Exploring the Habitat Value of Kelp Aquaculture and Kelp-Shellfish Co-culture

A COMPARATIVE STUDY OF KELP FARMING SYSTEMS IN NORTHERN AND SOUTHERN COLD-TEMPERATE ECOSYSTEMS

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DISCLAIMER

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01 Executive Summary

With the right practices and in the right locations, certain aquaculture systems and species can provide a range of benefits to the broader environment. These benefits, known as ecosystem services, supplement aquaculture's primary benefit of providing food and raw materials. In particular, the farming of seaweed and shellfish species could support measurable benefits by providing habitat for species ranging from microbiota to megafauna (Corrigan *et al.,* 2022). However, while there is anecdotal evidence of these benefits, experimental research on the extent of these effects and the factors that influence their occurrence remains limited.

This project, *Understanding the Habitat Value of Kelp Aquaculture and Kelp-Shellfish Co-culture in Aotearoa and Maine,* was an in-water evaluation of the habitat value of kelp aquaculture and kelp-mussel co-culture in the Gulf of Maine, USA, and the Hauraki Gulf, Aotearoa (New Zealand). The project aimed to identify and quantify the potential habitat benefits of these systems for fish and invertebrates in the local environment as well as the general ecological principles and farming practices contributing to those benefits.

Despite representing relatively comparable farming systems, (e.g. similar species, cultivation gear) the habitat value between the two geographies varied noticeably; while there was no detectable effect on the abundance or diversity of invertebrates and fishes in the Gulf of Maine, there was a marked benefit observed in Aotearoa, with habitat values equivalent to or greater than that provided by wild kelp. Several species were observed in larger numbers within the Aotearoa farm habitat. Additionally, *Chrysophrys auratus* (Australasian snapper) within the farms consistently consumed different and more nutritious prey compared to snapper caught outside the farm, meaning that snapper living within farms were in better nutritional condition compared to snapper living in adjacent natural habitats.

To adequately monitor habitat benefits from kelp and kelp-shellfish aquaculture, future research should account for the influence of local environmental conditions. Further research in a much larger number of geographic settings is needed to improve our understanding of how ecological variables influence farm sites, in comparison to non-farm sites. Policy and management approaches that aim to acknowledge ecosystem services from these aquaculture systems should explicitly consider that farms could display high, low, or no benefit, depending on the season and location.

KEY TAKEAWAYS

- Seaweed aquaculture sites in two distinct temperate and cold-water ecosystems both formed habitat, but the use of these systems by wild fauna differed from neutral in Maine, USA to positive in New Zealand (Figure 1).

- This research identified that the habitat benefits provided by seaweed farms are highly context dependent. Local environmental conditions appeared to be the primary driver of whether additional habitat value was provided as well as the type and extent of the benefit.

- In the Gulf of Maine – where a seaweed industry for sugar kelp, *Saccharina latissima*, has been operating for more than 10 years – four sites sampled between November 2020 through August 2022 (across growing and non-growing seasons), had similar abundance and diversity of fish and invertebrates living within the aquaculture habitat as adjacent non-farm areas and did not appear to either positively or negatively impact biodiversity (Schutt *et al.,* 2023). Further benefits or secondary effects, such as contributions to productivity, may have been present but were not sampled and assessed.

- As seaweed farming in the Gulf of Maine is seasonal and all gear and biomass is required to be removed from the water in spring, these results provide important evidence that the current industry does not have a direct negative effect on mobile fish and invertebrates. If Maine seaweed farms were providing significant habitat benefits during the winter, there could be potential for negative impacts from removing biomass and gear from the water, as any fauna associated with the farms would lose the availability of this habitat in the spring.

- In the Hauraki Gulf, two mussel and kelp-mussel farming systems studied during the Austral summer in 2020-21 provided habitat benefits, with wild fish found to be foraging and recruiting within the farms (Underwood and Jeffs, 2023; Underwood *et al.,* 2023; Underwood *et al.,* 2024). For mussel aquaculture, these benefits were equivalent to or greater than those provided by nearby wild habitat. Snapper foraging in the mussel farms, sampled at two established farm and two non-farm sites in May and June 2022, were also found to be in better nutritional condition than those living and feeding outside the farm. This suggests that extensive mussel farming occurring in Aotearoa could be a significant positive contributor to the productivity of this important fish species and its fisheries.

- The experimental nature of kelp farming in Aotearoa limited the capacity to determine the extent of its positive effects more precisely. However, experimental sites using transplanted individuals of common kelp, *Ecklonia radiata*, had similar abundance and diversity of invertebrates living within the aquaculture habitat as adjacent natural habitats (McArthur, 2023).

- In both locations, seasonality and the types of fish and invertebrates within the local area and their behavior (e.g. the seasonal presence of certain species, schooling fish as opposed to benthic fish species) may have influenced the overall abundance of taxa. Winter samples were found to have lower overall abundance.

- To adequately assess the habitat benefits of kelp and kelp-shellfish aquaculture, future research should account for the influence of local environmental conditions, (Figure 1) ideally sampling across multiple seasons, water temperatures, key biophysical factors such as tidal flow and wave exposure, and other seasonal or ecosystem influences. At this time, habitat interactions will be best quantified by using a combination of sampling methods and should include methods that detect mobile fauna, such as fish and crabs, as well as smaller invertebrates that may be living amongst the farmed biomass and equipment.

- Novel research through ecosystem services education and a consumer awareness survey found that, regardless of the product or the respondent's demographics, consumers indicated that they were willing to pay more for the same products after seeing the educational video on potential ecosystem services from seaweed aquaculture (Bolduc *et al.*, 2023).

- In managing the aquaculture industry to provide habitat and wildlife benefits, industry and supporting organizations need to understand how these facilities respond to local environmental conditions and potentially help operations make adjustments to maximize the positive environmental outcomes.

Researcher processing water samples to collect eDNA

Researcher holds up seaweed specimen

02 Background

Recent research on aquaculture's environmental benefits indicates that farm systems can form valuable habitat for a range of fauna. It also identifies key gaps in knowledge that need to be addressed to maximize these benefits. A recent publication identified 129 papers that demonstrated commercial aquaculture's ecological benefits, yet only 20 documented a positive habitat effect (Gentry *et al.,* 2020). A further review of research on aquaculture's role as habitat identified just seven studies globally that provided quantitative information, all of which focused on tropical seaweed aquaculture's value as fish habitat (Theuerkauf *et al.,* 2022). This review found that seaweed farms had an abundance of fish and invertebrates an average 1.4 times higher than nearby sites without farms. Additional harvestable fish species production could be an average of 494 (range 158 - 2,339) total kilograms per hectare per year from seaweed farms, worth an average of $1,087 (range 143 - 3,454) per hectare per year to recreational fishing and $972 (range 538 - 4,994) per hectare per year to commercial fishing (Barrett *et al.,* 2022). Oysters and mussels can similarly enhance production, with the increased production of harvestable fish species estimated to be an additional, 1,110 (range 158 – 2,237) kilograms per hectare per year and 348 (range 57 – 741) kilograms per hectare per year, respectively.

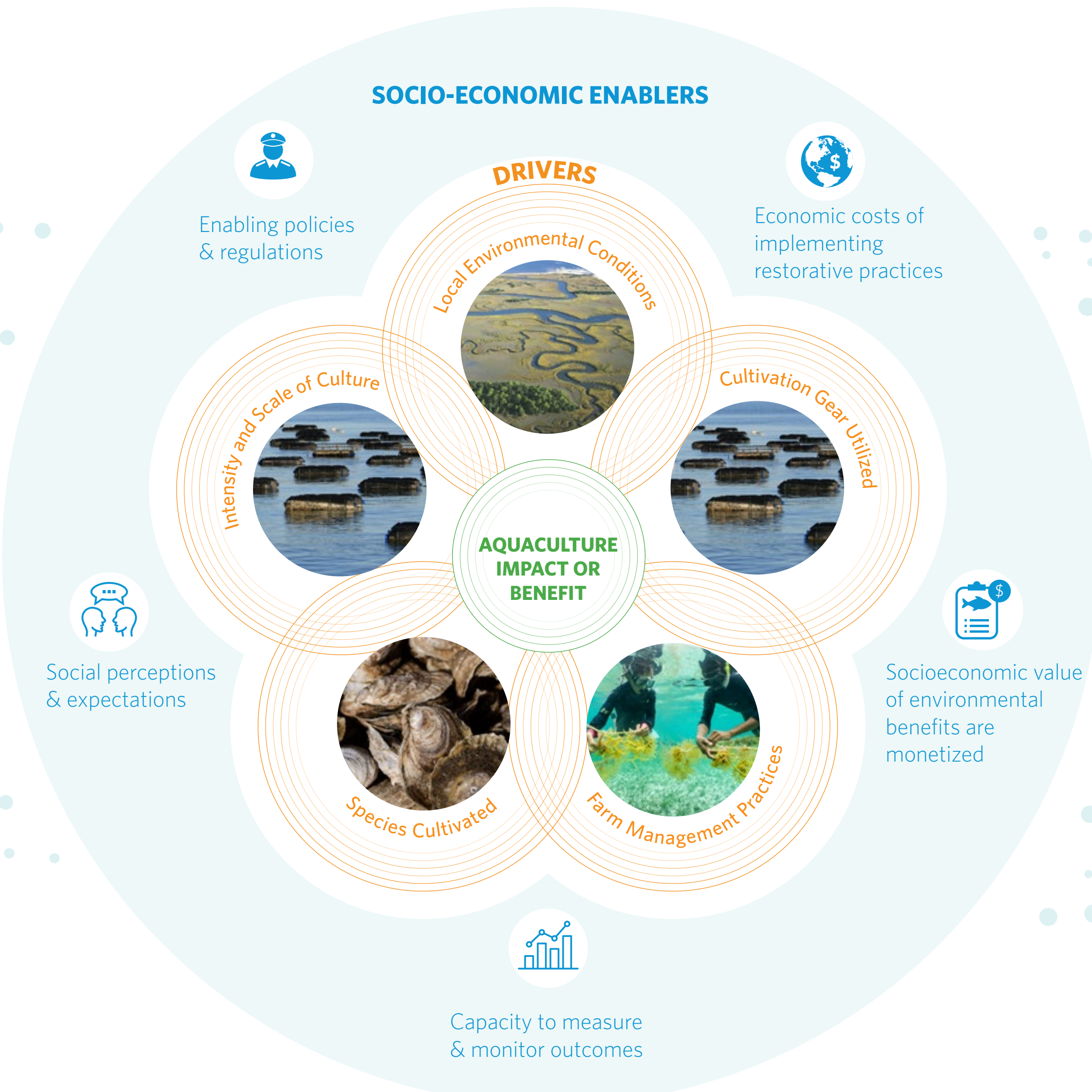
While seaweed and shellfish aquaculture likely offers a range of measurable habitat benefits for species ranging from microbiota to megafauna (Corrigan *et al.,* 2022), the geographic diversity represented in current research is limited. More information is needed in additional geographies and a wider variety of environments, especially temperate ecosystems. The potential environmental benefits provided by aquaculture are driven by numerous interacting factors, including the intensity and scale of culture, the type of farming gear used, farm management practices, the species cultivated, and local environmental conditions (The Nature Conservancy, 2021; Theuerkauf *et al.,* 2022). As a result, the ecosystem outcomes reflect a spectrum where, for instance, some species

Researchers processing kelp samples for reproduction in a laboratory

or modes of culture could return a greater benefit than others, depending on the scale of culture and the environmental issues within the water body.

