Provision of ecological and ecosystem services by mussel farming in the Marlborough Sounds

A literature review in context of the state of the environment pre- and post-mussel farming

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Executive summary

The Marine Farming Association Inc. (MFA) commissioned the National Institute of Water and Atmospheric Research (NIWA) to review and summarise exisiting literature on the ecological services (EcolS - services that benefit the marine ecosystem) and ecosystem services (ES - services that benefit human wellbeing) provided by mussel farming in the Pelorus and Queen Charlotte Sounds, Marlborough, New Zealand.

This review was prompted by two emergent issues: (1) the growing international recognition that shellfish aquaculture can contribute toward the resilience of coastal ecosystems rather than be viewed solely as detrimental to the environment or causing adverse environmental impacts and (2) the need to inform the emerging chapter on aquaculture in the Marlborough Environment Plan (MEP) that will govern the rules around Marlborough's marine farming for the next ten years and the process of consent renewal for 60% of farms by 2025.

The purpose of this report is to collate and review information concerning the provision of EcolS and ES provided by mussel aquaculture in the context of the Marlborough Sounds' State of Environment (SOE). It is important to benchmark the SOE for understanding the present-day services of mussel farming in the sounds.

This review was based on available published literature, NIWA reports on mussel farming in the area, compliance reports provided by MFA, and grey literature from internet searches. No new empirical data has been collected for this review. We reviewed the SOE of the Marlborough Sounds before (ca. <1970) and after mussel farming started and, in this context considered service provision within the four broad categories: (1) *Regulating*, which encompasses services that regulate the environment such as improving water quality through sequestering suspended particulates, nitrogen and carbon; (2) *Habitat and supporting,* which includes physical creation of habitats, habitat provision for species and maintaining diversity and (3) *Provisioning*, meaning the production of food, water or other goods and (4) *Cultural*. In this review, we address the first three categories and referred to cultural aspects where necessary and included fish, seabirds and marine mammals.

SOE of the Marlborough Sounds

It was important to benchmark the SOE of the Marlborough Sounds to contextualise both perceived and quantified environmental impacts of mussel farming and to assess the degree to which EcolS and ES provided by mussel farming may have compensated for lost ecosystem functionality or added new services.

By 1970 benthic trawling for demersal fish and dredging for mussels and scallops had severely reduced these stocks and destroyed most of the benthic biogenic reefs (algae meadows, rhodolith reefs, bryozoan thickets, calcareous tubeworm mounds and shellfish beds) in both the Pelorus and Queen Charlotte Sound (QCS). These reefs and mussel beds have not yet recovered. The loss of hard surfaces upon which many invertebrate species settled, impoverished the communities preyed upon by several ecologically and economically important finfish species. One of the top key predatory fish, rig, was overfished and stocks have not recovered, being replaced by short-lived predatory species. Reductions in the abundance of pilchard, blue cod, flatfish, gurnard, kahawai, groper, snapper and crayfish have led to the view that the Marlborough Sounds ecosystem has experienced a top-down trophic cascade. There is scant information on the population densities of seabirds and marine mammals in the sounds before mussel farming. It's likely that the abundance of seabirds declined after human settlement largely due to the introduction of rats and other predators of eggs and chicks. Seals and whale populations were decimated by hunting by 1970 when most commercial activity came to an end.

Besides the removal of top predators (e.g., rig, fur seals) the sounds had also undergone a bottom-up ecosystem step-change with the removal of benthic suspension feeders from the lower food web (e.g., mussels, scallops, horse mussels, bryozoans, sponges, ascidians and tubeworms). This removal goes beyond impacts on the food web because many of these species are bioengineers, transforming energy and influencing sediment characteristics and landscape heterogeneity through their capacity for filtration and biodeposition. Because green-lipped mussel beds provided multi-faceted EcolS and ES their loss from the sounds' ecosystem was likely to have more far reaching food web effects than the change in balance caused by a different predation pressure when removing a top predator. Land-based farming and forestry activities have led to a sediment accumulation rate that has increased ten-fold post-European settlement. Increased sedimentation has been identified as potentially the most important land-based stressor in marine environments.

Besides high sediment loading, other pressures on water quality have substantially increased since mussel farming started leading to sounds-wide monitoring for contaminants and biotoxins led by marine farmers to primarily ensure the quality of their product. Mussel and salmon farms are also required to monitor potential adverse effects on natural resources. Hydrodynamic models developed by NIWA suggest it's unlikely that the current number of consented fish and mussel farms in the sounds will make a marked change in nutrient levels in the ecosystem.

In the last ten years increasing attention has been given to locating, identifying and protecting remaining biogenic habitats and to this end, all dredging for scallops has been suspended indefinitely and recreational trawling for demersal fish is not permitted in the inner sounds and QCS. These remaining biogenic reefs together with a list of fish, seabirds and mammals have been declared ecologically significant to the sounds' ecosystem. Blue cod are now a managed recreational fishery. The rare king shag population has fluctuated in the last 20 years, but this species is now being carefully monitored, especially with respect to interactions with marine farms. Seabird and mammal numbers are generally on the increase since beingbeing fully protected in the early 1980s.

Although we have shown that cultured green-lipped mussels in the sounds do have some degree of equivalency with the previous unmodified wild mussel beds and that there are parallels in biodiversity with benthic biogenic reefs, we do not know the spatial scales of these lost habitats and hence we cannot quantify the full extent of service "substitution" provided by mussel culture.

Regulating services

Mussels undoubtedly capture suspended sediment and parcel it up into mucous-bound particles (pseudo-faeces) which tend to sink rapidly. One might suppose that the sediment-content of water will decline as it passes through a mussel farm – however a variety of field data from Pelorus Sound and the Firth of Thames all suggest that mussel farms have an immeasurably small effect upon bay-scale concentrations of suspended sediment. The pseudofaecal particles degrade in a matter of days and it is likely that the fine inorganic sediments contained in them are readily resuspended as they fall away from the degrading pseudo-faecal particle.

Approximately 6 kg N are harvested per tonne of harvested green mussel weight. For Pelorus Sound, the green-lipped mussel harvest has been estimated to equate to approximately 266 tonne N per year whilst inputs from the catchment via Pelorus/Rai and Kaituna rivers and several other smaller sources have been estimated to amount to about 580 tonne per year. The nitrogen removed as crop amounted to more than 50% of the total estimated nitrogen loss through denitrification in the seabed of the entire Pelorus Sound. Nitrogen is also temporarily locked up in the fouling community, but since most of this is returned to the sea when the mussels are harvested, there is limited net removal. We note that there are emerging markets for blue mussel and the invasive seaweed *Undaria pinnatifida*. Blue mussels can occupy an average of about 9% of the total dropper length – suggesting that a full harvest of the blue mussel population growing on droppers might remove about 24 tonne N per year from the coastal waters of the Marlborough region. The *Undaria* harvest is around 150 tonne wet weight per year at present and may rapidly grow to around 300 tonne per year. An annual harvest of 300 tonne fresh weight would equate to approximately 10 tonne N year.

Denitrification operates to convert nitrogen-nutrient into less bio-available N_2 gas. Incubations in the laboratory and on intact mussel droppers in the field have both indicated that the mussel-crop-matrix generates a flux of N_2. Whilst one study suggested that rates of denitrification at the seabed below a mussel farm were suppressed, another study at a different site suggested that they were enhanced. Whilst data are scarce, such data as do exist suggest that the denitrification flux arising from the crop-matrix exceeds that arising from the seabed below the crop. Overall, we consider it more likely that mussel-farms increase the magnitude of the area-specific denitrification flux that is generated in the waters and seabed enclosed within a marine-farm perimeter – but we acknowledge that few studies have been carried out and that there are some contradictions amongst those few studies.

In the atmosphere, CO_2 is a key greenhouse gas. In water, CO_2 naturally (and rapidly) partitions itself across four dissolved inorganic forms (CO_2, H_2CO_3, HCO_3^- and CO_3^{2-}, collectively dissolved inorganic carbon or DIC). The reactions occur spontaneously and rapidly. They are reversible and, because they involve uptake of H_2O and, more importantly, release of H^+ ions, they influence the water's pH. When water is acidic, most dissolved inorganic carbon (DIC) is present as CO_2 and H_2CO_3. When waters are mildly alkaline, more of the DIC is present as HCO_3^- and when strongly alkaline, more is present as CO_3^{2-}. Shell formation consumes two forms of carbonate (carbonate ions, HCO_3^-). One of those becomes incorporated into the calcium carbonate of the shell, whilst the other is released as aqueous CO_2. Thus, whilst calcification is a net sink for DIC, it is a source for CO_2. Depending upon local conditions (especially pH and the CO_2-saturation state of the water), this 'new' CO_2 may return to the atmosphere (where it will serve as a warming gas) or convert to a carbonate ion again. The key point is that whilst shell-formation certainly sequesters dissolved inorganic carbon into a particulate form, it also tends to render CO_2 more available to the atmosphere. A recent review of ecosystem services of bivalve aquaculture explicitly chose to ignore carbon-sequestration as a possible eco-service and a forthcoming paper concludes that blue mussel aquaculture would be a net source of CO_2 to the atmosphere – with colder-water sites (e.g., Baltic Sea) being stronger sources of CO_2 than warm-water ones (e.g., Galicia).

It is worth noting that, just as shell-formation in water is associated with net release of CO_2 to the water (but net uptake of DIC), shell-dissolution is associated with net uptake of CO_2 (net release of DIC). Thus, any CO_2 burden that is induced by shell-formation can be relieved if the harvested shell is allowed to dissolve in water. Dissolution rates will be higher in strongly acidic conditions, but studies suggest that even in less extreme environments (e.g., the upper parts of coastal marine sediments) around 50% of shell-hash may dissolve over the course of a year. Whether the shell-formation process is a net source or a net sink for atmospheric CO_2, this source (sink) flux is likely to be reversed/countered if the shell is later allowed to dissolve under similar environmental conditions.

Habitat and supporting

Most of the service provision in this category was manifested as EcolS. We recorded a total of 139 taxa associated with suspended farm structures from the literature, of which most were suspension feeders (ca. 61%) followed by scavengers, predators and detritivores. Ascidians contributed the most, followed by macroalgae, sponges, crustaceans - amphipods, isopods and crabs, cnidarians – hydroids and sea anemones, bryozoans and annelids - tube worms, feather-duster worms, carnivorous polychaetes and other bivalves. Biofouling suspension feeders together with the cultured green-lipped mussels contribute a substantial standing biomass to the sounds ecosystem that may go some way to compensate for that lost in the past.

Mussel-culture derived reefs beneath mussel farms were dominated by patchy mounds of mussel shells and clumps of live green-lipped mussels covered with discarded biofoulers and biodeposits. These mussel-culture derived reefs form three-dimensional heterogenous habitats that provide EcolS of food, shelter and protection for other marine flora and fauna and help to stabilise bottom sediments. Benthic biodiversity was supported by local mobile epifauna such as sea cucumbers, starfish, sea urchins and gastropods being attracted from outside farms to the food supply afforded by the mussel-culture derived reefs. Other sedentary species (sponges, ascidians and bryozoans) were more likely to have originated from biofouling discards or incidental drop-off from mussel structures. Overall species diversity appeared marginally higher with a greater abundance of these species associated with mussel-culture derived reefs.

We calculated that if (theoretically) mussel droppers were laid on the seabed, this area together with the area of mussel-culture derived reefs under farms provide an equivalency of 3693 ha versus around 2000 ha of historical wild mussel beds. For this area green-lipped mussels filter approximately 192,000 m^3/ ha /day which is 2.5% of the entire Marlborough Sounds volume – so if our spatial equivalency to historic beds is realistic, cultured mussel would filter the same volumes of water filtered by lost wild stocks. In addition, the species diversity found on mussel droppers are akin to those found associated with present day benthic algae meadows, rhodolith beds, bryozoan thickets and calcareous tube worms. Mussel-culture derived reefs are perhaps akin more to soft bottom non-calcareous tubeworm mounds that attract a predominance of scavengers, detritivores and predators. Thus, to some degree mussel farms compensate for the loss of both wild mussel beds and biogenic reefs by providing renewable mussel stocks and habitats that increase the abundance of organisms that once that would have been plentiful among the now-destroyed benthic habitats.

In this category ES were demonstrated through primary production (colonising diatoms and macroalgae), nutrient regeneration and habitat provision for species.

Provisioning services

Mussel farming provides provisioning ES through food, raw material and medicinal resources for human wellbeing. Harvested mussels are mostly consumed as mussel meat, but a rapidly increasing proportion provides neutraceutucal products (powder and mussel oil) for the treatment of inflammatory diseases and general health benefits. Discarded mussel shells are used as land mulch. Wild *Undaria pinnatifida* is now being collected as a byproduct off mussel lines and used as land fertiliser and blue mussels are being harvested for exploratory market. There is significant potential provision of a wide variety of bioactives from macroalgae ad sponges that grow on mussel farms.

Fish, seabirds and mammals

Mussel farms provide habitat EcolS (food and shelter) for spotties and triplefins throughout the year and for the occasional leatherjackets, stargazers, blue cod, mullet and flatfish. Snapper have been observed feeding off mussel droppers. ES is demonstrated through food and habitat provision for species (snapper and blue cod) that are of interest to fishermen.

Mussel farms provide an EcolS by providing feeding and roosting opportunities for some seabirds. Buoys on mussel farms provide EcolS haul-out for seals and at harvest foraging opportunities are afforded for seals. The common and bottlenose dolphins use farms to herd their prey.

Knowledge gaps and the way forward

The lack of underpinning data precludes quantifying most of the EcolS provided by mussel farming that have been identified in this review. Key areas that require investigation are biochemical pathways (especially denitrification), biodiversity measures, food webs, discard biomass and reef formations and sound scientific studies on the interactions between mussel farms and fish, seabirds and mammals. In terms of quantifying and refining our understanding of ES provision by mussel farming, a scoring matrix approach could be applied in a workshop setting by using a combination of peer-reviewed scientific literature and expert opinion.

Even though this review does not fully quantify the services of mussel farming, it does provide the first step towards developing a service-approach that can underpin future aquaculture regulatory and monitoring requirements. The review goes a step further by framing the service inventory within the present state of the environment of the Marlborough Sounds. At some point into the future once key services provided by mussel farming have been quantified the provision of these services can be incorporated into an evidence- and knowledge- based approach leading onto an ecosystem-based approach, and an integrative management framework that includes economic, environmental and social considerations.

1 Introduction

The Marine Farming Association Inc. (MFA), which represents marine farmers operating in the top of the South Island, commissioned the National Institute of Water and Atmospheric Research (NIWA) to review and summarise exsiting literature on the services provided by mussel farming in the Marlborough Sounds, New Zealand. In our assessment of service provision, we make a distinction between ecological services - EcolS - (services that benefit the marine ecosystem of the Marlborough Sounds) and ecosystem services – ES - (services that benefit human wellbeing).

This review was prompted by two emergent issues:

(1) the growing international recognition that shellfish aquaculture can contribute toward the resilience[1] of coastal ecosystems (Lindahl, Hart et al. 2005; Coen, Dumbauld and Judge 2011; Arreguín-Sánchez 2013; Saurel, Ferreira et al. 2014; Rose, Bricker and Ferreira 2015; Kluger, Taylor et al. 2016; Kluger, Filgueira and Wolff, 2017; Bricker, Ferreira et al. 2018) rather than be viewed solely as detrimental to the environment or causing adverse environmental impacts.

(2) the need to inform the emerging chapter on aquaculture in the Marlborough Environment Plan (MEP) which will govern the rules around Marlborough's marine farming for the next ten years and the process of consent renewal for 60 % of farms by 2025.

Regarding (1), debate on shellfish environmental ecosystem services (henceforth ES)[2] has emerged around finding solutions to maintain overall coastal health and the ability of near-shore marine ecosystems to remain resilient to excessive sedimentation and nutrient input, natural resource exploitation and climate change (Dewey, Davis, Cheney 2011). In this context bivalve aquaculture has been seen as a green industry (Saurel, Ferreira et al. 2014 and references therein), providing ecosystem goods and services that include: (a) reduction of turbidity and nutrient control through filtration of inorganic and organic particulates; (b) water quality improvement through reduction of primary eutrophication symptoms, thereby minimizing secondary symptoms such as hypoxia (Ferreira and Bricker 2016); (c) carbon sequestration (Filgueira, Byron et al. 2015); (d) habitat provision for shelter, food and invertebrate recruitment and (e) biodiversity maintenance and / or restoration (Murray, Newell and Seed 2007).

Regarding (2), renewal costs for existing space in the Marlborough Sounds between now and 2024 are conservatively estimated at $30 million (iclusive of mussels and salmon) (NZIER 2017). This report is also intended as an information resource that applicants and interested parties can draw on in relation to marine farm consent applications.

The purpose of this report is to collate and review information concerning the provision of EcolS and ES by mussel aquaculture in the context of the Marlborough Sounds' State of Environment (SOE) pre- and post-mussel farming and to provide a scientific context for decision makers when considering assertions that this activity has a cumulative detrimental effect on the long-term sustainability of the sounds' ecosystem. It is important to benchmark the SOE for understanding present-day service provision by mussel farming in the sounds.

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[1] Ecosystem resilience represents the capacity of a system to persist or maintain its function in the presence of exogenous disturbance (Holling 1973, Walker et al. 2004)

[2] The concept of Ecosystem Services (ES) has been created to address the interactions between nature and society. It describes the relevance of ecosystem functions for human wellbeing.

This review is based on available published literature, NIWA reports on mussel farming in the area, compliance reports and any other grey literature that has come to light. All information used in this review has been sourced from published material. No new empirical data has been collected for this review.

To structure this review, we pose the following questions:

1. What was the SOE in Marlborough Sounds before green-lipped mussel farming commenced?
2. What is the present SOE of the Marlborough Sounds inclusive of green-lipped mussel farming?
3. What are the recognisable EcolS and ES provided by mussel farming?
4. Can mussel farms serve to replace some of the lost benthic habitats?

Within this structure, we review the past and present SOE of the sounds and in this context, we consider the service provision within the four broad categories used in the international literature to classify ES (Gentry, Alleway et al. 2019): (1) Regulating, which encompasses services that regulate the environment such as improving water quality through sequestering suspended particulates, nitrogen and carbon; (2) Habitat and supporting, which includes physical creation of habitats, habitat provision for species and maintaining diversity and (3) Provisioning, meaning the production of food, water or other goods and (4) Cultural. We address the first three categories and refer to cultural aspects where necessary. We also include fish, seabirds and marine mammals. Within these categories we make a distinction between ecological (EcolS) and ecosystem (ES) services.

This information will be used to provide:

- A comprehensive understanding of the shifting SOE bench-mark against which ES are assessed;
- Improved ability to contextualise the provision of ES by mussel farming and
- An underpinning contribution to assist in enabling sustainable management of aquaculture in the Marlborough Sounds.

2 The Marlborough Sounds marine ecosystem

The Marlborough District Council (MDC) has embarked on a project to identify how coastal ecosystems have changed since human habitation of the Marlborough Sounds (Pelorus and Queen Charlotte Sounds). The results so far show that there have been significant human-driven changes to habitats and ecosystem processes, which have caused a dramatic loss of abundance of fish, shellfish and crayfish over the last 150 years[3]. The baseline has shifted such that what exists today in supposedly unimpacted locations is no longer the same as historical components of marine communities and seabed composition.

Here we first appraise the state of the Marlborough Sounds[4] environment before mussel farming commenced in the 1970s (section 2.1). Much of this information is anecdotal or semi-quantitative but still provides context against which the interactions between mussel farming and the environment can be considered subsequently. We then consider the introduction and growth of

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[3] https://www.marlborough.govt.nz/environment/coastal/historical-ecosystem-change

[4] See glossary for the areas considered to be part of the Marlborough Sounds in this review.

mussel farming in the sounds in section 2.2, concomitant with more recent assessments on the SOE based in most part on quantifiable information. Section 2 provides the context (benchmark) for evaluating the provision of services by mussel farms in Section 3.

In our evaluation we are not asking if shellfish services promote a return to a (poorly quantified) pre-European past state, but rather seek to what extent present mussel farms enhance the resilience and health of the system – such that it is better able to withstand other stressors. We acknowledge that some have argued that shellfish farming itself represents a significant stressor[5] but we will provide evidence suggesting that even the environmental cumulative effects of many small farms are usually subtle or benign, at least for benthic and water-quality properties that have been sampled to date.

2.1 Before mussel farms

2.1.1 Sedimentation and sediments

Pre-human mean sedimentation accumulation rates (SAR) in the Pelorus Sound have been estimated to be low, in the order of 0.5 mm/year, and mostly dominated by subsoils from slips (Handley, Gibbs et al. 2017). In its unmodified state, the inner Pelorus received less sediment and nutrients from land, and likely had clearer waters with good visibility. This state *“reflected a relatively stable native forest cover with low background sediment inputs historically, punctuated by infrequent large seismic or storm disturbances, which the ecosystem had evolved to accommodate”* (Handley, Gibbs et al. 2017).

Increase in SAR would have started with the commercial exploitation of natural resources in the Marlborough Sounds in the late 1880s with land-based activities such as gold mining, timber milling, and land clearance for farming and forestry (Handley 2015, 2016; Handley, Gibbs et al. 2017). By 1911 many of the hills in both the Pelorus Sound and Queen Charlotte Sound (QCS) were laid bare of indigenous vegetation resulting in the inevitable slips and sediment entering the sea. This would have been the beginning of reduced seabed habitat integrity in the sounds (Newcombe and Johnston 2016 in Handley 2016) which continues to this day (Davidson, Duffy et al. 2011, Ulrich 2015, Handley, Gibbs et al. 2017, Davidson and others 2017[6]). Excessive sedimentation reduces the amount of light which penetrates to deeper parts of the water column, smothers habitats and thereby changes ecological composition by killing and displacing marine invertebrates, shellfish, and algae. Indeed, increased sedimentation has been identified as potentially the most important land-based stressor in marine environments (Morrison, Jones et al. 2014).

Bottom trawling for fish and dredging for shellfish damaged benthic reefs and softbottom communities, leaving behind expanses of open ‘near featureless’ muddy terrain. These physical effects reduced the density of common infauna[7] populations and populations of important bioturbators with implications for the seafloor to absorb and release nutrients (Thrush, Hewitt et al. 1995; Newcombe, Clarke et al. 2015). It is therefore probable that by the early 1970s when mussel farming was first trialled, the seabed had changed from more sandy sediments interspersed with biogenic reefs to a muddy/silt terrain with infrequent reef patches.

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[5] https://www.stuff.co.nz/marlborough-express/opinion/74539294/future-of-sounds-a-balancing-act; https://www.stuff.co.nz/business/farming/aquaculture/83055865/environment-court-declines-admiralty-bay-mussel-farm-applications; https://www.stuff.co.nz/business/104827048/king-shags-seal-the-fate-of-two-marlborough-mussel-farms

[6] https://www.marlborough.govt.nz/environment/coastal/coastal-ecosystems/significant-marine-sites-inventory-report-2011

[7] see glossary

2.1.2 Biogenic habitats

The extent and associated biodiversity of biogenic habitats before marine resource exploitation are not known. We can surmise from the identification of isolated pockets of reef habitat in recent benthic surveys (Davidson, Duffy et al. 2011, 2017, Anderson, Morrison et al. 2018) that the range must have been diverse including algal meadows, rhodolith beds, bryozoan beds, sponge gardens, *Galeolaria hysticx* (serpulid worm) reefs and shellfish beds. The extensive damage of these early biogenic reefs by sedimentation, dredging and bottom-trawling not only removed a benthic patchwork of filter-feeding organisms but also a complex array of interdependent species that inhabited the reefs. Information on the species diversity associated with these reefs prior to their destruction is scarce and can only be partially deduced from more recent data (see section 2.2.5).

We do not know whether these biogenic structures provided a critical settlement surface for green-lipped mussel larvae and if their destruction is part of the reason mussel beds have not recovered. We do know mussel larvae attach to seaweed from the mass stranding of this material on the Northland Coast which is the main spat source for the industry. It is therefore feasible that the algae meadows that once existed in Kenepuru Sound (c.f. Bull 1976 in Handley, Gibbs et al. 2017) served the same purpose as a settlement surface for larvae. Lack of recovery could also relate to the possible preference of larvae to recruit into established adult beds that once thrived on intertidal rocky and cobble areas.

This lack of knowledge makes it difficult to answer the question posed by Handley (2015): ‘Does the current extent of mussel farms and associated shell deposits have a broadly equivalent ecological role as benthic habitats to historical green-lipped mussel beds?’ Nonetheless we attempt to answer this question with the information we have at hand in Section 3.

2.1.3 Shellfish

Shellfish including the green-lipped mussel (*Perna canaliculus*), the blue mussel (*Mytilus galloprovincialis*), and the horse mussel (*Atrina zelandica*) were an important component of the diet of Māori prior to European settlement (Handley 2015 and references therein). It is likely that these shellfish were collected from the intertidal and shallow subtidal areas.

With the onset of European settlers, exploitation of this resource for commercial trade commenced, firstly with collections from the intertidal zone and then dredging with the first licence in 1961 (Dawber 2004). At this time green-lipped mussels in the Pelorus Sound were associated with broken shell reefs, rhodolith reefs (calcified red coralline algae), exposed rocky headlands or in clusters along cobble and boulder-strewn beaches (Handley 2015). Mussels formed a very thick carpet in the upper Kenepuru Sound, especially in Waitaria Bay (Handley, Gibbs et al. 2017) and green-lipped and blue mussels were found scattered throughout the inner Pelorus out to Beatrix Bay in the late 1960s and even harvested from the outer Pelorus at Forsyth Reef. Horse mussels dominated most dredge tows for mussels in the 1960s with a much lower number of dredge oysters.

By 1969 seabed dredging had led to most of the extensive intertidal and nearshore subtidal green-lipped mussel reefs being lost and conservation measures were put in place allowing only hand-picking. Even then a tonne of green-lipped mussels could be collected from Waitaria Bay during a single low tide (Chris Guard, pers. comm. in Handley 2015). A mussel survey in Kenepuru Sound in 1969 confirmed that commercial densities of wild stock mussel beds had been dredged out (Stead 1971a) leaving behind mud, broken shell and ‘a coral substrate’ (presumably rhodolith fragments) and a patchy distribution of mussels concentrated mostly inshore (Stead 1971b) (Figure 2-1). An upper estimate of area covered by mussels at this time could have been in the order of 2000 ha (Handley 2015).

However, a recent analysis of extracted deep sediment cores (2 m) from immediately inshore of the former wild green-lipped mussel reefs that existed in Kenepuru Sound until being harvested during the early 1960s to mid-1970s, showed a peak in mollusc shells from 1950 to 1974 (Handley, Gibbs et al. 2017) suggesting that perhaps these mussel beds did not exist prior to pre-European settlement. It’s possible that land-based activities such as the aerial application of superphosphate fertiliser from 1956 to 1975 to previously infertile land for sheep pastures increased nutrients in the local marine environment leading to higher phytoplankton production and hence more filtering shellfish (Handley, Gibbs et al. 2017). Besides green-lipped mussels, the deep cores contained the shells of at least eight other bivalve species.

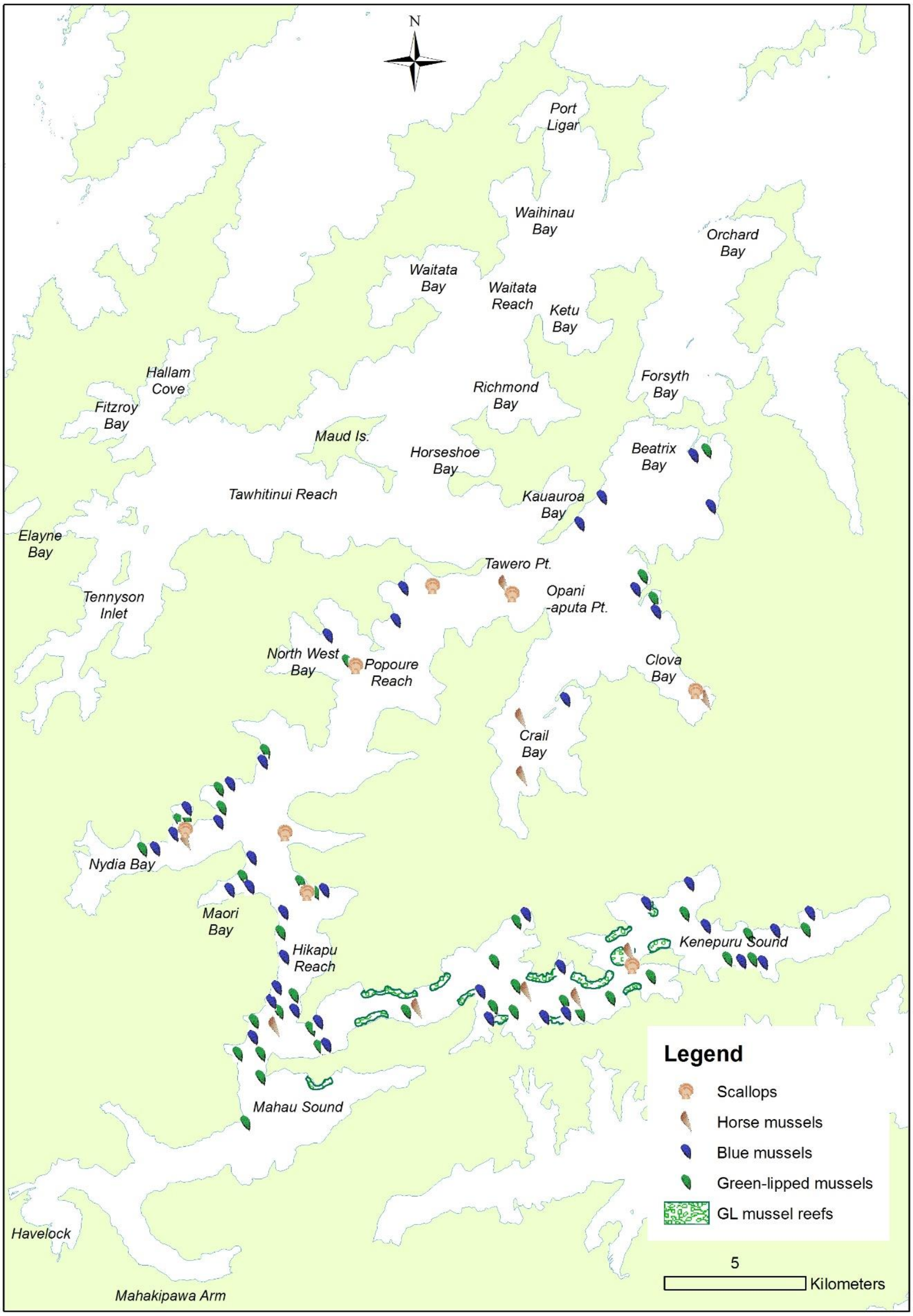

Figure 2-1: Historic shellfish beds from Pelorus Sound (excluding large scallop beds). Mapped by Sean Handley (NIWA) from information on surveys undertaken in 1969 (Stead 1971a, b; Davidson et al. 2011). GL = green-lipped. Copy of Figure 3-1, page 16, in Handley (2015).

We do not know to what extent mussels were associated with biogenic[8] habitats such as rhodolith reefs, algae meadows, sponge beds or serpuld tube mounds. There are anecdotal accounts of mussels being dredged with sponges (Handley 2016) and possibly rhodolith material (Handley 2015). We also do not know what densities of mussels, if any, were dredged with scallops in the central channels of Pelorus Sound and QCS. The surveys by Stead (1971 a, b) interestingly found that mussel recruits (<5 mm) were only evident among adults on rock substrate with no evidence of recruitment onto mud, stony, or 'shell-coral' substrate. This may indicate that mussel larvae prefer the micro-habitat offered between the adult mussel shells. We do know that green-lipped mussel spat recruit onto seaweeds as demonstrated by the stranding of drift algae covered in spat onto the beaches around Kaitaia. *Mytilus galloprovincialis* spat also attach to drift macroalgae (Carl et al. 2012) as well as recruiting to mussel beds. It is possible therefore that the same once occurred in the Sounds when nearshore algae meadows were more prevalent.

Extensive scallop beds were recorded in central deeper areas of Pelorus Sound around 1974 (Bull 1976, in Handley 2015). At this time scallop juveniles were attached to brown alga *Cystophora retroflexa,* red algae attached to horse mussels *Atrina zelandica*, and drifting seagrass *Zostera* debris, with spat not colonising mud and broken shell. Commercial scallop harvesting started after the collapse of mussel stocks (Dawber 2004) but in turn this fishery also crashed leading to closure ca. 1982, followed by a successful scallop enhancement programme which enabled the re-opening of the fishery. Other shellfish such as dredge oysters (*Tiostrea chilensis*) and horse mussels (*Atrina zealandica*), although not targeted by fishers, were incidental by-catch of benthic scallop dredging.

2.1.4 Fish

Bottom trawling for demersal fish stocks added to the damage caused by shellfish dredging. In the sounds' finfish (rig, pilchard, blue cod, flatfish, gurnard, kahawai, groper and snapper), shellfish and kina trawling led to reduction of seed stocks by 1939 and extensive damage to the seabed as well as kelp forests and crayfish associated with the kelp. Receding *Macrocystis pyrifera* forests were recorded since 1942 (Hay 1990). Demersal fish juveniles, like blue cod, are associated with biogenic reefs and damage to these complex heterogenous habitats has had a knock-on effect for fisheries stocks in the Marlborough Sounds (Cole 1999, Beentjes and Carbines 2012). As reported elsewhere in New Zealand and overseas, removal of apex fish predators and engineering species like crayfish and mussels can lead to "trophic-cascade effects", altering finfish species composition and benthic communities over time (Handley 2015). So even before mussel farming commenced in the sounds, the loss of hard surfaces upon which many invertebrate species settled directly and indirectly impoverished the communities preyed upon by several ecologically and economically important finfish species (Paul 2012, Morrison, Jones et al. 2014).

2.1.5 Seabirds and marine mammals

There is scant information on the population densities of seabirds and marine mammals in the Marlborough Sounds before mussel farming. It's likely that the abundance of seabirds declined after human settlement largely due to the introduction of rats and other predators of eggs and chicks as asserted for the Hauraki Gulf ecosystem where a decline of 69% was estimated for the seabird population over the last 1000 years (Pinkerton, MacDiarmid et al. 2015).

At the time of first human arrival in New Zealand in the 13th century, the fur seal population possibly numbered at least 2 million (Taylor 1992, Richards 1994, Cawthorn 2012). Fur seals likely frequented

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[8] – defined as those created by living plants (e.g. kelp forests, seagrass meadows) or animals (e.g. bryozoan thickets, sponge garden, tubeworm fields) where their three-dimension structure provides shelter, protection and resources for other marine flora and fauna

the sounds in search of prey and occupied non-breeding haul-outs as they do today, but it is not known if they established breeding colonies. Subsistence hunting by Maori followed by commercial sealing decimated the population and by 1946 sealing became commercially non-viable (Smith 1994). It is therefore likely that the number of fur seals in the sounds was greatly reduced during this time not necessarily because they were hunted inside the sounds, but because nearby colonies such as in the Cook Strait were decimated.

The Cook Strait is a gateway for marine mammals (cetaceans) moving between the North and South Islands and on to the Pacific region (Deanna Clement, Cawthron Institute)[9]. Humpback whales passed through the strait on their northern migration to Tonga from the east coast of the South Island to the west coast of the North Island, traversing past the entrances to the sounds in their journey (Norton 2018).

In the 19th century, the Cook Strait-Marlborough region was a centre of coastal whaling exploiting the large numbers of southern right whales that congregated in Cloudy Bay. In 15 years of intense whaling (1830-1845) the southern right whale stock was almost reduced to local extinction (Smith 1994). The global pre-whaling southern right population size may have been ca.100,000 and reached its lowest point in the 1920s, at around perhaps only 300 animals (Cawthorn 2012). By the 1930s right whaling was commercially nonviable and the species became fully protected by the International Whaling Commission in 1935[10].

The humpback whale stock sustained coastal whaling operations in New Zealand from the first decade of the 1900s until 1963. Numbers declined following heavy exploitation by international whaling fleets fishing legally and illegally in Antarctic waters which led to insufficient numbers of humpbacks migrating through Cook Strait to sustain commercial shore whaling (Kevin Oldham, pers. comm.). This species was protected from all commercial exploitation by the International Whaling Commission (IWC) in 1966 (Cawthorn 2012).

Whalers never recorded whales entering the sounds and all whaling was confined to the Cook Strait and the east coast the Marlborough District outside QCS and the Tory Channel (Norton 2018, Peranao 2018). However, on rare occasions migrating whales get lost and find their way into QCS. Nadine Bott, a Department of Conservation migratory whale research specialist, has said that after a few days they find their bearings and leave (Oldham 2017).

2.2 After mussel farms

2.2.1 Growth of mussel farming

In response to the depletion of commercial densities of wild mussels, farming trials commenced in 1969, with the first harvest of 7 tonnes in 1971 leading to a well-established industry a decade later (Dawber 2004). Today there are 3378 hectares of active mussel farms in the Pelorus Sound and 818 hectares in QCS[11] (Figure 2-2). The area consented for marine farming production is about 2.1% of the area of the Marlborough Sounds (mostly in the Pelorus Sound, Port Underwood and Admiralty Bay areas), and about 20% of the sounds is zoned for aquaculture (Coastal Zone 2 in Figure 2-2). Farms are mostly located about 50 to 80 m from the coastline in water of 15 to 30 m depth and the mussels are grown on ropes suspended 10 to 15 m from the surface along and between double longlines (the backbone) supported by buoys.

