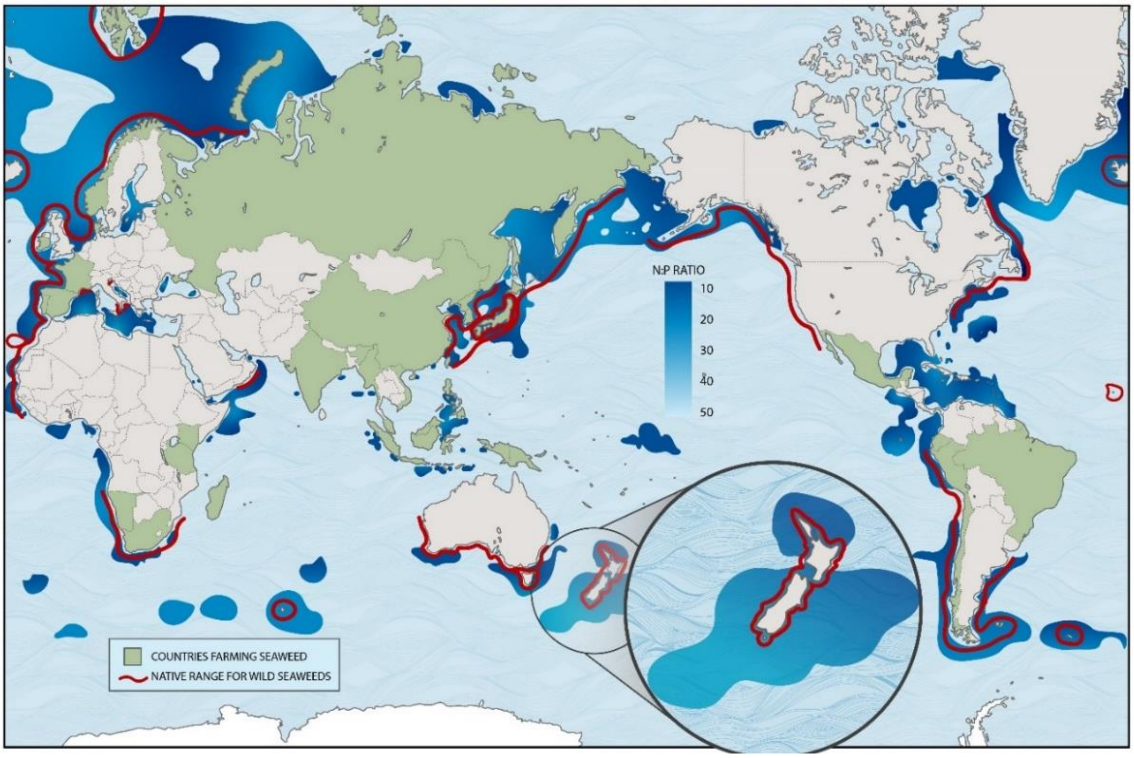

Figure 1. Ecological suitability map for seaweed aquaculture. Adapted by Revell Design with permission from Froelich et al. (2019).

Aims and Objectives

This report is part of Sustainable Seas project 2.5, Building a seaweed sector: developing a seaweed sector framework for Aotearoa New Zealand. The overall aim of this Sustainable Seas research is to develop and test a framework for a sustainable and high value Aotearoa New Zealand seaweed sector that is focused on identifying a future for the sector based on EBM principles. The purpose of this report is to provide characterise Aotearoa New Zealand seaweed species of commercial interest and to identify Te Tiriti o Waitangi/Treaty of Waitangi considerations.

This report sits alongside two companion reports (Bradly et al. 2021; Clark et al. 2021) that have been written to provide background and recommendations for the framework being developed.

Aotearoa New Zealand's seaweed sector is in its infancy and there are many uncertainties for those looking to enter the sector. In this report, we have synthesised the available information and identified surrounding knowledge gaps to enable sector stakeholders to develop a strategic plan to overcome them and ensure the development of a sustainable, successful seaweed sector.

Te Tiriti o Waitangi/Treaty of Waitangi Considerations

Prior to discussing the potential for native seaweeds to be used for commercial value, it is important to recognise the Māori world view with regard to their whakapapa relationship with native flora and fauna, their rights as Te Tiriti o Waitangi/Treaty of Waitangi partners, and implications of the findings of the Wai 262 treaty claim, including utilisation of species considered taonga.

To contextualise the relationship between Māori and native species, it is important to understand how whakapapa (Māori genealogy) links all livings things as well as spiritual and inanimate beings. For example, Tāne-matua is the Atua or God of the Forest, but also an ancestor of the claimants. He appears in their whakapapa as does Tangaroa (Atua of the Sea), Tāwhirimātea (Atua of Weather) and others. They are the children of Papatuūānuku (Earth Mother) and Ranginui (Sky Father). Tāne made the first human and, as such, they are all elder siblings of Māori. Whānau, hapū and iwi are therefore related to the indigenous flora and fauna through whakapapa. This can be partly misunderstood by conventional science and the associated commercialisation process that might arise from research. Utilising native organisms for commercial gain could be considered akin to utilising one's own family member – but we note that this is an area open to debate for Māori. There are ethical, moral, cultural, and spiritual considerations that need to be taken into account. From this perspective, the claim could also be considered to raise opposition to genetic modification of the DNA structures of native flora and fauna. It could be looked at as tampering with the claimant's whakapapa.

Māori fisheries and aquaculture rights are recognised under the Treaty of Waitangi (Fisheries Claims) Settlement Act 1992 and the Māori Commercial Aquaculture Claims Settlement Act 2004. The Crown's obligation to Māori in terms of new aquaculture is provided under the Māori Commercial Aquaculture Claims Settlement Act 2004 (Ministry for Primary Industries 2021). The Act requires the Crown to provide iwi aquaculture organisations (at a regional level) with settlement assets equivalent to 20% of any new aquaculture space consented under the Resource Management Act. As the seaweed aquaculture sector grows, the Crown and iwi will need to sit down and work through the Act to ensure the Crown's obligations are delivered in accordance with the above.

Wai 262 Overview

Wai 262 is a claim by six claimants on behalf of themselves and their iwi of Ngāti Kuri, Ngāti Wai, Te Rarawa, Ngāti Kahungunu, Ngāti Porou and Ngāti Koata to the Waitangi Tribunal for recognition and protection of the cultural and intellectual heritage rights in relation to indigenous flora and fauna and their mātauranga, customs and practices related to that flora and fauna. Te Waka Kai Ora also joined later as claimants. The inquiry is among the most complex and far-reaching in the history of the Waitangi Tribunal (Waitangi Tribunal 2021). It was the first whole-of-government inquiry for the Tribunal and the first that went beyond the settlement of historical grievances to focus specifically on the Treaty relationship.

The claim has a protracted history. The initial claim was lodged in October 1991 but it was not until 1995 that the first hearing was held, with the closing submission in 2007. The Waitangi Tribunal released its report in 2011: Ko Aotearoa Tēnei: A report into the Claims Concerning New Zealand Law and Policy Affecting Māori Culture and Identity. In 2019, the government then launched Te Pae Tāwhiti, a targeted engagement process to help inform the Crown's approach to addressing Wai 262 (Waitangi Tribunal 2021).

The description given in the original Statement of Claim gives good insight into the original intention of the claim: 'a claim relating to the Protection, Conservation, Management, Treatment, Propagation, Sale, Dispersal, Utilisation and Restriction on the use of and transmission of the knowledge of New Zealand Indigenous Flora and Fauna and the genetic resources contained therein'. Commercial utilisation of native New Zealand species of seaweed for aquaculture or through further fishing and beach harvest is therefore highly likely to fit within the intentions of the Wai 262 claim.

What this means for the development of a seaweed sector

Wai 262 should be a key consideration for any enterprise engaged in developing value from native seaweeds. The way that Wai 262 will be managed by the New Zealand government is still evolving. Understanding and defining the position of seaweed sector interests and ensuring that a framework for the sector honours Te Tiriti, associated Treaty obligations and respects the Wai 262 claim is important. Outcomes from the tribunal findings that are most relevant to seaweed sector development relate to intellectual property, indigenous flora and fauna, science and the making of international instruments. In practice, through the existing relationships and partnerships seaweed sector interests have with whānau, hapū, iwi and Māori enterprises (noting that they could, themselves, be Māori entities) discussions on intellectual property must be addressed early and expectations must be made clear on any benefits that are derived from the commercialisation of seaweeds when they come to fruition.

It is important to note that there is potential risk when any entity attempts to derive commercial value from native flora and fauna (in this case seaweed species) in the absence of partnerships with whānau, hapū, iwi and to some extent, Māori enterprise.

Independent of how the Crown chooses to respond to hapū and iwi about Wai 262, it is important for research organisations and their industry partners to take a more proactive role in engaging with Māori in more meaningful and mutually beneficial ways. There is a huge amount of relevant material within the Waitangi Tribunal's report and momentum across the science sector to enable this engagement and to design appropriate methodologies and frameworks. These frameworks should be co-designed with Māori to acknowledge kaitiaki rights and protect interests in taonga species and the associated mātauranga so that commercialisation projects meet the highest ethical standards of informed consents, access protocols and benefit sharing.

Additionally, there is the need for appropriate processes and frameworks to engage with whānau, hapū, iwi and Māori enterprises relating to appropriate use and management of mātauranga. Industry organisations such as Aquaculture NZ or the formation of a seaweed sector body may present an avenue through which appropriate protocols or framework could be developed in conjunction with iwi to guide and influence the three kete outcomes, especially in how mātauranga Māori is appropriately used and managed in a seaweed industry.

Tribunal Findings and the government's kete approach

The eight primary findings from the tribunal were:

- 'That a kaitiaki relationship exists between those who are responsible for taonga works and the works themselves, whether they created them or not. Consequently, an interface exists 'between the obligations of kaitiaki of taonga works and the intellectual property system' (Te Puni Kōkiri 2018).
- 'That where there was a risk that bioprospecting, genetic modification, or intellectual property rights could affect kaitiaki relationships with taonga species, those relationships were entitled to a reasonable degree of protection' (Te Puni Kōkiri 2018).
- 'That the Treaty requires the Crown to actively protect the continuing obligations of kaitiaki towards the environment as one of the key components of te ao Māori' (Te Puni Kōkiri 2018).
- 'The Crown estate contains most of the surviving examples of the environment that greeted the first people to arrive in this country and was the environment in which mātauranga Māori evolved' (Te Puni Kōkiri 2018).
- 'That the Crown's obligations to protect mātauranga can only be achieved through partnership with Māori, and that neither Māori nor the Crown can succeed in protecting or transmitting mātauranga without the help of the other' (Te Puni Kōkiri 2018).
- 'The Tribunal urged the Crown to recognise that rongoā Māori [traditional Māori medicine including herbal medicines as well as physical and oral therapies] has significant potential as a weapon in the fight to improve Māori health, to see the philosophical importance of holism in Māori health'(Te Puni Kōkiri 2018).
- 'The Treaty of Waitangi requires Māori interests to be protected to the extent that it is reasonable and practicable in the international circumstances'(Te Puni Kōkiri 2018).
- The Tribunal also recommended changes to the Crown's laws (e.g. Patents Act 2013), policies (e.g. New Zealand Biodiversity Strategy) and practices/process (e.g. Hazardous Substances and New Organisms Act).