Furthermore, enabling a positive outcome from aquaculture is a shared responsibility, not just for industry, but also all levels of government and supporting organizations (e.g. industry bodies, private entities, environmental NGOs), all of which influence social perceptions of aquaculture and the ways in which we value ecosystem services. Social and economic factors impact and modify the extent to which aquaculture operators can derive non-market and market benefits from restorative aquaculture, which in turn impacts the extent to which they engage in a restorative approach (Figure 1).

Figure 1. **The physical, operational, and ecological drivers and socioeconomic enablers of restorative aquaculture.**



The Nature Conservancy, 2021

The Project

This project, *Understanding the Habitat Value of Kelp Aquaculture and Kelp-Shellfish Co-culture in Aotearoa and Maine,* was an in-water evaluation of the habitat value of kelp aquaculture and kelp-mussel co-culture in the Gulf of Maine, USA, and the Hauraki Gulf, Aotearoa (New Zealand) (Figure 2).

This research aimed to identify and quantify both the potential habitat benefits of these systems for fish and invertebrates in the local environment as well as the general ecological and farming principles contributing to those benefits.

Using comparative sampling methodology and equipment, the research quantified species richness and abundance at aquaculture sites and non-aquaculture control sites, focusing on two key factors:

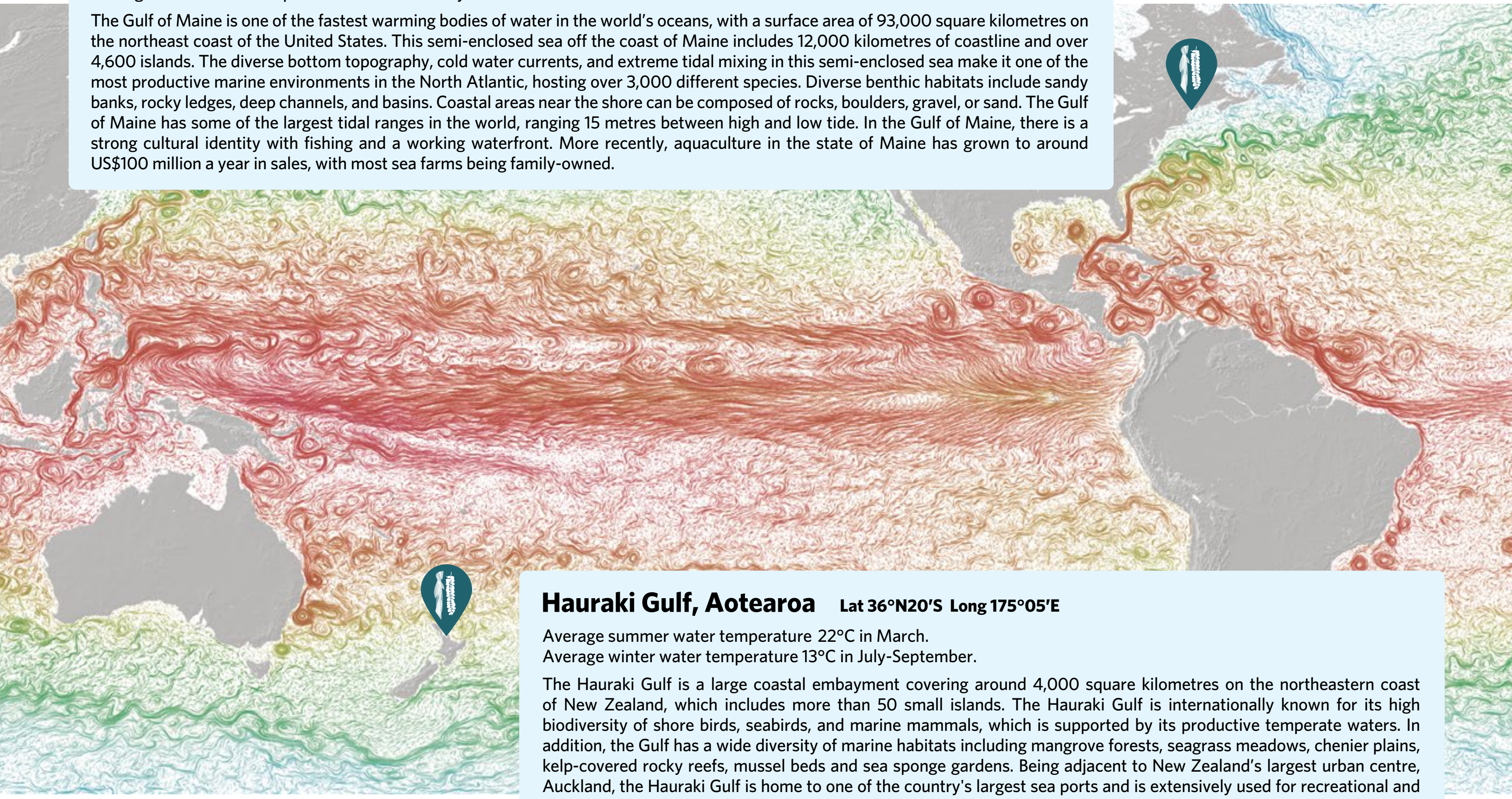
1. The benefits of kelp aquaculture and mussel-kelp co-culture as habitat for fish.
2. The benefits of kelp aquaculture and mussel-kelp co-culture for invertebrate biodiversity.

The Gulf of Maine and Hauraki Gulf have favourable environmental conditions for producing kelp, a baseline of socioeconomic and regulatory conditions that allow for industry development, and opportunities for scaling seaweed farming through existing aquaculture and fishing industries. Furthermore, in TNC's global assessment of priority ecoregions for restorative aquaculture, the Gulf of Maine and northern Aotearoa ranked in the top 25 priority marine ecoregions globally for seaweed and shellfish aquaculture (Theuerkauf *et al.,* 2019).

Undertaking this research in multiple geographies and temperate marine environments fills a gap in understanding of the potential environmental benefits of seaweed aquaculture in cold water ecosystems. It also enables the analysis of results at successive spatial scales and the exploration of both unique and common learnings.

Yellowtail kingfish swimming among mussel aquaculture lines in Aotearoa

Figure 2. **Locations of sampling to assess the habitat value of kelp aquaculture and kelp-mussel co-culture.**



Gulf of Maine, USA **Lat 43°N Long -68°W**

Average summer water temperature 17°C in August.
Average winter water temperature 2°C in February.

The Gulf of Maine is one of the fastest warming bodies of water in the world's oceans, with a surface area of 93,000 square kilometres on the northeast coast of the United States. This semi-enclosed sea off the coast of Maine includes 12,000 kilometres of coastline and over 4,600 islands. The diverse bottom topography, cold water currents, and extreme tidal mixing in this semi-enclosed sea make it one of the most productive marine environments in the North Atlantic, hosting over 3,000 different species. Diverse benthic habitats include sandy banks, rocky ledges, deep channels, and basins. Coastal areas near the shore can be composed of rocks, boulders, gravel, or sand. The Gulf of Maine has some of the largest tidal ranges in the world, ranging 15 metres between high and low tide. In the Gulf of Maine, there is a strong cultural identity with fishing and a working waterfront. More recently, aquaculture in the state of Maine has grown to around US$100 million a year in sales, with most sea farms being family-owned.

Hauraki Gulf, Aotearoa **Lat 36°N20'S Long 175°05'E**

Average summer water temperature 22°C in March.
Average winter water temperature 13°C in July-September.

The Hauraki Gulf is a large coastal embayment covering around 4,000 square kilometres on the northeastern coast of New Zealand, which includes more than 50 small islands. The Hauraki Gulf is internationally known for its high biodiversity of shore birds, seabirds, and marine mammals, which is supported by its productive temperate waters. In addition, the Gulf has a wide diversity of marine habitats including mangrove forests, seagrass meadows, chenier plains, kelp-covered rocky reefs, mussel beds and sea sponge gardens. Being adjacent to New Zealand's largest urban centre, Auckland, the Hauraki Gulf is home to one of the country's largest sea ports and is extensively used for recreational and commercial activities, including commercial fishing, recreational fishing and boating, as well as coastal aquaculture. The Hauraki Gulf includes an extensive area of coastal mussel farms which produce around 30,000 tonnes of green-lipped mussels each year, worth around US$100 million.

Hauraki Gulf, Aotearoa

PRIMARY SPECIES FARMED

Common kelp - *Ecklonia radiata*

OVERVIEW OF FARMING

There are currently more than 170 coastal marine farms around New Zealand with permits to grow various seaweed species. However, at this time, there is negligible cultivation of local species; instead, the majority of seaweed used commercially is supplied from either wild harvest, including collection of beach-cast seaweed, or from cultivating the non-native kelp species wakame, *Undaria pinnatifida*, which is harvested from biofouling on mussel farms (Bradly *et al.*, 2021; White and White, 2020). While interest in native species aquaculture is high, only one commercial site for *E. radiata* has been established. A commonly used line and spool method in an array is being piloted, with hatchery-produced seed and an incremental increase in the number of lines until the timing of seeding and growth rates of seed are better resolved.

ENVIRONMENTAL CONDITIONS

The environment for sampling in Aotearoa can be characterised as a nearshore subtidal habitat of 'very sheltered shallow sand,' with adjacent coastline and island habitat classified as 'very sheltered shallow rocky reef' (Jackson, 2014). Degradation of coastal habitats due to sedimentation, nutrient pollution, and overfishing has had a significant impact in some areas (Aguirre *et al.,* 2016).

Two farm sites in Coromandel Harbour were used to assess the recruitment of fish into mussel farms without kelp and co-cultured with a mix of *Ecklonia radiata* and *Undaria pinnatifida* (Figure 3). The farm study sites were all located over muddy sediment seafloor, in accordance with permitting regulations that dictate that farms should be sited over soft sediment habitat. The farms had a maximum depth of 15 metres. These sites, as well as current and proposed farming locations, overlap with the wider coastal environment in the Hauraki Gulf in which coastal habitats have experienced stress and decline (Hauraki Gulf Forum, 2023).