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[9] http://www.cawthron.org.nz/coastal-freshwater/news/2013/marine-mammal-monitoring-marlborough-sounds/

[10] https://iwc.int/south-pacific-southern-right-whale

[11] data supplied by Steve Ulrich, Marlborough District Council (MDC), September 2018

Mussel farming is based on the longline (backbone) float-system from which droppers (crop-lines) are suspended. The droppers are seeded with spat obtained from three sources: harvested from seaweed washed ashore at Ninety Mile Beach, captured on suspended Christmas tree ropes on spat farms and recently, on a small scale, from hatcheries (see Figure 3-8 in section 3.5.1). The spat grow on suspended nursery lines for 6 to 8 months before reseeding to reduce density and on-growing until harvestable size over the next 12 to 18 months. A three-hectare farm would typically have ten lines of 110 – 160 surface metres length each (MFA pers. comm.). Each line is supported by 50 to 70 large plastic floats. Each float may support one tonne of mussels. One 160-metre backbone line will generally support 3500 to 4000 metres of crop-rope (John Young, Clearwater Mussels, pers. com.).

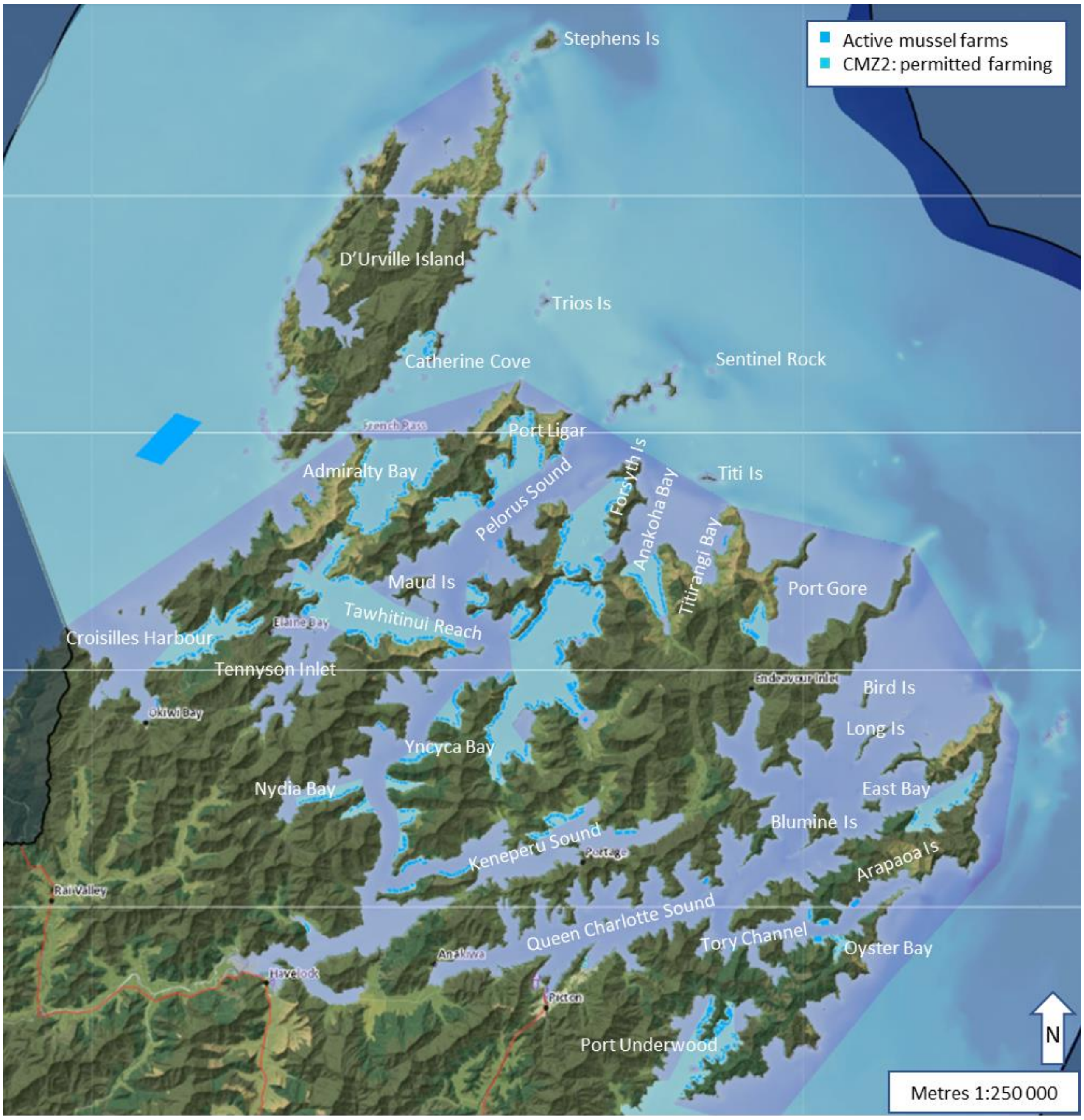

Figure 2-2: Location and extent of active mussel farms in the Marlborough Sounds. Active individual mussel farms along parts of the sound's coastline. Included are place names referred to throughout the document. The red lines demarcate areas closed to benthic trawling. *Adapted from MDC maps (https://maps.marlborough.govt.nz/smaps/?map=6af1f32120314f569f780dafba2647cf)*

Aquaculture reforms in 2004 placed a moratorium on the processing of new or farm-extension applications, to give councils time to undertake planning for the activity. Part of this process was the requirement to undertake bay-wide environmental assessments throughout the Marlborough Sounds, called Fisheries Resource Impact Assessments (FRIAs) (MPI 2013a) for the renewal of farm consents for the next 15 to 20 years. Many of these assessments, which considered UAE (Undue Adverse Effects)[12] on fisheries resources, were undertaken by NIWA and some of this information is used in sections 2.2.4 and 3.6.2.

As the industry has grown it has initiated several self-governing protocols that relate to both product quality and the growing environment. Shellfish quality assurance is assured through the industry-funded Marlborough Shellfish Quality Programme (MSQP)[13] which operates across the top of the South Island to monitor risks arising from biotoxins, diseases, bacteria and heavy metals. There are two parts to this programme: monitoring water quality and testing the quality of mussel flesh.

Concomitant with MSQP, the industry has developed an Environmental Code of Practice (best practice)[14] to minimise potential effects of mussel farming on the environment, inclusive of biosecurity monitoring[15], removal to land of all debris from farming activities and regular shoreline collection of waste from marine faming and other anthropogenic sources.

2.2.2 Activity pressures on water quality

The suite of pressures on water quality have changed since early 1900s and even since 1970 when mussel farming commenced. There have been diverse changes in the surrounding catchment (harbours, factories, holiday home developments, forestry, farming, oxidation ponds) with the concomitant risk of water contamination (heavy metals, pesticides, fertilizers, faecal bacteria and viruses) introduced by rivers, discharges, storm-water and run-offs. However, in parallel there have been changes that have reduced the impact of land-based activites: (a) fertilizer applications have greatly reduced following the withdrawal of government subsidies of the early 1970s and areas in use for terrestrial land farming have shrunk in the Marlborough Sounds; (b) the quality of wastewater treatment at Picton sewerage plant has been vastly improved since the days when raw sewage was dumped into QCS[16]; (c) the Picton freezing works closed in 1983, which likely released poorly treated, or untreated discharges; (d) the use of heavy metals in a range of industries, including as antifouling (tri-butyl-tin) has been prohibited, removing these anthropgenic sources and (e) long-lived pesticides such as DDT have been replaced by biomimics such an neonicotonoids with more subtle effects (Kevin Oldham, pers. comm.).

On-water activities have also changed (reduced commercial fishing and dredging pressure but increased recreational vessel traffic for fishing, touring and ferrying, moorings) with associated risks related to disturbance, biosecurity, oil spills and discharge of human waste etc. The MSQP has been effective in managing chronic effects such as bacterial contamination and toxic algae blooms (Campbell 2018, Davies, Hills and Carter 2018) to ensure farmed product quality. In addition, discharge is prohibited within 500 m of a marine farm (Clause 11 of the Resource Management (Maritime Pollution) Regulations 1998) and MEP is proposing this be extended to 1000 m in the sounds.

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[12] This assessment, known as the UAE test, assesses the effects of an aquaculture activity on commercial, recreational and customary fishing. The UAE test requires the effects of the aquaculture activity to not be undue in order for the activity to proceed.

[13] http://www.marinefarming.co.nz/quality.asp

[14] 14 http://www.environmentguide.org.nz/activities/aquaculture/

[15] http://www.marinefarming.co.nz/public/mfa-environmental-certification-programme/ & https://www.aquaculture.org.nz/environment/a/

[16] https://www.marlborough.govt.nz/services/utilities/sewerage/picton-sewerage-upgrade

On-water activities from salmon and mussel farming have received much attention from regulatory authorities and the public. King salmon (*Oncorhynchus tshawytscha*) have been farmed in the Marlborough Sounds for more than 25 years and presently there are two operational farms in Pelorus Sound and four in QCS. The discharge of greywater from farms is a permitted activity under the MDC resource management plan, and as such, there has been no monitoring of existing greywater quality or quantity. The estimation of greywater loads by Barter (2011) showed that salmon farm contribution is negligible compared to the myriad other point-source and non-point source discharges of similar constituents into the sounds. Mussel and salmon barges operate under a strict code of practice[17] whereby steps are taken to ensure that there is no discharge of contaminants such as oil, diesel, petrol or effluent into the marine environment.

Fish wastes and uneaten fish fed from salmon farms can increase suspended particulates and nutrients in the water column with potential effects on algal growth and reduced water clarity (Forrest, Keeley et al. 2007). Chlorophyll-*a* concentrations (proxy for phytoplankton) and dissolved oxygen concentrations are monitored monthly and to date no adverse effects on water quality have been established (e.g. Elvines, Knight et al. 2017). Hydrodynamic models developed by NIWA (Hadfield, Broekhuizen and Plew 2014; Broekhuizen, Hadfield and Plew 2015) suggest that the combination of wintertime light limitation, relatively rapid-flushing, and seabed denitrification make it unlikely that the current number of consented fish and mussel farms in the sounds are having a pronounced effect on nutrient levels in the ecosystem.

Aspects of water quality that relate to ecological parameters (dissolved nutrients, suspended particulates, chlorophyll-*a*, phytoplankton and zooplankton) are considered in Section 3.1.

2.2.3 Biosecurity issues

Vessel biofouling is the main mechanism implicated in most (c. 87%) of the marine pest introductions into New Zealand (Forrest 2018) and is also a vector for spreading non-indigenous species after arrival. The increase in vessel traffic in the Marlborough Sounds has significantly escalated biosecurity risks. Indeed, there are almost 2,000 vessels in marina berths in the Tasman, Nelson and Marlborough regions, and around 3,500 consented swing moorings, most of which (c. 3,100) are in Marlborough (Floerl, Fletcher and Hopkins 2015). The extent of vessel traffic was also demonstrated in a recent study on underwater noise in QCS that found the sole anthropogenic contributor to the soundscape was from vessel traffic, particularly from small vessels (Goetz and Hupman 2017).

Mussel farm structures pose a biosecurity risk by providing surfaces for the potential settlement of marine non-indigenous species that can rapidly multiply. Farms are therefore closely scrutinised for the clubbed tunicate *Styela clava* (Forrest 2013), the Japanese carpet sea squirt, *Didemnum vexillum* (Denny 2008; Pannell and Coutts 2007; Coutts and Forrest 2007; Fletcher, Forrest and Bell 2013), the Mediterranean fan-worm *Sabella spallanzanii* (Russell 2017), and the caprellid amphipod *Caprella mutica*, a native of northeast Asia (Willis et al. 2009). Only *D. vexillum* and *C. mutica* have been detected on mussel farms in the Marlborough Sounds. The former was first noted in Picton in 2001 and by 2007 had spread throughout the Marlborough Sounds and onto mussel farms but effective management at that time contained this species (Pannell and Coutts 2007). Caprellids were first detected in the Port of Timaru in 2002 and on farms in Pelorus Sound in 2008.

Styela clava, detected in Picton in 2013, poses the greatest threat to the industry because of its ability to over-settle and smother mussels and compete for food with shellfish and eat their larvae. A response management plan is in place (Forrest 2013) to suppress the clubbed tunicate population in Picton and prevent it from reaching mussel farms. The most recent detection of this species in the

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[17] http://www.marinefarming.co.nz/media/1070/industry-cop-reducing-pollution-on-water.pdf

Pelorus was on a vessel in Duncan Bay in 2015[18] and on the seabed in Nydia Bay in 2017[19]. *Styela clava* is still present around Picton.

The Asian kelp *Undaria pinnatifida* is a global invasive species and found throughout New Zealand except from the west coast of the South Island, and large areas of the North Island's west coast (Epstein and Smale 2017). It is common on mussel farms and can create difficulties with mussel harvesting operations if it is not removed beforehand (Sinner, Forrest and Taylor 2000). Until recently, *Undaria* from farms had to be taken to landfill but in 2010 MPI introduced a revised policy on the commercial use of *Undaria* which allows harvesting from structures and farming in selected heavily infested areas such as the Marlborough Sounds, Wellington, and Banks Peninsula.

There are also several globally distributed non-indigenous bryozoan and other ascidian species that colonise mussel farms (see Table 3-2) but these do not form extensive settlements.

2.2.4 Sedimentation and sediments

The source of the terrestrial sediments since the time mussel farming started in the Pelorus Sound has primarily been the Pelorus and Kaituna rivers, followed by subsoil from large slips, bracken from repeated land clearance associated with sheep farming, and pine-harvest soils which now dominatesurface sediments even under mussel farms (Handley, Gibbs et al. 2017). The SAR in the Pelorus has increased ten-fold post-European settlement, a rate marginally lower than that estimated for QCS (Handley 2016). A substantial part of this sediment becomes trapped within the Pelorus Sound due to hydrodynamics being shaped by river input from the head of the sound and ocean input at the mouth (Carter 1976). Sedimentation is greatest at the head of the Sound, and at the entrance where seston is delivered from the Cook Strait on flood tides (Bostock, Jenkins et al. 2018 and references therein).

Sediment becomes suspended throughout the sounds after heavy rains and transported seawards as was evident in a satellite image after three days of rain in July 2018 (Figure 2-3). At other times sediments are more likely to be suspended and widely dispersed in fast flowing locations with the ebb and flood tides and then settle out in slower flowing side bays (Hadfield, Broekhuizen and Plew 2014; Broekhuizen, Hadfield and Plew 2015). Therefore, the deposition of eroded sediment on the seabed depends somewhat on the hydrodynamics at a bay- and reach-scale (Urlich 2015). Sustained particulate loads greater than 26 mg/L can have negative impacts on filter feeding organisms such as sponges, oysters and mussels (Schwarz et al. 2006 in Handley, Gibbs et al. 2017), although loads this high are rare (Broekhuizen and Plew 2018).

Damage to biogenic reefs impacts sediment texture with fished areas having a higher silt–mud component, and less shell–gravel (Handley, Willis et al. 2014). This shift can be seen in the composition of sound sediments today. Grain-size evidence shows that Pelorus Sound sites have lower sand contents but that marginal bays were found to contain a full range of the sediment sizes - sand, silt, and clay (Handley, Gibbs et al. 2017).

A recent study updated more than 30,000 surface sediment data from NIWA and other international databases within the New Zealand Exclusive Economic Zone (EEZ) and extended continental shelf to generate a new database – nzSEABED (Bostock, Jenkins et al. 2018). The database was imported in to ArcGIS and layered maps were generated inclusive of the Marlborough Sounds (Figure 2-4, note caveats). These data show that within the sounds, sediments are dominated by mud (60– 100%). At the entrance flood tide dominates and transports sediment from Cook Strait into the sounds

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[18] https://www.stuff.co.nz/business/farming/75444100/marine-pest-hitches-ride-on-boat-to-pelorus-sound-in-marlborough

[19] https://www.marinebiosecurity.org.nz/project-map-all-data/

resulting in slightly more sand in this area (up to 40%). The higher gravel content of the outer sounds (20–60%) correlates with regions of high carbonate content at the entrance of the sounds (40–80%). Sampling of the mud has found abundant benthic organisms including ophiuroids, bivalves, gastropods, crustacea and holothurians (Estcourt 1967) and benthic foraminifera (Hayward, Grenfell and Reid 1997), which all produce carbonate shells or skeletons that contribute to the high carbonate content of the sediments.

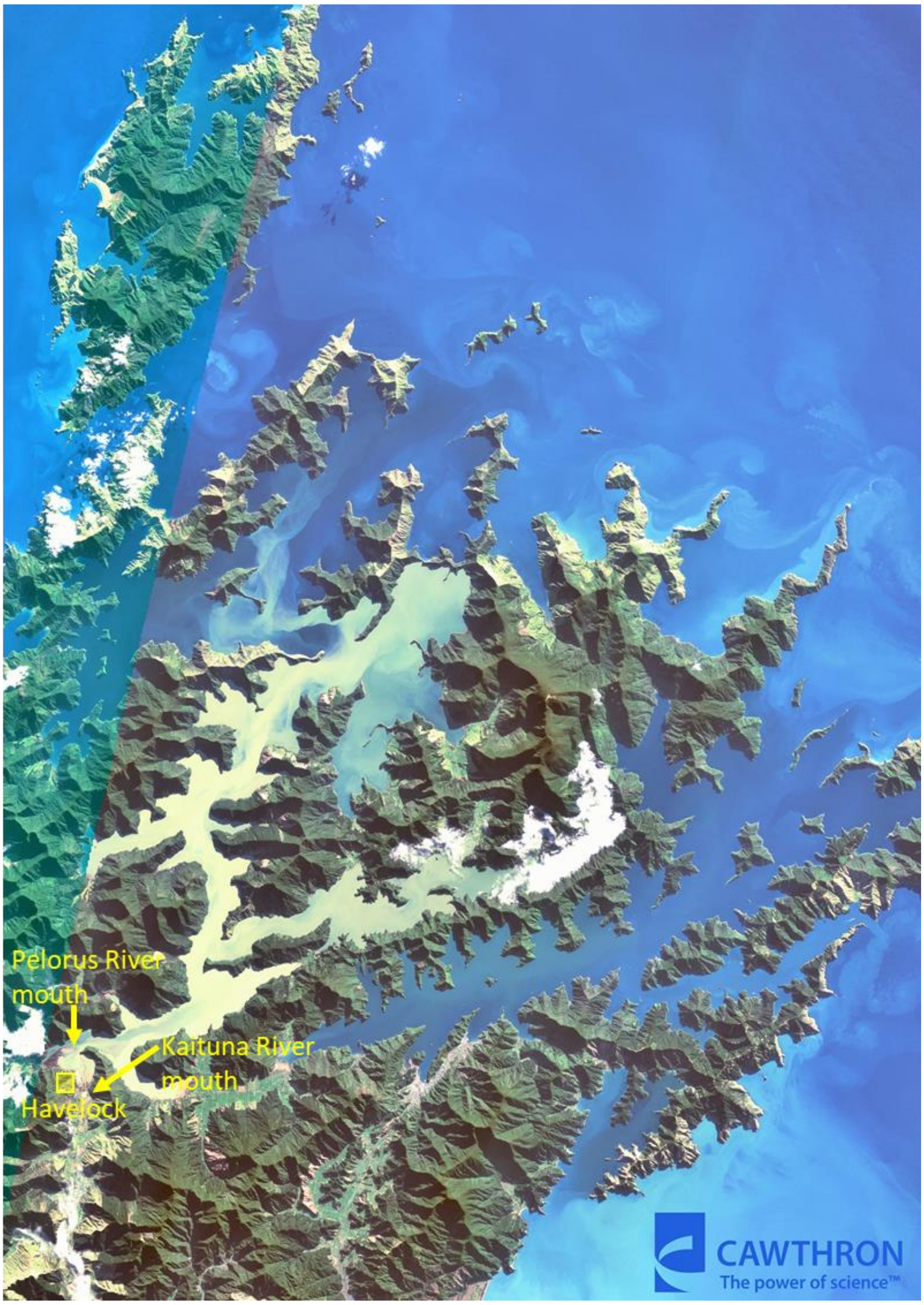

Figure 2-3: Sediment in Pelorus Sound after three days of heavy rain in July 2018. Supplied by Steve Ulrich, MDC. Original figure from the Cawthron Institute, Nelson.

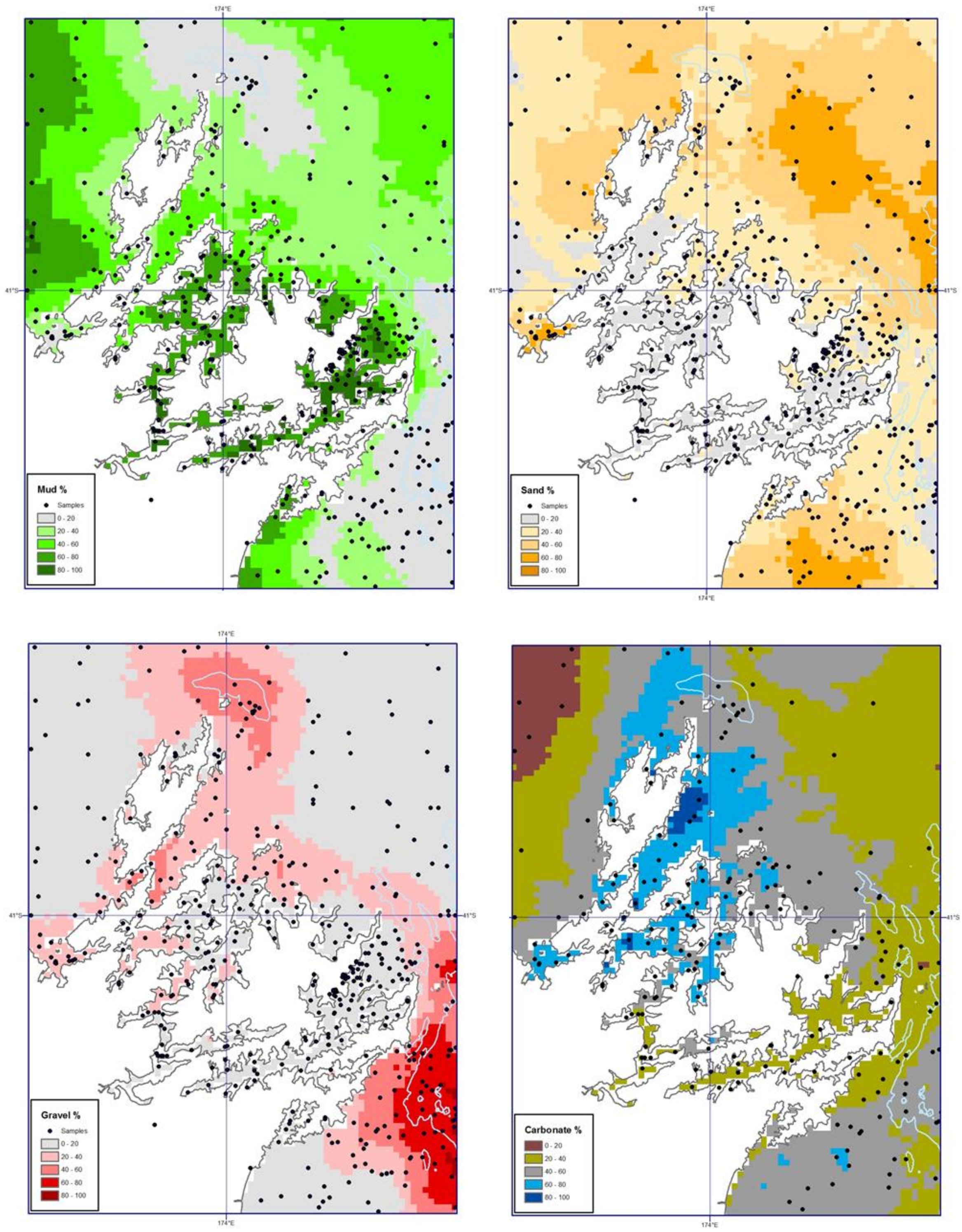

Figure 2-4: Seabed sediment characteristics of the Marlborough Sounds. Figure provided by Helen Bostock, NIWA, after Bostock, Jenkins et al. (2018). Several caveats should be noted; rocks are not included in this database; thus, the interpolated sediments will superimpose over rock outcrops; and the traditional methods for sampling sediments struggle to admit shell, pebble and cobbles and thus the methods are inherently biased against these larger grain sizes.

Mussel farms are mostly positioned over mud (i.e., silt and clay) sediments, 50 to 200 m from the shoreline. This substratum type is considered suitable for marine farming activities in the

Marlborough Sounds. We cannot be certain to what extent these areas once supported biogenic reefs but have now been reduced to vast muddy terrains by dredging and trawling. In section 3.4 we consider to what extent mussel farms may be a substitute for these destroyed reefs and former wild shellfish beds.

Data from the FRIAs undertaken by NIWA between 2004 and 2007 showed no consistent differences in mean sediment variables (grain size, organic content and redox depth) between areas inside farms and 50 m seawards of the farm boundaries (Figure 2-5). By example, across areas such as Beatrix/Crail/Clove Bays, the Pelorus channel and Admiralty Bay mean mud/silt fraction was 60 – 90%; medium grain sizes, 2 – 30%; coarse sediment, 10 – 25%; and organic content, 5 – 10%. In general, the discontinuity between oxic and anoxic sediment (the redox depth) was gradual and poorly defined in most samples and ranged between 23 – 36 mm inside and 45 – 50 mm outside, indicative of marginal organic enrichment under farms. In most cases, these slightly elevated levels of organic enrichment increase the productivity of coastal sediments without major disruption to seabed communities (Keeley, Forrest et al. 2009).

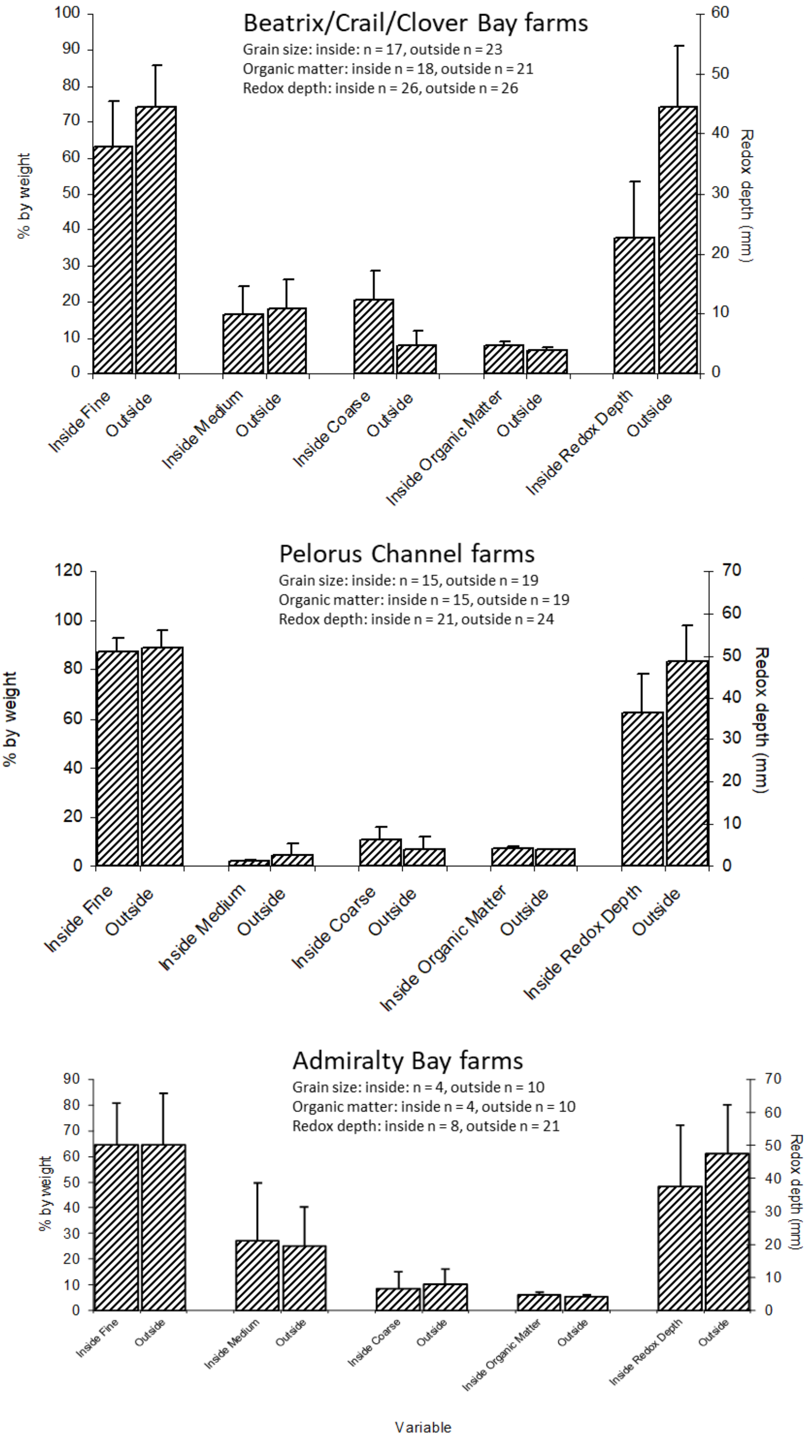

Figure 2-5: Mean values (95% CI) of sediment-related variables inside and outside mussel farms. Fine = silt/mud (%<63 µm), sand (%63-200 µm) and coarse (%>200 µm). The average estimates are obtained from all surveyed farms in each bay. Redox depth = the discontinuity between oxic and anoxic sediment. The outside samples were taken 50 m from the farm boundary. Data from NIWA FRIA reports.

2.2.5 Biogenic habitats today

There is little doubt that the distribution, abundance and composition of biogenic habitats has altered since the arrival of humans to the Marlborough Sounds. The lack of innate recovery of these habitats is likely a combination of fishing pressure, continuing high sediment accumulation rates (Davidson, Richards et al. 2010; Handley 2015, 2016) and the long recovery time for some of the fragile components such as rhodoliths which are long-lived and slow growing (Nelson et al. 2012 in Davidson, Richards et al. 2018). Removal of heterogenous, complex habitats leaves behind open mud/silt areas which favour the abundance of scavengers, predators and deposit feeders at the expense of filter feeders and grazers (Handley, Wills et al. 2014). High sediment accumulation is also conjectured to have serious consequences at the ecosystem level from indirect effects, through reduced epifaunal[20] abundance, as epifauna are responsible for about 80% of the flow of energy and materials through rocky reef animal communities (Taylor and Cole 1994).

Biogenic habitats contribute disproportionate numbers of species and are therefore key elements that support biodiversity (e.g. Nelson, Neill et al. 2012). In the last ten years increasing attention has been given to locating and identifying biogenic habitats in the sounds, which are now included in a list of 129 individual sites that support rare or special features and given the status of "Ecologically Significant Marine Sites (ESMS) in Marlborough"[21] (Davidson and Richards 2015, 2016, 2017; Davidson, Richards and Rayes 2017; Davidson, Baxter et al. 2015, 2016, 2017; Davidson, Duffy et al. 2011, 2013, 2014; Davidson, Richards et al. 2010, 2018). Threats to these special areas remain although recently (July 2018) all dredging for scallops has been suspended indefinitely[22]. In addition, recreational trawling for demersal fish is not permitted in the inner sounds and QCS (see Figure 2-2). However, a threat in exclusion areas is the dragging of anchors or anchor chains through delicate reef structures such as tubeworm mounds (*Galeolaria hystrix)* (Davidson, Richards et al. 2018).

Recent research by NIWA addressing the issue of juvenile fish habitats as 'bottlenecks' to increasing coastal fishery production for juvenile blue cod and tarakihi in the Marlborough Sounds[23] has added new knowledge on the location of biogenic habitats (Anderson, Morrison et al. 2018) and this has been advanced further by extensive seabed multibeam mapping of QCS (Neil et al. 2018). All information to date indicates that most of the remaining soft bottom biogenic reefs are to be found in isolated patches, often in proximity to headlands and islands where currents are stronger, and which have escaped the more intense fishing pressure and sediment smothering suffered in areas that provide fewer hazards to boating/fishing/mooring/dredging activities (Davidson et al. references, Anderson, Morrison et al. 2018). These reefs include algae meadows, rhodoliths, bryozoans, tubeworms, horse mussels and sometimes a combination of biogenic habitat-forming species such as ascidians, hydroids, sponges, anemones and bryozoans and relict shell (horse mussels and dog cockles) (Davidson, Richards et al. 2010; Morrison, Jones et al. 2014; Davidson, Baxter et al. 2016, Anderson, Morrison et al. 2018) (Figure 2-6). Most of these organisms comprising biogenic habitats are suspension / filter feeders.

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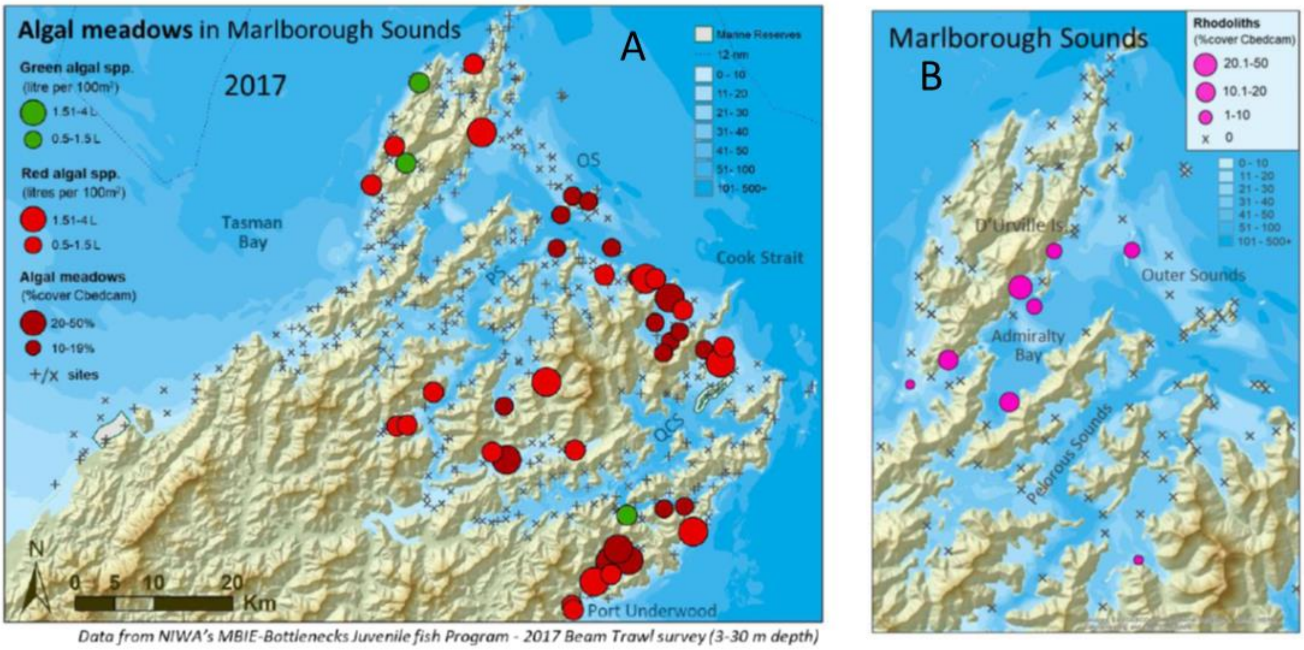
[20] see glossary

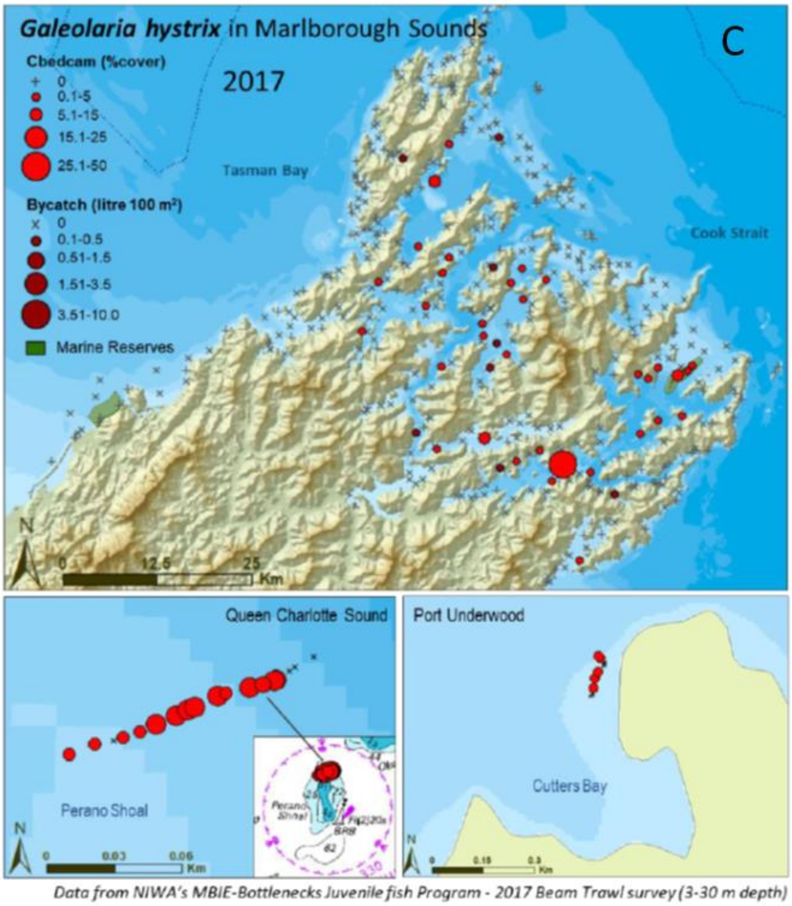
[21] https://www.marlborough.govt.nz/environment/coastal/coastal-ecosystems/significant-marine-sites-inventory-report-2011

[22] https://www.mpi.govt.nz/travel-and-recreation/fishing/fishing-rules/challenger-region-fishery-management-area/

[23] http://www.marlmarinefutures.co.nz/news/niwas-mbie-bottlenecks-programme/277417



Data from NIWA's MBIE-Bottlenecks Juvenile fish Program - 2017 Beam Trawl survey (3-30 m depth)



Data from NIWA's MBIE-Bottlenecks Juvenile fish Program - 2017 Beam Trawl survey (3-30 m depth)

A) Algae meadows: : Figure 3-19: Anderson, Morrison et al. 2018) sampled using beam trawls and video during NIWA's-MBIE Bottlenecks programme (C01X1618). Burgundy circles and + = Sites sampled using NIWA's high-definition CBedcam video system, where circle size represents % cover of algae on the seabed (as per legend). Red and green circles and x = Sites sampled by small (3-m wide) benthic beam trawl, where circle size represent the volume of algae caught in the net, divided by tow length and standardised to 100 m2.