The Government decided to take a whole of government approach to look at the issues raised in the report and by the claimants. A ministerial oversight group was established with three workstreams or "kete" of issues:

1. Taonga Works & Mātauranga Māori

2. Taonga Species & Mātauranga Māori

3. Kawenata Aorere / Kaupapa Aorere.

Work programmes within each kete have an associated ministerial group (Te Puni Kōkiri 2019). Te Puni Kōkiri have been the lead agency and conducted targeted engagement with Māori technical experts, advisory boards, national Māori organisations and subject specialists in 2019. Feedback was positive and seen by those engaged as an opportunity to refocus the relationship between the Crown and whānau, hapū, iwi, Māori by working collaboratively to achieve meaningful dialogue and outcomes. It is expected that Ministers will progress the work programmes already established as many whānau, hapū, iwi, and Māori enterprises are looking at what Wai 262 means to them in the context of their businesses and work programmes. The first two kete are focused on how the Crown and Māori can collaborate to enable kaitiaki to exercise kaitiakitanga over taonga work, taonga species and the associated mātauranga. The third kete, Kawenata Aorere, refers to how the Crown will represent Māori interests at international level and how the Crown should work with Māori to identify their interests when

Seaweed attributes and species profiles

Central to Aotearoa New Zealand's ability to develop a thriving, sustainable seaweed sector is to effectively identify opportunities within the wide range of species found in the country's coastal waters. However, there is a lack of knowledge regarding key aspects of the biology, ecology, and compositional attributes of these endemic and native seaweeds, information that is required to evaluate their potential for commercialisation. This information will allow stakeholders to make decisions concerning what seaweed species to grow, the method and location of production, product types, degrees of value creation and possible routes to market.

This section is a summary of the state of sector-relevant knowledge of the seaweed species currently growing in New Zealand waters that we believe should be considered for their commercial potential. This summary builds from the companion report which outlines the potential market opportunities for the New Zealand seaweed sector (Bradly et al. 2021). The species or groups that are discussed here either meet the criteria as a market opportunity, or have previously been identified as of interest under Schedule 4C of Fisheries Act.

For each species or group, we provide context with regard to relevant commercial activities that have occurred in New Zealand or are occurring worldwide. While wild harvesting of seaweed has historically been the main approach to the commercialisation in New Zealand, our underlying assumption is that future commercial activities will be based on sustainable aquaculture practices that minimise environmental impacts (see Bradly et al. (2021) and Clark et al. (2021) for more information on these). For each species or group, the following topics are addressed:

- Biological aspects, including natural range, habitat, reproduction and prevalence
- Record of traditional use and commercial activity
- Compositional attributes
- Cultivation methods and ecological requirements for biomass production
- Species-specific opportunities and challenges to commercialisation.

Collectively, this report is intended to provide insight into to developing a vision and action plan for growth of New Zealand's seaweed industry. Some specific recommendations are presented.

Karengo (*Pyropia* spp., *Porphyra* spp.)

Biology

Karengo is the Māori name that is typically used for several endemic red algae species within the genera *Pyropia* and *Porphyra* (Figure 2) though some East Coast iwi use the name parengo (O'Connell-Milne and Hepburn 2015). Among the most prominent species of karengo in New Zealand waters are *Pyropia cinnamomea*, *Pyropia virididentata*, *Pyropia plicata*, and the *Porphyra* "GRB" species complex (Nelson 2013). Many other species within these two genera grow in temperate regions worldwide (Sutherland et al. 2011). Karengo predominate in the intertidal zone on rocky coasts with high-energy wave action or water movement where they can be found at high cover and density (Wheeler et al. 2020b). *Pyropia* and *Porphyra* species have complex life cycles that include the familiar blades that are commonly collected and eaten, and a microscopic phase that is known as a conchocelis. The blades reproduce sexually via sperm and eggs to produce mobile spores

(Royer et al. 2019). The mobile spores then colonise hard surfaces, such as oyster shells or rocks, and form the conchocelis. Conchocelis in turn produce their own spores that eventually develop into blades to complete the life cycle (Figure 3; Saga and Kitade 2002; Blouin et al. 2011). The blade stage typically develops in the winter months with blades growing to 30 cm or more in length, before deteriorating in spring-early summer. Internationally, *Pyropia* and *Porphyra* species have received considerable research attention into their life cycle characteristics, methods for aquaculture, and uses as food (Kim et al. 2017).

Environmental cues are important drivers of the seasonality of karengo with decreasing daylength and water temperature triggering spore release and blade development (Dring 1967). In New Zealand, each species of karengo has a distinct set of attributes, including geographical range and morphology (Nelson 2013). However, the differences in commercially relevant biological traits among each of the New Zealand species and how they compare with species in commercial production overseas, have not yet been systematically examined.

Figure 2. Karengo species from around the intertidal areas of New Zealand (A) Porphyra GRB108, Kaikōura region (image credit: Tom Wheeler, Cawthron) (B) Pyropia virididentata, Kaikōura region (image credit: Rita Lee, Cawthron) (C) Pyropia cinnamomea, Banks peninsula (image credit: Tom Wheeler, Cawthron).

Traditional and Commercial Uses

World-wide, *Pyropia* and *Porphyra* species have a well-established tradition as whole foods, and this is still the dominant use. Commonly eaten species include *Pyropia tenera*, *Pyropia yezoensis* and *Pyropia haitanensis* in Japan (known as nori) and *Porphyra umbilicalis* in Europe (known as laver) (Fleurence 2016). Members of these genera are also eaten in China and Korea, where they are known as zicai and gim, respectively. Karengo is considered taonga by Māori. They are a traditional food and were historically traded by Māori (Colenso 1880, Adams 2007, O'Connell-Milne and Hepburn 2015). Commercial-scale production of *Pyropia* and *Porphyra* through aquaculture is well established in several East Asian countries, and the total global production of *Pyropia* and *Porphyra* species was 3 million tonnes in 2019 (FAO 2021). As a commodity, nori has the highest value of any commercially produced seaweed biomass (McHugh 2003). In New Zealand, wild harvesting has been the only method of biomass procurement. The reported annual commercial landings are sporadic and varied form 1.9 -5.7 tonnes between 2006 and 2018 ((White and White 2020) This commercial harvest has historically occurred on the Kaikōura coast of the South Island (Schiel and Nelson 1990; O'Connell-Milne and Hepburn 2015). However, this commercial wild harvesting ceased in 2016 with the Kaikōura earthquake and the associated uplift.

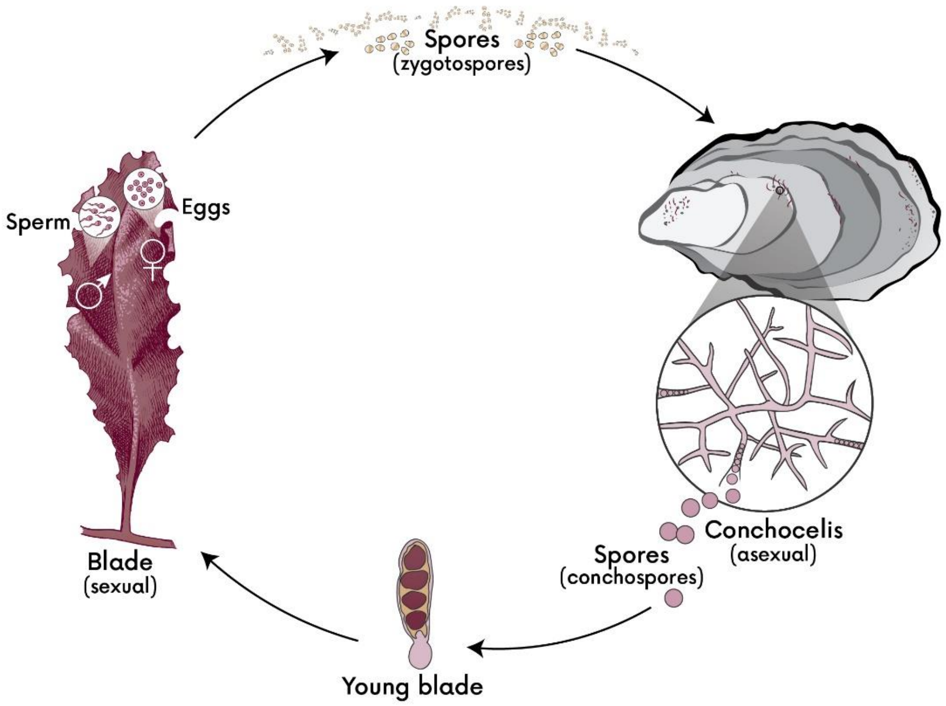

Figure 3. Life cycle of karengo (design: Revell Design, illustrations: https://adlysia.wordpress.com/).

Composition

The nutritional profiles of commercial species of *Pyropia* and *Porphyra* grown internationally feature very high levels of protein compared to other seaweeds (30-35% of total dry weight) or indeed compared with any terrestrial vascular plants (Hwang et al. 2013; Taboada et al. 2013). Additionally, there are appreciable amounts of omega-3 fatty acids (2%), and high levels of vitamin B12, iodine, iron and dietary fibre (50%) present in these species (Hwang et al. 2013; Taboada et al. 2013). New Zealand species have a similar nutritional profiles to overseas commercial species, with high levels of protein (>30%) (Smith et al. 2010), and a range of health-promoting macromolecules, micronutrients, vitamins and bioactivities (Wheeler and Romanazzi 2019; Wheeler et al. 2020a). The cell walls of at least some *Pyropia* and *Porphyra* species from other parts of the world have been shown to contain significant quantities of sulphated galactans, known as porphyrans (Noseda et al. 2000). Porphyrans have been reported to possess a range of potentially health-promoting attributes such as antioxidant and anti-inflammatory bioactivities (Isaka et al. 2015). Also, some red seaweeds, including *P. umbilicalis*, at certain stages of their life cycle contain an amylopectin-like energy storage polysaccharide, called floridean starch (Peat et al. 1961). Like other seaweeds, New Zealand *Porphyra* and *Pyropia* may contain a range of secondary metabolites with commercially relevant activities. For example, mycosporine-like amino acids, which are metabolites that are associated with response to UV stress, have been reported for one New Zealand *Porphyra* species (Diehl et al.

2019). *Pyropia* and *Porphyra* are also known to contain peptides with angiotensin converting enzyme (ACE) inhibiting activity; such inhibitors are often used to lower blood pressure (Seca and Pinto 2018). These species are not known as a significant source of phlorotannins or carotenoids.

Cultivation Methods

Farming of *Porphyra* and *Pyropia* is well established in Asia and accounted for 99.9% of a global production of 3 million tonnes (USD$2.7 billion in value) in 2019 (FAO 2021) . Almost all farmed *Pyropia* and *Porphyra* is sold as a commodity for use as a whole food (McHugh 2003). Cultivation of *Pyropia* and *Porphyra* species requires purpose-designed infrastructure both on land and at sea, due to their complex life cycle. Typically, the conchocelis stage is grown and induced to sporulate in a hatchery. Spores are settled onto ropes and then the developing blades are outgrown on nets placed in the ocean before harvesting when they are mature (Levine and Dahoo 2010). Besides this traditional farming approach, other approaches may be possible that prioritise visual impact over quantity of production.

In New Zealand, efforts to develop karengo farming have been minimal. An environmental impact assessment of karengo farming in Bluff Harbour was published in 1988 (New Zealand Nori Products 1988), and in the early 2000s, an attempt was made to establish commercial-scale farming of karengo in Bluff Harbour. However, the effort was not successful and the company looked to pivot to other species in 2007 (NZ Aquaculture 2007). Information regarding the technical approach used in Bluff has not been able to be sourced. The well-established commercial-scale aquaculture of *Pyropia* and *Porphyra* species overseas would be a good knowledge base from which to establish conditions and infrastructure for farming of karengo species. At least one study has been undertaken to establish conditions for controlling the life cycle in culture for a karengo species (Packer 1991, 1994), but to date this has not been extended to investigate the feasibility for aquaculture. The applicability of overseas methods to New Zealand species has not been tested and is a high research priority toward establishing the viability of karengo farming.

