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Report

Key environmental considerations for seaweed aquaculture in Aotearoa New Zealand

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For more information on this project, visit:

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About the Sustainable Seas National Science Challenge

Our vision is for Aotearoa New Zealand to have healthy marine ecosystems that provide value for all New Zealanders. We have 75 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 the Ministry of Business, Innovation & Employment.

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Executive summary

Marine farmers across Aotearoa New Zealand are interested in expanding into seaweed aquaculture, particularly mussel farmers looking to add seaweeds to their existing consents. To help facilitate the consent application process, this report compares the environmental effects of seaweed and mussel aquaculture (Figure 1), and proposes some key management considerations.

We conclude that the environmental effects of a seaweed farm are likely to be less than, or similar to, those of a mussel farm of equal scale. Consequently, if the environmental effects of a mussel farm have been evaluated and deemed acceptable, the same site should be able to accommodate the environmental effects of seaweed farming.

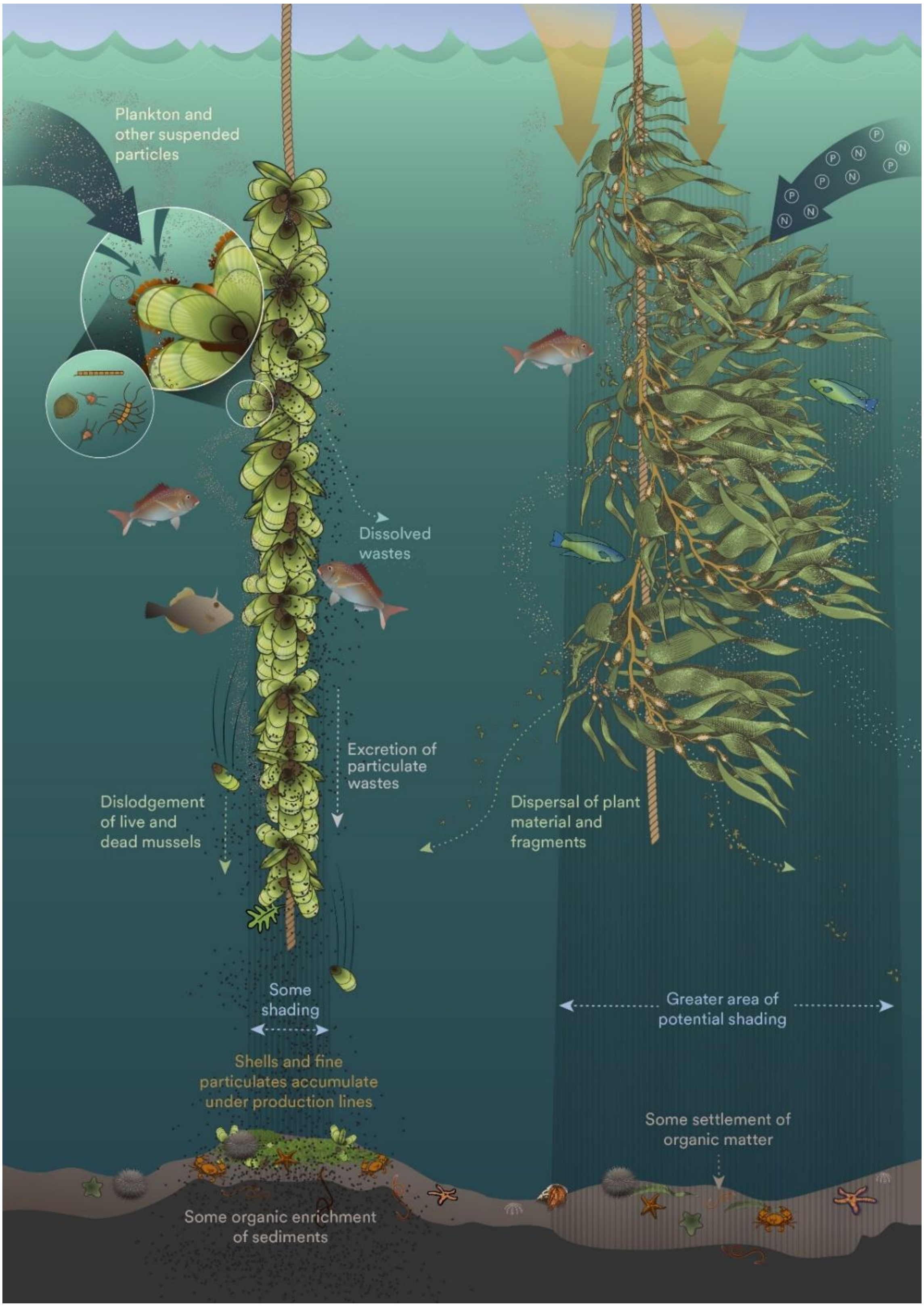

Figure 1 | The key environmental effects of seaweed and mussel aquaculture.