Two sites in the Firth of Thames were used to evaluate the habitat benefits for *Ecklonia radiata* (Figure 3). These sites were previously Greenshell™ mussel farms that had been consented to support the development of a pilot commercial kelp aquaculture operation. The sites were in sheltered (Esk Point) and moderately exposed environments (Ponui Island), located within a broader area including rocky reef habitat but sufficiently far away from the reef area for farming effects to be distinguished. The water at Esk Point, at the entrance to Coromandel Harbour, was 13 to 21 metres deep, and 25 kilometres away at Ponui Island, it was 23 to 29 metres deep.

A range of invertebrates and small fish can be permanent residents in mussel farms, most likely recruiting into the habitat due to the isolation from natural reef habitats where they are most typically found. For example, the fishes *Forsterygion lapillum* and *Grahamina gymnota* (common and Tasmanian robust triplefins, respectively), *Parika scaber* (leatherjacket), and *Notolabrus celidotus* (spotty) have commonly been found on mussel lines in southern New Zealand (Morrisey *et al.,* 2006). Anecdotally, Australasian snapper form feeding 'frenzies' within mussel farms during harvesting operations in northern New Zealand, suggesting snapper intermittently use the byproducts of farming – mussel biomass that is dislodged or broken during harvest and associated epibiota – for consumption (Gibbs, 2004).

Figure 3. **Study sites in the Hauraki Gulf, Aotearoa.**

Gulf of Maine, USA

PRIMARY SPECIES FARMED

Sugar kelp – *Saccharina latissima*

OVERVIEW OF FARMING

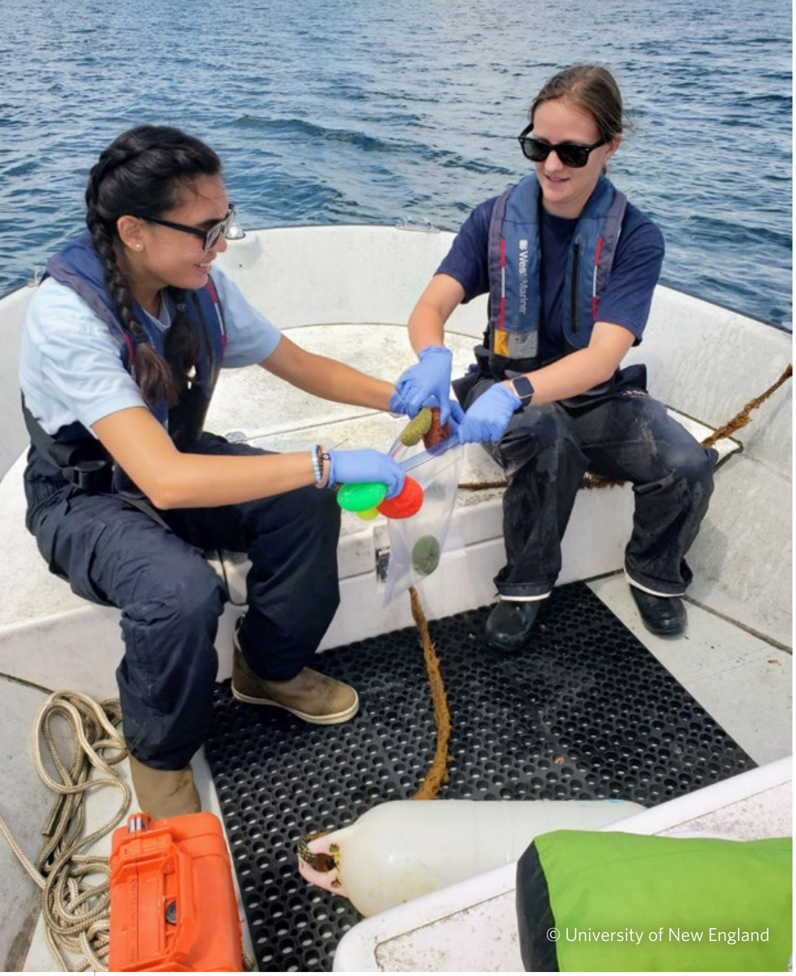
Maine has a well-established kelp aquaculture industry focused on the production of fast-growing *Saccharina latissima* (sugar kelp). The sector plays an important role in the coastal community and its economy (McClenachan and Moulton, 2022). In the coastal waters of New England, it is one of the fastest growing maritime industries (Kim, Stekoll and Yarish, 2019). From 2015 to 2018, there was a steady increase of kelp cultivated in the state, with approximately 10,000 more wet pounds of marine algae harvested each year. From 2018 to 2019, there was more than a fivefold increase in harvest, with strong continued growth (Brayden and Coleman, no date). The activity is highly seasonal due to spatial competition with lobster trapping and seasonal differences in kelp growth rates. Seaweed is grown using submerged long lines, with seeded lines produced in a land-based nursery in late summer and transferred to the ocean in fall for approximately 6 months of growing out.

ENVIRONMENTAL CONDITIONS

The Gulf of Maine is a productive cold-water environment and dynamic coastal area characterised by a complex and varied geomorphology and biodiversity. Consistent with a global trend of decline, natural kelp forests in the Gulf of Maine are disappearing due to climate change and other stressors, with continued shifts in kelp distribution and abundance anticipated in the future (Krumhansl *et al.,* 2016). Two study sites were

Researchers harvesting seaweed aquaculture lines in Maine, USA

Researcher from the University of Maine inspecting growth of seaweed on a farming line in Maine, USA



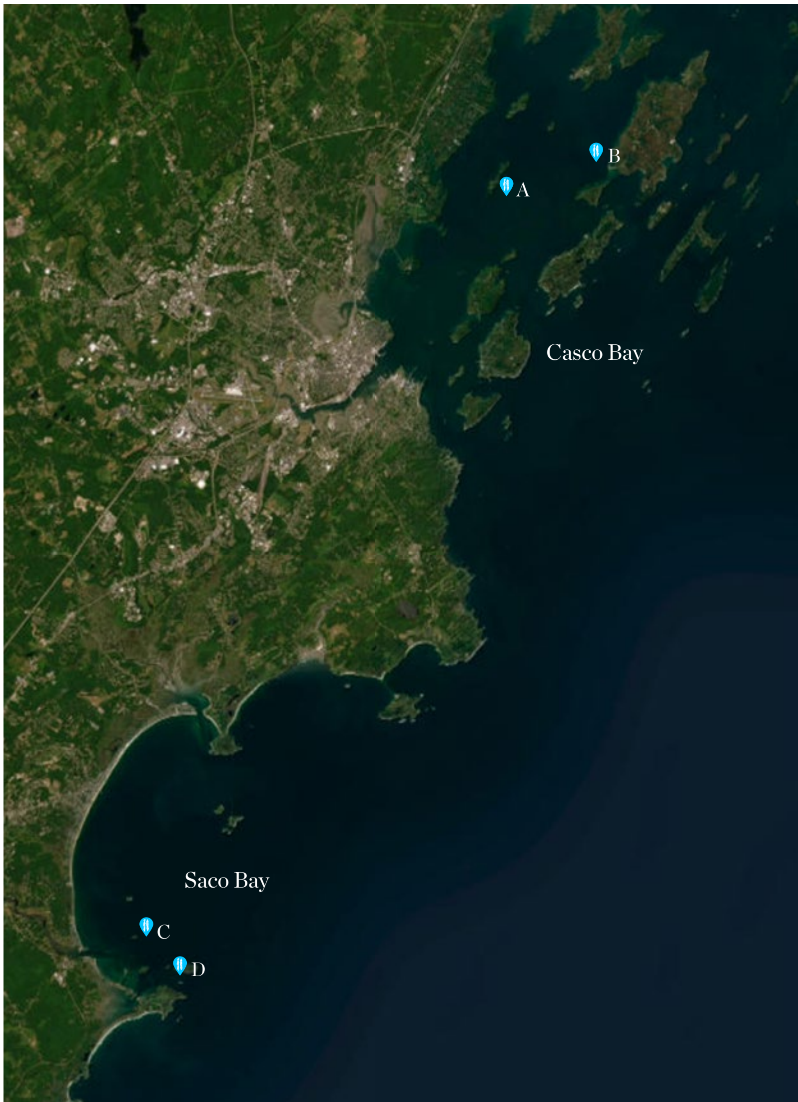
Researchers recovering invertebrate collectors used to sample epifauna

Researchers collecting water samples for analysis of environmental DNA

used in Maine, including an aquaculture farm and a corresponding non-farm site in each of Saco Bay and Casco Bay (Figure 4).

In Saco Bay, two seaweed farms near Ram Island and Wood Island, which were 13 to 16 metres deep and 6 to 3 metres deep, respectively, were used as study sites. In Casco Bay, the study sites included one seaweed farm off Chebeague Island and one co-culture farm off Clapboard Island. The co-culture farm is cultivating blue mussels, sea scallops, seaweed, and oysters in 15 and 12 metres depth. The seaweed-only site in Casco Bay is growing in 12 to 30 metres of water during low and high tide, respectively. The non-farm sites are 100 metres away from the farms and have a similar benthic substrate.

Figure 4. **Study sites in the Gulf of Maine, USA.**



03 Research Approach and Methods

Comparative Sampling Methods

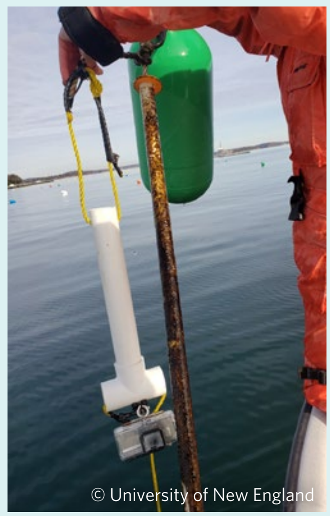
In both geographies, the presence of fish and crustaceans in kelp farms versus nearby control sites was quantified using visual census through underwater video via remote collection with GoPro cameras (Picture 1). Video footage was viewed to record the species seen and their abundance.

Marine invertebrates arriving at kelp farm habitat and nearby control habitat were collected using kitchen scrubbers/sponges, placed inside large mesh bags or baskets, hung from a buoy, and suspended 2 metres below the surface of the water near growing lines (Picture 2). These units were collected, and invertebrates that had accumulated within the sponges were identified to the lowest taxonomic level possible and counted.