Opportunities and Challenges

The commercial opportunity for karengo may initially be based on the existing markets for similar species both overseas and in Aotearoa New Zealand. *Pyropia* and *Porphyra* spp. are widely accepted as a food in many parts of the world (e.g., sushi), and there are established worldwide markets for a range of consumer products containing nori and laver. Since the 2016 Kaikoura earthquake, New Zealand suppliers and processors are importing *Pyropia* and *Porphyra* species to sell domestically (Pacific Harvest 2021).

The nutritional profiles of this group of seaweeds have several positive attributes that would assist in marketing karengo seaweeds as high-value functional foods or food ingredients. In order to make nutrient content claims, the levels of nutrients in specific species and products need to be measured, and for functional food health claims, clinical studies that demonstrate the food health relationship will need to be undertaken to ensure such products meet the labelling requirements of the countries where they will be sold (see also Bradly et al. (2021) for more information).

The challenges to realising the potential value of karengo centre on the lack of specific knowledge of the biology, physiology, and ecology of these New Zealand species, which necessarily forms the foundation for any farming system. There is a considerable base of knowledge, centred in Asia, of how to cultivate related species in hatcheries and then on-grow the biomass but it is unclear to what extent overseas farming methods and systems will be suitable for karengo farming in New Zealand. Any venture into farming karengo will need to build up knowledge systematically, ideally through a mix of pragmatic trial-and-error and fundamental knowledge-gathering. This would lead to an approach that suits local conditions and purpose. Another challenge is the development of growing systems that produce biomass at the required scale, whilst minimising environmental impact and achieving social licence. The intertidal habit of karengo may restrict where farms could be placed, though innovative farming approaches could manage this with understanding of the importance of air exposure and water for different species. For example, *Porphyra* farming has been undertaken as part of multitrophic systems in combination with finfish farming (Levine and Dahoo 2010).

Priorities

- Develop hatchery and cultivation technology
- Develop market for locally produced karengo
- Identify cultivars and species with characteristics of interest
- Conduct research that enables health claims to be made on karengo food products

Asparagopsis

Biology

Asparagopsis is a genus of red algae within the Bonnemaisoniales order, which has two species, *A. armata and A. taxiformis. Asparagopsis armata* grows in temperate waters and is native to Australia and New Zealand, but is now also found in the Mediterranean Sea and around Western Europe as an invasive species. The New Zealand distribution of *A. armata* extends from the Three Kings Islands in the North to the sub-Antarctic Auckland Islands (Adams 1994; Shears and Babcock 2007). In contrast, *Asparagopsis taxiformis* grows in warmer tropical and subtropical waters and is only found on the Kermadec Islands in the far north of New Zealand (Adams 1994).

Like karengo, both *Asparagopsis* species have a complex life cycles with different stages that vary in size, form and ploidy level (Figure 4), but they are generally subtidal rocky shore species and are often found growing on other seaweeds (Andreakis et al. 2004). The conspicuous, sexually reproducing gametophyte stage of the life cycle produces branched fronds of up to 20 cm resembling a mature asparagus plant, while the smaller, asexual spore-producing tetrasporophyte stage has a branched, filamentous morphology of up to 15 mm, resembling a pom-pom (Figure 5) (Guiry 2021). Importantly, fronds and tetrasporophyte forms of *A. armata* can fragment and propagate vegetatively, and this may be a useful consideration for farming.

Traditional and Commercial Uses

As a food, *Asparagopsis* is not generally considered a significant source of human nutrition although, *A. taxiformis* is traditionally eaten as a condiment in the native Polynesian culture of Hawai'i where it is known as limu kohu (Burreson et al. 1976). *Asparagopsis armata* has been used as the active ingredient in a cosmeceutical product marketed as a treatment for acne (Algues et Mer 2021).

Both *Asparagopsis armata* and *Asparagopsis taxiformis* have come into prominence in recent years as potential animal feed supplements to suppress methane production in ruminants (Machado et al. 2014;, Machado et al. 2016; Roque et al. 2019; Roque et al. 2021). This property of *Asparagopsis* is associated with the presence of halogenated hydrocarbons within the biomass, particularly bromoform (tribromomethane) (Machado et al. 2016). Both species are being actively researched to evaluate their utility as naturally produced feed supplements (Muizelaar et al. 2021; Roque et al. 2021). Intellectual property relating to the claim of *Asparagopsis* reducing methane emissions in livestock was developed through a partnership of CSIRO, Meat and Livestock Australia and James Cook University and is now held by FutureFeed and is patent protected (FutureFeed 2021). A licence fee is payable if *Asparagopsis* is supplied for the purpose of using as a stock food supplement to reduce methane emissions.

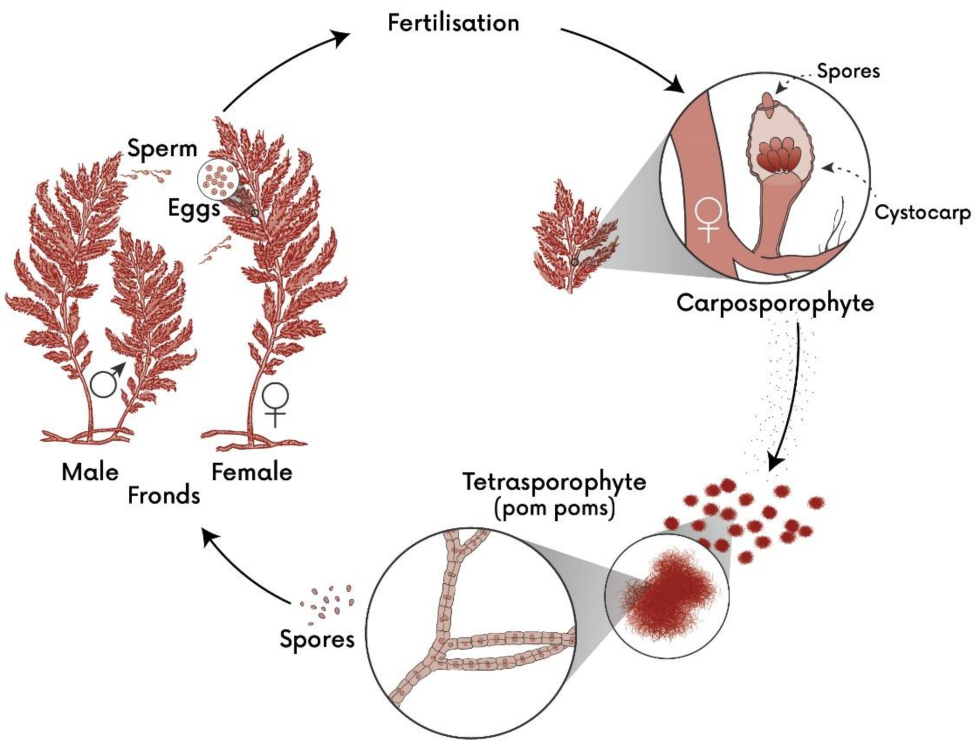

Figure 4. Life cycle of Asparagopsis spp. (design: Revell Design, illustrations: https://adlysia.wordpress.com/).

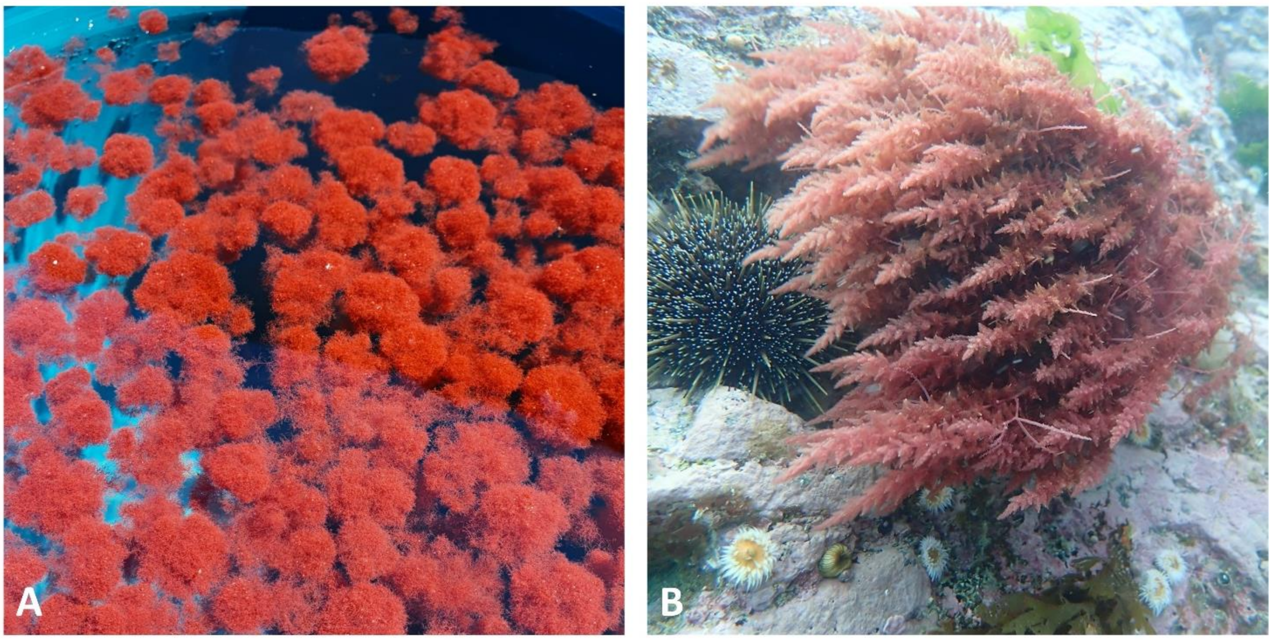

Figure 5. A) Asparagopsis pom-poms (tetrasporophytes) at the Cawthron Aquaculture Park (Photo Mike Packer/Cawthron). B) Gametophyte stage of Asparagopsis armata from D'Urville Island (Photo Anna Berthelsen/Cawthron).

Composition

Studies of the composition of *Asparagopsis* have mainly focused on the content of bromoform or that of other halogenated hydrocarbons (Paul and Pohnert 2011). Levels of bromoform in *Asparagopsis* have been reported to be between 0.2 to 4.3% of dry weight (Paul et al. 2006). Differences in bromoform content may be in part the result of species differences, sample handling, analytical methodology or biological control of the synthesis of this volatile metabolite. Cawthron Institute has developed standardised procedures for assessing bromoform levels in both fresh and freeze-dried seaweed biomass (Cawthron Institute 2021). In future, standardised content of the feed supplements will be important for methane reduction claims and quality assurance.

As a possible food, the nutritional profile of *Asparagopsis* appears similar to that of karengo, with high levels of protein (36-39%) and approximately 4% lipid (McDermid and Stuercke 2003). The antimicrobial properties of *A. taxiformis* have been recognised (Vedhagiri et al. 2009; Pinteus et al. 2020); however, lipid profiles or other health-promoting bioactivities appear to have been little studied for these species.

Cultivation Methods

The ecological and infrastructure requirements for farming *Asparagopsis* species are not yet fully developed, although commercial *A. armata* farms have been operating in France and Ireland since the 1990s (Kraan and Barrington 2005). In at least some of these enterprises, *Asparagopsis* is propagated onto ropes using vegetative methods, which are then suspended in the sea for on-growing (Kraan and Barrington 2005). This production of up to 30 tonnes per annum is used in the cosmetics industry (Algues et Mer 2021).

