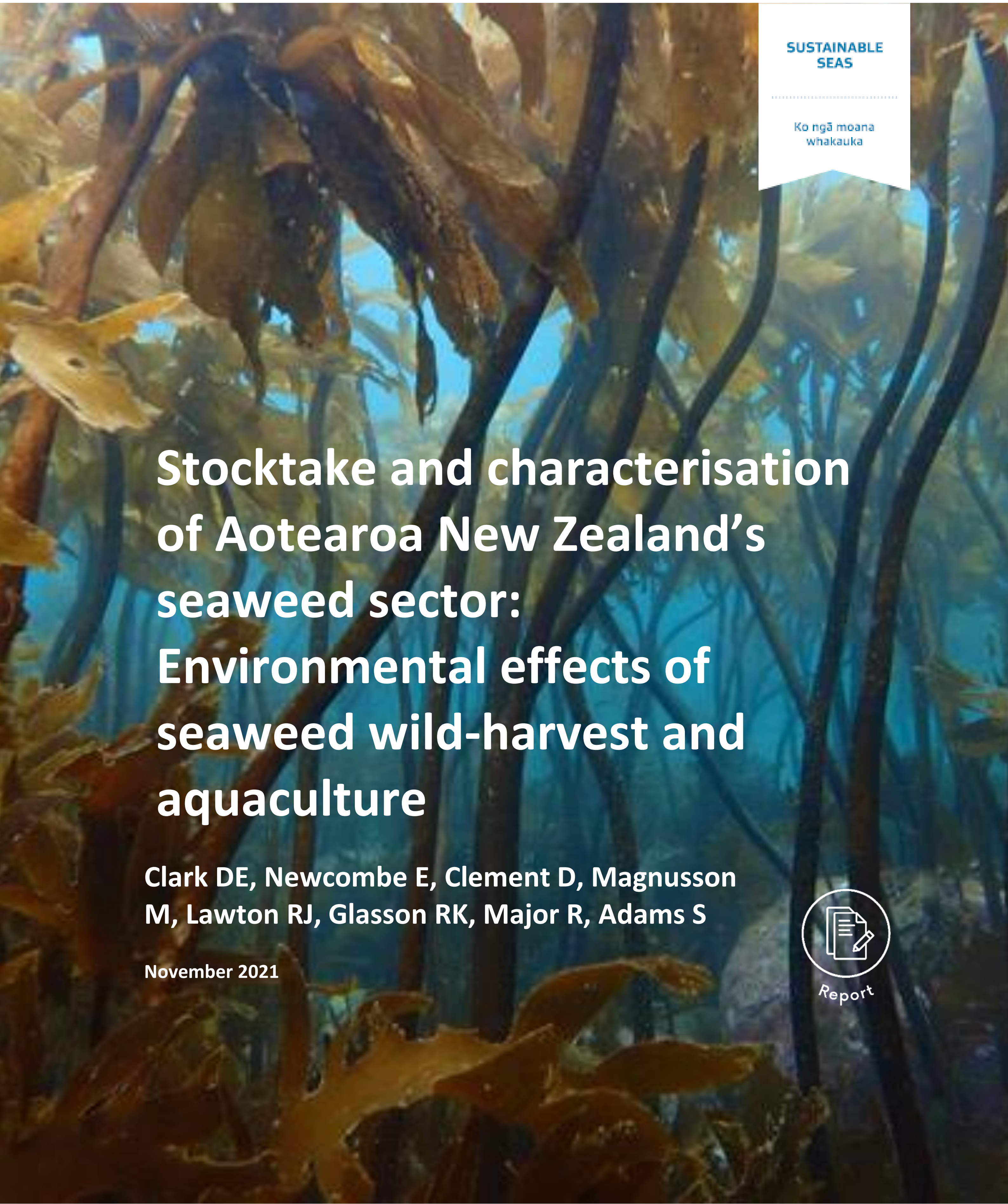
National SCIENCE Challenges

SUSTAINABLE SEAS

Ko ngā moana whakauka



Stocktake and characterisation of Aotearoa New Zealand's seaweed sector: Environmental effects of seaweed wild-harvest and aquaculture

Clark DE, Newcombe E, Clement D, Magnusson M, Lawton RJ, Glasson RK, Major R, Adams S

November 2021

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)*

Report authors

Clark DE[1], Newcombe E[1], Clement D[1], Magnusson M[2], Lawton RJ[2], Glasson RK[2], Major R[1] & Adams S[1]

[1] Cawthron Institute, 98 Halifax Street East, Nelson 7010, New Zealand
[2] University of Waikato, Private Bag 3105, Tauranga 3110, New Zealand

Date of publication

November 2021

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

SUSTAINABLE SEAS Ko ngā moana whakauka

National Science Challenges

CAWTHRON

THE UNIVERSITY OF WAIKATO *Te Whare Wānanga o Waikato*

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.

www.sustainableseaschallenge.co.nz

Cover image: Ecklonia radiata kelp forest. Ohad Peleg.

Acknowledgements

Thank you to our Project Advisory Group (Dave Taylor, Andy Elliot, Paul Creswell and Chris Karamea Insley) and leaders of the Sustainable Seas National Science Challenge for advice throughout this project. Thank you to Grant Hopkins (Cawthron Institute), Dave Taylor (Aquaculture New Zealand) and Nick Lewis (University of Auckland) for reviewing this report. Kirsten Revell from Revell Design produced the graphics.

Author contribution statement

- Conceptualisation: SA, RM, EN
- Writing – original draft: DEC, EN, DC, MM, RL, CG
    - Lead author for *Environmental effects of wild seaweed harvest*: DEC/EN
    - Lead author for *Ecosystem services provided by seaweed aquaculture*: DEC
    - Lead author for *Bioremediation of waste*: DEC/MM
    - Lead author for *Environmental effects of seaweed aquaculture*: EN
    - Lead author for *Wildlife entanglement*: DC
    - Lead author for *Appendix 1*: MM
- Writing - review and editing: DEC, EN, DC, SA, RM, MM
- Project administration and funding acquisition: SA, RM

CONTENTS

Executive summary

The environmental effects of harvesting wild seaweed and cultivating it on farms were reviewed to inform the development of an Ecosystem-Based Management (EBM) framework to guide the progression of the Aotearoa New Zealand seaweed sector. Growth of seaweed aquaculture would allow the scale of the seaweed industry to increase without placing pressure on wild populations and provide greater control over the consistency and quality of the product. While the potential for seaweed aquaculture to supply ecosystem services beyond the provision of biomass is often promoted as a key benefit of seaweed farming, the delivery of these services is highly dependent on scale and context. Seaweed farming is considered to have a lower environmental risk than most other forms of aquaculture. Genetic interactions with wild populations, disease and marine pests, and wildlife entanglement pose the greatest environmental risk. The site-specific nature of many of the benefits and risks, and the associated uncertainty about their effects, highlights the importance of developing an EBM framework for the seaweed sector in Aotearoa New Zealand.

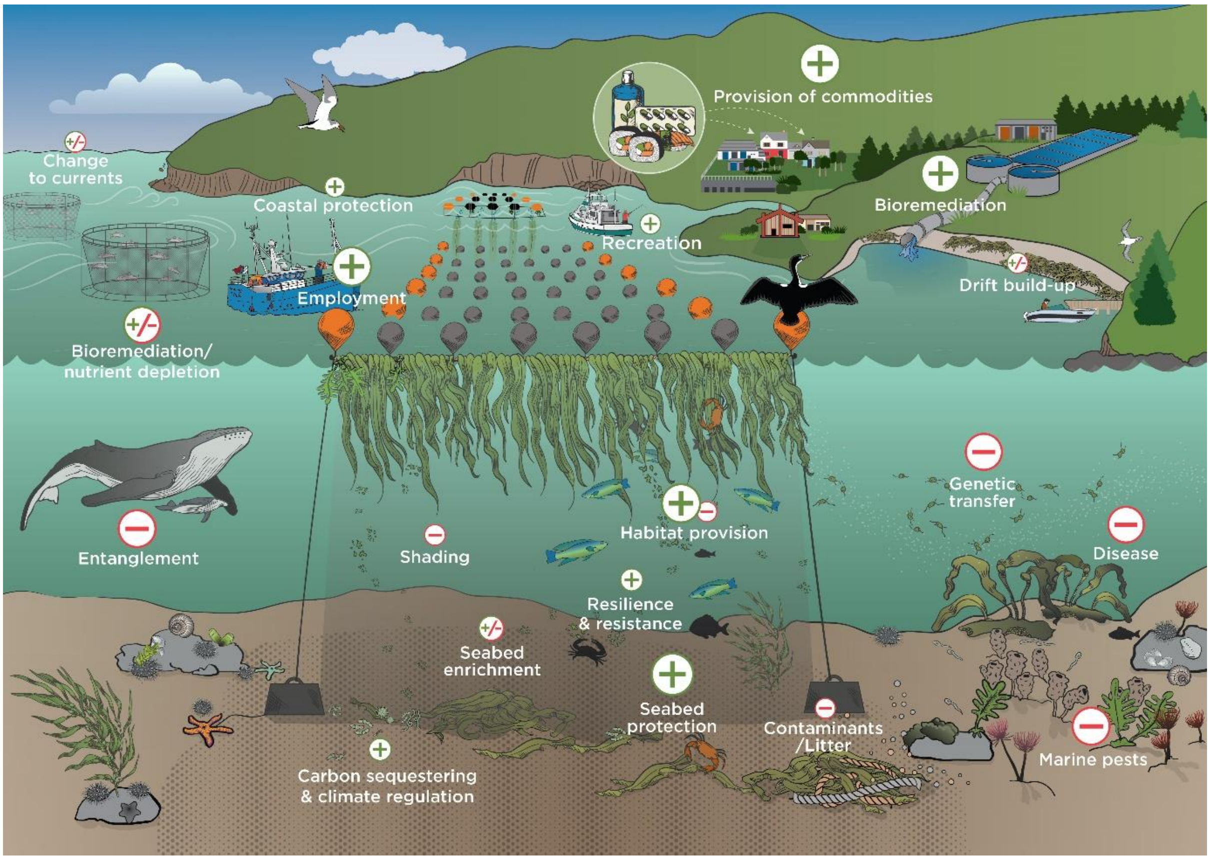
This report considers all potential environmental effects of harvesting wild seaweed and cultivating it on farms and highlights those benefits and risks that will need to be considered further in developing an ecosystem-based management framework for a sustainable and high-value Aotearoa New Zealand seaweed sector. The report is a companion to Bradly et al. (2021), which characterises the existing Aotearoa New Zealand seaweed sector and describes the current markets and regulatory environment, and also to Wheeler et al. (2021), which provides an overview of seaweed species in Aotearoa New Zealand that have commercial potential, as well as recognition of their cultural importance and the role of Māori in the emerging seaweed sector. Together, these three reports form the background to the development of a Seaweed Sector Framework for Aotearoa New Zealand, part of the broader Blue Economy workstream of the Sustainable Seas National Science Challenge.

Aotearoa New Zealand's seaweed industry currently relies on the harvest of wild seaweed. Harvesting seaweed from natural beds poses a greater environmental risk than harvest from artificial structures or the collection of beach-cast seaweed. The consequences of harvesting seaweed from natural beds depends on the extent and method of harvest as well as characteristics of the harvested seaweed and the associated ecosystem. At current levels of harvest, the environmental consequences are likely to be negligible but there could be sustainability issues if the scale of the industry increases. Wild harvest of seaweed communities from artificial structures is likely to be environmentally benign as there may be little or no disturbance of natural habitat associated with harvest. However, like wild harvest from natural beds, there are biosecurity risks associated with the transfer of pests and disease. Collection of beach-cast seaweed can create physical disturbance, spread disease and pests, and remove a resource used by ecological communities. The environmental consequences of these effects vary with the method of harvest and amount of seaweed removed.

Development of a seaweed aquaculture sector would allow Aotearoa New Zealand to sustainably increase yields and provide greater control over the consistency and quality of seaweed products. Possible ecosystem services and negative environmental effects of seaweed aquaculture are summarised in the figure below. While the potential for seaweed aquaculture to supply ecosystem services beyond the provision of biomass is often promoted as a key benefit of seaweed farming, the delivery of these services is highly dependent on scale and context. In many cases, the research to demonstrate the provision of these benefits, and how they vary in different situations, has yet to be carried out. In an Aotearoa New Zealand context, where coastal eutrophication is not widespread, the potential for bioremediation is unlikely to be fully realised unless seaweed is farmed specifically for this this purpose on land, in an integrated multitrophic aquaculture setup or in highly enriched coastal waters. Carbon sequestration pathways in farmed seaweeds have not yet been quantified, but it is likely that much of the sequestered carbon will be released back into the atmosphere at some stage in the lifecycle of the final product. The role of seaweed farms in coastal protection is likely to be limited unless farms are designed to optimise the provision of this service. Seaweed farms will create (or protect) habitat for other marine organisms, but the long-term value of this habitat depends on a range of factors including harvesting practices and the availability of suitable natural habitats nearby. If this habitat enhances biodiversity, seaweed aquaculture could contribute to the resilience and resistance of the ecosystem. Seaweed aquaculture also offers a range of potential cultural (societal) benefits, which are often place specific and context dependent.

Globally, seaweed farming is considered to have a lower environmental risk than most other forms of aquaculture. Within Aotearoa New Zealand, seaweed aquaculture has the potential for relatively minimal impacts but, as with ecosystem services, the extent of environmental changes are currently uncertain. The environmental issue of most concern for the development of seaweed aquaculture in Aotearoa New Zealand are genetic interactions with wild populations, disease and marine pests, and wildlife entanglement. While there are good mitigation precedents for most of the negative environmental effects from current shellfish aquaculture practices, any potentially high-risk effects require further consideration of proactive mitigation actions and robust management/monitoring programmes.

When considering the ecosystem services and the negative environmental effects of seaweed aquaculture, three consistent themes emerge: the strong influence that both 1) appropriate farm placement and 2) scale can have on environmental changes and 3) the uncertainty associated with many of these effects. Most negative environmental effects are expected to be low and at manageable levels within small-scale, properly sited farms but could reach a ‘tipping point’ with unintended ecological consequences if farms are too extensive or inappropriately placed. Furthermore, some environmental changes are only likely to be problematic if seaweeds are farmed on a large scale, while some benefits will only be realised at large scales. The final balance between the positive (ecosystem services) and negative environmental effects of seaweed farming will largely depend on the size, number and intensity of seaweed farms placed along the Aotearoa New Zealand coast, where they are sited, and the species chosen to be cultivated.



Development of Aotearoa New Zealand's seaweed sector will require a shift towards aquaculture to allow an increase in yields without placing pressure on wild seaweed populations. This diagram shows the possible negative environmental effects and ecosystem services associated with seaweed aquaculture in subtidal environments. The likely nature and degree of effect is indicated by large or small '-' or '+' symbols. Graphic by Revell Design.

The site-specific nature of many of these benefits and risks, and the associated uncertainty about their effects, highlights the importance of developing an ecosystem-based management (EBM) framework for seaweed aquaculture in Aotearoa New Zealand. EBM is tailored to a specific time and place and recognises ecological complexity and connectedness. It promotes flexible, adaptive monitoring that acknowledges the uncertainty associated with many of these environmental effects. Environmental monitoring and targeted research will be critical in the early developmental stages of seaweed farming in Aotearoa New Zealand to minimise these uncertainties and ensure management approaches are knowledge-based. This knowledge can be in the form of both science and mātauranga Māori and should be informed by community values and priorities. It is also essential that management approaches consider the cumulative impact of other human activities occurring alongside seaweed aquaculture. Collaborative decision-making and co-governance structures that provide for Treaty of Waitangi partnerships will provide a holistic and inclusive way of managing seaweed aquaculture effects on the marine environment. Ultimately, the goal of the EBM framework will be to enable the development of a thriving seaweed sector while ensuring that the values and uses of Aotearoa New Zealand's marine environment are safeguarded for future generations.

Seaweed aquaculture represents a timely opportunity for Aotearoa New Zealand to develop a sustainable, high-value industry. Cultivation of seaweeds would allow the scale of the industry to increase without placing pressure on wild populations and provide greater control over the consistency and quality of the product. Seaweed aquaculture does have the potential to cause environmental change, both as positive benefits to humans and as negative effects to the environment. Fortunately, there is a unique opportunity for industry, government, science providers, tangata whenua and the community to co-design an EBM framework that considers these concerns, ensuring this sector can meet the environmental, social, economic and cultural aspirations of New Zealanders.

1. Introduction

1.1 Sustainable Seas National Science Challenge

This report contributes to the Sustainable Seas National Science Challenge Theme 2: Creating value from a blue economy. The objective of Sustainable Seas (2018) 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.

Ecosystem-based management (EBM) is at the core of Sustainable Seas. EBM is a holistic and inclusive way to manage marine environments and the competing uses for, demands on, and ways that New Zealanders value them (Sustainable Seas 2018). The overarching aim of EBM is to maintain ecosystems in a healthy, productive and resilient condition so that they continue to provide the ecosystem services that humans rely on. It moves away from a single-sector or single-species approach by considering the cumulative effects of multiple human activities (McLeod et al. 2005). Seven principles have been proposed for EBM in Aotearoa New Zealand (Figure 1; Hewitt et al. 2018).

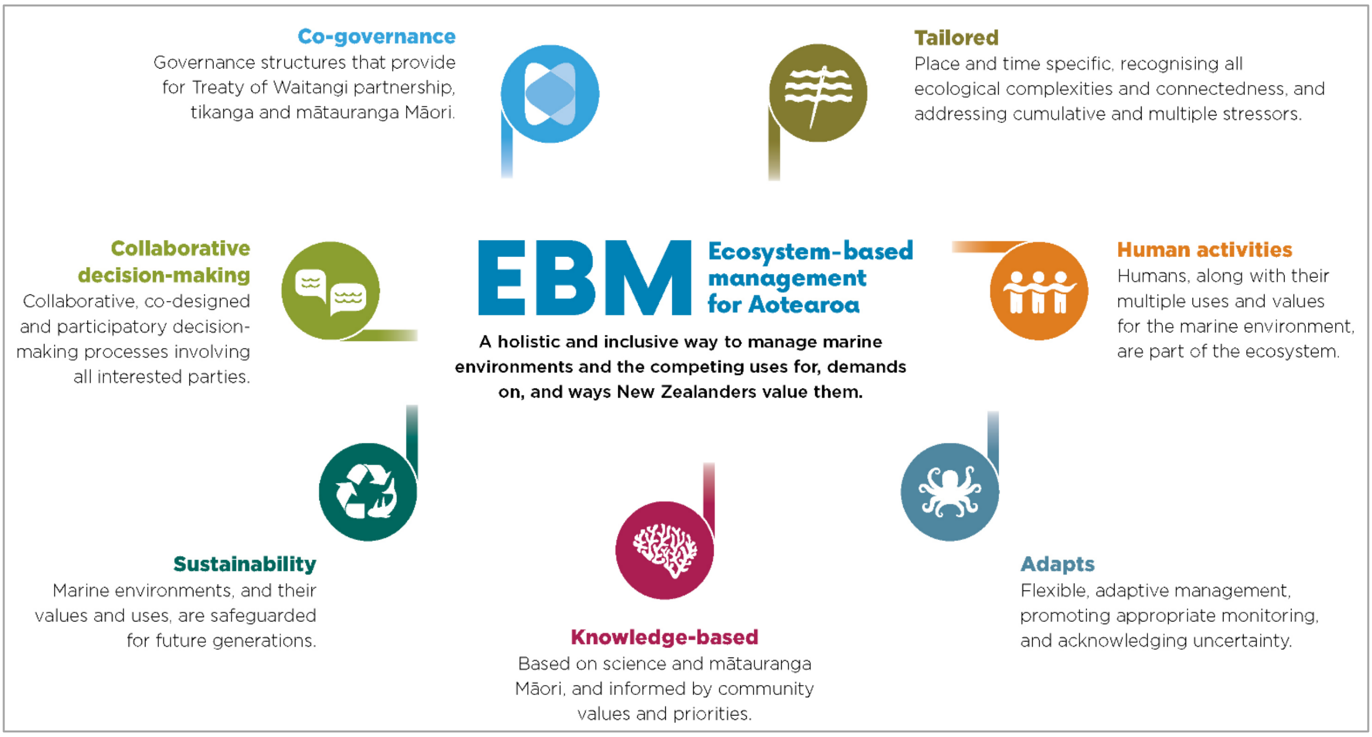


Figure 1. Ecosystem-based management (EBM) principles for Aotearoa New Zealand. Graphic by Sustainable Seas.

Sustainable Seas promotes research to underpin a marine economy that will deliver healthy ecosystems and support the diverse values of New Zealanders. This will require an economy that is not ‘business as usual’ and instead creates value from marine resources in novel ways. Sustainable Seas defines a blue economy as ’marine activities that generate economic value and contribute positively to social, cultural and ecological well-being’ (Sustainable Seas 2021). Research within the Blue Economy programme is focused on helping to grow activities that are sustainable, resilient to climate change, minimise waste, and have positive impacts on society and culture. Managing these activities within an EBM framework could allow the blue economy to grow while maintaining healthy marine ecosystems that provide value for every New Zealander.

1.2 Background

There is growing interest in the contribution that seaweed could make to the blue economy, both internationally and here in Aotearoa New Zealand. The global seaweed industry is valued at over US$14 billion per year and continues to expand (FAO 2021). Most of this seaweed is farmed, with only 3% of seaweed collected from the wild (FAO 2020). Aotearoa New Zealand has a fledgling seaweed industry, which primarily relies on the harvest of seaweed from wild populations (Bradly et al. 2021). Wild harvest includes the exploitation of seaweed from wild seaweed beds, the collection of drift seaweed from the shoreline and the harvest of seaweed growing on artificial structures. However, wild harvest is constrained by both sustainability concerns and the reliability and quality of the harvested seaweed (Bradly et al. 2021). Development of a seaweed aquaculture sector would allow Aotearoa New Zealand to substantially increase existing yields without placing pressure on our wild populations. It would also enable greater control over the consistency and quality of the product. Seaweed aquaculture is rapidly expanding overseas (FAO 2018), and Aotearoa New Zealand is well positioned to grow this sector due to the suitability of our environment for seaweed cultivation (Figure 2). With the right framework grounded in EBM principles (Figure 1), a thriving seaweed sector could provide meaningful economic, environmental, social and cultural benefits to local communities and broader impacts nationally.

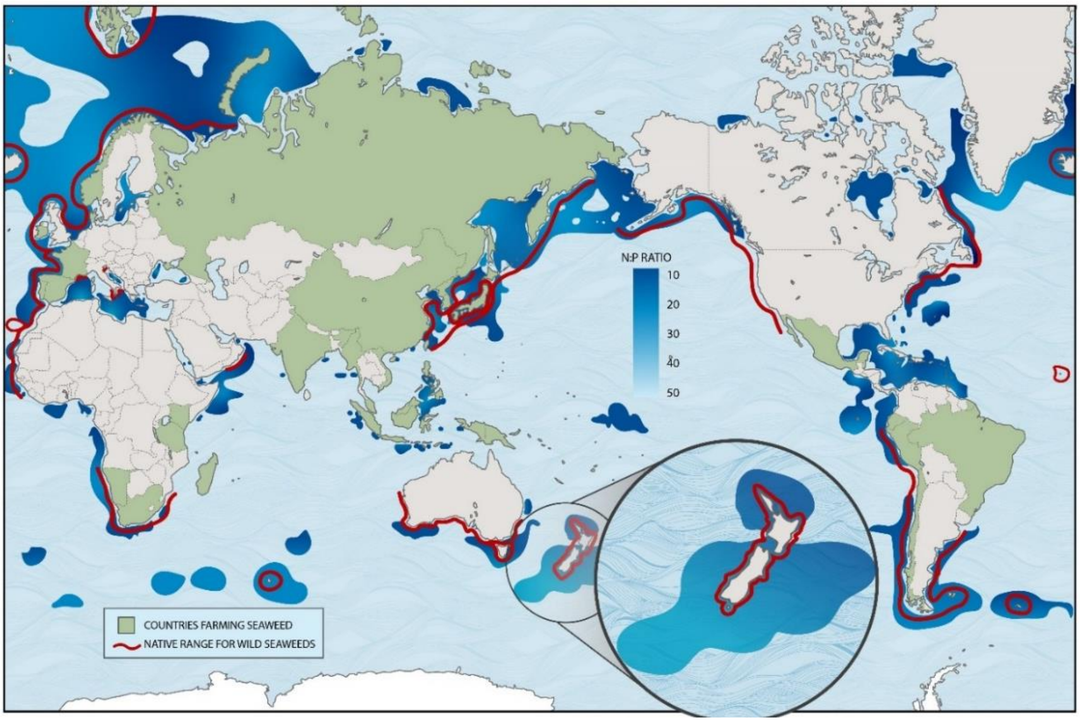


Figure 2. Ecological suitability map for seaweed aquaculture. Adapted by Revell Design with permission from Froelich et al. (2019).

Development of an EBM framework to guide the seaweed sector in Aotearoa New Zealand requires consideration of the benefits and environmental risks that seaweed wild-harvest and cultivation create. Benefits can be considered in terms of the ecosystem services offered by seaweed aquaculture, which include the provision of seaweed biomass to produce commodities, as well indirect benefits such as the potential for carbon sequestration and bioremediation (Gentry et al., 2020). Although seaweed cultivation is widely viewed as a sustainable form of aquaculture (e.g., Theuerkauf et al. 2021, FAO 2018), negative environmental effects are possible; for example, nutrient depletion or the introduction of disease. Without an understanding of the environmental benefits and risks (and their associated uncertainties) in an Aotearoa New Zealand context, the opportunity to achieve blue economy outcomes could be wrongly assessed or missed. Consideration of environmental benefits and negative effects is also a key step toward meeting the EBM principle of Sustainability: ensuring that marine environments, and their values and uses, are safeguarded for future generations (Figure 1).

1.3 Aims and scope

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 the project is to develop and test a framework for a sustainable and high value Aotearoa New Zealand seaweed sector. The project focuses on identifying a future for the sector based on EBM principles. The purpose of this report is to provide an overview of environmental benefits and risks of harvesting wild seaweed and cultivating it on farms; however, some consideration of wider ecosystem services is also presented.

Companion reports, which will feed into the overall framework being developed for this project are:

- Stocktake and Characterisation of New Zealand's Seaweed Sector: Market and Regulatory Focus (Bradly et al. 2021).
- Stocktake and Characterisation of New Zealand's Seaweed Sector: Species Characteristics and Te Tiriti o Waitangi Considerations (Wheeler et al. 2021).

In our report, we first consider the environmental effects of wild seaweed harvest (Section 2), which is currently the primary source of seaweed in Aotearoa New Zealand. We then review the potential ecosystem services (Section 3) and negative environmental effects (Section 4) associated with seaweed aquaculture, which offers a promising avenue for the development of Aotearoa New Zealand's seaweed sector. We finish with a short summary (Section 5) that includes the possible implications of these benefits and environmental risks for economic use and management, and research recommendations. This will feed into an EBM framework to develop a pathway for the seaweed sector that generates multiple co-benefits at different scales for communities, regions and sector participants.

2. Environmental effects of wild seaweed harvest

Wild seaweeds have a long history of collection by Māori for traditional uses (Colenso 1980) and have been commercially harvested in Aotearoa New Zealand since the 1940s (Moore 1994). Two main types of wild seaweed may be exploited; attached populations growing on natural or artificial structures, or detached material, which is generally collected when it is cast up on the shore ('beach-cast'). Today's commercial harvest primarily relies on small volumes harvested from mussel lines or wild beds and beach-cast collection (Bradly et al. 2021). Only bladder kelp (*Macrocystis pyrifera*) and beach-cast seaweed collected for the supply of green-lipped mussel (Perna canaliculis) spat are managed within the Quota Management System but several regulations (e.g., fishing permits, marine farming consents) constrain the harvest of other seaweed species (Bradly et al. 2021). The following section outlines the environmental effects associated with wild harvest of seaweeds. There are few cases where wild harvest of seaweeds would be expected to have positive environmental benefits, although some scenarios are possible when considering exotic invasive species (e.g., in Aotearoa New Zealand wakame, *Undaria pinnatifida*).

2.1 Harvest of wild seaweed from natural beds

Harvest from wild seaweed beds can affect marine species beyond those directly targeted (Lotze et al. 2019). Many seaweeds create habitat for other species that live on or near them (e.g., Taylor & Cole 1994, Anderson et al. 1997, Christie et al. 2003, 2007, Anderson 1994), including species of commercial and conservation importance (e.g., Hinojosa et al. 2015). Seaweeds can provide attachment substrate, shelter, food, refuge or shade to these associated species (Dayton 1985, Teagle et al. 2017). Thus, removal of habitat-forming species can cause direct mortality of associated species and change the community structure and functioning of harvested areas (e.g., see seaweed clearance effects in Edgar et al. 2004, Schiel & Lilley 2011, Tait & Schiel 2011). As many of these species are important food sources for animals at higher trophic levels, wild harvest of seaweed has the potential for wider ecosystem consequences as well. For example, Lorentsen et al. (2010) demonstrated that harvest of kelp (*Laminaria hyperboreal*) in Norway reduced the foraging efficiency of seabirds. Similarly, removal of bladder kelp (*M. pyrifera*) has been shown to reduce fish biomass (Ebeling & Laur 1985, Bodkin 1988, Carr 1989, Vanella et al., 2007). Removal of canopy-forming seaweeds can also affect ecological communities by altering the environmental conditions (e.g., light regimes, currents; Connell 2003, Eckman et al. 1989) and increasing the provision of settlement substrate (Kennelly 1987).