For all sites sampled, species abundance and diversity were quantified using the Shannon diversity index. A range of statistical analyses were used to further test for potential differences in biodiversity and the interactive effects of treatment, season, location, site, and the position of sampling within the water column (for the visual census) or sampling period (for the invertebrate collection).

Monitoring Equipment

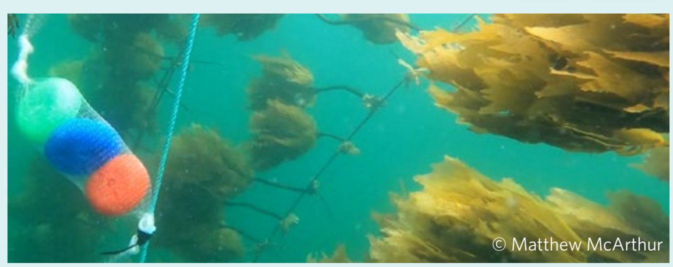
Picture 1.



GoPro camera configuration used to collect remote video recordings for visual census of fish and crustaceans.

Picture 2.

Invertebrate sampling sponges used to collect invertebrates associated with kelp aquaculture.



Geographic-Specific Methods

While a comparative approach was taken, each location presented specific opportunities and constraints for sampling.

In Aotearoa, commercial production of kelp is still nascent and has yet to reach market-scale production. This meant that during sampling, there was no commercial farm on which the research could be conducted reliably. To replicate a native kelp farm, adult *E. radiata* was removed at the holdfast from nearby habitat and transplanted onto a series of dropper lines installed on unused mussel farms at the study sites. The target native species for commercial aquaculture in the Hauraki Gulf is the common kelp, *Ecklonia radiata*. The kelp was attached at approximately 400-millimetre intervals on each of the vertical dropper lines (7 metres long) and suspended at 1-metre intervals from surface backbone lines, mirroring a substantial kelp farm habitat (see Picture 2).

However, kelp aquaculture in Aotearoa has a longer history of production through the harvesting of *Undaria pinnatifida* (wakame), which naturally settles onto mussel long lines and is harvested for sale. A kelp-mussel co-culture ecosystem, formed in this manner, was among the farm sites sampled.

Standardized monitoring units for recruitment of fish (SMURFs) were deployed on a range of aquaculture and natural coastal habitats (i.e., kelp-mussel co-culture farm, mussel farm, kelp rocky reef habitat, sandy seafloor), and the fish 'recruits' arriving into the SMURFs were recovered and analyzed. Because of the strong anecdotal evidence of snapper using mussel aquaculture sites for foraging, the gut contents of fish sampled from these habitats and non-farm control sites were investigated through visual and molecular genetic methods and through biochemical analyses of gut contents. The nutritional condition of the fish and their flesh were assessed using Fulton's condition index and biochemical analyses.

In Maine, environmental DNA (eDNA) was collected simultaneously with visual surveys. These eDNA samples were compared to matching video footage of fish from farm and control sites to assess eDNA's ability to rapidly and reliably detect the presence of fish and crustaceans in aquaculture facilities. Samples were amplified using the universal 12S MiFish and universal 18S primers to broadly assess the crossover with visual surveys. In addition, species-specific primers for crustaceans were examined, including the iconic species American lobster (*Homarus americanus*), native species of rock crab (*Cancer irroratus, C. borealis*), and cryptic invaders that are either established (green crab [*Carcinus maenus*], Asian shore crab [*Hemigrapsus sanguineas*]) or predicted to soon arrive in the Gulf of Maine (blue crab, [*Callinectes sapidus*]).Preliminary results suggest that crustaceans are difficult to capture with eDNA techniques since they are covered with a hard shell and are likely to shed less DNA than fleshy animals such as finfish (Danziger and Frederich 2022; Danzinger *et al.,* 2022). Though both eDNA and visual surveys did reveal the presence of crustaceans, there was little consistency between the two methods, suggesting that one method cannot be used as a replacement for the other.

04 Research Results

Hauraki Gulf, Aotearoa

An effective study of fish recruitment into the Esk Point farm site was completed (Underwood and Jeffs, 2023). This site has significant quantities of naturally seeded kelp on existing mussel lines, which was compared to mussel culture, mussel-kelp co-culture, and natural habitats. SMURFs were deployed in December 2020, with fish arriving into the units in January, February, and March 2021. The SMURFs were then recovered and analysed. A total of 730 fish from nine distinguishable species, classified to the lowest taxonomic level possible, were captured in the SMURFs during the three sampling events. The total number of species (i.e., species richness) found within the four habitats was similar. Common species included the common triplefin (*Forsterygion lapillum*) and bearded rock cod (*Pseudophycis barbata*), both found within all four habitats, and schooling mackerel (*Trachurus* spp.), found within two habitats (Figure 5). Across both depths that were sampled in every habitat, the aquaculture habitats (i.e. mussel and mussel-kelp co-culture) collected 373 fish, while natural habitats (i.e. sand and reef) collected 357 fish. The common triplefin was the dominant species collected at all habitats, comprising roughly 74% of the total catch. Significant differences were identified in the mean abundance of fish in SMURFs between the two depths and among the four habitats over three months. The main factor effects of habitat and depth were significant, as were interactions between the month of sampling and habitat and depth.

Common triplefins have previously been found within mussel dropper lines and likely have occupied the habitat since larval stage (Morrisey *et al.,* 2006). However, no direct evidence was previously available, and this study provides the first known documentation of the recruitment of fish to mussel longline habitat. The results of this sampling support the premise that aquaculture structures can provide habitat for fish, with no negative effects/differences identified between farm and non-farm habitat. The attraction of the larvae and their subsequent survival and establishment also supports the premise that aquaculture farms can provide a settlement and nursery habitat function for fish. There was no difference between fish recruitment into mussel culture versus co-culture habitat, which suggests the kelp was not providing additional benefit for fish settlement and recruitment above that of mussels alone.

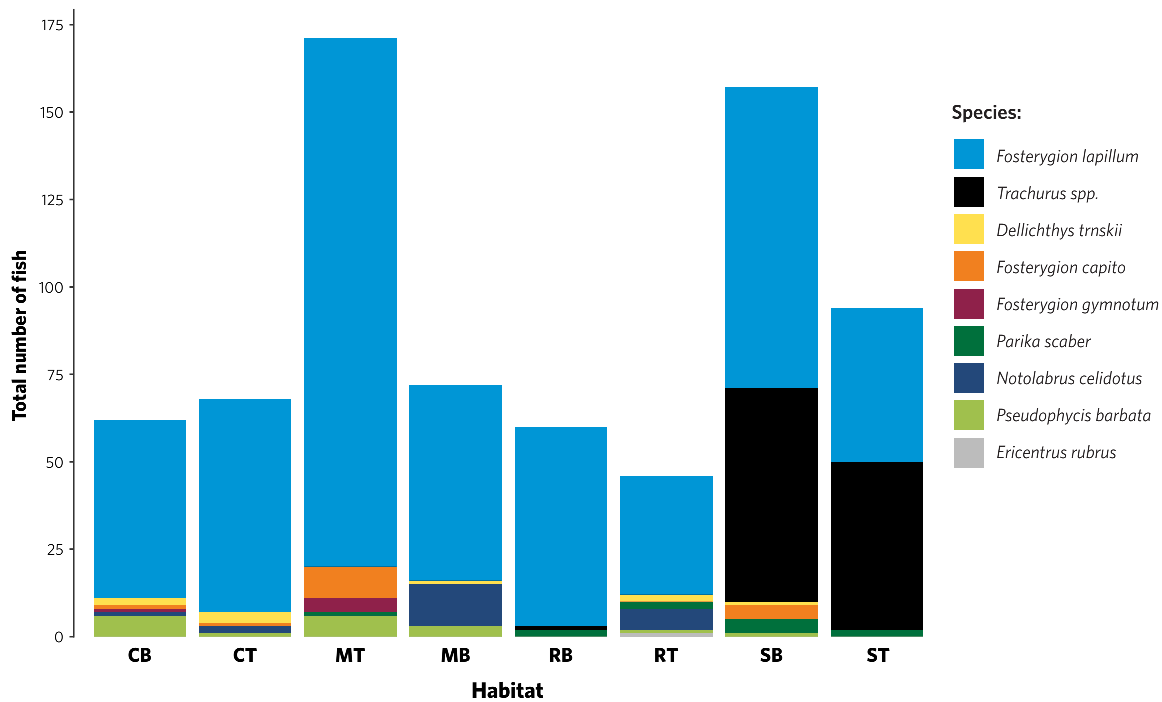


Figure 5. **Total catches of different fish species caught in SMURFs from three sampling events (monthly) between December 2020 to February 2021 at co-culture (C), monoculture (M), reef (R), and soft sediment (S) habitats. Each habitat is split into surface (T) and seafloor (B) depths (n=5 for each habitat, depth, and month combination).**

Initial analysis of samples taken from within the kelp aquaculture habitat indicates that total abundance of invertebrates did not differ significantly between the kelp farm or non-farm sites, though there were differences in total abundance due to site and season. Further analysis of this site using DNA methods is being undertaken to determine if more detailed biodiversity differences can be detected that are not readily distinguishable by visual identification.

In addition to the collection of fish recruits, 16 adult Australasian snapper were obtained from each of three sampling sites – Motukopake Island mussel farm, Motukopake Island control site, and Rat Island mussel farm – and 13 snapper from Rat Island control site (total N = 61 fish), ranging in size from 26 to 42 centimetres fork length, were collected for gut contents analysis (Underwood, van der Reis and Jeffs, 2023). Snapper sampled from mussel farm habitat were found to be consuming a distinctly different diet compared to those sampled from control sites due to the prey species made available through the presence of the mussel farm habitat, such as harvested and common biofouling species, which are not available in nearby soft-sediment habitats without the presence of a mussel farm. Most notably, the gut contents of snapper from the farm sites contained a significant quantity of mussels (green-lipped and blue) and barnacles, which were not present in gut content samples from the control sites (Figure 6). The gut contents of snapper from inside the mussel farms had a higher nutritional value than for those outside the farm, which corresponded to the better nutritional condition of the snapper sampled from inside the farms (Underwood, Mugica and Jeffs, 2024).