Supply of *Asparagopsis* for research into methane suppression in livestock appears to be mostly through wild harvest; however, for commercialisation a large amount of biomass is required and it is widely recognised that this will only be achieved through aquaculture. Several initiatives are underway globally to develop hatchery and farming methodology for these species. For example, Cawthron Institute is undertaking research into growing *A. armata* and gaining full understanding and control of the life cycle and bromoform content (Cawthron Institute 2021). Similarly, Sea Forest, based in Tasmania Australia, in collaboration with the University of Waikato, James Cook University and the University of Tasmania, is developing methodologies to produce *A. armata* at scale using a combination of land-based hatchery seed supply and ocean farming on vertically suspended ropes (Sea Forest 2021). Another company, CH4 Global (CH4 Global 2021), is pursuing wild harvest of *A. armata* in Southern New Zealand while also developing biomass production methods and systems with NIWA and University of Otago. Greener Grazing is focused on the tropical species, *A. taxiformis,* and is undertaking field trials of a commercial-scale tubular net system for ocean aquaculture (Greener Grazing 2021). There are other initiatives globally. The activities of each of these companies and research institutions are motivated by the anticipated demand for large quantities of *Asparagopsis* for incorporation into animal feed for livestock production and the potential benefit that such an industry could contribute to climate change mitigation.

While production of *Asparagopsis* at sufficient scale is yet to be realised, mature farming systems are likely to involve both an on-shore hatchery and grow-out in either an outdoor pond or in marine-based infrastructure.

Opportunities and Challenges

The positive trials using *Asparagopsis* species in livestock animal feed that demonstrate significant methane emission reductions have spurred investment from a range of sources into these species. While it is still early days, the nature and scale of these investments has led to the Australian seaweed industry labelling *Asparagopsis* as the single largest opportunity for rapid growth in Australia and have estimated that it will contribute to approximately 70% of the Australian seaweed industry by 2025 (Kelly 2020). In New Zealand, more than half of our greenhouse gas emissions are derived from agricultural emissions (Ministry for the Environment 2021). Given New Zealand has a beef and lamb export industry made up of 3.9 M beef cattle and 27 M sheep and worth $NZD9.2B, and a dairy industry worth $NZD 20.1 B in export revenue, made up of around 6.3 M dairy cattle (Statistics New Zealand 2021), there is a significant opportunity for the New Zealand seaweed sector to support the sustainability goals of New Zealand's traditional primary industries through the supply of *Asparagopsis* feed supplements (Granwal 2021; Meat Industry Association 2021). However, there is currently limited knowledge on how to cultivate these species in hatcheries, methods to on-grow commodity-scale amounts of biomass, as well as knowledge of how to handle and process the biomass into supplement products tailored to both feed lot and pasture-fed animals to maximise the bioactivity (bromoform content) and methane reducing effects. As outlined already, research is currently underway at a number of institutions and enterprises both in New Zealand and overseas to address some of these knowledge gaps.

The commercial viability of *Asparagopsis* farming needs to be proven. Current commercial interest is focused on its use as a natural-based way of reducing greenhouse gas emissions from farmed ruminants. Although there has been significant venture-capital driven activity in this area, there are still hurdles to overcome before the value chain and market for feed supplement *Asparagopsis* products is fully developed. The size and value of this business opportunity is driven by consumer demand, future regulation (including for agricultural greenhouse gas emissions), and the availability of alternative methane inhibitors or successful methane reducing strategies (e.g. vaccines, breeding) in market. As outlined above, efficient scalable production methods are still being investigated and developed, as is our understanding of the natural variability of bromoform content and control over its biosynthesis.

Bromoform has been identified as a possible carcinogen at high concentrations (Theiss et al. 1977; Chu et al. 1982; Program 1989), beyond those shown to be effective in livestock studies to date. Like many other halogenated algal metabolites, it is also a naturally ozone depleting substance (Fraser et al. 2015; WMO 2018). Some studies have indicated minimal/background levels of bromoform in milk derived from cows fed *Asparagopsis* (Li et al. 2018; Roque et al. 2019). It is conceivable that the presence of bromoform in milk is limited through dehalogenation mechanisms occurring within the animal (Wood et al. 1968; Krone et al. 1989). However, the metabolic fate of bromoform in livestock needs further study to fully address these issues. The possibility of consumer resistance should also be considered, and a regulatory framework for use of methane inhibitors and bromoform levels in meat and milk may need to be established.

There are already alternative methane-suppressing veterinary products coming to market. For example, the Dutch company DSM is marketing 3-nitrooxypropanol under the brand name Bovaer as an additive to suppress methane production in ruminants (DSM 2021). Mootral is another supplement produced from garlic and citrus that is also being marketed for methane reduction, albeit at lower rates than has been achieved for *Asparagopsis* (Mootral 2021). *Asparagopsis* feed supplement suppliers will need to compete with these products in market and this may impact the price that supplements can be sold and the commercial viability of such enterprises.

Finally, bromoform can be synthesised relatively cheaply and at scale from simple chemicals, and this approach to supply of bromoform may undercut *Asparagopsis* farming enterprises dedicated to this purpose. Overall, there is a degree of uncertainty surrounding the commercial opportunity for *Asparagopsis* that requires further and ongoing evaluation.

Priorities

- Development of hatchery and farming systems to meet the current demands for livestock trials
- Long-term livestock trials and studies with pasture fed livestock including understanding the metabolic fate of bromoform
- Research into bromoform variability and the causes of this. For example, handling methods post-harvest and within the supply chain.

Agarophytes

Biology

Agarophytes are a group of red seaweeds characterised by production of agar or agaroid as their main structural polysaccharide. They include a range of species in the *Gelidium*, *Pterocladia* and *Gracilaria* genera (McHugh 1987). Agar has a wide range of applications (see below) and is produced at an industrial scale as a commodity. Agarophytes that have been of commercial interest for agar production and are also found in New Zealand waters are *Pterocladia lucida* and *Pterocladiella capillacea* (hereafter referred to as *Pterocladia*) and *Agarophyton chilense* (formerly known as *Gracilaria chilensis*).

Pterocladia and *A. chilense* have sexual and asexual life stages, and these have similar appearances (Kain and Destombe 1995; Serviere-Zaragoza and Scrosati 2002). *Agarophyton chilense* can propagate vegetatively and commonly forms dense, free-living beds from detached fragments in sheltered areas such as estuaries. Vegetative propagation has also been reported in *P. capillacea* through fragmentation of attached individuals (Patarra et al. 2020). *Pterocladia* grow as branched fern-like fronds in the low intertidal and subtidal zones of rocky coastlines. Their range in New Zealand extends from Northland to the Kaikōura Peninsula (Schiel and Nelson 1990; Adams 1994). *Pterocladia lucida* (Figure 6) has fronds of up to 50 cm in length and has historically comprised the large majority of the agarophyte harvested in New Zealand, while the smaller and more delicate *P. capillacea* has fronds up to 18 cm in length (Schiel and Nelson 1990). *Agarophyton chilense* is a moderately-sized red seaweed with a tubular wiry appearance. Growth requires a water temperature of at least 20 °C for three months of the year (McHugh 2003). While *A. chilense* appears to have originated in the western Pacific, it is now widely distributed throughout the tropical and temperate regions of the world (Bird et al. 1986; Bird et al. 1990; Santelices 2021). Growth is seasonal at the cooler end of its temperature range, with the greatest biomass occurring in summer. It is found from the mid intertidal to subtidal zone, mostly in sheltered waters, harbours and estuaries (Bird et al. 1986; Bird et al. 1990; Santelices 2021), and is found throughout New Zealand's coastal waters (Nelson 2013).

Traditional and Commercial Uses

Agarophytes have a wide range of applications. In East Asia, agarophytes or the agar derived from them have a long history as a traditional food (known as ogonori) and they are also eaten in the western Pacific (McHugh 1987; Armisen 1995). Agarophytes do not appear to be a significant traditional source of nutrition for Māori.

The commercial utility of agarophytes has expanded markedly since agar was adopted as a substrate for bacterial culture in the 1880s (McHugh 1987; Smith 2005). Currently, there is considerable demand for agar or agarose as a stabilising substrate for a range of analytical applications and as a microbiological growth substrate in research and diagnostics. Other applications include plant propagation, food manufacture, and photography (McHugh 1987). *Gelidium* and *Pterocladia* are known as good sources of high-quality agar that are suited to analytical applications (McHugh 1987; Schiel and Nelson 1990). Historically, significant quantities of these species have been processed, with one estimate of the worldwide harvest being 86 megatonnes, mainly from Portugal (McHugh 1987). In New Zealand, commercial harvesting and processing of beached-cast *Pterocladi*a dates back to the 1940s (Luxton and Courtney 1987). Harvesting of *Pterocladi*a mostly occurred in spring and summer (Schiel and Nelson 1990). Annual takes have varied, with estimates reporting up to 240 tonnes for 1983 (Luxton and Courtney 1987; Schiel and Nelson 1990). In more recent years these have been reduced ranging from 0.1-7.6 tonnes per year between 2006 and 2017, however this did increase to 12.3 tonnes in 2018 (White and White 2020). Currently, NZ Seaweeds/Manuka Group (www.nzseaweeds.co.nz) is the only agar producer in New Zealand. Recently there has been renewed interest in agarophytes in response to a worldwide shortage of high-quality agar resulting from a limited supply of wild-harvested *Pterocladi*a and *Gelidium* biomass (Callaway 2015).

Figure 6. Pterocladia sp. from Kaikoura (photo Robyn Dunmore/Cawthron).

Internationally, *Gracilaria*-like species, including *A. chilense* are also used as a source of agar but they generally considered not to be as good as *Pterocladia* (McHugh 1987). In part, this is because the polysaccharide structure of *Gracilaria*-like species contain sulphate, resulting in agar of low gel strength. Therefore, processing of these species for agar production usually includes alkali treatment to remove the sulphate (McHugh 1987). World-wide, commercial processing of *Gracilaria*-like species is extensive with 3.6 million tonnes being harvested in 2019 (FAO 2021). However, *A. chilense* has not been a significant contributor to agar production in New Zealand, with around 3 tonnes being harvested between 2006-2018 (Schiel and Nelson 1990; White and White 2020). *Gracilaria*-like species have also been used as biofilters for nutrient remediation as part of municipal developments and integrated multi-trophic aquaculture schemes (Neori and Nobre 2012).

Composition

The composition of New Zealand agarophytes has not been very well characterised, and those studies that have been reported focus on the agar content. An investigation into the potential for aquaculture of *P. capillacea* in the Marlborough Sounds found yields of agar to be 10-20% of the dry weight of the alga, depending on the site and environmental conditions (Rhodes et al. 2001). In overseas studies, *Gracilaria*-like species have been reported to yield 15-30% agar (Buriyo and Kivaisi 2003). The agar yield from New Zealand *A. chilense* has not been reported. As a food source, neither species appears to have attributes that differ remarkably from other red seaweeds. *Pterocladiella capillacea* from Egypt was reported to contain approximately 22% protein, 50% carbohydrate 2-3% lipid (Khairy and El-Shafay 2013). Most of the fatty acid is palmitic acid, with only 12% being polyunsaturated. *Gracilaria*-like species have been reported to contain 14% protein, 66% carbohydrate and 1.3% lipid (Ortiz et al. 2009). Overall, while definitive investigations of the composition of New Zealand *Pterocladia* and *A. chilense* have not been reported, none of these species seems likely to be of greater value than more traditionally eaten red seaweeds (e.g., karengo) as a source of human nutrition.