B) Rhodolith beds: (Figure 3-23, Anderson, Morrison et al. 2018); mean percent cover recorded during NIWA's CBedcam benthic video sites. x = stations where no rhodoliths were observed.

C) Calcareous mound-building tubeworm, *Galeolaria hystrix* (Figure 3-52, Anderson, Morrison et al. 2018): Red bubbles = ranked % cover from underwater towed video; burgundy bubble = volume in litres of bycatch collected from 3-m wide beam trawl towed for 300 m. Data presented are from NIWA's MBIE-Bottlenecks Juvenile fish program - 2017 Beam Trawl and CBed-camera survey.

Figure 2-6: The distribution of biogenic reefs (algae meadows, rhodolith beds and tubeworm mounds) in the Marlborough Sounds. After Anderson, Morrison et al. (2018).

The remaining biogenic habitats and their associated epibiota provide a diverse suite of services that fall within both ecological services (services that benefit the marine ecosystem of the Marlborough

Sounds) and ecosystem services (services that benefit human wellbeing) (Table 2-1). Ecological services include (1) remineralisation of particulates by suspension feeders; (2) enhancement of benthic-pelagic coupling; (2) stabilise benthic sediments; (3) add complexity to the seabed topography; (4) formation of heterogeneous habitats that provide food, shelter and recruitment centres for marine species and (5) maintenance and/or enhancement of biodiversity. Many of these services overlap with ecosystem services but the distinction lies in the latter being viewed only for the benefit of humanity and being formally grouped into categories (see Appendix A; TEEB 2010; Haines-Young and Potschin (2013); Geange, Townsend et al. (2019)). The three broad categories applied here are: (1) *Regulating services*; (2) *Habitat and supporting services* and (3) *Provisioning services*. In section 3.4 we explore the parallels in these services with green-lipped mussel culture.

Table 2-1: Provision of ecological and ecosystem services by biogenic habitats in the Marlborough Sounds. Description of biogenic habitats, their biota and ecological services from Morrison, Jones et al. (2014); Anderson, Morrison et al. (2018) and references therein; Davidson, Baxter et al. (2016) references. ES categories from Geange, Townsend et al. (2019).

Biogenic Habitats and key species	**Associated taxa**	**Ecological Services (to the ecosystem)**	**Ecosystem Services (to humanity) (after Table 2 in Geange, Townsend et al. (2019))**
Red algal meadows *Stenogramma interruptum* *Gracilaria truncata* *Adamsiella chauvinii*	red and brown algae scallops tube worms (soft) sea cucumbers horse mussels brittle starfish	*modify water flow and sediment regimes *facilitate benthic-pelagic coupling *add to the detrital pool through fragmentation *provide living structure to a wide range of flora and fauna for food, refuge and recruitment (e.g. nurseries for fish, shellfish larvae) *support biodiversity	Habitat and supporting services: Primary production, habitat for species Regulating services: Carbon sequestration and storage, erosion prevention, local climate & air quality, waste water treatment Provisioning services: Food, raw materials, medicinal resources
Rhodoliths (calcareous red algae) *Sporolithon durum* *Lithothamnion crispatum*	algae encrusting sponges bryozoans boring polychaetes starfish anemones gastropods triplefins blue cod	*modify water flow and sediment regimes (add calcareous fragments to sediments) *facilitate benthic-pelagic coupling *add complexity to the seabed topography * form complex living and relict structures that provide refuge for a wide range of flora and fauna for food, refuge and recruitment (e.g. nurseries for fish, shellfish larvae) *support biodiversity	Habitat and supporting services: Primary production, habitat for species, sediment formation & composition Regulating services: Carbon sequestration & storage, erosion prevention, local climate & air quality, Provisioning services: Medicinal resources
Bryozoan thickets *Celleporaria agglutinans* *Galeopsis porcellanicus*	anemones hydroids nesting mussels colonial ascidians triplefin tarakihi	*remineralisation of organic matter through suspension feeding *sediment stabilisation (some species) and habitat-forming (adding to structural habitat complexity) for secondary species	Habitat and supporting services: Nutrient regeneration, habitat for species, sediment formation & composition Regulating services:

Biogenic Habitats and key species	**Associated taxa**	**Ecological Services (to the ecosystem)**	**Ecosystem Services (to humanity) (after Table 2 in Geange, Townsend et al. (2019))**
	blue cod	*provision of food to predators (generally micro-predators) *support biodiversity	Carbon sequestration & storage, erosion prevention, local climate & air quality Provisioning services: Medicinal resources
Bivalve beds dog cockles, *Tucetona laticostata* horse mussels, *Atrina zelandica* scallops, *Pecten novaezelandiae* green-lipped mussels, *Perna canaliculus*	algae bryozoans sponges hydroids ascidians brittle starfish scallops gastropods	*remineralisation of organic matter through filtering high volumes of water *facilitate benthic-pelagic coupling *altering the flow dynamics across the seabed *add complexity to seabed topography * reworking sediment as they move / burrow *modify and stabilise the sediments *modify neighbouring macrofaunal communities *provision of hard biogenic structures for epibiota to settle (e.g. Horse mussel beds support higher diversity and abundances) – increase biodiversity *provision of relict shell habitats: an important initiating-role that enables other biogenic habitats to colonise soft-sediment habitats – increase biodiversity * horse mussels can serve as nursery habitat for juvenile blue cod especially where bryozoan and sponge communities co-occur	Habitat and supporting services: Nutrient regeneration, habitat for species, sediment formation & composition Regulating services: Carbon sequestration & storage, erosion prevention, local climate & air quality, waste water treatment Provisioning services: Food, raw materials, medicinal resources
Calcareous tubeworm mounds *Galeolaria hystrix* (Family: Serpuliidae)	Polychaete worms (*Spirobranchus latiscapus*), burrowing anemones (*Cerianthus* sp.), octopus, blue cod, tarakihi, spotted wrasse, blue moki, pigfish, red cod, butterfly perch and triple fins	*modify water flow and sediment regimes (add calcareous fragments to sediments) *remineralisation through suspension feeding *facilitate benthic-pelagic coupling *add complexity to the seabed topography * form complex living and relict structures that provide refuge for a wide range of flora and fauna for food, refuge and	Habitat and supporting services: Nutrient regeneration, habitat for species, sediment formation & composition Regulating services: Carbon sequestration & storage, erosion prevention, local climate & air quality, waste water treatment

Biogenic Habitats and key species	Associated taxa	Ecological Services (to the ecosystem)	Ecosystem Services (to humanity) (after Table 2 in Geange, Townsend et al. (2019))
		recruitment (e.g. nurseries for fish, shellfish larvae) *support biodiversity	
Non-calcareous tubeworm *Spiochaetopterus sp.* *Acromegalomma suspiciens* *Owenia petersenae*	algae sponges scallop spat	*remineralisation of organic matter through suspension feeding *facilitate benthic-pelagic coupling *soft-sediment bioengineers *consolidate and stabilises sediments *habitat provision * support higher biodiversity in, on and around worm fields *an important food source to some fish species	Habitat and supporting services: Nutrient regeneration, habitat for species, sediment formation & composition Regulating services: Carbon sequestration & storage, erosion prevention, local climate & air quality, waste water treatment
Multispecies biogenic clumps	relict shells (cockle, horse) bryozoans ascidians sponges hydroids hermit crabs horse mussels dog cockles tarakihi blue cod sea perch	*remineralisation of organic matter by suspension feeding members of clumps *facilitate benthic-pelagic coupling *add complexity to the seabed topography * consolidate and stabilises sediments * modify neighbouring macrofaunal communities *provision of hard biogenic structures (relict and living shells) for epibiota to settle, shelter and feed *support biodiversity	Habitat and supporting services: Nutrient regeneration, habitat for species, sediment formation & composition Regulating services: Carbon sequestration & storage, erosion prevention, local climate & air quality Provisioning services: Medicinal resources

2.2.6 Shellfish

The surveys of biogenic habitats discussed above found no green-lipped mussel beds other than mixed biogenic beds with small isolated clumps of green-lipped mussels growing on the seabed on the northern side of Kenepuru Sound (Anderson, Morrison et al. 2018) but it is unclear whether these originate from nearby farms or represent naturally settled patches.

Handley, Gibbs et al. (2017) postulate that the wild populations of green-lipped mussels have not recovered because previous pathways for larval recruitment have been blocked by fundamental restructuring of the Marlborough Sounds marine ecosystem. Old recruitment surfaces such as the intertidal, cobble and nearshore biogenic reefs require other mussels to be present for the larvae to settle (new recruits grow between adults).

Mussel bed restoration efforts to increase green-lipped spat settlement (which has dwindled in the last five years in the sounds) are in the early planning stage with mussel farmers, equipment makers and science providers teaming up with the aim of returning mussels to the seabed in strategic locations around the Kenepuru Sound[24]. A similar situation exists in the Hauraki Gulf, where the Mussel Reef Restoration Trust was established in 2013 with the aim of restoring green-lipped mussel reefs[25]. In December 2013 the first seven tonnes of mussels were deposited in the Hauraki Gulf. These quickly congregated into contiguous mussel beds but after two years only 26% survived and with no sustainable recruitment being observed (Wilcox, Kelly and Jeffs 2018).

Intertidal blue mussels are relatively common in QCS with up to 80% cover when measured as part of ferry wake monitoring, whereas in Pelorus coverage is as little as 10% (Rob Davidson pers. comm. in Handley, Gibbs et al. 2017). However, blue mussels can be numerous on Pelorus green-lipped mussel culture droppers and are considered a pest biofouler by industry (Forrest and Atalah 2017; Atalah, Rabel, and Forrest 2017). Despite large inter-annual and spatial variability in recruitment patterns onto mussel farms, Atalah, Rabel, and Forrest 2017 found an upward trend in the abundance of *M. galloprovincialis* over the last 20 years.

Davidson, Richards et al. (2010) recorded horse mussels in relatively high densities forming biogenic habitat in Crail Bay, Clova Bay, inner Port Gore, around Motuarua Island and East Bay, QCS. In the outer sounds, beds have been reported from around the Trios, Titi and Chetwode Islands (Davidson, Baxter et al. 2016; Anderson, Morrison et al. 2018). Sparse horse mussels also occur throughout the sounds, but many of these show significant signs of shell damage (e.g., Guards Bank, Waitui Bay and Port Gore - where scallop dredge fishing has repeatedly been undertaken while rare patches of horse mussels are resigned to hollows on the seafloor, that may have provided refuge from past fishing activity) (Anderson, Morrison et al. 2018).

After the collapse of the scallop fishery in the sounds in 1982, an enhancement programme was initiated leading to large-scale reseeding of juvenile scallops caught from larval settlement in mesh spat bags suspended under marine farms, with landings again peaking by the late 1980s. However there has been a significant decline in scallop abundance over the past 10 years[26]. Scallop biomass in Golden and Tasman Bays collapsed in the 2000s and has remained at negligible levels since then. Biomass in the Marlborough Sounds followed a declining trend from 2009 to 2015 and a marginal increase to 2018. However, the overall biomass of scallops remains low and confined to relatively few beds in the outer sounds. Therefore, the fishery has been closedsince 2016 and recreational fishing suspended since 15 July 2018. Ongoing fisheries research is investigating the resilience and recovery of scallop fisheries (Tuck, Hewitt et al. 2017).

2.2.7 Fish

Based on a 33-year study netting fish in Duncan Bay, Tennyson Inlet (Bray and Struick 2006) and anecdotal information, Handley (2015) commented that the composition of fish populations in the sounds has changed, with reductions in especially larger predatory sharks (rig), with a notable increase in smaller sharks and that the changes recorded by Struik are an example of a trophic cascade. Handley (2015) continues: "*For example, it has been reported that the loss of large apex predatory sharks can lead to increasing numbers of smaller sharks and rays that top predators feed on (Myers et al., 2007). A similar trophic cascade is also very likely to have occurred in the rocky reef communities of Pelorus as a result of the reductions in snapper abundance and of lobster as noted by Clarke (2014). It has been shown in marine reserve studies that at fished locations without predation of lobster and snapper, kina populations increased and created grazed barrens, with reductions in the*

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[24] Aquaculture New Zealand Magazine, February 2018, at p 3. A copy is available here: http://www.aquaculture.org.nz/wp-content/uploads/2018/02/February-2018-Magazine.pdf.

[25] http://www.environmentguide.org.nz/activities/aquaculture/im:1738/im:1782/

[26] https://www.mpi.govt.nz/news-and-resources/consultations/temporary-closure-of-the-southern-scallop-sca-7-fishery-2/

extent of macroalgae and associated abundance of invertebrates and fish (Cole and Keuskamp,1998, Shears and Babcock, 2002; Shears and Babcock, 2003; Eddy et al. 2014)."

The collapse of the rig *(Mustelus lenticulatus*) fishery by the early 1970s supports the above viewpoint. Bottom trawling of this once dominant species in the sounds led to overfishing by 1974 with no rig stocks present from 1980 to 1988 followed by a small increase. The rig appeared to be replaced by short-lived species such as kahawai, flounder and grey mullet. Jones, Francis et al. (2015) established that there is no significant rig nursey in the Pelorus Sounds which means adults have not re-established in this area from offshore to spawn.

Nowadays, a number of fish have been recognised as being of ecological significance in the sounds,[27] all of which have the potential to interact with mussel farm systems: snapper, blue cod, groper (hapuku), elephant fish and rough skate.

Snapper (*Pagrus auratus*) can be found throughout the sounds where they are regarded as an iconic species by recreational fishers. Snapper can become a dominant or keystone predator and it is probable that their feeding activity impacts the abundance and distribution of prey for both soft and rocky shores. Crustaceans (crabs, shrimps, etc.) form the basis of the diet, but marine worms, starfish, sea urchins, shellfish and fish are also important. Their abundance in the area has been reduced compared to pre-1970's and the stock biomass for snapper in Tasman and Golden Bay was at low levels during the 1990s and early 2000s. However, since the late 2000s, biomass is estimated to have increased considerably, following the recruitment of several strong year classes (Langley 2018).

Blue cod (*Parapercis colias*) is the second most important recreational target species in the Marlborough Sounds and in Tasman/Golden Bay, after snapper (Beentjes and Carbines 2012; Beentjes, Page et al. 2018). They are found throughout the sounds but are most abundant around D'Urville Island, the Chetwood Islands, and the Cook Strait side of Arapaoa Island. They are mainly at the bottom of reef systems, at the general reef-sediment interface, or in biogenic habitat areas with juveniles <10 cm often preferring sand with a strong component of dead whole shell (Morrison, Jones et al. 2014) (Figure 2-7). Blue cod feed mainly on small fish and crabs. Stock abundance declined by one-third to a half between 1995/96 and 2001 in the inner Pelorus Sound which indicated that local depletion had occurred, and this area was closed to fishing from October 2008 to April 2011. Within two years biomass had increased and this stock is now managed on a seasonal basis (Beentjies, Page et al. 2018).

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[27] https://www.marlborough.govt.nz/environment/coastal/coastal-ecosystems/significant-marine-sites-inventory-report-2011

Figure 2-7: Juvenile blue cod within a biogenic habitat in the Marlborough Sounds. Credit Rob Davidson in MDC State of the Environment Report 2015: Coastal https://www.marlborough.govt.nz/environment/state-of-the-environment-reporting/state-of-the-environment-report-2015

Groper occur in large schools, small groups or as solitary individuals in a wide range of habitats including rocky reefs, canyons and flat, open sandy and muddy sea floor to depths of at least 400 m. Before they were heavily fished, groper was commonly found in shallow inshore waters and could be caught from the shore in some parts of their range. Historically they were regularly caught in the deeper parts of Queen Charlotte and Pelorus Sounds but they are now largely restricted to the outer Marlborough Sounds and Cook Strait. Around the South Island groper used to be most abundant in shallow water from October to May and moved offshore in June and July. Tagging has shown that groper around South Island tend to migrate north towards Cook Strait from July to September. Groper feed on a wide size range and variety of fishes, cephalopods (octopus and squid) and crustaceans (including rock lobsters). They also occasionally take small seabirds such as blue penguins. The Cook Strait region has always supported the main groper fishery, followed by the Canterbury Bight; both show the same slow decline from 1949 to 1986. Estimates of fishery parameters and present abundance are not available because of seasonal movements of hapuku through this area and moderately long-distance movements (Fisheries New Zealand 2018).

Elephant fish (*Callorhinchus milii*) appear to be recovering following over fishing in the 1970s and early 1980s. They are most often found on soft bottom habitats and spawning grounds (spring time) have been identified at several locations in Pelorus Sound; Garne Bay, Saville Bay, Kumutoto Bay and Grove Arm. They are demersal and feed mainly on shellfish.

The rough skate (*Zearaja nasuta*) breeds in the sounds; spawning occurs in inner QCS and Port Underwood; females lay pairs of eggs in leathery cases on the seabed which makes them vulnerable to disturbance and smothering by sediments. Skates are demersal and feed on fish, shellfish, crabs, and worms.

2.2.8 Seabirds

The “Ecologically Significant Marine Sites (ESMS)” project identified seabirds of importance to the Marlborough Sounds (Davidson, Duffy et al. 2011 and references therein, MDC website[28]) based on several criteria some of which are ecological status, ecosystem role, rarity and commercial, cultural or recreational importance. A summary follows on species that may have interactions with mussel farms and that will be referred to in the section on provision of services.

The number of Australasian gannets has increased since 1974 with two new breeding colonies in the sounds, one on the mainland in Waimaru Bay and a second colony established at Anatohia Bay, on the western shores of Arapaoa Island (outer QCS). They are regarded as a significant species in Marlborough because there are relatively few breeding areas in New Zealand. They are often seen in association with feeding dolphins.

The Fluttering shearwater is found on most rodent-free islands with the largest colonies on Trios and Long Island. They are regarded as a significant species in Marlborough because of their abundance and contribution to the fertility of the island ecosystems where they breed. This species is the most abundant shearwater in Marlborough and is often seen in large flocks inside and outside the sounds making it one of the most characteristic seabirds in the area.

The little penguin is found in the outer Sounds on Titi Island and within the Pelorus Sound on Maud Island. Their status is “declining” within New Zealand due to a variety of reasons including predation, disturbance and loss of breeding habitat. They are the only penguin in the Marlborough Sounds.

The Red-billed gull is endemic to New Zealand and there are two main breeding colonies in the Marlborough Sounds, one on Stephens Island and the other on Bird Island, Forsyth Bay. Their status is “nationally vulnerable” due to a recent decline in numbers, probably brought about by loss of food availability at sea.

Two shag species are encountered in the Marlborough Sounds, the spotted and king shag. The breeding colonies of spotted shag range from the Croisilles Harbour in the west throughout the sounds to Port Underwood in the east and although found all year round, they are most active from August to February. The number of breeding colonies in the sounds has trebled over the last 30 years.

King shag is endemic to the Marlborough Sounds and is classified as Vulnerable. Because of this classification and because questions have arisen regarding the effect of mussel farms on king shags, we discuss this species in some detail.

Breeding occurs between March and June and their diet is almost exclusively witch flounder (90%) and a left-eyed flatfish (Lalas and Brown 1998, Schuckard 2017). They are solitary feeders usually foraging within about 24 km of breeding colonies and are deep divers to depths of 20-40 m, rarely >50 m (Schuckard 1994, 2006 a, b; Lalas and Brown 1998; Butler 2003). Prior to 1992 the total population was estimated to be about 300 individuals and between 1992 and 2002, about 645 birds with around 92% of all birds occurring at Duffers Reef, North Trio Island, Sentinel Rock, and White Rocks, with an estimated 102-126 breeding pairs (Bell 2008; Schuckard, Melville and Taylor 2015 and references therein).

In 2015 the first aerial census of king shag was undertaken to fulfil the consent condition for the granting of salmon farms in Waiata Reach, a known feeding area for the Duffers Reef colony. The numbers were assessed to be 834 birds (Figure 2-8, Schuckard, Melville and Taylor 2015). In

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[28] https://www.marlborough.govt.nz/environment/coastal/ecologically-significant-marine-habitats

accordance with the New Zealand King Salmon (NZKS) king shag management plan (Schuckard 2015), a second aerial census was taken after three years (2018) and recorded a decline in the number of birds down to 634, about 200 fewer compared to 2015 (Schuckard 2018). In terms of the management plan, an annual aerial survey is now required until numbers are deemed to have stabilised.

Uncertainty whether the decline is attributable to a one-off event or by multiple key demographic parameters (e.g., cyclones, climate change, reduced immunity to infections and naturally-occurring population density changes or increased boat activity in general) is partially caused by historic underinvestment in the management of this species. If the surveys show an annual decrease of 3% or more, NZKS must investigate if their salmon farms are contributing to the decrease, and if so, put measures in place to prevent it. It is also uncertain whether a decrease in the bird's prey fish could be a cause because of trawling, dredging, sediment runoff or warmer water temperatures. An extreme weather event with big waves in August 2018 destroyed all the nests at the White Rocks colony in the Cook Strait[29].

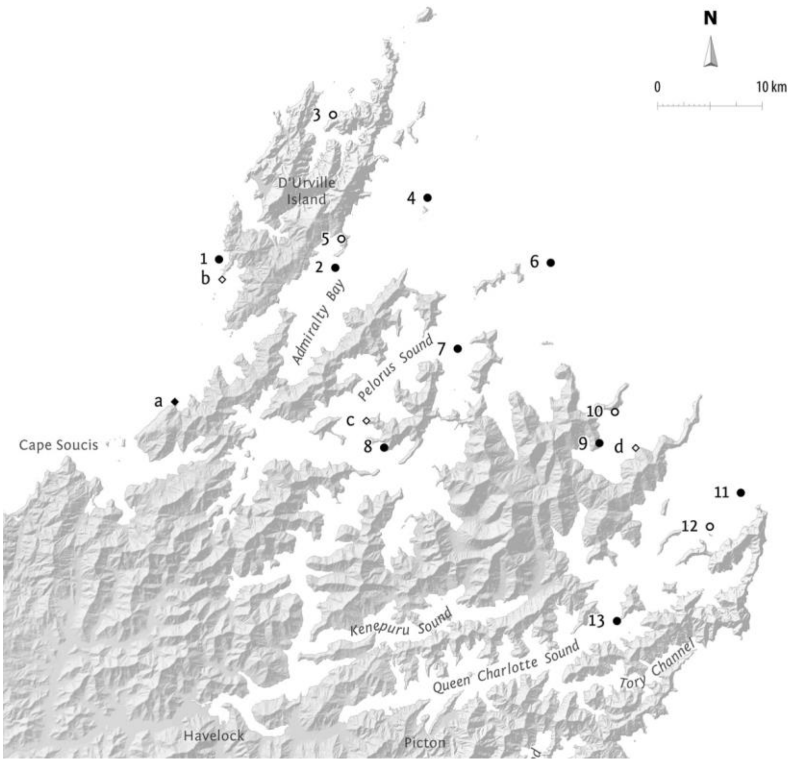

Figure 2-8: Location of breeding (number) and roosting (letter) sites of New Zealand king shags in the Marlborough Sounds recorded since 1951. Reproduced from Figure 1, page 210, in Schuckard, Melville and Taylor et al. (2015). (open symbol - abandoned, closed symbol - active). 1 - Rahuinui Island; 2 - Stewart Island; 3 - Squadron Rocks; 4 - North Trio; 5 - D'Urville Peninsula; 6 - Sentinel Rock; 7 - Duffers Reef; 8 - Tawitinui; 9 - Hunia Rock; 10 - Taratara; 11 - White Rocks; 12 - The Tnins; 13 - Blumine Island; a - Pahakorea Point; b - Hapuka Rock; c - Te Kaiangapipi; d - Blackhead Rock. A new roosting/breeding area was found in 2018 on eastern side of Forsyth Island (MFA, pers. comm.)

Uncertainty around effects on the king shag has been a regular feature of mussel farm consent applications, causing some mussel farm applications to be turned down. A new farm application in Beatrix Bay was declined in 2014 and two consents in the outer sounds were not renewed in 2018 as the farms were within 25 kilometres of three king shag breeding colonies[30]. In Admiralty Bay,

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[29] https://www.stuff.co.nz/marlborough-express/107393362/Rated-PG-King-shags-need-proud-parents-to-get-back-on-their-feet

[30] https://www.stuff.co.nz/business/104827048/king-shags-seal-the-fate-of-two-marlborough-mussel-farms?rm=m

applications for new farm space were declined on the same grounds together with the fact that this bay is a predominant feeding area for dusky dolphins[31]. However, an application for a 10.5-hectare mussel farm in the Kenepuru Sound was granted in July 2018 despite concerns raised about king shags as the consensus was that the birds do not feed in this area and there are no nearby breeding colonies[32].

The Department of Conservation (DOC) has developed a research project with MPI, MDC, NZKS and MFA to look at population dynamics, breeding biology and foraging ecology. As part of this research eleven fledgling chicks and one adult from the Tawhitinui colony were banded in August 2018 and will be monitored weekly (Aquaculture NZ 2018).

2.2.9 Marine mammals

All marine mammals are now fully protected under the Marine Mammals Protection Act 1978[33]. Several mammals have been recognised as being of ecological significance in the sounds,[34] some of which have the potential to interact with mussel farms.

The Cook Strait-Marlborough fur seal population increased at rates estimated up to 25% per year from 1970 to 1995 and was in a vigorous 're-colonisation' phase with the population size estimated to be 2410 individuals at this time (Berkenbusch, Abraham and Torres 2013; Cawthorn 2016 and references therein). Wherever possible, fur seals will haul-out on accessible coasts as close to their food sources as possible. In the Marlborough Sounds fur seals have established non-breeding haul-outs on accessible promontories close to salmon farms and in some instances will climb onto farm structures and onto mussel buoys. Fur seals appear to have become habituated or at least desensitised to the noise associated with shipping and vessel traffic and are not readily deterred by floating farm structures, lights, noise or human presence (Cawthorn 2012).

There are five species of dolphin encountered in the Marlborough Sounds; bottlenose, dusky, short-beaked common, Hector's and orcas. The bottlenose dolphin is estimated to have a population around 211 semi-resident individuals and these are thought to be part of a larger population of about 385 animals utilising the northern part of the South Island (Merriman, Markowitz et al. 2009). They are found throughout the sounds year-round with new born calves being observed during summer and autumn months. Bottlenose dolphins are thought to feed mostly on small schooling fishes and squid but there is very little diet information specific to the area (Davidson, Duffy et al. 2011). In general, they have a diverse repertoire of feeding behaviours and are highly adaptable foragers. Bottlenose dolphin is a significant species in Marlborough on conservation grounds and is classified as Nationally Endangered in New Zealand waters.

Dusky dolphins have been observed throughout the Marlborough Sounds, including Admiralty Bay, QCS and Tory Channel, Pelorus Sound and Croisilles Harbour. They are most common during winter and early spring months (Markowitz, Harlin et al. 2004). The population in Kaikoura is estimated to be about 2000 at any one time, from a total South Island east coast population of over 12,000 (Markowitz, Harlin et al. 2004; Würsig, Duprey and Weir 2007). Admiralty Bay is now recognised as an important feeding area for some overwintering dolphins (around 220 individuals) that are found off Kaikoura during the summer. Feeding in Admiralty Bay occurs during daylight hours, with primary targets being small schooling fishes e.g. pilchards. Feeding behaviour is highly coordinated, with dolphins herding fish into bait balls, often during multi-species feeding bouts with other species including fur seals, gannets, shearwaters (Vaughn, Würsig et al. 2008) and king shags. On four

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[31] https://www.stuff.co.nz/business/farming/aquaculture/83055865/environment-court-declines-admiralty-bay-mussel-farm-applications

[32] https://www.stuff.co.nz/business/105735319/king-shag-argument-doesnt-fly-for-mussel-farm-commissioners?rm=m

[33] http://www.legislation.govt.nz/act/public/1978/0080/latest/DLM25111.html

[34] https://www.marlborough.govt.nz/environment/coastal/coastal-ecosystems/significant-marine-sites-inventory-report-2011

occasions dusky dolphins have died after being entangled in salmon farm nets in Pelorus Sound (Crail Bay (Cawthron 2016), Waihinau Bay and Kopaua[35].

Common dolphins are the most frequently encountered dolphin species in New Zealand waters being distributed along the entire coastline of the North and South Islands and Stewart Island. This species exhibits seasonal inshore-offshore movements that have been related to seasonal prey availability of small schooling fish and squids, including epi-pelagic species (Berkenbusch, Abraham and Torres 2013). In the Marlborough Sounds region, common dolphins are seen near D'Urville Island, Admiralty Bay, outer Pelorus Sound, Tory Channel and around the northern entrance to QCS. While the common dolphin may be relatively abundant in New Zealand waters, there is an unquantified by-catch issue that exists largely in the jack mackerel trawl fishery through Cook Strait and off the west coast of the North Island (du Fresne, Grant et al. 2007).

Hector's dolphins have a patchy distribution nearshore around the South Island and in Marlborough they are encountered in QCS. Groups ranging from 1-50 individuals were recorded most frequently in the middle reaches of QCS and are concentrated in the area around Blumine Island (Cawthorn 2016 and references therein). These dolphins are possibly a sub-group of a sub-population of about 950 found in nearby Clifford and Cloudy Bays (McKenzie and Clement 2014). Hector's dolphins feed on a variety of fish including mid-water and bottom dwelling species such as red cod, ahuru, arrow squid, yellow-eyed mullet, stargazer, sole, hake and hoki (Dawson 2009; Dawson and Slooten 1996).

Passive acoustic monitoring in QCS from July - December 2016 detected Hector's dolphins on 38% of the recording days with peak activity in mid-July, mid-August, and October with few detections between and after these periods. The restricted range of Hector's dolphins combined with the limited listening radius of the recorder suggests that the numbers of individuals in the area is probably less than 20 (Goetz and Hupman 2017). Hector's dolphin is a significant species on conservation grounds having a Nationally Endangered status.

Killer whales (orcas) are top predators and forage for rays along rocky shores on both sides of Cook Strait and in the Marlborough Sounds. They also feed on marine mammals, seabirds, sharks and fish (Visser 2007) and have known to arrive off the Stephens Island fur seal rookery in Cook Strait in early winter as weaned fur seal yearlings begin to leave (Cawthorn 2012). Sightings of killer whales near salmon farms may be as much to do with the abundance of either fur seals or stingrays in the area rather than salmon (Cawthorn 2016). Killer whales are extremely manoeuvrable and have never been recorded entangled in New Zealand. There is a resident population (132 in 2006, Visser 2007) that is augmented by seasonal migrants from the Ross Sea that travel to New Zealand to overwinter (Eisert, Ovsyanikova et al. 2015).

There are two whale species that have a presence around the Marlborough Sounds, the southern right whale and the humpback whale. They are occasionally seen during their winter migrations as singletons, or as a female with a calf, mostly within Cook Strait or along the east coast.

Humpback whale stocks have been recovering at rates of 10% in South African, Australian and South American waters. However, there is no evidence of recovery for populations in Oceania, where there may be as few as 2,000 animals[36]. The average number of whales recorded per annum in surveys in the Cook Strait from 2004 to 2016 was 58 (range 15-137). Of all baleen whales, humpbacks are the species most frequently involved in entanglements with craypot buoy lines. In July 2011 a single humpback entangled in craypot buoy lines had floats attached to its tail by DOC staff and these floats

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[35] https://www.stuff.co.nz/national/108920343/divers-find-dead-dolphins-in-new-zealand-king-salmon-nets

[36] https://iwc.int/status 2018

became entangled in a mussel-rope buoy line when the whale entered Tory Channel (Cawthorn 2016). The IUCN classifies humpback whales as being of “Least Concern” globally whereas since 2008 humpbacks have been classified in New Zealand as Endangered.

The New Zealand population of southern right whale appears to be increasing, based on a mark-recapture study of individuals[37]. During the breeding season in winter and spring, they are mostly found in the waters around the sub-Antarctic Auckland and Campbell Islands, but they are occasionally seen close inshore. A few sightings have been recorded in waters around the Marlborough Sounds (Cawthorn 2012 and references therein): four sightings (around 2002), 19 right whale observations between 1991-2001, seven observations between 2009-2010. Although right whales have a propensity to rub and scratch themselves on anchor chains and warps, there has never been any recorded adverse incident involving right whales with aquaculture farms in New Zealand. Possible reasons for this are that operating regulations discourage the presence of loose-ended lines, prohibit the dumping of cordage and other waste into the sea, and anchor warps are always taut and well-spaced (Cawthorn 2012, 2016).

A present research project (Cawthron, Deanna Clements)[38] is investigating the perception that marine mammals leave the sounds area when boat traffic increases in summer. While their research has confirmed there are fewer species in the sounds around this time, it is unclear if it is related to boat interference or natural movements.

3 Provision of ecological and ecosystem services by mussel farms

In our assessment of service provision by mussel farms we make a distinction between ecological services - EcolS - (services that benefit the marine ecosystem of the Marlborough Sounds) and ecosystem services – ES - (services that benefit human wellbeing). This distinction is necessary because the important milestone of ES research was the Millennium Ecosystem Assessment (MA 2005)[39] which made prominent the idea that human well-being depends on ecosystems, and that such linkages can be tracked and framed through the notion of ecosystem services. The MA found that more than 60% of ES are being degraded or transformed endangering future human well-being and to address this, the ES framework is now widely used among scientists and policy makers to highlight the importance of the ecosystems in sustaining human livelihoods.

Since MA-2005, ES research has evolved substantially, and definitive terminology has evolved to describe ES in marine ecosystems (see Appendix A, TEEB 2010, Haines-Young and Potschin 2013, Geange, Townsend et al. 2019, Gentry, Alleway et al. 2019). There are four broad categories for classifying ES: (1) *Regulating*, which encompasses services that regulate the environment such as improving water quality through sequestering suspended particulates, nitrogen and carbon; (2) *Habitat and Supporting*, which includes physical creation of habitats, habitat provision for species and maintaining diversity; (3) *Provisioning*, meaning the production of food, water or other goods and (4) *Cultural*. We address the first three categories and refer to cultural aspects where necessary. A recently published digital book edited by Smaal, Ferreira et al. (2019) presents comprehensive reviews and analyses of the goods and services of both cultured and wild bivalves wherein a distinction is made between ecological and ecosystem services.

Geange, Townsend et al. (2019) in their study on the ES of natural biogenic reefs in New Zealand included primary production and nutrient regeneration as important ‘intermediate’ services and a

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[37] https://www.doc.govt.nz/nature/native-animals/marine-mammals/whales/southern-right-whales-tohora/

[38] http://www.cawthron.org.nz/coastal-freshwater/news/2013/marine-mammal-monitoring-marlborough-sounds/

[39] https://www.millenniumassessment.org/en/index.html

prerequisite of other ‘final’ services under *Habitat and Supporting* services (see Appendix A). These ES underpin marine food webs and are thus included in our review.

A further reason for making a distinction between EcolS and ES is our endeavour to assess to what extent mussel farms return ecological services to the Marlborough Sounds that are akin to those offered by the former natual shellfish beds and biogenic reefs. We use the ES categories in our EcolS assessments but make a distinction under these categories between EcolS and ES.

3.1 Regulating services

In this section we focus on *Regulating* services, which encompasses services that regulate the environment such as improving water quality through sequestering suspended particulates, nitrogen and carbon. We draw on inferences from historical water-quality data from the Marlborough Sounds.

Marlborough District Council initiated a formal water-quality monitoring programme for Pelorus Sound in July 2012, but numerous prior studies of Pelorus Sound have included measurements of water-quality. They measure concentrations of nutrients, chlorophyll-*a* and suspended solids (inorganic and organic)[40]. Many of those were one-off surveys but a small number repeatedly occupied the same stations over prolonged periods of time. By combining data from several studies (Table 3-1) it is possible to generate composite time-series that stretch back at least to the mid-1990s (and, in the case of Schnapper Point, to the early 1980s) at four different candidate sites (outer Pelorus, west Beatrix Bay, Laverique Bay (east Beatrix) and Schnapper Point (Kenepuru Sound)) (Figure 3-1). Inevitably, however, each composite time-series contains numerous missing values. These comprise: (a) long periods during which there was no sampling, and (b) missing values arising from the fact that the NIWA1997 samples were collected weekly, whilst other programs sampled less frequently.

In this report, we will focus upon data related to water-clarity (turbidity and total suspended solids) We seek to determine whether these properties exhibit any substantive changes (trends) and endeavour to determine what might have caused any inter-annual fluctuations (and/or long-term change) and how these might relate to mussel farming in the sounds in terms of EcolS and / or ES. Details of our statistical methods are presented in Appendix B.