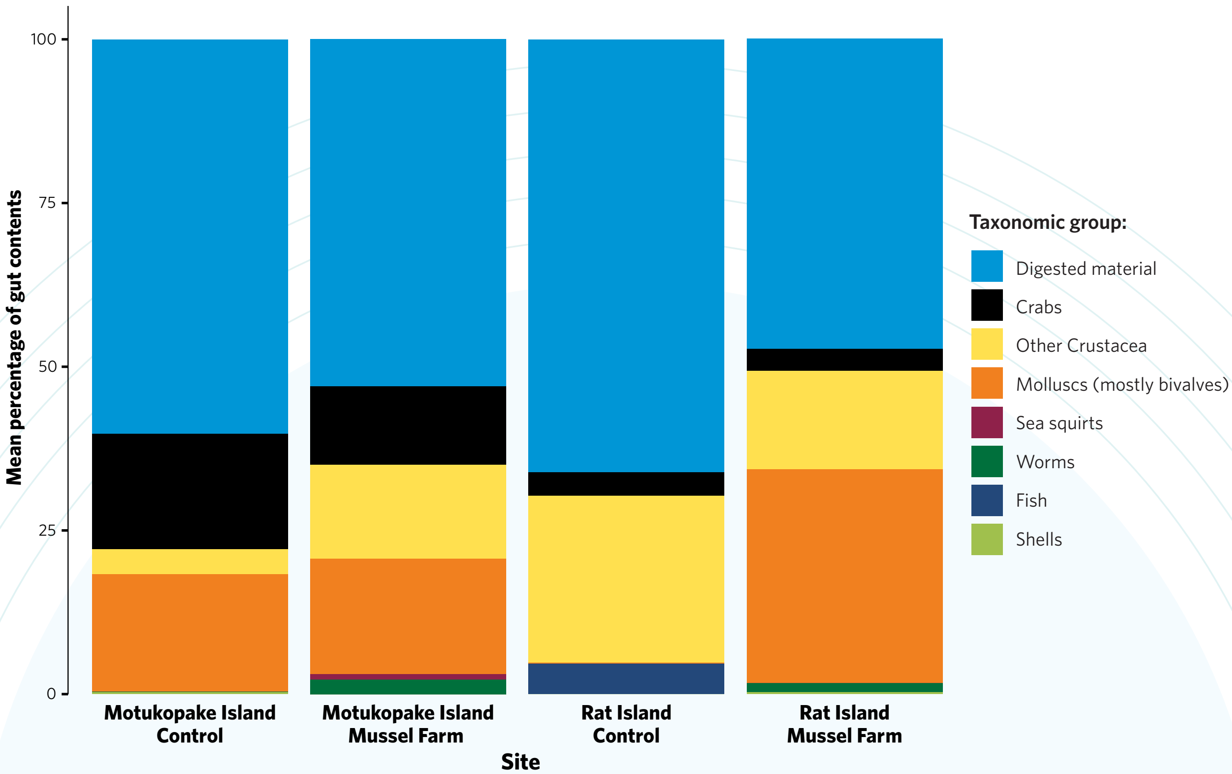
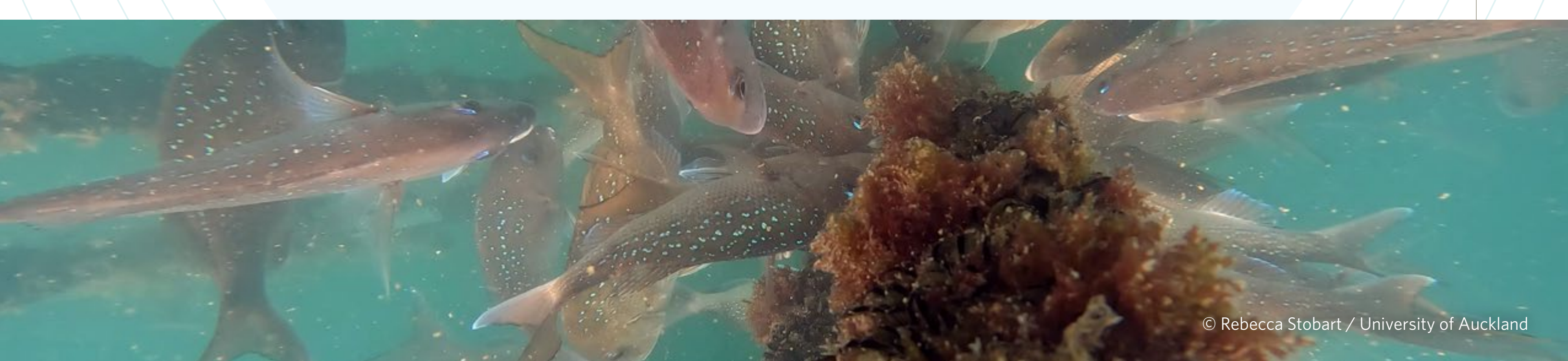


Figure 6. **Remote underwater video observations of mobile fauna found much higher abundance and diversity of fish within mussel farms compared to adjacent soft-sediment habitat without a mussel farm.**

The higher abundances of fish within mussel farms consisted of a variety of fish species with different feeding ecology; some omnivorous demersal species (e.g., snapper and parore) used additional food resources available in the mussel farm habitat, while others, such as pelagic planktonic feeders (e.g., koheru), appeared to use the farm only for the physical shelter it provided.

Australasian snapper foraging on mussel farm dropper lines



Gulf of Maine, USA

Across 160 camera deployments of an average 2.11 (s.d. ± 0.3) hours each, 16 finfish, large crustacean, and mammal species were observed within the seaweed farm and non-farm control sites (Schutt *et al.,* 2023). Typically, 1 to 2 species were seen per camera deployment, with an overall range between 0 and 7 species per deployment. In this same study, 88 invertebrate collectors revealed 15 species, with a single species of amphipod (*Lembos websteri*) comprising nearly 35% of total small invertebrates caught. The copepod (*Paracalanus* spp.) was the second most abundant at 25%, and the skeleton shrimp (*Caprella linearis*) was the third most abundant at 20%. Across 16 independent samples, eDNA detected the presence of 43 species of finfish. Seven joint presences between eDNA and camera visual surveys were observed, seven species were present on cameras but not eDNA, and 21 occurrences of organisms were present in eDNA but not on a camera. For small invertebrate collections, four joint presences between eDNA and small invertebrate collectors were observed, 35 occurrences of organisms were present in collectors but absent in the eDNA, and two occurrences of organisms were present in eDNA but not in collectors. While results between methods varied noticeably, the overall conclusions remained the same, as eDNA results showed no differences between the farm and non-farm areas – the same conclusion from visual surveys and small invertebrate collections.

For all sampling methods, no significant differences in species richness or diversity were found between kelp farms and non-farm reference sites. However, significant community differences in the types of species between Saco Bay and Casco Bay as well as between sites within the bays were identified, with Atlantic rock crabs (*Cancer irroratus*), green crabs (*Carcinus maenas*), Jonah crabs (*Cancer borealis*), and winter flounder (*Pseudopleuronectes americanus*) variously driving this difference.

Season exhibited a strong temporal effect on species richness and biodiversity, with both being higher in summer than winter. Seasonal differences were primarily driven by American lobster (I), which contributed nearly 50% of the difference in types of species seen between the winter growing and summer non-growing season, and schools of Atlantic menhaden (*Brevoortia tyrannus*), which contributed 22.8% to differences seen between seasons. Both species were only seen during summer non-growing seasons and migrate seasonally to the area (REF). These results highlight the potential influence of water temperature on organism abundance. Since primary fish species in the Gulf of Maine are seasonal and mostly benthic, and because kelp biomass is cultivated near the water's surface, seaweed farms may not be benefitting these species by providing additional valuable habitat. Overall, kelp farms were found to neither enhance nor deter organisms, as there are few species present during the winter growing season compared to the summer non-growing season.

Geographic Comparison

Despite representing relatively comparable farming systems, (e.g. similar species, cultivation gear) the habitat value between the geographies varied noticeably. There was largely no discernible effect of kelp farms on invertebrates when compared to non-farm sites, but marked benefits were observed in Aotearoa from mussel and mussel-kelp co-culture sites, potentially greater than habitat values provided by wild kelp. In each geography, an effect associated with season was observed, with higher abundance and diversity of invertebrates present in summer in both kelp farm and adjacent natural habitat without a kelp farm. In Aotearoa, the differences observed were also influenced by site, while in the Gulf of Maine they were not.

In the Gulf of Maine, the finding that seaweed aquaculture was having neither a positive nor negative effect on fish and invertebrates is important because of the seasonal nature of the industry and removal of all biomass and infrastructure at the end of each farming season (Figure 7). If a high diversity of abundance of fauna were associated with seaweed farms in the region, this interaction would need to be managed to mitigate negative effects at harvest time. There is an inherent separation of wild species from farm sites, both spatially and temporally. For example, the primary commercial species in Maine is lobster, which is a benthic species and would not interact with floating kelp farms. In addition, lobster move offshore to deeper waters during seaweed's winter growing season. In fact, many lobster fishers also farm seaweed because the different seasonality of these two products allow them to work on the water year-round and thereby build security into their livelihood. The Gulf of Maine iconic species assemblage (lobster, cod, and other groundfish) is characteristically benthic and has suffered severe declines, making it increasingly unlikely that there would be direct interaction between commercial species and floating seaweed farms.

In Aotearoa, the habitat benefit provided by kelp and kelp-mussel co-culture, including the range of ways with which fish and invertebrates are using the sites (shelter, foraging, recruitment), validates the premise that temperate seaweed and shellfish farms can provide this ecosystem service. *Chrysophrys auratus* (snapper) were consistently found to have consumed different and potentially more nutritious prey groups than snapper caught outside the farm. Snapper foraging in the mussel farms were found to be in better nutritional condition than those living and feeding outside the farm, suggesting the extensive mussel farming occurring in Aotearoa could be a significant positive contributor to the productivity of this important fish species and fisheries.