Cultivation Methods

Internationally, there has been some development of farming systems for agar production for *Gracilaria*-like species, but very little for *Pterocladia*. Farming of *Gracilaria*-like species occurs mainly in eastern Asia. Several different approaches are used, including on the sea floor, on nets or ropes or rafts on the sea surface, or in land-based systems such as tanks or ponds (Santelices and Doty 1989). Approximately 1.5 million tonnes of wet biomass are produced each year in Asia through cultivation (Santelices 2021). In principle, these systems could be transferable to New Zealand, but this has not yet been attempted and to date the commercial motivation appears to be lacking. In New Zealand there appears to have been little research on farming of native agarophytes. However, one study investigated the growth rate and agar yield of both *P. capillacea* and the carra-agar producer *Grateloupia urvilleana* in a number of marine environments by transplanting wild-harvested specimens onto ropes (Rhodes et al. 2001). Biomass growth of up to 400% of the original transplant, yielding between 10 and 20% agar, was reported.

Opportunities and Challenges

The commercial opportunity for farming of native agarophytes in New Zealand is likely to be based on production of agar of high or unusual quality and in response to an ongoing acute or specific market demand. *Pterocladia*, which produces higher quality agar than *A. chilense* (Murano 1995), would most likely be the species of choice. However, there are currently no hatcheries or scalable farming systems for this group of species. As there is already commercial agar production existing in New Zealand relying on imported biomass, this could enable a viable supply and value chain.

Establishing *Pterocladia* farming would require considerable research on the reproductive and growth biology of the species as well as developing farming infrastructure systems tailored to their biology. There is very little international research or experience to draw from. Thus, there is significant investment required and a high level of risk.

Priorities

- Investigate the market demand for NZ produced agar
- Identify bioactive compounds in New Zealand species and potential applications.

Fucoids

Biology

Fucoids are a globally distributed order of typically large, habitat-forming brown seaweeds. New Zealand has a large diversity of fucoids; ten fucoid genera are present (*Carpophyllum*, *Cystophora*, *Durvillaea*, *Landsburgia*, *Hormosira*, *Marginariella*, *Notheia*, *Phyllotrichia*, *Sargassum*, and *Xiphophora*) that hold 29 species (Nelson 2013, Velasquez et al. 2020). Sizes range from around 30 cm for *Hormosira banksii* to over ten metres for the southern bull kelps, *Durvillaea antarctica* (Figure 7) and *D. poha*. Fucoids are common, conspicuous components of low intertidal to shallow (~10 m) subtidal rocky shores on semi-exposed to exposed coastlines. Many of the species, such as *Carpophyllum flexuosum*, *Cystophora retroflexa*, *H. banksii*, and *Landsburgia quercifolia*, are found all around New Zealand, although some have more restricted distributions. For example, *Carpophyllum angustifolium*, *C. plumosum*, and *Xiphophora chondrophylla* are only found in the far north of the country whereas species such as *Durvillaea willana*, *D. poha*, and *Marginariella boryana* are distributed south of the southern North Island. Fucoids often form dense single or multi-species forests in intertidal and shallow marine systems and control local biodiversity (Schiel and Foster 2006; Schiel 2019). The life cycle of fucoid algae is relatively simple in that there is only one distinct life stage which reproduces sexually via sperm and eggs that are produced in the blades of the algae or on specialist branches (receptacles), and released into the water column (Lee 2018). Zygotes (resulting from sexual fusion of sperm and eggs) adhere onto hard substrates such as rock or encrusting coralline algae, where they grow into their typical form (Figure 8). Some species, such as *H. banksii* can propagate vegetatively (Bishop et al. 2009; Coleman et al. 2019). The southern bull kelps (*Durvillaea* spp.) and *Xiphophora gladiata* have their reproductive peaks in winter whereas *Carpophyllum* spp., *Cystophora* spp. and *Sargassum sinclairii* reproduce during the warmer months.

Traditional and Commercial Uses

Māori used *D. antarctica* and *D. poha* as storage and transport vessels (pōhā) and clothing (Velasquez et al. 2020). Internationally, fucoids are some of the most widely distributed seaweeds throughout the world and are valued as sources of food, alginate, and polysaccharides (Zemke-White and Ohno 1999; Wozniak et al. 2015). The annual take of *Durvillaea* spp. can vary considerably, for example, approximately 35 tonnes of *Durvillaea* species were reported to the Ministry of Fisheries as having been harvested in New Zealand in 1997 (White et al. 1999). Since then, the harvest of *Durvillaea* has greatly reduced with 0.2 tonnes being reported in 2018 (White and White 2020). *Durvillaea* spp. are typically harvested as beach-cast material, which is mainly used for garden fertiliser, fodder for cattle, or as a source of sodium alginate (Schiel and Nelson 1990).

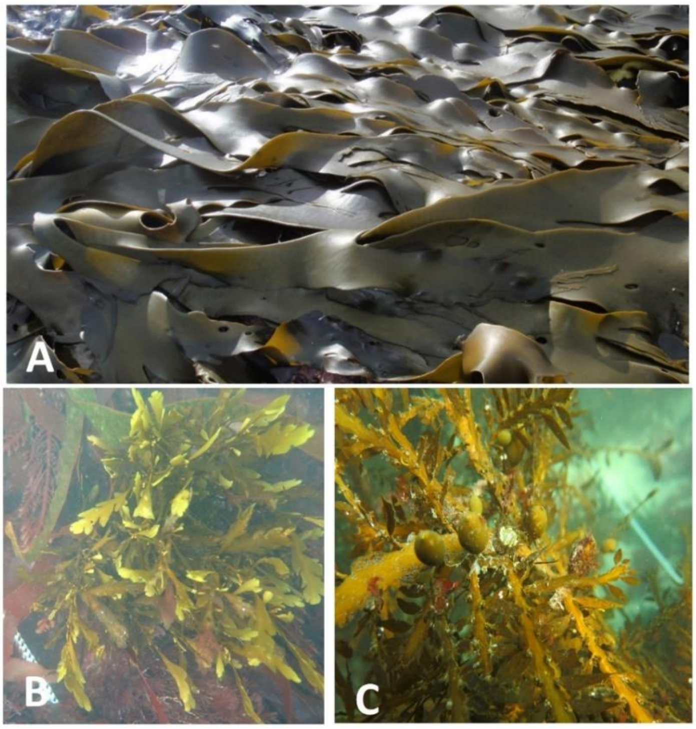

Figure 7. A) Durvillaea antarctica in the intertidal zone at Moeraki, north Otago (credit Paul South/Cawthron) B) Subtidal Landsburgia quercifolia from Kaikoura (photo Robyn Dunmore/Cawthron) c) Subtidal Carpophyllum maschalocarpum from Kaikoura (photo Robyn Dunmore/Kaikoura).

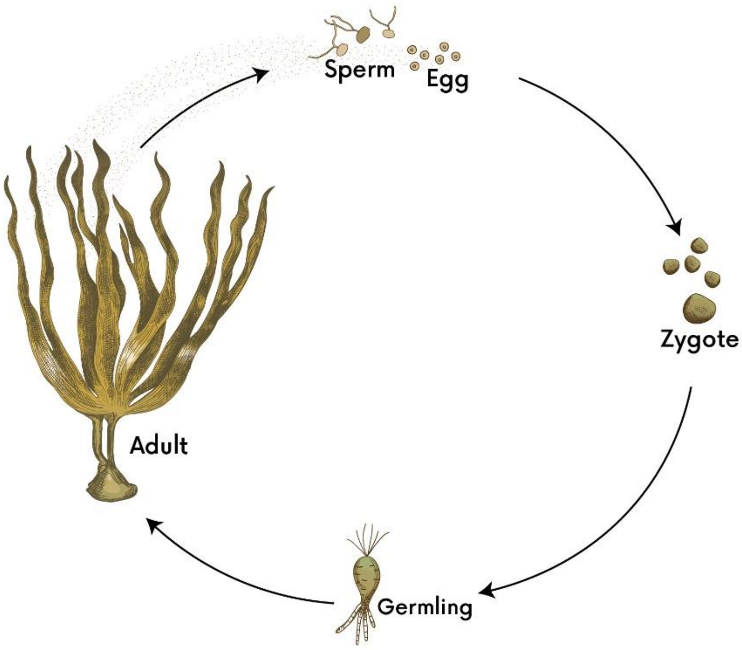

Figure 8. Life cycle of fucoid algae (design: Revell Design, illustrations: https://adlysia.wordpress.com/).

Composition

Fucoids are generally considered to contain relatively high levels of polysaccharide and low levels of protein. Consistent with this, an analysis of *D. antarctica* (rimurapa) from the South Island of New Zealand produced levels of 60% carbohydrate, 5% protein, and 1% lipids (Smith et al. 2010; Romanazzi et al. 2017). These levels were also comparable to samples collected from the same species in the North Island (Smith et al 2010). One distinguishing characteristic of fucoids is the presence of fucans, sulphated polysaccharides rich in the hexose deoxy sugar unit, L-fucose (Berteau and Mulloy 2003). Fucans have been shown to have a range of health-related effects. Most notably they have anticoagulant properties, but also anti-inflammatory and antiviral effects (Boisson-Vidal et al. 1995). Some New Zealand fucoids (*D. antarctica*, *M. boryana*) have relatively high abundances of another complex polysaccharide, alginate (Panikkar and Brasch 1996), which are valued for their property of forming high-viscosity hydrogels. They have a wide range of commercial uses such as in wound healing, drug delivery and tissue engineering (Lee and Mooney 2012), as well as in the food industry as thickeners and gelling agents (Qin et al. 2018). Some companies are producing and marketing a polysaccharide extract from fucoids, termed fucoidan (Li et al. 2008). Their marketing is supported by studies reporting a range of biological properties, including anti-cancer (Fritton et al. 2015). In New Zealand, fucoids have not yet been investigated as possible commercial sources of polysaccharides. Finally, like other seaweeds, fucoids contain a range of secondary metabolites, some of which have commercial potential. Examples of secondary metabolites include phlorotannins and other polyphenols, and carotenoids such as fucoxanthin (Bedoux and Bourgougnon 2015).

Cultivation Methods

Internationally, many fucoid seaweeds for commercial use are sourced from the wild, which has led to their depletion in some regions (Stengel and Connan 2015; Mac Monagail et al. 2017; Falace et al. 2018). Studies have been undertaken to better understand the sustainability and resilience of wild harvesting of fucoids in the face of their continued commercial utilisation and their response to climate change (Mac Monagail et al. 2017; Wilson et al. 2019). Techniques for cultivation and growth to support ecosystem restoration have also been investigated (Falace et al. 2018). The aquaculture of fucoids is dominated by the culture of various species of *Sargassum* in Asia (Liu et al. 2016; Ko et al. 2020). To date, no fucoid species has been farmed in New Zealand and significant research will be required to establish sustainable aquaculture production systems.

Opportunities and Challenges

No fucoid species are currently being commercialised in New Zealand. However, as there are existing markets for fucoidan and other extracts from laminarian species (see below) there is the potential for fucoid extracts to be commercialised. Supporting the case for developing an industry in New Zealand that is focused on fucoids is the relative abundance of these seaweeds throughout New Zealand's temperate marine coastal environment, the large amount of biomass produced by each individual organism, established methods for processing and the existence of multiple routes to market.

Unfortunately, commercial-scale systems for aquaculture have not yet been developed for New Zealand fucoids, and it is not clear to what extent systems designed for overseas species will be transferable. Factors that could favour succeeding in developing production systems include the relatively rapid growth rate of New Zealand fucoids, although data on this are difficult to find for many species, as well as their subtidal habit.