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[40] The particulates (incl. chlorophyll-*a*) are those that are retained on a GF-C filter – which has a nominal pore-size of 1.2 µm

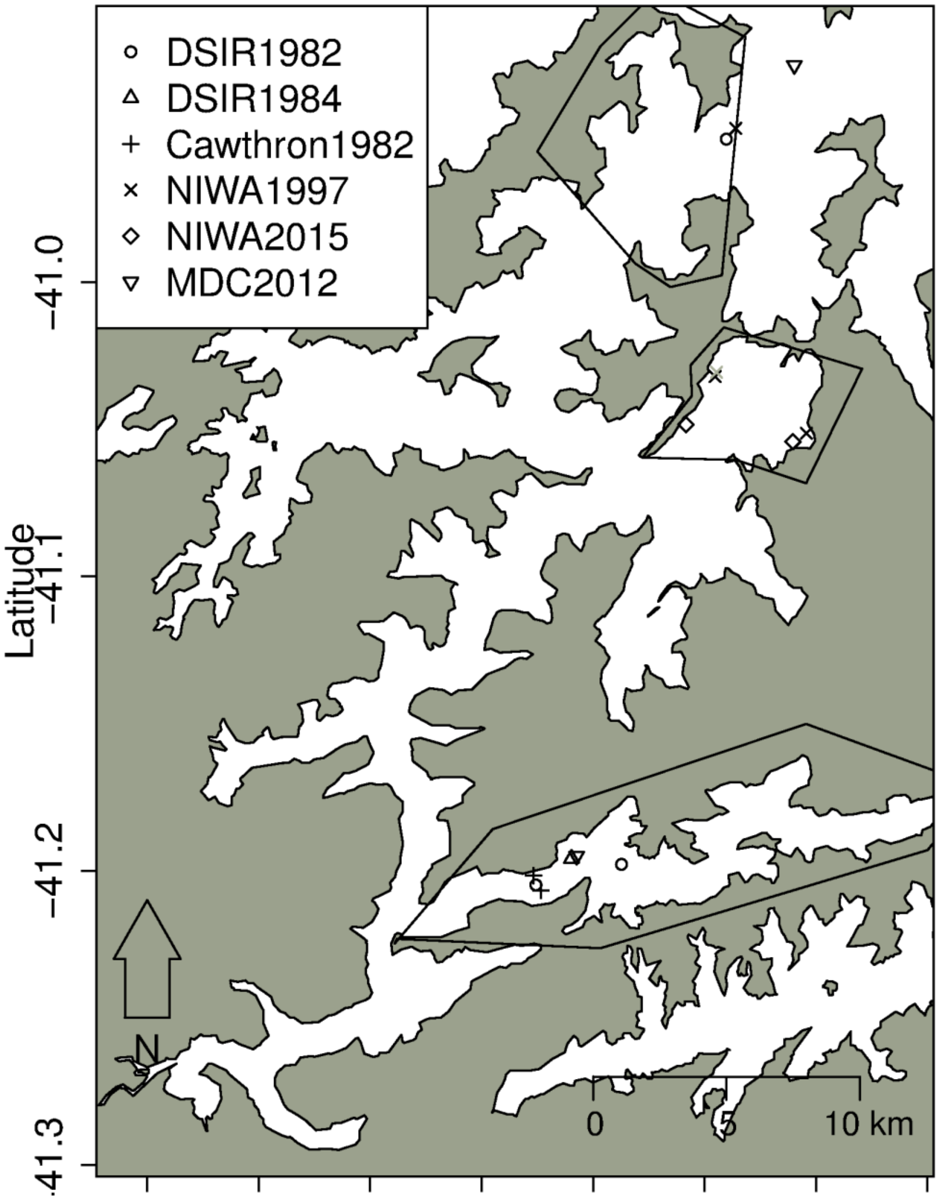

Figure 3-1: Study sites which contribute to the composite time-series. See Table 3-1 for details of the studies alluded to in the legend of this figure.

Table 3-1: Summary details for the sources of water-quality data used in this study. See Figure 3-1 for site-locations. Very recently, an additional data-set (described in MacKenzie, 2018) has been published. They span the period 1986-1989. Dr MacKenzie has recently made those data available to us, but we have not yet been able to incorporate them into the analysis described here.

Study name	Time-span and sampling frequency	Composite time-series to which these data contribute	References	Laboratory Methods	Comments
DSIR1982	Data from July 1981 & May 1982	Schnapper Point	(Bradford, Chang et al. 1987)		No chlorophyll-*a* data.
Cawthron1982	October 1982, January 1983	Schnapper Point	(Kaspar, Gillespie et al. 1985; MacKenzie, Kaspar and Gillespie 1986)	Chlorophyll-*a* and particulates caught on a GF-C filter. Chlorophyll-*a*: acetone digestion and spectrophotometry;	
DSIR1984	1984-1985, bi-monthly, 7 sampling occasions	Schnapper Point	(Gibbs, James et al. 1991; Hickman, Waite et al. 1991; Gibbs, Pickmere et al. 1992)	Chlorophyll-*a* and particulates caught on a GF-C filter. Chlorophyll-*a*: acetone digestion and spectrophotometry; PC: high temperature combustion; PN Kjedahl digestion NOx-N by cadmium reduction. NHx-N by phenol-hypochlorite	We use data from some of the transect stations described in (Gibbs, M.M., James et al. 1991)
NIWA1997	1997-2010, weekly or fortnightly	Schnapper Point, West Beatrix, Laverique, Outer Pelorus	(Gibbs, Ross and Downes et al. 2002; Zeldis, Howard-Williams et al. 2008; Broekhuizen 2013)	Chlorophyll-*a* and particulates caught on a GF-C filter. PC and PN by high temperature combustion (Carlo Erba NC2500 elemental analyser), Chlorophyll-*a* by acetone extraction and spectrophotometry. Nutrients by AlpKern series 500 autoanalyzer.	Several stations were sampled – each for differing time-spans (most for only one-two years). We examine data from stations which were sampled for longer-periods.

Study name	Time-span and sampling frequency	Composite time-series to which these data contribute	References	Laboratory Methods	Comments
MDC2012	July 2012-present, monthly	Schnapper Point, Outer Pelorus	(Broekhuizen and Plew 2015)	Chlorophyll-*a* and particulates caught on a GF-C filter. PC and PN by high temperature combustion (Carlo Erba NC2500 elemental analyser), Chlorophyll-*a* by acetone extraction and spectrophotometry. Nutrients: to June 2017 Astoria autoanalyzer; subsequently SEAL autoanalyzer by Astoria autoanalyzer	There are seven water-quality stations in Pelorus Sound. We use data from three of the stations.
NIWA2015	July 2015-present, monthly	West Beatrix, Laverique	-	Chlorophyll-*a* and particulates caught on a GF-C filter. PC and PN by high temperature combustion (Carlo Erba NC2500 elemental analyser), Chlorophyll-*a* by acetone extraction and spectrophotometry. Nutrients: to June 2017 Astoria autoanalyzer; subsequently SEAL autoanalyzer by Astoria autoanalyzer	We restarted sampling at two of the NIWA1997 stations (West Beatrix Bay, Laverique Bay).

3.1.1 Sequestration of suspended inorganic sediment to the seabed

Mussels capture their food by filtering the water that they pump across their gills. The initial filtration/capture process operates primarily on a particle size-basis. Green-lipped mussels readily capture particles in the size-range 2-200 µm (approximately, e.g., Safi and Hayden 2010) [provided only that the particles are not sufficiently motile to evade feeding currents]. If the particles are within the right size range, mussels will capture suspended inorganic particulates as readily as organic ones. The ISO 14688-1:2002 classification scheme defines clays to be inorganic particles <=2 µm. Similarly, fine silts span the range 2-6.3 µm, medium silts 6.3-20 µm, coarse silts 20-63, and fine sands 63-200 µm. Thus, mussels are capable of readily capturing larger clays, silts and smaller sands. They ingest relatively little of the inorganic matter into their gut. Rather, the majority is expelled as mucous-coated particles (so-called pseudo-faeces). Even that which does enter the gut is later expelled as faecal particles. Both types of particle sink comparatively quickly (pseudo-faeces: 0.1-4.0 cm s^{-1}, faeces: 0.2 – 4.3 cm s^{-1}: Giles and Pilditch 2004). In the absence of resuspending vertical currents and eddies most (pseudo-) faecal particles will settle to the seabed in less than an hour in a water-column that is 30 m deep. Even assuming moderately high horizontal current velocities (0.2 m s^{-1}), this implies that most particles will first sink to the seabed within a few hundred metres of the droppers. Collectively, these observations suggest that suspended-rope aquaculture may have the potential to scavenge suspended sediment out of near-surface waters and divert it towards deeper parts of the water-column (or even the seabed). That said, it is not clear that such particles will remain on the seabed indefinitely: the laboratory studies discussed above (Giles and Pilditch 2004) also revealed that fresh particles eroded from the seabed at moderately low bed shear velocities (around 0.15-0.6 cm s^{-1}).

Long-term records of turbidity and suspended sediment in Pelorus Sound

The time-series of total suspended solids concentrations measured at outer Pelorus, west Beatrix, Laverique and Schnapper Point are illustrated Figure 3-2. The figure also shows time-series of river-flow, one relevant climate index (Nino-3.4) and approved mussel farm area within each bay. Figure 3-3 shows similar plots for turbidity. Clearly, both total suspended solids and turbidity tend to decline as one moves from the inner sound (Schnapper Point) to the outer sound. Furthermore, all sites show substantial high-frequency fluctuations. The signs of the long-term Sen-slopes[41] for turbidity are positive at three sites (outer Pelorus, west Beatrix and Schnapper Point) and negative at the fourth (Laverique). For total suspended solids, the Sen-slopes are positive at all four sites though the confidence bounds for encompass zero for west Beatrix and Laverique. The signs of the long-term Sen-slopes for turbidity are positive at three sites (outer Pelorus, west Beatrix and Schnapper Point) and negative at the fourth (Laverique). Again, however, the confidence bounds for the slopes at West Beatrix and Laverique encompass zero. Note in particular, that whilst the total area of marine farms in the vicinities of each ‘site’ have increased substantially over time, the long-term trends for suspended solids and turbidity have (if anything) tended to trend upward at the majority of sites.

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[41] The Sen slope is the median of the linear slopes calculated for all pair-wise combinations of points Akrita, M. G., S. A. Murphy and M. P. LaValley (1995). "The Theil-Sen estimator with doubly censored data and applications to astronomy." Journal of the American Statistical Association **90**(429): 170-177. It is regarded as a robust estimator of any linear long-term trend. It is less sensitive to outliers and missing data than the least-squares linear regression slope estimate.

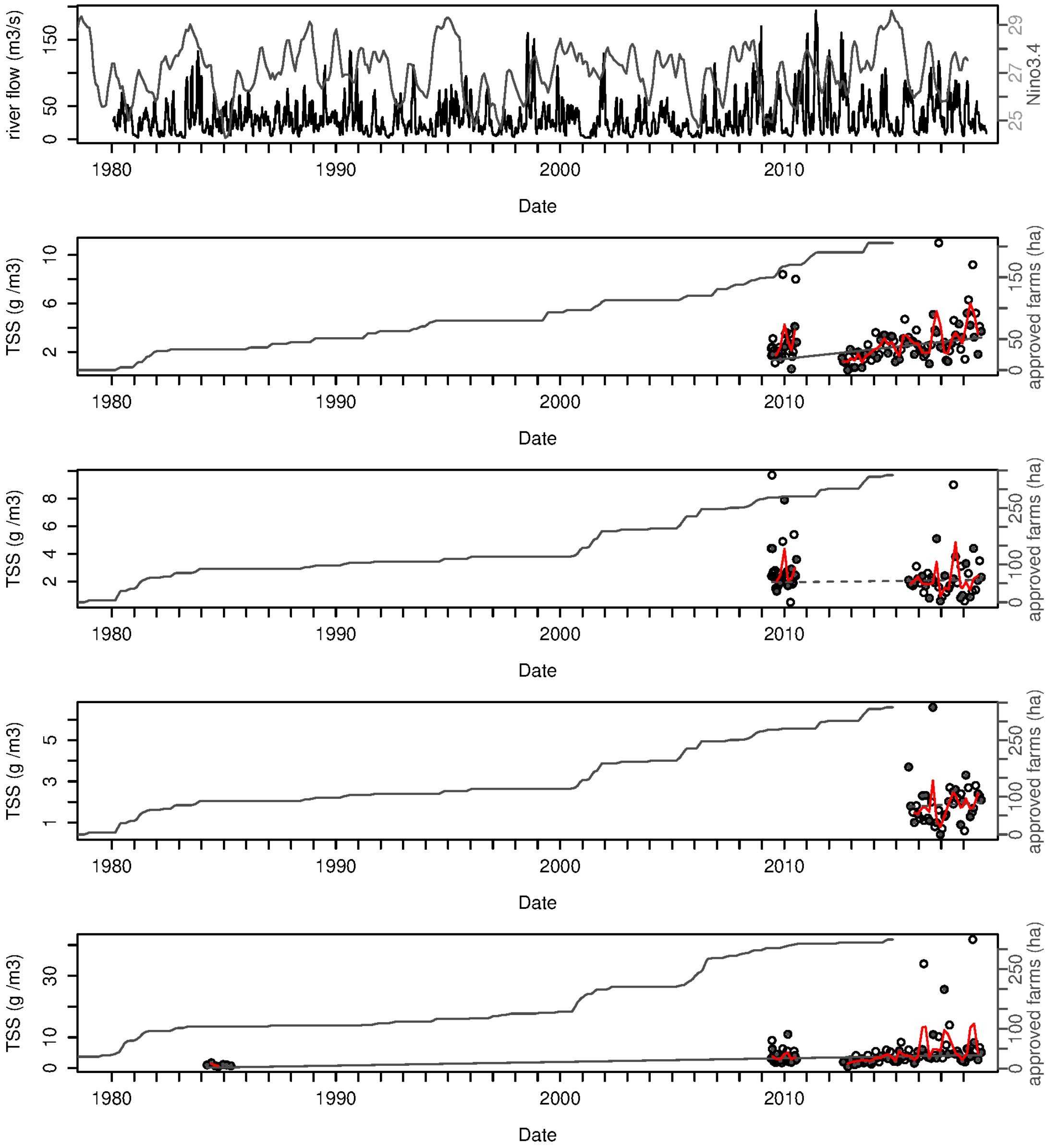

Figure 3-2: Time-series of suspended solids at (top-to-bottom): outer Pelorus, west Beatrix, Laverique and Schnapper Point. Time-series of Pelorus river flow, Nino-3.4 index and sub-region-specific total approved area of marine-farm are also shown. The filled symbols denote data used in calculating the Sen-slopes[42]. Open symbols denote data that were excluded by sub-sampling. The green-lines indicate the Sen-slope linear trends. The fact that they are dashed indicates that signs of none of the slopes can be reliably determined (i.e., the 95% confidence limits bracket zero). The red-lines illustrate the 90-day, time-centred moving average.

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[42] When the frequency of sampling has varied through time (as has been the case here), the higher-frequency data must be sub-sampled to yield a time-series which has similar sampling frequency throughout. This reduces the likelihood that any one sub-period within the time-series will falsely dominate the ultimate linear trend value.

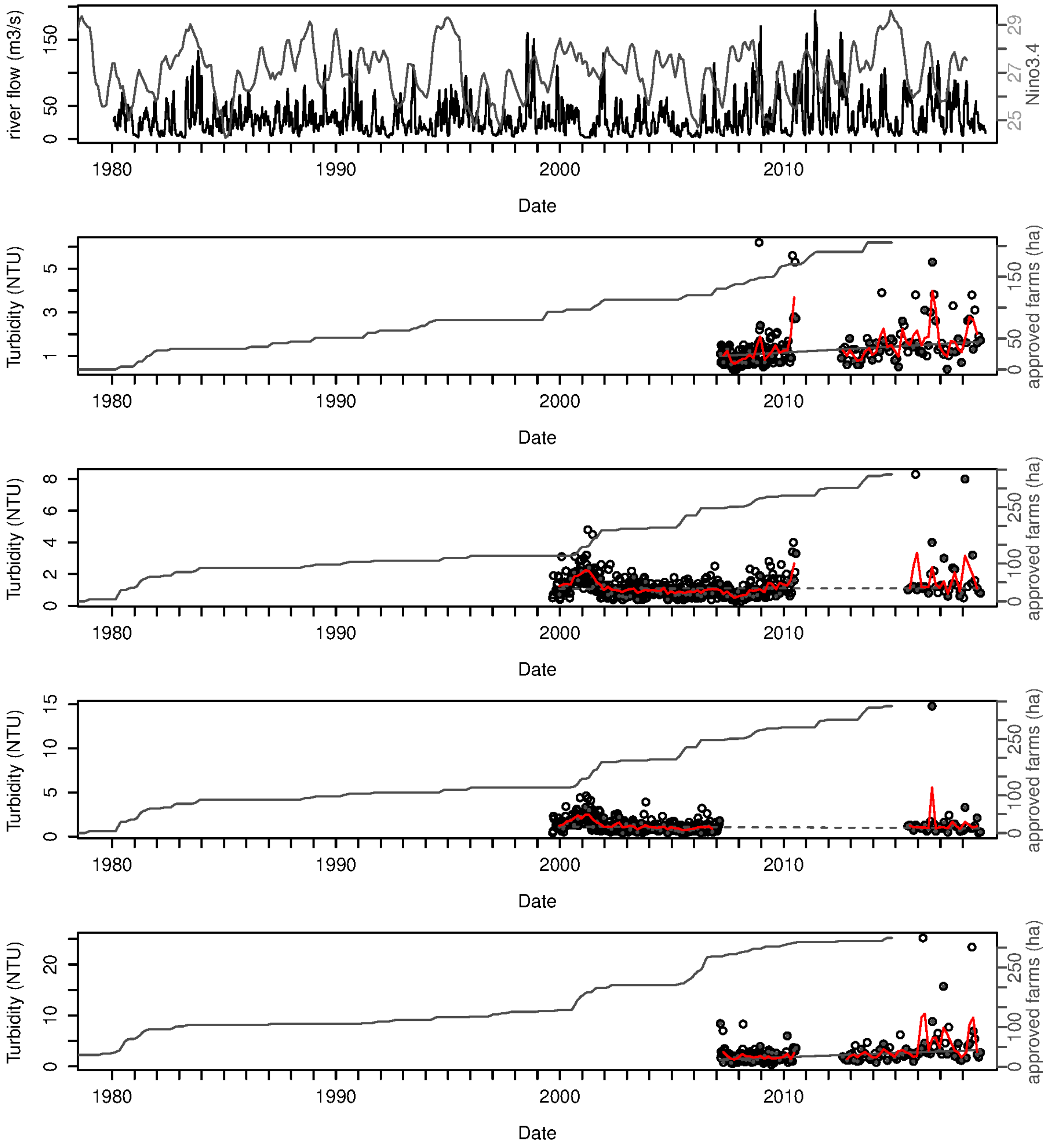

Figure 3-3: Time-series of turbidity at (top-to-bottom): outer Pelorus, west Beatrix, Laverique and Schnapper Point. Time-series of Pelorus river flow, Nino-3.4 index and sub-region-specific total approved area of marine-farm are also shown. The filled symbols denote data used in calculating the Sen-slopes. Open symbols denote data that were excluded by sub-sampling. The green-lines indicate the Sen-slope linear trends. The fact that they are dashed indicates that signs of none of the slopes can be reliably determined (i.e., the confidence limits bracket zero). The red-lines illustrate the 90-day, time-centred moving average.

Absence of a depletion halo for turbidity around the Wilson Bay development in the Firth of Thames

Satellite-derived images provide a means of sensing some of the properties of near-surface waters across large areas (albeit that suitable ground-truthing data are also required to calibrate the values read from the images). Properties which can be measured include: water temperature, turbidity and chlorophyll-*a* concentration. Recently satellite images of the Firth of Thames have been used to determine whether the farms within the two [43]Wilson Bay marine farming zones are having any perceptible influence upon these water-properties (Pinkerton, Gall et al. 2018). They collated

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[43] Wilson Bay Areas A and B are two large (>1000 ha) rectangular blocks of water-space that have been approved for mussel farming. Wilson Bay Area A is nearing full occupation. In contrast only about 10-15% of Area B is occupied by mussel farms at present.

approximately 890 useable[44] images from the NASA MODIS-Aqua satellite from the period July 2002-February 2017. This satellite yields images in which each pixel has a horizontal resolution of approximately 500 m.

Their analysis technique postulates that the mussels (and associated biofoulers and crop-lines etc.) associated with the Wilson Bay marine farming zones may modify the properties of the waters in the immediate vicinity of the marine farming zone. Their manuscript provides full details of their methods but, loosely speaking, they sought to detect these halos as follows:

- They assume that spatial variability in the raw data from the satellite images derives from two components: (a) a localised farm-effect and (b) larger-scale 'natural' gradients (arising from eg the influence of rivers in the southern Firth, oceanic waters to the north and north-east of the Firth and bathymetric variation throughout the Firth, etc).
- They define a relatively small 'core region' encompassing only the Wilson Bay Area A marine farm and its immediate environs (approx. 14 km^2, 56 pixels of a satellite image).
- They also defining a larger 'host region' centred upon the core region but extending somewhat beyond (125 km^2, 400 pixels) the core one. They use the term 'skirt region' to refer to that part of the 'host-region' which is not also a part of the 'core region'.
- They fit a smoothing surface through only those pixels within the 'skirt region'. The coefficients used in this fitting procedure stemmed from an analysis of the patterns of spatial cross-correlation in the entire 'host region'. This surface is assumed to contain only the larger-scale, 'natural' spatial gradients. The surface can be used to derive interpolated values for each pixel of the 'core' region. These are assumed to reflect the influence of the large-gradients only.
- The differences between the (satellite-)observed values in the 'core' region and those predicted by spatial interpolation from the 'skirt region' are assumed to equate to the local-scale effects induced by the marine farm.

The method was applied for each useable satellite image. For each image, it was applied to four non-overlapping 'host-regions'. One of these was centred upon the Wilson Bay Area A marine farm region. The three others were at locations which did not contain any marine farms. These three areas serve as 'control-regions' against which the method can be validated. For the analysis that was centred on the Wilson Bay marine farm, they found:

1. Sea-surface temperatures within the core-region were slightly elevated (+0.03 C) during the summer months and slightly depressed during the summer months (-0.11 C) relative to what was predicted by interpolation across the skirt-data.
2. Chlorophyll-*a* concentrations were slightly suppressed within the core area relative to what was predicted by interpolation across the skirt-data (approximately 2% on average across an area of 1.5 times that of the marine-farming zone). Chlorophyll-*a* suppression tended to be slightly greater during the early winter months than during the late summer.

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[44] An image was considered useable only if clouds obscured less than 50% of the water-surface in and around the Wilson Bay Area A farming zone.

3. Turbidity in the core area did not differ from that predicted by interpolation across the skirt data.

4. There was some evidence that the effects upon temperature and chlorophyll-*a* became larger year-upon-year as the number of mussel lines within the Wilson Bay Area A marine farming zone increased.

5. Importantly, they did not find consistent and convincing (ie mechanistically plausible), coherent spatial patterns when the same method was applied at any of the three 'control' sites. Furthermore, at Wilson Bay, the quantitative nature of the results changed in a manner consistent with *a-priori* expectation as the size of the 'core' and 'skirt' regions changed (in particular, the magnitude of inferred farm-induced change tended to be greatest at intermediate core-sizes).

Pinkerton, Gall et al. (2018) attributed the temperature effects to enhanced vertical mixing arising from the interaction between tidal flows and the crop-matrix on the droppers. This enhanced vertical mixing brings greater quantities of deep water towards the surface. In the summer months, the deep water tends to be cooler than the surface waters. In the winter-months, the surface waters are sometimes slightly cooler than the deep ones. They attributed the reduced near-field chlorophyll-*a* concentrations to the filtration and feeding activities of the mussels.

In the context of this discussion (potential removal of suspended sediment by mussel filtration), the key finding is that whilst Pinkerton, Gall et al. (2018) detected small, but mechanistically plausible changes in water-temperature and chlorophyll-*a* abundance but no change in turbidity around Wilson Bay Area A. This suggests that those mussel farms are not removing measurable quantities of turbidity (induced by suspended particulates, esp inorganic ones) from the water-column.

Suspended sediments and mussel farms

Two independent data-sets (time-series of turbidity and total suspended particulates) directly measured in water-samples from Pelorus Sound. A third data-set (maps of turbidity inferred from satellite images of the Firth of Thames) all suggest that mussel farms have had little or no perceptible influence upon concentrations of suspended particulates (most of which are suspended inorganic sediments). Mussels certainly do capture suspended sediment and 'package' that material into rapidly sinking particles of faeces and pseudofaeces, so these results are a little surprising. Nonetheless, several explanations offer themselves.

Considering first the time-series analysis of Pelorus Sound data: it is conceivable that inputs of sediment to the water-column from the catchment have increased over time in a manner that has countered/masked any increased removal induced by the mussels. We have not explored this possibility (for example by seeking time-series of historical riverine concentrations of suspended solids).

Secondly, recalling (i) that our measurements of suspended sediments stem from GF-C filters (1.2 µm nominal pore size), (ii) that the lower particle size-bound for maximal filtration by green-lipped mussel is around 2 µm and recognising (iii) that smaller particles (e.g. the finest clays – which are finer than 2 µm) induce greater light-scattering (hence, greater turbidity) than larger ones, it may be that a substantial component of the suspended sediment (and an even larger fraction of the turbidity) are fine-clays which the mussels are not able to capture and divert into faeces or pseudo-faeces[45].

Finally, we reiterate that there is evidence to suggest that even fresh faeces and pseudo-faeces can be readily eroded from the seafloor (Giles and Pilditch 2004). It might (legitimately) be argued that fresh (intact) faeces are unlikely to remain resuspended for long if they sunk in the first instance, but both faeces and pseudofaeces will tend to break apart as their organic contents decay. The specific rate of mineralization for the organic components has been estimated to be around 0.16 d^{-1} (Giles and Pilditch 2006) (equating to a half-life of about 4.3 d). Once freed from the organic matrix, the finer inorganic materials within the former (pseudo-)faeces are likely to resuspend (and sink more slowly) than the pre-cursor (pseudo-)faecal particles did. This resuspension will serve to reduce the efficacy with which mussels induce a net long-term export of suspended sediments onto the seabed.

Collectively, these findings do not necessarily imply that farms have no net influence upon suspended sediment concentrations – but they do suggest that farms are not having an overwhelming influence upon suspended sediments.

Regulating Services Sediment Sequestration

***Regulating* ecological service (EcolS): inorganic sediment sequestration**	***Regulating* ecosystem service (ES): inorganic sediment sequestration**
Mussels readily capture particles in the size-range 2-200 µm (approx.). This will include larger clays, silts and finer sands. These inorganic particles are packaged into faecal and pseudo-faecal particles that tend to sink rapidly. The organic matter in the (pseudo-) faecal particles will break down rapidly and the fine sediments within those particles may then readily resuspend.	Whilst we know of no local measurements of sediment concentrations immediately down-stream of a farm, there are long-term measurements of suspended sediment concentrations (and / or turbidity) from several parts of the Sounds and from the Firth of Thames. These data reveal little or no evidence to indicate that the farms are having a substantial influence upon concentrations of suspended sediment measured in the upper parts of the water-column.

3.1.2 Nitrogen removal

Phytoplankton (and other algae and plants) require elemental nutrients to build new tissue. The nutrients are usually classified into one of two groups: macro- and micro-nutrients. The former are required in substantial quantities (i.e., comprise more than approximately 0.1% of the dry weight of a living cell). The latter are required only in trace quantities (often within enzyme systems). The macro-nutrients are nitrogen (N), phosphorus (P) and silicon (Si). Of these, the first two are required by all algae but Si is required only by siliceous taxa[46]. The trace nutrients include elements such as iron and manganese. When a nutrient is not sufficiently abundant in the water, algae will grow only poorly. Conversely, when nutrients are overly abundant, algal populations may accrue to excessive levels – leading to undesirable symptoms of eutrophication such as frequent/prolonged algal blooms and hypoxia as that organic matter subsequently decays. Whilst moderately low dissolved oxygen does

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[45] We know of no estimates of the size-distribution of suspended inorganic sediments in either the Marlborough Sounds or the Firth of Thames.

[46] This latter group is dominated by diatoms – which are often the most abundant phytoplankton taxon (by biomass) in coastal waters.

occur in the near-bed waters of inner Queen Charlotte during the late-summer/early autumn period (Broekhuizen and Plew 2018), dissolved oxygen concentrations are usually close to saturation and it is rare for algal concentrations (as measured by chlorophyll-*a* concentration) to exceed 5 mg m^{-3}.

There is ample evidence to indicate that nitrogen is the element that limits primary production in the Marlborough Sounds (and many other coastal waters of New Zealand) (Gibbs, Ross and Downes 2002; Broekhuizen and Plew 2018) and little or no evidence that the sounds exhibit signs of eutrophication at present. Nonetheless, we consider that it is useful to recognise the roles that the shellfish crop plays in the nitrogen cycle of the sounds.

Nitrogen harvesting

Mussels grow by consuming particulate organic matter and retaining some of the material which they consume as new flesh mass, additional byssus and organic layers within the shell. If the mussels are later removed from the water (i.e., harvested), then the nutrients which they have fixed into new body tissue are also removed. Mussel harvesting can therefore be viewed as a mitigation measure that may buffer against coastal eutrophication. Indeed, in Europe, there have been commercial-scale trials in which mussels have been grown with the primary purpose of absorbing nutrient emissions to mitigate eutrophication effects (rather than for meat production) (Petersen, Hasler et al. 2014; Nielsen, Cranford et al. 2016).

Rose, Bricker et al. (2015) calculated nitrogen harvest rates for 14 different shellfish farming locations around the world (for seven different species). The rates ranged between 12 g N m^{-2} seabed y^{-1} and 152 g N m^{-2} y^{-1}. For the three long-line systems (growing *Mytilus edulis* or *M. galloprovincialis*) the rates were estimated to range between 12 and 65 g N m^{-2} y^{-1}. Rates of nitrogen harvest in the green-lipped mussel crop have also been calculated for several sites around New Zealand. For the Firth of Thames, Zeldis (2008) estimated that approximately 6 kg N are harvested $tonne^{-1}$ mussel green weight harvested. That implied that the 2006 mussel harvest from Wilson Bay Area A amounted to approximately 84 tonne N (cf. estimated annual inputs of 7000 tonne N from rivers that enter the Firth of Thames). For Pelorus Sound, the mussel harvest has been estimated to equate to approximately 266 tonne N y^{-1} whilst inputs from the catchment via Pelorus/Rai and Kaituna rivers and several other smaller sources have been estimated to amount to about 580 tonne y^{-1} (Knight 2012). Interestingly, Knight (2012, Table 3) indicates that, despite the comparatively small surface area of mussel farms in the sound, the nitrogen removed as crop amounted to more than 50% of the total estimated nitrogen loss through denitrification in the seabed of the entire Pelorus Sound (see below for further comments on denitrification).

As the mussel crop grows, it accumulates a substantial biofouling community (Watts, Goldstein et al. 2015). Historically, much of this community has stripped from the crop and returned to the water during reseeding and harvest operations. Thus, little, if any of the nitrogen in that fouling community has been permanently removed from the sounds by past harvest activities. Recently, however, the industry has begun to develop markets for blue mussel (*M. galloprovincialis*) and Asian kelp (*Undaria pinnatifida*).

Blue mussel occupies an average 9% of the dropper length in the sounds (Forrest and Atalah 2017). If this resource were to be harvested with the same efficiency as the green-lipped mussel crop, then the total nitrogen removal associated with the blue mussel crop might amount to about 9% of the nitrogen harvested in green-lipped mussel[47]. That is, the blue mussel harvest might amount to approximately 24 tonne N y^{-1}.

At present, the annual harvest of *U. pinnatifida* from the Marlborough Sounds amounts to approximately 120-150 tonne y^{-1} and could quickly expand to about 300 tonnes y^{-1} (J. Large, MFA, pers. comm.). The protein content of *U. pinnatifida* is around 20% of the blotted wet weight (Park, Kim et al. 2012). Proteins are generally around 16% nitrogen by dry weight. Collectively, this suggests that an annual harvest of 300 tonne fresh weight would amount to approximately 10 tonne N y^{-1}.

Denitrification

Phytoplankton (and other algae and plants) require nitrogen to build new tissue. Whilst cyano-bacteria (so-called blue-green algae) can fix elemental nitrogen (N_2), most phytoplankton taxa are unable to do so. Some can secure a portion of their requirements by absorbing small, organic molecules – but most rely upon uptake of nitrate (NO_3^-) and ammonium (NH_4^+) to supply their nitrogen demands. The concentrations of these two forms of dissolved inorganic nitrogen can become unnaturally elevated when loadings to a water-body become too high relative to the rates at which the nitrogen can be exported elsewhere. In many coastal waters, algal production (growth) is constrained by nitrogen availability. Thus, should nitrate or ammonium inputs increase, algal concentrations may also increase. Ultimately, this can lead to symptoms of eutrophication that include: more frequent algal blooms, changes in the taxonomic composition of the algae, suppression of benthic algae and plants and intermittent hypoxia/anoxia in deeper parts of the water-column.

Denitrification is a term that is used to refer to processes by which soluble oxidised nitrogen (nitrate (NO_3^-) and nitrite (NO_2^-)) are converted to gaseous end products (NO, N_2O, N_2) that are less accessible to plants and algae[48]. By removing nitrate (and, indirectly, ammonium), denitrification processes provide an ES that to some degree can buffer the development of eutrophication in systems which are subject to heavy nitrogen loading.

Two denitrification pathways exist (so-called 'dissimilatory nitrate reduction' and 'anammox' – the latter having only recently become well understood). Both are dependent upon the activities of specialized bacteria and both are restricted to anaerobic environments.

Dissimilatory denitrification is the term used to describe the conversion of molecular nitrate-nitrogen (NO_3) into elemental di-nitrogen (N_2).

The stoichiometry of the dissimilatory denitrification reaction is (Gypens, Lancelot et al. 2008):

$$(CH_2O)_x(NH_3)_yH_3PO_4 + 0.8xHNO_3 \rightarrow xCO_2 + yNH_3 + 0.4xN_2 + H_3PO_4 + 1.4xH_2O$$

Focussing upon nitrogen and oxygen, the reaction proceeds as follows:

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$$

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[47] Noting that Blue mussel occupies an average of about 9% of the dropper and assuming that the nitrogen-density (g N m^{-1}) of blue mussel infested dropper is similar to that of dropper growing only green-lipped mussel.

[48] Though some authors define it more broadly to include conversion of ammoniacal nitrogen and organic nitrogen into those gaseous products Fennel, K., Brady, D., DiToro, D., Fulweiler, R.W., Gardner, W.S., Giblin, A., McCarthy, M.J., Rao, A., Seitzinger, S.P., Thouvenot-Korppoo, M., Tobias, C. (2009) Modeling denitrification in aquatic sediments. *Biogeochemistry*, 93: 159-178. 10.1007/s10533-008-9270-z) citing Devol, A.H. (2008) Denitrification including anommox. In: D. Caperone, E. Carpenter, M. Mulholland & D. Bronk (Eds). *Nitrogen in the marine environment*. Elsevier, Amsterdam: 263-302.

Note that N_2O is an intermediary product and that CO_2 is another end-product of the overall reaction. Both are green-house gases. Dissimilatory denitrification requires (a) organic matter, (b) nitrate (NO_3^-), (c) denitrifying bacteria and (d) anaerobic conditions.

The stoichiometry of the anammox reaction is as follows:

$$NH_4^+ + NO_2^- \rightarrow N_2 + 2H_2O$$

The reaction utilizes inorganic ammonium and nitrite rather than organic matter and nitrate. Nitrite is usually present only at very low concentrations in marine waters. It is generated as an intermediary/temporary product during dissimilatory denitrification (in sub-oxic environments[49]) and as an intermediary/temporary product within the bacterially-mediated nitrification process (in aerobic environments).

Whilst dissimilatory denitrification can occur only under anaerobic conditions, nitrate can be generated (by oxidation of ammonium) only in aerobic conditions. Thus, prolonged dissimilatory and/or anammox denitrification can only occur in regions where: (a) solutes can readily exchange between aerobic and anaerobic micro-environments, or (b) the local environment fluctuates between aerobic and anaerobic states moderately rapidly.

In the seabed, aerobic sediments are usually found only in the upper few mm-cm of sediment. Anaerobic conditions exist below that surface layer. Molecular-scale diffusion within interstitial waters combined with active 'pumping' of water by benthic invertebrates and wave-action etc. provide plentiful opportunity for solutes to exchange between aerobic and anaerobic zones. Thus, it should come as no surprise that coastal sediments are usually net denitrifying. That is, denitrification fluxes tend to be larger than nitrification fluxes (Fennel, Brady et al. 2009).

Traditionally, rates of denitrification have been measured using the so-called acetylene block technique. This method measures the accrual of N_2O after first blocking conversion of that molecule to N_2. More recently, other methods (e.g. using nitrogen-isotope tracing) have been developed.

Using the acetylene block method, Kaspar, Gillespie et al. (1985) measured in-situ benthic denitrification rates of 0.14 and 0.85 mmol N_2 m^{-2} d^{-1} at reference sites in Kenepuru Sound and between 0.66 and 6.07 mmol N_2 m^{-2} d^{-1} under a nearby mussel farm (measurements made during summer and autumn). Subsequently, Christensen, Glud et al. (2003) measured the rate of benthic denitrification under a mussel farm in Beatrix Bay to be 8.3 µm N_2 m^{-2} h^{-1} (0.2 mmol m^{-2} d^{-1}) using an isotope-tracing technique (measurements made during summer). At two nearby sites that were not under farms, the rates were 10.9 and 15.3 µm N_2 m^{-2} h^{-1} (0.26 & 0.37 mmol m^{-2} d^{-1}). Thus, one study suggests substantially elevated denitrification below a mussel farm whilst the other suggests slightly depressed rates below the mussel farm.

We know of no other measurements of denitrification under suspended rope shellfish farms but Giles, Pilditch et al. (2006) noted unusually low levels of nitrate and ammonium efflux from the sediments below a mussel farm in the Firth of Thames during a summer period – leading them to speculate that denitrification activity may have been enhanced under the farm relative to the far-field.

From the three studies cited above, we infer that rates of denitrification in sediments below suspended rope mussel farms are unlikely to become dramatically suppressed and may even be somewhat increased relative to those that would exist in the absence of a farm.

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[49] <2 mg O_2 L^{-1} (Fennel et al (2009)

Denitrification is not restricted to marine sediments. It can also occur within flocs of organic detritus floating in the water-column if anaerobic pockets begin to form within the flocs (Bianchi, Weber et al. 2018). Mussel droppers accrue considerable organic matter as they age (Woods, Floerl and Hayden 2012) and provide an environment that is likely to favour both: (a) maintenance of persistent anaerobic zones in close proximity to aerobic ones and (b) development of intermittently anaerobic environments. Indeed, there is evidence that mussel droppers are associated with denitrification. For example, Kaspar, Gillespie et al. (1985) estimated the rates of dissimilatory denitrification associated with '10 to 15 mussels of about 10 cm length including their epifloral, epifauna and detritus cover' taken from a short section of mussel line and returned to the laboratory for incubation. They report the mussel-associated denitrification as a corresponding sediment-area-specific rate [1.4 mmol N_2 (m^2 of farm-seabed)$^{-1}$ d^{-1}].