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Introduction

Seaweed aquaculture is an emerging industry in Aotearoa New Zealand. Marine farmers from across the country are becoming increasingly interested in expanding into seaweed aquaculture, particularly green-lipped mussel (*Perna canaliculus*) farmers looking to add seaweeds to their existing consents. To help facilitate the consent application process, this report[1] compares the environmental effects of seaweed and mussel aquaculture, and proposes some key management considerations.

Overview of farming operations

Mussel aquaculture

The farming of green-lipped mussels represents more than 80% of aquaculture production in Aotearoa New Zealand.[2] The majority of seed (i.e. mussel spat) for this industry is obtained from seaweed (and other flotsam) washed up on Te Oneroa-a-Tōhē / Ninety Mile Beach (reviewed in Alfaro et al. 2011, Peart 2019). The remainder is obtained from spat collectors deployed in Golden Bay / Mohua, Tasman Bay / Te Tai-o-Aorere and other regions. In addition, some industry members have recently begun securing spat from commercial hatcheries.

Once on-site, the spat (and any associated material) are packed into biodegradable mesh stockings, fixed onto nursery lines, and suspended in the water using a series of longlines, floats, anchors and warps. After several months, the spat are stripped from the lines and reseeded at lower densities to maximise survival and growth. The mussels are then harvested once they reach a marketable size, a process that usually takes between 1 and 3 years. The use of spat from different areas, which have different growth rates and maturation times, helps to spread harvests across the year. Thus, different areas of a mussel farm often support mussels at various stages of development.

Seaweed aquaculture

As seaweed aquaculture is in the early stages of development in Aotearoa New Zealand, it is unclear which species and cultivation methods will be adopted by industry. However, initial trials have focused on growing seaweeds on longlines, similar to mussel farming (MPI 2023). Likewise, seaweed farms in USA, Canada, Norway and other temperate countries often use longline systems adapted from the mussel aquaculture industry (Stenton-Dozey et al. 2021, Hargrave et al. 2022, Arantzamendi et al. 2023).

Production typically begins by collecting reproductive tissues from wild seaweeds (reviewed in Mouritsen 2013, Howarth et al. 2023). These tissues are then transferred to aquaria, where environmental conditions are manipulated to stimulate spore release. The spores settle onto nursery lines or nets and are allowed to mature for several weeks before being transferred to open water. Unlike mussels, some seaweeds can yield multiple harvests in a single year, and as they require light, seaweed lines have to be nearer to the water's surface than mussel lines.

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[1] The key conclusions of this report are also summarised in a 4-page fact sheet: sustainableseaschallenge.co.nz/tools-and-resources/environmental-considerations-for-seaweed-aquaculture-key-conclusions

[2] Data for 2022, provided by Aquaculture New Zealand (AQNZ).

Comparison of environmental effects

The environmental effects of aquaculture are primarily driven by the feeding and excretion of the cultured species, and the methods and equipment used to culture them (Forrest & Hopkins 2016). The following comparisons assume seaweed farms will use floating longline production systems, similar to those used on mussel farms.

Organic enrichment of sediments

Mussel aquaculture

Mussels feed by filtering seston from the water, which comprises bacteria, phytoplankton, zooplankton, detritus and other organic particles (Newell 2004). After ingestion, these particles are either digested and excreted as faeces, or ejected as undigested 'pseudofaeces'. Both sink towards the seafloor after release and are collectively referred to as 'biodeposits' (Shumway et al. 1985, Beninger et al. 1999). Consequently, biodeposits can transfer nutrients from the water column to the seabed, which can increase the organic content of sediments underlying production lines (Crawford et al. 2003, Dumbauld et al. 2009). Other sources of organic matter include live and dead mussels, which commonly fall from production lines, and detritus released from biofouling communities that develop on farm infrastructure (e.g. buoys, ropes and anchors) (reviewed in Keeley et al. 2009). Together, these various sources of organic matter can enhance bacterial activity within the sediment, and where oxygen depletion occurs, lead to an increase in sulphide concentrations (Nizzoli et al. 2006, Hargrave et al. 2008, Vinther & Holmer 2008, Richard et al. 2013).