As well as supporting biodiversity through habitat provision, wild seaweed beds offer many of the other ecosystem services provided by farmed seaweeds (refer Section 3), including bioremediation of nutrients and contaminants, climate regulation via carbon sequestration, and coastal protection (Smale et al. 2013). Thus, large scale-removal of seaweed could also affect the provisioning of these services (Lotze et al. 2019). Furthermore, harvesting activities have the potential to spread diseases and pests present in wild populations (Cunningham et al. 2020).

The effects of harvest from wild beds are dependent on a range of harvesting considerations including:

- the extent and patchiness of the area harvested (e.g., Foster & Barilotti 1990, Schiel & Nelson 1990)
- the frequency and timing of harvesting (e.g., Thompson et al. 2010, Schiel & Nelson 1990)
- the proportion and part of the seaweed harvested (e.g., Borras-Chavez et al. 2012, Santelices & Ojeda 1984)
- whether the holdfast is left intact (while this is likely to be preferable in most cases, the relative benefits of each method may differ depending on the seaweed species; Schiel & Nelson 1990)
- the degree of disturbance to associated communities (e.g., trampling, by-catch, mechanical harvesting methods).

The biology and ecology of the seaweed will also dictate the degree of effect, for example:

- size
- growth rate
- seasonality
- role in the ecosystem (e.g., is the species habitat-forming or competitively dominant)

- nature of adjacent communities, particularly the degree of propagule supply of the target species and competitors
- ability of the seaweed to regenerate or recolonise after harvest.

The environmental conditions of the harvest area (e.g., intertidal versus subtidal, location within biogeographic range, warming seawater temperatures; Phillippi et al. 2014, Thompson et al. 2010, Krumhansl et al. 2017) will also influence the level of effect. In some cases, an influx of herbivores (e.g., sea urchins; Fagerli et al. 2013) or invasive species could prevent recolonisation (e.g., wakame; South et al. 2017).

The effects of harvest are more likely to be benign where: a small proportion of the population is removed or only part of the seaweed is harvested; the target species does not create habitat for many other species; regrowth or recolonisation is reliable and rapid; harvest methods do not disturb the rest of the community; and/or the environment is adapted to disturbance. Environmental effects of harvest are likely to be strongly negative where: whole plants are harvested, particularly where those plants provide or adapt habitat; harvest occurs in a season or on a scale such that the target species cannot recolonise the harvested area; and/or the species occurs at the limit of its biogeographic range.

Schiel and Nelson (1990) reviewed the potential effects of harvesting several seaweeds (*Pterocladia* spp., *Porphyra* spp., *Agarophyton chilense*, *Durvillaea* spp., *M. pyrifera*, and *Ecklonia radiata*) from wild beds in Aotearoa New Zealand. They noted that there is little information with which to judge whether harvest was sustainable. However, their conclusion was that the restriction of wild harvesting through the use of fishing permits has proved to be an adequate approach to regulating seaweed harvest in Aotearoa New Zealand. Wild harvest of these species (as well as *Lessonia variegata and Ulva* spp.) is now restricted under the Fisheries Act 1996 in response to potential management and sustainability issues under the current 'open access' fishing regime (Bradly et al. 2021). Harvest of these seaweeds can only occur if they are taken as 'inevitable bycatch', although targeted collection is permitted for a few fishers that were entitled to catch these species before 1992 (Bradly et al. 2021). They can also be collected as beach-cast within approved commercial seaweed harvest areas (refer Section 2.3). Bladder kelp (*M. pyrifera*) is the primary species harvested from wild beds, accounting for 92% of the 50 tonnes (wet weight) of seaweed harvested each year between 2006 and 2018 (White & White 2020). Overall, the environmental consequences of harvest from wild seaweeds beds are likely to be negligible given the scale of harvest in Aotearoa New Zealand. However, there could be sustainability issues (with direct and indirect effects to other parts of the ecosystem) if the scale of this industry increases.

2.2 Harvest of wild seaweed from artificial structures

Marine farmers are permitted to harvest several species of seaweed if they naturally settle on their marine farm (Bradly et al. 2021). These include:

- Bladder kelp (*M. pyrifera*)
- Bull kelp (*Durvillea* spp.)
- Karengo (*Porphyra* spp.)
- Lessonia (*L. variegata*)
- Agar weed (*Pterocladia* spp.)
- Sea lettuce (*Ulva* spp.)
- Gracilaria weed (*Gracilaria* spp.)

Figure 3. Wakame (Undaria pinnatifida) attached to mussel aquaculture ropes in Marlborough, New Zealand (Photo Cawthron Institute)

Harvest of the unwanted species wakame (*U. pinnatifida*) from marine farms is also permitted provided the farmer has consent to do so and approval under the Biosecurity Act 1993 (Bradly et al. 2021; Figure 3). Data on seaweed harvested from marine farms is not available but are likely to be minimal, although interest in wakame is growing (White & White 2020). Similar to wild harvest from natural beds, harvesting seaweed from artificial structures (e.g., associated with ports or aquaculture) poses risks associated with the transfer of disease and pests (Cunningham et al. 2020). This includes, for example, the release of biofouling pests or pathogens into the environment via hull fouling or equipment (Cunningham et al. 2020). Aside from biosecurity and disease risks, harvest of fouling seaweed communities from artificial structures is likely to be environmentally benign as there may be little or no disturbance of natural habitat associated with harvest. Indeed, harvest of these seaweeds may have a commercial benefit by reducing crop loss in shellfish aquaculture where seaweeds would have otherwise exerted sufficient drag to detach crop on which they have grown. Harvest of wakame on either artificial or natural substrates could conceivably reduce propagule pressure on the surrounding environment, which may have some environmental benefits. However, as harvest is most likely to occur in areas where the target species is abundant, these potential benefits may be limited.

2.3 Collection of beach-cast seaweed

The commercial use of beach-cast seaweeds dates back to the 1940s when Aotearoa New Zealand was isolated from its Asian supply of agar due to the Second World War (Zemke-White et al. 2005). This led to the development of a small-scale domestic industry for the harvest of agar weed (*Pterocladia* spp.). Beach-cast collection is still the primary method of wild harvest in Aotearoa New Zealand, with an average of 390 tonnes (wet weight) harvested each year between 2006 and 2018, largely as a source of Greenshell™ mussel spat (Figure 4; White & White 2020). In addition to agar extraction and spat supply, the other key uses for beach-cast seaweed in Aotearoa New Zealand are as feed for cultured pāua and the production of agricultural fertilisers (Zemke-White et al. 2005). Species collected include brown kelp (*E. radiata*), bladder kelp (*M. pyrifera*), *Lessonia* spp., bull kelp (*Durvillea* spp.), agar weed (*Pterocladia* spp.), gracilaria weed (*A. chilense*), and *Gigartina* spp. (Zemke-White et al. 2005). Beach-cast seaweed may also be removed for non-commercial purposes, including beach grooming to remove offensive build-ups of seaweed and private harvest for use in garden fertiliser.

Figure 4. Beach-cast seaweed on Te Oneroa-a-Tōhē (Ninety Mile Beach) (Photo Bruce Green/Cawthron Institute).

Beach-cast seaweed is an important component of natural ecosystems, with up to 25% of annual kelp production cast ashore (Zemke-White et al. 2005). As this seaweed decomposes it can provide both particulate and dissolved nutrients to near-shore communities (Kirkman & Kendrick 1997), and directly or indirectly provide food to many species including crustaceans, insects, fish, birds (Kirkman & Kendrick 1997) and lizards (Barrett et al. 2005). When deposited on the high shore, beach-cast seaweed can also provide habitat for the development of dune-forming vegetation (Zemke-White et al. 2005). Furthermore, if washed back into the sea, drift seaweed can play important roles as habitat, mode of dispersal, and food (Zemke-White et al. 2005).

Undesirable effects associated with the harvest of beach-cast seaweed depend on the scale and intensity of harvest and can include the physical disturbance that may occur during harvest, the removal of resources for terrestrial coastal and near-shore communities, and the risk of spreading disease and pests. The mode and scale of collection may mean that the disturbance is inconsequential. For example, hand-picking in culturally significant areas means minimal vehicle use is required. Or in the case of mechanical harvesting, the small number of days that beach-cast seaweed is collected (e.g., < 40 days per annum on Te Oneroa-a-Tōhē; pers. comm. Dave Taylor, Aquaculture New Zealand, 31 August 2021). Negative effects of disturbance could be greater where harvest requires trampling on rocky shores, disruption of shorebird populations, or harvesting by mechanical means.

Similarly, effects on decomposer communities and food webs may be slight. In some cases, the target species represent a relatively small component of the total beach-cast seaweed (Schiel & Nelson 1990), and in that case, the food web may remain largely unaffected. The collection of beach-cast seaweed from an Australian estuary was shown to create temporary (in the order of days to weeks) changes to ecological communities and mimic the natural flushing of beaches over the longer term (Lavery et al. 1999). However, large-scale or frequent removal of beach-cast seaweeds may remove an important food source from the food web.

While the collection of beach-cast seaweeds is unlikely to have environmental benefits, social benefits (beyond economic) are possible, particularly where rotting beach-cast can become unpleasant. For example, removing sea lettuce (*Ulva* spp.) from Tauranga Harbour costs the council tens of thousands of dollars a year (White & White 2020). In the case of sea lettuce, its high sulfur content (resulting in release of hydrogen sulphide during decomposition; White & White 2020) means that removal may be considered to have some environmental benefits, however the decomposition of beach-cast seaweed is a natural phenomenon, so the value of changing this process is debatable. Another example of wider societal benefits includes the gifting of seaweed from Te Oneroa-a-Tōhē to iwi for re-seeding over rocky reefs to enhance local mussel beds (pers. comm. Dave Taylor, Aquaculture New Zealand, 31 August 2021).

3. Ecosystem services provided by seaweed aquaculture

Ecosystem services are the benefits that people obtain, directly or indirectly, from ecosystems (Millennium Ecosystem Assessment 2005). These services can be separated into four categories: provisioning, regulating, supporting and cultural (Table 1). Provisioning services refer to the capacity of ecosystems to create biomass and thereby produce goods such as food, raw materials, and energy resources. Regulating services are benefits obtained from the ability of ecosystems to regulate ecological processes (e.g., bioremediation of pollutants, climate regulation via carbon sequestration, and protection of the coastline). Supporting services are those that are necessary for the production of all other ecosystem services (e.g., the provision of habitat). Cultural (societal) services are the non-material benefits that people obtain from ecosystems through spiritual enhancement, cognitive development, reflection, recreation and aesthetic experiences.

The primary purpose of seaweed aquaculture is generally to deliver provisioning services (i.e., seaweed biomass grown as a resource to produce commodities). However, seaweed cultivation has the potential to create a range of benefits beyond the provision of goods. Here we use an ecosystem service framework (Table 1) to consider the full suite of benefits provided by seaweed aquaculture. The aim of this section to is highlight the broader benefits that can arise when seaweeds are cultivated to produce a commercially valuable output, with a particular focus on benefits that flow to people via maintenance or improvement of environmental functioning (rather than directly to people). Therefore, we consider provisioning services only briefly in Section 3.1 and focus principally on the delivery of supporting and regulating services (Section 3.2 and 3.3). Cultural (societal) services can be difficult to generalise, due to their place-specific nature, so our assessment of these services is kept to a high-level (Section 3.4). Although many of the services provided by seaweed aquaculture are similar to those provided by wild seaweed beds, there are important differences between the two systems that will be discussed in the following sections.

We draw upon a range of examples to describe how, when and where service delivery may occur, noting that ecosystem services provision is influenced by a range of factors. Research on the ecosystem services associated with aquaculture is still at a fairly early stage (see review by Gentry et al. 2020). Accordingly, the necessary quantification, valuation and market development of these ecosystem services in relation to seaweed aquaculture are still lacking (Naylor et al. 2021), but examples are provided where possible. By recognising the broad range of ecosystem services provided by seaweed aquaculture, we hope to demonstrate the full value potentially provided by this industry. Seaweed aquaculture, and the development of associated operational practices that enhance ecosystem service delivery, could be further incentivised through payment for these wider ecosystem services (e.g., similar to that occurring for the Great Barrier Reef https://greencollar.com.au/reef-credits/).

Table 1. Descriptions of ecosystem services provided by seaweed aquaculture (modified from Beaumont et al. 2007).

Provisioning services
Food: *The extraction of marine organisms for human consumption*
Raw materials: *The extraction of marine organisms for purposes other than human consumption*
Regulating services
Bioremediation of waste: Role of marine organisms in removing pollutants through storage, burial and recycling
Gas and climate regulation: The balance and maintenance of the chemical composition of the atmosphere and oceans by marine living organisms
Coastal protection[1]: Natural defense of the coastal zone by living marine organisms (and farm structures, in the case of seaweed aquaculture) against inundation and erosion from waves, storms or sea level rise
Support services
Habitat provision[2]: Habitat that is provided by living marine organisms (and farm structures, in the case of seaweed aquaculture)
Resilience and resistance: The extent to which ecosystems can absorb recurrent natural and human perturbations and continue to regenerate without slowly degrading or unexpectedly flipping to alternate states
Cultural (societal) services[3]
Spiritual and physical connection with marine environments (e.g., traditional practices of seaweed harvesting, taonga species)
Sense of place and livelihood (e.g., employment opportunities, alternative income)
Tourism and recreation (e.g., ecotourism, food tourism, recreational fishing)
Education and research (e.g., education-orientated activities, pilot-scale experiments)
Non-use benefits (e.g., existence value, bequest value)

[1] From Liquete et al. (2013)

[2] Referred to as 'Biologically mediated habitat' by Beaumont et al. (2007)

[3] From Custódio et al. (2020)

3.1 Provisioning services

Provisioning services refer to the capacity of ecosystems to create biomass, which can be used for human consumption or other purposes (Beaumont et al. 2007). The delivery of provisioning services is generally the primary motivation for seaweed cultivation. In this section, we briefly overview the key provisioning services offered by seaweed aquaculture but direct the reader to Bradly et al. (2021) for a more comprehensive review of the current status of seaweed markets in Aotearoa New Zealand and internationally.

Figure 5. Seaweed can be used as fresh and dried ingredients in food (Photo Bruce Green/Cawthron Institute).

Seaweeds have long been consumed for food in Asian countries (Hotchkiss & Murphy 2014) and are becoming increasingly popular as a food source worldwide due to their high vitamin, mineral and plant protein contents (Macartain et al. 2008, Abreu et al. 2014, Boukid et al. 2021; Figure 5). Wheeler et al. (2021) provides a comprehensive review of the nutritional composition of key Aotearoa New Zealand seaweed species. In addition to direct consumption, seaweeds are used as thickening agents in foods and beverages (e.g., alginate, agar, carrageenan; Pereira et al. 2014, Carvalho & Pereira 2014). Seaweeds are also grown for purposes beyond human consumption. These range from low-value commodities such as biofuels (Gao et al. 2020), animal feed (Dantagnan et al. 2009) and fertilisers (Wang et al. 2016, Sathya et al. 2010), to high value ingredients used in cosmetics (Pereira et al. 2014, Balboa et al. 2015), nutraceuticals (Himaya & Kim 2015, Nadeeshani et al. 2021) and pharmaceuticals (Carvalho & Pereira 2014, Smit 2004). Bradly et al. (2021) provides further detail on the commodities produced from cultivated seaweed.

In addition to the direct provision of food and raw materials, seaweed aquaculture can also indirectly augment or diminish food provision services obtained from wild fisheries. Augmentation may occur if fish are attracted to the habitat provided by seaweed farms (see *Habitat provision* Section 3.3.1 for further details). However, the long-term sustainability of an increase in food provision arising from the harvest of fish (recreationally or commercially) around seaweed farms depends on whether farms aggregate fish from the wider area, making them more vulnerable to capture by humans, or enhance populations due to the provision of additional habitat and food. Seaweed farms can also reduce people's ability to catch wild fish because the presence of farm structures can interfere with or exclude some fishing methods (e.g., trawling, dredging).

3.2 Regulating services

3.2.1 Bioremediation of waste

Bioremediation refers to role that marine organisms play in removing pollutants via storage, burial and recycling (Beaumont et al. 2007). Coastal areas act as a sink for pollutants (e.g., nutrients and metals) arising from rural, urban and industrial activities. As primary producers, seaweeds remove nutrients (e.g., nitrogen, phosphorus, carbon) from the water to fuel their growth, converting these substances into molecules such as proteins and pigments. Seaweeds also have the capacity to accumulate metals and other contaminants, reaching concentrations thousands of times higher than the surrounding seawater (Akcali & Kucuksezgin 2011). Due to their ability to extract substances from the water as they grow, seaweeds are often referred to as 'biofilters', 'nutrient scrubbers' or ‘biosorbents’ (e.g., Gadd 2009, Troell et al. 2009, Wu et al. 2017). To achieve the ecosystem service of bioremediation, the seaweed biomass needs to be harvested and removed from the system where it has grown, thereby removing the assimilated nutrients and contaminants. Ideally, the harvested biomass is subsequently utilised to produce bioproducts (refer *Provisioning services* Section 3.1), although this can be constrained by the quality (e.g., content of nutrients, heavy metals, organic contaminants, and microorganisms) of the harvested seaweed and social acceptance of the product.

This section focuses primarily on bioremediation of nutrients (nitrogen and phosphorus), but we recognise that seaweed can also bioremediate metals and other contaminants (Kim et al. 2019, Wang et al. 2014b, Luo et al. 2020, Evans & Edwards 2011, Amado Filho et al. 1997). Seaweed can utilise a broad range of dissolved nutrients, including urea, ammonia, and organic phosphorus, as well nitrate and inorganic orthophosphate (Phillips & Hurd 2003, Roleda & Hurd 2019). Different cultivation strategies (land based, marine farms, and integrated multitrophic aquaculture, IMTA) are compared. The importance of appropriate species and cultivar selection for the cultivation strategy are also considered. The current status and future trends for bioremediation both internationally and within Aotearoa New Zealand are discussed further in Appendix 1.

Cultivation strategies for bioremediation

The cultivation strategy of seaweeds used for bioremediation will influence not only the choice of species for cultivation, but also the way any bioremediation effect or potential is quantified. Strategies include land-based farms, marine farms, and IMTA, which can be implemented both in land-based farms and on marine farms. The cultivation of seaweed specifically for bioremediation purposes is primarily constrained to land-based systems (e.g., Bolton et al. 2009, Mata et al. 2010), while ocean-based seaweed aquaculture is predominantly focused on the production of biomass, with bioremediation as a secondary benefit. This incidental bioremediation (i.e., where bioremediation is a by-product of cultivation for a different purpose) is an example of the broader ecosystem services that arise when seaweeds are farmed for the provision of goods. In terms of environmental effects, ocean-based and IMTA bioremediation are of particular interest. Land-based bioremediation can be used to prevent or limit coastal eutrophication, and this is considered in Box 1 (and Appendix 1).

Box 1: Land-based algal bioremediation

Land-based macroalgal aquaculture is typically performed in raceway type systems (also referred to as high rate algal ponds) or large parabolic tanks (Figure 6), which are fed by nutrient-rich effluent from a point source discharge (e.g., land-based aquaculture farms). Algae are typically maintained as a free-floating, non-attached 'tumble-culture', although filamentous algal turf scrubbers (ATS) are also in use. In ATS, the nutrient-rich water is allowed to flow over a mat of attached algae, often a mixed assemblage of species, growing on screens in shallow troughs or raceways. While ATS has been trialled with seaweed (Ray et al. 2015), they are more commonly implemented in freshwater systems (Mulbry et al. 2005, 2008, Craggs et al. 1996). Advantages of land-based systems include the potential for high-intensity (i.e., high stocking density) cultivation yielding high annual areal productivity (tonnes dry weight ha^{-1} $year^{-1}$), frequent (typically at least weekly) harvesting, and the capacity to manage biomass productivity, and in some regards composition, by varying water exchange rates and therefore nutrient flux (concentration x flow) in the system. Importantly, the performance of the system in terms of nutrient removal rate can also be managed by operational parameters. For example, biomass stocking density or culture depth and thus light availability (self-shading/light penetration), or water exchange rate (residence time) and thus nutrient availability (Cole et al. 2014, Mata et al. 2010). Land-based systems can be designed as one-pass flow through (e.g., pacificbio.com.au and vikingaquaculture.co.za) or as recirculating aquaculture systems (Mata et al. 2016, Revilla-Lovano et al. 2021). In both systems, nutrient removal and bioremediation of other undesired contaminants result not only from direct assimilation by the macroalgae, but also from the physical environment of the cultivation system, and from microbial processes. For example, the freshwater macroalga *Oedogonium* was cultivated in aerated parabolic tanks for 8 weeks with primary effluent from a domestic wastewater treatment plant as the nutrient source, added at a rate of 5% (v:v) per day (final proportion of primary effluent 90%) (Neveux et al. 2016). Along with reductions in chemical oxygen demand (57%), and concentrations of nitrogen (62%) and phosphorus (75%), there was a 99% reduction in the concentration of microbes (*E. coli*, *Pseudomonas aeruginosa*, faecal and total coliforms) and metals (including arsenic, cadmium, lead and zinc; Neveux et al. 2016). The high UV-irradiance and the highly oxygenated environment resulting from algal photosynthesis and system aeration lead to this degradation and reduction of organic compounds and microbes. In land-based systems, these combined processes of bioremediation occur in a one-way system, typically with a point source of influent nutrient rich wastewater, and with a point source discharge of bioremediated water low in nutrients. The outcome is that bioremediation capacity and nutrient removal can be quantified as the concentration of dissolved nutrients in the influent vs. effluent water, thus delivering a direct determination of the quantity of nutrients removed by the whole system.

Figure 6. Land based cultivation systems. Left: High rate algal ponds, PacificBio, Australia. One-pass flow through commercial bioremediation of prawn farm effluent using the green seaweed Ulva ohnoi (Photo G. Supple/PacificBio). Right: Aerated parabolic tanks, James Cook University, Australia. Research scale recirculating system, here stocked with the filamentous green freshwater alga Oedogonium (Photo R. de Nys,/James Cook University).

Ocean farming for algal bioremediation

Diffuse nutrient loading to coastal environments (e.g., nutrient runoff from land) is difficult to regulate due the broad and incremental nature of these inputs. Natural biofilters, like seaweeds, are one of the few tools available to mitigate nutrient pollution once it has entered our oceans (Racine et al. 2021). The absence of point source influent and effluent water, and the 'leaky' nature and rapid dilution of existing point sources (e.g., open-water fish farm cages) means the bioremediation effect needs to focus on ecosystem level impacts (e.g., entire bay/estuary) rather than a point source direct offset. Due to the challenging nature of directly quantifying algal bioremediation using water quality measures in an open and dynamic system, the most direct and simple measure to use is the concentrations of nitrogen and phosphorus (or any other target compound) in the seaweed tissue (Box 2).

In contrast to land-based pond and tank systems, ocean farming of seaweed is extensive in nature (i.e., areal stocking densities are comparatively low due to the need for space for manoeuvring service vessels). Additionally, particularly for smaller growing species (e.g., karengo or *Kappaphycus*/*Eucheuma*), only the upper layer of the water column is used (Figure 7). Ocean farming allows for one to a few crops per year, as opposed to the much more frequent (daily to weekly; Mata et al. 2010, 2016, or in some case monthly; Revilla-Lovano et al. 2021) harvesting of land-based intensive seaweed cultivation systems.

The ability of ocean-based seaweed aquaculture to remove nutrients has been demonstrated in a range of studies (e.g., He et al. 2008, Kim et al. 2014, Huo et al. 2011). For example, *Gracilaria* cultivation was associated with an improvement in water quality and a reduction in ammonium and nitrate levels (54% and 76%, respectively) and the concentrations of red tides species in China (Huo et al. 2011). Large-scale seaweed aquaculture in China removes approximately 75,000 t nitrogen from coastal waters annually, helping to mitigate coastal eutrophication (Xiao et al. 2017).

Despite the potential for seaweed farming to assimilate nutrients, the scale of farming required to completely offset anthropogenic nutrient inputs may be unrealistic. China, the largest producer of seaweed globally, would need to increase its production area by 17 times to remove the nitrogen entering its coastal waters (Xiao et al. 2017). In a scenario more relevant to remediation potential in Aotearoa New Zealand, it has been shown that even the seaweed biomass required to compensate for effluent generated by a typical salmon farm is much greater than that produced by a small to medium-sized seaweed farm (Campbell et al. 2019). Yet, large-scale seaweed farming may not be ubiquitously feasible due to restrictions on suitable marine space (Stelzenmüller et al. 2017), the need for social licence (Krause, et al. 2020) or even the carrying capacity of the environment (Duarte et al. 2003). For example, seaweed farming may have negative effects if nutrient levels are reduced below that required for natural populations of primary producers such as phytoplankton and wild kelp forests (Park et al. 2018, Shi et al. 2011; refer *Changes in nutrients* Section 4.2). As such, seaweed aquaculture cannot be expected to replace land-based nutrient management but could act as part of a suite of management tools. Refer to Appendix 1 for further discussion of the current status and future trends of ocean-based bioremediation.

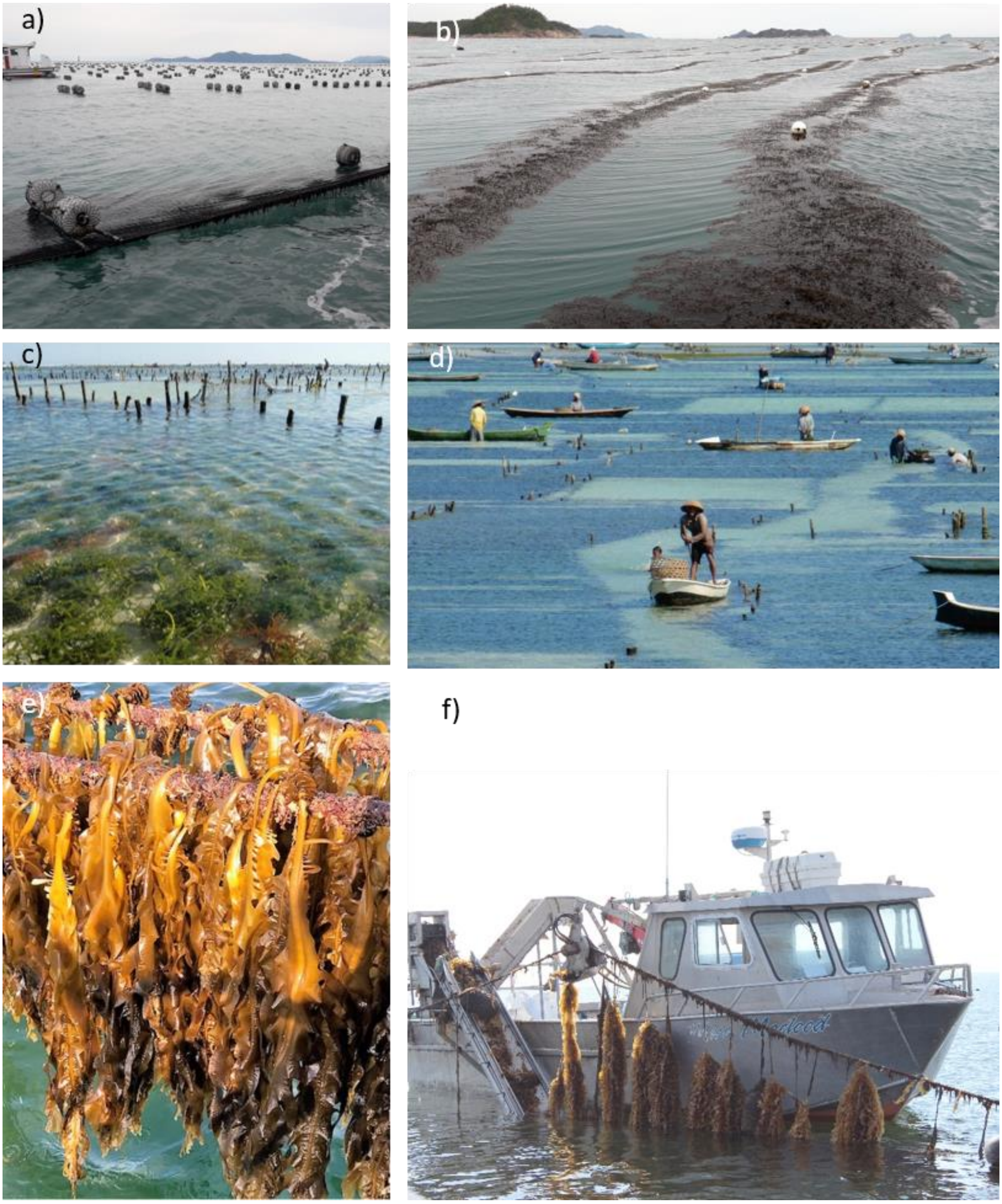


Figure 7. Ocean farming systems a) Pyropia (nori) on horizontal nets, Korea, b) Sargassum fusiforme (Hijiki) on long lines, Korea, c – d) shallow water farming of Kappaphycus, Indonesia, e) Undaria pinnatifida (wakame) on longlines, Aotearoa New Zealand, f) Saccharina lattisima on longlines, Denmark (Photos a-d Marie Magnusson/University of Waikato, e Lucas Evans/Premium Seas, f Annette Bruhn/Aarhus University).