This rate exceeded the one associated with the seabed under the farm by a factor of about two and exceeded that associated with sediments at an unfarmed "reference" site by a factor of about ten. If one makes the bold assumption that mussel-associated denitrification rate [1.4 mmol N_2 (m^2 of farm-seabed)$^{-1}$ d^{-1}] can be extrapolated to all farms within Pelorus Sound, this amounts to approximately 240 tonne N y^{-1} for Pelorus Sound as a whole. That amounts to about 50% of the annual riverine nitrogen load. Note however, that we believe that this may be an over-estimate of denitrification associated with the droppers. Kaspar, Gillespie et al. (1985) worked with mussels of harvest size. The organic matter content of newly seeded droppers will be lower and therefore the denitrification potential is likely to be lower.

More recently, NIWA has demonstrated that denitrification is also associated with intact, *in-situ* mussel droppers. Ten semi-permeable membrane bags were attached to the outer face of the crop-matrix on a dropper (Figure 3-4). The outer face of the bags was sealed against diffusive exchange (such that all solute exchange had to occur across the face that was in contact with the crop). A further two control bags were hung in the open water between the droppers. The bags were left in place for a period of about 17 hours (late afternoon – mid morning). The net N_2 concentration-change within the bags over the duration of the incubation was measured using the N_2/Ar method. The N_2/Ar ratio did not change significantly in the control-bags. In contrast, the ratio increased markedly in eight of the ten bags hung against the crop. The average N_2 increment across the ten treatment bags amounted to approximately 0.1 µmol bag^{-1}. This trial was merely an initial 'proof-of-concept' study and it is not possible to derive a reliable denitrification rate from it (any rate that we estimate will be an under-estimate, but we cannot yet determine the degree of under-estimation).

Figure 3-4: Semi-permeable membrane bag attached to a mussel dropper. This study was undertaken at a farm in Homewood Bay, Pelorus Sound. NIWA is grateful to Sanford Ltd. - who gave us access to their farm and provided logistical support for the study.

In summary, there is conflicting evidence as to whether seabed denitrification rates are increased or reduced under mussel farms, but two very different studies have demonstrated that the matrix of mussel-crop does promote denitrification in the water-column. In the study from which rates can be inferred, the total denitrification flux arising in the crop in the water-column exceeded that arising from the seabed below the farm (which, in turn exceeded that arising from the nearby unfarmed seabed).

Whilst the data are scant and more detailed studies are warranted, it is our opinion that existing data indicate that mussel farms are more likely to increase the area-specific, depth-integrated denitrification rate than they are to reduce that rate. Note, however, that if this is the case, it also implies the production of two key green-house gasses (CO_2 and N_2O).

Temporary nitrogen removal from surface waters

Crop-harvest and denitrification both cause long-term removal of nitrogen from the local system. Marine farms can also foster temporary removal of labile dissolved nitrogen from the water—column. Nitrogen that becomes incorporated into the biofouling assemblage is (temporarily) unavailable to fuel further phytoplankton growth.

Pseudofaeces, faeces and most biofouling material tends to sink rapidly once released from the crop-matrix. This is evident from the fact that rates of organic matter deposition to the seabed in the immediate vicinities of mussel farms tend to be higher than those further afield (Dahlbäck and Gunnarsson 1981; Giles, Broekhuizen et al. 2009) and that the organic content of the sediments below the marine farms can be higher than that of sediments further afield (Dahlbäck and Gunnarsson 1981). Whilst much of the nitrogen will later mineralize back into labile form in a matter of days-to-weeks[50], the resultant inorganic nutrient (for nitrogen, primarily ammonium in the first

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[50] see Enríquez, S., Duarte, C.M., Sand-Jensen, K. (1993) Patterns in decomposition rates among photosynthetic organisms: the importance of detritus C:N:P content. *Oecologia*, 94: 457-471. for a review of degradation rates of differing types of plant material and Giles, H., Pilditch, C.A. (2006) Effects of mussel (Perna canaliculus) biodeposit decomposition on benthic respiration and nutrient fluxes. *Marine Biology*, 150: 261-271. for estimates of the degradation rates of mussel faeces and pseudo-faeces.

instance) will often be released into the water adjacent to the seabed (rather than into the surface waters from which it was first scavenged).

Thus, the marine farms serve to shunt nutrient out of near-surface waters. By pushing the nutrient into areas where light intensities may be insufficient to support rapid algal growth, suspended rope mussel farms may sometimes help to reduce the likelihood of unwanted algal proliferations[51]. As noted above, denitrification activity can change but net rates of dissolved inorganic nitrogen efflux from the sediment tend to rise (Kaspar, Gillespie et al. 1985; Christensen, Glud et al. 2003; Giles and Pilditch 2006). Given that the organic loading to the seabed is increased, this is an almost inevitable outcome. The consequences for benthic faunal abundance and diversity are less clear-cut. Both Kaspar, Gillespie et al. (1985) and Christensen, Glud et al. (2003) reported lower faunal diversity below mussel farms, but this is not a universal outcome. Indeed a recent review (MPI 2013, chapter 3) states: *"In terms of infaunal community composition, grey literature from numerous studies conducted within the Marlborough Sounds and Firth of Thames indicates that animal abundance tends to be slightly elevated directly beneath mussel farms…. Enrichment is variable amongst sites, depending upon environmental conditions such as depth and average current velocity, and, as a result, species diversity can be either slightly depressed or slightly enhanced. Generally, the level of compositional change is that of mild, positive enrichment …. The abundances of opportunistic polychaetes tend to be slightly elevated whilst the composition of other major infaunal groups (eg molluscs, crustaceans, echinoderms) remain comparable between farmed and unfarmed locations… Higher level enrichment impacts (above ES3) are likely to be observed at farm sites that are predisposed to impacts (i.e., shallow, low flow)"*.

We do note, however that, by design, a majority of mussel farms have been placed over soft-bottom sediments, and that these parts of the sea-floor may already have been highly modified relative to their original state by sedimentantion and dredge fishing. Mussel-farm effects over hard-substrate/pristine seabed may be greater, but resource consents preclude placing farms over these habitats.

None of the preceding statements regarding nutrient removal should lead the reader to infer that the Marlborough Sounds are in a state that might be symptomatic of an excess of nutrient supply. Dissolved oxygen concentrations are usually close to saturation[52]. Furthermore, algal concentrations (as measured by chlorophyll-*a* concentration) are generally low-moderate - exceeding 3 mg Chl-a m^{-3} in 8% (or fewer, depending upon location) of records (Morrisey, Anderson et al. 2015).

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[51] Note however, that in systems which exhibit an estuarine circulation (seaward flow of relatively fresh near-surface waters and landward flow of saltier water close to the bed – such as Pelorus Sound), shunting nutrients towards the seabed may promote retention of nutrient within the system. If/when this additional stored nutrient is mixed to the surface, it may fuel more algal growth than would otherwise have been possible.

[52] though near-bed DO concentrations have fallen below 70% (minimum 46%) during late summer/early winter in inner Queen Charlotte Sound in each year since Marlborough District Council began monitoring in 2011) Broekhuizen, N., Plew, D. (2018) Marlborough Sounds Water Quality Monitoring: review of Marlborough District Council monitoring data 2011-2018. *National Institute of Water & Atmospheric Research Ltd. Client Report (to Marlborough District Council)*, 2018248HN (project MDC18201): 203.

Regulating Services Nitrogen Removal

***Regulating* ecological service (EcolS): nitrogen removal**	***Regulating* ecosystem service (ES): nitrogen removal**
Mussels consume particulate organic nitrogen (as seston) and much of this is ultimately returned to the water-column as solute, and as such enters the biochemical pathways of the sounds' ecosystem; Most of the nitrogen that accrues in the biofouling community enters the benthic-pelagic coupling biochemical pathways; Denitrification occurs within the mussel-crop matrix that grows on a dropper; however, we are uncertain of the magnitude of this denitrification flux; Some evidence suggests that when the crop is approaching harvest size, the denitrification flux emanating from the droppers may exceed that associated with the seabed below the farm; Denitrification also naturally arises within the seabed but studies to date provide conflicting evidence of fluxes beneath mussel farms: denitrification rates may be either reduced or enhanced relative to those at control sites.	Mussels consume particulate organic nitrogen some of which is retained in flesh and protein within the shell. This nitrogen is removed from the system at harvest; Mussel harvest may remove nitrogen equivalent to about 45% of the annual riverine nitrogen-load to Pelorus Sound; Some of the nitrogen that accrues in the biofouling community may be returned to land (e.g. the small, but growing *Undaria* harvest). At present, this is negligibly small relative to the nitrogen harvested as mussel; Extrapolation from one quantitative study of a relatively mature mussel crop to an annual- and Pelorus Sound-scale, suggests that denitrification associated with the suspended crop-matrix could, on an annual-scale amount to approximately 50% of the annual-scale riverine nutrient load (likely an overestimation since nursery and intermediate crop-lines would likely have much lower fluxes); Data on denitrification beneath mussel farms are conflicting.

3.1.3 Carbon sequestration

Carbon dioxide is an important greenhouse gas. Furthermore, anthropogenic emissions of CO_2 are promoting acidification of the world's waters. Biogenic calcification becomes more energetically costly as waters become more acidic and there are fears that this acidification may harm shellfish and corals etc.

Even though mussel shells are rich in inorganic carbon (as calcium carbonate), it is unlikely that shell formation acts as a sink for CO_2. Indeed, it probably promotes export of dissolved inorganic carbon (specifically, CO_2) from the sea to the atmosphere (thus on balance no ecosystem service is provided). Conversely, if the shell material later dissolves back into water, it will tend to promote absorption of CO_2 from the atmosphere (an ecosystem service). This carbon cycle feeds into the biochemical pathways of the sounds' ecosystem, thereby providing EcolS.

These counter-intuitive results arise from the complexities of the behaviour of dissolved inorganic carbon when dissolved in water. The remainder of this section endeavours to explain why shell-formation is likely to be a net source of CO_2 to the atmosphere.

In the atmosphere, inorganic carbon is found only as gaseous CO_2. This CO_2 can pass across water surfaces (in either direction) and dissolve into the water. Once dissolved, however, the CO_2 partitions itself across four inorganic forms: CO_2, H_2CO_3, HCO_3^- and CO_3^{2-} (the latter being respectively carbonic acid, carbonate and bicarbonate).

Equation 3-1: The carbonate buffering system.

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+ \leftrightarrow CO_3^{2-} + 2H^+$$

Initially, the aqueous CO_2 combines with water (H_2O). Subsequently, the $H_2CO_3^-$ may dissociate by shedding a hydrogen ion to yield HCO_3^- and this may then further dissociate to yield a second hydrogen ion to yield CO_3^{2-}. These inorganic reactions occur readily and rapidly in water – such that an individual carbon atom can rapidly switch from one molecular form to another. The fact that two of these reactions involve release (or uptake) of hydrogen ions implies that they influence the pH (acidity) of the water (the so-called bicarbonate buffer system). Furthermore, because the presence of free hydrogen ions in the water tends to inhibit the two afore-mentioned dissociation reactions, the reactions themselves operate (in concert with other acids/bases) to buffer/regulate the pH of the sea-water.

The reaction equation for calcium carbonate formation/dissolution is:

Equation 3-2: the cacification reaction.

$$CaCO_3 + CO_2\text{ (aq)} + H_2O \leftrightarrow Ca^{2+}\text{(aq)} + 2\ HCO_3^-\text{ (aq)}$$

Whilst calcium carbonate can form by direct, abiotic precipitation, the majority of calcium carbonate is formed through biogenic processes (ones driven by living organisms). Shell-formation by bivalves is one such biogenic process and several authors have suggested that shell-harvest could serve as a means of CO_2 sequestration. Unfortunately, that argument is naïve.

Inspection of Equation 3-2 reveals that whilst formation of calcium carbonate consumes *two* carbon atoms (as carbonate ions), only one of those becomes incorporated into the calcium carbonate molecule. The other becomes incorporated into a molecule of CO_2. Formation of calcium carbonate *reduces* the total concentration of DIC in the water but *increases* the concentration of dissolved CO_2 (despite this being one of the components of DIC). This CO_2 may then return to the atmosphere where it can operate as a greenhouse gas or be converted to carbonate through the carbonate buffering system. The probability that a CO_2 molecule will return to the atmosphere (rather than be converted to carbonate) increases as the partial pressure of CO_2 in the water rises and as the pH falls (as the water becomes more acidic). Unfortunately, calcification causes the partial pressure of CO_2 in the water to rise and also induces pH to fall[53]. Thus, calcification tends to increase the likelihood that aqueous CO_2 will return to the atmosphere (Munari, Rossetti and Mistri 2013). It seems that shell formation may be likely promote carbon sequestration only in waters that [54]are both persistently unusually alkaline and exhibit persistent CO_2 under-saturation. Indeed, van der Schatte, Jones et al. (2018) explicitly chose to exclude carbon sequestration as a possible ecosystem service of shellfish aquaculture *"… Due to a lack of consensus on whether calcification represents a source or a sink of* CO_2*"*. Furthermore, Morris and Humphreys (2019) make a detailed examination of the influence of blue mussel aquaculture on CO_2 exchange with the atmosphere in four coastal regions. They calculated that shell-formation is likely to be a net source of CO_2 to the atmosphere at all sites. The

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[53] Because the two hydrogen ions that were generated when the two HCO_3^- molecules were formed subsequently get 'left behind' when those carbonate ions are converted to calcium carbonate and CO_2.

[54] To counter the acidification that is associated with calcification – such that the CO_2 arising from calcification is likely to quickly convert to HCO_3^-.

strength of the source is predicted to vary across approximately 0.27 – 0.41 g CO_2 / g $CaCO_3$ (tending to be stronger in colder waters).

At harvest size, a green-lipped mussel shell weighs approximately 23 g (J. Stenton-Dozey, NIWA *unpubl. data)*. Carbon makes up around 10-15% of a mussel shell's dry weight. Thus, the shell contains about 3 g C at harvest size. Whilst some of this is organic material that derives from the food that the mussels ingest, most is inorganic calcium carbonate synthesized from dissolved calcium ions, dissolved CO_2 and hydroxyl ions. The annual harvest of mussels from the Marlborough Sounds have fluctuated between about 40k tonne y^{-1} and about 60 k tonne y^{-1} (whole, wet weight) over the last decade (figures supplied by the MFA). The shell accounts for approximately 55% of the crop green weight (J. Stenton-Dozey, *unpubl data*). This implies that approximately 2-5 $x10^3$ tonne carbon may become immobilised each year in the mussel shell that is subsequently harvested from the Marlborough region (approx. 55-83 kg C (tonne harvested green weight)$^{-1}$). By way of comparison, for the Scottish blue mussel industry, it has been calculated that approximately 218 kg CO_2 tonne^{-1} harvested crop (59 kg C tonne^{-1} harvest) are sequestered into shell material (Meyhoff-Fry 2012). Carbonate in the shells of fouling blue mussels has also been sequestered from solution – perhaps representing an additional 5-8 kg C (tonne harvested green weight)$^{-1}$ of green-lipped mussel crop[55] if harvested. Whilst it is tempting to claim this shell carbonate as CO_2 sequestration, the reader should recall that, for every atom of carbon sequestered into shell carbonate, another atom is released back into the water as CO_2.

Provided that the harvested mussel shell is neither burned nor 'stored' in a damp, acidic [56]environment (which would promote dissolution of the $CaCO_3$ – releasing CO_2), this harvested shell carbonate will remain immobilized for very long periods of time. Nonetheless, for the reasons described above, that immobilised carbon may also have generated a corresponding release of CO_2 to the atmosphere from the water.

Shell-formation is likely to be a source of CO_2 as are other activities (generation of energy to construct and run boats and processing plants, etc.). Nonetheless, it is important to acknowledge that all farming-for-meat operations are likely to be net CO_2 sources and that the CO_2-yield for shellfish farming is much lower than that for other meat crops that are commonly farmed in western agricultural systems. For example, in Scotland, a cradle-farm-gate analysis concluded that their Scottish mussel industry emitted less CO_2 per unit of edible crop than alternatives in the British farming system (salmon, poultry, pork, sheep & beef[57]).

Just as shell formation will tend to promote release of CO_2 to the atmosphere, shell dissolution will tend to promote absorption of CO_2 from the atmosphere. Degradation of organic matter tends to

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[55] Noting that Blue mussel occupies an average of about 10% of the dropper (Forrest, B.M., Atalah, J. (2017) Significant impact from blue mussel *Mytilus galloprovincialis* biofouling on aquaculture production of green-lipped mussels in New Zealand. *Aquaculture Environment Interactions*, 9: 115-126. 10.3354/aei00220) and assuming that the shell-mass m^{-1} of blue mussel infested dropper is similar to that of dropper growing only Greenshell mussel.

[56] If shells are sent to landfill sites that also receive significant quantities of organic matter, they will find themselves in an acidic environment that will promote dissolution and volatilization of the carbon. In contrast, if they are sent to sites that receive little or no organic matter (or other sources of acid), the carbon will remain immobilized for centuries or longer. Unfortunately, it is probable that near-surface marine coastal sediments do yield sufficient acids to promote shell dissolution (Davies, Powell et al. 1989 Davies, D. J., E. N. Powell and R. J. Stanton (1989). "Relative rates of shell dissolution and net sediment accumulation - a commentary: can shell beds form by the gradual accumulation of biogenic debris on the sea floor?" Lethaia **22**(207-212). Dissolution rates will undoubtedly vary across regions, but it has been calculated that around 50% of any carbon within freshly generated shell hash may dissolve to CO_2 within a year or so Davies, D.J., Powell, E.N., Stanton, R.J. (1989) Relative rates of shell dissolution and net sediment accumulation - a commentary: can shell beds form by the gradual accumulation of biogenic debris on the sea floor? *Lethaia*, 22(207-212). The shell carbon is also likely to be remobilised if the shell is placed amongst terrestrial soils (which contains organic matter and at least some water that foster acid production) or any other acidic environment.

[57] Note however that this study appears to have given the industry credit for carbonate that is sequestered in shell, but not penalised the industry for carbonate-ions that are converted back to CO_2 during shell-formation.

release acids which promote shell dissolution and rates of shell dissolution in the upper layers of coastal sediments can amount to several tens of percent of hash weight year^{-1} (Davies, Powell and Stanton 1989; Powell and Klinck 2007). If harvested shell is returned to the seabed, it will tend to promote CO_2 absorption from the atmosphere as (if) it dissolves. This will help to counter any net CO_2 export to the atmosphere that arose because of the initial formation of the shell.

Regulating Services Carbon Sequestration

***Regulating* ecological service (EcolS): carbon sequestration**	***Regulating* ecosystem service (ES): carbon sequestration**
Biochemical pathway of carbon: formation of one mole of calcium carbonate (shell) consumes two moles of HCO_3^- (along with one calcium ion, and a molecule of water) - but only one of the two CO_3^- ions becomes immobilised in the shell. The other is released back into the water as a CO_2 molecule: in short, whilst shell-formation is a sink for dissolved inorganic carbon, it is a source of aqueous CO_2. Shell-formation therefore tends to increase the partial pressure of CO_2 in seawater: in turn, this implies that the seawater has less capacity to absorb CO_2 from the atmosphere. Shell material will dissolve in an (even mildly) acidic aqueous environment. As it does so, it will consume aqueous CO_2. Returning harvested shell to aqueous, acidic environments (eg surficial soils and surficial seabed sediments that contain sufficient supply of rotting organic matter) will tend to compensate for the prior CO_2 enrichment that arose when the shell was formed.	Shell formation: even though mussel shells are rich in inorganic carbon (as calcium carbonate), it is unlikely that shell formation acts as a sink for CO_2. Indeed, it probably promotes export of dissolved inorganic carbon (specifically, CO_2) from the sea to the atmosphere (thus on balance no ecosystem service is provided). Conversely, if the shell material later dissolves back into water, it will tend to promote absorption of CO_2 from the atmosphere (an ecosystem service is provided). By balance carbon sequestration through shell formation is unlikely; Shell discard in the sea: Shell material will dissolve in an (even mildly) acidic aqueous environment. As they do so, they will consume aqueous CO_2. Returning harvested shell to aqueous, acidic environments (eg surficial soils and surficial seabed sediments that contain sufficient supply of rotting organic matter) will tend to compensate for the prior CO_2 enrichment that arose when the shell was formed; Shell discards on land: Mussel shell discards from processing that are stored on land equate to approximately 2-5 x10^3 tonne inorganic carbon being immobilised from the sounds each year.

3.2 Habitat provision and supporting services

In this section we distinguish between *habitat provision and supporting* services in the water column on suspended structures and the seabed. In each of these sections we first discuss the physical nature of habitat provision and then biodiversity support. We consider the influence of the water column environment on the patterns of biotic habitat settlement (e.g. currents, temperature, salinity, seasons, light attenuation). Associations between mussel farm habitats and higher organisms (fish, seabirds and mammals) are discussed in sections 3.4 to 3.6.

Mussel farm structures occupy an area of 4196 ha in the Pelorus and Queen Charlotte Sounds (see Figure 2-2) providing extensive new and revolving habitat colonised by marine organisms in the water and on the seabed. The longline (backbone) surface buoys protrude above the water surface and are often used by birds and seals. The anchor warps extend from the end buoys at the surface to the seabed where they are held in place with screw anchors (which have relaced the previous use of concrete blocks); longlines lie just below the water surface (depending on the weight of the mussel crop) and the droppers extend to approximately 10 to 15 m deep (Figure 3-5).

An individual farm typically has crop longlines at different stages of grow-out; hence, some longlines may be close to harvest whereas others may have been recently seeded. Attached organisms are removed at the last reseeding stage (Forrest and Atalah 2007; Rabel and Forrest 2017) and at final harvest. The longlines and droppers are stripped of mussels and attached organisms (biofouers) and the latter are discarded on site together with broken mussel shells. Thus, the mussel production cycle provides temporary pelagic habitats and a dynamic benthic reef environment that is regularly reshaped by deposition of stripped material and particulate matter generated by the suspended rope biota (mussels and attached organisms) and mussel faeces and pseudofaeces (biodeposits).

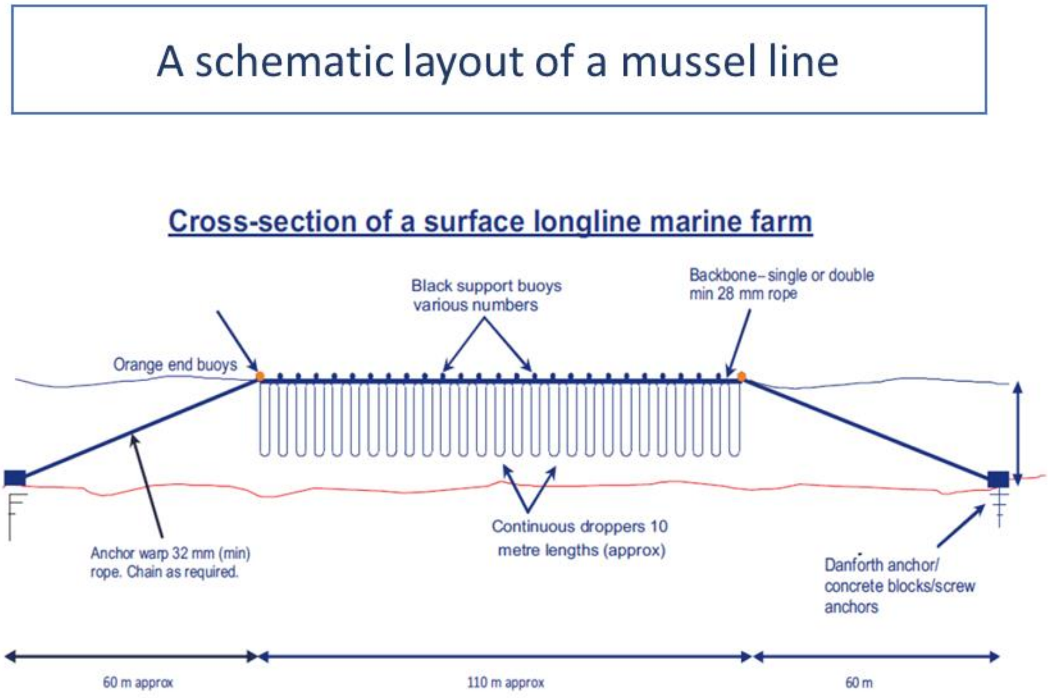

Figure 3-5: Schematics of a longline mussel farm in the Marlborough Sounds. (Credit MFA http://www.marinefarming.co.nz/media/1099/surface-sub-surface-farms.pdf

Habitat preference by biota on mussel droppers and epifauna on the seabed is also shaped by water depth, crop stage, season (Woods, Floerl and Hayden 2012; Fitridge, Dempster et al. 2012; Sievers, Fitridge et al. 2013; Watts, Goldstien and Hopkins 2015), local geomorphology and hydrodynamic characteristics. In Pelorus, freshwater river input creates strong salinity gradients in the inner sector modified by oceanic exchange from the upwelling waters of the Cook Strait (Figure 3-6). The tidal and wind-driven circulation system drives good flushing past mussel farms in or near the central channel, but this rate is reduced in side arms and embayments (Broekhuizen, Hadfield and Plew 2015). The mean water residence times vary from 21 days in Pelorus channel to 60 days in the Kenepuru. Annual mean temperatures are also warmer near the head of Pelorus, although Broekhuizen, Hadfield and

Plew (2015) recorded seasonal variation in this pattern with cooler winter temperatures and warmer summer temperatures near the head of Pelorus compared to the outer Sound (Figure 3-6).

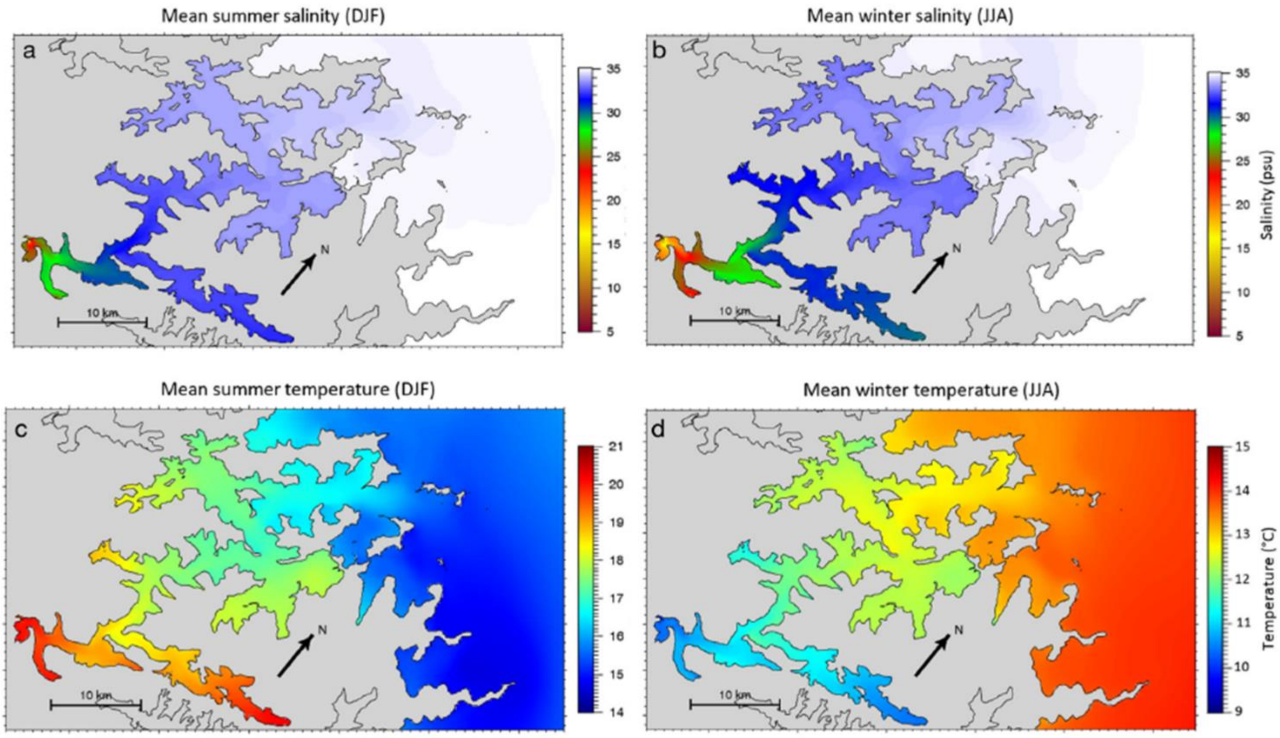

Figure 3-6: Seasonal temperature and salinity in Pelorus Sound. Summer (DJF: Dec 2012–Jan–Feb 2013) and winter (JJA: Jun–Jul–Aug 2013) mean (a, b) salinity and (c, d) temperatures from a Pelorus Sound model (figure by Mark Hadfield, NIWA). This model was compared with, and matched monthly CTD surveys conducted by NIWA in Pelorus Sound from 2012 to 2014 (Broekhuizen et al. 2015). Graphs are on a rotated map projection; colour scales represent temperature and salinity ranges and units.

The settlement of biota on mussel farms in Oyster Bay off the Tory Channel (QCS) is influenced by large tidal flows that keep the waters in this region well-mixed throughout the year (Hadfield, Broekhuizen and Plew 2014) (Figure 3-7). There is a flow of cooler and more saline water from Tory Channel into inner QCS that joins the prevailing estuarine circulation pattern in QCS. Cooler, deeper water from outer QCS also flows into the inner sound, which is then transported to the outer QCS as warmer surface waters out in a clockwise direction around Arapawa Island. This would influence habitat preferences by biota on the mussel farms in East Bay / Onakuku Bay. The inner and outer QCS are stratified in summer (warmer waters in surface layer). Flushing times vary as a result, with flushing occurring more quickly in summer as warmer waters are replaced by upwelled deeper water from Tory Channel. Residence times of water were estimated as being up to 35-46 days in the inner QCS and 11 days in Tory Channel.

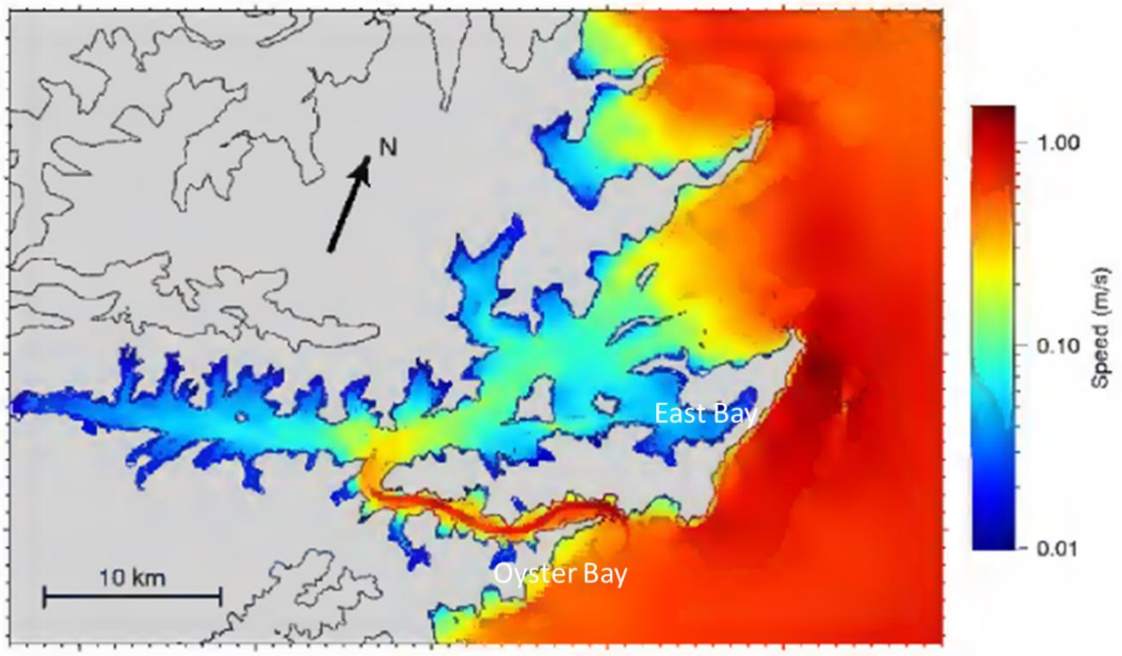

Figure 3-7: Mean current speeds in Queen Charlotte Sounds. Model of mean current speed based on one year's hourly data. The colour chart reflects the relative speed of the current in a log scale, with the red colour 100 times faster than the dark blue.

Our discussions on biodiversity focus on the inventory of species within suspended and seabed habitats across the sounds and their contribution to different functional feeding groups (FFGs). Functional diversity reflects the biological complexity of an ecosystem and, *inter alia*, its resilience to change, and to some extent may be the most meaningful way of assessing biodiversity while avoiding the difficult and usually impossible task of cataloging all species in marine ecosystems[58]. We consider the following FFGs among colonizing fauna: scavengers (including omnivores with a mixed diet of plant and detritus), suspension feeders (filter-feeders), deposit feeders, and predators. Scavengers eat particulate organic matter (detritus). Suspension feeders remove particles from the water column. Deposit feeders pick particles from the ocean bed and predators consume other living animals. A knowledge of feeding behaviors of colonising organisms underpins our interpretation of their environmental ES to the wider sounds' ecosystems.

3.2.1 Suspended habitats

Physical habitat characteristics

Green-lipped mussel spat is seeded out at approximately 1000 to 5000 spat per metre of rope and after three to six months, the nursery lines are lifted, and the young spat are stripped from the ropes and reseeded on a final production rope. There may, on occasion, be an intermediate reseeding step if juveniles become too densely packed at an early stage within the first six months. Juvenile mussels are reseeded onto thicker grow-out ropes at densities of 150 - 200 per metre and remain in the water for 12 to 18 months (Figure 3-8).

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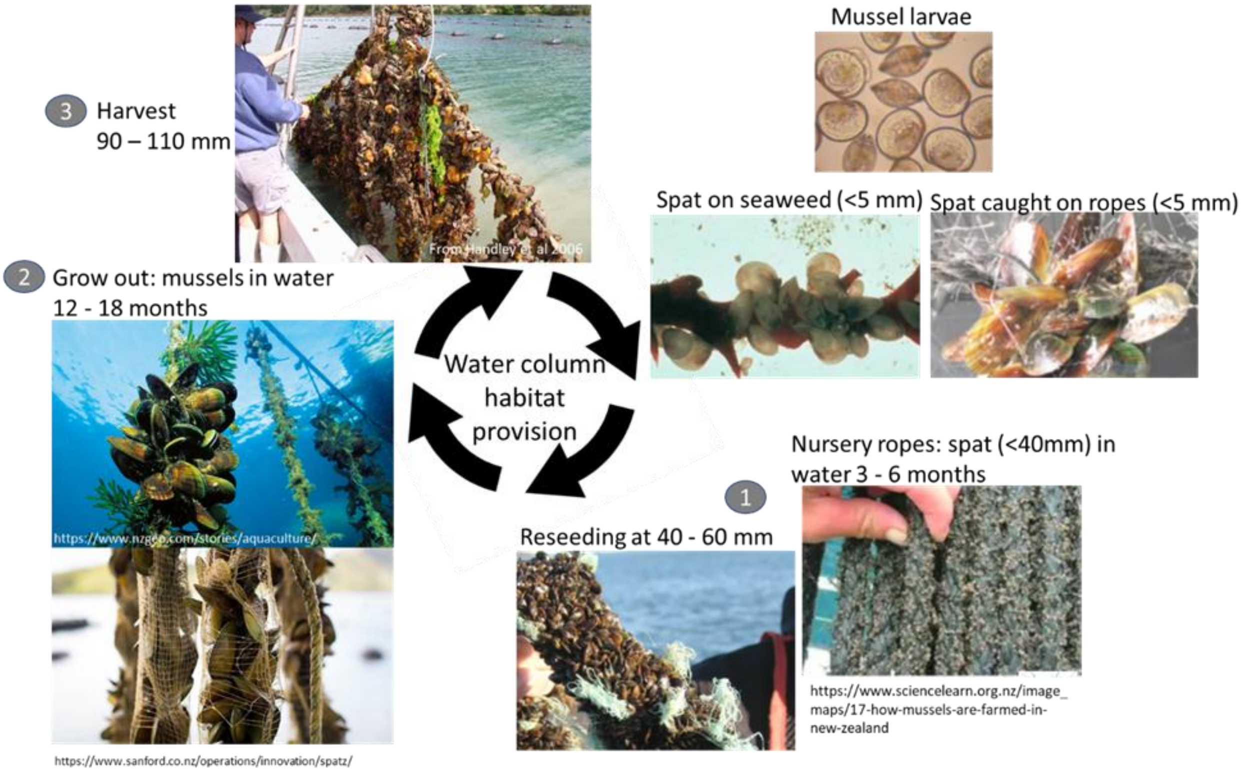
[58] Sohier, Charlotte (2009): Functional diversity in marine ecosystems. Available from http://www.coastalwiki.org/wiki/Functional_diversity_in_marine_ecosystems [accessed on 15-11-2018]



https://www.nzgeo.com/stories/aquaculture/

https://www.sciencelearn.org.nz/image_maps/17-how-mussels-are-farmed-in-new-zealand

https://www.sanford.co.nz/operations/innovation/spatz/

Figure 3-8: Habitat provision by mussel droppers in the water column at different stages of farm production.