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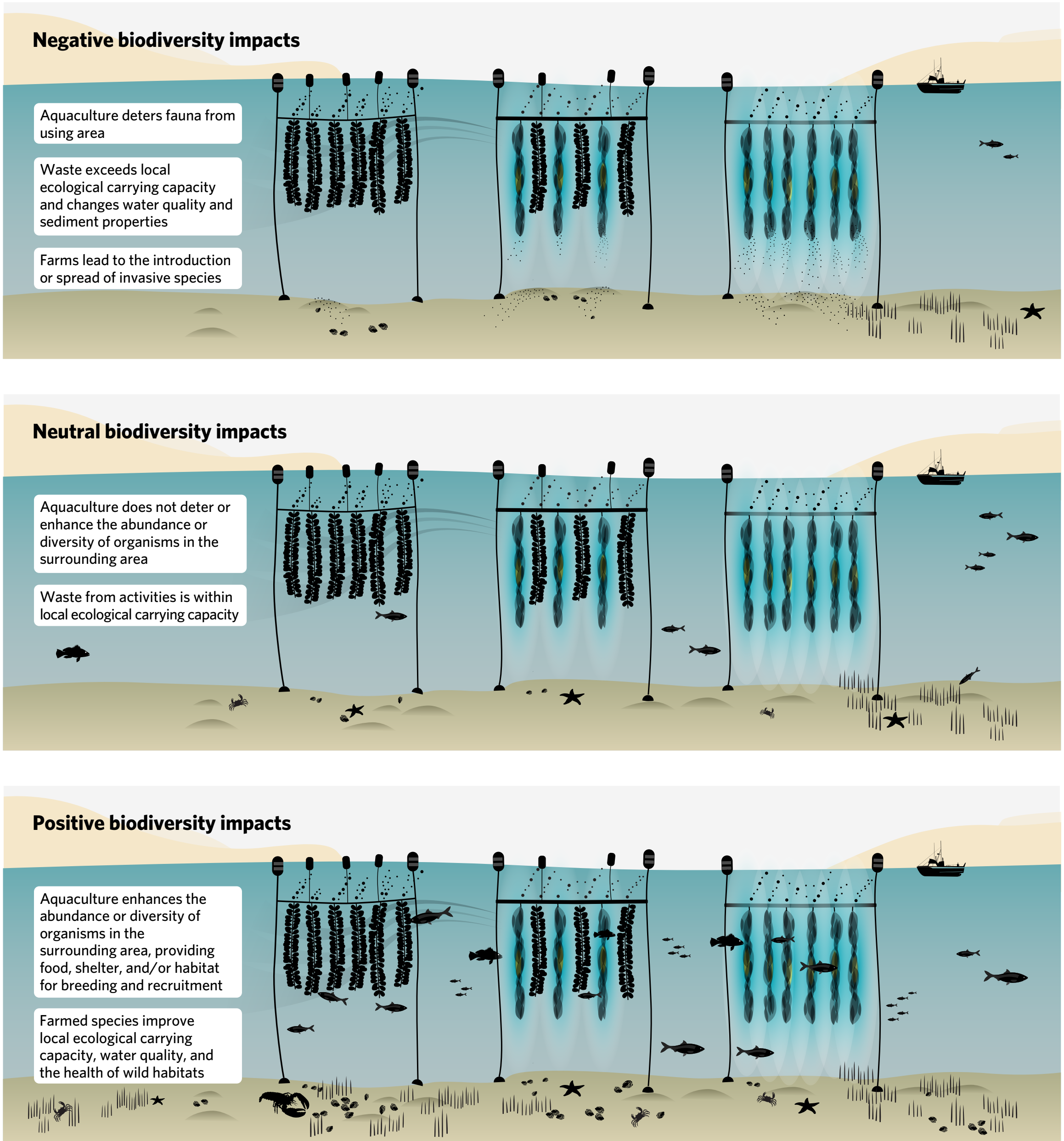


Figure 7. **Biodiversity impacts of aquaculture.**

Together, these results highlight the significance of local environmental conditions and the scale of farms in determining the habitat benefit that is provided (Figure 7). These conditions most certainly include ecological variables, such as water temperature, as well contextual factors, such as the seasonal presence/absence and movement of fish and invertebrate species most likely to be attracted to farms. The scale of farms encompasses obvious factors, including the 2D footprint and the biomass on site, but also other 3D factors, such as the physical structure of the aquaculture stock and equipment, the depth of the farm, and proximity of the stock and equipment to the seafloor. In Aotearoa, dense and highly complex mussel and mussel-kelp co-culture farms are common, with longlines hanging well down in the water column. In contrast, kelp farming in

Maine occurs primarily in shallower waters, with kelp hung at or just below the surface to maximize the availability of light for growth.

Across the geographies, multiple sampling methods were applied. To adequately assess the potential habitat benefits of kelp and kelp-shellfish aquaculture, future research should account for the influence of local environmental conditions within the sampling design, ideally including sampling across multiple seasons, water temperatures, and other seasonal or ecosystem influences. A combination of sampling methods will also be needed and some species, such as cryptic or seasonally migratory fish, may require targeted approaches. In this research, the use of eDNA sampling was tested; while there was a degree of coherence between eDNA and visual methods (GoPro cameras), eDNA samples did not always detect species seen via visual sampling.

Importantly, learnings from this research verify important ecological-social outcomes. Species of fish used by people for food were found in farms in both Aotearoa and Maine, with the highly popular snapper potentially benefiting in multiple ways from the presence of mussel farms (shelter, food availability, nutritional quality of food consumed). Yet to have a benefit to society, aquaculture need not be enhancing or increasing biodiversity. This research clearly showed that at least, kelp and shellfish farming practices can cause no harm to the surrounding environment and wild organisms, and at best, they can provide valuable habitat that supports a range of critical functions with noticeable benefits to nature.

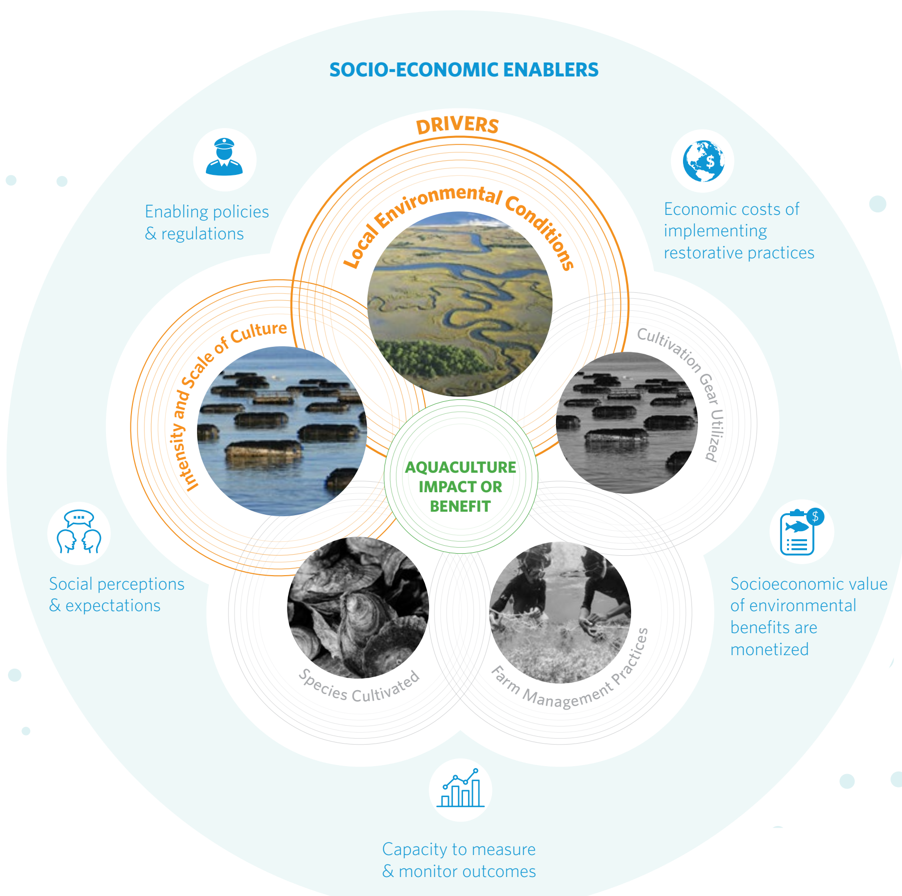


Figure 8. **Ecological and local environmental factors influence the habitat benefit of seaweed and shellfish aquaculture.**

Social-Ecological Values of the Industry

Social acceptability – also known as the social license to operate – plays an influential role in the extent to which certain species, systems, and locations are farmed (Alexander, 2022). High social acceptability can support greater adoption of sustainable practices and reward farmers for their efforts to create a positive environmental outcome. Low social acceptability can arise from direct social impacts, such as conflict with other users of waterways or noise pollution, but they can also be based on misconceptions about what aquaculture is and how it can be managed.

A novel approach was used in this project to better understand the importance of the ecosystem system services provided by aquaculture to consumers (Bolduc, Griffin and Byron, 2023). A survey was given to 41 consumers across the USA, asking them what price they were willing to pay for a range of seaweed products or products containing seaweed ingredients, including a kelp toothpaste, pinch (seasoning), shampoo, a dietary supplement, and vodka. Consumers then viewed a 90-second video that introduced the term 'ecosystem services' and showed examples of ecosystem services associated with seaweed farming. After this video-based education, consumers were once again asked the price they were willing to pay for the same products.

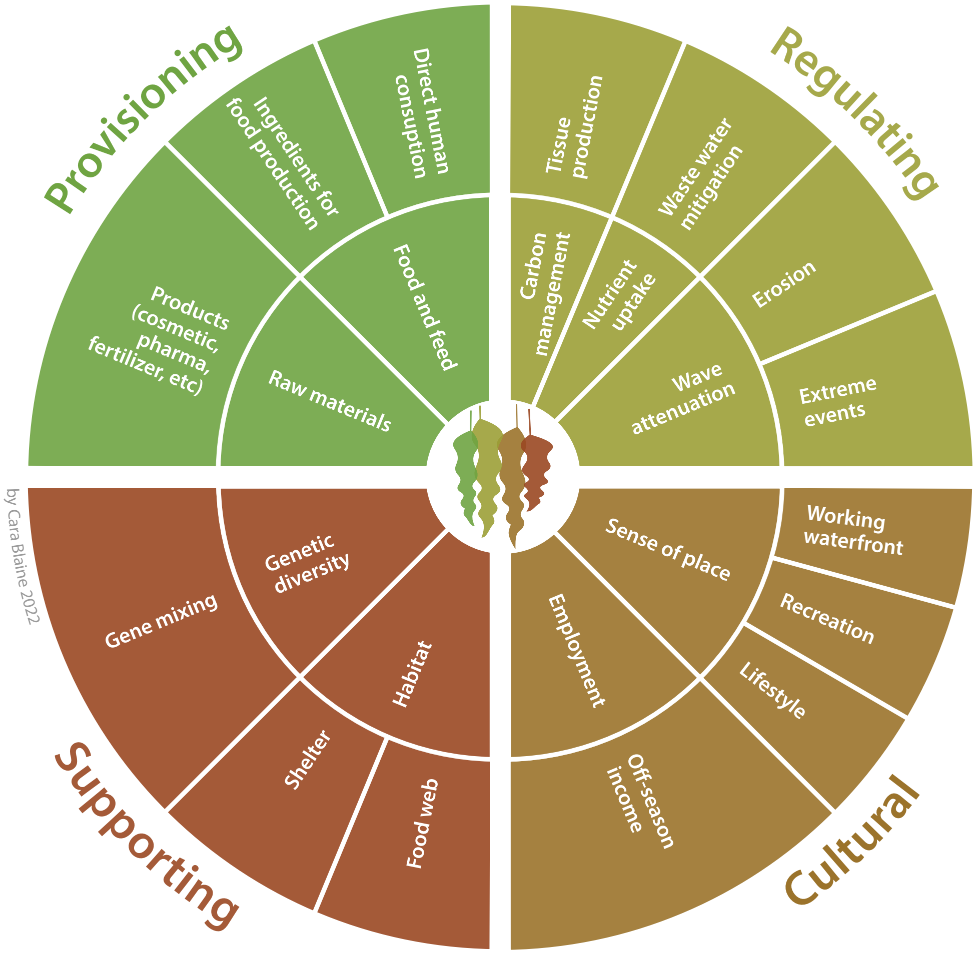
Regardless of the product or the demographics of the survey respondents, they indicated they were willing to pay more for the same products after the educational video. Importantly, while it seemed likely that respondents would value the provisional services provided by seaweed farms (e.g. food) or the regulating services (e.g. improved water quality or resilience to climate change), respondents ranked supporting and habitat services as most important. Knowing that consumers value supporting services and their importance for biodiversity justifies continued research in this area.