Seaweed aquaculture

Seaweeds do not produce biodeposits. However, their blades continually break down and enter the water column (Leclerc et al. 2013) as particulate organic matter (POM). Theoretically, the release of POM from large-scale seaweed farms could lead to enhanced microbial decomposition and localised oxygen depletion within sediments and the water column (reviewed in Campbell et al. 2019). However, there has been little empirical research into this and it is likely that seaweed farms would have to be very large in scale to generate such effects. Larger seaweed fragments and blades will inevitably fall from production lines, as will detritus from biofouling communities, which would likely form on farm infrastructure to a similar degree to mussel farms. Nonetheless, it is likely that a seaweed farm would cause less sediment organic enrichment than a mussel farm of equal scale.

Sediment composition

Mussel aquaculture

Mussels and shells commonly become dislodged and fall to the seafloor during mussel harvesting, maintenance operations or storm events. Thus, a conspicuous effect of mussel farms is the accumulation of mussels and shell material on the seabed (reviewed in Brown & Gillespie 1999, Hartstein & Stevens 2005, Davidson et al. 2018). Sometimes these accumulations are restricted to just below production lines, while in other cases they can be spread throughout the consented area.

Together, accumulations of shells and biodeposits can change the particle size of underlying sediments (reviewed in Brown & Gillespie 1999, Keeley et al. 2009, MPI 2013, Howarth et al.

2022). Mussel lines and mussel farm infrastructure can also slow water currents, which can further promote the settlement of fine sediment particles (Plew 2011). Any sedimentation from mussel farms has the potential to impact biogenic (e.g. sponge) and rocky reefs (Keeley et al. 2009). This is a key reason why aquaculture operations are preferentially located over soft-sediment habitats, which are less sensitive to the effects of sedimentation than other habitats (Lloyd 2003, MPI 2013).

Seaweed aquaculture

Seaweed farms also have the potential to slow water currents and enhance sedimentation of fine particles (Liu et al. 2016). However, they are unlikely to cause sedimentation to the same degree as mussel farms as they do not produce biodeposits (Clark et al. 2021).

Benthic community composition

Mussel aquaculture

As sediment organic content and particle size strongly influence benthic ecology, the environmental effects of mussel farms (described above) can alter the composition of benthic communities. A common trend observed in enriched sediments is the displacement of larger-bodied benthic invertebrates (e.g. heart urchins, brittle stars and large bivalves) and the proliferation of smaller-bodied, disturbance-tolerant ‘opportunistic’ species such as capitellid polychaetes and other marine worms (reviewed in Keeley et al. 2009). However, most studies have reported that mussel farms in Aotearoa New Zealand have non-existent to moderate effects on benthic communities (Kaspar et al. 1985, Christensen et al. 2003, Hartstein & Rowden 2004, Giles et al. 2006, Wong & O'Shea 2011). In the cases where negative effects have been detected, the effects were highly localised, typically not extending for more than tens of metres from production areas.

In some cases, mussel aquaculture has been observed to benefit benthic communities. For example, some evidence suggests that the shell material released from mussel farms can act as biogenic reefs and promote the formation of diverse benthic assemblages, such as sponges, ascidians, calcareous worms, echinoderms, crabs and other mobile taxa, as well as a variety of scavengers and predators (Kaspar et al. 1985, Davidson & Brown 1994, Major & McMullin 2021a,b, Bridger et al. 2022). However, there is also evidence that accumulations of mussel shell material can be relatively barren, providing little apparent value as reef habitat (Brown & Gillespie 1999, Benjamin 2023).

Seaweed aquaculture

To date, there has been little research on the effects of seaweed aquaculture on benthic community composition. A study in Ireland reported that seaweed aquaculture had no impact on benthic communities and habitats (Walls et al. 2017), while a study in Chile observed increases in benthic biomass and body size of polychaetes (Martínez-Curci et al. 2023). Nonetheless, seaweed farms are expected to have less pronounced effects on benthic communities than mussel farms.

Shading

Mussel aquaculture

Mussel farm infrastructure can shade the underlying water column and seafloor. In other countries, this reduction in light availability has been reported to negatively affect the growth and survival of marine plants (e.g. seaweeds and seagrass) growing within the immediate vicinity of mussel farms (reviewed in Howarth et al. 2022). Conversely, it has been argued that mussel aquaculture could be beneficial to marine plants in some cases (Newell & Koch 2004, Ferreira & Bricker 2019, Petersen et al. 2019). For example, by removing particles suspended in the water column, high densities of filter-feeding mussels could potentially reduce water turbidity and increase the amount of light reaching the seafloor (reviewed in Howarth et al. 2022). There is also potential for farm infrastructure to shade phytoplankton, but this will only be temporary as phytoplankton travel with water currents through farm areas (Campbell et al. 2019).