Nursery and out-growing ropes provide short-term habitats that are rapidly colonised by an array of marine organisms including sessile taxa (algae, sponges, hydroids, anemones, bivalves, bryozoans and ascidians) and mobile taxa (flatworms, polychaete worms, amphipods, isopods, crabs, shrimps, starfish, brittle stars and fish) (Woods, Floerl and Hayden 2012). These species are so-called r-strategists whose populations are governed by rapid growth, maximum reproduction and short lifespans. Many are free spawners, the larvae of which settle in open spaces, on mussel shells and on the accumulating biota and some also occupy backbone ropes, floats, anchor warps and neighbouring mussel droppers.

Depending on water depth and farm location, attached biota can contribute a substantial proportion of the biomass on a mussel rope. Woods, Floerl and Hayden (2012) studied two farms exposed to strong tidal currents in the Pelorus channel (Capsize Pt and Yncyca Bay) during intermediate and final seed on-growing stages (each of 6 months duration, from December 2007 to May 2008) with sampling of mussel ropes at 0, 3, 5 and 6 months during each on-growing stage. Colonising biota represented ca. 54% of overall biomass on nursery ropes at the end of the first six months and ca. 15% at the end of out-growing (Figure 3-9). Suspension feeding organisms (blue mussels, bryozoans and ascidians) contributed the most to this biomass (ca. 88%). These authors found reduced biomass and less diversity in communities with increased depth on marine farm structures.

Watts, Goldstien and Hopkins (2015) determined percentage coverage by different taxa from photographic quadrants of droppers across 73 commercial farms from throughout the sounds (i.e., farms exposed to a wide range of hydrodynamic conditions) during summer (January 2013) (Figure 3-10). Here too, more biota was recorded near the surface of mussel long-lines but in this study, communities were dominated by red filamentous algae and the Asian kelp *Undaria pinnatifida* (macroalgae) and then suspension feeders - blue mussels, hydroids, bryozoans and ascidians. Less abundant taxa included sponges, anemones and mobile taxa, such as amphipods, isopods, sea cucumbers and crabs (Figure 3-11). Community structures were also influenced by location, specifically the inner sounds from the middle and outer areas. Overall biota cover was greatest in the outer sounds where hydroid species and macroalgae dominated within the surface 3 m of droppers. Blue mussel cover tended to be highest in the surface 3 m of droppers in the middle area and problematic exotic ascidians (*Didemnum vexillum* and *Ciona intestinalis*) had a tendency for high cover near the head of Pelorus Sound, also within the surface 3 m.

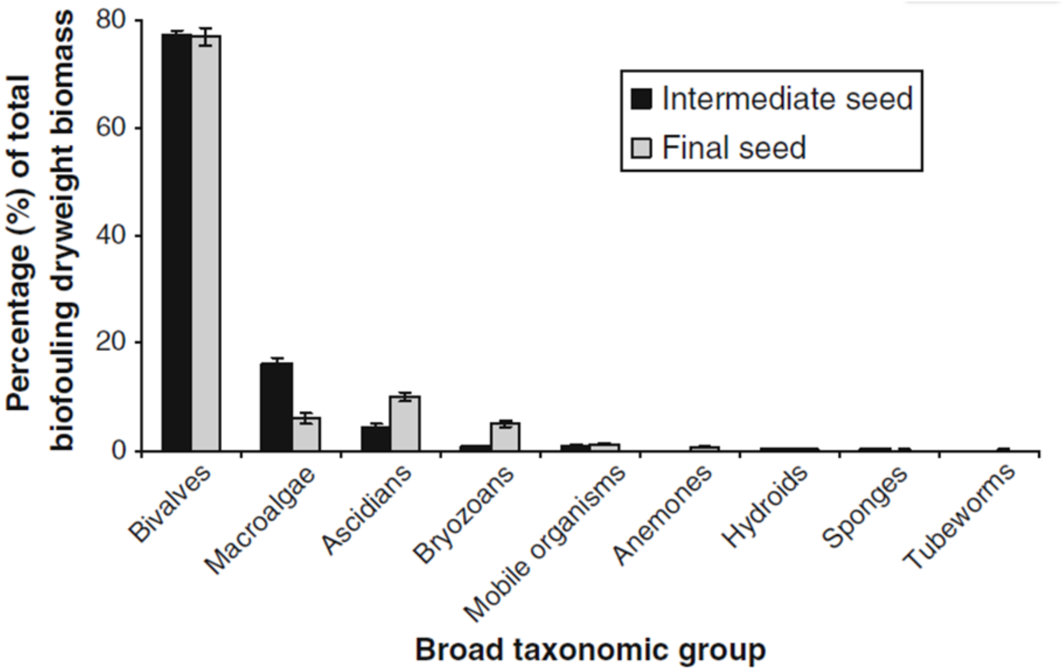


Figure 3-9: Percentage of total biofouling biomass on mussel droppers. Mean (± 1 SE) relative biomass (%) contribution of broad taxonomic groups of biofouling organisms to total biofouling biomass on mussel ropes for Intermediate and final seed crops. Data are averaged across two farms (Capsize Point and Yncyca Bay) and two sampling depths (2 an 8 m). Intermediate = 6-month old nursery rope (June – December 2007) and final seed = 6-month old grow-out rope (December 2007 – May 2008). (After Woods, Floerl and Hayden et al. 2012).

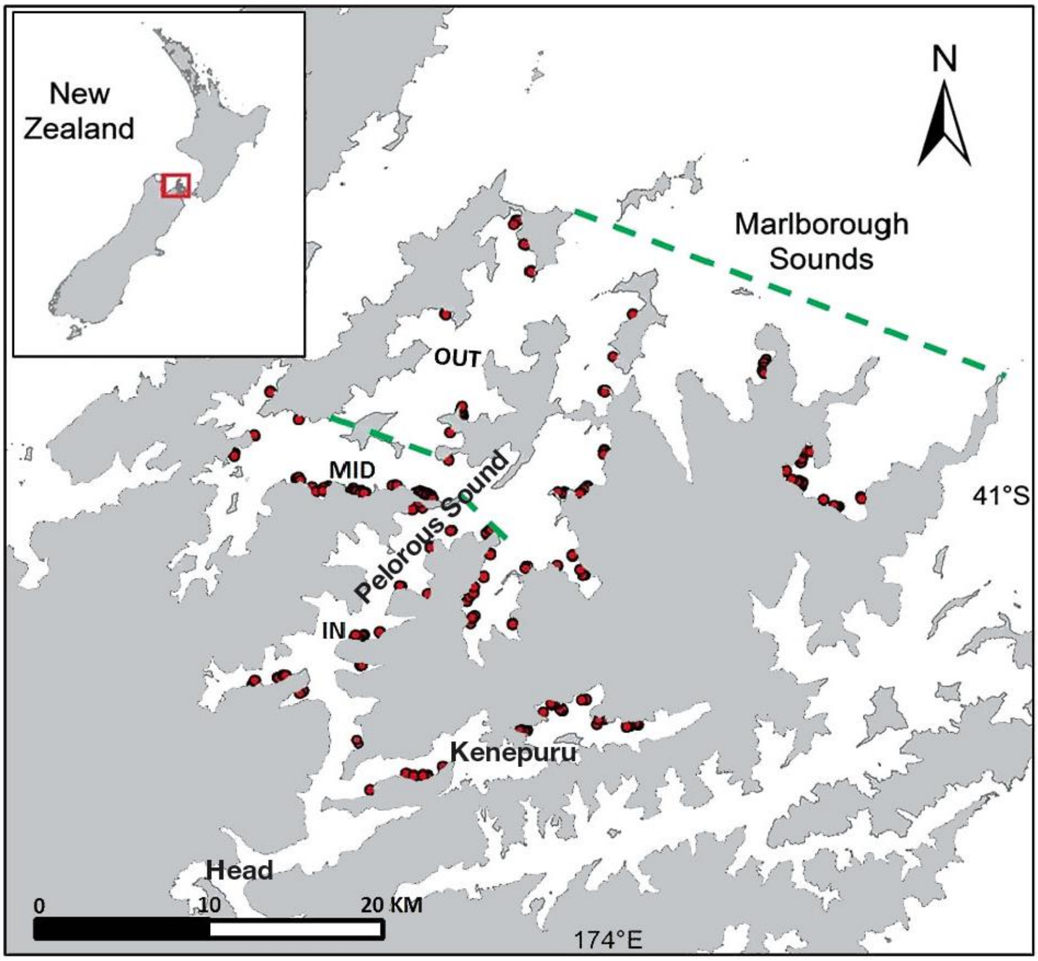


Figure 3-10: Location of commercial green-lipped mussel farms sampled in Pelorus Sound. (filled red circles), from the inner (IN), middle (MID), and outer (OUT) areas. Dashed green lines: delineation of the three areas. The 'head' of the Pelorus Sound and the Kenepuru Sound are indicated. (After Figure 1 in Watts, Goldstien and Hopkins 2015)

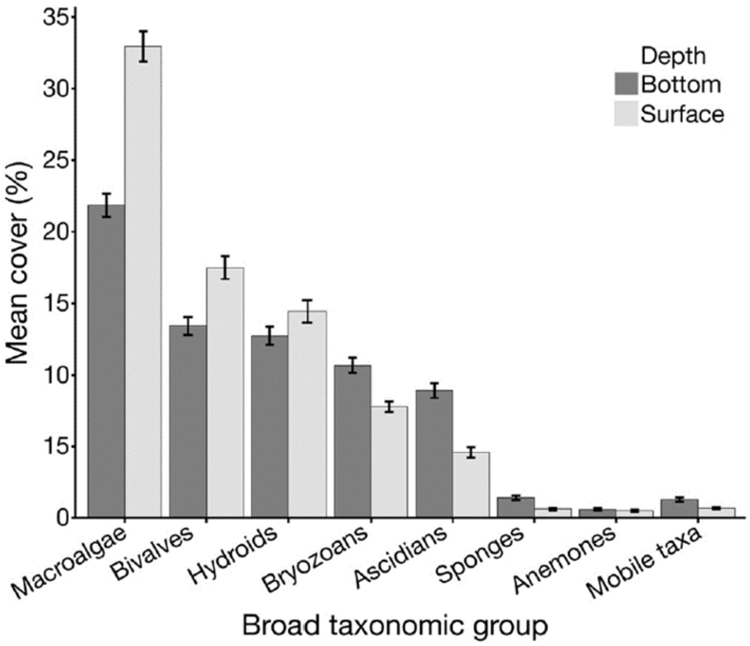


Figure 3-11: Percentage cover of epibiota on mussel droppers. Mean (±SE) percentage cover of the broad epibiotic taxonomic groups found at the surface and bottom of mussel droppers. Results are the means across 73 commercial farms sampled in January 2013 from the inner, middle and outer Pelorus Sound. After Figure 3 in Watts, Goldstien and Hopkins (2015).

While the spat ropes are in the water they provide micro-niches for the settlement of planktonic larvae such as the well documented incursions of juvenile blue mussels, *Mytilus galloprovincialis* on and between green-lipped mussel shells (Atalah, Rabel, and Forrest 2017, Forrest and Atalah 2017). *M. galloprovincialis* that settle on spat ropes are often carried over after reseeding and compete with green-lipped mussels for space on the grow-out ropes, and as mature adults will spawn and add to the plankton pool in the sounds. Encrusting organisms that settle on shell surfaces are the most likely to survive reseeding onto grow-out ropes; e.g, colonial tunicates such as *Didemnum* spp. which reach sexual maturity in just a few weeks and have extended breeding seasons. They attach tenaciously to substrates, but the tunic is flaccid and tears easily. If even a small bit adheres to any organisms that are transported, it can rapidly colonize a new substrate and may already be in reproductive mode (Lambert 2001). Organisms that are not firmly attached will be dislodged during reseeding and discarded overboard on site.

Seasons also influence the proportional settlement of the major taxa discussed above. In winter Handley, Sim-Smith et al. (2006) recorded the settlement of more species, especially among the macroalgae, ascidians and poriferans, in the inner Pelorus and a high proportion of macroalgae in the outer sounds (Horseshoe Bay). In summer the abundance of macroalgae, poriferans and bryozoans declined in the inner sounds and there was also a drastic decline in the variety of macroalgae in the outer area. It’s likely these shifts in taxa abundance from the head to the entrance of Pelorus are shaped not only by the spatial variability in the local hydrodynamics (salinity, temperature, current speeds, flushing rates) (Figure 3-12), but also seasonal nutrient dynamics and phytoplankton abundance (Broekhuizen, Hadfield and Plew 2015) as well as the seasonal breeding patterns of the biota.

Other studies have found that the occurrence and impacts of specific colonising species on marine farm structures varies spatially and temporally including variation in community structure among years, locations and depths (Watts, Goldstien et al. 2015 and references therein). Some biofouling populations also proliferate rapidly and then gradually retreat. This is especially true for taxa such as the ascidians, including invasive pest species such as *D. vexillum, Ciona intestinalis* and *Styela clava* (Valentine, Carman et al. 2007; Forrest, Hopkins et al. 2011, Fletcher, Forrest and Bell 2013).

However, despite the studies discussed above, our knowledge about the spatial and temporal variation of colonising organisms associated with these mussel farms is limited. Explanations presented for the observed distribution patterns are theoretical and no direct cause and effect studies have been undertaken to date.

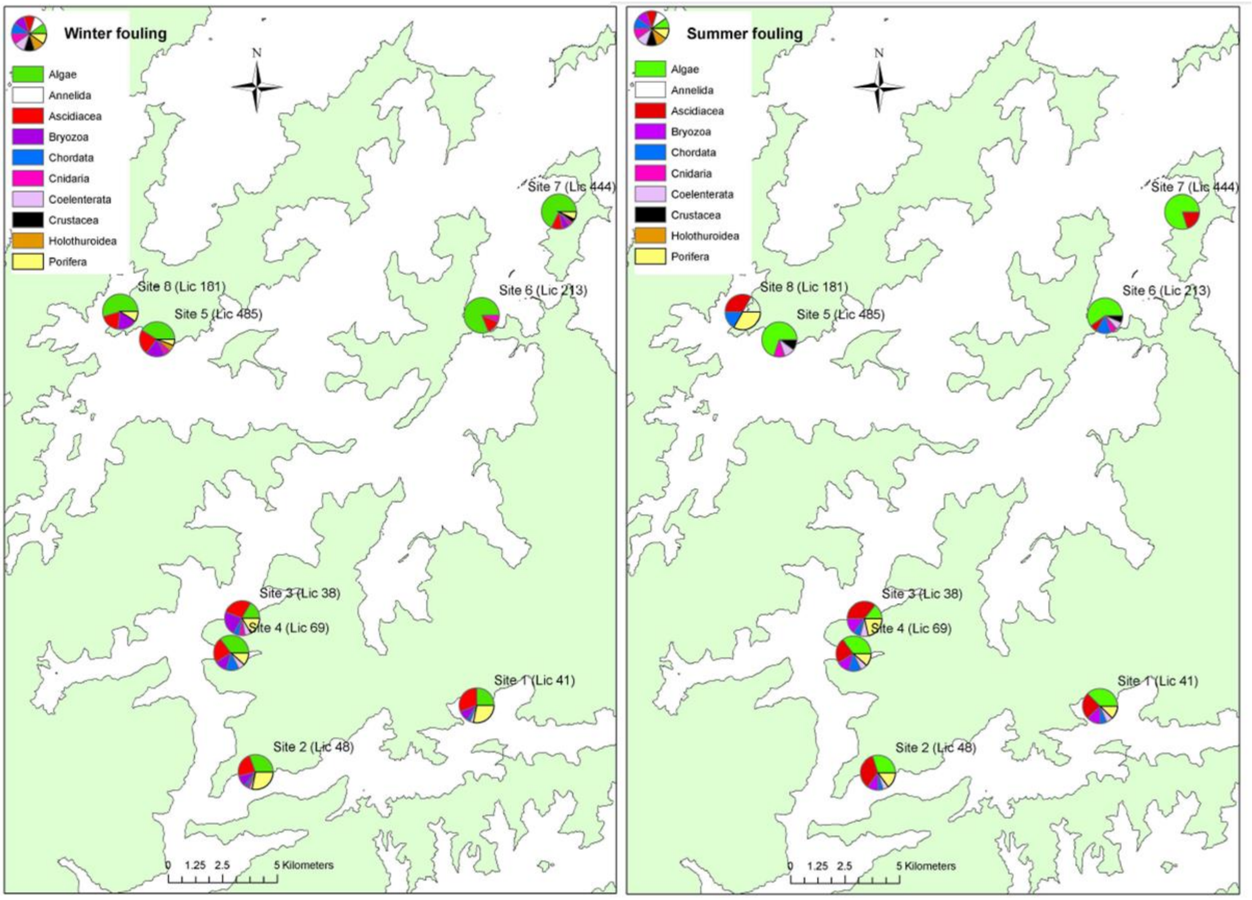


Figure 3-12: Spatio-temporal distribution of the major biota taxa on mussel farm structures. In the Pelorus Sound in winter 2005 and summer 2006. After Figure 1 in Handley, Sim-Smith et al. 2006

Handley, Sim-Smith et al. (2006) observed that except for macroalgae and some solitary ascidians, most species were in intimate ecological associations, often encrusting and overgrowing other species on the mussel structures in Pelorus Sound. These authors recorded relative abundance (0, absent to 5, abundant) of biota on different structural components of the farm, namely whether on buoys, longlines, droppers or green-lipped mussel shells and we have summarised these data in Figure 3-13.

The double backbones (longlines) were only occupied by macroalgae and sponges (Porifera) with green (Cladophora) and brown (Phaeophyta) macroalgae being the most abundant. *Undaria pinnatifida*, crowded the backbones on every farm surveyed. Eight taxa were found on buoys across the two seasons and sites but only between one to five of these taxa were present at any one time on any one buoy site. Sponges and hydroids (Cnidaria) were the most abundant, followed by ascidians. Hydroids were commonly attached to the submerged side of buoys. Tubeworms (Annelida) were recorded as an infestation on buoys in Hallam (Site 8) and Picnic Bays (Site 5) in the summer and bryozoans were abundant at inner sites in winter. The number of different taxa on buoys was greater at the inner sound sites (3 to 5 taxa) than towards the entrance (1 to 3 taxa).

There was an abundance of most taxa on droppers across all sites and seasons (except summer at the outer sound sites). In this study species numbers were significantly reduced in summer due to the disappearance of algae, sponges and bryozoans primarily from these sites. The sole echinoderm sp., the sea-cucumber *Australostichopus mollis,* was found as juveniles on the dropper lines amongst the mussels at Picnic Bay (site 5). The surface of green-lipped mussel shells was favoured by encrusting taxa; sponges, hydroids, bryozoans and ascidians.

The above studies suggest biota settlement patterns on these suspended habitats is dependent on the local water environment. This environment is shaped by local geomorphology, salinity (specially in Pelorus Sound where strong salinity gradients can occur from the head to the entrance), depth, currents, temperature, season and local food supply, specially plankton (phytoplankton and zooplankton) and seston for the abundant suspension feeders. The intrinsic breeding cycles of the invertebrates that colonise farm structures is also a factor, as is the growth cycle of macroalgae which thrive in autumn but not mid-summer. By example, industry have recognised that blue mussels spawn and their larvae settle on nursery droppers at different times of the year between the inner and outer sounds (John Young pers. comm.). A web tool has been developed that models the spatio-temporal patterns of blue mussel recruitment to help farmers synchronise seeding of green-lipped spat to prevent over-settlement by blues (Atalah, Rabel, and Forrest 2017).

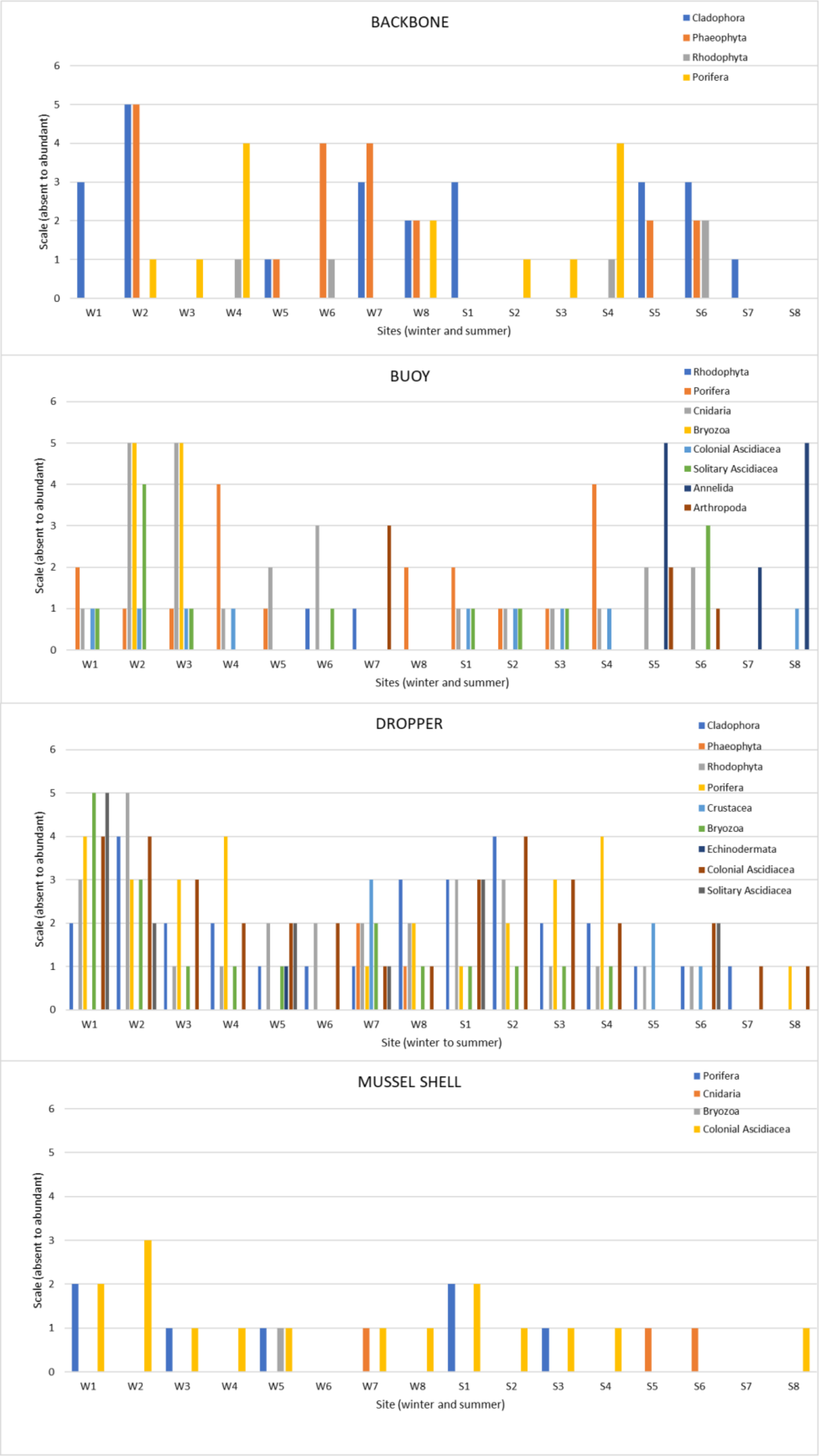


Figure 3-13: Habitat occupation on the structural components of a mussel farm by different taxa. Data are scaled from 0 (absent) to 5 (abundant). Data sourced from Handley, Sim-Smith et al. (2006). W1 to W8 = sites in winter; S1 to S8 = sites in summer.

Suspended biodiversity

The services provided by biofouling species are mostly EcolS, but these services are tempered by the presence of non-indigenous species among the suspended biotic community. ES is provided through primary production and nutrient regeneration.

We compiled a combined inventory of taxa on suspended mussel culture structures that were identified by Handley, Sim-Smith et al. (2006), Woods, Floerl and Hayden (2012) and Watts, Goldstien and Hopkins (2015) (Table 3-2). There was a total of 139 taxa plus a possible additional six unidentified macroalgae). Ascidians contributed the most taxa (33; 18 colonial spp. and 15 solitary spp.), followed by macroalgae (23 spp.), sponges (17 spp.), crustaceans - amphipods, isopods and crabs (16 spp.), cnidarians – hydroids and sea anemones (13 spp.), bryozoans (13 spp.) and annelids - tube worms, feather-duster worms and carnivorous polychaetes (11 spp.) (Figure 3-14). Of the 139 taxa, 70 specimens were identified to species level and among these, 17 were non-indigenous (24%), mostly among the bryozoans and ascidians. Images of some of these species are shown in Figure 3-15, Figure 3-16, Figure 3-17, Figure 3-18 and Figure 3-19.

All these colonising flora and fauna are considered biofouling pests by the industry but nonetheless their settlement is unavoidable, and they will always be part of the mussel-culture system and hence part of the wider sounds ecosystem.

Table 3-2: Species composition of biota communities on mussel farm structures in the Pelorus Sound. Y/N = present/absent within each study. IN = indigenous, NIN = non-indigenous. Note: sampling methods differed between studies.

Taxon	Group	Genus and species	no. unknown species	Watts et al. 2015	Woods et al. 2012	Handley et al. 2006	Indigenous (IN) or non-indigenous (NIN)[59]
				Y/N	Y/N	Y/N	
Macroalgae	Chlorophyta	*Cladophora* sp.	1	Y	Y	N	?
	(greens)	*Codium fragile*		Y	N	Y	?
		Green filamentous sp	1	Y	N	N	?
		Ulva sp.	1	Y	Y	Y	?
	Phaeophyta	*Carpophyllum maschalocarpum*		N	N	Y	IN
	(browns)	*Colpomenia* sp.	1	Y	Y	Y	?
		Macrocystis pyrifera		Y	N	N	IN
		Scytosiphon sp.	1	N	N	Y	?
		Spatoglossum sp.	1	Y	N	N	?
		Striaria attenuata		N	N	Y	NIN
		Undaria pinnatifida		Y	Y	Y	NIN
	Rhodophyta	*Asparagopsis* sp.	1	Y	Y	N	?
	(reds)	*Brongniartella australis*		N	Y	N	IN
		Ceramium uncinatum		N	Y	N	IN
		Ceramium sp.	1	Y	Y	N	?
		Echinothamnion lyalli		Y	Y	N	IN

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[59] https://www.marinebiosecurity.org.nz/project-map-all-data/

Taxon	Group	Genus and species	no. unknown species	Watts et al. 2015	Woods et al. 2012	Handley et al. 2006	Indigenous (IN) or non-indigenous (NIN)[59]
		Gigartina sp.	1	N	N	Y	?
		Gracilaria sp.	1	Y	N	N	?
		Lophurella sp.	1	N	Y	N	?
		Myriogramme sp.	1	N	Y	N	?
		Polysiphonia abscissoides		N	Y	N	IN
		Porphyra sp.	1	Y	N	N	?
		Schizoseris sp.	1	N	N	Y	?
		Unknown	1	Y	N	Y	?
		Unknown	2	Y	N	Y	?
		Unknown	3	Y	N	Y	?
		Unknown	4	Y	N	Y	?
		Unknown	5	Y	N	Y	?
		Unknown	6	N	N	Y	?
Porifera	Haplosclerida	*Callyspongia* sp.	1	N	N	Y	?
(Sponges)		*Callyspongia* sp.	2	N	N	Y	?
	Halichondrida	*Halichondria* sp.	1	Y	Y	Y	?
		Halichondria sp.	2	N	N	Y	?
		Halichondria sp.	3	N	N	Y	?
		Halichondria sp.	4	N	N	Y	?
		Halichondria sp.	5	N	N	Y	?
		Halichondria sp.	6	N	N	Y	?
		Halichondria sp.	7	N	N	Y	?
		Halichondria sp.	8	N	N	Y	?
		Halichondria sp.	9	N	N	Y	?
		Haliclona sp.	1	Y	Y	Y	?
		Haliclona sp.	2	N	N	Y	?
	Suberitida	*Hymeniacidon* sp.	1	N	N	Y	?
	Tedaniidae	*Tedania* sp.	1	N	N	Y	?
	Sycettidae	*Sycon* sp.	1	Y	Y	N	?
		Sponge ?	1	Y	N	N	?
Cnidaria	Hydrozoa	*Amphisbetia bispinosa*		Y	Y	N	IN
	hydroids	Hydroid sp.	1	Y	N	Y	?
		Hydroid sp.	2	Y	N	N	?
		Plumularia setaceoides		N	Y	N	IN
		Sertularella sp.	1	Y	Y	N	?
		Silicularia rosea		N	Y	N	IN

Taxon	Group	Genus and species	no. unknown species	Watts et al. 2015	Woods et al. 2012	Handley et al. 2006	Indigenous (IN) or non-indigenous (NIN)[59]
		Symplectoscyphus johnstoni		N	Y	N	IN
	Anthozoa	*Actinothoe albocincta*		Y	Y	N	IN
	sea anemones	*Bunodeopsis* sp.	1	Y	N	N	?
		Culicia rubeola		Y	N	N	IN
		Diadumene neozelanica		N	Y	N	IN
		Diadumenidae sp.	1	Y	N	N	IN
		Anthozoan *sp.*	1	N	N	Y	?
Platyhelminthes	Polycladida	*Stylochus sp.*	1	N	Y	N	?
Annelida		Oligochaete sp.	1	N	Y	N	?
	Terebellida	*Neoleprea papilla*		N	Y	N	IN
		Terebella plagiostoma		N	Y	N	IN
	Sabellida	*Galeolaria hystrix*		Y	Y	N	IN
		Megalomma sp.	1	N	Y	N	?
		Pomatoceros sp.	1	Y	N	N	?
		Serpulidae sp.	1	Y	N	N	?
		Spirorbidae sp.	1	Y	N	N	?
	Phyllodocida	*Lepidonotus polychromus*		N	Y	N	IN
	Nereididae	*Nereis falcaria*		N	Y	N	IN
		Perinereis pseudocamiguina		N	Y	N	IN
Crustacea	Amphipoda	*Amphithoe* sp.	1	N	Y	N	?
		Apocorophium acutum		N	Y	N	NIN
		Caprella equilibra		N	Y	N	IN
		Caprella sp.	1	Y	N	N	?
		Gammaropsis typica		N	Y	N	IN
		Ischyrocerus longimanus		N	Y	N	IN
		Ventojassa frequens		N	Y	N	IN
	Isopoda	*Paridotea ungulata*		Y	Y	N	IN
	Brachyura	crab sp.	1	Y	N	N	?
		Halicarcinus innominatus		N	Y	N	IN
		Halicarcinus varius		N	Y	N	IN
		Halicarcinus sp.	1	Y	N	N	?
		Hemigrapsus sp.	1	Y	N	N	?
		Notomithrax minor		Y	Y	N	IN
		Notomithrax peronii		Y	Y	N	IN
	Caridea	*Hippolyte bifidirostris*		N	Y	N	IN
	Sessilia	*Balanus trigonus*		Y	N	N	IN

Taxon	Group	Genus and species	no. unknown species	Watts et al. 2015	Woods et al. 2012	Handley et al. 2006	Indigenous (IN) or non-indigenous (NIN)[59]
		Elminius modestus		Y	N	N	IN
Mollusca	Bivalvia	*Limaria orientalis*		N	Y	N	NIN
		Modiolarca impact		N	Y	N	IN
		Mytilus galloprovincialis		Y	Y	N	IN
		Pecten novaezelandiae		N	Y	N	IN
		Talochlamys zelandiae		N	Y	N	IN
Bryozoa	Cheilostomata						
	Erect	*Bugula* sp.	1	Y	N	Y	?
		Bugula sp.	2	N	N	Y	?
		Bugula sp.	3	N	N	Y	?
		Bugula stolonifera		Y	Y	N	NIN
		Bugula flabellate		Y	Y	N	NIN
		Bugula neritina		Y	Y	N	NIN
		Caberea zelandica		N	Y	N	IN
		Unknown sp.	1	Y	N	Y	?
	Encrusting	Bryozoan sp.1	1	Y	N	Y	?
		Electra scuticifera		N	Y	N	IN
		Watersipora sp.	1	Y	N	Y	NIN
		Watersipora arcuata		N	Y	N	NIN
		Watersipora subtorquata		N	Y	N	NIN
Echinodermata	Aspidochirotida	*Australostichopus mollis*		Y	N	Y	IN
	Ophiuroidea	*Ophionereis fasciata*		Y	Y	N	IN
	Asteroidae	*Coscinasterias muricata*		Y	Y	N	IN
		Patiriella sp.		Y	N	N	IN
Ascidiacea	Colonial	*Aplidium phortax*		Y	Y	N	IN
tunicates		*Botrylloides leachii*		Y	Y	N	NIN
		Botryllus schlosseri		Y	Y	N	NIN
		Colonial ascidian sp.	1	Y	Y	Y	?
		Colonial ascidian sp.	2	Y	N	Y	?
		Colonial ascidian sp.	3	Y	N	Y	?
		Colonial ascidian sp.	4	Y	N	Y	?
		Colonial ascidian sp.	5	Y	N	Y	?
		Colonial ascidian sp.	6	N	N	Y	?
		Didemnum incanum		Y	N	N	IN
		Didemnum lambitum		Y	N	N	IN
		Didemnum vexillum		Y	N	N	NIN
		Didemnum sp.	1	Y	Y	N	?

Taxon	Group	Genus and species	no. unknown species	Watts et al. 2015	Woods et al. 2012	Handley et al. 2006	Indigenous (IN) or non-indigenous (NIN)[59]
		Diplosoma sp.	1	Y	N	N	?
		Diplosoma listerianum		N	Y	N	NIN
		Diplosoma velatum		N	Y	N	IN
		Leptoclinides novaezelandiae		Y	N	N	IN
		Lissoclinum notti		Y	Y	N	IN
	Solitary	*Ascidiella aspersa*		Y	N	N	NIN
		Asterocarpa humilis		Y	Y	N	IN
		Ciona intestinalis		Y	Y	Y	NIN
		Cnemidocarpa bicornuta		Y	Y	N	IN
		Cnemidocarpa hemprichi		N	Y	N	IN
		Corella eumyota		Y	Y	N	IN
		Molgula sp.		Y	N	N	?
		Pyura pachydermatina		Y	N	N	IN
		Solitary ascidian sp.	1	Y	N	Y	?
		Solitary ascidian sp.	2	Y	N	Y	?
		Solitary ascidian sp.	3	Y	N	Y	?
		Solitary ascidian sp.	4	Y	N	Y	?
		Solitary ascidian sp.	5	Y	N	Y	?
		Solitary ascidian sp.	6	Y	N	Y	?
		Solitary ascidian sp.	7	N	N	Y	?
Teleostei	Tripterygiidae	*Fosterygion varium*		Y	Y	N	IN

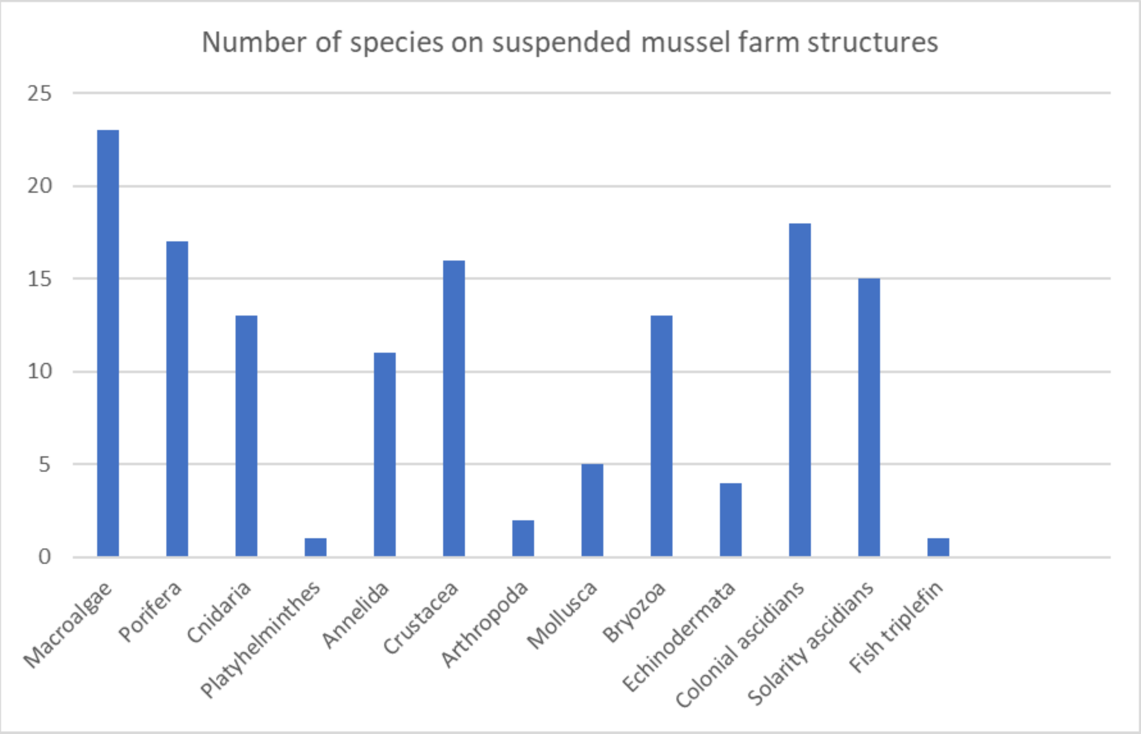

Figure 3-14: Number of species per taxon on suspended mussel farm structures.