Divers preparing to deploy a seaweed farm and monitoring equipment in Maine, USA

Presenting the results of the project in Maine, USA

Measuring growth of seaweed on aquaculture lines

Figure 9. **Kelp aquaculture in temperate regions can generate a wide range of ecosystem services.**



05 Outcomes and Key Learnings

Recent research is painting a positive picture of seaweed aquaculture farms and their role in providing habitat for fish and other fauna and flora. **This project has identified that these benefits are, however, highly context dependent. Local environmental conditions, seasonal movement of species, and the timing of farming to coincide with the requirements of species play a key role in determining what type of habitat can be provided (e.g., habitat for foraging, shelter, recruitment) and to what extent.**

To adequately determine the potential habitat benefits of kelp and kelp-shellfish aquaculture, future research should account for the influence of local environmental conditions, ideally sampling across multiple seasons, water temperatures, key biophysical factors such as tidal flow and wave exposure, and other seasonal or ecosystem changes. More research in additional geographic and environmental settings is needed. Additionally, research that quantifies interlinked factors, such as the role of dissolved organic and particulate organic carbon released from cultured kelp in enhancing productivity within and beyond the kelp farm, and therefore effects on biodiversity, will be valuable. This will improve our understanding of how ecological variables influence aquaculture's ecosystem benefits and paint a picture of common ecological and farming principles that may apply. A consistent approach to this sampling should also be taken so that data can be successfully compared across studies and locations. In 2024, The Nature Conservancy and partners published *A global monitoring, evaluation, and learning framework for regenerative and restorative aquaculture: Helping nature thrive through aquaculture*, which describes goals, objectives, indicators, and monitoring methods that can be used to assess and value the habitat benefits of seaweed, shellfish and marine finfish farms (The Nature Conservancy, 2024). To better understand ecological-social values, research should prioritize quantifying benefits to wild species that are of conservation significance or valuable to recreational and commercial fisheries.

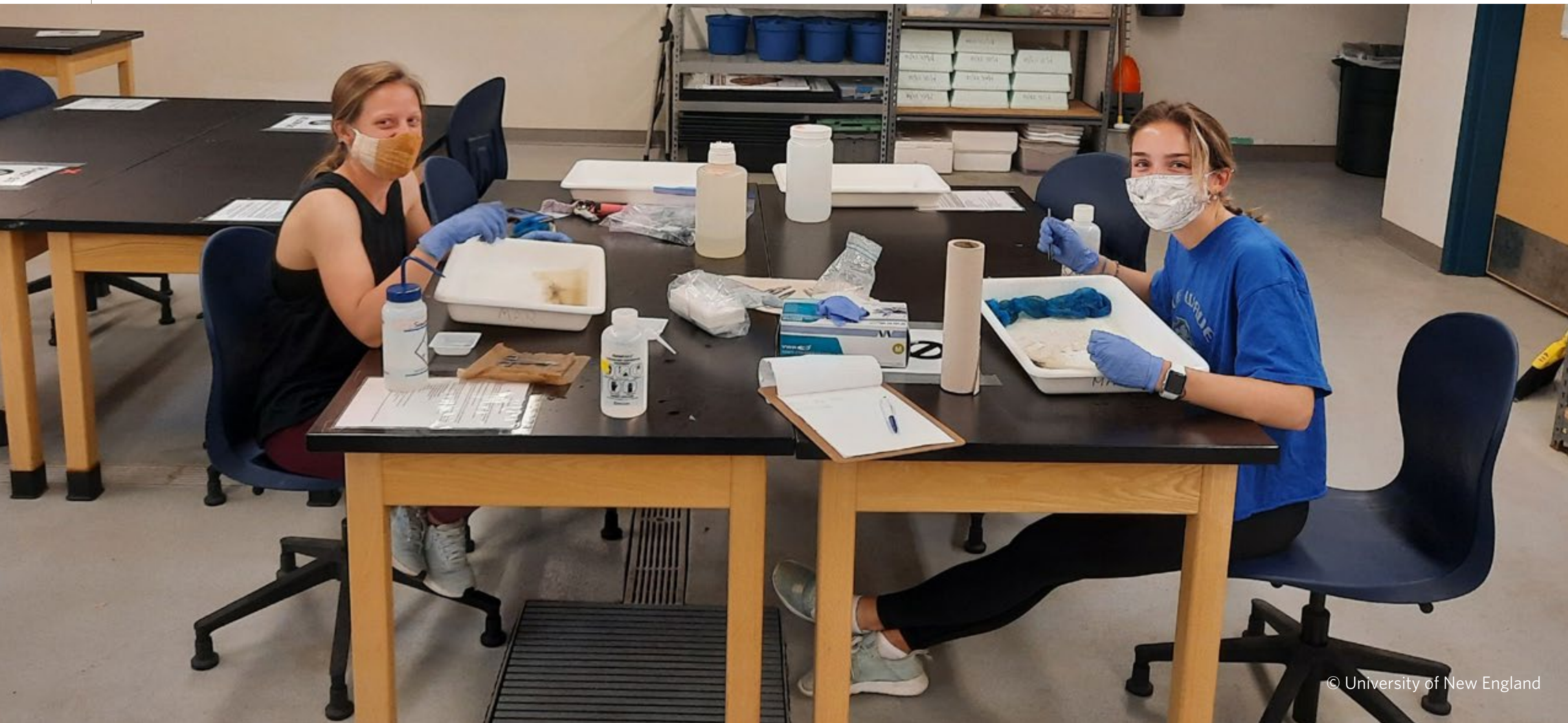
In managing the kelp aquaculture industry to have a positive impact as habitat, and to not inadvertently have a negative impact on local species, industry and supporting

organizations will need to understand how these facilities respond to environmental conditions within their local area and help operations work in harmony with those conditions. A growing number of low-cost and easy-to-adopt to technologies – such as GoPro cameras – can assist farmers in monitoring habitat impacts. AI software that can ID fish and other species is also becoming more readily available. All these technologies, as well as more advanced methods such as analysis of water samples for the presence of species through environmental DNA, are now well within the capabilities of many university and research providers, who can be a valuable source of support for industry in measuring ecosystem services.

Policy and management approaches that aim to acknowledge ecosystem services from these aquaculture systems and species should explicitly consider that farms could display high, low, or no benefit depending on their location, and that the benefits provided could vary markedly from season to season. Policies that aim to specifically encourage the provision of habitat benefits will need to be responsive to these differences, given they could occur at a sub-state or regional level (i.e. benefits within a state jurisdiction could vary). They will also need to avoid introducing unanticipated consequences, such as attracting fish species that then use the area for spawning but may be negatively affected when kelp is harvested. Building an evidence-based approach to supporting habitat benefits from aquaculture will better inform regulatory and societal perceptions and expectations.

This project has been a critical step in advancing understanding of the role of seaweed and shellfish aquaculture systems in forming valuable habitat for wildlife. In particular, it helps fill a knowledge and data gap for temperate marine ecosystems and farms, highlights the need for more research on environmental benefits from aquaculture in more locations, and validates this as an important line of enquiry worthy of effort and investment.

Researchers sorting invertebrate fauna collected from farms



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Underwood, L.H. and Jeffs, A.G. (2023) 'Settlement and recruitment of fish in mussel farms', *Aquaculture Environment Interactions*, 15, pp. 85–100.

Underwood, L.H., van der Reis, A. and Jeffs, A.G. (2023) 'Diet of snapper (*Chrysophrys auratus*) in green-lipped mussel farms and adjacent soft-sediment habitats', *Aquaculture, Fish and Fisheries*, 3(3), pp. 268–286. Available at: **https://doi.org/10.1002/aff2.113**.

Underwood, L.H., Mugica, M, Jeffs, A. 2024. Feasting in mussel farms fattens up snapper (*Chrysophrys auratus*) compared to adjacent natural habitats. Aquaculture, Fish and Fisheries. 4, e155. **https://doi.org/10.1002/aff2.155**

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Appendix 1. Published Research

Bolduc, W., Griffin, R.M., Byron, C.J., (2023) **Consumer willingness to pay for farmed seaweed with education on ecosystem services.** *Journal of Applied Phycology* 35, 911–919. **https://doi.org/10.1007/s10811-023-02914-3**

Abstract

Kelp aquaculture in the US is expected to grow significantly in the coming years. While the market potential is substantial, increasing demand is widely seen as a key step towards realizing this potential. Recent work on restorative aquaculture practices has led to increased study and valuation of ecosystem services of kelp aquaculture. This study demonstrates the efficacy of education on ecosystem services of kelp aquaculture as marketing material for kelp end products. Through an online willingness to pay survey, this study found a significant increase in consumer willingness to pay for end products after a brief education on ecosystem services. Price point of the product, income, gender, knowledge of ecosystem services, and frequency of kelp product consumption were found to be significant predictors of the magnitude of change in consumer willingness to pay. Of the four major categories of ecosystem services, supporting services were reported to be most important to consumers. These findings can guide private and public organizations in marketing efforts to drive consumer behavior and to actualize the large potential of kelp aquaculture in the USA.