Priorities

- Investigate the potential to transfer and adapt hatchery and cultivation technology for kelp species to fucoids
- Investigate the market demand for New Zealand produced fucoid extracts
- Identify other bioactive compounds of interest and potential applications
- Investigate the feasibility of a biorefinery approach

Laminariales – kelps

Biology

Brown seaweeds in the order Laminariales, commonly referred to as kelps (Figure 9), are among the largest macroalgae, growing up to 20 metres in length. They are typically found in the subtidal zone up to 30 m in depth, where they form forests, which provide habitat for a range of other species (Schiel and Foster 2006). New Zealand has seven species within four genera (*Ecklonia*, *Lessonia*, *Macrocystis* and *Undaria*). *Lessonia* is the only genus with more than one species, with three of its species being confined to offshore Islands. Therefore, there are four species of kelp (*Ecklonia radiata*, *Lessonia variegata*, *Macrocystis pyrifera* and *Undaria pinnatifida*) on mainland New Zealand. Kelps are commonly found on sheltered to exposed rocky coastlines throughout the country with the exception of bladder kelp (*M. pyrifera*) that has a southern distribution from around Cook Strait (Nelson 2013). *Lessonia* are the only endemic kelps with *E. radiata* and *M. pyrifera* having Australasian and Pacific-wide distributions, respectively. In contrast, wakame (*Undaria pinnatifida*) is an invasive species that has spread to most parts of the country since its introduction in the 1980s (South et al. 2017). This species is often found in high abundance in the low intertidal zone between to a depth of around 4 m (South et al. 2017).

Kelps have two distinct life stages: the large sporophyte stage that is that is commonly recognised as a kelp and that asexually produces spores, and a microscopic sexual stage known as a gametophyte (Figure 10). Most of the New Zealand species produce spores and undergo gametophyte development through winter and subsequently recruit in spring (Nelson 2005; Schwarz et al. 2006). In contrast, wakame (*U. pinnatifida*) produces spores from late winter through spring, but does not recruit until the following winter when seawater temperature drops below 15 °C (James et al. 2015). Kelps can grow very quickly, with wakame (*U. pinnatifida*) and bladder kelp (*M. pyrifera*) growing over 1 cm and 10 cm per day, respectively (Zimmerman and Kremer 1986; South et al. 2017).

Figure 9. A) Wakame (Undaria pinnatifida) in the intertidal zone at Moeraki, north Otago (credit Paul South/Cawthron). B) Bladder kelp (Macrocystis pyrifera) in the intertidal zone at Moeraki, north Otago (photo Paul South/Cawthron) C) Subtidal Lessonia variegata in Kaikoura (photo Robyn Dunmore/Cawthron).

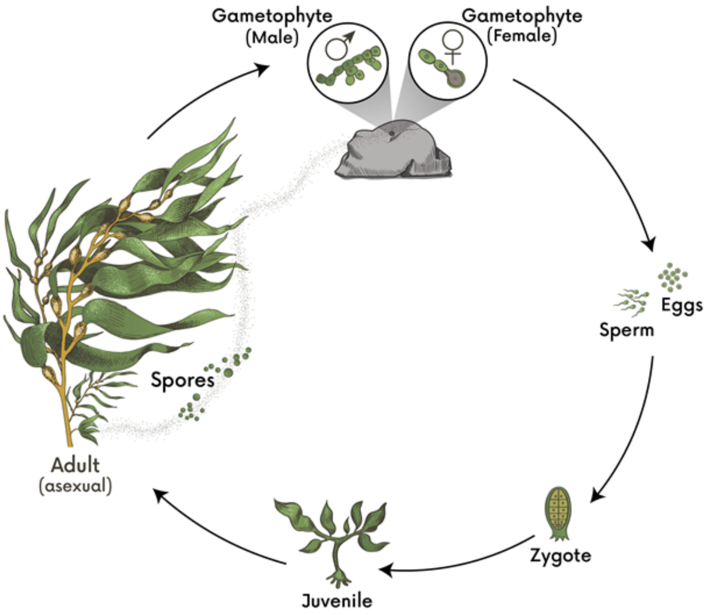

Figure 10. Kelp life cycle (design: Revell Design, illustrations: https://adlysia.wordpress.com/).

Traditional and Commercial Uses

Kelps are widely harvested and grown for food, fertiliser, and as source of alginates, polysaccharides and bioactive ingredients around the world (Barilotti and Zertuche-González 1990; Forbord et al. 2012; Vásquez et al. 2012; Wells et al. 2017; Hu et al. 2021). Globally, there is growing interest in using polysaccharides (such as fucoidan) and carotenoids (like fucoxanthin), which are abundant in kelps, for their therapeutic and medical uses that include anti-tumour, anti-viral, and anti-inflammatory properties (Chang et al. 2019). In New Zealand, bladder kelp (*M. pyrifera*) is a quota managed species and is harvested from the wild from attached populations and as detached, beach cast seaweed (see Bradly et al., 2021 for further information). Bladder kelp (*M. pyrifera*) has been used to provide potash, alginates, fertiliser, food for abalone and as a human food and dietary supplement (Schiel and Nelson 1990; White and White 2020). Similarly, *E. radiata* and *L. variegata* are used as dietary supplements for humans and animals, and as fertiliser. However, *E. radiata* and *L. variegata* are permitted to be collected only from beach-cast material and their commercial landings from this source are small (< 0.5 tonne per year). Presently, all three native mainland kelp species have a moratorium in place on new permits for their harvesting (White and White 2020; Bradly et al. 2021). Wakame (*Undaria pinnatifida*) is widely grown in Asia as a food and has been the focus of much research attention pertaining to its culture, use as food, and bioactive properties (Li et al. 2013; Wang et al. 2018; Hu et al. 2021). Because *Undaria* is an unwanted species, both fishing and farming of wakame must be authorised under the Biosecurity Act (Biosecurity New Zealand 2019; Bradly 2021). Farming wakame (i.e., growing crops from spores) is allowed in four heavily infested areas (Wellington Harbour, Marlborough Sounds, Lyttelton Harbour, and Akaroa Harbour), but doing so requires local and central government permission and currently, there are no wakame farms in any of these locations.

Composition

The composition of kelps has been well studied. They are typically relatively low in protein (5-10% of dry weight) and high in polysaccharides (50-60%) compared with red seaweeds (Lorenzo et al. 2017;

Yu et al. 2018; Garcia-Vaquero et al. 2021; Purcell-Meyerink et al. 2021). The polysaccharide component includes polymers that have commercial value. Many brown seaweeds including kelps contain alginates, which are used primarily as a food ingredient (see fucoid section above) (McHugh 2003). Internationally, harvesting of kelps for alginate extraction is substantial (McHugh 1987). Some seaweed polysaccharides, including those from kelps, have been shown to have potentially valuable bioactivities (Tanna and Mishra 2019). Fucoidan is a polysaccharide-enriched extract from brown seaweeds, which is marketed as a health-promoting extract (see previous section). Besides polysaccharides, kelps also contain a range of bioactive compounds and micronutrients, including carotenoids such fucoxanthin, phlorotannins and other polyphenols, and some vitamins and mineral micronutrients (Swanson and Druehl 2002; Kanazawa et al. 2008, Kim and Bhatnagar 2011). The antioxidant activity of fucoxanthin from New Zealand wakame (*U. pinnatifida*) has been demonstrated (Fung et al. 2013). In New Zealand, several companies are producing biostimulants and fertilisers from beach cast, wild harvest and farmed kelps (Bradly et al 2021).

Cultivation Methods

Approximately 90% of total global production of kelps is through cultivation (Zemke-White and Ohno 1999). The aquaculture of kelps typically uses suspended systems much like those used to grow mussels in New Zealand with the kelp either growing on the surface of the sea or on suspended longline or single dropper ropes to about 2 m (Peteiro et al. 2016; Visch et al. 2020). Typically, kelps are harvested after a 5-8 month growing period (Peteiro et al. 2016). Farming of *Saccharina* and *Undaria* species is well established in Asia and some commercial-scale cultivation also occurs in parts of Europe (Peteiro and Freire 2009; Xu et al. 2009; Pang et al. 2015-2021; Hu et al. 2021). Most commercial production is for consumption as a whole food or for processing for alginates (Pang et al. 2015-2021). Besides the traditional methods described above which are typically situated in sheltered inshore waters, integrated multi-trophic systems and open ocean aquaculture methods have been investigated for these species (Peteiro et al. 2014; Fossberg et al. 2018). There has been some small-scale commercial aquaculture activity in New Zealand. Bladder kelp (*M. pyrifera*) is being farmed in the Marlborough Sounds by Tory Channel Natural Kelp (NZ Natural Kelp 2021)(www.naturalkelp.co.nz). Wakame (*U. pinnatifida*) naturally settled on mussel lines is being harvested, processed, and marketed by Waikaitu (Waikaitu 2021). Methods have also been developed in New Zealand to seed and on-grow wakame (*Undaria pinnatifida*) (Hay and Gibbs 1996; Gibbs et al. 1998; Gibbs et al. 2000).

Opportunities and Challenges

New Zealand currently has a well-established industry for kelp biomass (typically *E. radiata,* bladder kelp and wakame) as biostimulants, fertilisers and animal feeds (Bradly et al. 2021). The industry is already heavily supply-constrained due to demand for such products domestically, and there is also export demand. The margins are typically lower than other product categories and because of this, seaweed farmers looking to supply these markets will need to achieve scale and efficiency to keep costs low and be profitable.

Native kelp species have also been the focus of restorative aquaculture and integrated multi-trophic aquaculture (IMTA) approaches and hatchery technology is being developed for *E. radiata* by Massey University Albany and the University of Waikato (Clark et al. 2021). Coupled with the existing long line techniques used to grow kelps around the world and experience from the mussel industry in New Zealand, there is a body of knowledge to support the development of aquaculture for these species.

From a longer-term perspective, there are also opportunities for kelp products in the nutraceuticals and functional foods sectors. There are a range of possible products and routes to market. For example, nanocellulose hydrogels that have a range of uses from aiding drug delivery and wound healing to supporting plant health have been made from wakame and *E. radiata* polysaccharides (Scion 2021). Producers and manufacturers may consider partnering and taking a biorefinery or circular economy approach to extraction to maximise the value from the kelp (Bradly et al. 2021) .

Further research and development are required to identify the health-related bioactivities of these extracts and the active compounds within them. The existence of multiple value-creation pathways serves to reduce the risk of establishing and growing a New Zealand based industry for commercial-scale production, extraction and marketing of kelps. Moreover, the current commercial activities provide some experience, which can be supplemented by the more extensive overseas experience.

One challenge will be choosing a species for kelp farming in New Zealand and while native species might provide an enduring point of difference, they also have had the least research and development applied to them. It is not clear to what extent expertise developed for overseas species can be applied to commercial development of New Zealand species. Nevertheless, overall, kelps would appear to be an attractive choice for developing the New Zealand seaweed sector.

Priorities

- Develop cost-effective hatchery and cultivation techniques to meet the current demand for kelp species
- Validate markets for application of known bioactives
- Conduct research that enables health claims to be made
- Identify further bioactive compounds of interest
- Development of biorefinery cascades for New Zealand kelp species and the by-products from any extracts

Green seaweeds (Chlorophyta)

Biology

There is a large variety of green seaweeds; however, only a few stand out as having some potential for commercialisation. This section will focus on only two orders of green algae (Chlorophyta); Ulvales (*Ulva* spp. or sea lettuce) and Bryopsidales. Within the latter group, the *Codium* (velvet weeds) and *Caulerpa* (sea grapes or sea rimu, Figure 11) genera will be described. These choices are based on a record of traditional or commercial use, as well as a body of scientific research addressing their attributes and utility.