Integrated Multitrophic Aquaculture

Integrated Multitrophic Aquaculture, or IMTA, combines the farming of fed (e.g., finfish, shrimp) and extractive (suspension- or deposit feeders, or algae) species (Chopin 2013, Neori et al. 2004). By farming such species in proximity to each other, the wastes and by-products from the fed species becomes the nutrient resource for the extractive species, with the potential to ameliorate enrichment effects and increase seaweed biomass (Wang et al. 2014a). For example, *Agarophyton chilense* cultivated in a small-scale experiment near a salmon farm in Chile achieved up to 40% higher seaweed growth rates than controls (Troell et al. 1997). Extrapolation showed that 1 ha of seaweed grown close to the fish pens had the potential to remove at least 5% of the dissolved nitrogen from the farm, reducing the nitrogen waste footprint by more than half (Troell et al. 1997, 1999). IMTA typically falls under one of the following categories: 1) the addition of a complementary species to an existing aquaculture farm, 2) custom designed new operations, or 3) incidental IMTA that occurs due to spatial proximity between different farms (Reid et al. 2020). There are also arguments that the IMTA concept should be interpreted at an integrated scale from land-ponds to coastal aquaculture systems over scales larger than individual farms or bays (Chopin 2013). From this perspective, most seaweed farming can be interpreted as IMTA, and in practice, quantification of bioremediation (nutrient extraction) capacity follows the same methods as for ocean farming (Box 2). Refer to Appendix 1 for further discussion of the current status and future trends of IMTA-based bioremediation.

Box 2: Quantifying bioremediation

Quantifying bioremediation services from ocean-based and Integrated Multitrophic Aquaculture (IMTA) primarily relies on measuring the concentration of nutrients or metals in the seaweed tissue (e.g., % dry wt) and multiplying it by the harvested biomass (e.g., t dry wt ha^{-1} cultivation area yr^{-1}) to calculate nutrient or metal sequestration (e.g., Park et al. 2021). Using this approach, Bjerregaard et al. (2016) calculated that seaweed farming in 2050 (predicted 500 million tons dry weight) could remove a third of the nitrogen (N) entering the oceans (10 million tons). The associated economic value of this bioremediation service can then be assessed using market rates. For example, Kim et al. (2014) estimated the economic value of N sequestration associated with *Graciliaria* cultivation in Long Island Sound, Connecticut (USA) to be between US$147-940 ha^{-1} if seaweed aquaculture was included in Connecticut's Nitrogen Trading Program. Using the cost to recover nitrogen and phosphorus at wastewater treatment plants, Chopin and Tacon (2021) calculated that the nutrient bioremediation service provided by global seaweed aquaculture is worth between US$1.2-3.5 billion. This value equates to more than a quarter of the present commercial value of seaweed (Chopin & Tacon 2021). Hence, not only is nutrient removal via seaweed farming likely to be more cost-effective than terrestrial-based methods of nutrient pollution control (Racine et al. 2021, Kim et al. 2014), this bioremediation service has the potential to generate additional revenue for farmers if recognised in nutrient trading schemes (e.g., BenDor et al. 2021; Reef Credit Scheme 2017). It has been calculated that more money could be made by trading nutrients (valued at US$10-30 kg^{-1} N and US$4 kg^{-1} P) than carbon (valued at US$0.03 kg^{-1} C; Chopin & Tacon 2021). However, nutrient trading is currently not available in Aotearoa New Zealand (Bradly et al. 2021). Appendix 1 (Section A2.3) provides further information on drivers and incentives for adoption of seaweed bioremediation.

More holistic approaches to quantifying and modelling nutrient transfer between trophic levels and whole-of-farm nutrient budgets include seaweed growth models (Hadley et al. 2015, Broch et al. 2013) and complex farm spatial/ecological ecosystem scale modelling (Fan et al. 2020). Stable isotope analysis can be used to trace connectivity in nutrient assimilation between trophic levels. For example, nitrogen isotope ratio (δ15N) tracing has been used to directly quantify the source of dissolved inorganic nitrogen assimilated in sugar kelp (*Saccharina latissimi*) cultivated near salmon cages in exposed waters in Norway (Wang et al. 2014a). Sugar kelp cultivated near the salmon farm had a 50% higher increase in frond length compared with kelp cultivated at a reference station, and the δ15N in the seaweed tissue changed concurrently with the δ15N signature in urine from the salmon farm, indicating direct uptake from farm effluent. See Reid et al. (2020) for a comprehensive review covering various performance measures and models for IMTA.

Bioremediation potential

The bioremediation potential of seaweed aquaculture depends on the species farmed, the scale of farming, and the environmental conditions. Species selection for high nutrient or contaminant assimilation capabilities, robustness, fast growth rates (productivity), and capacity for harvest are key factors for delivering consistent bioremediation (Lawton et al. 2013, Lawton et al. 2021, Kang et al. 2021). This is critical in land-based systems where year-around production is a primary aquaculture target, and therefore ongoing remediation of the point-source discharge across seasons, is required. This necessitates species that are adapted to variable conditions, and robust enough to be tolerant to environmental extremes, which often means intertidal species.

Selection of specific cultivars can be just as critical as the selection of a suitable species. For example, a recent study aimed at selecting species and cultivars of sea lettuce (*Ulva* spp.) for land-based production in Aotearoa New Zealand found 2-fold differences in productivity (g dry weight m^{-2} day^{-1}) between cultivars and growth morphology within the same species (Lawton et al. 2021). Similar large (2.1 to 8.4-fold) inter-cultivar variation in area-specific growth rates has been demonstrated in *Ulva* spp. previously (Fort et al. 2019, 2020).

Ocean-farmed species of seaweed are typically selected with a specific commodity or high-value end-product in mind (e.g., hydrocolloids or food), rather than for their capacity to provide ecosystem services in the form of nutrient remediation. Nevertheless, cultivar selection and selective breeding efforts remain aimed at higher biomass productivities (Hwang et al. 2019, Zhang et al. 2007) as these normally translate to higher yields of the target product, along with selection efforts for increased disease resistance, temperature tolerance, extended or shifted growth periods, and improved nutritional profiles (Hwang et al. 2018, 2014, 2020a). Development of molecular breeding techniques started emerging for the main seaweed crops in the early 2000s (Xu et al. 2015, Kim et al. 2011, Hwang et al. 2020b, Hwang et al. 2019, Hu et al. 2021). In principle, the same selection criteria of robustness, productivity, and capacity for harvest apply for selecting seaweed species and cultivars for bioremediation by ocean farming as for land-based farming. Refer to Section 4.4 for a consideration of the negative environmental effects that may arise from interactions between selectively-bred seaweeds and wild populations.

Nutrient recycling efficiency can be optimised through site selection (e.g., position in relation to nutrient sources and prevailing currents; Chopin et al. 2008). Coupled hydrodynamic-biological models (e.g., Shi et al. 2011) can be used to estimate sources and sinks of nitrogen to ensure that seaweed farming maximises bioremediation potential without negatively affecting the environment.

3.2.2 Gas and climate regulation

Gas and climate regulation refers to the balance and maintenance of the chemical composition of the atmosphere and oceans by marine living organisms (Beaumont et al. 2007). As seaweeds grow, they remove dissolved inorganic carbon (DIC) from the seawater and store it in their tissues as organic carbon via the process of photosynthesis. The removal of DIC decreases the partial pressure of CO_2 in the seawater, triggering oceanic uptake of CO_2 from the atmosphere (Jiang et al. 2013, Delille et al. 2009). As such, the cultivation of seaweed has the potential to reduce CO_2 levels in the atmosphere, thereby mitigating the effects of climate change. For example, Duarte et al. (2017) estimate that seaweed aquaculture could capture up to 2.48 million tonnes of CO_2 per year. This means that each km^2 of seaweed aquaculture offsets the annual CO_2 emissions of approximately 200 New Zealanders[1] (Duarte et al. 2017). Climate change mitigation would have benefits for marine species and ecosystems as well as directly for human communities.

[1] Based on 2017 value of 7.6 tonnes of CO_2 emissions per capita in Aotearoa New Zealand (https://ourworldindata.org/co2/country/new-zealand)

The length of time that carbon is sequestered depends on the fate of the seaweed, with most of the carbon stored in harvested seaweeds likely to be released back to the atmosphere at some stage in the lifecycle of the final product (Figure 8; Park et al. 2021). For example, carbon will be rapidly regenerated via respiration if seaweed is consumed as food, providing no net climate benefit. Conversely, seaweed that is used to create more durable products (e.g., bioplastics) will store carbon for longer. Despite the transient nature of this carbon sequestration, seaweed aquaculture can still have net positive benefits for climate change mitigation if seaweed-based products are used to replace commodities with higher greenhouse gas footprints. For example, by substituting fossil fuels for seaweed biofuel (e.g., Chen et al. 2015) or producing animal feeds that reduce methane emissions (e.g., Zhu et al. 2021).

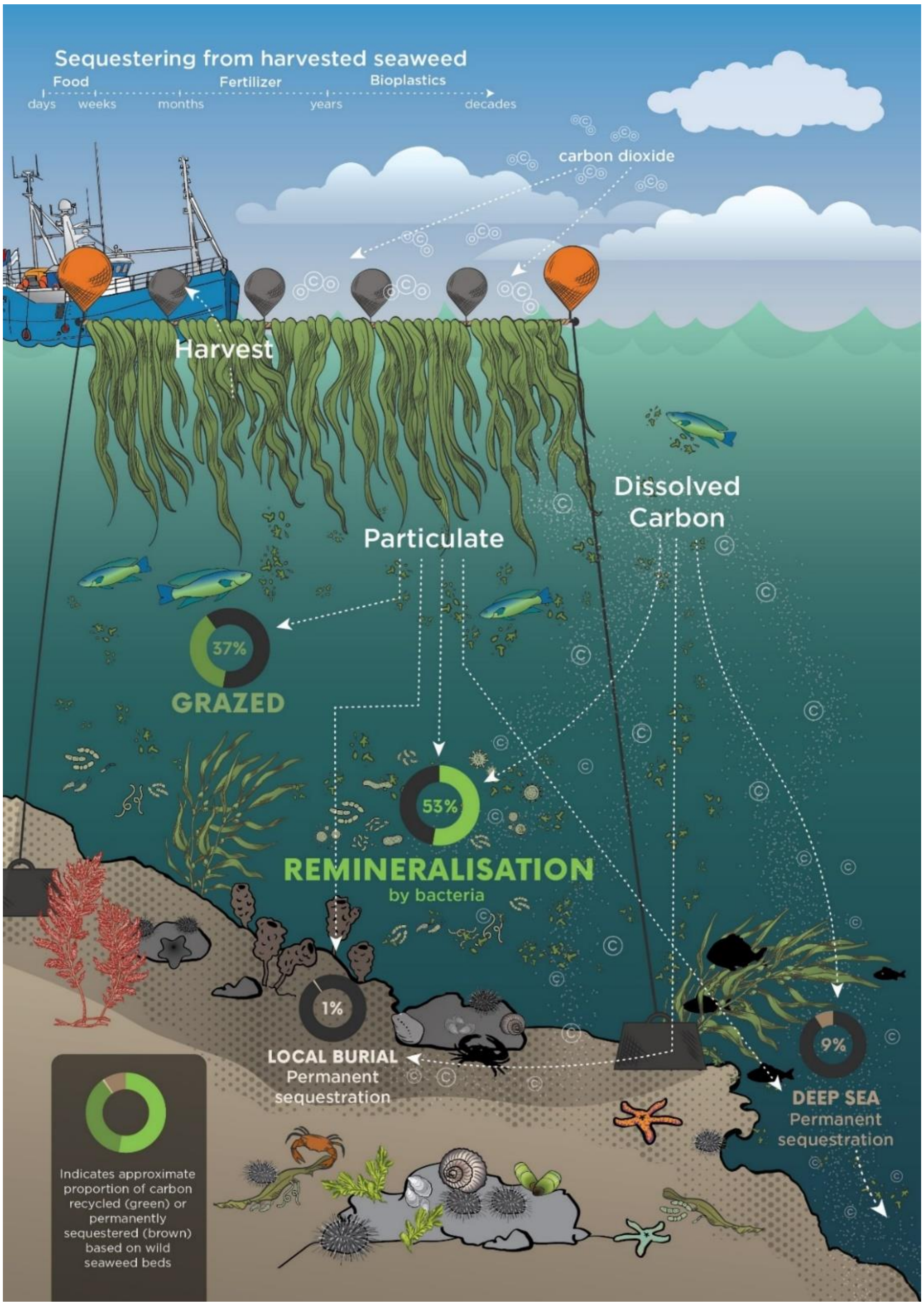


Figure 8: Pathways of carbon flow from seaweed aquaculture based on measurements and calculations of carbon sequestration pathways in wild seaweed beds (Krause-Jensen & Duarte 2016). The amount of carbon removed from the ocean in harvested seaweed is not quantified. Graphic by Revell Design.

Although much of the carbon sequestered by farmed seaweeds is likely to be released back into the atmosphere post-harvest, some carbon will be permanently sequestered in the ocean. Seaweed fragments that are exported to the deep sea (> 1000 m depth), or which become buried in the seafloor sediments, represent long-term carbon storage by removing carbon from the ocean-atmosphere pool (Krause-Jensen & Duarte 2016, Gundersen et al. 2021). Carbon is also released from seaweeds in the form of dissolved organic carbon (DOC), which are organic molecules dissolved in water (e.g., Wada et al. 2007). Although most of this carbon is remineralised back to CO_2 when it is consumed by microbes, a proportion of DOC is thought to be resistant to biological decomposition (e.g., Wada et al. 2008, Bauer et al. 1998). This refractory DOC will be permanently sequestered if it is exported below the mixed surface layer of the water column. While seaweed deposited in the deep ocean is likely to sequester carbon for centuries (Krause-Jensen & Duarte 2016), it is unknown how long carbon will be retained within near-shore seafloor sediments (Hill et al. 2015).

In wild seaweed beds, approximately 9% of carbon from net primary production is exported to the deep sea and 1% is buried in seafloor sediments (Figure 8; Krause-Jensen & Duarte 2016). Due to the large biomass of wild seaweeds, this represents a vast global store of carbon (between 61 to 268 Tg C yr^{-1}; Krause-Jensen & Duarte 2016) and is comparable to the amount of carbon collectively sequestered by salt marshes, mangroves and seagrasses (Duarte et al. 2013). However, it is not clear how sequestration pathways would differ between wild populations and cultured seaweeds. For example, as harvest is likely to occur before large amounts of product are lost, cultured seaweeds may contribute much less particulate matter to the environment than their wild counterparts. On the other hand, seaweed farms are typically located over soft sediments, and therefore the potential for any fragments that are generated to be sequestered in the sediments is greater than for detritus originating from wild seaweed growing on rocky substrata. Further research is required to quantify the amount of carbon permanently sequestered in seafloor sediments and the deep ocean following export from seaweed aquaculture (refer Oceans 2050 project https://www.oceans2050.com/seaweed). Sequestration rates are likely to vary depending on the location of the farm relative to habitats suitable for permanent sequestration (i.e., undisturbed soft sediments or the deep ocean), the species farmed, and the stage of growth at which seaweeds are harvested. For example, large, long-lived species have greater potential for carbon sequestration (Cebrian & Duarte 1995). Seaweeds with buoyancy mechanisms (e.g., pneumatocysts of Fucales and Laminariales) facilitate long-distance transport, where they can sink to deep sea environments once buoyancy structures degrade (Krause-Jensen et al. 2018). Additional carbon may also be taken up by filter feeding biofouling organisms living upon the farm structures (e.g., ascidians; Tang et al. 2011), but like seaweeds, the long-term storage of this carbon depends on the fate of these organisms. Box 3 outlines how to quantify the economic value of carbon sequestration.

Box 3 – Carbon offsetting with cultured seaweeds

If the potential for permanent carbon sequestration from seaweed aquaculture is significant, then the industry may benefit from financial and regulatory incentives to encourage seaweed farming (Chopin & Tacon 2021, Duarte et al. 2017). Carbon offsetting, where credits are received for reducing, avoiding or sequestering carbon, is one such scheme (van Kooten et al. 2004). Farmers could sell carbon credits to emitters in return for growing seaweed that will be permanently sequestered via disposal in the deep ocean (e.g., Running Tide, https://www.runningtide.com/removing). Alternatively, farmers may be required to grow seaweed alongside other forms of aquaculture (e.g., crustaceans, finfish) to offset their emissions (Froehlich et al. 2019). As noted in Bradly et al. (2021) the New Zealand Emissions Trading Scheme does not allow for seaweed-based blue carbon credits. However, voluntary certification markets are emerging globally, and may provide revenue opportunities both domestically and internationally in the absence of domestic regulated trading markets.

The economic value of the carbon sequestered by seaweeds can be calculated in a similar manner to that used to quantify bioremediation services. The carbon content of seaweed (e.g., % dry wt) is multiplied by the harvested biomass (e.g., t dry wt yr^{-1}) and then converted to an economic value using market rates for carbon trading credits (e.g., Sondak & Chung 2015). Using this approach, Chopin & Tacon (2021) demonstrated that carbon sequestration by global seaweed aquaculture is worth approximately US$29 million, a comparable value to that estimated for seaweed aquaculture in the Asia-Pacific region (Sondak et al. 2017). Similarly, Kim et al. (2014) estimated the economic value of carbon sequestration associated with *Graciliaria* cultivation in Long Island Sound, Connecticut (USA) to be between US$2.59-13.32 ha^{-1} if seaweed aquaculture was included in Connecticut's Nitrogen Trading Program. However, these studies, like many, do not consider the long-term fate of the carbon stored in harvested seaweed. A complete lifecycle assessment (e.g., Langlois et al. 2012) is required to understand the overall contribution that seaweed aquaculture makes to climate change mitigation (Hasselström et al. 2018).

It should be noted that the scale of seaweed required to offset a substantial portion of global carbon emissions is not feasible, nor would it be desirable. For example, mitigation of CO_2 emissions arising from global agriculture (12% of total global emissions) would necessitate increasing the area of seaweed aquaculture from 1.9 thousand km^2 to 7.3 million km^2, which is twice the area currently occupied by wild seaweed (Froehlich et al. 2019). The ecological consequences of seaweed aquaculture at large scales, including direct deposition into the deep ocean, are poorly understood (e.g., Bach et al. 2021 and Section 4). Moreover, getting resource consent for very large-scale aquaculture (> 1000 ha) could be challenging under the existing regulatory regime in Aotearoa New Zealand. Even offsetting global emissions from the aquaculture industry would require depositing 14% of worldwide aquaculture-produced seaweed into the deep ocean (Froehlich et al. 2019). Nevertheless, targeted expansion of seaweed aquaculture could be part of a portfolio of climate change mitigation tools. Bjerregaard et al. (2016) estimated that global seaweed production predicted for the year 2050 (500 million tons dry weight) would require only 0.03% of ocean space (12.5% of Aotearoa New Zealand's Exclusive Economic Zone) and could remove approximately 3.2% of the carbon added to seawater each year from greenhouse gas emissions (135 million tons). However, the value of proposed carbon tax schemes would need to be increased to incentivise farmers to bury seaweed biomass rather than sell it for more profitable applications (Chopin & Tacon 2021). For example, the estimated carbon sequestration market value for seaweed aquaculture in the Asia Pacific region is only 0.6% of the harvest value obtained for other products (Sondak et al. 2017). Additional challenges include verifying carbon uptake and sequestration for deep water disposal of seaweed (Bach et al. 2021) and tracing carbon sequestered via indirect processes (Krause-Jensen et al. 2018).

In addition to reducing atmospheric CO_2, uptake of carbon by seaweeds can also help to offset the negative effects of ocean acidification (Clements & Chopin 2017), which is a lowering of seawater pH resulting from the increased absorption of CO_2 into the oceans. Lower seawater pH has detrimental effects on calcifying organisms (e.g., shellfish, sea urchins, corals) because it makes it more difficult for them to extract calcium carbonate from the water to make their calcified structures (e.g., shells; Parker et al. 2013). Because seaweeds take up dissolved CO_2 when they photosynthesise, farming seaweeds could increase ocean pH, potentially alleviating the negative effects of ocean acidification on a local scale. Evidence to support this is conflicting, with some studies reporting positive effects (e.g., Saderne & Wahl 2013, Young & Gobler 2018, Mongin et al. 2016) and others finding no benefit (e.g., Pettit et al. 2015, Greiner et al. 2018). Ocean acidification buffering capacity will likely depend on the farmed seaweed (e.g., biomass, buffering effects, CO_2 sink capacity) and hydrodynamic conditions (Fernández et al. 2019), with greatest effects occurring where seaweed biomass is high and water flow is restricted. Sites with restricted water flow are considered less appropriate for shellfish and finfish aquaculture in Aotearoa New Zealand but existing sites could be converted to co-culture for this purpose. Further research is required to understand the dynamics between seaweed aquaculture and ocean pH, but any effects are likely to be on a local (e.g., farm or bay) rather than global scale.

Seaweed aquaculture also has the potential to mitigate other climate change effects. Ocean de-oxygenation due to warming sea surface temperatures (Keeling et al. 2010) could be offset by the oxygen produced by seaweeds as they photosynthesise. For example, Zheng et al. (2019) calculated that Chinese seaweed cultivation released 1,440,612 t of oxygen, worth US$86 million based on the cost of industrial oxygen production in China. The use of seaweed-based products could also help to transition away from high emission commodities (e.g., replacing animal-based foods with low-carbon seaweed food products), indirectly contributing to climate regulation.

3.3.3 Coastal protection

In the context of seaweed aquaculture, coastal protection refers to the role that seaweed farm structures and stock biomass play in protecting coastlines from inundation and erosion arising from waves, storms and sea level rise (Liquete et al. 2013). Much of this coastal protection will be provided by the seaweed aquaculture structures themselves, rather than the crop, apart from the cultivation of large brown seaweeds (i.e., fucoids and Laminariales). Farmed large brown seaweeds are expected to dissipate energy in a similar manner to wild kelp forests, which in some cases have no effect on wave transmission (e.g., Elwany et al. 1995) and in other places reduce wave heights by as much as 60% (e.g., Mork 1996). However, seaweeds farmed using suspended cultivation methods have greater capacity for wave attenuation than wild kelp forests because their canopies are suspended from the surface, where wave energy is greatest, rather than attached to the seafloor (Zhu et al. 2020). The matrix of interconnected farm structures also increases drag and, therefore, wave attenuation. Thus, in general terms, the wave attenuation provided by suspended seaweed aquaculture is expected to be greater than wild kelp forests and comparable to other forms of suspended aquaculture (e.g., mussels).

Research on the wave energy dissipation associated with seaweed aquaculture is limited but suggests that seaweed farms will be more effective at dissipating short period waves (e.g., those generated boat wake or wind) than the long period ocean swells that cause inundation and erosion (Zhu et al. 2020). Mussel farms have been shown to attenuate waves by 5-20%, and like seaweed farms, are most effective at reducing short period waves (Plew 2005). This suggests that role of seaweed farms in providing disturbance prevention services from larger-scale disturbances (e.g., storms, cyclones or tsunamis) may be limited. However, further research is required to understand the effects that seaweed farms would have on wave energy and thus coastal protection.

The ability for seaweed farms to prevent coastal disturbance will depend on the characteristics of the farming method (e.g., long-lines vs racks, spacing, scale), the biomass and morphology (e.g., length of fronds) of the farmed seaweed, the location of the farm relative to the coastline and its orientation relative to the prevailing swell direction (Zhu et al. 2020, Zhu & Zou 2017, Mou 2015). For example, large, dense, rigid seaweeds (e.g., bull kelp, *Durvillaea* spp.) are likely to provide the most energy dissipation. Delivery of this ecosystem service also varies with the need for coastal protection. For example, a seaweed farm protecting a stretch of uninhabited coastline would provide a limited contribution to the service of coastal protection, as would a farm located in a sheltered area where exposure is not an issue. However, this is not to say that attenuation of wave energy could not have other environmental benefits that are not directly tied to human well-being (e.g., limitation of coastal erosion, even in remote places, could benefit marine communities that are sensitive to smothering). There can also be temporal mismatches if storms, cyclones or tsunamis occur when biomass is low (Koch et al. 2009). For example, spring harvesting may reduce the protection provided by seaweed farms during autumn and winter, when seasonal storms are more likely to occur. Hence, the quantification of coastal protection services is both site and time specific, but it is likely that this service could be optimised through farm structure design and orientation.

3.3 Support services

3.3.1 Habitat provision

Habitat provision refers to habitat that is provided by living marine organisms (e.g., seaweeds; Beaumont et al. 2007), though in the case of seaweed aquaculture we extend this definition to include the artificial farm structures as well. There is substantial evidence that aquaculture farms, like other semi-permanent coastal structures, can provide novel habitat (above and below the water line) for a variety of wildlife (e.g., invertebrates, fish, marine mammals, seabirds; e.g., Barrett et al. 2019, Dempster et al. 2009, Morrisey et al. 2006, Fernandez-Gonzalez et al. 2014, Díaz López 2017). Aquaculture farms increase habitat complexity in an otherwise structureless water column. Organisms may be attracted by the three-dimensional structure and/or food provided by the farm and its associated biomass (including that of biofouling organisms), the addition of hard substrate on the seafloor (e.g., anchors) and the alteration of local hydrodynamics (refer *Physical effects* Section 4.1.1). Seaweed that breaks off and drifts away from the farm can also provide habitat for organisms (e.g., Ince et al. 2007). The value of habitat provision can be quantified in terms of the number, diversity or biomass of species using an area; however, the reproductive output and survival of inhabitants are also key considerations.

Research on the habitat provided by seaweed farms is limited but may differ from finfish or shellfish farms because seaweed cultivation does not increase food supply to the same extent (e.g., the presence of mussel drop-off or uneaten fish feed). Direct comparisons with wild seaweed beds, which are known to support high levels of biodiversity (e.g., Christie et al. 2009, Norderhaug et al. 2005, Teagle et al. 2017), may also be inappropriate because the biomass on a seaweed farm is suspended, rather than attached to the seafloor. For example, Walls et al. (2016) found that holdfast communities associated with cultivated kelp were more diverse and differed to communities in adjacent wild benthic kelp forests, although the number of individuals was comparable between habitats. Although benthic grazers (e.g., gastropods, crustaceans) will not be able to easily access suspended biomass, planktonic larval stages can still settle onto the seaweed and use it as food and habitat (e.g., Kerrison et al. 2015). Harvesting also means the capacity of seaweed farms to offer habitat will be transient and may vary depending on how and when the seaweed is harvested (e.g., Visch et al. 2020; refer *Biological effects* Section 4.1.3).

Cultivated seaweed has been shown to provided habitat for a range of invertebrates (e.g., Visch et al. 2020, Walls et al. 2016, Radulovich et al. 2015) and create favourable conditions for seafloor infauna communities in some cases (e.g., Visch et al. 2020). However, studies on the influence of seaweed farms on fish populations have produced variable results, with positive effects reported in some studies (e.g., Bergman et al. 2001, Hehre et al. 2016, Radulovich et al. 2015, Hasselström et al. 2018, Anyango et al. 2017) and neutral to negative effects in others (e.g., Bergman et al. 2001, Hehre et al. 2015, De Carvalho et al. 2017). As noted in Gentry et al. (2020), it is unclear whether the attraction of larger, mobile species (e.g., fish, seabirds, marine mammals) increases species' productivity or simply displaces them from nearby habitats. If the farms are providing additional food and habitats, then attracted wildlife populations may be enhanced (e.g., Dempster et al. 2011, Tallman et al. 2007). However, if the farms are simply aggregating wildlife from wider, nearby regions and not supporting population growth or fitness (e.g., Bacher et al. 2012, Hehre et al. 2016), then any such benefits may be equivocal. See sections on *Biological effects* (4.1.3), *Wildlife entanglement* (4.1.4) and *Biosecurity risks, pests and disease* (4.5) below for consideration of ways in which habitat provision may have negative environmental effects.

The nature of wildlife attraction to seaweed farms will differ between wildlife species and will depend on the type of culture method, the intensity and scale of farming, farm management practices, the species of wildlife present in the cultivation area and the availability of suitable natural habitats nearby (Theuerkauf et al. 2021). Further research is required to understand how these factors affect the habitat provision of seaweed farms. For seaweed farms to provide habitat value, a species' mortality must be reduced or reproductive success increased, despite the risk of being displaced or captured during harvest and maintenance (Theuerkauf et al. 2021). Understanding the factors controlling the value of habitat provision could allow for the development of reward schemes that incentivise operational practices to enhance the delivery of this service (Theuerkauf et al. 2021). In Aotearoa New Zealand, research on the role that kelp farms, and co-culture of kelp and mussels, plays in providing habitat for fish and marine invertebrates is being carried out by the University of Auckland. They will examine whether fish species are using the aquaculture habitats and if there are any negative effects on these fish and invertebrates during maintenance and harvesting cycles (Jones et al. 2021). In addition to the provision of new habitat, the presence of seaweed farms also has the potential to protect existing biogenic habitats from destructive fishing methods, such as trawling and dredging. Conversely, negative effects could occur if farms are installed above sensitive habitats (e.g., seagrass), which is typically not the case in Aotearoa New Zealand (refer *Shading* Section 4.1.2).