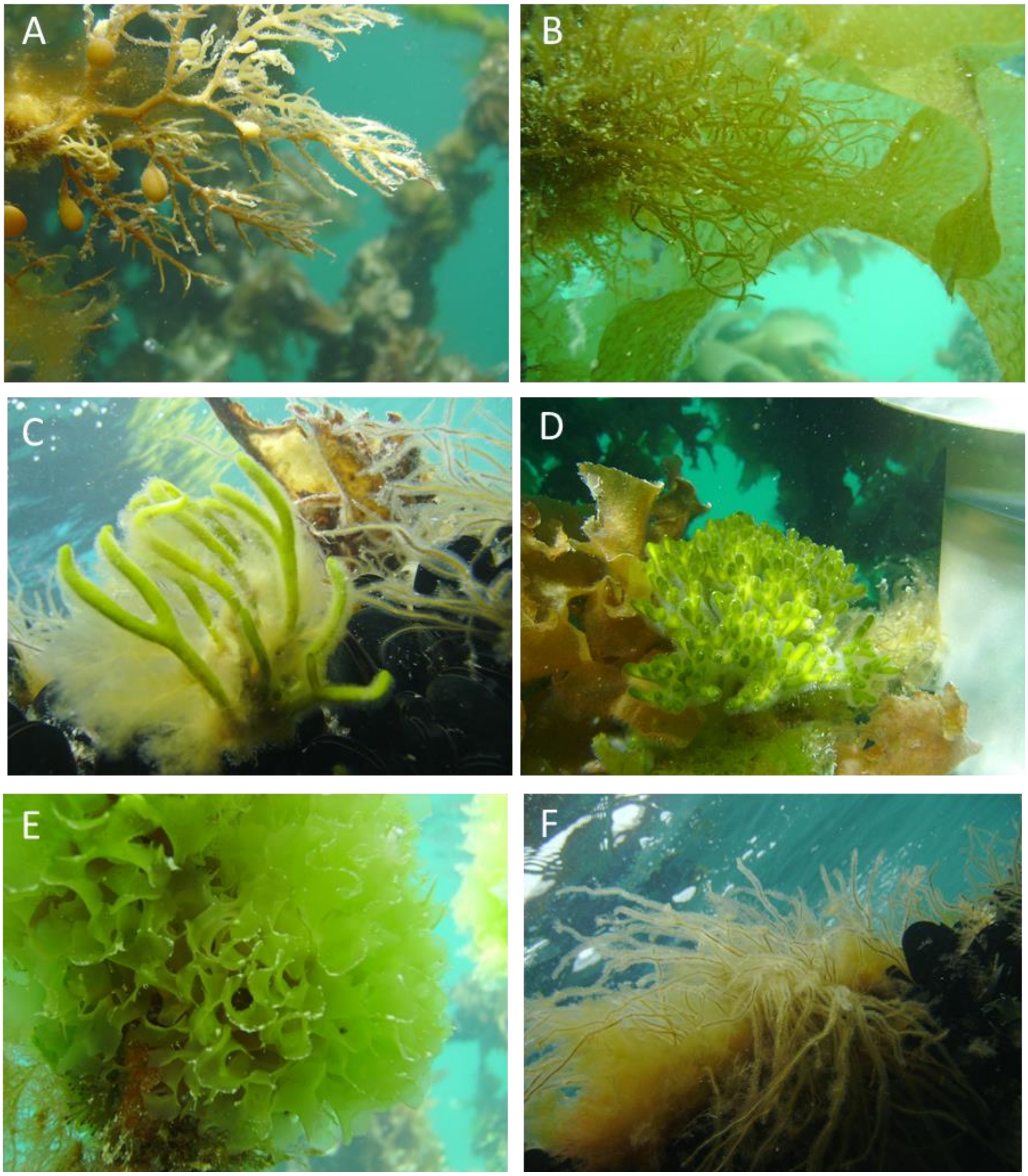

Figure 3-15: Macroalgae associated with droppers on green-lipped mussel farms in the Marlborough Sounds. (A) *Phyllotricia* sp. *or Cystophora* sp.*,* (B) *Cutleria multifida*. (C) *Codium* sp. *1.* (D) *Codium* sp. *2*. (E) *Ulva* sp. (F) *Scytosiphon* sp. Photo credits, Sheryl Miller, NIWA.

Figure 3-16: *Undaria pinnatifida* growing on mussel lines in the Marlborough Sounds. (A) and (B) *Undaria* sporophytes (reproductive structure). (C) and (D) *Undaria* growth on droppers. Photo credits Sheryl Miller, NIWA.

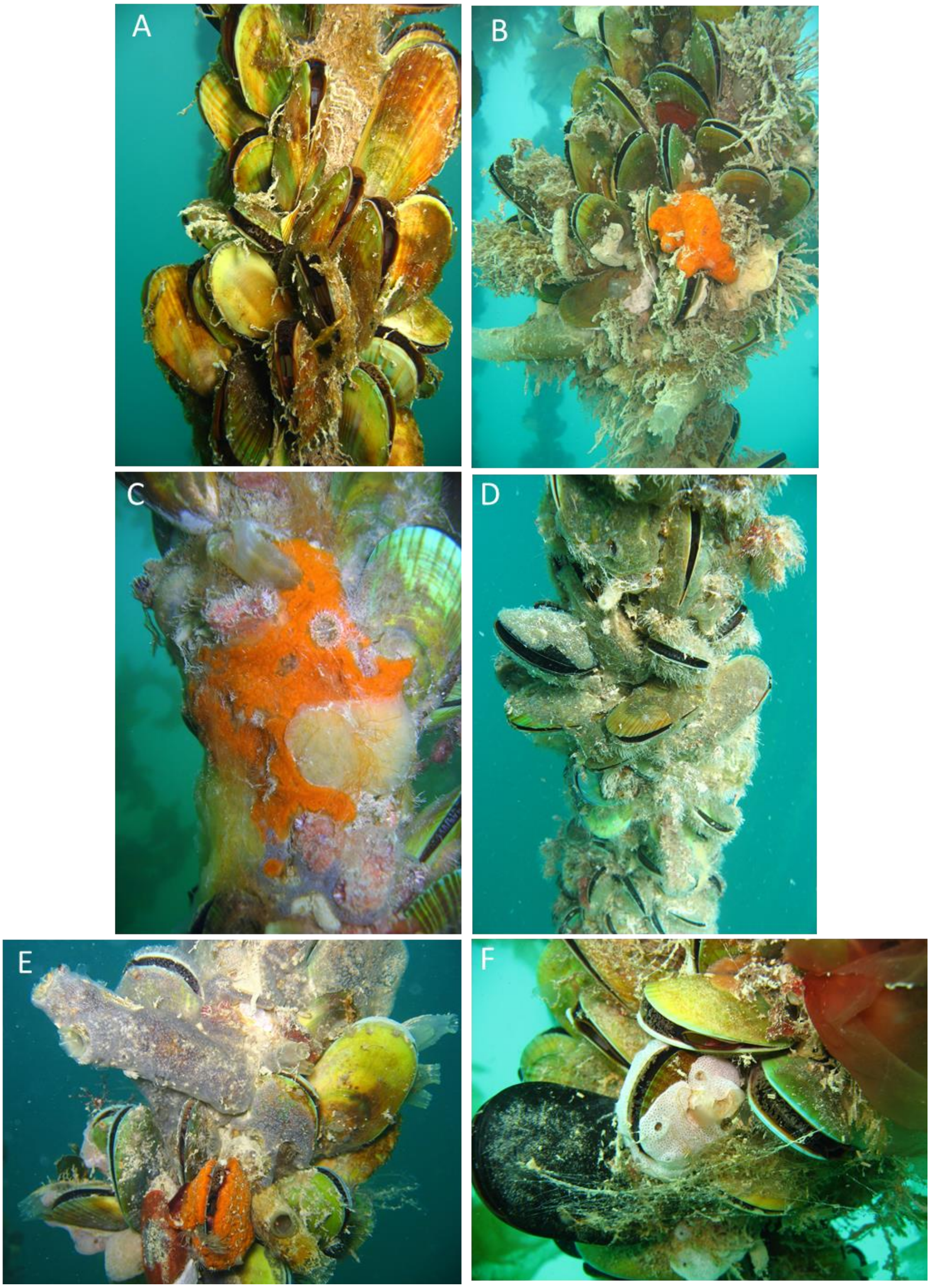

Figure 3-17: Fauna associated with mussel lines on green-lipped mussel farms in the Marlborough Sounds. (A) Relatively clean mussels; and mucilaginous diatom cover. (B) Solitary ascidians (*Ciona intestinalis*); colonial ascidians; encrusting bryozoans; sponges; hydroids; and mucilaginous diatom cover (appears as a coating of sediment-like slime). (C) Colonial ascidians; solitary ascidians; sea anemones; and terebellid worm (fine orange tentacles). (D) Colonial ascidians, sea anemones; and sponges (E) Colonial ascidians (e.g., *Diplosoma* sp.); and solitary ascidians (*Ciona intestinalis*). (F) Colonial ascidian (*Lissoclinum notti*). Photo credits Chris Woods, NIWA.

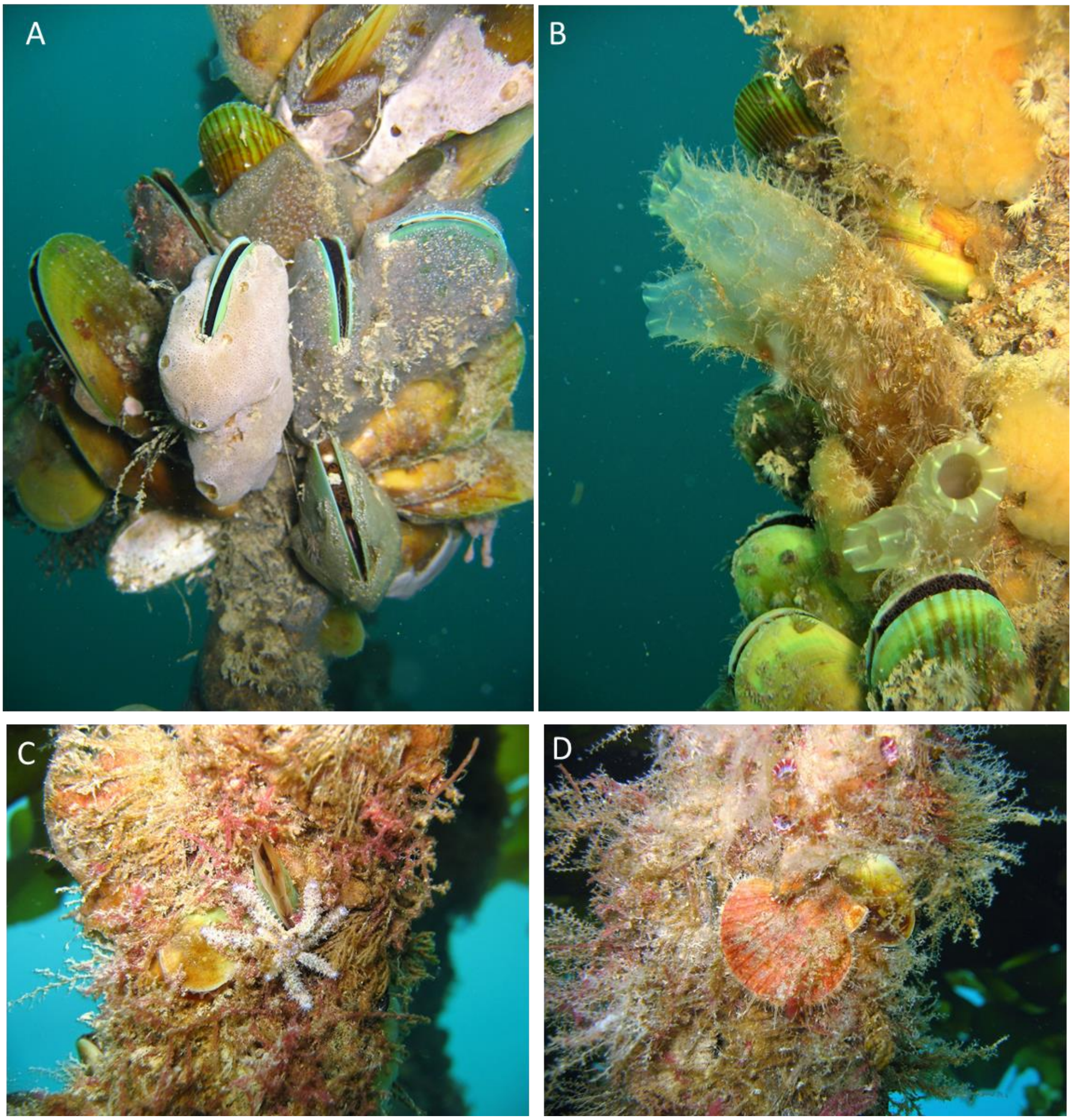

Figure 3-18: Fauna associated with mussel lines on green-lipped mussel farms in the Marlborough Sounds. (A) Colonial ascidians. (B) Solitary ascidians (*Ciona intestinalis*); colonial ascidians; caprellid amphipods; and sea anemones. (C) Juvenile starfish settled on line (*Coscinasterias muricata*); red alga; and hydroids. (D) Juvenile scallop settled on line (*Pecten novaezelandiae*); red alga, hydroids; and solitary ascidians. Photo credits: Chris Woods, NIWA.

Figure 3-19: Fauna associated with mussel lines on green-lipped mussel farms in the Marlborough Sounds. (A) Blue mussels (*Mytilus galloprovincialis*); red alga; green alga (*Ulva* sp.); and brown alga (*Undaria pinnatifida*). (B) Erect bryozoans; and blue mussels. (C) Solitary ascidians (*Pyura pachydermatina*); erect bryozoans, hydroids; drift brown alga (*Macrocystis pyrifera*). (D) Blue mussels (*Mytilus galloprovincialis*) on a backbone. Photo credits: Chris Woods, NIWA.

The majority of the macroalgae taxa were red algae (12 species plus a possible further six unidentified species) (Table 3-2). All algae are ecologically significant as primary producers, providers of structural habitat for other marine organisms, and through their important role in the primary establishment and maintenance of marine ecosystems. Algae fragment when grazed or abraded and the resultant particulates become a food source in the water column or sink to the seabed to be consumed by detritivores or to be sequestered into sediments. The invasive *Undaria pinntifida* was by far the most prolific macroalgae in terms of contributing biomass (see Section 3.2.1 and Figure 3-16) and was recorded on all farms surveyed in the three studies. Clearly suspended habitat provided by mussel lines and the environmental conditions in the Marlborough Sounds favour the life cycle of this species. The macroscopic sporophytes grow during winter and release spores as summer approaches which disperse, settle and germinate into gametophytes. When conditions are favourable these gametophytes produce sperm and eggs which fertilise and grow into the plant i.e. the sporophyte (see Figure 3-16). Temperature, light and depth are all important cues in development[60]. Although not yet conclusive, *Undaria* may cause some ecological impact, but it does not appear to drive ecosystem change in most invaded regions (Epstein and Smale 2017). One other macroalgae found on droppers is non-indigenous, *Striaria attenuate* (arrived ca. 1957) (Nelson and Maggs 1996). There are three subspecies of *Codium fragile* in New Zealand, one of which is indigenous and the other two non-indigenous (arrived ca. 1972) (Kate Neill, NIWA. pers. comm.). We do not know which subspecies was recorded by Handley, Sim-Smith et al. (2006) and Watts, Goldstien and Hopkins (2015).

Clearly macroalgae biomass on farms can be significant but we have no current measure of the primary production rates or average biomass per unit area of marine farm across the sounds to be able to quantify the services to the overall primary production of the sounds. The harvest of *Undaria* (currently 150 tonnes per annum, but likely to increase) represents some removal of nitrogen from the sounds (see section 3.1.2). In terms of contribution to the food web, likely resident grazers of macroalgae on droppers are amphipods and isopods although these taxa would also feed on diatom mats and detritus and we have therefore placed this group in the scavenger category in our FFG analysis. After macroalgae are stripped from crop-lines and discarded, they contribute to the benthic food web either by continuing to grow as whole plants, or as fragments that enter the detrital pool.

There was great diversity among sponges which were differentiated but not identified to species level in the Handley, Sim-Smith et al. (2006) study. Nearly all belong to the class Demospongiae, the most common group found throughout New Zealand (Kelly 2015; Rush and Kelly 2017). These are silica-based encrusting sponges that are likely self-perpetuating within and between mussel farms through free spawning. One calcareous species was recorded (*Sycon sp.*). Sponges filter small particulates from water that passes through their bodies.

Seven hydroid and six sea anemone species were recorded (Table 3-2) and like sponges, they attach onto hard substrata such as mussel shells and other encrusting organisms. They are predatory on small invertebrates such zooplankton and tiny amphipods and isopods.

The Annelida were represented by two species of terrebellids (spaghetti worms); these are semi-sessile deposit feeders that extend long white tentacles from their tubes to gather surface particulates that coat the droppers and other colonising organisms. Three predatory polychaete species were among the Annelida (phyllodocids): these are mobile species that move across surface of the droppers in search of prey.

Five species of sabellid worms were recorded, all of which are sessile tube-living filter feeders. One species, *Galeolaria hystix*, is the largest and most significant aggregating serpulid in New Zealand and has been recorded on the seabed in the sounds (Anderson, Morrison et al. 2018). They have a

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[60] http://www.iucngisd.org/gisd/species.php?sc=68 on 15-11-2018.

distinctive bright red branchial crown and live in calcareous tubes. This species can grow as individuals or in colonies that can form complex benthic mounds (or reefs) that can become more than a metre high and several metres in diameter (MacDiarmid, Bowden et al. 2013).

The Crustacea were represented by seven amphipod species, one isopod, seven crabs and one shrimp (*Hippolyte bifidirostris*), all of which are mobile foragers feeding on varied diets of algae, detritus, dead and/or living animals. We therefore consider each species as a scavenger. The amphipod *Apocorophium acutum* is a non-indigenous species. Two filter-feeding barnacle species were also among the crustaceans, *Balanus trigonus* and *Elminius modestus* both of which have spread around the world from their native origins, mainly through attachment onto the hull of ships. There are no specific economic or ecological impacts reported for these species.

Besides green-lipped mussels, five species of filter-feeding bivalves colonised mussel farms, the most conspicuous being *M. galloprovincilias* (see Figure 3-19). There were two pectin species, the small fan shell *Talochlamys zelandiae*, a species usually found under rocks at low tide to 40 m, and juvenile scallops, *Pecten novaezelandiae*. The other two species, *Limaria orientalis* and *Muscula impactus* are small bivalves usually associated with rocky/cobble below mid-tidal areas, the former being an invasive species first recorded in New Zealand in 1972.

Bryozoans, small filter-feeding colonial organisms, were recorded in two groups, arborescent (branching, and tree-like) (8 species) and encrusting (5 species). Most species from the former group belong to the genus *Bugula,* an assemblage considered as biofouling bryozoans that have spread worldwide via ship's hulls (i.e., likely to all be non-indigenous species). The encrusting species *Electra scruticifera* is endemic and forms irregular circular, linear or lobed patches on blades of red and brown algae (Gordon and Hills 2016). *Watersipora* species appear to be introduced to New Zealand and are widely distributed around the globe. They settle on hard substrata and *Watersipora subtorquata,* for instance, is known to outcompete congeneric species in some areas of its introduced range[61].

Four species of echinoderms were found on mussel farm structures. Juveniles of the deposit feeding sea cucumber *Australostichopus mollis* are often found on droppers, feeding on detritus in the crevices between green-lipped mussels and colonising organisms. The seabed below mussel farms are often heavily populated by *A. mollis* (Davey, Stenton-Dozey et al. in prep) and it is tempting to theorise that farm structures provide an EcolS service to the life cycle of this species. The benthic adults spawn from October to February in synchronicity with lunar cycles (Morgan 2009) and free-swimming larvae settle after 24 hours (Stenton-Dozey and Heath 2009). Droppers provide complex microhabitats, especially during the second production cycle, for both larvae settlement and subsequent predator-evasion. These juveniles are returned to the seabed when biofouling material is discarded at harvest. Of the three starfish species, two are scavengers, the brittle star *Ophionereis fasciata* and the cushion star, *Patiriella* sp. and the other, the eleven-armed starfish, *Coscinasterias muricata*, is a predator with a preference for mussels.

Suspension-feeding colonial and solitary ascidian species (tunicates, sea squirts) were abundant on mussel droppers (18 and 16 species respectively) but although several were distinguishable as separate species, genus-identities were not recorded in the three studies from which Table 3-2 was complied.

Colonial *Aplidium phorta* is a very common species fouling wharf piles and aquaculture structures in ports, bays, and harbours; *Botrylloides leachiiis* and *Botryllus schlosseri* are encrusting ascidians that

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[61] http://www.exoticsguide.org/watersipora_subtorquata

often co-occur - both species have been introduced into New Zealand; *Didemnum incanum* and *D. lambitum* form species complexes (indistinguishable from one another) and are common on marine farm lines; *Diplosoma listerianum* (non-indigenous) and *D. velatum* encrust a variety of submerged surfaces including shellfish, algae and barnacles; *Leptoclinides novaezelandiae* often encrusts other ascidians and overgrows sessile fauna on marine farms and *Lissoclinum notti* is common on shallow subtidal reefs, wharf piles and aquaculture structures (see Figure 3-17, (F)) (Page and Kelly 2016).

Didemnum vexillum is an exotic ascidian and problematic for the mussel farming industry where it can form extensive sheets over green lipped mussels. Cylindrical or frondlike outgrowths can often arise off the main colony which can form extremely long dripping tendrils, sometimes meters long. The spread of this species is actively managed by the aquaculture industry in the sounds (see section 2.2.3).

The solitary ascidian *Ascidiella aspersa* (non-indigenous) is a distinctive dark chocolate brown to black colour and encrusts bivalves, solitary ascidians and dead black coral trees - it is more typically recorded from Bluff to Fiordland; *Asterocarpa humilis* is often found on bivalves around New Zealand; *Ciona intestinalis* is a problematic invasive species for industry and can be found in high abundance on aquaculture structures covering green-lipped mussels; *Cnemidocarpa* species are often fouled with hydrozoans, bryozoans and filamentous algae and can be locally abundant on shallow reefs; *Corella eumyota* prefers calm protected waters, found in shallow subtidal environments attached to submerged structures and *Molgula* species are tolerant of high sediment and low salinity and may occur in large aggregations on the seafloor living among shells and other large solitary ascidians and lastly, *Pyura pachydermatina*, the ‘sea tulip’, grow in high energy environments and can form dense forests on the sea floor from the intertidal down to greater than 30 m (Page and Kelly 2016).

The only fish species found within droppers was the triplefin (*Fosterygion varium*), a native to New Zealand, that can be found in rock pools and depths down to 30 metres in reef areas of broken rock with kelp. Other fish species that associate with crop-lines are discussed in the section on fish (3.7).

Approximately 61% of all colonising fauna were suspension feeding species, 14% were scavengers, 15%, predators and 10%, detritivores (Figure 3-20). The dominance of suspension feeders is an important contribution to the food web of the sounds. This FFG filters particles, including phytoplankton, particulate organic matter, inorganic particles, and planktonic larvae of some marine invertebrates, from the water column and discharge faeces, a process that removes phytoplankton and biotic and abiotic particulates from suspension and transfers organic- and nutrient-rich particulates into the water column and to the seabed. Bivalves in particular can continuously filter large volumes of water (see section 3.10) thereby creating micro-currents around crop-lines and the attached organisms. Although there is no evidence that cultured green-lipped mussels are having a substantial influence upon concentrations of suspended inorganic sediment measured in the upper parts of the water-column in the sounds, they, like all suspension feeders, play a role in remineralisation of organic matter. Indeed, in the most intensively farmed area in the sounds (Beatrix Bay), mussel crop-mediated rates of mineralization of suspended particulate organic matter may exceed those arising from ‘natural’ (primarily bacterial) processes. For example, it has been variously estimated that mussels filter around 10% of the bay’s volume per day (unpublished advice to the Marlborough Sounds Aquaculture Working Group[62]). If all the organic matter consumed by mussels were to be mineralized (in reality, most is, but some is retained as additional mussel flesh),

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[62] One member of the group calculated that the filtration rate might be 25% /d, but most other members felt this calculation relied upon extreme worst-case assumptions.

this implies that mussels drive a mineralization rate of 10-20% d^{-1}. ‘Natural’ (predominatly, bacterially-mediated) mineralization rates for phytoplankton-derived detritus are around 2-5% d^{-1}.

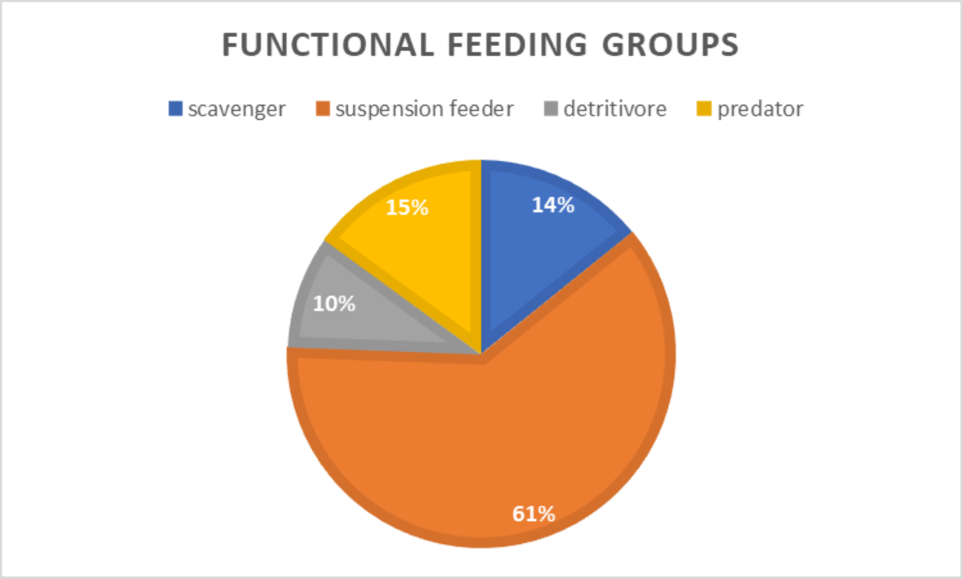


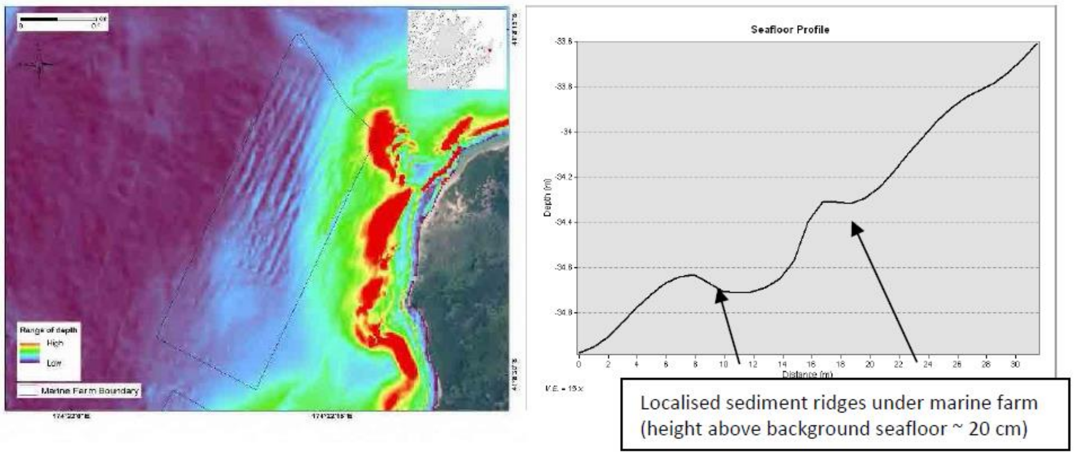
Figure 3-20: The proportion of different functional groups among the colonising fauna on mussel farm structures.

Habitat and Supporting Services in the water column

Habitat and supporting **ecological services (EcolS): in the water column**	***Habitat and supporting*** **ecosystem services (ES): in the water column**
Suspended farm structures:	
Provide complex, temporary habitats -backbones, buoys, mussel shells and a heterogenous inter-twined matrix of open spaces and biofoulers on droppers;	Primary production: colonising diatoms and macroalgae use solar radiation to create organic material from inorganic compounds- underpins food webs and ecosystem;
Provide temporary shelter, protection and resources (i.e., homes and food) for other marine flora and fauna;	Nutrient regeneration: breakdown and conversion of organic matter into inorganic nutrients by activity of marine species.
Near-surface sunlight provision for opportunity for algae photosynthesis: knock-on dissolved nitrogenous uptake and temporary carbon sequestration;	
Support an invertebrate community dominated primarily by suspension feeders (61%) which play a role in the sound's food web by the capture and remineralisation of plankton and suspended organic particulates;	
Supply of metabolic waste and discarded biofoulers to the seabed - food for benthic organisms and	
Support of 139 taxa thereby helping to maintain (or perhaps enhance) biodiversity and ecosystem resilience (but a minus service is the habitat provision for non-indigenous species).	

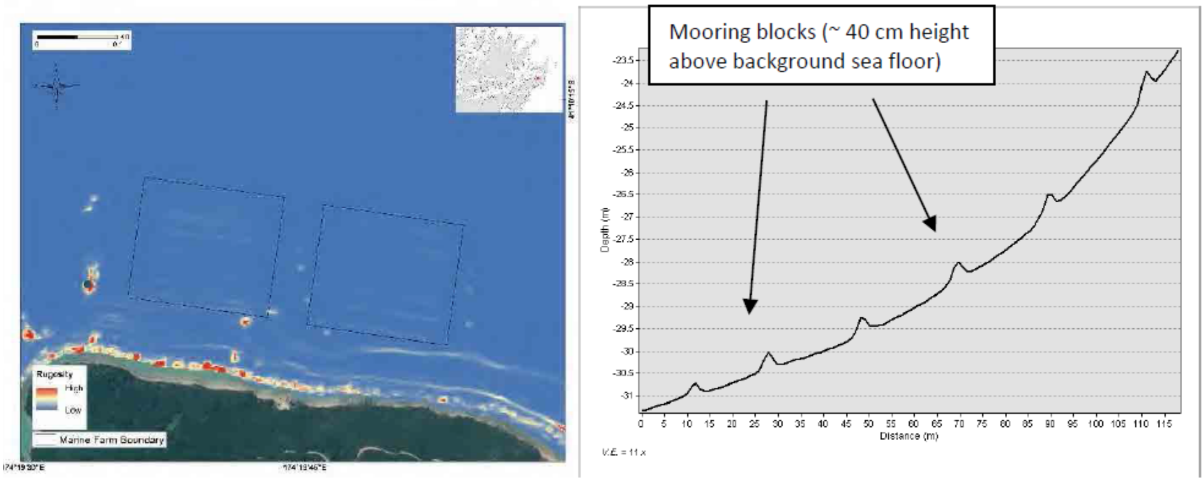
3.2.2 Seabed habitats

All biota stripped from the mussel backbone lines and droppers plus broken green-lipped mussel shells are discarded onto the seabed on site twice in a production cycle (i.e., two discards within 18 months to two years). In addition to these episodic discards, there is a regular addition to the seabed of green-lipped mussel faeces and pseudofaeces (biodeposits), metabolic waste from settled biota and material that incidentally falls off the droppers. This results in the re-structuring of the seabed under farms (most are placed over silty/sandy seabed) into heterogenous patchy reef-like mounds. A recent multibeam survey of East Bay in Queen Charlotte Sound captured imagery of these mounds aligned in ridges below mussel droppers that were ca. 20 cm high (Figure 3-21, Neil, Mackay et al. 2018). This study also captured the anchor blocks around farms (ca. 40 cm high) which provide a hard substrate for biota colonisation (Figure 3-22).



Localised sediment ridges under marine farm (height above background seafloor ~ 20 cm)

Figure 3-21: Multi-beam imagery of seabed reef-like ridges aligned in rows below a mussel farm. In East Bay, QCS. After Figure 3-61 in Neil et al. (2018).



Mooring blocks (~ 40 cm height above background sea floor)

Figure 3-22: Multi-beam seabed imagery of mussel farm anchor blocks. In East Bay, QCS. After Figure 3-64 in Neil et al. (2018).

Shell drop is the principal hard substrata in these mussel-farm derived benthic reefs and this material either accumulates, becomes buried and/or is displaced depending on local conditions. At mussel farms located in exposed areas (e.g. Blowhole in Pelorus), strong currents disperse shell debris and biodeposits beyond the farm boundary (up to 200 m away) compared to the accumulation of material under farms in sheltered areas (e.g. Elaine's Bay) (Hartstein and Rowden 2004; Hartstein and Stevens 2005; Keeley, Forrest et al. 2009) and East Bay.

Where shell drop remains, living mussels and clumps of living organisms (including some that likely fell from the droppers) form heterogenous habitats that continuously receive biodeposits and fall-off from the above suspended mussels. Hatcher, Grant, and Schofield (1994) have suggested that as mussel faeces and pseudofaeces are derived from phytoplankton and suspended sediment they would have a similar organic content to the natural sedimentation. Hence, the large volume of mussel biodeposits found beneath farms represent an increase in total organic deposition driven by a total increase in sedimentation. In effect, the farm is acting as a filter, forming fast-settling pellets from planktonic particles. The resulting complex reef-like environment can cover up to 55% of the seafloor beneath farms (de Jong 1994; Inglis and Gust 2003). The cumulative effect of deposition over many harvest cycles results in a dominance of mussel shells (Kaspar, Gillespie et al. 1985) and a small percent of living green-lipped mussels, (<8% depending on the harvest history of the farm) (Inglis and Gust 2003).

Given that mussel farms are usually deliberately sited over soft-sediment habitats, mussel-culture derived reefs increase the structural complexity of the underlying seafloor. This alters the hydro-sedimentary processes by modifying currents and stabilising seabed sediment (i.e., inhibit resuspension) (McKindsey, Archambault et al. 2011; Hartstein and Rowden 2004; Hartstein and Stevens 2005). Biogeochemical processes and nutrient cycling are shifted to be more akin to that of biogenic habitats (McKindsey, Anderson et al. 2006; McKindsey, Archambault et al. 2011): increases in oxygen exchange, nitrate fluxes, and overall benthic regeneration are often evident (Hartstein and Stevens 2005; Giles, Pilditch and Bell 2016).

These reefs provide settlement surfaces, refuge and food for other benthic dwelling organisms from the wider environment (e.g. sea cucumbers, starfish) and vagile species such as fish (spotties, triplefins and leatherbacks, Morrisey, Cole 2006). Shell mounds are patchily distributed and interspersed with sections of exposed sediment over which many epifauna species forage, a feeding behaviour which enhances bioturbation. For example, sea cucumbers (*Australostichopus mollis)* gather in large numbers under mussel farms (Davey, Stenton-Dozey et al. in prep) and their deposit feeding activity shifts the microbial balance and redistributes dissolved nutrients from the sediments into the pelagic environment (MacTavish, Stenton-Dozey et al. 2012). The associated ecosystem-level effects are changes in nutrient cycling and sediment organic matter content, demonstrating the key functional role sea cucumbers play in the ecology of mussel-culture derived reef ecosystems. Other bioturbating species that live and move at the sediment-water interface under farms in areas where shell does not dominate (i.e., in areas between longlines), like the heart urchin (*Echinocardium* sp.), can also mix surficial sediments and in doing so, can enhance benthic primary production or microscopic seabed plant growth[63] (Lohrer, Thrush and Gibbs 2004).

These mussel-culture derived reefs are now a consistent feature of the Marlborough Sounds seabed and as such provide both ecological and ecosystem services.

Seabed biodiversity

Mussel clumps, shell litter and biofouling waste beneath a mussel farm serve as a substrate for the formation of reef-type communities. Unfortunately, most studies of epifauna communities under mussel farms have only recorded broadly on taxa present without species differentiation other than noting the presence of some conspicuous species (e.g. de Jong 1994; Kaspar, Gillespie et al. 1985; Inglis and Gust 2003; Davidson and Brown 1999; Davidson and Richards 2017, pers. obs.). In contrast there is extensive information on infauna species under and near mussel farms (i.e., control sites) and the reason for this difference has been driven by the requirements of environmental assessment impacts for resource consent renewals.

Indication of organic enrichment and the biological health of the seabed beneath farms is traditionally assessed by enumerating macrofaunal organisms (measuring a length > 0.5 or 1 mm) living within the sediment matrix. As stated by Keeley, Forrest et al. (2009): "*According to models of organic enrichment (Pearson and Rosenberg 1978), sediments subject to increased organic loading will exhibit increased animal abundance, decreased species richness (number of different taxa) and animal biomass, and a shift in dominance of trophic groups (Weston 1990). Seabed enrichment selects for species more adaptable to low oxygen levels and/or to the instability of finer-textured, high organic sediments (Tenore et al. 1982).*" In these assessments sediment samples are obtained

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[63] Provided that there is sufficient light reaching the seabed -The under-farm area is likely to be shaded and turbid (light limited) relative to outside of it

using a benthic grab winched overboard and in addition, photo quadrants are taken of the seabed surface with a drop camera or a Remotely Operated Vehicle (ROV). The former is a quantitative assessment providing data on infauna species numbers and abundance while the latter is a qualitative assessment that records the presence, and sometimes the relative abundance, of epifauna and thus does not provide a full inventory of species biodiversity. However, it is important to note that grab samples can only be taken from areas without cobbles and shell debris otherwise the jaws of the grab cannot close or penetrate sediments to extract infauna from the required depth of 10 to 20 cm.

These methodologies were applied in the FRIAs undertaken by NIWA for consent renewals for 82 plus mussel farms in the Marlborough Sounds between 2004 and 2007 (Stenton-Dozey, Ross et al. 2004 a, b; Stenton-Dozey, Morrisey et al. 2005, 2006 a, b, 2007 a, b, c, d, e). It is beyond the scope of this review to synthesis all these data, but some general observations can be made to provide perspective on benthic biodiversity service provision by mussel farms.

In general, infauna biodiversity beneath mussel farms (in areas without shell debris) was not markedly different to reference sites 50 m seaward from farm boundaries across all FRIAs. Multi-dimensional scale (nMDS) plots[64] of similarities of infauna species and their abundance between sampling sites did not distinguish between communities inside and outside mussel farms in either inner Pelorus, the Crail-Cover-Beatrix region or Admiralty Bay (Figure 3-23).