Ulva spp. are common seaweeds in New Zealand and around the world. There are at least 19 species in New Zealand and they vary in morphology from leafy blades, to more tubular forms that can grow in a wide variety of habitats from the upper intertidal to > 15 m depths in the subtidal (Lawton et al. 2013; Nelson 2013). Reproduction in *Ulva* spp. is complex, with alternating sexual and asexual life stages occurring on blades with a similar appearance (Figure 12) through fragmentation and vegetative growth. *Ulva* spp. spores can also directly develop essentially bypassing the alternating asexual and sexual phases (Alström-Rapaport et al. 2010).

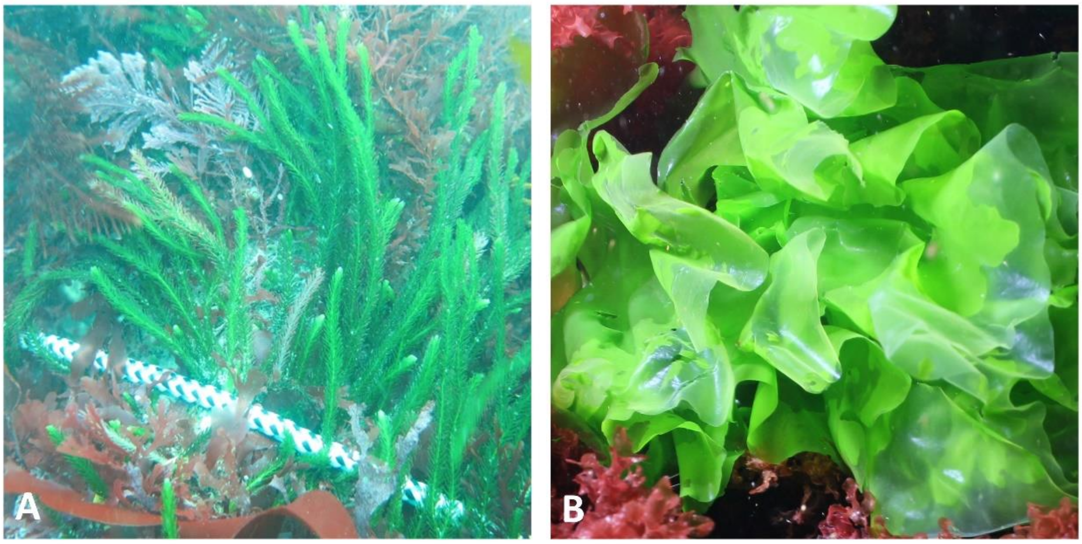

Figure 11. A) subtidal Caulerpa brownii (photo Robyn Dunmore/Cawthron). B) Subtidal Ulva spp. (photo Chris Cornelisen/Cawthron).

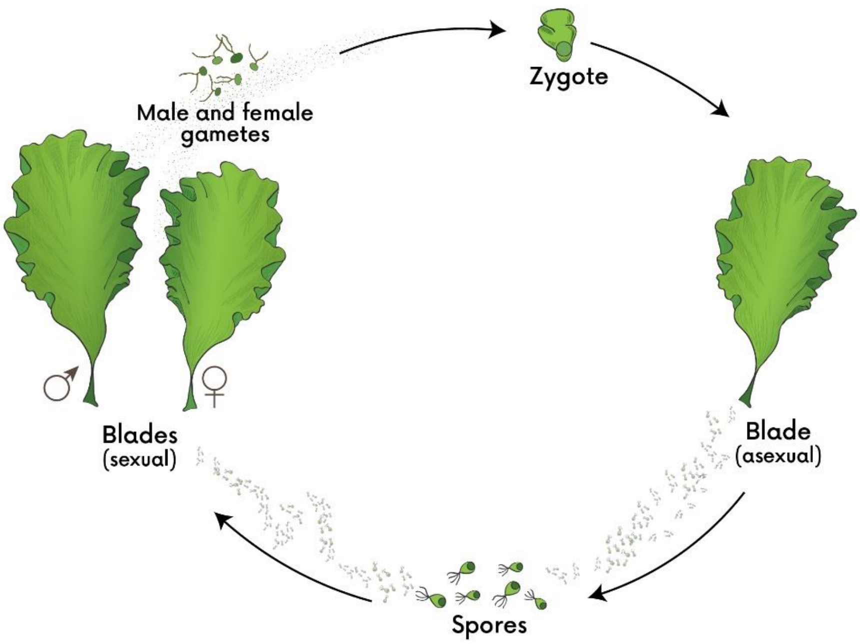

Figure 12. Life cycle of Ulva sp. (design: Revell Design, illustrations: https://adlysia.wordpress.com/).

Bryopsidales of the genera *Codium* and *Caulerpa* are made up of single macroscopic cell membranes with multiple nuclei and are widely distributed globally. There are 9 species of *Codium* and around 13 species of *Caulerpa* in New Zealand with one species of *Codium* (*Codium fragile* subspecies *tomentosoides*) being invasive (Trowbridge 1995; Nelson 2013). There are two distinct life-habits within *Codium*, with some species spreading out as pads on hard substrates (around 10 species) and the other forming erect, branching structures (3 species: *C. fragile* ssp. *novae-zelandiae*, *C. gracile and C. fragile* ssp. *tomentosoides*). The branched forms of *Codium* are found throughout New Zealand while *C. fragile* ssp. *tomentosoides* is confined to the north of the country (Trowbridge 1995; Armitage et al. 2017). *Codium* spp. are typically found in the low intertidal and subtidal zones on rocky open coastlines (Adams 1994). *Codium* species either reproduce sexually or through direct asexual development of gametes (sperm and eggs) (Churchill and Moeller 1972; Prince and Trowbridge 2004). *Caulerpa* spp. are composed of many fronds that arise from a creeping, basal stolon (Nelson 2013). They are typically warm water species in New Zealand and, for all but one species, their southern distribution ends at around the Marlborough Sounds. The exception is *Caulerpa brownii* (or sea rimu), which is found from the lower North Island southwards (Adams 1994; Nelson 2013). *Caulerpa* spp. are typically low intertidal to subtidal species that colonise rocky or cobble and shell hash habitats (Adams 1994). *Caulerpa* can reproduce sexually, but have a tremendous capacity for reproduction through fragmentation and vegetative growth (Phillips 2009).

Traditional and Commercial Uses

Internationally, *Ulva* spp. have historically been harvested from the wild for food in parts of Asia and the Pacific and are increasingly being incorporated into western cuisine (Silva et al. 2013; Roleda and Heesch 2021). Other uses include as feed for marine animals that are farmed in either land or marine-based production systems (Pallaoro et al. 2016), and as a means of bioremediation of waste water or effluent (Lahaye and Jegou 1993; Nielsen et al. 2012; Lawton et al. 2013; Moreira et al. 2020; Lawton et al. 2021). Integrated multitrophic aquaculture (IMTA) systems have been investigated in which effluent from marine animal farming is used to grow *Ulva* that is recirculated back into the marine farm industry as animal feed (Calheiros et al. 2019; Nardelli et al. 2019). Remediation and IMTA applications take advantage of the ability of *Ulva* to take up large amounts of nitrogen from the water in which they grow (Nielsen et al. 2012; Bolton et al. 2016). *Ulva* species have also been investigated for use as biofuel (Zhuang et al. 2012; Mata et al. 2016). Cultivation of *Ulva* is most commonly undertaken as free-living vegetative-growing fragments in tanks (common in bioremediation and nutrient extraction systems) (Lawton et al. 2013), although marine systems have also been investigated (Chemodanov et al. 2019). Information on the level of aquaculture production of *Ulva* is hard to find, but it appears very low compared with some other seaweed species (Bolton et al. 2016). The use of *Ulva* spp. for bioremediation is covered in Clark et al. (2021).

Like *Ulva*, *Codium* (sea velvets) and *Caulerpa* (sea grapes) also have a history of traditional use as food or medicines (Chengkui and Junfu 1984; Nagappan and Vairappan 2014; de Gaillande et al. 2017). The approach to obtaining biomass is almost always through wild harvest, although some subsistence-scale farming of *Caulerpa* occurs in the Pacific using a range of approaches (de Gaillande et al. 2017). Some research has been conducted to establish conditions for farming *Codium* and *Caulerpa*, either to increase biomass production or as part of IMTA systems (Hwang et al. 2007a, b). The utility of *C. fragile* as a bioremediation agent has been assessed (Kang et al. 2008; Paul and de Nys 2008). Also, the potential of *Codium* species has been as evaluated as a source of biogas (Maiguizo-Diagne et al. 2018) or biodiesel (Kang et al. 2008; Karthikeyan et al. 2020). However, it appears that commercial-scale aquaculture for these two genera has not yet been established.

Composition

In common with other seaweeds, the composition of *Ulva spp*. is dominated by polysaccharides (50-60% of dry weight), but they have an intermediate level of protein (~5 to 25% of dry weight) – higher than brown seaweeds, but less than that of most red seaweeds, although individual species compositions vary widely (Pena-Rodriguez et al. 2011; Balar et al. 2019; Jatmiko et al. 2019). Lipid content has been variously reported as below 5% (Balar et al. 2019) to as much as 15% (Satpati and Pal 2011, Mata et al. 2016). Thus, *Ulva* has been of interest for use as a biofuel (Mata et al. 2016). The polysaccharides within a range of *Ulva* species have been characterised (Tian et al. 2015; Tabarsa et al. 2018). The production, composition and health-related bioactivities of *Ulva*-derived polysaccharides have been reviewed (Kidgell et al. 2019). As with polysaccharide extracts from red and brown seaweeds, those from Ulva also have been shown to be rich in a range of health-related bioactivities, including immunomodulatory and antiviral activities. Besides polysaccharides, *Ulva* species also contains a range of secondary metabolites such as polyphenols, some with health-relevant bioactivities (Silva et al. 2013).

The composition and bioactivities of *Codium* and *Caulerpa* species have also been investigated. Like other seaweeds in general, these species are potentially good sources of nutrition and health-promoting bioactivities. The proximate compositions are variable among species with both of these genera having approximately 50% of dry weight as carbohydrate, 3-20% as protein, and 2-4% as lipid (de Gaillande et al. 2017; Lalitha and Dhandapani 2018; Seo et al. 2019). Besides their nutritional value, sea velvets and sea grapes have additional potential uses. Some species have been shown to contain a range of bioactive sulphated polysaccharides and lipids, including PUFAs and oxylipins (da Costa et al. 2015). These have been reported to have a range of health-promoting properties including anticoagulant, antinociception (pain-killing), immunomodulation, anticancer and antiviral activities (Ghosh et al. 2004; Lee et al. 2010; Rodrigues et al. 2012; Kulshreshtha et al. 2015; Li et al. 2015; Park et al. 2020a; Park et al. 2020b). In common with other green seaweeds, sea velvet (*Codium*) and sea grapes (*Caulerpa*) also have potential as sources of bioactive metabolites (Barzkar et al. 2019). At least one such compound, caulerpin, has been evaluated for use as a novel pain-killer (de Souza et al. 2009). There appears to be very little, if any, research investigating the composition or bioactivities of *Codium* or *Caulerpa* species growing in New Zealand waters.