3.3.2 Resilience and resistance

The service of resilience and resistance refers to the extent to which ecosystems can absorb recurrent natural and human perturbations and continue to regenerate without slowly degrading or unexpectedly flipping to alternate states (Beaumont et al. 2007). This benefits both marine species and ecosystems as well as human communities. This ecosystem service is underpinned by a healthy ecosystem with high biodiversity and a range of species with differing responses to environmental perturbations. Seaweed aquaculture can contribute to resilience and resistance if biodiversity is enhanced by the habitat provided by the seaweed farm and its biomass (refer *Habitat provision* Section 3.3.1). Like other semi-permanent structures within coastal systems, seaweed farms can also serve as protection for fish from commercial fishing pressure, depending on the farm's location relative to fishing grounds (e.g., Cornelisen 2013). For example, the farm's presence may prevent commercial fishing, which creates a commercial 'no-take' area similar to a marine reserve (Dempster et al. 2006). This 'no-take' zone may protect species (from extraction) and habitats (from disturbance e.g., dredging, trawling), further enhancing biodiversity, and thus the resilience and resistance of the area.

It has been suggested that in areas where wild seaweed beds have been lost, or are in decline, the escape and establishment of farmed seaweeds could increase the resilience or resistance of the system by restoring or maintaining wild populations and the diverse flora and fauna that they support (Alleway et al. 2018). Where the genetic diversity of wild populations has been limited by bottlenecks, integration of farmed genotypes could also enhance genetic diversity increasing their ability to recover from environmental changes (see Thompson et al. 2017 for discussion of this effect with respect to shellfish populations). However, integration of farmed seaweeds into wild populations could also generate negative effects particularly if the farmed species is not native to the area, if outcompetes healthy populations of diverse seaweed species, or it reduces the genetic fitness of wild populations because it has been selectively bred for other traits (e.g., fast growth; refer *Genetic interactions with wild populations* Section 4.4). Moreover, the loss of wild seaweeds beds is often linked to environmental stressors, and unless these sources of stress have been removed, propagule supply from seaweed farms is unlikely to result in the re-establishment of seaweed beds on nearby substrates. It is likely that the negative risks posed by genetic interactions with wild populations would outweigh any potential resilience and resistance services offered by the integration of farmed seaweeds into wild populations.

3.4 Cultural (societal) services

Cultural (societal) services refer to the non-material benefits that people obtain from ecosystems (Beaumont et al. 2007) and encompasses indigenous values as well as other aspects of a society. These include the association of species or ecosystems with cultural heritage and identity, the sense of place, livelihood options and opportunities for relaxation and tourism that natural environments offer, the stimulus that the natural ecosystems provide for education and research, and non-use benefits that are derived from organisms or ecosystems without using them. Cultural (societal) services are difficult to quantify, particularly using economic methods, because they have no material value (Small et al. 2017). As many of these services are place specific and context dependent, they are also challenging to generalise. Yet these less tangible services often shape societies and cultures and drive environmental change (Small et al. 2017) so should not be overlooked. An understanding of these values can only be obtained through engagement with local communities, and in the case of Aotearoa New Zealand, mana whenua and mana moana. Keeping this in mind, the following section provides only a high-level overview of some of the cultural services that seaweed farms could offer society.

New Zealanders have a close connection to the marine environment, generated through a long history of living near the coast. Māori have a special whakapapa relationship with native flora and fauna, including our seaweed species (Wheeler et al. 2021). Many seaweed species are recognised as taonga by Māori and are harvested for a range of uses (Zemke-White et al. 2005). For example, the red seaweed karengo (*Pyropia* and *Porphyra* spp.) is an important traditional food source for Māori (Wheeler et al. 2021). It is harvested from intertidal rocks in winter and spring and air-dried before eating (Wassilief 2021). Rimurapa (bull kelp, *Durvillaea* spp.) is harvested for a variety of uses including food, pōhā storage bags, clothing, the construction of waka and medicinal treatments (Wassilief 2021, Brooker et al. 1987). We have not assessed Māori cultural service provision in this report as this is a specialist area and is highly location specific. However, the cultural connection that Māori have with taonga seaweeds and their kaitiaki rights, interests, and associated mātauranga should be a prime consideration in the development of seaweed aquaculture, including consideration of its alignment with the Wai 262 claim (see Te Tiriti o Waitangi Considerations section of the companion report, Wheeler et al. 2021).

Seaweed aquaculture provides employment opportunities, which can contribute to a sense of place and the opportunity for alternative livelihoods. For example, in areas where fishing is overexploited or terrestrial resources are limited, seaweed farms can provide a source of income. Jobs can be created throughout the value chain and include employment associated with hatcheries, cultivation, harvesting, processing, marketing and sales (Chopin & Tacon 2021). Seaweed aquaculture can also support businesses that supply goods and services to the aquaculture industry (e.g., feed, equipment, advice) as well as sectors that benefit from spending by those directly or indirectly employed in seaweed cultivation (Buschmann et al. 2017). The questions generated by an emerging seaweed aquaculture industry could also contribute to research (e.g., new uses for seaweed products, technology innovations, improved understanding of carbon cycling).

Wildlife attracted to seaweed farms could offer a range of recreation and tourism opportunities. For example, marine farms are generally viewed as good recreational and charter fishing locations, due to their habitat attraction effect (Cornelisen 2013). This also makes them appealing areas for other recreational activities, such as snorkeling and diving. Where seaweed farms attract larger wildlife (e.g., fur seals, seabirds), eco-tourism operators may benefit.

Non-use benefits include the value people place on knowing marine biodiversity exists or that seaweed aquaculture provides positive effects for the local economy and ecosystem, even if they do not experience it themselves (existence value). It also encompasses the value of knowing that future generations can access the resources and opportunities provided by a healthy environment (bequest value). Seaweed cultivation has the potential to negatively impinge upon these values if farming is perceived to reduce ecosystem health and functioning. Seaweed farms could have negative effects on other cultural (societal) services too, including the visual impacts of seaweed farms, conflict with other users of the marine space and issues related to negative environmental effects if aquaculture operations are poorly managed (refer Section 4).

3.5 Connections between ecosystem services

Although considered individually in the sections above, ecosystem services are interconnected and the enhancement of one service may affect the supply and delivery of other ecosystem services. Interactions between services can be synergistic, where multiple services are enhanced, or cause conflict where one service increases at the expense of another (Bennett et al. 2009). In the past, a narrow focus on the provisioning services offered by marine ecosystems has contributed to the decline of other ecosystem services (Lee & Lautenbach 2016). For example, single-species fisheries management with a focus on maximising food provision has led to a loss of structurally complex seafloor habitats, diminishing the delivery of habitat provision services (Thrush & Dayton 2002, Muntadas et al. 2015). The relationship between these two services is reversed in the context of seaweed aquaculture, where the benthic protection offered by seaweed farms may increase habitat provision for bottom-dwelling fauna and flora, at the detriment of food provision obtained via commercial fishing. On the other hand, additional settlement substrate provided by farm structures could have negative effects on the resilience and resistance of ecosystems if the farm acts as a reservoir for pests and diseases. Trade-offs may also occur between gas and climate regulation and food provision, where the benefits of carbon uptake by seaweeds is negated if the seaweed is consumed and the carbon respired back into the atmosphere. Cultivating a taonga species for an economic return may also be in conflict with cultural values. Conversely, synergies between services can occur, for example, increased seaweed biomass is likely to have beneficial effects on bioremediation, gas and climate regulation, and habitat provisioning services.

Delivery of ecosystem services and the potential for synergies and trade-offs is likely to vary with scale and environmental context. These factors can also influence the thresholds where positive effects become negative. For example, whereas small to medium scale seaweed aquaculture could provide positive bioremediation services (albeit limited), farming at larger scales or densities could have negative environmental effects if nutrients become limited. Management approaches that recognise seaweed aquaculture as an interconnected part of the ecosystem in which it occurs (e.g., EBM; (Custódio et al. 2020) have the best chance of maximising the overall benefits for the environment and people. A holistic approach to management needs to consider the full range of ecosystem services provided by seaweed aquaculture, the potential for interactions with other industries (e.g., commercial fishing) and how this may vary across different scales and in different locations.

4. Environmental effects of seaweed aquaculture

While a range of positive effects of seaweed aquaculture are possible (discussed as ecosystem services in Section 3), a number of negative effects could also arise (e.g., Weitzman et al. 2020, Campbell et al. 2019, MPI 2013 reviews). Here we consider a range of possible negative effects from both subtidal and intertidal seaweed farming in the context of Aotearoa New Zealand. We address first the effects caused by the farm structures and crop in the immediate vicinity of the farm, and then the larger-scale risks to population genetics and biosecurity. Where appropriate, the environmental effects of seaweed farming are compared with those of mussel farming, and in the case of intertidal seaweeds, to oyster farming. Although considered individually within this report, the ecological effects arising from seaweed aquaculture can occur cumulatively across different spatial and temporal scales. They may also interact with other natural processes and anthropogenic stressors occurring within the marine environment.

4.1 Structural habitat changes

4.1.1 Physical effects

Disturbance of the seabed occurs as farm structures are installed – although these effects tend to be localised and, apart from the physical farm structures replacing a small amount of seabed, effects are also temporary. Once in place, farm structures and cultivated seaweed can disrupt water currents, alter water stratification, and dampen wave action (Campbell et al. 2019). For example, modelling shows that suspended kelp aquaculture (where shellfish or seaweed aquaculture covered most of a 140 km^2 bay) in China could reduce currents by 40% (Shi et al. 2011) and by 54% in combination with scallop aquaculture (Grant & Bacher 2001). This current attenuation is comparable to other forms of aquaculture, which have been shown to reduce currents by 28% (mussel rafts; e.g., Boyd & Heasman 1998), 40% (suspended scallops; e.g., Pilditch et al. 2001) and 36-70% (suspended mussels in Aotearoa New Zealand; e.g., Gibbs et al. 1991, Waite 1989, Plew et al. 2005). Conversely, reductions in current speeds within an aquaculture area can cause an increase in speeds around or below aquaculture structures (Plew et al. 2005).

Currents play important roles in the transport and delivery of seston (drifting sediment and plankton) and dissolved nutrients, and in flushing of wastes out of the system. As such, changes to water flow could affect nutrient supply (refer *Changes in nutrients* Section 4.2), the exchange of nutrients between the benthos and the overlying water column and the resuspension of sediment, with associated changes to ecological communities. Currents that occur around farming structures can also cause scouring or build-up of sediments on the seabed (Forrest et al. 2009). In addition to changes in currents, seaweed farms can attenuate wave energy (Zhu et al. 2020), with potential positive effects in the form of *Coastal protection* (Section 3.3.3).

The effects of seaweed farms on hydrodynamics will depend on the species and structures used for farming. These effects could be greater or less than those caused by mussel farms and will vary with the amount of water column occupied and the frequency of harvest. Seaweed farms are expected to differ from mussel farms because the seaweed crop is unlikely to extend to the same depth as mussel droppers (Forrest & Hopkins 2016) and could instead have more biomass growing at or near the surface. Furthermore, seaweed crop, and the associated effect on water movement, is likely to vary much more throughout the year then mussel crop.

For seaweeds that can be cultured subtidally, undesirable effects of structures on the seabed and water column can be substantially mitigated by appropriate farm placement (Campbell et al. 2019). For example, siting farms far enough offshore to avoid changing the coastal current and wave regime, in sufficiently deep water so that changes in water flows around farms structures do not produce problematic scouring, and over seabeds that do not suffer negative effects resulting from any hydrodynamic changes that do occur. Risk is likely to be higher where farms are large and located in areas with restricted water movement (Campbell et al. 2019). However, problematic effects of changes to flow regimes have not been detected around large mussel farms in Tasman Bay and Golden Bay, nor around near-shore farms in the Hauraki Gulf (Clark et al 2012a, 2012b, Newcombe et al. 2019). The environmental effects of altered hydrodynamics should be assessed on a case-by-case basis and incorporate the cumulative effects of other marine activities occurring within the marine space (Campbell et al. 2019).

Farming seaweeds in intertidal areas could produce similar effects to intertidal oyster farming. In a review of intertidal oyster aquaculture in Aotearoa New Zealand (using elevated culture on racks, trestles, and other structures), seabed effects were second only to biosecurity risks in terms of potential negative effects (Forrest et al. 2009). Changes in seabed topography were identified as one aspect of those undesirable seabed outcomes (Forrest et al. 2009). For example, sediments built up under oyster farm structures due to hydrodynamic changes disturb the seabed, and at times, render the racks unusable. Such changes would presumably be similar for seaweeds farmed using comparable methods. However, many intertidal oyster farms are now transitioning to surface floating bags or baskets with a single or double backbone line (pers. comm. Dave Taylor, Aquaculture New Zealand, 31 August 2021), which could reduce these physical effects. Additional disturbance of the seabed occurs during farming or harvesting operations, when equipment or personnel tend and harvest the crop. Development of ways to farm intertidal seaweed species offshore would be a key means to mitigating effects. Where existing intertidal oyster farms are being considered for conversion to seaweed aquaculture, the predicted change in disturbance needs to be assessed to establish whether negative environmental effects would be lesser with seaweed than oysters.

4.1.2 Shading

Seaweed farming shades the environment below the crop, with potential to negatively affect primary producers that require light for growth (e.g., benthic micro- and macroalgae, seagrass, rhodoliths, or pelagic phytoplankton). Seaweed aquaculture has could cause greater shading effects than mussel cultivation because the fronds can cover large areas of the water surface, particularly when farmed using horizontal grid structures. For example, pre-harvest light attenuation of 40% was measured in a Swedish kelp farm (Visch et al. 2020), although the authors recognised that peak biomass (and therefore maximum shading) persisted for only a short time. Shading of wild seaweeds, seagrass and rhodoliths would be detrimental to these habitats (e.g., Eklöf et al. 2005, 2006), and should be avoided. However, new aquaculture developments in Aotearoa New Zealand are unlikely to be permitted in areas where these habitats are present. On soft-sediment seabeds, microphytobenthic mats are often the dominant primary producer. These often-overlooked habitats are an important food source (e.g., for scallops; Rhodes et al. 2001) and play key roles in stabilising sediments (Tolhurst et al. 2008) and biogeochemical pathways (e.g., nutrient recycling; Hope et al. 2020). Shading could conceivably reduce development of these mats. However, in many aquaculture areas the protection from seabed disturbance by bottom contact fishing would be expected to have far greater benefits for mat development and seabed stability than any disadvantage that may occur due to shading.

Unlike benthic primary producers, phytoplankton will only be temporarily subjected to shading effects from seaweed aquaculture as they move through the farm with water currents. Therefore, to markedly affect phytoplankton communities, coverage of farmed seaweed would have to be substantial, and current speeds (turnover of the waterbody) low. Suppression of phytoplankton and associated food web effects have nonetheless been shown under large-scale cultivation (Campbell et al. 2019 and references therein). In a modelling study of kelp farming in Northern Ireland, it was predicted that impacts on phytoplankton and farmed shellfish due to nutrient competition and light shading manifested after more than 10,000 lines (100 m long) of seaweed were installed in a semi-enclosed water body (Aldridge et al. 2021).

The potential for shading effects from intertidal farming is greater than in the subtidal, as the levels of light reaching seabeds at low tide is high, and the relative change due to shading from aquaculture would be substantial (Forrest et al. 2009). Even an incremental reduction in light by shading might be important in turbid systems, where primary producers are already limited by light (Mangan et al. 2020a, 2020b). Where existing intertidal oyster farms are considered for conversion to seaweed aquaculture, the predicted change in shading may be minimal compared with that generated by oyster biomass, but this would be dependent on characteristics of the seaweed crop and local environmental conditions.

For both intertidal and subtidal seaweed aquaculture, the possibly of negative shading effects should be considered when siting farms. In areas with large-scale aquaculture, monitoring changes in phytoplankton would determine the potential for negative effects.

4.1.3 Biological effects

As discussed in Section 3.3.1 on *Habitat provision*, seaweed farms are expected to attract fish and other highly mobile wildlife (e.g., seabird, sharks and marine mammals) because, like wild kelp forests (Wood et al. 2017), they provide shelter, refuge from predators and food. Sessile (immobile) species (such as sponges and other seaweeds) and bottom-dwelling mobile species (such as crustaceans) may settle on to aquaculture structures or the crop itself. However, the temporary nature of farm-associated habitats may be problematic. During harvest, organisms that have migrated to or preferentially settled in seaweed farms may be removed, destroyed, displaced from their food source, or exposed to predation. Dependent on the scale of aquaculture and factors affecting the wider populations of non-target species, these effects may be benign or negative. Visch et al. (2020) noted that many of the non-target organisms associated with kelp aquaculture may not spawn prior to harvest of the kelp and would, therefore, not contribute to local populations. If non-target occupants of the farm do not survive harvesting activities, and aquaculture structures have diverted settlement from stable habitats, this could have a negative effect on natural populations. Adjusting the timing of harvesting or intercropping may solve some of these issues (Visch et al. 2020). Retaining holdfasts and small fronds may also facilitate more permanent habitat as older and larger seaweeds generally support a greater species diversity (e.g., epiphytic algae, crustaceans, gastropods) than smaller or juvenile specimens (Christie et al. 1998, Christie et al. 2003). Seaweed farms may also provide habitat for pests and diseases that could spread to natural populations (refer *Biosecurity risks, pests and disease* Section 4.5).

4.1.4 Wildlife entanglement

The potential for wildlife entanglement within seaweed farms presents a high environmental risk. Campbell et al. (2019) points out in their review of potential effects of seaweed aquaculture, 'entanglement of animals cannot be ruled out, even when assuming cultivation practices will be managed to reduce the likelihood of entanglement.' Loose, thin ropes that are flexible and not under tension are the main risk factor to wildlife entanglement in marine waters. A curious animal will investigate, play and even bite novel structures that they encounter. Under-tensioned ropes or lines are dangerous when an animal comes in contact with them, becomes spooked or naturally rolls and wraps the lines around themselves, and becomes entangled (e.g., Clement 2013). Based on global reviews of seabird and marine mammal entanglements in both stationary fishing and aquaculture gear (e.g., moorings, floating sub-surface lines and/or pot-type lines), similar risks are likely with existing types of seaweed farm gear and structures (e.g., Benjamins et al. 2014, Knowlton et al. 2012).

Within Aotearoa New Zealand, marine wildlife entanglement in aquaculture structures has been a relatively small issue, despite over 30 years of sea-pen salmon farming and several decades of oyster and mussel farming (e.g., Clement 2013, Sagar 2013). However, it is unknown if there is a paucity of entanglements because farms are relatively benign or alternatively, if the density of farming and reporting is too low to detect potentially injurious interactions (e.g., Price et al. 2017). Regardless, the consequences of even an extremely rare fatal entanglement have potentially serious regional or population level repercussions if endangered species are involved.

In Aotearoa New Zealand, seaweed aquaculture is expected to have a higher entanglement risk than other non-finfish culture methods, such as mussel aquaculture (Forrest & Hopkins 2016). The main factors that put seaweed farms at risk of entangling wildlife include:

- moorings and lines that have low tension,
- overlapping or crossing of warp and/or crops lines,
- poor visibility leading to reduced avoidance
- potentially large farms, and
- mooring and associated components that are unable to resist the forces of an encounter (e.g., by a whale).

There is still considerable uncertainty in the level of effect for some of these factors due to lack of data, particularly in association with large scale or multiple large farm blocks (Clement 2013, Price et al. 2017). Several Aotearoa New Zealand reviews (e.g., Clement 2013, Keeley et al 2009, Forrest & Hopkins 2016) have emphasised that entanglement risk of marine wildlife in aquaculture farms is related to culture method, extent of overlap with critical habitats, and farm management. Minimising entanglement risks will require implementing proper siting, design, layout and operational standards. The scale and design of the farms will be important considerations especially when dealing with large protected species, such as whales or sharks. Farm developers will need to consider farm placement (e.g., parallel to migration pathways) and layouts (e.g., multiple farms grouped in blocks rather than spread across a wide area) that reduce the risk of adverse effects, as well as ensuring that any animals who might enter a farm block (especially air-breathing mammals and birds) will have an escape path through farms (i.e., no dead-ends).

Being aware that entanglement risk increases with any increased attraction of protected wildlife to the farm means that several mitigation options are available. Underwater noise is one of many attractants (and disturbers) of wildlife. Ensuring proper upkeep and maintenance of farming vessels, harvest machinery and other mechanically operated gear will help minimise the levels of noise generated by farming activities.

4.2 Changes in nutrients

Seaweed farming could result in both a reduction in dissolved nutrients and an increase in particulate material in and around the farm. As primary producers, seaweeds take up nutrients from the water column and convert them to biomass. Nitrogen is generally considered the most important of those nutrients in coastal environments (Roleda & Hurd 2019). When coastal waters are eutrophic (excessively high in nutrients), removal of nutrients could have positive environmental effects (refer *Bioremediation of waste* Section 3.2.1). However, seaweed farms could have undesirable effects if nutrient levels are reduced below that required for natural populations of primary producers (e.g., phytoplankton). This could lead to changes in natural populations of primary producers through competition with the farmed seaweeds for nutrients. In subtidal areas (> 20-30 m depth), the community most likely to be affected would be the phytoplankton that are transported into (and out of) the farmed area by water movement. Several studies have shown that seaweed aquaculture has minimal effects on dissolved nitrogen (e.g., Visch et al. 2020, Buschmann et al. 2014, Abhilash et al. 2019, van der Molen et al. 2018). However, nutrient depletion could occur if farming took place at a sufficiently large scale and high density, particularly in areas that are naturally nutrient poor or have limited water exchange. For example, nutrient modelling in a large estuary with restricted water exchange showed that large-scale (> 10,000 lines) kelp (*Saccharina latissimi*) farming may have measurable impacts on phytoplankton and mussel growth within the estuary (Aldridge et al. 2021). The nature of nutrient competition with phytoplankton will depend on the species of seaweed being farmed. Fast growing species (e.g., sea lettuce, *Ulva* spp.) tend to rely on external nutrient concentrations because they have small internal storage capacity relative to demand. These species are therefore likely to lead to greater nutrient competition with phytoplankton than species that store nutrients (e.g., kelp; Aldridge et al. 2021).

Effects of nutrient depletion from seaweed farming may be of more concern in the intertidal, as the crop would sit in close proximity to primary producers on the seabed. On the other hand, intertidal habitats often experience higher nutrient loading than areas further offshore so are less likely to be nutrient limited. Development of intertidal seaweed farms (e.g., new farms or conversion of an oyster farm) in close proximity to valuable habitats that could be affected by nutrient depletion (e.g., seagrass) should be undertaken with caution. Modelling of nutrients could be considered prior to establishment and development should be contingent on monitoring of valuable habitats.

While dissolved nutrients may be depleted near large seaweed farms, particulate material could cause localised enrichment. Organic and inorganic nutrients captured from water passing through the farm are incorporated into the tissues of crop or fouling organisms. If these detach and are deposited below or nearby the farm, detectable seabed enrichment may occur. Seabed enrichment associated with non-fed aquaculture (e.g., seaweeds, mussels, oysters) is generally much lower than for fed aquaculture species (e.g., finfish; Keeley et al. 2009). Localised enrichment has been detected under mussel farms in Aotearoa New Zealand (Christensen et al. 2003, Giles et al. 2006); however, enrichment effects from seaweed farming are expected to be less intense than from shellfish farming as no biodeposits (i.e., faeces and pseudofaeces) are produced (Forrest & Hopkins 2016). Seaweed crop is also more likely to drift away from the immediate area of the farm, reducing enrichment effects via dispersal over a wide area.

Research quantifying the degree of seafloor enrichment associated with seaweed farming is limited. Buschmann et al. (2014) reported no increase in organic matter, and few detached kelp blades, beneath a 21 ha kelp (*Macrocystis pyrifera*) farm in Chile over three years of cultivation. However, they recommended that further studies should be undertaken if the scale of cultivation were to be increased. Similarly, Visch et al. (2020) found no evidence of enrichment beneath a 2 ha Swedish kelp (*Saccharina latissima*) farm, reporting no difference in sediment oxygen uptake compared to reference sites and positive effects on infaunal species diversity and abundance. These studies are encouraging but more research is required to understand the extent and fate of particulate material originating from seaweed farms and what scales and environmental conditions could lead to negative environmental effects (Campbell et al. 2019).

Beyond the farm, an increase in drift algae may occur. It is possible that this could cause undesirable build-up along the coastline, particularly in the case of high crop-loss during a storm event. However, we note that the amount of natural seaweed around Aotearoa New Zealand coasts has diminished in recent years (Handley 2016). Factors such as food web changes (increases in herbivore abundance as predators have been fished out), increased suspended sediment, and changing water temperature have been identified as global drivers of such change (Krumhansl et al. 2016). Our natural systems are likely to have included more drift algae in the past than has been present in more recent decades, therefore an increase in drift algae is not necessarily a negative change.

4.3 Contaminants and litter

Seaweed aquaculture is likely to have minimal contaminant inputs. If treated wood is used in the construction of structures for intertidal aquaculture, as it has been for oyster culture, there is the potential for a degree of contamination of nearby sediments to occur. However, based on leaching from marine pilings, Forrest et al. (2009) concluded that such effects are likely to be negligible for oyster farming and this would presumably be the same for intertidal seaweed farms. Toxic antifouling materials have historically been used to avoid biological fouling of marine structures and vessels. However, the Aotearoa New Zealand aquaculture industry recognise that use of manual cleaning, desiccation and paints without copper are best practice approaches for antifouling[2]. Environmental effects should be considered before using chemicals to treat the seaweed crop (e.g., to control disease outbreaks; Loureiro et al. 2015) or biofouling. Where the use of potential toxins is required, Australasian standards (ANZG 2018) are commonly used to assess acceptability of contaminant levels in sediments.

Some seaweeds can themselves produce toxins (metabolites), which often serve as chemical defences against grazers (e.g., Paul et al. 2006). Their potential for undesirable effects should be considered prior to development. For example, bromoform produced by *Asparagopsis* spp. has been identified as a possible carcinogen at high concentrations, and it is also a naturally ozone-depleting substance (Wheeler et al. 2021).

Seaweed farming is expected to heavily rely on synthetic ropes, lines or netting; such materials often float and are resistant to degradation (Laist et al. 1999). If discarded or lost, they represent a significant choking or entanglement hazard for wild fish, seabirds and marine mammals (e.g., Hinojosa & Thiel 2009). These materials could also act as vectors for non-indigenous species (e.g., Campbell et al. 2017) and contribute to the wider issue of plastic pollution in the marine environment. As with all other forms of aquaculture in Aotearoa New Zealand, a proper and well-regulated waste management programme to control all potential waste products is necessary. Assuming seaweed aquaculture is managed responsibility, the contribution of litter to the marine environment should be minimal.

4.4 Genetic interactions with wild populations

The potential effects of genetic interaction between cultivated seaweed species and natural populations are not well understood and represents one of the highest risks to the environment (Campbell et al. 2019). Many seaweeds in Aotearoa New Zealand have relatively restricted natural distributions (e.g., Shears et al. 2008, Buchanan & Zuccarello 2012, Muangmai et al. 2015), compared to other cultivated species such as mussels. As a result, the potential for disruption of natural genetic structure is relatively high if new species or genotypes are introduced to a region. Like mussels, cultured seaweeds have the potential to spread from farmed to wild populations during their planktonic life stages (Loureiro et al. 2015, Valero et al. 2017, Tano et al. 2015). If a farmed seaweed species established outside its natural range, it could potentially alter the genetic composition of the wild population due to interbreeding (as documented for salmon and wrasse in Norway; Glover et al. 2013, Jansson et al. 2017, Faust et al. 2018). Alternatively, the cultivated species may simply outcompete individuals from the wild population. Hybridisation and gene flow could result in altered ecosystem function or a loss of genetic fitness in wild populations, particularly if farmed cultivars have been bred for commercially valuable traits (e.g., biomass, blade width, texture, colour; Li et al. 2016, Goecke et al. 2020) at the detriment of genetic diversity (Halling et al. 2013, Valero et al. 2017).

[2] http://www.environmentguide.org.nz/activities/aquaculture/im:1738/

The potential for seaweed farming to cause changes to the genetic structure or fitness of the wild population must be assessed on a case-by-case basis as such risks vary depending on a range of factors including: the relative reproductive output of the crop compared to local seaweed populations (which may be determined by farm size), whether the species can reproduce from fragments or only by production of reproductive structures, whether the crop is harvested before it reaches reproductive maturity, the genetic distinctiveness of any sub-populations, the distance to suitable settlement substrates and the potential for human-mediated spread (e.g., via commercial and recreational vessel movements).