Seaweed aquaculture

In addition to the shading caused by farm infrastructure, seaweeds have evolved to capture light and floating fronds can spread out horizontally through the water column and therefore shade the underlying seabed to a greater extent than would a mussel farm of equal size (Visch et al. 2020, Clark & Morrisey 2021, Clark et al. 2021, Morrisey & Clark 2021). Furthermore, some seaweeds produce fronds many metres in length, which would further increase the area of shading.

Water column effects

Mussel aquaculture

Filter-feeding mussels remove plankton from the water column.[3] Thus, very high levels of mussel farming can potentially reduce plankton abundance, which could have knock-on effects for higher-trophic organisms. Assessing plankton depletion and its potential ecological consequences is complex and tends to yield extremely variable results (Duarte et al. 2008, Petersen et al. 2008, Cranford et al. 2014). However, most studies suggest that any effects on plankton abundance tend to be highly localised and confined to poorly flushed, shallow areas with intensive levels of bivalve aquaculture (reviewed in Cranford 2019, Smaal & van Duren 2019). Also, by selectively feeding on larger plankton and other particles, mussels farmed intensively can theoretically promote a shift towards smaller-sized plankton and seston (reviewed in Byron & Costa-Pierce 2013, Filgueira et al. 2015). The ecosystem consequences of this are largely unknown (Cranford 2019).

Lastly, mussels excrete dissolved wastes into the water column. These can increase local nutrient levels and potentially stimulate the growth of phytoplankton, including harmful algal species. However, while this is a concern, no occurrences of harmful algal blooms have been linked to shellfish farming in Aotearoa New Zealand waters (MPI 2013).

[3] Plankton can potentially include fish and shellfish eggs and larvae.

Seaweed aquaculture

Seaweeds rapidly absorb nutrients (e.g. nitrogen, phosphorus, potassium and sulphur) from the surrounding water, which theoretically could reduce the amount of nutrients available to plankton and aquatic plants (Lüning & Pang 2003, Marinho et al. 2015), potentially affecting the base of marine food webs. However, seaweed farms would have to be very large in scale to cause an ecologically significant reduction in dissolved nutrient levels. While there is some evidence that seaweed farms can influence the abundance and composition of plankton communities (Jiang et al. 2012, Aldridge et al. 2021, Zhang et al. 2022), the ecological consequences of these changes are poorly understood. Nonetheless, as seaweeds do not directly consume plankton, seaweed farms are likely to have less of an effect on plankton communities than mussel farms of equal scale.

Genetic interactions with wild populations

Mussel aquaculture

There is little genetic differentiation between green-lipped mussels across Aotearoa New Zealand. However, some distinct differences do exist between North Island and South Island populations (Quigley et al. 2022). Due to these low levels of genetic differentiation, and the industry's heavy reliance on wild spat, there is currently little risk of cultured mussels genetically contaminating wild mussels. However, as the Aotearoa New Zealand mussel aquaculture industry is beginning to use hatchery-reared mussels, there is the potential for hatchery populations to genetically diverge from wild populations, especially if strains with desirable traits (e.g. greater size, growth, nutrient content and disease resistance) are actively selected and maintained. Once these cultivated strains are moved to open water, they could release gametes and larvae into the surrounding environment, which could theoretically compete or cross-breed with wild populations. The effects of such gene flow from cultivated to wild populations are currently unknown but could be mitigated through responsible breeding practices or the development of sterile, triploid mussel spat.

Seaweed aquaculture

Cultured seaweeds also have the potential to disperse and colonise outside of farm boundaries through the release of spores, gametes, larvae and, potentially, tissue fragments. While the genetic structure of most seaweed species has received little study in Aotearoa New Zealand (Nepper-Davidsen et al. 2021), it has been argued that seaweed farming has greater potential to genetically alter wild populations as most seaweeds have relatively limited dispersal and natural distributions (reviewed in Clark et al. 2021). Therefore, cultivated strains could potentially change the genetic structure of wild populations if they introduce new genotypes to a region.