Cultivation Methods

Commercial-scale cultivation of *Ulva* on-shore most often employs pond-based systems (Mata et al. 2016; Zertuche-Gonzalez et al. 2021). However, tank-based systems are also used, most often in a research or pre-commercial setting (Jimenez del Rio et al. 1996; Al-Hafedh et al. 2015; Mata et al. 2016). Systems using *Ulva* in ITMA systems associated with fish, prawn or abalone farms in South Africa and Australia employ onshore raceways (Bolton et al. 2009) Aquaculture systems for producing commercial-scale quantities of *Ulva* in a marine environment have also been investigated, using fine-mesh cages and a system to create water movement (Chemodanov et al. 2019). The optimal conditions for growth in some of these systems has been investigated (Praeger et al. 2019). In New Zealand, research and pilot scale systems for on-shore tank-based cultivation of *Ulva* have been established in the Bay of Plenty (University of Waikato 2018). Commercial-scale farming of *Codium* and *Caulerpa* species has not yet been established and there is insufficient experience with small-scale aquaculture to determine which are best suited for scale-up. Possible approaches include land-based tanks or raceways, or marine-based systems using hanging ropes.

Opportunities and Challenges

There may be opportunities for utilising green seaweeds in a future New Zealand aquaculture sector. *Ulva* species are currently being used as point source treatment for wastewater in land-based facilities (more details in bioremediation section of Clark et al (2021)). The University of Waikato is currently developing *Ulva* cultivars and growing them in land-based facilities for use as biostimulants and for human consumption. These cultivars have been observed to have significantly higher levels of protein than wild harvested *Ulva* (Battershill et al. 2021). There is also the opportunity to develop cultivars for extracts to potentially be used in cosmeceuticals and health supplements. The composition and bioactivities described for these species suggest that such a value-add approach is possible.

The main challenge to establishing commercial-scale aquaculture for *Ulva* is the relatively high cost of the most well-characterised system, land-based tanks. For *Codium* and *Caulerpa*, large-scale systems have yet to be devised.

Priorities

- Continued identification and development of different *Ulva* spp. cultivars for different markets.
- Identification of uses for *Ulva* grown for bioremediation purposes
- Investigate other green algal species to identify other bioactive compounds of interest

Discussion

The above summary of knowledge illustrates that New Zealand has a wealth of biological resource in the diversity of seaweeds growing along our coastlines. However, practical experience in producing, processing, and marketing seaweeds in this country is limited. There are significant knowledge gaps in all areas required to successfully establish seaweed aquaculture. This information is summarised in Table 1. Building a thriving sustainable seaweed sector in New Zealand will require a strategic research plan to address these knowledge gaps, produce practical outputs, commercialise and build capability at all levels. This can be achieved through leveraging overseas expertise where appropriate, and also by ensuring that knowledge generated through New Zealand research is publicly accessible and enables the industry to 'give it a go' using approaches that are appropriate for the New Zealand situation.

The current knowledge gaps mean that there is uncertainty surrounding the best opportunities and which species or markets to focus on. One way to reduce the technical or strategic risks of developing the sector is to initially focus on what is currently working with relatively low-value products, for example building from the existing biostimulant and soil conditioner markets domestically, and using this as a platform to build up high-value products taking a biorefinery or circular economy type of approach. These approaches and potential market pathways are outlined in the market analysis companion report (Bradly et al. 2021).

Government funded research and development has begun to lay the foundation for progression to high-value products; for example, karengo is being investigated as a high-value functional food (High Value Nutrition 2020) and food ingredient (Ministry of Business Innovation and Employment 2020), the potential of processing to add value to *Undaria* is being assessed (Ministry of Business Innovation and Employment 2020), as are commercial applications for *Ulva* (University of Waikato 2018). Further funding into biomass production and post-harvest value creation is crucial to stimulating development of the seaweed sector as is the development of practical guides for aspiring sector participants and investors.

Investors and entrepreneurs will develop their own business cases specific to the sites, species and markets they are interested in (Cameron Inskeep, Nautilus Advisors Ltd, pers. comm.). However, there are currently multiple risks in developing production methods and markets, and the first mover in each case will have to carry out the fundamental science on hatchery seed production, farming and processing since this work either hasn't been done or isn't publicly accessible (Bradly et al. 2021). To reduce the disadvantage of being a first mover, aspiring stakeholders should collaborate to fund the necessary research that will underpin the industry and is essential for all businesses. This would reduce the costs and risk of entry.

From a longer-term perspective, the scale of biomass production in New Zealand will likely be relatively small in terms of the international market and the labour costs will undoubtedly be relatively high compared with commodity production in Asia (Bradly et al. 2021).

Building towards high-value, low biomass input products such as health supplements, topical actives, and premium functional food ingredients for niche markets, as opposed to on-going and large scale production of commodities that compete head-to-head with low-cost established production overseas is likely the categories for Aotearoa New Zealand to focus product development.

The unique aspects of New Zealand's natural and cultural heritage could add value to this approach. Two potential long-term opportunities that fit this approach are:

1. Karengo, which could be sold either as a whole biomass (as food or functional food) or an extract and marketed as a health-promoting food ingredient or cosmeceutical since karengo contains high levels of vitamin B12, micronutrients, omega-3 fatty acid EPA, soluble dietary fibre, UV blocking compounds, and has anti-inflammatory and energy metabolism bioactivities (Wheeler et al., unpublished results). Likely health benefits include gut health, as well as anti-inflammatory and anti-obesity properties. Also, reducing the uncertainty is that this possibility leverages existing knowledge of the composition of karengo species that has recently been attained (Wheeler and Romanazzi 2019; Wheeler et al. 2020a), as well as the extensive body of knowledge of composition of very similar species from overseas. Another risk reduction factor is that cultivation is well-understood for closely related overseas species. The most significant knowledge gaps are choice of karengo species on which to focus, understanding of how to grow it using aquaculture systems suited for New Zealand conditions, and verification of health benefits.

2. Extracts of one or more species of kelps or fucoids as health-promoting functional food, food ingredient, cosmeceutical, or health supplement. These products will be based on the presence of hydrocolloid polysaccharides such as alginates, bioactive polysaccharides and bioactive low molecular weight compounds such as fucoxanthin. There are a wide range of species from which to choose as well as routes to market, thereby increasing the uncertainty and risk but also the potential opportunity. This possibility draws on overseas research on the composition of sometimes more distantly related species, along with both local and overseas knowledge of cultivation for some of them and some well-developed routes to market for overseas species that could also be targeted by New Zealand producers. Significant knowledge gaps include the composition of New Zealand species and the bioactivities of extracts from them, as well as how to produce biomass efficiently at scale for most of the species in this group.

Table 1. Summary outlining key New Zealand species and seaweed groups of interest, their biology, uses, composition, related cultivation methods and opportunities and challenges for their commercialisation.

Group	NZ Species	Biology	Uses	Composition	Cultivation	Opportunities and Challenges
Karengo	Generally *Pyropia* spp. and *Porphyra* spp.	Distributed around eastern and southern coasts of NZ Complex multi-stage life cycle	Traditional food and taonga species for Māori Related species are consumed around the world as food (i.e. nori in Japan)	High protein, omega-3 fatty acids, vitamin B12, low iodine	Large scale cultivation of similar species on nets throughout Asia Hatchery techniques well developed for similar species	Unique NZ food products with health benefits Research required to characterise NZ species, make health claims and adapt overseas cultivation methods Low in iodine
Asparagopsis	*Asparagopsis armata* and *Asparagopsis taxiformis*	*A. armata* distributed around NZ, *A. taxiformis* only found on the Kermadec Islands Complex multi-stage life cycle	*A. taxiformis* is traditionally eaten as a condiment in Hawai'i Potential feed supplement to reduce methane emissions from livestock.	Bromoform is the key bioactive associated with methane reduction	Currently cultivated in France, using vegetative propagation onto ropes. Wild harvest currently supplies research efforts.	Large amount of investment and drive Uncertainties surrounding the stability and consistency of the bromoform content, possible bromoform toxicity issues Competition from other methane inhibitors
Agarophytes	*Pterocladia lucida* and *Pterocladiella capillacea* *Agarophyton chilense* (formerly *Gracilaria chilensis*).	Distribution varies by species, but widely found throughout coastal NZ waters Complex multi-stage life cycle	Used as a food source in Asia and the Pacific. Commercially used as a source for agar	Agar yields range from 10-30% of dry weight depending on species	Established methods in Chile and Asia 1.5 million tonnes produced in Asia	Agar is a commodity product, and it may be challenging to compete internationally R&D needed to adapt international methods to NZ conditions or develop cultivation of local species
Fucoids	10 genera in NZ, including *Durvillaea* spp. (bull kelp), *Carpophyllum* spp., *Landsburgia* spp.	Distribution varies by species, but widely found throughout coastal NZ waters. Form dense forests. Simple lifecycle, with seasonal reproductive peaks depending on species	Māori used *Durvillaea* spp. for pōhā (storage bags) Internationally, fucoids are used as sources of food, alginates and polysaccharides	High levels of polysaccharides, including fucans and alginates	Cultivation techniques exist for *Sargassum* spp. widely farmed in Asia.	Abundance of these species in NZ represents an opportunity Gaps surrounding cultivation methods which are suitable for NZ conditions and product types
Laminarians (kelps)	*Ecklonia radiata*, *Lessonia* spp., *Macrocystis pyrifera* and *Undaria pinnatifida* (invasive)	Subtidal species which are distributed throughout NZ, typically forming forests Complex multi-stage life cycle	Kelps are widely harvested and grown for food, fertiliser, and as source of alginates, polysaccharides and bioactive ingredients	Low in protein and high in polysaccharides Many species contain alginate, fucoidan and carotenoids	Kelps are grown on suspended long-line systems throughout the world. Trials have occurred in NZ.	Existing biostimulant market, currently supply limited Need to identity/develop nutraceuticals and functional food products R&D to develop cultivation techniques for local species
Green algae	*Ulva* spp. *Codium* spp. *Caulerpa* spp.	*Ulva* spp. are widespread throughout NZ, *Codium* spp. and *Caulerpa* spp. distribution varies by species	Widely used as food sources as well as biomass for bioremediation and biofuels	High levels of bioactive polysaccharides	*Ulva* is typically grown in land-based systems in raceway ponds or tanks	Opportunities to use *Ulva* for point source bioremediation. Existing market for biostimulants and fertilisers

Regardless of which species become a focus for development, the biggest uncertainty is how to produce biomass at a commercial scale in the New Zealand context. Sustainable wild harvest alone is unlikely to provide the scale required. Therefore, development of commercially viable farming systems is probably the most pressing hurdle to overcome. Understanding and controlling the life cycle and growing requirements will have to be investigated for each species. Addressing this knowledge gap should be the initial focus of developing a thriving sustainable seaweed industry in New Zealand.

Recommendations and next steps

1. Develop appropriate methods, processes and frameworks to engage with whānau, hapū, iwi and Māori enterprises to ensure mutual benefit and true partnership, acknowledge kaitiaki rights and interests in taonga species and ensure appropriate use and management of mātauranga. Engage with all relevant Māori groups to ensure co-design, informed consent and true partnership in the developing sector.

2. Agree priority research and development propositions for a BE-EBM pathway with policy-makers and stakeholders

3. Identify alignments of seaweed species, products, and routes to market with interested industry, Iwi and government stakeholders, and sketch out provisional detailed knowledge maps and business cases.

4. Secure a commitment to prioritise government-funded research toward priority commercial-scale biomass production and post-harvest value creation of New Zealand seaweeds, and ensure such research can either be publicly accessed or held in a way that maximises return to New Zealand. Ensure resource tagged to these activities is allocated to appropriate funding bodies and projects that develop to development models based on BE-EBM principles.

5. Establish broad industry and research collaborative partnerships focused on distinct species groups and routes to market, to maximise sharing of know-how and minimise competition within the relatively small New Zealand research and development community.

Collectively, these actions will give New Zealand the best opportunity to realise the potential of its natural seaweed heritage, and at the same time to broaden its aquaculture sector to help achieve the government's strategic goal of establishing a $3 billion aquaculture industry by 2035 (New Zealand Government 2019).

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