Farming local seaweed cultivars/strains will lessen the potential for genetic changes (Barbier et al. 2019), although genetic depression of local populations can still occur through 'crop-to-wild' gene flow (Loureiro et al. 2015, Valero et al. 2017). Furthermore, population genetics and dynamics at species and regional levels requires further research to define local populations in Aotearoa New Zealand. Where breeding programs are in place, these should ensure maintenance of sufficient genetic diversity and disease resistance, both now and in the future (Campbell et al. 2019). Sterilisation technologies for seaweeds are not widely available but are technologically feasible and could mitigate crop-to-wild gene flow (Loureiro et al. 2015, Goecke et al. 2020).

4.5 Biosecurity risks, pests and disease

The development of seaweed aquaculture poses high environmental risks associated with biosecurity, pests and disease (Campbell et al. 2019). The pathways that could spread pests and disease are likely to be similar to those associated with shellfish aquaculture (refer Keeley et al. 2009 for a review). These include the movement of vessels and the transfer of juveniles and equipment between growing regions and/or aquaculture facilities. Farms may also act as a reservoir for pests and disease that could spread to natural populations (Loureiro et al. 2015, Valero et al. 2017), or other aquaculture operations. Large-scale seaweed aquaculture could potentially cause different effects than previously seen in Aotearoa New Zealand. For example, the reservoir role performed by seaweed farms has been linked to the development of extensive sea lettuce (*Ulva prolifera*) blooms in the Yellow Sea (Zhou et al. 2015). In that case, however, the reservoir effect was likely greatly exacerbated by the eutrophication of the surrounding environment. Farming of non-native seaweed species (e.g., wakame, *U. pinnatifida*) presents additional biosecurity risks (Cunningham et al. 2020).

The potential for seaweed farms to introduce and spread pests and disease depends on the species farmed, the location of the farm and operational activities. Loss of genetic diversity through domestication (refer *Genetic interactions with wild populations* Section 4.4) can also make farmed seaweed more susceptible to disease and pests (Valero et al. 2017). Risks associated with biosecurity, pests and disease to be assessed on a case-by-case basis (Forrest & Hopkins 2016). Useful and additional information on management of biosecurity risks associated with farming seaweeds (focused on wakame) can be found in Cunningham et al. (2020). In addition, Bradly et al. (2021) considers the regulatory context of biosecurity management of aquaculture operations in Aotearoa New Zealand in detail, and references existing best practice guidance and the need for ongoing development of such guidance.

5. Summary

Developing a successful and sustainable seaweed industry in Aotearoa New Zealand is contingent on the ability to avoid, remedy, or mitigate significant adverse effects to the environment while endeavouring to maximise potential benefits. Growing the seaweed aquaculture sector would allow Aotearoa New Zealand to sustainably increase yields and provide greater control over the consistency and quality of seaweed products. Possible ecosystem services and negative environmental effects of seaweed aquaculture are summarised in Figure 9 and Table 2. While the potential for seaweed aquaculture to supply ecosystem services beyond the provision of biomass is often promoted as a key benefit of seaweed farming, the delivery of these services is highly dependent on scale and context. Seaweed farming is considered to have lower environmental risk than most other forms of aquaculture. Genetic interactions with wild populations, disease and marine pests, and wildlife entanglement pose the greatest environmental risk. While there are good mitigation precedents for most of the negative environmental effects from current shellfish practices, these potentially high-risk effects require further consideration in regard to proactive mitigation actions and robust management/monitoring programmes (Table 2).

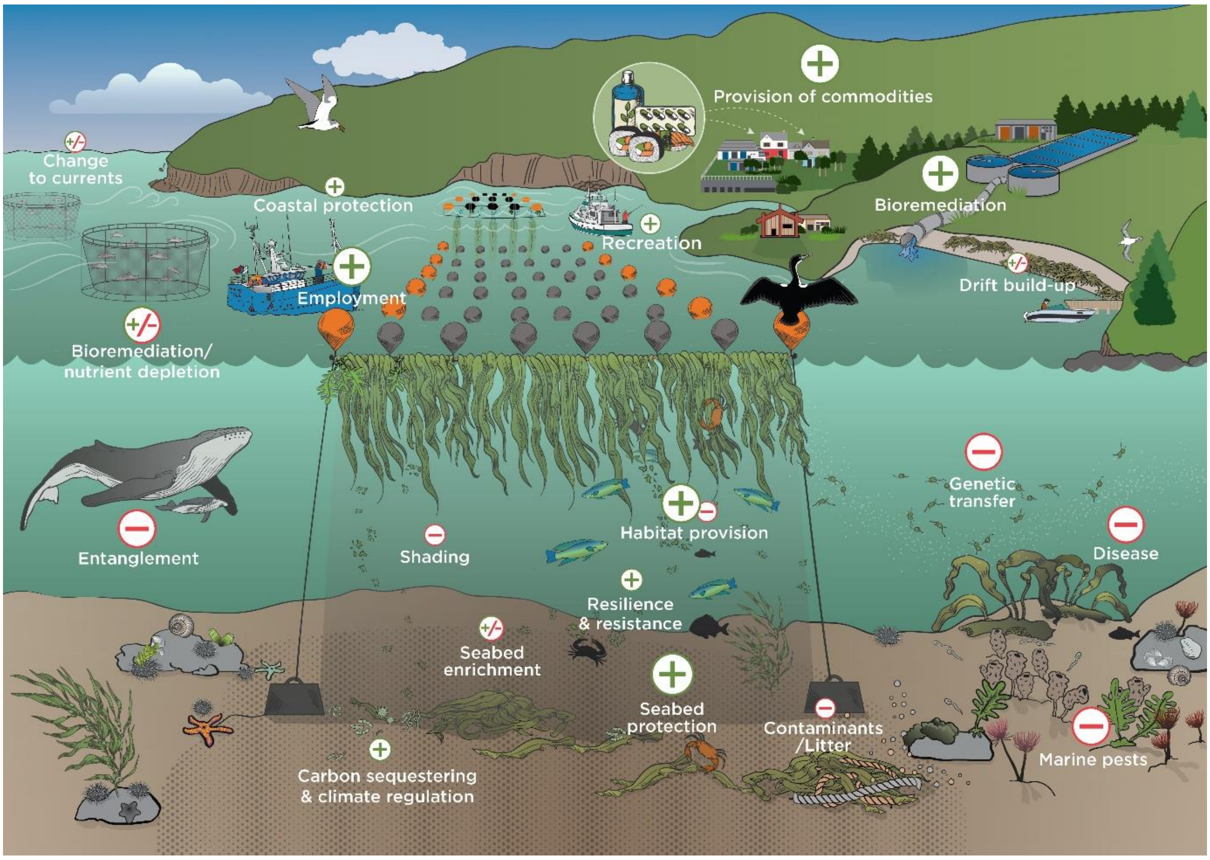


Figure 9: Development of Aotearoa New Zealand's seaweed sector will require a shift towards aquaculture to allow an increase in yields without placing pressure on wild seaweed populations. This diagram shows the possible negative environmental effects and ecosystem services associated with seaweed aquaculture in subtidal environments. The likely nature and degree of effect is indicated by large or small '-' or '+' symbols. Graphic by Revell Design.

When considering the ecosystem services and negative environmental effects of seaweed aquaculture, three consistent themes emerged: the strong influence that both 1) appropriate farm placement and 2) scale can have on environmental changes and 3) the uncertainty associated with many of these effects. Most negative environmental effects are expected to be low and at manageable levels within small-scale, properly sited farms but could reach a 'tipping point' with unintended ecological consequences if farms are extensive or inappropriately placed. Furthermore, some environmental changes (e.g., shading and nutrient depletion) are only likely to be problematic if seaweeds are farmed on a large scale, while some benefits (e.g., coastal protection, carbon sequestration) will only be realised at large scales. The final balance between the positive (ecosystem services) and negative environmental effects of seaweed farming will largely depend on the size, number and intensity of seaweed farms placed along the Aotearoa New Zealand coast, where they are sited, and the species chosen to be cultivated.

The site-specific nature of many of these benefits and risks, and the associated uncertainty about their effects, highlights the importance of developing an EBM framework for the seaweed sector in Aotearoa New Zealand. EBM (Figure 1) is tailored to a specific time and place and recognises ecological complexity and connectedness. It promotes flexible, adaptive monitoring that acknowledges the uncertainty associated with many of these negative environmental effects. Environmental monitoring and targeted research (Table 2) will be critical in the early developmental stages of seaweed farming in Aotearoa New Zealand to minimise these uncertainties and ensure management approaches are knowledge-based. This knowledge can be in the form of both science and mātauranga Māori and should be informed by community values and priorities. It is also essential that management approaches consider the cumulative impact of other human activities occurring alongside seaweed aquaculture. Collaborative decision-making and co-governance structures that provide for Treaty of Waitangi partnerships will provide a holistic and inclusive way of managing seaweed aquaculture effects on the marine environment. Ultimately, the goal of the EBM framework will be to enable the development of a thriving seaweed sector while ensuring that the values of uses of Aotearoa New Zealand’s marine environment are safeguarded for future generations.

Seaweed aquaculture represents a timely opportunity for Aotearoa New Zealand to develop a sustainable, high-value industry. Cultivation of seaweeds would allow the scale of the industry to increase without placing pressure on wild populations and provide greater control over the consistency and quality of the product. Seaweed aquaculture does have the potential to cause environmental change, both as positive benefits to humans and as negative effects on the environment. Fortunately, there is a unique opportunity for industry, government, science providers, tangata whenua and the community to co-design an EBM framework that considers these concerns, ensuring this sector can meet the environmental, social, economic and cultural aspirations of New Zealanders.

Table 2. Possible environmental effects (both positive and negative) associated with seaweed aquaculture in subtidal environments within Aotearoa New Zealand.

Environmental change	Possible ecosystem service or *negative effect*	Description	Potential degree of effect within Aotearoa New Zealand waters	Implications for economic use and management *Research recommendations*
Biomass production and nutrient cycling				
Nutrient uptake	Bioremediation	• Help prevent eutrophication by growth then harvest of seaweed	Likely applicable to localised enrichment only (e.g., bioremediation of land based nutrient sources or finfish farming) although there could be benefits in locations with enriched coastal waters (e.g., Firth of Thames)	• Greatest ecosystem service value obtained by siting of farms in water bodies with high anthropogenic sources of nitrogen *Determine baseline productivity and nutrient assimilation data for locally cultivated seaweed species (grown in the ocean at meaningful scales) to enable direct quantification and modelling of ecosystem level effects*
	Nutrient depletion	• Out-competes local communities (planktonic or benthic) for essential nutrients	Nutrient uptake is a certainty, whether undesirable depletion occurs is dependent on location and scale. Likely localised effects unless large-scale and intensive farming or in low-flow areas.	• Appropriate site selection (including sufficient turnover of water) and scale • Nutrient modelling in planning stages • Monitoring of effects *Determine what intensity of farming (i.e., scale and density) and environmental conditions results in nutrient depletion*
	Gas (carbon) and climate regulation	• Capture and storage of carbon in seaweed tissues via photosynthesis • Uptake of CO_2 can: ○ mitigate global warming ○ buffer ocean acidification	Low-level effect only, scale required to offset anthropogenic inputs likely unrealistic	• Develop large standing stock of algae • Prevent release of captured carbon by burial (land or sea) or use in products with a long lifespan • Positioning close to valued shellfish (cultured or wild) to offset ocean acidification *Quantify carbon pathways from cultured seaweeds*
Export (non-harvest) of nutrients and biomass	***Seabed enrichment***	• Increased nutrient-rich particulate material (i.e., lost seaweed/fouling organisms) under and near farms causing localised enrichment	Some low-level effect likely this may or may not be detectable, dependent on intensity of farming and characteristics of site. It is possible that low-level enrichment could have beneficial effects on benthic communities in some cases.	• Appropriate site selection and scale • Monitoring of effects *Determine the extent and fate of particulate material originating from seaweed farms and what scales and environmental conditions could lead to negative environmental effects*
	Drift algae build-up	• Drift algal build up on coast	May occur, more likely after storm events. Extent of possible build-up situation specific	• Appropriate site selection • Recognise that this may be a natural phenomenon, which occurs less now than in the past due to the loss of natural seaweed beds *Model quantity and location of drift-build up from farms*
Physical and biological structures/materials introduced				
Hydrodynamic changes	Coastal protection	• Dampen wave action (particularly short-period) • Protect coastlines from erosion arising from waves and storms	Benefit possible if designed specifically for this purpose	• Design specifically for coastal protection purposes • Understand social challenges of developing near-shore aquaculture *Quantify wave attenuation of seaweed farms with different designs/orientations/scales and environmental conditions*
	Changes to currents	• Increase or decrease in currents	Low-level effects, unlikely to be of concern if not large-scale	• Appropriate site selection and scale *Quantify how seaweed farms with different designs/orientations/scales modify currents under different environmental conditions*
	Disturbance of seabed	• Scouring/build-up of sediments	Low-level effects, unlikely to be of concern if not large-scale	• Appropriate site selection and scale
Habitat creation and seabed protection	Resilience and resistance	• High biodiversity provides an ecosystem that is resilient and/or resistant to environmental perturbations	Possible benefits, site specific	• Targeting of aquaculture development in sites with otherwise low biodiversity values *Quantify biodiversity in locations with and without seaweed farms and how this affects the resilience and resistance of the ecosystem*

Environmental change	Possible ecosystem service or *negative effect*	Description	Potential degree of effect within Aotearoa New Zealand waters	Implications for economic use and management *Research recommendations*
	Habitat provision	• Novel substrate, predator refuge, food and favourable environmental conditions • Includes drift seaweed • Potential to attract sessile and mobile species • Protection of seafloor habitats from anthropogenic disturbance such as bottom trawling	Possible benefits, likely to be temporary, therefore nature of effect uncertain	To establish whether this ecosystem service is expressed: • Assess the farm-associated biodiversity relative to natural populations • Identify highly valued species • Record and analyse identity, abundance, and reproductive state of associated species at harvest time. Assess survival, potential for migration to stable habitat, etc. *Role and relative importance of individual drivers (e.g., production intensity, local environmental characteristics, farm management practices) on habitat value for wild marine organisms*
	Ephemeral habitat creation	• Attracted organisms removed, destroyed, displaced during harvest or exposed to high predation risk • Attraction potentially depleting local sources (sink)	Possibility of diversion and disruption of organisms that would otherwise have settled on natural substrates, nature of effect uncertain	• Appropriate site selection and scale • Potential mediation via harvesting strategy • Conservation status of potentially affected species needs consideration (i.e., threatened or endangered) *Investigate how different harvesting strategies affect the habitat value of seaweed farms*
Shading	*Shading of water column and seabed*	• Reduced primary productivity	Wild macroalgae/seagrass/rhodoliths unlikely to be shaded (appropriate site selection) Some reduction in productivity of microphytobenthic mats Phytoplankton only substantially affected under large-scale and intensive farming or in low-flow areas	• Appropriate site selection and scale *Model shading effects of large-scale seaweed aquaculture on the microphytobenthic and phytoplankton communities*
Physical structures that create entanglement risk	*Entanglement of marine mammals*	• Injury or death of animals, including endangered or protected species	Risk always present when ropes, lines, or nets overlap with marine wildlife Detrimental consequences for protected or endangered species / populations	• Minimise risk with appropriate siting, scale, layout and operational standards, such as avoiding overlap or crossing of warp lines between farms • Avoid or minimise operational changes during critical breeding, feeding or migration periods • Avoid loose nets, keep all lines under some degree of tension, avoid loss of equipment • Make lines easily detectable and investigate methods to stiffen • Minimise potential attractants such as lightening, underwater noise • Monitoring of effects
Contaminants and litter	*Toxins*	• Leaching from treated wood structures • Toxic chemicals • Biogenic toxins	Leaching of toxic substances from treated wood unlikely Environmentally harmful chemicals unlikely to be approved for use Possible negative effect of biogenic toxin produced by *Asparagopsis* spp.	• Use of non-toxic antifouling methods (e.g., manual cleaning, desiccation, paints without copper) • Monitoring to ensure ANZECC standards for environmental contamination are not exceeded • Environmental effects should be considered before using chemicals to treat crops or biofouling • Careful assessment of the environmental effects of toxin-producing cultivars
	Litter	• Discarded or lost materials contribute to marine pollution. Consumption, choking, entanglement risks for range of wildlife	Likely some litter escapes farm	• A proper and well-regulated waste management programme to control all potential waste products (e.g., organic, plastic, etc.) • Mitigation of lost materials with beach clean-up programmes
Export of living material (including pathogens) to wild populations or other aquaculture operations				
Genetic structure of crop differs to local population	*Gene flow (cultured species) to wild population*	• Introduction of new genotypes into wild populations • Wild population outcompeted by farmed species • May result in loss of natural fitness or altered community composition/function	Potential important regional or national consequences for wild populations Of particular concern as seaweed species can have restricted natural distributions/high regional diversity	• Risk assessment and modelling of potential genetic effects on a case-by-case basis • Culture of: ○ native species and local genetic stock that maintain the genetic integrity of local communities, or ○ sterile cultivars *Determine the natural ranges of potential seaweed aquaculture species, and their genotypes*

Environmental change	Possible ecosystem service or *negative effect*	Description	Potential degree of effect within Aotearoa New Zealand waters	Implications for economic use and management ***Research recommendations***
Farm introduces or incubates disease	***Disease transfer***	• Spread of pathogen/parasite to other seaweed populations in the area	Potential widespread and ecologically important consequences for cultivated and wild species and communities	• Risk assessment and modelling of potential disease transmission under various scenarios • Prudent siting, farm spacing and scaling to mitigate critical challenges associated with disease transmission • Ensure 'clean' status of hatcheries/processing facilities, monitor stock for signs of infection, monitor and treat out-goings • Breeding programmes that support sufficient disease resistance • Development of a site-specific Biosecurity Management Plan that addresses disease, including adhering to best-practice guidance with regards to vector management (e.g., vessels)
Farm introduces or incubates pest species	***Marine pests***	• Vessel, gear and stock movements may introduce pests not previously found in the area • Novel habitat for colonisation by fouling organisms • May act as a population reservoir for marine pests that then spread to the wider environment. • Farm may act as a 'stepping stone' in the regional spread of pest species	Potential widespread and ecologically important consequences for cultivated and wild species and communities	• Optimised siting and appropriate spacing of farms for effective area-based management of sites and reduced pest transfer • Geographic isolation of new sites to limit secondary spread • Adequate management of transport vectors • Regular farm surveillance to enable timely detection of pest species • Proactively minimise biofouling development on crop farm structures to prevent establishment of populations of pest species • Development of a site-specific Biosecurity Management Plan that addresses marine pest risks

6. References

Abhilash KR, Sanka R, Purvaja R, Deepak SV, Sreeraj CR, Krishnan P, Sekar V, Biswas A, Kumarapandiyan G, Ramesh R 2019. Impact of long-term seaweed farming on water quality: a case study from Palk Bay, India. Journal of Coastal Conservation 23(2): 485-499.

Abreu MH, Pereira R, Sassi, JF 2014. Marine algae and the global food industry. In: Pereira L, Neto JM editor. Marine Algae : Biodiversity, Taxonomy, Environmental Assessment, and Biotechnology. Baton Rouge, United States, Taylor & Francis Group.

Akcali I, Kucuksezgin F 2011. A biomonitoring study: Heavy metals in macroalgae from eastern Aegean coastal areas. Marine Pollution Bulletin 62(3): 637-645.

Aldridge JN, Mooney K, Dabrowski T, Capuzzo E 2021. Modelling effects of seaweed aquaculture on phytoplankton and mussel production. Application to Strangford Lough (Northern Ireland). Aquaculture 536: 736400.

Alleway HK, Gillies CL, Bishop MJ, Gentry RR, Theuerkauf SJ, Jones R 2018. The Ecosystem services of marine aquaculture: valuing benefits to people and nature. BioScience 69(1): 59-68.

Amado Filho GM, Karez, CS, Andrade, LR, Yoneshigue-Valentin Y, Pfeiffer WC 1997. Effects on growth and accumulation of zinc in six seaweed species. Ecotoxicology and Environmental Safety 37(3): 223-228.

Anderson R, Carrick P, Levitt G, Share A 1997. Holdfasts of adult kelp *Ecklonia maxima* provide refuges from grazing for recruitment of juvenile kelps. Marine Ecology Progress Series 159: 265-273.

Anderson TW 1994. Role of macroalgal structure in the distribution and abundance of a temperate reef fish. Marine Ecology Progress Series 113(3): 279-290.

Anyango JO, Mlewa CM, Mwaluma, J 2017. Abundance, diversity and trophic status of wild fish around seaweed farms in Kibuyuni, South Coast Kenya. International Journal of Fisheries and Aquatic Studies 5(3): 440-446.

ANZG 2018. Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Australian and New Zealand Governments and Australian state and territory governments, Canberra ACT, Australia. Available at www.waterquality.gov.au/anz-guidelines

Bach LT, Tamsitt V, Gower J, Hurd CL, Raven JA, Boyd PW 2021. Testing the climate intervention potential of ocean afforestation using the Great Atlantic *Sargassum* Belt. Nature Communications 12(1): 1-10.

Bacher K., Gordoa A, Sagué O 2012. Spatial and temporal extension of wild fish aggregations at *Sparus aurata* and *Thunnus thynnus* farms in the north-western Mediterranean. Aquaculture Environment Interactions 2(3): 239-252.

Balboa EM, Conde E, Soto ML, Pérez-Armada L, Domínguez H 2015. Cosmetics from marine sources. In: Kim SK editor. Springer Handbook of Marine Biotechnology. Berlin, Heidelberg, Springer Berlin Heidelberg. pp. 1015-1042.

Barbier M, Charrier B, Araujo R, Holdt SL, Jacquemin B, Rebours C (Eds.) 2019. Phycomorph European guidelines for a sustainable aquaculture of seaweeds. Roscoff, France: COST Action FA1406.

Barrett K, Anderson WB, Wait DA, Grismer LL, Polis GA, Rose MD 2005. Marine subsidies alter the diet and abundance of insular and coastal lizard populations. Oikos 109(1): 145-53.

Barrett LT, Swearer SE, Dempster T 2019. Impacts of marine and freshwater aquaculture on wildlife: a global meta-analysis. Reviews in Aquaculture 11(4): 1022-1044.

Bauer JE, Druffel, ERM 1998. Ocean margins as a significant source of organic matter to the deep open ocean. Nature 392(6675): 482-485.

Beaumont NJ, Austen MC, Atkins JP, Burdon D, Degraer S, Dentinho TP, Derous S, Holm P, Horton T, van Ierland E, Marboe AH, Starkey DJ, Townsend M, Zarzycki, T 2007. Identification, definition and quantification of goods and services provided by marine biodiversity: Implications for the ecosystem approach. Marine Pollution Bulletin 54(3): 253-265.

BenDor TK, Branham J, Timmerman D, Madsen B 2021. Predicting the existence and prevalence of the US water quality trading markets. Water 13(2): 185.

Benjamins S, Harnois V, Smith H, Johanning L, Greenhill L, Carter C, Wilson B 2014. Understanding the potential for marine megafauna entanglement risk from renewable marine energy developments. Prepared for Scottish Association for Marine Science Research Services Ltd and the University of Exeter. Scottish Natural Heritage Commissioned Report No. 791.

Bennett, EM, Peterson GD, Gordon LJ 2009. Understanding relationships among multiple ecosystem services. Ecology Letters 12(12): 1394-1404.

Bergman KC, Svensson S, Öhman MC 2001. Influence of algal farming on fish assemblages. Marine Pollution Bulletin 42(12): 1379-1389.

Bjerregaard R, Valderrama D, Radulovich R, Diana J, Capron M, Mckinnie CA, Cedric M, Hopkins K, Yarish C, Goudey C 2016. Seaweed aquaculture for food security, income generation and environmental health in tropical developing countries. Prepared for The World Bank Group.

Bodkin JL 1988. Effects of kelp forest removal on associated fish assemblages in central California. Journal of Experimental Marine Biology and Ecology 117(3): 227-238.

Bolton JJ, Robertson-Andersson DV, Shuuluka D, Kandjengo L 2009. Growing *Ulva* (Chlorophyta) in integrated systems as a commercial crop for abalone feed in South Africa: a SWOT analysis. Journal of Applied Phycology 21(5): 575-583.

Borras-Chavez R, Edwards M, Vásquez JA 2012. Testing sustainable management in Northern Chile: harvesting *Macrocystis pyrifera* (Phaeophyceae, Laminariales). A case study. Journal of Applied Phycology 24(6): 1655-1665.

Boukid F, Rosell CM, Rosene S, Bover-Cid S, Castellari M 2021. Non-animal proteins as cutting-edge ingredients to reformulate animal-free foodstuffs: Present status and future perspectives. Critical Reviews in Food Science and Nutrition: 1-31.

Boyd AJ, Heasman K 1998. Shellfish mariculture in the Benguela system: Water flow patterns within a mussel farm in Saldanha Bay, South Africa. Journal of Shellfish Research 17(1): 25-32.

Bradly N, Syddall V, Ingram C, Clarkson R, Elliot A, Major R & Adams S 2021. Stocktake and characterisation of Aotearoa New Zealand’s seaweed sector: market and regulatory focus. Prepared for Sustainable Seas National Science Challenge project 2.5. 58 p. plus appendices.

Broch OJ, Ellingsen IH, Forbord S, Wang X, Volent Z, Alver MO, Hand A, Andresen K, Slagstad D, Reitan KI, Olsen Y, Skjermo J 2013. Modelling the cultivation and bioremediation potential of the kelp *Saccharina latissima* in close proximity to an exposed salmon farm in Norway. Aquaculture Environment Interactions 4(2): 187-206.

Brooker SG, Cambie RC, Cooper RC 1987. New Zealand medicinal plants. Reed Publishing, Auckland, New Zealand. pp. 268.

Buchanan J, Zuccarello GC 2012. Decoupling of short- and long-distance dispersal pathways in the endemic New Zealand seaweed *Carpophyllum maschalocarpum* (Phaeophyceae, Fucales). Journal of Phycology 48(3): 518-529.

Buschmann AH, Camus C, Infante J, Neori A, Israel Á, Hernández-González MC, Pereda SV, Gomez-Pinchetti JL, Golberg A, Tadmor-Shalev N, Critchley AT 2017. Seaweed production: overview of the global state of exploitation, farming and emerging research activity. European Journal of Phycology 52(4): 391-406.

Buschmann AH, Prescott S, Potin P, Faugeron S, Vásquez JA, Camus C, Infante J, Hernández-González, MC, Gutíerrez A, Varela DA 2014. Chapter Six - The status of kelp exploitation and marine agronomy, with emphasis on *Macrocystis pyrifera*, in Chile. In N. Bourgougnon (Ed.), Advances in Botanical Research (Vol. 71, pp. 161-188): Academic Press.

Campbell ML, King S, Heppenstall LD, van Gool E, Martin R, Hewitt CL 2017. Aquaculture and urban marine structures facilitate native and non-indigenous species transfer through generation and accumulation of marine debris. Marine Pollution Bulletin 123(1-2): 304-312.

Campbell I, Macleod A, Sahlmann C, Neves L, Funderud J, Øverland M, Hughes AD, Stanley M 2019. The environmental risks associated with the development of seaweed farming in Europe - prioritizing key knowledge gaps. Frontiers in Marine Science 6: 107.

Carr MH 1994. Effects of macroalgal dynamics on recruitment of a temperate reef fish. Ecology 75(5): 1320-1333.

Carvalho LG, Pereira L 2014. Review of marine algae as a source of bioactive metabolites: a narine biotechnology approach. In: Pereira L, Neto JM editors. Marine algae : biodiversity, taxonomy, environmental assessment, and biotechnology. Baton Rouge, United States, Taylor & Francis Group.

Cebrian J, Duarte CM 1995. Plant growth-rate dependence of detrital carbon storage in ecosystems. Science 268(5217): 1606-1608.

Chen H, Zhou D, Luo G, Zhang S, Chen J 2015. Macroalgae for biofuels production: Progress and perspectives. Renewable and Sustainable Energy Reviews 47: 427-437.

Chopin T 2013. Integrated multi-trophic aquaculture (IMTA). In: Christou P, Savin R, Costa-Pierce BA, Misztal I, Whitelaw CBA editors. Sustainable food production. New York, New York, Springer. pp. 184-205.

Chopin T, Robinson SMC, Troell M, Neori A, Buschmann A H, Fang J 2008. Multitrophic integration for sustainable marine aquaculture. In: Encyclopedia of Ecology. Amsterdam, Netherlands, Elsevier. pp. 2463-2475.

Chopin T, Tacon AGJ 2021. Importance of seaweeds and extractive species in global aquaculture production. Reviews in Fisheries Science & Aquaculture 29(2): 139-148.

Christensen PB, Glud RN, Dalsgaard T, Gillespie P 2003. Impacts of longline mussel farming on oxygen and nitrogen dynamics and biological communities of coastal sediments. Aquaculture 218: 567-588.

Christie H, Fredriksen S, Rinde E 1998. Regrowth of kelp and colonization of epiphyte and fauna community after kelp trawling at the coast of Norway. Hydrobiologia 375/376: 49-58.