The potential for cultured seaweeds to alter the genetic composition of wild populations must be assessed on a case-by-case basis as such risks vary with species, genetic composition of wild and farmed populations, growing and harvesting practices, distance to suitable settlement substrates and the potential for human-mediated dispersal (Clark et al. 2021). However, responsible breeding practices (e.g. ensuring adequate genetic diversity and disease resistance of cultivated strains) could help mitigate any potential genetic interactions (Campbell et al. 2019).

Hydrodynamics

Mussel (Gibbs et al. 1991, Plew et al. 2005, Plew 2011, Zhong et al. 2022) and seaweed (Shi et al. 2011, Campbell et al. 2019) farms can disrupt water currents, dampen wave energy and promote water stratification. In some cases, these effects can cause the scouring or accumulation of sediments (Forrest et al. 2009). Overall, these impacts are typically highly localised and should be similar for both seaweed and mussel aquaculture as they use similar structures. However, as seaweeds have a larger surface area, they could potentially alter surface currents and dampen wave energy to a greater extent than mussels.

Wildlife entanglement

There is potential for birds, marine mammals and other wildlife to become entangled in aquaculture gear. Such incidents are likely to be rare but data and research are lacking (reviewed in Clark et al. 2021). Loose, thin ropes that are flexible and not under tension are considered to be the main risk for wildlife entanglement (Clement 2013). Consequently, some authors have suggested that seaweed farming may have a higher entanglement risk as moorings and lines will be subjected to lower loads, and that seaweed fronds may reduce visibility and therefore make it more difficult for marine wildlife to avoid obstacles (e.g. Forrest & Hopkins 2016). Nonetheless, responsible farm practices can help mitigate any entanglement risks posed by mussel and seaweed aquaculture.

Physical disturbance

The installation, and any subsequent movements, of farm infrastructure can physically disrupt the seafloor and damage benthic organisms. These effects are typically highly localised and will be similar for both seaweed and mussel aquaculture as they use similar equipment.

Biosecurity

Aquaculture infrastructure can provide a suitable biofouling surface for a variety of marine pests, and can therefore help enable their spread and dispersal (Naylor et al. 2001, Castinel et al. 2019, Atalah et al. 2020). The movement and transfer of boats and equipment between sites can accelerate this. In this sense, as seaweed and mussel farms use similar equipment, they pose a similar biosecurity risk (Keeley et al. 2009, Campbell et al. 2019).

Ecosystem services

Seaweed cultivation has the potential to create a range of benefits beyond the provision of biomass. The full range or potential ecosystem services of seaweed aquaculture were reviewed in the context of an ecosystem service framework by Clark et al. (2021). This framework categorises the ecosystem services into four categories: provisioning, regulating, supporting and cultural, based on the benefits people obtain from the ecosystems.

Here we focus on the services that are related to the maintenance or improvement of environmental functioning (rather than direct benefits to people), which are typically categorised as supporting and regulating services. Other services, such as coastal protection, are primarily driven by the presence of farming infrastructure; because longline-based culture methods will provide similar protection, they are not discussed.

The potential for seaweeds to regulate the climate through carbon sequestration is an area of ongoing research and discussion. This is a particular focus because the length of time carbon is sequestered is dependent on the final use of the biomass, and most of the carbon stored in harvested seaweeds is likely to be released back to the atmosphere at some stage in the life cycle of the final product (Park et al. 2021). As this is outside the scope of this report, we direct the reader to Clark et al. (2021).

Habitat and food provision

Mussel aquaculture

Shells accumulating under mussel farms can promote the formation of shell reefs and associated benthic communities, which can attract more abundant and species-diverse fish communities compared to surrounding areas (Underwood 2023). Furthermore, cultured mussels and their associated biofouling communities can provide food to a variety of fish species, including snapper and parore.

Seaweed aquaculture

Seaweed farms also have potential to attract fish communities and provide habitat to a wide variety of biofouling species. In support of this, several studies have observed greater abundances and diversity of fish and invertebrates within seaweed farms compared to reference areas (reviewed in Theuerkauf et al. 2021). Cultured seaweeds are associated with different communities of organisms compared to naturally occurring seaweeds (Walls et al. 2016). This is likely because of their unnatural suspension above the seabed, and their placement in greater water depths over different sediments (reviewed in Campbell et al. 2019). Overall, food and habitat provision from seaweed farms will likely differ from that associated with mussel farms because seaweed cultivation does not increase sediment organic content or provide high mussel densities to opportunistic predators.