McArthur, M., (2023) **The Effect of Aquaculture of Common Kelp (*Ecklonia radiata*) on Biodiversity** (MSc Thesis). University of Auckland, Auckland, New Zealand. **https://researchspace.auckland.ac.nz/docs/uoa-docs/rights.htm**

Abstract

The ecosystem benefits from the aquaculture of extractive species, such as seaweed and bivalves, are not well known in Aotearoa New Zealand. Overseas studies have demonstrated the presence of various ecosystem benefits, but their extent appears to be highly location and species-specific. There is current commercial interest in developing the aquaculture of the common kelp (*Ecklonia radiata*) in New Zealand, either alone or in combination with greenlipped mussels. This study aims to explore one aspect of the potential ecosystem effects of the aquaculture of common kelp in the Hauraki Gulf, i.e., determining whether the presence of kelp aquaculture alters the associated marine biodiversity. However, at the time of this study, there were no commercial-scale kelp farms in the Hauraki Gulf, so wild adult kelp was transplanted to sections of two existing, but unused, mussel farm lines in the Hauraki Gulf in a manner that would be typical of a kelp farm. Marine biodiversity was then compared for the abundance and diversity of invertebrates establishing in standardised artificial habitats (AUH) placed within the kelp farms versus AUH placed adjacent to the farms as controls. To assess possible seasonal differences in biodiversity, the sampling was undertaken at one study site for four consecutive seasons, and the other site for three seasons.

Two groups of amphipods, caprellids and gammarids, were the most abundant taxa observed in the AUH regardless of whether they were in kelp farms or controls. Smaller numbers of other taxa, including polychaetes, crabs, bivalves and tanaids were also observed. The total abundance of organisms in the AUHs was not influenced by whether they were placed in a kelp farm or adjacent to the kelp farm, but there were differences in the total abundance due to site and season. The diversity of organisms in the AUHs, as measured by Shannon Diversity Index was influenced by the presence of kelp farm but this was modulated by site and by season. Likewise, the evenness of diversity, as measured by Pielou's Evenness Index, was also influenced by the presence of a kelp farm but this was modulated by site. The abundance of 14 groups of taxa were found to be influenced by the presence of the kelp farm, but with the extent of this influence varying with the combination of both site and season.

Seasonality influenced the overall abundance of all taxa, with winter samples at one site having the lowest abundance in both farm and controls of all taxa. These results differ to a parallel study in the Gulf of Maine that was unable to detect an effect of kelp farms on invertebrates sampled with AUHs, indicating that the influence of kelp farms on invertebrates may be context dependent.

Collectively, these results contribute to an improved understanding of the ecosystem effects of kelp aquaculture in temperate waters on invertebrate diversity. In essence, these factors have the capacity to modify or alter the impact of the kelp farm has on diversity. This aligns with previous research that has highlighted the location specific nature of kelp's habitat provisioning ability. This effect of the presence of kelp farm on invertebrates can now be accounted for in environmental regulatory processes when considering the establishment of new kelp farms.

Underwood, L.H., Jeffs, A.G., (2023) **Settlement and recruitment of fish in mussel farms.** *Aquaculture Environment Interactions* 15, 85–100. **https://doi.org/10.3354/aei00454**

Abstract

Fish are thought to settle and recruit to shellfish and seaweed farms; however, there is little published evidence to support this assumption. Shellfish and seaweed farms increase structural complexity and epibiota productivity, which may attract settling fish larvae. In this study, fish settlement and recruitment patterns into 2 aquaculture habitats, mussel-kelp co-culture and mussel farm monoculture, were compared to 2 adjacent natural habitats, soft-sediment seafloor and rocky reef, within a settlement season. Standard monitoring units for the recruitment of fish (SMURFs) were used, as they are a common and reliable method for measuring temporal and spatial variability in fish settlement and recruitment among habitat types. The communities of fish species settling and recruiting to both sets of aquaculture and natural habitats were equivalent. This was most likely due to the artificial 3D structure of the mussel farm habitats functioning in a similar manner to the structural complexity of a rocky reef habitat. Further, there was indication that for at least the most abundant fish species, *Fosterygion lapillum*, the 2 aquaculture habitats were of sufficient quality to support growth from settlement to juvenile size classes (i.e. in mussel monoculture habitat 65% were newly settled in December, and 86% were of juvenile size class by February). Overall, these findings provide foundational quantitative evidence of the interactions that fish have with mussel farms and increases the understanding of restorative opportunities for aquaculture operations.

Underwood, L.H., van der Reis, A., Jeffs, A.G., (2023) **Diet of snapper (*Chrysophrys auratus*) in green-lipped mussel farms and adjacent soft-sediment habitats.** *Aquaculture, Fish and Fisheries* 3, 268–286. **https://doi.org/10.1002/aff2.113**

Abstract

Wild fish utilise aquaculture habitats for shelter and/or food resources. It is often assumed that fish respond to feed input, the abundance of the farmed species or the associated assemblage of biofouling which naturally colonises the structural habitats. However, few studies have directly analysed the composition of the diet of fish within aquaculture habitats, and of these most have focused on fed finfish aquaculture. Snapper are commonly present as adults within coastal mussel farms and tend to become a resident species of these farms. Therefore, they are a suitable case study species for exploring differences in diet between natural and aquaculture habitats. This study investigated the gut contents of snapper in soft-sediment habitats within and outside of New Zealand green-lipped mussel farms. Visual gut analysis and DNA metabarcoding methods were used to provide complementary analyses on the composition of gut contents between the mussel farm and natural (i.e., control) sites. Snapper within mussel farms were consistently found to have consumed different prey groups compared to the control snapper. Prey groups identified from mussel farm snapper gut contents could be directly linked to species commonly present in the farms, that is cultured green-lipped mussels, blue mussels and barnacle biofouling. There was good alignment between the visual gut and genetic analyses for the key species identified. Overall, the results show that the highly abundant prey groups consumed by snapper in mussel farm habitats are likely to be beneficial to the snapper population, reducing foraging effort and potentially supplying more nutritious prey. These findings provide evidence towards the supporting services of mussel farm habitats through the provision of food resources.

Underwood, L.H., Mugica, M, Jeffs, A. 2024. **Feasting in mussel farms fattens up snapper (*Chrysophrys auratus*) compared to adjacent natural habitats**. *Aquaculture, Fish and Fisheries.* 4, e155. **https://doi.org/10.1002/aff2.155**

Abstract

The presence of wild fish in and around aquaculture habitats is often assumed a response to food resources within these habitats, either from input feed, the presence of cultured species, and/or the assemblage of biofouling that naturally colonises aquaculture structures. The nutritional quality of the food resources consumed by wild fish in aquaculture habitats is also important in determining their nutritional condition and subsequent productivity. Few studies have investigated the nutritional quality of prey in aquaculture habitats, and these have mostly focused on fed aquaculture by tracking manufactured fish pellets into the diets of wild fish. However, in non-fed aquaculture, the assemblage of cultured and biofouling species may also provide a nutritional benefit to fish feeding in these habitats. The Australasian snapper, Chrysophrys auratus, are commonly present as adults within coastal mussel farms in New Zealand and tend to become a resident species. This study investigated the nutritional quality of the gut contents of snapper in soft-sediment habitats within and outside of New Zealand green-lipped mussel farms. Total lipid, protein, carbohydrate and total calorific content were measured from the gut contents of snapper sampled from mussel farm and natural (i.e. control) habitats. Snapper in mussel farms had double the dietary intake of lipid (16% vs. 8%) from consuming lipid-rich bivalves and barnacles which are in abundance in mussel farms. Higher lipid intake can contribute to improved nutritional condition, reproduction

and growth in snapper. However, the higher dietary lipid intake of snapper in mussel farms did not increase their overall body condition (i.e. Fulton condition index). This may be due to the coarse nature of this measure, or the use of the additional lipid in more rapid somatic growth or reproductive outputs, possibilities that warrant examination through further research. Overall, this study shows for the first time the potential ecosystem benefits of shellfish aquaculture in provisioning nutritionally valuable prey for coastal fish populations.

Schutt, E., Francolini, R., Price, N., Olson, Z., Byron, C.J., (2023) **Supporting ecosystem services of habitat and biodiversity in temperate seaweed (*Saccharina* spp.) farms.** *Marine Environmental Research* 191, 106162. **https://doi.org/10.1016/j.marenvres.2023.106162**

Abstract

Habitat provisioning, and the biodiversity within, is considered a type of "supporting" ecosystem service. Ecosystem services are the benefits humans receive from healthy ecosystems. We assess whether kelp (*Saccharina* spp.) farms provide seasonal habitat for wild organisms. Contrary to other studies conducted in tropic seaweed farms, we did not observe habitat provisioning or increased biodiversity at seasonal temperate seaweed farm sites compared to neighboring non-farm sites, which is encouraging news for the aquaculture industry given that most farm gear is removed from the water after the spring harvest. We quantified fish and crustaceans interacting with kelp farms using GoPro cameras. We also assessed small (<5 mm) invertebrates using mesh settling devices suspended at the same depth as kelp lines (2m). Visual surveys were paired with eDNA. There was coherence in the conclusions drawn from observational and eDNA methods, despite weak coherence in the specific species identified between the methods. Both farm and non-farm sites exhibited higher species richness and biodiversity in the summer non-growing season compared to the winter growing season, attributed to expected seasonal species movements.

Underwood, L.H., Mugica, M, Jeffs, A. 2024. **Feasting in mussel farms fattens up snapper (*Chrysophrys auratus*) compared to adjacent natural habitats.** *Aquaculture, Fish and Fisheries.* In Press

Abstract

The presence of wild fish in and around aquaculture habitats is often assumed a response to food resources within these habitats, either from input feed, the presence of cultured species, and/or the assemblage of biofouling that naturally colonises aquaculture structures. The nutritional quality of the food resources consumed by wild fish in aquaculture habitats is also important in determining their nutritional condition and subsequent productivity. Few studies have investigated the nutritional quality of prey in aquaculture habitats, and these have mostly focused on fed aquaculture by tracking manufactured fish pellets into the diets of wild fish. However, in non-fed aquaculture the assemblage of cultured and biofouling species may also provide a nutritional benefit to fish feeding in these habitats. The Australasian snapper, Chrysophrys auratus, are commonly present as adults within coastal mussel farms in New Zealand and tend to become a resident species. This study investigated the nutritional quality of the gut contents of snapper in soft-sediment habitats within and outside of New Zealand green-lipped mussel farms. Total lipid, protein, carbohydrate and total calorific content were measured from the gut contents of snapper sampled from mussel farm and natural (i.e., control) habitats. Snapper in mussel farms had double the dietary intake of lipid (16 versus 8 %) from consuming lipid-rich bivalves and barnacles which are in abundance in mussel farms. Higher lipid intake can contribute to improved nutritional condition, reproduction and growth in snapper. However, the higher dietary lipid intake of snapper in mussel farms did not increase their overall body condition (i.e., Fulton condition index). This may be due to the coarse nature of this measure, or the use of the additional lipid in more rapid somatic growth or reproductive outputs, possibilities that warrant examination through further research. Overall, this study shows for the first time the potential ecosystem benefits of shellfish aquaculture in provisioning nutritionally valuable prey for coastal fish populations.

Yellowtail kingfish swimming among mussel aquaculture lines in New Zealand