Christie H, Jørgensen NM, Norderhaug KM 2007. Bushy or smooth, high or low; importance of habitat architecture and vertical position for distribution of fauna on kelp. Journal of Sea Research 58(3): 198-208.

Christie H, Jørgensen NM, Norderhaug KM, Waage-Nielsen E 2003. Species distribution and habitat exploitation of fauna associated with kelp (*Laminaria Hyperborea*) along the Norwegian Coast. Journal of the Marine Biological Association of the United Kingdom 83(4): 687-699.

Christie H, Norderhaug K, Fredriksen S 2009. Macrophytes as habitat for fauna. Marine Ecology Progress Series 396: 221-233.

Clark D, Newcombe E, Forrest R, Keeley N, Taylor D, Goodwin E, Jiang W 2012. Stage One development of subzones (I) and (K) in Tasman Bay AMA 3: summary report. Prepared for Tasman Bay Ring Road Farming Ltd. Cawthron Report No. 2176. 70 p. plus appendices.

Clark D, Newcombe E, Forrest R, Keeley N, Taylor D, Goodwin E, Jiang W 2012. Stage One development of subzones (P) and (Q) in Golden Bay AMA 2: summary Report. Prepared for Golden Bay Ring Road Farming Ltd. Cawthron Report No. 2215. 73 p. plus appendices.

Clement D 2013. Literature review of ecological effects of aquaculture: effects on marine mammals. Prepared for Ministry for Primary Industries. 19 p.

Clements JC, Chopin T 2017. Ocean acidification and marine aquaculture in North America: potential impacts and mitigation strategies. Reviews in Aquaculture 9(4): 326-341.

Cole AJ, de Nys R, Paul NA 2014. Removing constraints on the biomass production of freshwater macroalgae by manipulating water exchange to manage nutrient flux. PLoS ONE 9(7): e101284.

Colenso W 1880. On the vegetable food of the ancient New Zealanders before Cook's visit. Transactions of the New Zealand Institute 13: 3-38.

Connell S D 2003. The monopolization of understorey habitat by subtidal encrusting coralline algae: a test of the combined effects of canopy-mediated light and sedimentation. Marine Biology 142(6): 1065-1071.

Cornelisen C 2013. Literature review of ecological effects of aquaculture: effects on wild fish. Prepared for Ministry for Primary Industries. 14 p.

Craggs RJ, Adey WH, Jenson KR, St. John MS, Green FB, Oswald WJ 1996. Phosphorus removal from wastewater using an algal turf scrubber. Water Science and Technology 33(7): 191-198.

Cunningham S, South P, Cahill P 2020. Biosecurity considerations for farming non-native seaweeds: a case study of *Undaria pinnatifida* in New Zealand. Prepared for the Ministry of Business, Innovation and Employment: Shellfish Aquaculture Research Platform CAWX1801. Cawthron Report No. 3395. 42 p. plus appendices.

Custódio M, Villasante S, Calado R, Lillebø AI 2020. Valuation of ecosystem services to promote sustainable aquaculture practices. Reviews in Aquaculture 12(1): 392-405.

Dantagnan P, Hernández AN, Borquez A, Mansilla AS 2009. Inclusion of macroalgae meal (*Macrocystis pyrifera*) as feed ingredient for rainbow trout (*Oncorhynchus mykiss*): effect on flesh fatty acid composition. Aquaculture Research 41(1): 87-94.

Dayton PK 1985. Ecology of kelp communities. Annual Review of Ecology and Systematics 16(1): 215-245.

De Carvalho LL, De Souza EGA, Da Mata Júnior MR, Villaça RC 2017. Assessment of rocky reef fish assemblages close to seaweed farming. Aquaculture Research 48(2): 481-493.

Delille B, Borges AV, Delille D 2009. Influence of giant kelp beds (*Macrocystis pyrifera)* on diel cycles of pCO_2 and DIC in the Sub-Antarctic coastal area. Estuarine, Coastal and Shelf Science 81(1): 114-122.

Dempster T, Sanchez-Jerez P, Fernandez-Jover D, Bayle-Sempere J, Nilsen R, Bjørn, PA, Uglem I 2011. Proxy measures of fitness suggest coastal fish farms can act as population sources and not ecological traps for wild gadoid fish. PLOS ONE 6(1): e15646.

Dempster T, Sanchez-Jerez P, Tuja F, Fernandez-Jover D, Bayle-Sempere J, Boyra A, Haroun R 2006. Coastal aquaculture and conservation can work together. Marine Ecology Progress Series 314: 309-310.

Dempster T, Uglem I, Sanchez-Jerez P, Fernandez-Jover D, Bayle-Sempere J, Nilsen R, Bjørn P 2009. Coastal salmon farms attract large and persistent aggregations of wild fish: an ecosystem effect. Marine Ecology Progress Series 385: 1-14.

Díaz López B 2017. Temporal variability in predator presence around a fin fish farm in the northwestern Mediterranean Sea. Marine Ecology 38(1): e12378.

Duarte CM, Losada IJ, Hendriks IE, Mazarrasa I, Marba N 2013. The role of coastal plant communities for climate change mitigation and adaption. Nature Climate Change 3(11): 961-968.

Duarte CM, Wu J, Xiao X, Bruhn A, Krause-Jensen D 2017. Can seaweed farming play a role in climate change mitigation and adaptation? Frontiers in Marine Science 4: 100.

Duarte P, Meneses R, Hawkins AJS, Zhu M, Fang J, Grant J 2003. Mathematical modelling to assess the carrying capacity for multi-species culture within coastal waters. Ecological Modelling 168(1-2): 109-143.

Ebeling AW, Laur DR 1985. The influence of plant cover on surfperch abundance at an offshore temperate reef. Environmental Biology of Fishes 12(3): 169-179.

Eckman JE, Duggins DO, Sewell AT 1989. Ecology of under story kelp environments. I. Effects of kelps on flow and particle transport near the bottom. Journal of Experimental Marine Biology and Ecology 129(2): 173-187.

Edgar GJ, Barrett NS, Morton AJ, Samson CR 2004. Effects of algal canopy clearance on plant, fish and macroinvertebrate communities on eastern Tasmanian reefs. Journal of Experimental Marine Biology and Ecology 312(1): 67-87.

Eklöf J, Henriksson R, Kautsky N 2006. Effects of tropical open-water seaweed farming on seagrass ecosystem structure and function. Marine Ecology Progress Series 325: 73-84.

Eklöf JS, De La Torre Castro M, Adelsköld L, Jiddawi NS, Kautsky N 2005. Differences in macrofaunal and seagrass assemblages in seagrass beds with and without seaweed farms. Estuarine, Coastal and Shelf Science 63(3): 385-396.

Elwany MHS, O'Reilly WC, Guza RT, Flick RE 1995. Effects of Southern California kelp beds on waves. Journal of Waterway, Port, Coastal, and Ocean Engineering 121(2): 143-150.

Evans LK, Edwards MS 2011. Bioaccumulation of copper and zinc by the giant kelp *Macrocystis pyrifera*. Algae 26(3): 265-275.

Fagerli C, Norderhaug K, Christie H 2013. Lack of sea urchin settlement may explain kelp forest recovery in overgrazed areas in Norway. Marine Ecology Progress Series 488: 119-132.

Fan LIN, Meirong DU, Hui LIU, Jianguang FANG, Lars A, Zengjie JIANG 2020. A physical-biological coupled ecosystem model for integrated aquaculture of bivalve and seaweed in Sanggou Bay. Ecological Modelling 431: 109181.

FAO 2018. The global status of seaweed production, trade and utilization. Globefish Research Programme. Food and Agriculture Organization of the United Nations. Rome. Volume 124.

FAO 2020. The State of the World Fisheries and Aquaculture 2020. Sustainability in Action. Food and Agriculture Organization of the United Nations. Rome.

FAO 2021. Fishery Statistical Collections. Global aquaculture production 1950-2019 (FishStatJ). Food and Agriculture Organization of the United Nations. Retrieved April 28, 2021, from http://www.fao.org/fishery/statistics/global-aquaculture-production/query/en and http://www.fao.org/fishery/statistics/software/fishstatj/en

Faust E, Halvorsen KT, Andersen P, Knutsen H, André C 2018. Cleaner fish escape salmon farms and hybridize with local wrasse populations. Royal Society Open Science 5(3): 171752.

Fernández PA, Leal PP, Henríquez LA 2019. Co-culture in marine farms: macroalgae can act as chemical refuge for shell-forming molluscs under an ocean acidification scenario. Phycologia 58(5): 542-551.

Fernandez-Gonzalez V, Fernandez-Jover D, Toledo-Guedes K, Valero-Rodriguez JM, Sanchez-Jerez P 2014. Nocturnal planktonic assemblages of amphipods vary due to the presence of coastal aquaculture cages. Marine Environmental Research 101: 22-28.

Forrest B, Hopkins G 2016. Grouping aquaculture species by environmental effects: Preliminary assessment. Cawthron Report No. 2914. 30 p. plus appendices.

Forrest BM, Keeley NB, Hopkins GA, Webb SC, Clement DM 2009. Bivalve aquaculture in estuaries: review and synthesis of oyster cultivation effects. Aquaculture 29: 1-15.

Fort A, Lebrault M, Allaire M, Esteves-Ferreira AA, McHale M, Lopez F, Fariñas-Franco JM, Alseekh S, Fernie AR, Sulpice R 2019. Extensive variations in diurnal growth patterns and metabolism among *Ulva* spp. strains. Plant Physiology 180(1): 109-123.

Fort A, Mannion C, Fariñas-Franco JM, Sulpice R 2020. Green tides select for fast expanding *Ulva* strains. Science of the Total Environment 698: 134337.

Foster MS, Barilotti DC 1990. An approach to determining the ecological effects of seaweed harvesting: a summary. Hydrobiologia 204-205(1): 15-16.

Froehlich HE, Afflerbach JC, Frazier M, Halpern BS 2019. Blue growth potential to mitigate climate change through seaweed offsetting. Current Biology 29(18): 3087-3093.

Gadd GM 2009. Biosorption: critical review of scientific rationale, environmental importance and significance for pollution treatment. Journal of Chemical Technology & Biotechnology 84(1): 13-28.

Gao G, Burgess JG, Wu M, Wang S, Gao K 2020. Using macroalgae as biofuel: current opportunities and challenges. Botanica Marina 63(4): 355-370.

Gentry RR, Alleway HK, Bishop MJ, Gillies CL, Waters T, Jones R 2020. Exploring the potential for marine aquaculture to contribute to ecosystem services. Reviews in Aquaculture 12(2): 499-512.

Gibbs MM, James MR, Pickmere SE, Woods PH, Shakespeare BS, Hickman RW, Illingworth J 1991. Hydrodynamic and water column properties at six stations associated with mussel farming in Pelorus Sound, 1984–85. New Zealand Journal of Marine and Freshwater Research 25(3): 239-254.

Giles H, Pilditch CA, Bell DG 2006. Sedimentation from mussel (*Perna canaliculus*) culture in the Firth of Thames, New Zealand: Impacts on sediment oxygen and nutrient fluxes. Aquaculture 261: 125-140.

Glover K, Pertoldi C, Besnier F, Wennevik V, Kent M, Skaala Ø 2013. Atlantic salmon populations invaded by farmed escapees: quantifying genetic introgression with a Bayesian approach and SNPs. BMC Genetics 14(1): 74.

Goecke F, Klemetsdal G, Ergon Å 2020. Cultivar development of kelps for commercial cultivation—past lessons and future prospects. Frontiers in Marine Science 7(110).

Grant J Bacher C 2001. A numerical model of flow modification induced by suspended aquaculture in a Chinese bay. Canadian Journal of Fisheries and Aquatic Sciences 58(5): 1003-1011.

Greiner CM, Klinger T, Ruesink JL, Barber JS, Horwith M 2018. Habitat effects of macrophytes and shell on carbonate chemistry and juvenile clam recruitment, survival, and growth. Journal of Experimental Marine Biology and Ecology 509: 8-15.

Gundersen H, Rinde E, Bekkby T, Hancke K, Gitmark JK, Christie H 2021. Variation in population structure and standing stocks of kelp along multiple environmental gradients and implications for ecosystem services. Frontiers in Marine Science 8: 360.

Hadley S, Wild-Allen K, Johnson C, Macleod C 2015. Modelling macroalgae growth and nutrient dynamics for integrated multi-trophic aquaculture. Journal of Applied Phycology 27(2): 901-916.

Handley S 2016. History of benthic change in Queen Charlotte Sound/Totaranui, Marlborough. Prepared for Marlborough District Council. NIWA Report No. NEL2015-018. 66 p.

Hasselström L, Visch W, Gröndahl F, Nylund GM, Pavia H 2018. The impact of seaweed cultivation on ecosystem services - a case study from the west coast of Sweden. Marine Pollution Bulletin 133: 53-64.

He P, Xu S, Zhang H, Wen S, Dai Y, Lin S, Yarish C 2008. Bioremediation efficiency in the removal of dissolved inorganic nutrients by the red seaweed, *Porphyra yezoensis*, cultivated in the open sea. Water Research 42(4-5): 1281-1289.

Hehre EJ, Meeuwig JJ 2015. Differential response of fish assemblages to coral reef-based seaweed farming. PLOS ONE 10(3): e0118838.

Hehre EJ, Meeuwig JJ 2016. A global analysis of the relationship between farmed Seaweed production and herbivorous fish catch. PLOS ONE 11(2): e0148250.

Hewitt JE, Faulkner L, Greenaway A, Lundquist C 2018. Proposed ecosystem-based management principles for New Zealand. Resource Management Journal: 10-13.

Hill R, Bellgrove A, Macreadie PI, Petrou K, Beardall J, Steven A, Ralph PJ 2015. Can macroalgae contribute to blue carbon? An Australian perspective. Limnology and Oceanography 60(5): 1689-1706.

Himaya SWA, Kim SK 2015. Marine Nutraceuticals. In: Kim SK editor. Springer handbook of marine biotechnology. Berlin, Heidelberg, Springer. pp. 995-1014.

Hinojosa IA, Green BS, Gardner C, Jeffs A 2015. Settlement and early survival of southern rock lobster, *Jasus edwardsii*, under climate-driven decline of kelp habitats. ICES Journal of Marine Science 72(suppl_1): i59-i68.

Hinojosa IA, Thiel M 2009. Floating marine debris in fjords, gulfs and channels of southern Chile. Marine Pollution Bulletin 58(3): 341-350.

Hope J A, Paterson DM, Thrush SF 2020. The role of microphytobenthos in soft-sediment ecological networks and their contribution to the delivery of multiple ecosystem services. Journal of Ecology 108(3): 815-830.

Hotchkiss S, Murphy C 2014. Marine Algae and Human Health. In: Pereira L, Neto JM editors. Marine algae : biodiversity, taxonomy, environmental assessment, and biotechnology. Baton Rouge, United States, Taylor & Francis Group.

Hu ZM, Shan TF, Zhang J, Zhang QS, Critchley AT, Choi HG, Yotsukura N, Liu FL, Duan DL 2021. Kelp aquaculture in China: a retrospective and future prospects. Reviews in Aquaculture 13: 1324-1351.

Huo YZ, Xu SN, Wang YY, Zhang JH, Zhang YJ, Wu WN, Chen YQ, He PM 2011. Bioremediation efficiencies of *Gracilaria verrucosa* cultivated in an enclosed sea area of Hangzhou Bay, China. Journal of Applied Phycology 23(2): 173-182.

Hwang EK, Choi HG, Kim JK 2020a. Seaweed resources of Korea. Botanica Marina 63(4): 395-405.

Hwang EK, Liu F, Lee KH, Ha DS, Park CS 2018. Comparison of the cultivation performance between Korean (Sugwawon No. 301) and Chinese strains (Huangguan No. 1) of kelp *Saccharina japonica* in an aquaculture farm in Korea. Algae 33: 101-108.

Hwang EK, Park CS 2020b. Seaweed cultivation and utilization of Korea. Algae 35(2): 107-121.

Hwang EK, Yotsukura N, Pang SJ, Su L, Shan TF 2019. Seaweed breeding programs and progress in eastern Asian countries. Phycologia 58(5): 484-495.

Hwang EY, Song Q, Jia G, Specht JE, Hyten DL, Costa J, Cregan PB 2014. A genome-wide association study of seed protein and oil content in soybean. BMC Genomics 15(1):1-12.

Ince R, Hyndes GA, Lavery PS, Vanderklift MA 2007 Marine macrophytes directly enhance abundances of sandy beach fauna through provision of food and habitat. Estuarine, Coastal and Shelf Science 74(1-2): 77-86.

Jansson E, Quintela M, Dahle G, Albretsen J, Knutsen H, André C, Strand Å, Mortensen S, Taggart JB, Karlsbakk E, Kvamme BO, Glover KA 2017. Genetic analysis of goldsinny wrasse reveals evolutionary insights into population connectivity and potential evidence of inadvertent translocation via aquaculture. ICES Journal of Marine Science 74(8): 2135-2147.

Jiang Z, Fang J, Mao Y, Han T, Wang G 2013. Influence of seaweed aquaculture on marine inorganic carbon dynamics and sea-air CO_2 Flux. Journal of the World Aquaculture Society 44(1): 133-140.

Jones R, Byron CJ, Jeffs A 2021. Assessing the habitat benefits of kelp aquaculture in New Zealand and Maine. The Fish Site. Retrieved from https://thefishsite.com/articles/assessing-the-habitat-benefits-of-kelp-aquaculture-in-new-zealand-and-maine

Kang YH, Kim S, Choi SK, Lee HJ, Chung IK, Park SR 2021. A comparison of the bioremediation potential of five seaweed species in an integrated fish-seaweed aquaculture system: implication for a multi-species seaweed culture. Reviews in Aquaculture 13(1): 353-364.

Keeley N, Forrest B, Hopkins G, Gillespie P, Clement D, Webb S, Knight B, Gardner J 2009. Review of the ecological effects of farming shellfish and other non-finfish species in New Zealand. Prepared for the Ministry of Fisheries. Cawthron Report No. 1476. 144 p. plus appendices.

Keeling RF, Körtzinger, A, Gruber N 2010. Ocean deoxygenation in a warming world. Annual Review of Marine Science 2(1): 199-229.

Kennelly SJ 1987. Physical disturbances in an Australian kelp community. Marine Ecology Progress Series 40(1/2): 145-153.

Kerrison PD, Stanley MS, Edwards, MD, Black KD, Hughes AD 2015. The cultivation of European kelp for bioenergy: Site and species selection. Biomass and Bioenergy 80: 229-242.

Kim E, Park HS, Jung Y, Choi DW, Jeong WJ, Park HS, Hwang MS, Park EJ, Gong YG 2011. Identification of the high-temperature response genes from *Porphyra seriata* (Rhodophyta) expression sequence tags and enhancement of heat tolerance of *Chlamydomonas* (Chlorophyta) by expression of the Porphyra HTR2 gene. Journal of Phycology 47(4): 821-828.

Kim J, Stekoll M Yarish C 2019. Opportunities, challenges and future directions of open-water seaweed aquaculture in the United States. Phycologia 58(5): 446-461.

Kim JK, Kraemer G, Yarish C 2019. Evaluation of the metal content of farm grown *Gracilaria tikvahiae* and *Saccharina latissima* from Long Island Sound and New York estuaries. Algal Research 40: 101484.

Kim JK, Kraemer GP, Yarish C 2014. Field scale evaluation of seaweed aquaculture as a nutrient bioextraction strategy in Long Island Sound and the Bronx River Estuary. Aquaculture 433: 148-156.

Kirkman H, Kendrick GA 1997. Ecological significance and commercial harvesting of drifting and beach-cast macro-algae and seagrasses in Australia: a review. Journal of Applied Phycology 9(4):311-26.

Knowlton AR, Hamilton PK, Marx MK, Pettis HM, Kraus SD 2012. Monitoring North Atlantic right whale *Eubalaena glacialis* entanglement rates: a 30 yr retrospective. Marine Ecology Progress Series 466: 293-302.

Koch EW, Barbier EB, Silliman BR, Reed DJ, Perillo, GME, Hacker SD, Granek EF, Primavera JH, Muthiga N, Polasky S, Halpern BS, Kennedy CJ, Kappel CV, Wolanski E 2009. Non-linearity in ecosystem services: temporal and spatial variability in coastal protection. Frontiers in Ecology and the Environment 7(1): 29-37.

Krause G, Billing SL, Dennis J, Grant J, Fanning L, Filgueira R, Miller M, Pérez Agúndez JA, Stybel N, Stead SM, Wawrzynski W 2020. Visualizing the social in aquaculture: How social dimension components illustrate the effects of aquaculture across geographic scales. Marine Policy 118: 103985.

Krause-Jensen D, Duarte CM 2016. Substantial role of macroalgae in marine carbon sequestration. Nature Geoscience 9(10): 737-742.

Krause-Jensen D, Lavery P, Serrano O, Marbà N, Masque P, Duarte CM 2018. Sequestration of macroalgal carbon: the elephant in the Blue Carbon room. Biology Letters 14(6): 20180236.

Krumhansl KA, Bergman JN, Salomon AK 2017. Assessing the ecosystem-level consequences of a small-scale artisanal kelp fishery within the context of climate-change. Ecological Applications 27(3): 799-813.

Krumhansl KA, Okamoto DK, Rassweiler A, Novak M, Bolton JJ, Cavanaugh KC, Connell SD, Johnson CR, Konar B, Ling SD, Micheli F 2016. Global patterns of kelp forest change over the past half-century. Proceedings of the National Academy of Sciences 113(48): 13785-13790.

Laist DW, Coe JM, O'Hara KJ 1999. Marine debris pollution. In: Twiss Jr, Reeves RR editors. Conservation and management of marine mammals. Washington DC, Smithsonian Institution Press. pp. 342–363.

Langlois J, Sassi JF, Jard G, Steyer JP, Delgenes JP, Hélias A 2012. Life cycle assessment of biomethane from offshore-cultivated seaweed. Biofuels, Bioproducts and Biorefining 6(4): 387-404.

Lavery P, Bootle S, Vanderklift M 1999. Ecological Effects of Macroalgal Harvesting on Beaches in the Peel-Harvey Estuary, Western Australia. Estuarine, Coastal and Shelf Science 49(2): 295-309.

Lawton RJ, Mata L, de Nys R, Paul NA 2013. Algal bioremediation of waste waters from land-based aquaculture using *Ulva*: selecting target species and strains. PLoS ONE 8(10): e77344.

Lawton RJ, Sutherland JE, Glasson CRK, Magnusson ME 2021. Selection of temperate *Ulva* species and cultivars for land-based cultivation and biomass applications. Algal Research 56: 102320.

Lee H, Lautenbach S 2016. A quantitative review of relationships between ecosystem services. Ecological Indicators 66: 340-351.

Li X, Zhang Z, Qu S, Liang G, Sun J, Zhao N, Cui C, Cao Z, Li Y, Pan J, Yu S, Wang Q, Li X, Luo S, Song S, Guo L, Yang G 2016. Improving seedless kelp (*Saccharina japonica*) during its domestication by hybridizing gametophytes and seedling-raising from sporophytes. Scientific Reports 6(1): 21255.

Liquete C, Piroddi C, Drakou EG, Gurney L, Katsanevakis S, Charef A, Egoh B 2013. Current status and future prospects for the assessment of marine and coastal ecosystem services: a systematic review. PlosOne 8(7): e67737.

Lorentsen S-H, Sjøtun K, Grémillet D 2010. Multi-trophic consequences of kelp harvest. Biological Conservation 143(9): 2054-2062.

Lotze HK, Milewski I, Fast J, Kay L, Worm B 2019. Ecosystem-based management of seaweed harvesting. Botanica Marina 62(5): 395-409.

Loureiro R, Gachon CMM, Rebours C 2015. Seaweed cultivation: potential and challenges of crop domestication at an unprecedented pace. New Phytologist 206(2): 489-492.

Luo H, Wang Q, Liu Z, Wang S, Long A, Yang Y 2020. Potential bioremediation effects of seaweed *Gracilaria lemaneiformis* on heavy metals in coastal sediment from a typical mariculture zone. Chemosphere 245: 125636.

Macartain P, Gill CIR, Brooks M, Campbell R, Rowland IR 2008. Nutritional value of edible seaweeds. Nutrition Reviews 65(12): 535-543.

Mangan S, Bryan KR, Thrush SF, Gladstone-Gallagher RV, Lohrer AM, Pilditch CA 2020a. Shady business: the darkening of estuaries constrains benthic ecosystem function. Marine Ecology Progress Series 647: 33-48.

Mangan S, Lohrer AM, Thrush SF, Pilditch CA 2020b. Water column turbidity not sediment nutrient enrichment moderates microphytobenthic primary production. Journal of Marine Science and Engineering 8(10): 732.

Mata L, Magnusson M, Paul N, de Nys R 2016. The intensive land-based production of the green seaweeds *Derbesia tenuissima* and *Ulva ohnoi*: biomass and bioproducts. Journal of Applied Phycology 28(1): 365-375.

Mata L, Schuenhoff A, Santos R 2010. A direct comparison of the performance of the seaweed biofilters, *Asparagopsis armata* and *Ulva rigida*. Journal of Applied Phycology 22(5): 639-644.

McLeod KL, Lubchenco J, Palumbi SR, Rosenberg AA 2005. Scientific consensus statement on marine ecosystem-based management. Signed by 221 academic scientists and policy experts with relevant expertise. Communication Partnership for Science and the Sea (COMPASS). Retrieved from http://compassonline.org/?q=EBM

Millennium Ecosystem Assessment Board 2005. Ecosystems and human well-being: synthesis. Island Press.

Mongin M, Baird ME, Hadley S, Lenton A 2016. Optimising reef-scale CO_2 removal by seaweed to buffer ocean acidification. Environmental Research Letters 11(3): 034023.

Moore LB 1944. New Zealand seaweed for agar manufacture. New Zealand Journal of Science and Technology 25: 183-209.

Mork M 1996. The effect of kelp in wave damping. Sarsia 80(4): 323-327.

Morrisey DJ, Cole RG, Davey NK, Handley SJ, Bradly A, Brown SN, Madarasz AL 2006. Abundance and diversity of fish on mussel farms in New Zealand. Aquaculture 252(2-4): 277-288.

Mou Y 2015. Study on the impacts of floating seaweed on wind waves. Unpublished Masters' thesis, Delft University of Technology, Delf, Netherlands.

MPI 2013. Literature review of ecological effects of aquaculture. Wellington: A collaboration between Ministry for Primary Industries, Cawthron Institute and National Institute for Water and Atmospheric Research Ltd. Ministry for Primary Industries.

Muangmai N, Fraser CI, Zuccarello GC 2015. Contrasting patterns of population structure and demographic history in cryptic species of *Bostrychia intricata* (Rhodomelaceae, Rhodophyta) from New Zealand. Journal of Phycology 51(3): 574-585.

Mulbry W, Kondrad S, Pizarro C, Kebede-Westhead E 2008. Treatment of dairy manure effluent using freshwater algae: Algal productivity and recovery of manure nutrients using pilot-scale algal turf scrubbers. Bioresource Technology 99(17): 8137-8142.

Mulbry W, Westhead EK, Pizarro C, Sikora L 2005. Recycling of manure nutrients: use of algal biomass from dairy manure treatment as a slow release fertilizer. Bioresource Technology 96(4): 451-458.

Muntadas A, De Juan S, Demestre M 2015. Integrating the provision of ecosystem services and trawl fisheries for the management of the marine environment. Science of the Total Environment 506: 594-603.

Nadeeshani H, Hassouna A, Lu J 2021. Proteins extracted from seaweed *Undaria pinnatifida* and their potential uses as foods and nutraceuticals. Critical Reviews in Food Science and Nutrition: 1-17.

Naylor RL, Hardy RW, Buschmann AH, Bush SR, Cao L, Klinger DH, Little DC, Lubchenco J, Shumway SE, Troell M 2021. A 20-year retrospective review of global aquaculture. Nature 591(7851): 551-563.

Neori A, Chopin T, Troell M, Buschmann AH, Kraemer GP, Halling C, Shpigel M, Yarish C 2004. Integrated aquaculture: rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture. Aquaculture 231(1-4): 361-391.

Neveux N, Magnusson M, Mata L, Whelan A, de Nys R, Paul NA 2016. The treatment of municipal wastewater by the macroalga *Oedogonium* sp. and its potential for the production of biocrude. Algal Research 13: 284-292.

Newcombe E, Giles H, Floerl L 2019. Seabed survey and mapping of Coromandel inshore mussel farms, 2018. Prepared for a collective of inshore mussel farmers. Cawthron Report No. 3297. 37 p. plus appendices.

Norderhaug KM, Christie H, Fosså JH, Fredriksen S 2005. Fish–macrofauna interactions in a kelp (*Laminaria hyperborea*) forest. Journal of the Marine Biological Association of the United Kingdom 85(5): 1279-1286.

Park JS, Shin SK, Wu H, Yarish C, Yoo HI, Kim JK 2021. Evaluation of nutrient bioextraction by seaweed and shellfish aquaculture in Korea. Journal of the World Aquaculture Society. 1-17.

Park M, Shin SK, Do YH, Yarish C, Kim JK 2018. Application of open water integrated multi-trophic aquaculture to intensive monoculture: A review of the current status and challenges in Korea. Aquaculture 497: 174-183.