Bioremediation

Mussel aquaculture

When mussels feed on the organic matter (including nutrients) suspended in water, some of it gets incorporated into their tissues. These nutrients are consequently removed from the water column when the mussel biomass is harvested, which represents a net loss in nutrients from the water column (Stenton-Dozey & Broekhuizen 2019). However, some of these nutrients are released back into the water as dissolved wastes, and fall to the seafloor as biodeposits.

Seaweed aquaculture

As seaweeds rapidly absorb dissolved nutrients (e.g. nitrogen and phosphorus) from the surrounding water and incorporate them into their tissues, seaweed farms could help reduce nutrient levels of coastal waters (Zheng et al. 2019). Thus, mid- to large-scale seaweed farms have been proposed as a potential tool to mitigate coastal eutrophication (reviewed in Howarth et al. 2023). For example, some studies suggest that China's expansive seaweed aquaculture industry is already removing 5.6 % (75,000 tonnes) of all annual nitrogen inputs and 40% (9,500 tonnes) of all phosphorus inputs (Xiao et al. 2017). Consequently, seaweed aquaculture in China may already have reached a scale where it is delivering tangible ecosystem services in the form of eutrophication mitigation.

Management considerations for seaweed aquaculture

There are three key considerations for assessing the environmental effects of seaweed aquaculture: (1) scale; (2) appropriate siting; and (3) management of uncertainties. Evaluating these will help ensure seaweed aquaculture has minimal environmental effects, as expected.

Scale

The environmental effects of seaweed farming are expected to manifest only at very large, industrial scales (Campbell et al. 2019, Clark et al. 2021). Consequently, the relatively small-scale operations currently being proposed in Aotearoa New Zealand are expected to have minimal and manageable environmental effects.

Assessment of scale is contextual. In Scotland, for example, scale is assessed by the number of lines being used, with small-scale farms being those with up to 50 lines 200 m in length and large-scale operations simply any that exceed this. For comparative purposes, the majority of mussel farms in Aotearoa New Zealand are less than 20 ha, with 3.33 longlines per ha, and therefore the < 50 lines cut-off is a reasonable approximation for scale here (Lloyd 2003, Stenton-Dozey & Broekhuizen 2019). However, it is also worth considering other farms in an area when assessing scale, as multiple farms in a single bay may have cumulative effects on the environment (Keeley et al. 2009).

Staging and adaptive management are effective approaches to dealing with uncertainty related to scale. Managers should consider advocating the use of staging steps and monitoring programmes to measure the effects of seaweed aquaculture at small scales, and then use this information to progress through different scales as appropriate.

Appropriate siting

The key approach to mitigating the environmental effects of aquaculture is to site farms away from sensitive habitats and in areas of reasonable water flow (Keeley et al. 2009). This will be no different for seaweed farms, where site-specific conditions will dictate the acceptable intensity and scale of the farming. The primary negative effects of seaweed farming on the seafloor are likely to be from shading and the installation of anchors and infrastructure. Therefore, the current best practice of siting aquaculture farms away from biogenic habitats and reefs will still apply to seaweed aquaculture.

Management of uncertainties

Seaweed aquaculture is an emerging industry in Aotearoa New Zealand and there are uncertainties associated with its potential environmental effects. Further research and industry collaboration will help address these uncertainties and ensure environmental risks remain low. It is also important to collaborate with, and learn from, other countries where seaweed aquaculture and research are more developed. Here, we highlight two areas of uncertainty that should be considered while this body of knowledge is still growing.

Species and seed stock

The risk of cultured seaweeds altering the genetic composition of wild populations can be minimised by culturing native species and local strains, and / or through the production of sterile cultivars. An understanding of the natural ranges of candidate species and genotypic variation will be required to mitigate this uncertainty. This knowledge gap could also be addressed through research into the release of reproductive material from seaweed farms (e.g. oceanographic modelling) and whether this can establish in local communities.

Wildlife entanglement

There is concern that seaweed farms may pose a greater entanglement risk for marine wildlife than mussel farms. This concern stems from the risk posed by the lower-tension ropes that are likely to be used in seaweed aquaculture, and the potential for floating seaweed to obstruct the vision of wildlife, leading to reduced avoidance. As with other marine farming operations, minimising entanglement risks requires implementing proper siting, design, layout and operational standards (e.g. developing marine mammal management plans).

Conclusion

At equal scales, the environmental effects of seaweed aquaculture are likely to be less than or similar to those of mussel aquaculture. If the environmental effects of a mussel farm have been evaluated and deemed acceptable, the same site should be able to accommodate the potential environmental effects of a seaweed farm.

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