Parker LM, Ross PM, O'Connor WA, Portner HO, Scanes E, Wright JM 2013. Predicting the response of molluscs to the impact of ocean scidification. Biology 2(2): 651-692.

Paul N, De Nys R, Steinberg P 2006. Seaweed-herbivore interactions at a small scale: direct tests of feeding deterrence by filamentous algae. Marine Ecology Progress Series 323: 1-9.

Pereira L, Riberiro-Claro JA 2014. Analysis by vibrational spectroscopy of seaweed with potential use in food, pharmaceutical and cosmetic industries. In: Pereira L, Neto JM editors. Marine algae : biodiversity, taxonomy, environmental assessment, and biotechnology. Baton Rouge, United States, Taylor & Francis Group. pp. 228-250.

Pettit LR, Smart CW, Hart MB, Milazzo M, Hall-Spencer JM 2015. Seaweed fails to prevent ocean acidification impact on foraminifera along a shallow-water CO_2 gradient. Ecology and Evolution 5(9): 1784-1793.

Phillippi A, Tran K, Perna A 2014. Does intertidal canopy removal of *Ascophyllum nodosum* alter the community structure beneath? Journal of Experimental Marine Biology and Ecology 461: 53-60.

Phillips JC, Hurd CL 2003. Nitrogen ecophysiology of intertidal seaweeds from New Zealand: N uptake, storage and utilisation in relation to shore position and season. Marine Ecology Progress Series 264: 31-48.

Pilditch CA, Grant J, Bryan KR 2001. Seston supply to sea scallops (*Placopecten magellanicus*) in suspended culture. Canadian Journal of Fisheries and Aquatic Sciences 58(2): 241-253.

Plew DR 2005a. The hydrodynamic effects of long-line mussel farms. Unpublished PhD thesis (civil engineering), University of Canterbury, Christchurch, New Zealand.

Plew DR, Stevens CL, Spigel RH, Hartstein ND 2005b. Hydrodynamic implications of large offshore mussel farms. IEEE Journal of Oceanic Engineering 30(1): 95-108.

Price CS, Keane E, Morin D, Vaccaro C, Bean D, Morris Jr JA 2017. Protected species & marine aquaculture interactions. NOAA Technical Memorandum NOS NCCOS 211. 85 p.

Racine P, Marley A, Froehlich HE, Gaines SD, Ladner I, Macadam-Somer I, Bradly D 2021. A case for seaweed aquaculture inclusion in U.S. nutrient pollution management. Marine Policy 129: 104506.

Radulovich R, Umanzor S, Cabrera R, Mata R 2015. Tropical seaweeds for human food, their cultivation and its effect on biodiversity enrichment. Aquaculture 436: 40-46.

Ray NE, Terlizzi DE, Kangas PC 2017. Nitrogen and phosphorus removal by the Algal Turf Scrubber at an oyster aquaculture facility. Ecological Engineering 78: 27-32.

Reid GK, Lefebvre S, Filgueira R, Robinson SMC, Broch OJ, Dumas A, Chopin TBR 2020. Performance measures and models for open-water integrated multi-trophic aquaculture. Reviews in Aquaculture 12(1): 47-75.

Revilla-Lovano S, Sandoval-Gil JM, Zertuche-González JA, Belando-Torrentes MD, Bernardeau-Esteller J, Rangel-Mendoza LK, Ferreira-Arrieta A, Guzmán-Calderón JM, Camacho-Ibar VF, Muñiz-Salazar R, Ávila-López MDC 2021. Physiological responses and productivity of the seaweed *Ulva ohnoi* (Chlorophyta) under changing cultivation conditions in pilot large land-based ponds. Algal Research, 56: 102316.

Rhodes L, Gillespie P, Adamson J 2001. Utilisation of subtidal benthic diatoms (*Bacillariophyceae*) by scallops (*Pecten novaezelandiae*) in Tasman Bay, New Zealand. Prepared for the Cawthron Institute. Cawthron Report No 705. 16 p. plus appendices.

Roleda MY, Hurd CL 2019. Seaweed nutrient physiology: application of concepts to aquaculture and bioremediation. Phycologia 58(5): 552-62.

Saderne V, Wahl M 2013. Differential responses of calcifying and non-calcifying epibionts of a brown macroalga to present-day and ruture upwelling pCO^2. PLOS ONE 8(7): e70455.

Sagar P 2013. Literature review of ecological effects of aquaculture: Seabird Interactions. Prepared for the Ministry for Primary Industries. 18 p.

Santelices B, Ojeda FP 1984. Effect of canopy removal on the understory algal community structure of coastal forests of *Macrocystis pyrifera* from southern South America. Marine Ecology Progress Series 14(2): 165-173.

Sathya B, Indu H, Seenivasan R, Geetha S 2010. Influence of seaweed liquid fertilizer on the growth and biochemical composition of legume grop, *Cajanus cajan* (L.) Mill sp. Journal of Phytology 2(5): 50-63.

Schiel DR, Lilley SA 2011. Impacts and negative feedbacks in community recovery over eight years following removal of habitat-forming macroalgae. Journal of Experimental Marine Biology and Ecology 407(1): 108-115.

Schiel DR, Nelson WA 1990. The harvesting of macroalgae in New Zealand. Hydrobiologia 204-205(1): 25-33.

Shears NT, Smith F, Babcock R C, Duffy CAJ, Villouta E 2008. Evaluation of biogeographic classification schemes for conservation planning: Application to New Zealand's coastal marine environment. Conservation Biology 22(2): 467–481.

Shi J, Wei H, Zhao L, Yuan Y, Fang J, Zhang J 2011. A physical–biological coupled aquaculture model for a suspended aquaculture area of China. Aquaculture 318(3-4): 412-424.

Smale DA, Burrows MT, Moore P, O'Connor N, Hawkins S J 2013. Threats and knowledge gaps for ecosystem services provided by kelp forests: a northeast Atlantic perspective. Ecology and Evolution 3(11): 4016-4038.

Small N, Munday M, Durance I 2017. The challenge of valuing ecosystem services that have no material benefits. Global Environmental Change 44: 57-67.

Smit AJ 2004. Medicinal and pharmaceutical uses of seaweed natural products: A review. Journal of Applied Phycology 16(4): 245-262.

Sondak CFA, Ang PO, Beardall J, Bellgrove A, Boo SM, Gerung GS, Hepburn CD, Hong DD, Hu Z, Kawai H, Largo D, Lee JA, Lim, P-E, Mayakun J, Nelson WA, Oak JH, Phang S-M, Sahoo D, Peerapornpis Y, Yang Y, Chung IK 2017. Carbon dioxide mitigation potential of seaweed aquaculture beds (SABs). Journal of Applied Phycology 29(5): 2363-2373.

Sondak, CFA, Chung IK 2015. Potential blue carbon from coastal ecosystems in the Republic of Korea. Ocean Science Journal 50(1): 1-8.

South PM, Floerl O, Forrest BM, Thomsen MS 2017. A review of three decades of research on the invasive kelp *Undaria pinnatifida* in Australasia: An assessment of its success, impacts and status as one of the world's worst invaders. Marine Environmental Research 131: 243-257.

Stelzenmüller V, Gimpel A, Gopnik M, Gee K 2017. Aquaculture site-selection and marine spatial planning: the roles of GIS-based tools and models. In: Aquaculture perspective of multi-use sites in the open ocean. Springer International Publishing. pp. 131-148.

Sustainable Seas 2018. Strategy for Phase II (2019-2024). Prepared for National Science Challenge, Sustainable Seas.

Sustainable Seas 2021. Blue economy, Sustainable Seas, National Science Challenge. Retrieved 10 March 2021, from https://www.sustainableseaschallenge.co.nz/our-research/blue-economy/

Tait LW, Schiel DR 2011. Legacy effects of canopy disturbance on ecosystem functioning in macroalgal assemblages. PLOS ONE 6(10).

Tallman JC, Forrester GE 2007. Oyster grow-out cages function as artificial reefs for temperate fishes. Transactions of the American Fisheries Society 136(3): 790-799.

Tang Q, Zhang J, Fang J 2011. Shellfish and seaweed mariculture increase atmospheric CO_2 absorption by coastal ecosystems. Marine Ecology Progress Series 424: 97-104.

Tano SA, Halling C, Lind E, Buriyo A, Wikström SA 2015. Extensive spread of farmed seaweeds causes a shift from native to non-native haplotypes in natural seaweed beds. Marine Biology 162(10): 1983-1992.

Taylor RB, Cole RG 1994. Mobile epifauna on subtidal brown seaweeds in northeastern New Zealand. Marine Ecology Progress Series 115: 271-282.

Teagle H, Hawkins SJ, Moore PJ, Smale DA 2017. The role of kelp species as biogenic habitat formers in coastal marine ecosystems. Journal of Experimental Marine Biology and Ecology 492: 81-98.

Theuerkauf SJ, Barrett LT, Alleway HK, Costa-Pierce BA, St. Gelais, A, Jones RC 2021. Habitat value of bivalve shellfish and seaweed aquaculture for fish and invertebrates: Pathways, synthesis and next steps. Reviews in Aquaculture 00: 1-19.

Thompson JA, Stow AJ, Raftos DA 2017. Lack of genetic introgression between wild and selectively bred Sydney rock oysters *Saccostrea glomerata*. Marine Ecology Progress Series 570: 127-139.

Thompson S, Knoll H, Blanchette C, Nielsen K 2010. Population consequences of biomass loss due to commercial collection of the wild seaweed *Postelsia palmaeformis*. Marine Ecology Progress Series 413: 17-32.

Thrush SF, Dayton PK 2002. Disturbance to marine benthic habitats by trawling and dredging: implications for marine biodiversity. Annual Review of Ecology and Systematics 33(1): 449-473.

Tolhurst TJ, Consalvey M, Paterson DM 2008. Changes in cohesive sediment properties associated with the growth of a diatom biofilm. Hydrobiologia 596(1): 225-239.

Troell M, Halling C, Nilsson A, Buschmann AH, Kautsky N, Kautsky L. 1997. Integrated marine cultivation of *Gracilaria chilensis* (Gracilariales, Rhodophyta) and salmon cages for reduced environmental impact and increased economic output. Aquaculture 156(1-2): 45-61.

Troell M, Joyce A, Chopin T, Neori A, Buschmann AH, Fang JG 2009. Ecological engineering in aquaculture — potential for integrated multi-trophic aquaculture (IMTA) in marine offshore systems. Aquaculture 297(1-4): 1-9.

Troell M, Rönnbäck P, Halling C, Kautsky N, Buschmann A 1999. Ecological engineering in aquaculture: use of seaweeds for removing nutrients from intensive mariculture. Journal of Applied Phycology 11: 89-97.

Valero M, Guillemin M-L, Destombe C, Jacquemin B, Gachon C, Badis Y, Buschmann A, Camus C, Faugeron S 2017. Perspectives on domestication research for sustainable seaweed aquaculture. Perspectives in Phycology 4(1): 33-46.

van der Molen J, Ruardij P, Mooney K, Kerrison P, O'Connor NE, Gorman E, Timmermans K, Wright S, Kelly M, Hughes AD, Capuzzo E 2018. Modelling potential production of macroalgae farms in UK and Dutch coastal waters. Biogeosciences 15(4): 1123-1147.

van Kooten GC, Eagle AJ, Manley J, Smolak T 2004. How costly are carbon offsets? A meta-analysis of carbon forest sinks. Environmental Science & Policy 7(4): 239-251.

Vanella FA, Fernández DA, Carolina Romero M, Calvo J 2007. Changes in the fish fauna associated with a sub-Antarctic *Macrocystis pyrifera* kelp forest in response to canopy removal. Polar Biology 30(4): 449-457.

Visch W, Kononets M, Hall POJ, Nylund GM, Pavia H 2020. Environmental impact of kelp (*Saccharina latissima*) aquaculture. Marine Pollution Bulletin 155: 110962.

Wada S, Aoki M, Mikami A, Komatsu T, Tsuchiya Y, Sato T, Shinagawa H, Hama T 2008. Bioavailability of macroalgal dissolved organic matter in seawater. Marine Ecology Progress Series 370: 33-44.

Wada S, Aoki MN, Tsuchiya Y, Sato T, Shinagawa H, Hama T 2007. Quantitative and qualitative analyses of dissolved organic matter released from *Ecklonia cava* Kjellman, in Oura Bay, Shimoda, Izu Peninsula, Japan. Journal of Experimental Marine Biology and Ecology 349(2): 344-358.

Waite RP 1989. The nutritional biology of *Perna canaliculus* with special reference to intensive mariculture systems. Unpublished thesis, University of Canterbury, Christchurch.

Walls A, Kennedy R, Fitzgerald R, Blight A, Johnson M, Edwards M 2016. Potential novel habitat created by holdfasts from cultivated *Laminaria digitata*: assessing the macroinvertebrate assemblages. Aquaculture Environment Interactions 8: 157-169.

Wang X, Broch OJ, Forbord S, Handå A, Skjermo J, Reitan KI, Vadstein O, Olsen, Y 2014a. Assimilation of inorganic nutrients from salmon (*Salmo salar*) farming by the macroalgae (*Saccharina latissima*) in an exposed coastal environment: implications for integrated multi-trophic aquaculture. Journal of Applied Phycology 26(4): 1869-1878.

Wang Y, Fu F, Li J, Wang G, Wu M, Zhan J, Chen X, Mao Z 2016. Effects of seaweed fertilizer on the growth of *Malus hupehensis* Rehd. seedlings, soil enzyme activities and fungal communities under replant condition. European Journal of Soil Biology 75: 1-7.

Wang Z, Wang X, Ke C 2014b. Bioaccumulation of trace metals by the live macroalga *Gracilaria lemaneiformis*. Journal of Applied Phycology 26(4): 1889-1897.

Wassilief M 2021. Seaweed - Traditional use of seaweeds. Te Ara – the Encyclopaedia of New Zealand. Retrieved 18 July 2021, from http://www.TeAra.govt.nz/en/seaweed/page-4

Weitzman J, Steeves L, Bradford J, Filgueira R 2019. Chapter 11 - Far-field and near-field effects of marine aquaculture. In C. Sheppard (Ed.) World seas: an environmental evaluation (second edition) (pp. 197-220): Academic Press.

Wheeler T, Major R, South P, Ogilvie S, Romanazzi D, Adams S 2021. Stocktake and characterisation of New Zealand's seaweed sector: species characteristics and Te Tiriti o Waitangi considerations. In prep.

White LN, White WL 2020. Seaweed utilisation in New Zealand. Botanica Marina 63(4): 303-313.

Wood D, Capuzzo E, Kirby D, Mooney-Mcauley K, Kerrison P 2017. UK macroalgae aquaculture: What are the key environmental and licensing considerations? Marine Policy 83: 29-39.

Wu H, Kim JK, Huo Y, Zhang J, He P 2017. Nutrient removal ability of seaweeds on *Pyropia yezoensis* aquaculture rafts in China's radial sandbanks. Aquatic Botany 137: 72-79.

Xiao X, Agusti S, Lin F, Li K, Pan Y, Yu Y, Zheng Y, Wu J, Duarte CM 2017. Nutrient removal from Chinese coastal waters by large-scale seaweed aquaculture. Scientific Reports 7(1): 46613.

Xu Y, Huang L, Ji D, Chen C, Zheng H, Xie C 2015. Construction of a dense genetic linkage map and mapping quantitative trait loci for economic traits of a doubled haploid population of *Pyropia haitanensis* (Bangiales, Rhodophyta). BMC Plant Biology 15(1): 1-11.

Young CS, Gobler CJ 2018. The ability of macroalgae to mitigate the negative effects of ocean acidification on four species of North Atlantic bivalve. Biogeosciences 15(20): 6167-6183.

Zemke-White WL, Speed SR, McClary DJ 2005. Beach-cast seaweed: a review. Prepared for the Ministry of Fisheries. New Zealand Fisheries Assessment Report 2005/44. 47 p.

Zhang Q-S, Tang X-X, Cong Y-Z, Qu S-C, Luo S-J, Yang G-P 2007. Breeding of an elite *Laminaria* variety 90-1 through inter-specific gametophyte crossing. Journal of Applied Phycology 19(4): 303-311.

Zheng Y, Jin R, Zhang X, Wang Q, Wu J 2019. The considerable environmental benefits of seaweed aquaculture in China. Stochastic Environmental Research and Risk Assessment 33(4-6): 1203-1221.

Zhu L, HuguenarBachd K, Zou Q-P, Fredriksson DW, Xie D 2020. Aquaculture farms as nature-based coastal protection: Random wave attenuation by suspended and submerged canopies. Coastal Engineering 160: 103737.

Zhu L, Zou Q 2017. Three-layer analytical solution for wave attenuation by suspended and nonsuspended vegetation canopy. Coastal Engineering Proceedings 1(35): 27.

Zhu P, Li D, Yang Q, Su P, Wang H, Heimann K, Zhang W 2021. Commercial cultivation, industrial application, and potential halocarbon biosynthesis pathway of *Asparagopsis* sp. Algal Research 56: 102319.

Appendix 1: Current status and future trends for bioremediation

Using seaweed for bioremediation and promoting restorative farming practices and ecosystem-based management (EBM) in aquaculture are increasingly popular topics both internationally and domestically. For example, there was a nine-fold increase in annual publications in the Web of Science between 2010 and 2020 for the search string 'seaweed' and 'bioremediation' (Web of Science, accessed 6 August 2021). Commercial seaweed aquaculture with a primary target of bioremediation (as opposed to biomass end-use, e.g. food, feed, or hydrocolloids) is, however, almost exclusively done in land-based systems where it is implemented at production scale to bioremediate. For example, the effluent from land-based aquaculture of black tiger prawns (PacificBio's Pacific Reef Fisheries in Australia) or abalone (Viking Aquaculture in South Africa) using species of *Ulva*, growing unattached in high rate algal ponds fed the aquaculture effluent (Bolton et al. 2009, Amosu et al. 2013). On the other hand, incidental bioremediation (where bioremediation is a by-product of cultivation for a separate primary purpose for the produced biomass) is occurring at large commercial scales in existing seaweed farms, where for example commercial production of seaweed in China removed 75,000 t of nitrogen during the 2014 production year (Zheng et al. 2019).

A1. Current status

A1.1 Land-based algal bioremediation

In a research context, the focal areas for land-based seaweed bioremediation include:

- species and cultivar selection (Mata et al. 2010, 2016, Lawton et al. 2013, 2021, Fort et al. 2019, Sarkar et al. 2021, Lavania et al. 2014, Neori et al. 2020)
- systems optimisation (Msuya & Neori 2008, Guttman et al. 2019, Mendoza et al. 2018, Praeger et al. 2017, 2018, 2019)
- potential environmental benefits (Mata et al. 2010, Sode et al. 2013, Schuenhoff et al. 2003), often in an Integrated Multitrophic Aquaculture (IMTA) context with research or commercial animal production systems (Mata et al. 2010, 2016, Bolton et al. 2009, Guttman et al. 2019, Schuenhoof et al. 2003, Robertson-Andersson 2008).

A multitude of systems and species combinations have been trialled at various scales, with commercial implementation realised in places such as South Africa and Australia (further details below). For example, the red seaweeds *Chondrus crispus*, *Gracilaria bursa pastoris* and *Palmaria palmata* were cultivated for 12 months with weekly harvests in a cascading system of tanks fed effluent from commercial fish aquaculture in Portugal (turbot and sea bass) via a sedimentation tank (Matos et al. 2006). Results demonstrated species-specific remediation capacity, and differential productivity between seasons, with *Chondrus* performing better during summer months, *Palmaria* unable to survive these warmer conditions, and *Gracilaria* the only species to demonstrate year-round production. Nitrogen uptake efficiency was improved by serial cultivation (water pumped first through the larger tanks with seaweed, then through the smaller tanks also with seaweed) prior to discharge, with maximum nutrient uptake efficiency reaching 83.5%. Yields of seaweed biomass varied substantially between species and across the year. Highest yields were achieved with *Palmaria* during spring (average yield 40.2 ± 12.8 g dry wt m^{-2} day^{-1}). While *Chondrus* had lower yield (average yield over spring and summer 29.1 ± 2.9 g dry wt m^{-2} day^{-1}), it was more tolerant to varying environmental conditions (Matos et al. 2006). Similarly, the performance of the red seaweed *Asparagopsis armata* and the green seaweed *Ulva rigida* as biofilters for effluent from land-based aquaculture of gilthead seabream (commercial production, 40 mt pa, Portugal) were compared

(Mata et al. 2010). The 110 L tanks were operated with varying water exchange rates (0.1 – 4 volumes hr^{-1}) to quantify effects of nutrient flux on the bioremediation capacity. While *Asparagopsis* consistently outperformed *Ulva* at higher water exchange rates, *Ulva* performed better at lower water exchange rates. This differential performance with varying water exchange rates is partly due to differences in carbon assimilation capacity between the two species. *Ulva* can use HCO_3^- that remains available in the water at elevated pH when CO_2 has been depleted (Axelsson et al. 1995), whereas *Asparagopsis* has a lower affinity for HCO_3^- (Mata et al. 2007). These examples highlight how species-specific biology can greatly influence operating parameters and performance of seaweed bioremediation systems, emphasising the need for species-, system-, and location specific optimisation.

Commercially, *Ulva* has been cultivated for bioremediation in raceway ponds (high rate algal pond, HRAPs) at multiple abalone farms in South Africa since 2002 (Rothman et al. 2020), producing 2000 t of fresh biomass annually (Bolton et al. 2016), or between 19.1 and 26.1 g dry wt m^{-2} day^{-1} (Bolton et al. 2009). Cultivation was originally initiated to supplement feed for abalone and was later demonstrated to bioremediate ammonia when cultivated in the abalone effluent (Robertson-Andersson et al. 2008). Ammonia removal allowed for partial recirculation of the effluent to take place, with reduced pumping costs as well as additional flow-on benefits in terms of both increased abalone productivity and decreased environmental footprint (Nobre et al. 2010). Two farms have been operating with a 50% water recirculation rate using *Ulva* cultivated in HRAPs for bioremediation since 2006 and additional farms are scaling up their abalone/*Ulva* systems (Bolton et al. 2009). The current recirculating systems are designed based on robust research executed by collaborating on-farm research scientists over multiple years (see Bolton et al. 2009 and references therein), and these systems have reduced farm pumping costs by approximately 40% (Rothman et al. 2008). The increased growth rates of abalone in the 50% recirculating systems are attributed to 1) increased temperature of the abalone tanks resulting from the water in the seaweed tanks typically being warmer than the ambient seawater used for flow-through, which is sub-optimal for abalone growth at most farm sites in South Africa (Bolton et al. 2009), 2) improved feed quality when using mixed species diets (cultivated *Ulva* + wild harvest kelp; Dlaza et al. 2008), and 3) high-quality protein-rich seaweed when cultivated on site in nitrogen rich abalone effluent (Naidoo et al. 2006). It should be noted, however, that temperature moderation varied with seasons, and may not always be optimal (Nobre et al. 2010), and the potential benefits of temperature moderation will be location dependent. Based on actual abalone and seaweed production data and farm costs for a South African 240-t $year^{-1}$ abalone farm that currently employs abalone/*Ulva* IMTA, Nobre et al. (2010) modelled an ecological–economic assessment of abalone mono-culture *vs*. two IMTA-schemes incorporating *Ulva* bioremediation at different abalone:seaweed ratios. The IMTA approach generated direct increases in farm profits by 1.4 – 5% (increased productivity, decreased pumping costs, decreased need for supplied feed). However, the value of environmental externalities (an economic term describing the negative environmental effects from production that are imposed on others and not accounted for in the production cost; Knowler et al. 2020) far exceeded the net profit gain for the farm. They included reduced nitrogen discharge (by 3.7 – 5.0 t N $year^{-1}$ depending on abalone:seaweed ratio), reduced harvest of wild kelp beds (by 2.2 – 6.6 ha yr^{-1}), and reduced greenhouse gas emissions (by 290 – 350 t CO_2e yr^{-1}, due to reduced electricity demand for pumping; Nobre et al. 2010). Together, the monetised value of these environmental benefits was estimated to between 1.1 and 3.0 million US dollar yr^{-1}. In Australia, commercial farming of *Ulva ohnoi* occurs at Pacific Reef Fisheries tiger prawn farm. Here, ocean intake water is pumped through the prawn farm, and the effluent goes through a settlement pond and a sand filter before entering the six 250 x 25 *Ulva* ponds, with productivities reaching an estimated 70 t dry wt ha^{-1} yr^{-1}. Although the main purpose of the seaweed cultivation is bioremediation to enable higher production of the primary aquaculture target within environmental discharge limits, the harvested biomass is also a product in its own right and is sold wholesale as a biostimulant (PlantJuice™). It would be of broad interest if a similar environmental and techno-economic assessment were available for the Australian circumstances as for South African abalone farms.

A1.2 Ocean farming and Integrated Multitrophic Aquaculture for algal bioremediation

In contrast to research around seaweed bioremediation in land-based systems, ocean farming research is more focused on quantifying potential and actual environmental benefits at various scales of seaweed cultivation, and in systems of increasing complexity (Fan et al. 2020, Fang et al. 2016, Kim et al. 2014, 2015), although there are examples of research into species selection for ocean farming in a bioremediation context (Kim et al. 2014, 2015, Kang et al. 2021). For example, Kim et al. (2014, 2015) cultivated the warm water species *Gracilaria tikvahiae* during summer, and the temperate/cold water species *Saccharina latissima* during winter in Long Island Sound, Connecticut, USA, specifically to quantify nutrient (nitrogen and phosphorus) and carbon bioremediation capacity. The research-scale farms consisted of 2 x 50 m long lines at each of two sites for *Gracilaria*, and 2 x 50 m long lines at each of three sites for *Saccharina*. Based on biomass productivities and the tissue nitrogen content of harvested biomass, annual nitrogen removal rates were modelled to be between 28 – 94 kg N ha^{-1} for *Gracilaria,* and 38 – 180 kg N ha^{-1} for *Saccharina*, where the lower values were the result of nitrogen-limitation at one of the sites (Kim et al. 2014, 2015). If scaled production of both species were implemented as alternating production over both summer (*Gracilaria*) and winter (*Saccharina*), they could remove between 98 and 274 kg N ha^{-1} yr^{-1} depending on site conditions. This equates to a value of US$1980 – 2540 ha^{-1} yr^{-1} if seaweed aquaculture was included in Connecticut's Nitrogen Trading Program, and above US$3000 ha^{-1} yr^{-1} if carbon trading was included (Kim et al. 2015), highlighting the potential farm value if seaweed and other extractive aquaculture species are included in nutrient trading schemes.

Due to the much larger scale and mature status of ocean farming of seaweed compared with land-based pond systems, the majority of ocean farming examples where bioremediation capacity of seaweed has been quantified are based on seaweed grown for another primary commercial purpose; e.g., production of food, feed, or hydrocolloids (Fan et al. 2020, Hu et al. 2021, Zheng et al. 2019, Fang et al. 2016, Xiao et al. 2017, He et al. 2008). Bioremediation effects or capacity has then been quantified as a secondary benefit or modelled in the context of integrated aquaculture carrying capacity (Shi et al. 2011). Much of the research cited above around ecosystem scale bioremediation from an IMTA perspective is in fact based around existing commercial operations in China, especially Sanggou Bay, where IMTA has been practiced since the 1980s (Fang et al. 2016). Here, the MoST-China Project on 'Sustainability of Marine Ecosystem Production under Multi-stressors and Adaptive Management' (2011−2015) has in essence been quantifying effects of ecosystem-based management over approximately 100 km^2 of ocean-based aquaculture production space, producing > 240,000 t of seafood per annum from over 30 production species (Fang et al. 2016). While research into location- and species-specific seaweed bioremediation capacity remains critical for optimising seaweed bioremediation, it is worth highlighting the scale of current seaweed aquaculture production and therefore incidental bioremediation (i.e., bioremediation resulting from the production of seaweed for other primary purposes, mainly food, feed, and hydrocolloids). For example, Chinese seaweed aquaculture produced 2 million tons dry weight of seaweed (mainly *Saccharina japonica* and *Gracilariopsis* spp.) in 2014, and the harvest of this seaweed removed approximately 75,000 t nitrogen and 9,500 t phosphorus from Chinese coastal waters (Zheng et al. 2019). This corresponds to ca. 5.6% of estimated total N-inputs and 40 % of P-inputs, and results from approximately 1,250 km^2 coastal area, a mere 0.3% of the Chinese territorial waters (Hu et al. 2021, Xiao et al. 2017). The potential for in-ocean bioremediation of diffuse source nutrient inputs is not trivial and can clearly have ecosystem scale effects.

A1.3 Trends in development of seaweed bioremediation

Increasingly, investment in research and development of seaweed farming in general, and for their contribution to ecosystem services including bioremediation in particular, is funded by impact investment sources (O'Shea et al. 2019). Impact investment is defined as investment with the intention to generate positive, measurable social and environmental impact alongside a financial return. For example, the World Wildlife Fund (WWF-US) recently launched their new Impact Investment strategy by contributing US$850,000 to a US$1.5 million fund raised by seaweed farming company Ocean Rainforest (Faroe Islands and US) to commence seaweed farming operations in the North Atlantic, recognising the potential for seaweed farming to reduce environmental pressures on surrounding ecosystems (https://www.worldwildlife.org/press-releases/world-wildlife-fund-announces-investment-in-seaweed-farming-through-ocean-rainforest, accesses 2021-06-13). In the United Kingdom, the Blue Impact Fund was launched in late November 2020, with a focus on investing in ocean recovery and resilience research and developments targeting production of seaweed, mussels, and oysters, and a pipeline of an estimated value of up to GBP90 million. The new fund is managed by Finance Earth and include WWF on the investment committee (https://finance.earth/fund/blue-impact-fund/).

Voluntary environmental trading schemes is another area gaining interest, and various nitrogen credit trading schemes are in effect globally (see e.g., BenDor et al. 2021, or the Reef Credit Scheme in Australia; https://greencollar.com.au/reef-credits/).

There is also a stronger push globally for the implementation of IMTA and further development of large-scale seaweed aquaculture from an ecosystem services perspective (Hu et al. 2021, Xiao et al. 2017, Chopin & Tacon 2021), including a renewed interest for IMTA in Aotearoa New Zealand (Stenton-Dozey et al. 2021).

A2. The Aotearoa New Zealand perspective

A2.1 Current status

Most of the research around algal bioremediation in Aotearoa New Zealand to date has related to using freshwater micro- or macroalgae to bioremediate primarily wastewater from municipal wastewater treatment plants and agricultural wastewater sources (Craggs et al. 2012, 2015, Sutherland et al. 2017, 2020, Sutherland & Craggs 2017), but also from diffuse sources (Kidgell et al. 2021). However, momentum is building around both research and implementation of seaweed for bioremediation or ecosystem restoration, with for example the Macroalgal Biotechnologies Programme (https://www.waikato.ac.nz/eri/algae/) at the University of Waikato, funded by the Tertiary Education Commission (TEC) and University of Waikato, which commenced in 2018. Research here includes developing aquaculture methodologies for seaweed and freshwater macroalgae, including early life history and hatchery management; improvement of water quality in marine and freshwater systems using macroalgal bioremediation technologies (Lawton et al. 2021); and the development of innovative macroalgal bioproducts (Kidgell et al. 2021). A new Facility for Aquaculture Research of Macroalgae (the FARM; Figure A1) was opened at the University of Waikato Coastal and Marine Field Station, Tauranga, in 2020, to support this research. Two Ministry of Primary Business, Innovation, and Employment (MBIE) grant applications related to seaweed bioremediation and ecosystem services were funded in 2019: the 3-year research programme 'Cultivating resilient marine forests to rebuild productive coastal ecosystems' led by the University of Otago, and the 3-year Smart ideas 'Carbon Sequestration and Mussel Productivity in Integrated Multi Trophic Aquaculture' involving Blue Carbon Services, University of Auckland, and the University of Otago (Ministry of Primary Business, Innovation, and Employment, www.mbie.govt.nz). The former project aims to generate the knowledge and infrastructure needed to restore and buffer Aotearoa New Zealand's bladder kelp (*Macrocystis pyrifera*) ecosystems against climate change, and the latter project aims to identify the potential importance of kelp to the productivity of farmed Greenshell™ mussels, and vice versa, especially when co-cultured. This research is primarily focused on *Ecklonia radiata* in the Hauraki Gulf, and *M. pyrifera* in the South Island. A combination of direct field experiments and biochemical markers are being deployed to understand the potential mutual contributions to the kelp and mussels in the culture situation.

A recent research collaboration between the University of Auckland, the National Institute for Water and Atmospheric research (NIWA), and aquaculture business Moana Ltd quantified the bioremediation capacity of locally collected *Ulva* cultivated in the effluent from a commercial pāua (abalone, *Haliotis iris*) farm (Moana Ltd, Bream Bay, Aotearoa New Zealand) in both HRAP (un-attached cultivation) and algal turf scrubber (ATS; attached cultivation) systems (Jang 2021). This research demonstrated system-specific differences in bioremediation performance and biomass productivity, and while both the HRAP and ATS systems had benefits and drawbacks, complete removal of ammoniacal-N and near complete removal of nitrate-N from the drum filter backwash effluent produced by the aquaculture facility could be achieved in seaweed culture systems with a surface area of 1,280 m^2 (100 × 12.8 m) (Jang 2021). Considering the large differences in productivity, and therefore bioremediation capacity, between cultivars of *Ulva*, including between different cultivars of the same species (Lawton et al. 2021), it would be beneficial to include cultivar selection in any future site-specific seaweed bioremediation research.

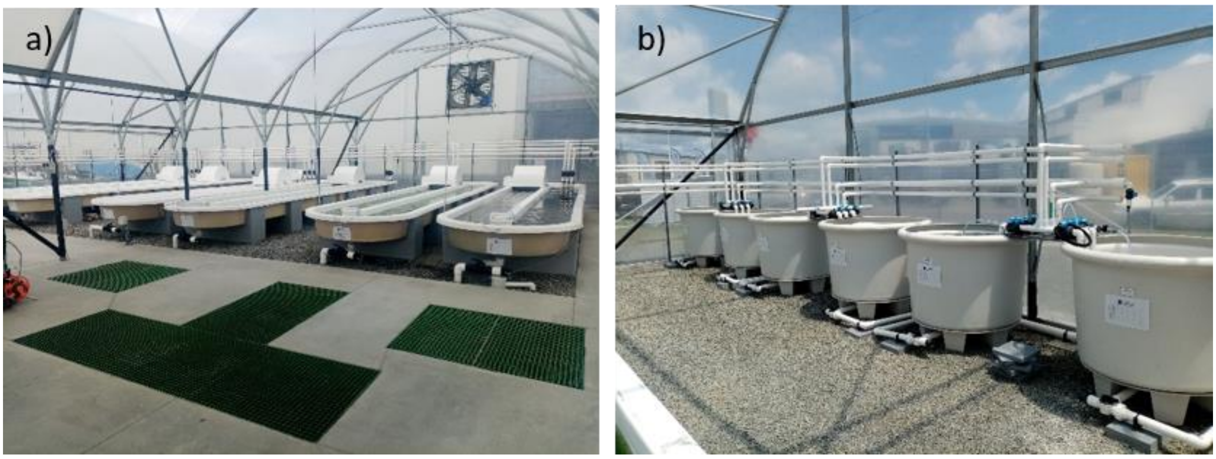


Figure A1. The Facility for Aquaculture Research of Macroalgae (the FARM) at the University of Waikato Coastal and Marine Field Station, Tauranga. The FARM houses two recirculating aquaculture systems, one for fresh-water and one for marine research. Each system consists of a) 6 x high rate algal ponds (10 x 2 m) and b) 6 x 1,000 circular tanks (Photos Marie Magnusson, University of Waikato)

A2.2 Future opportunities for seaweed bioremediation in Aotearoa New Zealand

There is mounting interest in seaweed aquaculture in Aotearoa New Zealand, and for any seaweed cultivation that occurs, there is an opportunity for bioremediation and ecosystem benefits. As discussed in Wheeler et al. (2021) and Bradly et al. (2021), Aotearoa New Zealand will need to develop their own species of seaweed for aquaculture, as most of the eight main genera that constitute nearly 97% (31.1 million tons in 2018) of cultivated seaweed internationally (Chopin & Tacon 2021) are either not present (e.g., *Saccharina japonica* and *S. latissima*, *Kappahycus* and *Euchema* spp.) or are non-native and invasive (*Undaria pinnatifida*) in Aotearoa New Zealand. For genera that are native to Aotearoa New Zealand (e.g., karengo or *Ulva* spp.), existing cultivation protocols still require adaptation to local cultivars and conditions, and this is in progress (e.g., Lawton et al. 2021). In addition, well established early life history (hatchery) and out-planting cultivation protocols for kelp (e.g., Redmond et al. 2014) could be adapted for local cultivars.

Broader opportunities and drivers for seaweed aquaculture in Aotearoa New Zealand are discussed elsewhere in this report as well as in Wheeler et al. (2021) and Bradly et al. (2021). Here, focus is on factors that may enable and facilitate the adoption of seaweed cultivation for bioremediation purposes. In this regard, baseline productivity (t dry wt ha^{-1} cultivation area yr^{-1}) and nutrient assimilation data (as % of dry wt seaweed harvested) are required for locally cultivated seaweed to enable direct quantification, and modelling of, ecosystem level effects. To achieve this, ocean farming trials at meaningful scales are required for empirical grounding of productivity data, as increasing farming density does not always lead to increased productivity (Shi et al. 2011).

Given the established aquaculture industry for shellfish and finfish, there is much opportunity for the development of co-cultivation and IMTA technologies in Aotearoa New Zealand, reviewed in a recent paper by Stenton-Dozey et al. (2021). It should be noted that local conditions may determine the most effective combination of species to cultivate for the specific purpose of bioremediation, and that overall carrying capacity of the system needs to be recognised (Hu et al. 2021, Shi et al. 2011, Holdt et al. 2014, Kaspar et al. 1985).

The implementation of open ocean seaweed aquaculture remains in early development globally, with a few exceptions. For example, the company Ocean Rainforest cultivates kelp (*Saccharina latissima* and *Alaria esculenta*) under open ocean conditions in the Faroe Islands (Bak et al. 2018, 2020). The potential for open ocean aquaculture of established (e.g., salmon, mussels) and novel (e.g., seaweed) species in Aotearoa New Zealand is recognised, and is in some cases operational, primarily for single species production of mussels (Heasman et al. 2020).

There is also increasing commercial and industry interest in freshwater macroalgal bioremediation from point source discharges (e.g., municipal wastewater treatment plants). Aotearoa New Zealand has a long history of developing microalgae and attached filamentous macro- or colonial algae for freshwater bioremediation (Craggs et al. 2012, 2015, Sutherland et al. 2017, Park et al. 2013, Sutherland et al. 2018), however, commercial uptake has been lacking. An ongoing collaboration between AquaCuro Ltd. and researchers at the University of Waikato has led to the construction of a pilot-demonstration scale bioremediation plant next to a municipal wastewater treatment plant in Te Puke (Figure A2). The plant was commissioned in early June 2021, and biomass production will be ongoing for 12 months to quantify seasonal algal productivity and bioremediation capacity.

Figure A2. AquaCuro's freshwater algae bioremediation pilot plant under construction in Te Puke in collaboration with researchers at the University of Waikato (Photo: Chris Praeger/AquaCuro). The plant consists of 3 x 10 m high rate algal ponds (HRAPs), 3 x 25 m HRAPs and 3 x 50 m HRAPs. The 50 m long HRAPs are here yet to be lined with high density polyethylene liner.

A2.3 Drivers and incentives for adoption of seaweed bioremediation

Taking the view of ecosystem-scale management and the broader definition of IMTA at the integrated scale from land-ponds to coastal aquaculture systems, there is a multitude of ways to foster adoption of seaweed cultivation in Aotearoa New Zealand with bioremediation capacity in mind. These include eco-certification (eco-labels) of both the seaweed product, and other aquaculture products that form part of the same managed system (Knowler et al. 2020, Gray et al. 2021). Research remains around location-specific comparative bioeconomic models of IMTA (e.g., environmental effects, system productivity, product quality; Knowler et al. 2020), especially in order to place a true value on and internalise parameters that are typically considered externalities. This true value (to the environment and society as well as the individual producer) of integrated production, and organisms grown this way, can then be communicated using eco-labelling to incur a premium price for products, thus also financially incentivising producers. Knowler et al. (2020) provide a useful review on the economics of IMTA, identify knowledge gaps, and provide recommendations for further research.

Incentives are needed if seaweed is to be cultivated for bioremediation rather than a primary product (food, feed, feedstock for production of secondary products such as biostimulants or high value nutraceuticals). Internalising external costs into production (Bolton et al. 2009, Knowler et al. 2020), and policy incentives around nutrient extraction (e.g., nutrient trading schemes) are major factors that can drive implementation of bioremediation. Policy incentives can include nutrient trading schemes, such as recently implemented in the Great Barrier Reef catchment in Australia (Reef Credit scheme, https://greencollar.com.au/reef-credits/), or in the United States (BenDor et al. 2021). The environmental and societal cost of nitrogen pollution and removal has been quantified and reviewed internationally (Dvarskas et al. 2020, Lassaletta et al. 2016, Reis et al. 2016, Sobota et al. 2015, van der Hoek et al. 2018, Vineyard et al. 2020). Similar analyses for Aotearoa New Zealand would be useful to contextualise and synthesise the cost of nutrient pollution and prevention versus remediation at local environmental and societal scales.

A critical enabler for the success of the commercial land-based abalone/*Ulva* systems in South Africa, is the availability of 'no-cost' nutrient rich water for the seaweed cultivation. The abalone production is commercially viable in its own right, and for an initial investment in infrastructure for seaweed cultivation, both financial and environmental benefits are gained (Bolton et al. 2009). Drivers and enablers for the commercial success of *Ulva* seaweed bioremediation were similar in Australia. There, legislation relevant to discharge of wastewater from land-based aquaculture in effect requires a net-zero discharge of nutrients (i.e., the water being discharged has to be of the same or better quality than the water being drawn into the farm over an annual basis with some flexibility for off-set policies; CIE 2013). A two-year research demonstration of bioremediation capacity in HRAPs growing *Ulva ohnoi* on prawn farm effluent enabled the farm to gain resource consents for increased production and the construction of a new farm (pers. comm. Prof. Rocky de Nys, James Cook University). Additionally, innovative farm managers with access to scientific support and expertise have been driving these developments in both South Africa and Australia, highlighting the collaborative need for industry and academia to deliver successful and meaningful bioremediation programmes with quantifiable outcomes. Although research on land-based tank cultivation of *Ulva* has been ongoing for over 30 years (DeBusk et al. 1986), and commercial production is realised since the early 2000s (Bolton et al. 2009), knowledge gaps remain, and location-specific selection for high-performing cultivars, along with detailed taxonomic analysis of cultivated material, remains priority issues (Lawton et al. 2013, 2021, Bolton et al. 2009) for expanding commercial operations. It is expected similar well-developed and ongoing relationships will be required between science providers and commercial operators of seaweed farming in Aotearoa New Zealand, for both bioremediation and primary production purposes, and regardless of species cultivated and whether this is in land-based aquaculture systems or ocean farming. Strong government support through policy incentives and streamlined legislation, and broader impact investment or philanthropic contributions will aid in developing a seaweed industry and market in Aotearoa New Zealand, both for primary products and for ecosystem services such as nutrient extraction (bioremediation).

A3. Appendix references

Amosu AO, Robertson-Andersson DV, Maneveldt GW, Anderson RJ, Bolton JJ 2013. South African seaweed aquaculture: A sustainable development example for other African coastal countries. African Journal of Agricultural Research 8(43): 5260-5271.

Axelsson L, Ryberg H, Beer S 1995. Two modes of bicarbonate utilization in the marine green macroalga *Ulva lactuca*. Plant, Cell & Environment 18(4): 439-445.

Bak UG, Gregersen Ó, Infante J 2020. Technical challenges for offshore cultivation of kelp species: lessons learned and future directions. Botanica Marina 63(4): 341-353.

Bak UG, Mols-Mortensen A, Gregersen O 2018. Production method and cost of commercial-scale offshore cultivation of kelp in the Faroe Islands using multiple partial harvesting. Algal Research 33: 36-47.

BenDor TK, Branham J, Timmerman D, Madsen B 2021. Predicting the Existence and Prevalence of the US Water Quality Trading Markets. Water 13(2): 185.

Bolton JJ, Cyrus MD, Brand MJ, Joubert M, Macey BM 2016. Why grow *Ulva?* Its potential role in the future of aquaculture. Perspectives in Phycology 3(3): 113.120.

Bolton JJ, Robertson-Andersson DV, Shuuluka D, Kandjengo L 2009. Growing *Ulva* (Chlorophyta) in integrated systems as a commercial crop for abalone feed in South Africa: a SWOT analysis. Journal of Applied Phycology 21(5): 575-583.

Chopin T, Tacon AGJ 2021. Importance of Seaweeds and Extractive Species in Global Aquaculture Production. Reviews in Fisheries Science & Aquaculture 29(2): 139-148.

CIE 2013. The CIE final report: aquaculture in Queensland prioritising regulatory reform. Canberra, Australia, Centre for International Economics.

Craggs R, Park J, Sutherland D, Heubeck S 2015. Economic construction and operation of hectare-scale wastewater treatment enhanced pond systems. Journal of Applied Phycology 27(5): 1913-1922.

Craggs R, Sutherland D, Campbell H 2021. Hectare-scale demonstration of high rate algal ponds for enhanced wastewater treatment and biofuel production. Journal of Applied Phycology 24(3): 329-337.

DeBusk TA, Blakeslee M, Ryther JH 1986. Studies on the Outdoor Cultivation of *Ulva lactuca* L. Botanica Marina 29: 381-386.

Dlaza TS, Maneveldt GW, Viljoen C 2008. Growth of post-weaning abalone *Haliotis midae* fed commercially available formulated feeds supplemented with fresh wild seaweed. African Journal of Marine Science 30(1): 199-203.

Dvarskas A, Bricker SB, Wikfors GH, Bohorquez JJ, Dixon MS, Rose JM 2020. Quantification and valuation of nitrogen removal services provided by commercial shellfish aquaculture at the subwatershed scale. Environmental Science and Technology 54(24): 16156-16165.

Fan LIN, Meirong DU, Hui LIU, Jianguang FANG, Lars A, Zengjie JIANG 2020. A physical-biological coupled ecosystem model for integrated aquaculture of bivalve and seaweed in Sanggou Bay. Ecological Modelling 431: 109181.

Fang J, Zhang J, Xiao T, Huang D, Liu S 2016. Integrated multi-trophic aquaculture (IMTA) in Sanggou Bay, China. Aquaculture Environment Interactions 8: 201-205.

Fort A, Lebrault M, Allaire M, Esteves-Ferreira AA, McHale M, Lopez F, Fariñas-Franco JM, Alseekh S, Fernie AR, Sulpice R 2019. Extensive variations in diurnal growth patterns and metabolism among *Ulva* spp. strains. Plant Physiology 180(1): 109-123.

Gray M, Barbour N, Campbell B, Robillard AJ, Todd-Rodriguez A, Xiao H, Plough L 2021. Ecolabels can improve public perception and farm profits for shellfish aquaculture. Aquaculture Environment Interactions 13: 13-20.

Guttman L, Neori A, Boxman SE, Barkan R, Shahar B, Tarnecki AM, Brennan NP, Main KL, Shpigel M 2019. An integrated *Ulva*-periphyton biofilter for mariculture effluents: Multiple nitrogen removal kinetics. Algal Research 42: 101586.

He P, Xu S, Zhang H, Wen S, Dai Y, Lin S, Yarish C 2008. Bioremediation efficiency in the removal of dissolved inorganic nutrients by the red seaweed, *Porphyra yezoensis*, cultivated in the open sea. Water Research 42(4-5): 1281-1289.

Heasman KG, Scott N, Ericson JA, Taylor DI, Buck BH 2021. Extending New Zealand's marine shellfish aquaculture into exposed environments – adapting to modern anthropogenic challenges. Frontiers in Marine Science 7: 751.

Holdt SL, Edwards MD 2014. Cost-effective IMTA: a comparison of the production efficiencies of mussels and seaweed. Journal of Applied Phycology 26(2): 933-945.

Hu ZM, Shan TF, Zhang J, Zhang QS, Critchley AT, Choi HG, Yotsukura N, Liu FL, Duan DL 2021. Kelp aquaculture in China: a retrospective and future prospects. Reviews in Aquaculture 13: 1324-1351.

Jang I 2021. Recycling the nutrients from pāua aquaculture effluent into a fresh seaweed feed. University of Auckland. pp. 118.

Kang YH, Kim S, Choi SK, Lee HJ, Chung IK, Park SR 2021. A comparison of the bioremediation potential of five seaweed species in an integrated fish-seaweed aquaculture system: implication for a multi-species seaweed culture. Reviews in Aquaculture 13(1): 353-364.

Kaspar HF, Gillespie PA, Boyer IC, MacKenzie AL 1985. Effects of mussel aquaculture on the nitrogen cycle and benthic communities in Kenepuru Sound, Marlborough Sounds, New Zealand. Marine Biology 85(2): 127-136.

Kidgell JT, Carnachan SM, Magnusson M, Lawton RJ, Sims IM, Hinkley SFR, de Nys R, Glasson CRK 2021. Are all ulvans equal? A comparative assessment of the chemical and gelling properties of ulvan from blade and filamentous *Ulva*. Carbohydrate Polymers 264: 118010.

Kim JK, Kraemer GP, Yarish C 2014. Field scale evaluation of seaweed aquaculture as a nutrient bioextraction strategy in Long Island Sound and the Bronx River Estuary. Aquaculture 433: 148-156.

Kim JK, Kraemer GP, Yarish C 2015. Use of sugar kelp aquaculture in Long Island Sound and the Bronx River Estuary for nutrient extraction. Marine Ecology Progress Series 531: 155-166.

Knowler D, Chopin T, Martínez-Espiñeira R, Neori A, Nobre A Noce A, Reid G 2020. The economics of Integrated Multi-Trophic Aquaculture: where are we now and where do we need to go? Reviews in Aquaculture 12(3): 1579-1594.

Lassaletta L, Billen G, Garnier J, Bouwman L, Velazquez E, Mueller ND, Gerber JS 2016. Nitrogen use in the global food system: past trends and future trajectories of agronomic performance, pollution, trade, and dietary demand. Environmental Research Letters 11(9):095007.

Lavania B, Azman S, Mohd Said MI, Ahmad F, Mohamad M 2014. Biofiltration potential of macroalgae for ammonium removal in outdoor tank shrimp wastewater recirculation system. Biomass and Bioenergy 66: 103-109.

Lawton RJ, Mata L, de Nys R, Paul NA 2013. Algal bioremediation of waste waters from land-based aquaculture using *Ulva*: selecting target species and strains. PLoS ONE 8(10): e77344.

Lawton RJ, Sutherland JE, Glasson CRK, Magnusson ME 2021. Selection of temperate *Ulva* species and cultivars for land-based cultivation and biomass applications. Algal Research 56: 102320.

Mata L, Magnusson M, Paul N, de Nys R 2016. The intensive land-based production of the green seaweeds *Derbesia tenuissima* and *Ulva ohnoi*: biomass and bioproducts. Journal of Applied Phycology 28(1): 365-375.

Mata L, Schuenhoff A, Santos R 2010. A direct comparison of the performance of the seaweed biofilters, *Asparagopsis armata* and *Ulva rigida*. Journal of Applied Phycology 22(5): 639-644.

Mata L, Silva J, Schuenhoff A, Santos R 2007. Is the tetrasporophyte of *Asparagopsis armata* (Bonnemaisoniales) limited by inorganic carbon in integrated aquaculture? 1. Journal of Phycology 43(6): 1252-1258.

Matos J, Costa S, Rodrigues A, Pereira R, Pinto IS 2006. Experimental integrated aquaculture of fish and red seaweeds in Northern Portugal. Aquaculture 252(1): 31-42.

Mendoza W, Mendola D, Kim J, Yarish C, Velloze A, Mitchell BG 2018. Land-based drip-irrigated culture of *Ulva compressa*: The effect of culture platform design and nutrient concentration on biomass production and protein content. PloS One 13(6): e0199287.

Msuya FE, Neori A 2008. Effect of water aeration and nutrient load level on biomass yield, N uptake and protein content of the seaweed *Ulva lactuca* cultured in seawater tanks. Journal of Applied Phycology 20(6): 1021-1031.

Naidoo K, Maneveldt G, Ruck K, Bolton JJ 2006. A comparison of various seaweed-based diets and formulated feed on growth rate of abalone in a land-based aquaculture system. Journal of Applied Phycology 18(3): 437-443.

Neori A, Bronfman Y, Van Rijn J, Guttman L, Krupnik N, Shpigel M, Samocha TM, Davis DA, Qiu X, Abelin P 2020. The suitability of *Ulva fasciata*, *Ulva compressa*, and *Hypnea musciformis* for production in an outdoor spray cultivation system, with respect to biomass yield and protein content. Journal of Applied Phycology 32: 3183-3197.

Nobre A, Robertson-Andersson D, Neori A, Sankar K 2010. Ecological–economic assessment of aquaculture options: comparison between abalone monoculture and integrated multi-trophic aquaculture of abalone and seaweeds. Aquaculture 306(1-4): 116-126.

O'Shea T, Jones R, Markham A, Norell E, Scott J, Theuerkauf S, Waters T 2019. Towards a blue revolution: catalyzing private investment in sustainable aquaculture production systems. Prepared for The Nature Conservancy and Encourage Capital.

Park J, Craggs R, Shilton A 2013. Enhancing biomass energy yield from pilot-scale high rate algal ponds with recycling. Water Research 47(13): 4422-4432.

Praeger C, de Nys R 2017. Seeding filamentous *Ulva tepida* on free-floating surfaces: A novel cultivation method. Algal Research 24: 81-88.

Praeger C, de Nys R 2018. Improvement of the seeding of filamentous *Ulva tepida* on free-floating surfaces. Algal Research 30: 73-78.

Praeger C, Vucko MJ, de Nys R, Cole A 2019. Maximising the productivity of the attached cultivation of *Ulva tepida* in land-based systems. Algal Research 40: 101507.

Redmond S, Green L, Yarish C, Kim J, Neefus C 2014. New England seaweed culture handbook-Nursery Systems, University of Connecticut & University of New Hampshire.

Reef Credit Scheme 2017. Retrieved from https://greencollar.com.au/reef-credits/

Reis S, Bekunda M, Howard CM, Karanja N, Winiwarter W, Yan X, Bleeker A, Sutton MA 2016. Synthesis and review: tackling the nitrogen management challenge: from global to local scales. Environmental Research Letters 11(12): 120205.

Robertson-Andersson DV, Potgieter M, Hansen J, Bolton JJ, Troell M, Anderson RJ, Halling C, Probyn T 2007. Integrated seaweed cultivation on an abalone farm in South Africa. Nineteenth International Seaweed Symposium. pp. 129-145.

Rothman MD, Anderson RJ, Kandjengo L, Bolton JJ 2020. Trends in seaweed resource use and aquaculture in South Africa and Namibia over the last 30 years. Botanica Marina 63(4): 315-325.

Sarkar S, Rekha PN, Ambasankar K, Vijayan K 2021. Bioremediation efficiency of indigenous seaweeds of Chennai coast in brackishwater system. Aquaculture International 29(1): 233-251.

Schuenhoff A, Shpigel M, Lupatsch I, Ashkenazi A, Msuya FE, Neori A 2003. A semi-recirculating, integrated system for the culture of fish and seaweed. Aquaculture 221(1-4): 167-181.

Shi J, Wei H, Zhao L, Yuan Y, Fang J, Zhang J 2011. A physical–biological coupled aquaculture model for a suspended aquaculture area of China. Aquaculture 318(3-4): 412-424.

Sobota DJ, Compton JE, McCrackin ML, Singh S 2015. Cost of reactive nitrogen release from human activities to the environment in the United States. Environmental Research Letters 10(2): 025006.

Sode S, Bruhn A, Balsby TJ, Larsen MM, Gotfredsen A, Rasmussen MB 2013. Bioremediation of reject water from anaerobically digested waste water sludge with macroalgae (*Ulva lactuca*, Chlorophyta). Bioresource Technology 146: 426-435.

Stenton-Dozey JM, Heath P, Ren JS, Zamora LN 2021. New Zealand aquaculture industry: research, opportunities and constraints for integrative multitrophic farming. New Zealand Journal of Marine and Freshwater Research 55(2): 265-285.

Sutherland DL, Craggs RJ 2017. Utilising periphytic algae as nutrient removal systems for the treatment of diffuse nutrient pollution in waterways. Algal Research 25: 496-506.

Sutherland DL, Heubeck S, Park J, Turnbull MH, Craggs RJ 2018. Seasonal performance of a full-scale wastewater treatment enhanced pond system. Water Research 136: 150-159.

Sutherland DL, Park J, Ralph PJ, Craggs RJ 2020. Improved microalgal productivity and nutrient removal through operating wastewater high rate algal ponds in series. Algal Research 47: 101850.

Sutherland DL, Turnbull MH, Craggs RJ 2017. Environmental drivers that influence microalgal species in fullscale wastewater treatment high rate algal ponds. Water Research 124: 504-512.

Van der Hoek JP, Duijff R, Reinstra O 2018. Nitrogen recovery from wastewater: possibilities, competition with other resources, and adaptation pathways. Sustainability 10(12): 4605.

Vineyard D, Hicks A, Karthikeyan K, Barak P 2020. Economic analysis of electrodialysis, denitrification, and anammox for nitrogen removal in municipal wastewater treatment. Journal of Cleaner Production 262: 121145.

Xiao X, Agusti S, Lin F, Li K, Pan Y, Yu Y, Zheng Y, Wu J, Duarte CM 2017. Nutrient removal from Chinese coastal waters by large-scale seaweed aquaculture. Scientific Reports 7(1): 46613.

Zheng Y, Jin R, Zhang X, Wang Q, Wu J 2019. The considerable environmental benefits of seaweed aquaculture in China. Stochastic Environmental Research and Risk Assessment 33(4-6): 1203-1221.