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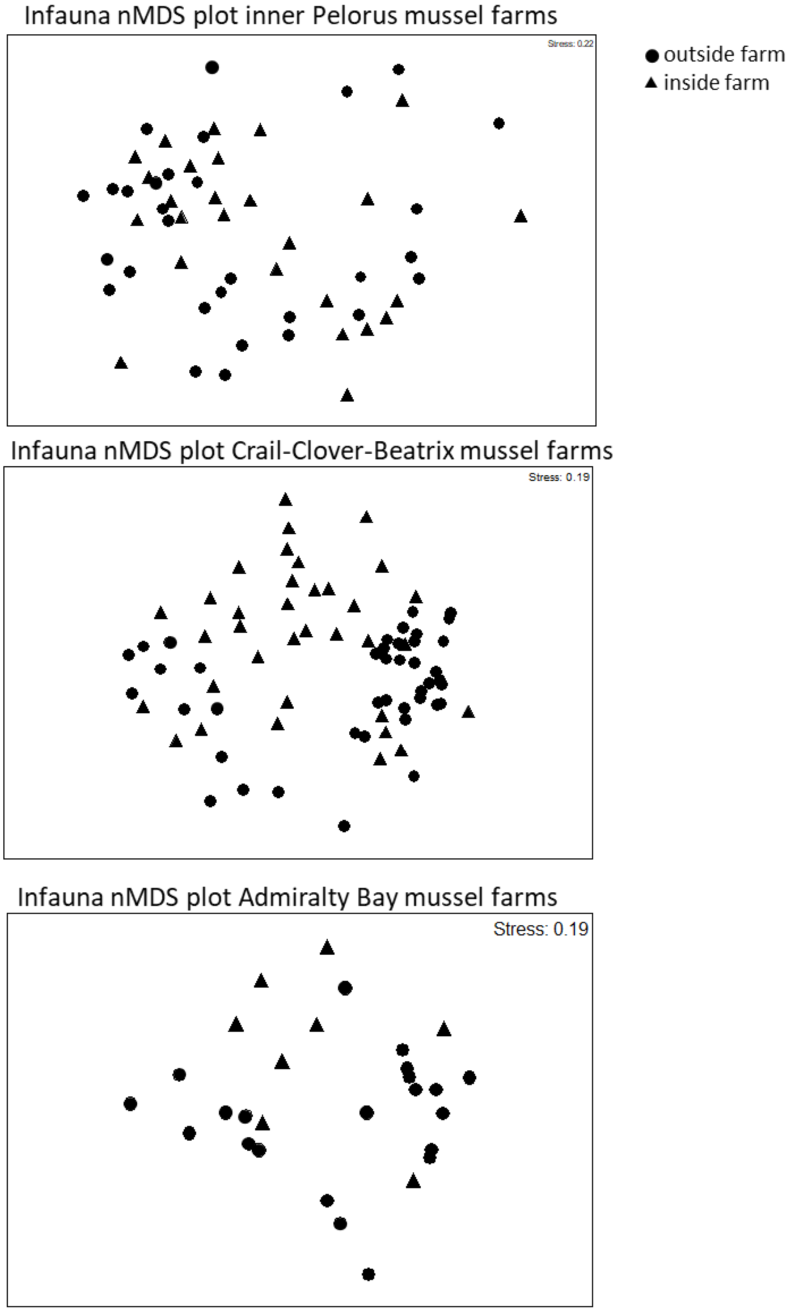
[64] a nMDS-plot is a spatial representation of the similarity in species abundance and diversity among community assemblages


Infauna nMDS plot inner Pelorus mussel farms

Infauna nMDS plot Crail-Clover-Beatrix mussel farms

Infauna nMDS plot Admiralty Bay mussel farms

Figure 3-23: Non-metric MDS plots of infaunal species based on abundance. Overlaid by sampling site (inside or outside a mussel farm) in Pelorus Sound. Data from all sampled sites per area (inner Pelorus, Crail-Clover-Beatrix and Admiralty Bay). Each symbol represents a sampling site. Sites with relatively similar infauna abundance lie closer together.

Indices of species richness and diversity further support the evidence of very little difference between infauna communities beneath the farm and outside reference sites (Table 3-3).

Table 3-3: Species diversity indices for infauna assemblages. Mean (SE) and ranges of values of faunal abundance and diversity indices for all grab samples collected in the Pelorus region. Samples are separated into those taken inside areas occupied by longlines and those taken outside.

Index		Mean	SE	Minimum	Maximum
Total number of taxa (S)	Inside	11.7	1.00	3	25
	Outside	10.7	0.51	5	17
Total number of individuals (N)	Inside	30.6	4.15	8	103
	Outside	29.0	2.26	9	60
Margalef's species richness (d)	Inside	3.166	0.2180	0.962	5.178
	Outside	2.956	0.1194	1.516	4.254
Pielou's evenness (J')	Inside	0.859	0.0164	0.670	0.969
	Outside	0.851	0.0154	0.620	0.970
Shannon-Wiener diversity (H'($\log_e$))	Inside	2.040	0.0931	0.736	2.748
	Outside	1.988	0.0541	1.255	2.469

Species richness explained by the number of species (S), the number of individuals (abundance of individual organisms, N), and an index of species richness (the Malgalef index 'd', where $d = \frac{S-1}{\ln(N)}$).

The diversity of infaunal assemblages is described by Prelou's Evenness (J') and the Shannon (Shannon-Weiner) (H') indices. Species evenness is a measure of the equality of numbers of individuals per species. The Shannon diversity index characterizes species diversity in a community and accounts for both abundance and evenness of the species present (Clarke and Warwick 2001).

Keely and Morrisey (2013) undertook a review of the extensive (but mostly, grey-) literature concerning the benthic effects of mussel farming in the Marlborough Sounds and Firth of Thames. They note that infaunal animal abundance tends to be slightly elevated directly beneath mussel farms. The caveat to this observation however is that since organic enrichment is variable amongst sites, depending on environmental conditions such as depth and average current velocity, species richness can be either slightly depressed or slightly enhanced. The abundances of opportunistic polychaetes may be slightly elevated, while the composition of other major infaunal groups (e.g., molluscs, crustaceans, echinoderms) remain comparable between farmed and unfarmed locations. It appears that mussel farms in the Marlborough Sounds afford no service in terms of increasing infaunal benthic biodiversity.

However, unlike studies on infauna communities and associated sediment physiochemistry (Dahlbāck and Gunnarsson 1981; Chamberlain, Fernandes et al. 2001; Christensen, Glud et al. 2003; Hartstein and Rowden 2003; Giles and Pilditch 2006; Giles, Pilditch and Bell 2006; Wong and O'Shea 2016; Newcombe, Berthelsen and Taylor 2016) no equivalent quantitative assessments have been undertaken on epifauna community structures in terms of species abundance or diversity. Observational accounts have described reef-like communities under an existing farm that included large biota such as tunicates, sponges, sea cucumbers, calcareous polychaetes, and mobile predatory species such as starfish, crabs and fish (Kaspar, Gillespie et al. 1985). Davidson and Richards (2017) noted that areas under a farm in Port Ligar supported species typical of silt and shell substratum (e.g., cushion starfish, sea cucumbers) as well as the predatory eleven-armed starfish (*C. muracata*), observed mostly in association with mussel shell; spotty were abundant and blue cod were observed inshore and under the farm. Biofouling drop-off and elevated biodeposition can lead to aggregations of scavenging and/or predatory organisms, such as sea cucumbers (Slater and Carton 2007; Davey, Stenton-Dozey et al. in prep.; MacTavish, Stenton-Dozey et al. 2012), sea stars (de Jong 1994, Grant, Hatcher et al. 1995, Inglis and Gust 2003, Garcia 2015).

Indeed, Davey, Stenton-Dozey et al. (in prep.) recorded densities of the sea cucumber *A. mollis* that were three times greater than outside farms. Sea cucumbers provide a mitigating ecoservice under farms as they are deposit feeders and obtain their nutritional requirements from processing large volumes of sediments on the seafloor, digesting the organic components (algae, diatoms, cyanobacteria) and excreting unwanted sediments (Uthicke 1999). Inglis and Gust (2003) recorded densities of the predatory starfish *C. muracata* between 14 to 39 times higher beneath mussel farms where live mussels were abundant, densities far greater than any other predatory or scavenging epifaunal species (such as other types of starfish or gastropods). This species feeds on mussel preferentially and have been associated with green-lipped mussel restorative beds in the Hauraki Gulf (Wilcox, Kelly and Jeffs 2018) and significant losses in Ohiwa Harbour, south of Tauranga (Paul-Burke and Burke 2016). In part, however, this may be considered a disservice since bolstering populations of these predators may have impacts on benthic mussel bed recovery as observed in the gulf.

The NIWA FRIA reports documented the relative abundance (scored as 1 (present) to 20 (abundant)) of epifauna beneath farms compared to outside from drop camera and/or ROV footage and we have summarised some of these data for areas that are moderately sheltered (Crail-Clover-Beatrix (CCB) area) (Figure 3-24) to exposed (Blowhole) in the Pelorus Sound (Figure 3-25). For each area we included observations for all sites sampled inside and outside farms. Images of some of the recorded taxa are shown in Figure 3-26 and Figure 3-27. We do not know how many of the epifauna taxa are non-indigenous under farms but it’s likely those that may be present would have originated mostly from biofouling discards (and mostly among the bryozoan and ascidian taxa).

In Clover and Crail Bays hydroids were notably abundant in both farmed and unfarmed areas indicating that this taxon can thrive in areas of high biodeposition. The number of taxa beneath farms was only marginally higher (3 to 4 more) in the CCB-area while in the outer sounds it was nearly double, but in all areas each taxon was more abundant inside than outside. The taxa that scored the highest abundance in association with mussel-culture derived reefs were live green-lipped mussels, blue mussels, tube worms, sea cucumbers (*A. mollis*), gastropods, eleven-armed starfish (*C. muracata),* cushion starfish *(Patiriella regularis),* brittle starfish (*Pectinura maculata*), sea urchin (*Evechinus chloroticus)* and triplefins. Present but less abundant were algae, sponges, ascidians, bryozoans, anemones, scallops, horse mussels, nudibranchs, crabs, leatherjackets, flatfish, spotties and blue cod. The presence of these fish species is discussed in section 3.3.

The information above and our semi-quantifiable data indicate local mobile epifauna such as sea cucumbers, starfish, sea urchins and gastropods are attracted from outside farms to the food supply afforded by the mussel-culture derived reefs. Other sedentary species (sponges, ascidians and bryozoans) are more likely to have originated from biofouling discards or incidental drop-off from mussel structures. Overall species diversity appears marginally higher under farms but there is a clear indication of a greater abundance of these species on the mussel-culture derived reefs.

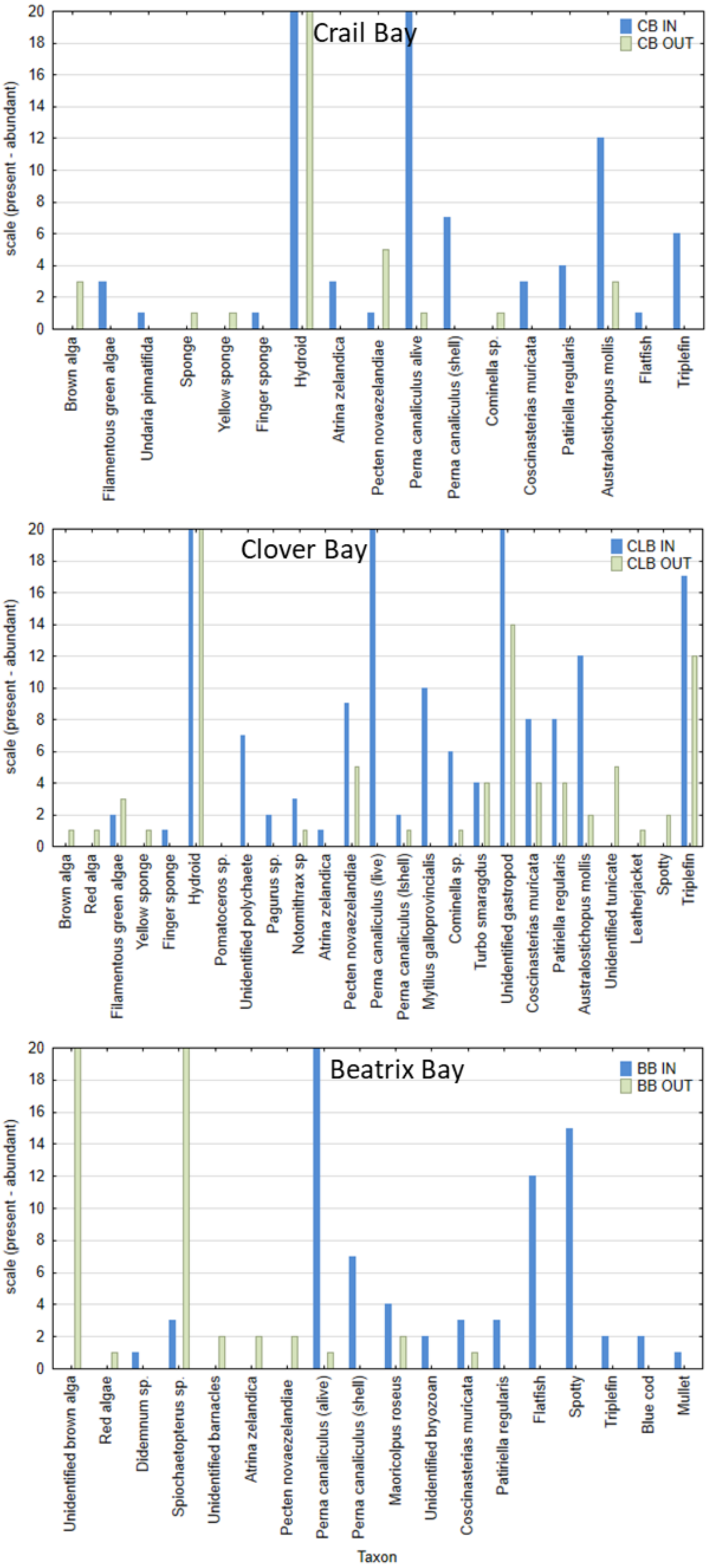


Figure 3-24: The relative abundance of epifauna taxa beneath and near mussel farms. In the mid-Pelorus Sound. Scale 1 to 20, present to abundant. (data from NIWA FRIA reports).

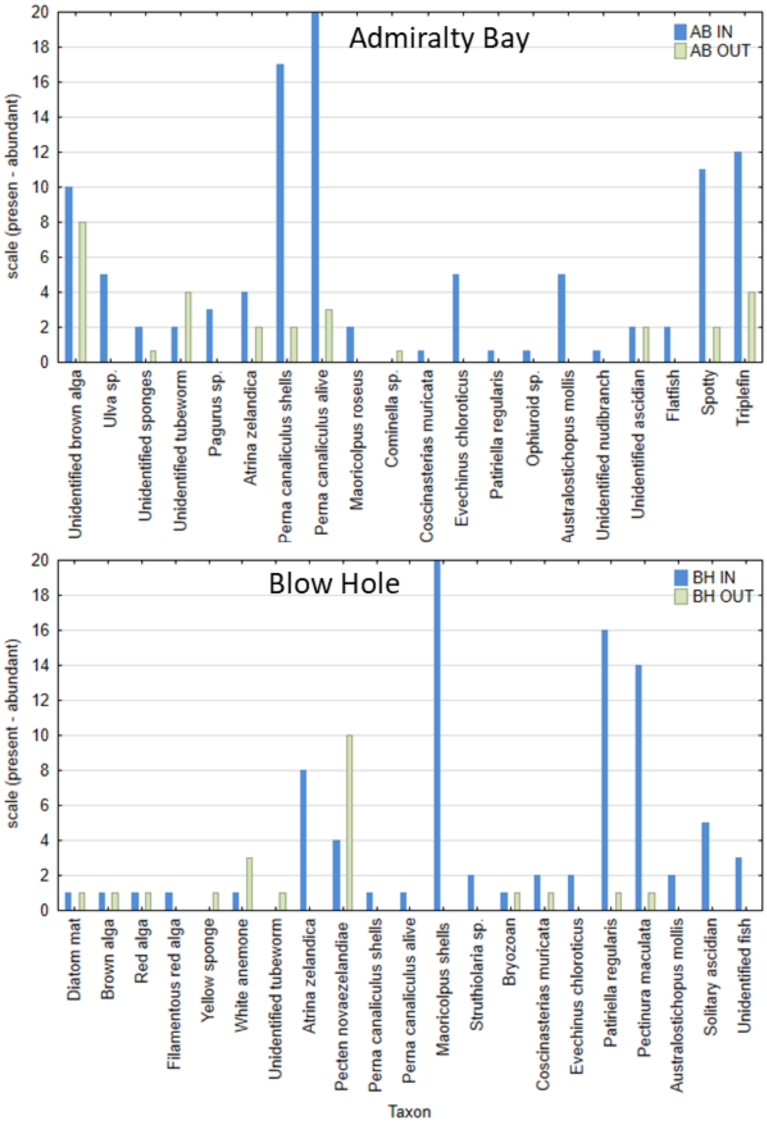


Figure 3-25: The relative abundance of epifauna taxa beneath and near mussel farms. In the outer Marlborough Sounds. Scale 1 to 20, present to abundant. (data from NIWA FRIA reports).

Figure 3-26: Epifauna on mussel culture fall-off reefs below farms in the Pelorus Sound. (photo credits NIWA, Chris Woods and Sheryl Miller).

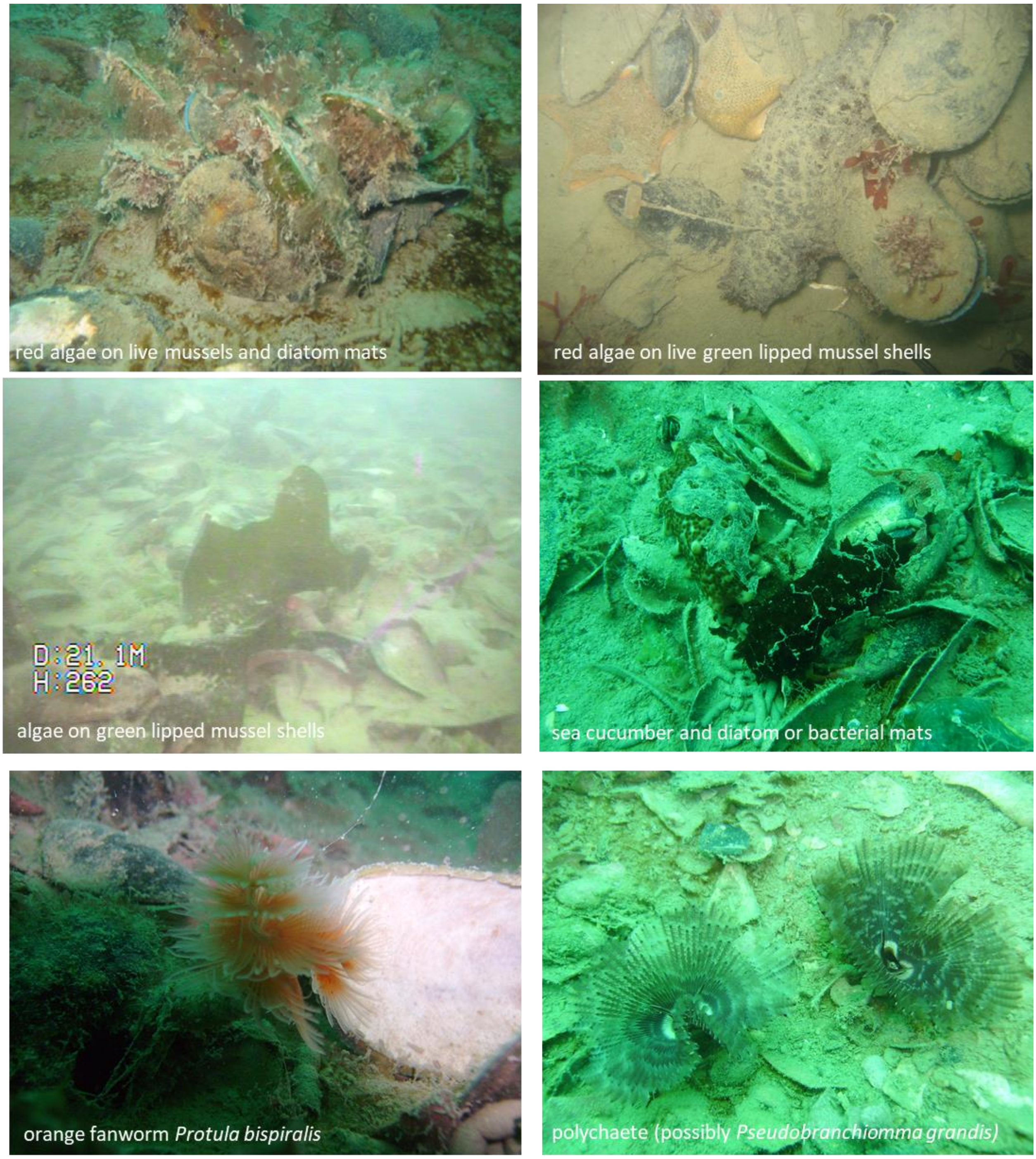


Figure 3-27: Epifauna on mussel culture fall-off reefs below mussel farms in the Pelorus Sound. (photo credits NIWA, Chris Woods and Sheryl Miller).

Habitat and Support Services on the seabed

Habitat and support **ecological services (EcolS): on the seabed**	***Habitat and support*** **ecosystem services (ES): on the seabed**
Mussel-culture derived reefs:	
Provide shelter, protection and resources (i.e., homes and food) for other marine flora and fauna;	Nutrient regeneration: breakdown and conversion of organic matter into inorganic nutrients by activity of marine species;
Increase structural complexity, alter hydro-sedimentary processes by modifying currents and stabilise seabed sediment;	Habitat for species: Sediment formation & composition
Shift biogeochemical processes and nutrient cycling to increases in oxygen exchange, dissolved inorganic nitrogen (DIN) fluxes, and overall benthic nutrient regeneration;	
Provide habitat for bioturbators that rework the sediment surface thereby enhancing ecosystem functioning in marine sediments by modifying geochemical gradients, redistributing food resources and altering nutrient fluxes;	
Maintain (or, perhaps, enhance) benthic biodiversity and hence ecosystem resilience;	
Provide a benthic reef-like ecosystem with a principal community (in terms of abundance) of mussels (filter feeders), detritivores (sea cucumbers), scavengers and predators (starfish, gastropods and triplefins) and a secondary community of algae, suspension feeders (sponges, ascidians, bryozoans, fan worms), scavengers (crabs, sea urchins) and predators (hydroids, sea anemones, polychaetes, gastropods, fish);	
Support overall benthic biodiversity and enhance the abundance of individuals on the seabed.	

3.3 Provisioning services

In this section we consider services through the *provision* of food, raw material and materials for human wellbeing (i.e., ecosystem services - ES). The mussel industry creates valuable products from the natural resources of the marine environment. Since 2003 the annual production of mussels from the Marlborough Sounds has ranged from 40000 to 70000 tonnes green weight which equates to around 62% of New Zealand’s green-lipped mussel production (Figure 3-28).

Most mussel production[65] enters the market as frozen half shell (80%) and the remainder as live, processed packaged, powder, mussel oil, frozen whole and frozen meat. Both mussel powder and oil are used by humans (and their pets) as nutraceutical. The industry is seeking uses for a large quantity of discarded mussel shell in Havelock with suggestions ranging from land mulch, stabilisation of seabed sediments in the sounds and substrate for benthic reef restoration. Crushed shell is now being used in the wine industry as mulch around vines in the Marlborough Sounds.

Undaria pinnatifida is now being harvested from mussel farms and used in a land fertiliser. There is significant potential provision of a wide variety of bioactives from macroalgae that grow on mussel farms including antioxidative, anti-inflammatory, antiviral, anticoagulant, anti-aging and hypolipidemic compounds (Handley, Sim-Smith et al. 2006) (e.g., *Ulva* sp., *Colpomenia* sp. and *Undaria* have bioactives with potential use in anti-inflammatory and heart diseases). Sponges also offer a high diversity if bioactive compounds presently untapped in New Zealand with potential in treating some cancers (references in Handley, Sim-Smith et al. 2006).

Mussel farms therefore fulfil all the ecosystem *provisioning* services: food, raw materials and medicinal (nutraceutical). Aspects of mussel aquaculture in the Marlborough Sounds relating to economics (e.g. revenue, GDP, etc.) and cultural provision (e.g. jobs creation) can be found in the 2015 report by the New Zealand Institute of Economic Research (NZIER 2015, 2018).

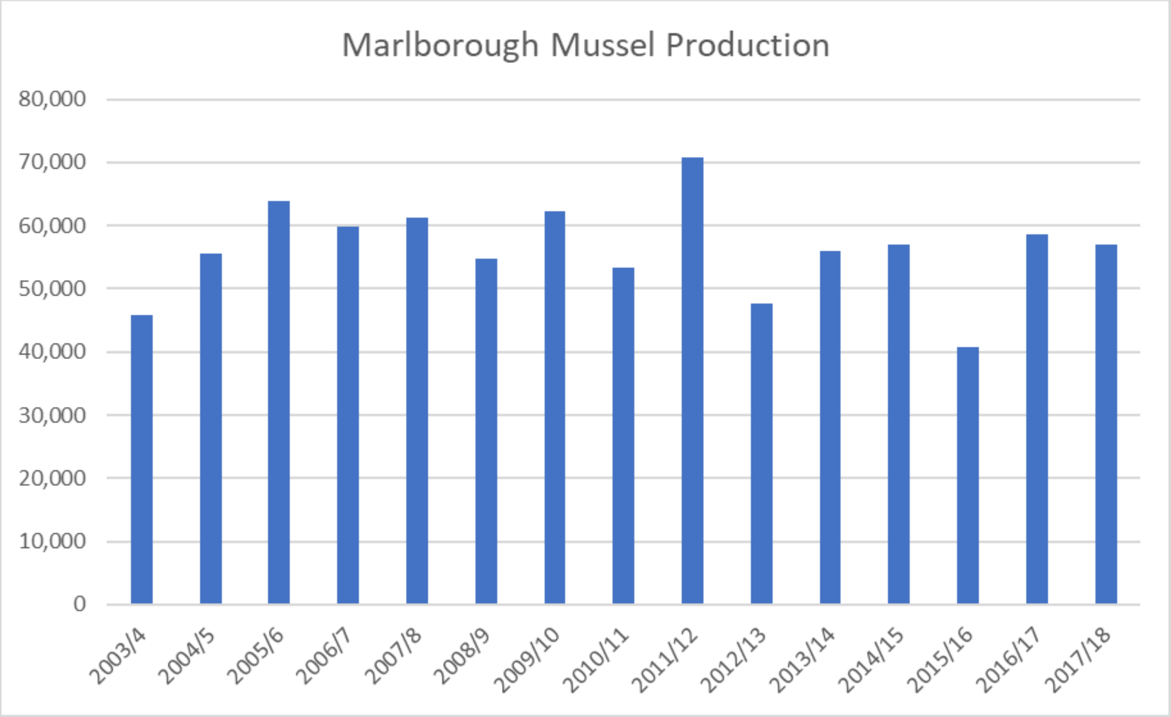


Figure 3-28: Green lipped mussel production (tonnes green weight) in the Marlborough Sounds. Provided by Aquaculture New Zealand.

3.4 Fish

During the FRIA drop camera and ROV surveys of the benthic environment around mussel farms in the Marlborough Sounds we recorded an abundance of mainly triplefins *(Forsterygion lapillum*) and spotties (the wrasse *Notolabrus celidotus*) and the occasional leatherjackets (*Parika scaber)* and stargazers (Figure 3-29). Blue cod, mullet and flatfish were also observed in ROV images. Similar observations were made by Carbines (1993) who found that spotties, which are characteristic of

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[65] https://www.aqua.org.nz/exports/history/2018-10

rocky reefs and benthic sediments in the sounds, were abundant around anchor blocks and on the seabed beneath longlines. A survey of thirteen mussel farms in Pelorus Sound from Tawhitinui Reach to Blowhole Point in which baited videos were used, recorded more fish inside than outside farms, the most abundant being spotty, leatherjacket and blue cod with smaller numbers of John dory, scarlet wrasse, yellow-eyed mullet and red gurnard (Grange 2002). Morrisey, Cole et al. (2006) recorded the same dominance of these small, demersal species feeding around mussel droppers. The industry has noted that small mussels (spat) suspended on dropper lines are vulnerable to predation by various fish species (snapper, spotty, leatherjacket) and as a management practice spat lines are kept in areas with low fish abundance (John Young, pers. comm.).

Mussel droppers and mussel-culture derived reefs provide food and shelter for spotties and triplefins throughout the year, but numbers are small relative to nearby reefs and compared to farm anchor blocks (Carbines 1993). These reefs and anchor blocks provide an EcolS service as habitat space for small fish that are not of direct benefit to humans but that contribute to the oveall ecosystem of the sounds. High densities of the caprellid amphipod *Caprella mutica* on suspended structures (discussed in section 2.2.7) could be a food source for these small fish.

Pelagic species do pass through the farms but there is no evidence that they make regular use of these areas (Morrisey, Cole et al. 2006). These authors recorded kingfish, kahawai and yellow-eyed mullet (*Aldrichetta forsteri*) and jack mackerel (*Trachurus novaezelandiae)* while diving on farms, as well as the occasional seahorse (*Hippocampus abdominalis*) on farm structures. However, there was no evidence on whether these fish use the mussel farm system as shelter or as a feeding ground.

Farmers tell of schools of snapper stripping freshly seeded farms, leaving buoys that were once well submerged floating light and high with their diminished loads[66] (Figure 3-30). Little is known about the extent of fish predation, but some farmers believe farms in deeper water are less vulnerable from bottom-dwelling fish than are shallower farms.

Mussel farms are often used as fishing sites by recreational anglers and anecdotal evidence suggests that they are considered good places to catch fish (this would be considered a cultural ES). Kingfish are targeted by recreational fishers in the farms in Tasman Bay where adults are found in large numbers once the water temperatures reach >16.5 ^{0}C (Dave Taylor, pers. comm.)[67]. A kingfish was captured in an image by John Young among mussel lines in Tasman Bay (Figure 3-31). Large quantities of snapper have been caught at Okiwi Bay mussel farm (Croisilles Harbour)[68] and have been observed feeding around mussel farms in Kenepuru Sound (John Young, pers. comm.). Interestingly Stead (1971a) commented that implementation of conservation measures for Pelorus mussel stocks around 1970 was eventually driven by a fear that “the depletion of the mussel fishery might be detrimental to snapper fishing and thus to the tourist trade.”

Similarly, anecdotally, the Wilson Bay marine farms in the Firth of Thames is a popular destination for recreational fisher-folk as well as commercial charter operations which target mussel barges during harvesting and reseeding as snapper are most abundant at this time (Dave Taylor, pers. comm.)[69].

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[66] https://www.nzgeo.com/stories/mussel-power/

[67] https://www.cawthron.org.nz/tascam/

[68] https://www.stuff.co.nz/business/farming/aquaculture/74680570/mussel-farms-are-marine-sanctuaries-says-farmer

[69] https://www.nzfishingworld.co.nz/latest/2015/07/coromandel-charter-fishing

Figure 3-29: Fish associated with mussel farms in the Marlborough Sounds. Photo credits, NIWA, Chris Woods, Sheryl Miller, FRIA surveys.

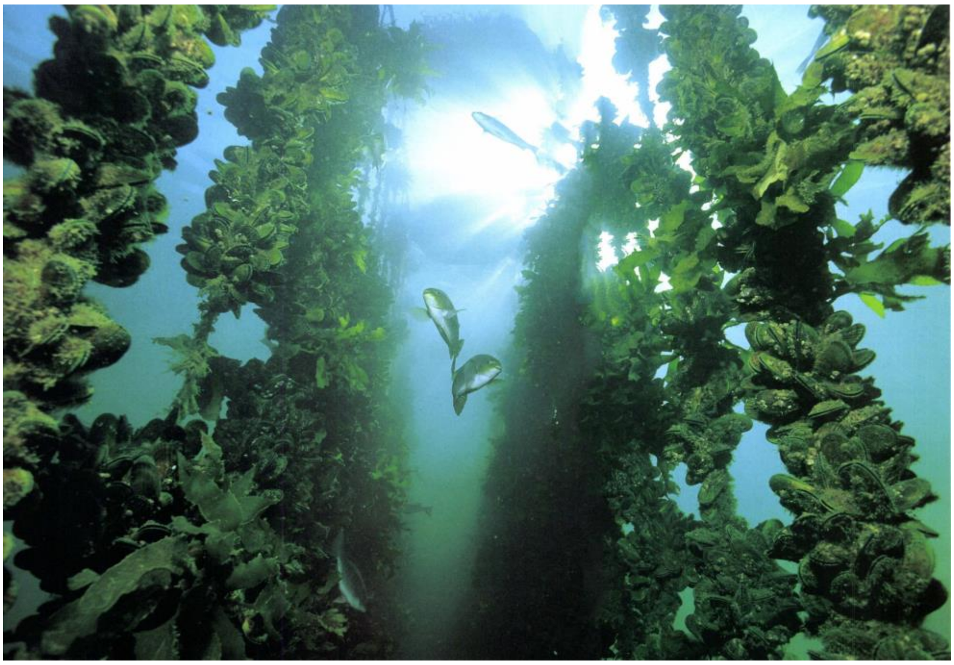

Figure 3-30: Snapper cruising between mussel droppers. Photo credit https://www.nzgeo.com/stories/mussel-power/

Figure 3-31: Kingfish on a mussel farm in Tasman Bay.

Service provision relating to fish

Fish: ecological services (EcolS)	Fish: ecosystem services (ES)
Provide food and shelter for mainly small demersal fish characteristic of nearby reefs and benthic sediments; Provide an environmental conduit (i.e., habitat complexity) visited on occasion by larger pelagic fish; Support the biodiversity of small demersal fish.	Habitat and supporting services: Habitat for species (possibly for snapper and blue cod) Provisioning services: Food

3.5 Seabirds

The association of seabirds with mussel farms is most evident at reseeding and harvesting time which is usually attended by large numbers of gulls and other piscivorous birds feeding on biofouling debris as well as the displaced spotties and triplefins (Morrisey, Cole et al. 2006).

Spotted and king shags have been observed feeding within farms on occasion and resting on surface buoys (Figure 3-32); king shags do not roost overnight on buoys like spotted shags (Lalas unpubl. 2001 in Butler 2003). Gannets have also been observed to visit farms especially in association with feeding dolphins. We found no information on any association between mussel farms and shearwaters or the little penguin, two seabirds listed among those regarded as significant to the Marlborough Sounds (see section 2.2.8).

We do not know whether seabirds aggregate disproportionately on farms or whether foraging or breeding success is improved (or impaired) by the presence of farms. However, even in the absence of definitive data, it may be legitimate to argue that since seabirds choose to forage around the farms/roost on the farms, this probably implies that the birds consider mussel farms to be favourable relative to the available alternatives – whether by yielding improved feeding rates or reduced commuting times or reduced exposure to larger predators.

Mussel farms provide an EcolS to the sounds' ecosystem by providing feeding and roosting opportunities for some seabirds. It could be argued that mussel farms provide a cultural ES through the value of seabirds to human wellbeing in providing enjoyment (e.g. viewing and photographing seabirds on mussel farms). Seabirds also hold cultural significance and importance to Tangata whenua, although none of the seabirds in this review are among listed taonga species[70].

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[70] https://www.doc.govt.nz/documents/about-doc/concessions-and-permits/conservation-revealed/ngai-tahu-taonga-animals-lowres.pdf

Figure 3-32: King shags resting at a mussel farm in Beatrix Bay, Pelorus Sound.
https://www.stuff.co.nz/environment/106162667/new-zealand-king-shags-doomed-if-plum

Service provision relating to seabirds

Seabirds: ecological services	Seabirds: ecosystem services
Provide foraging and roosting opportunities for seabirds.	Habitat provision: Roosting sites.

3.6 Marine mammals

Seals are the most frequently seen marine mammals around mussel farms - where pups haul-out in calm weather onto surface mussel buoys, slipping in and out of the water to feed around the farms, especially when crop-lines are being harvested and biofouling material is being discarded (Figure 3-33).

Using data from Woods, Floerl and Hayden (2012) on the amount of biofouling material that is discarded we made a rough estimate of how much this may mean as food to seals (and seabirds like sea gulls and shags). In summary:

A. The biofouling community mass can range from about 10% to 100% of green-lipped biomass;

B. At stripping or harvest, biofouling community is very roughly 500-1000 g DW/m;

C. Blue mussels can be about 80% of the biofouling community by biomass

D. ‘Mobile species’ are maybe 2% of biofouling biomass.

When a line is stripped, the minimum amount of material produced might be 500 * 0.02=10 g DW /m dropper, whilst the max might be 1000*0.80=800 g DW /m. About half of that will be shell, so flesh DW might be about 5 – 400 g /m. With 4196 ha of mussel farms in the sounds (Pelorus and QCS) with 3.33. longlines / ha and 4000 m of dropper/line (see Table 3.4 in the next section), this adds up to 55,900 km of dropper. If we assume each dropper is stripped once per year, 153 km of dropper are stripped per day. That equates to a discard biomass between 765 kg flesh DW/d and 60,981 kg DW/d which is potential food for seabirds and seals, presumably only at the water surface and /or the upper water column.

There are five species of dolphin encountered in the Marlborough Sounds; bottlenose, dusky, short-beaked common, Hector's and orcas. Only common and bottlenose dolphins have been seen to forage within a farm and appeared to use a farm's lines as a barrier to help them herd fish for feeding (Figure 3-34) – and it is common for predatory seabirds to aggregate around feeding dolphin pods in order to exploit any fish that endeavour to escape by fleeing towards the sea-surface. In Spain a long-term study of common bottlenose dolphin behaviour confirmed that areas of mussel production are frequently utilized by common bottlenose dolphins, presumably because of the large aggregations of fish species around these mussel rafts (Lopez and Methion 2017).

Orcas are occasional seen near farms, but it is not certain if they use farm structures to assist in catching sting-rays. According to Visser (2007) orcas avoid entering shellfish farm areas. The QCS is almost an attraction for the orca as there is an abundance of these rays in the sound (Figure 3-35).

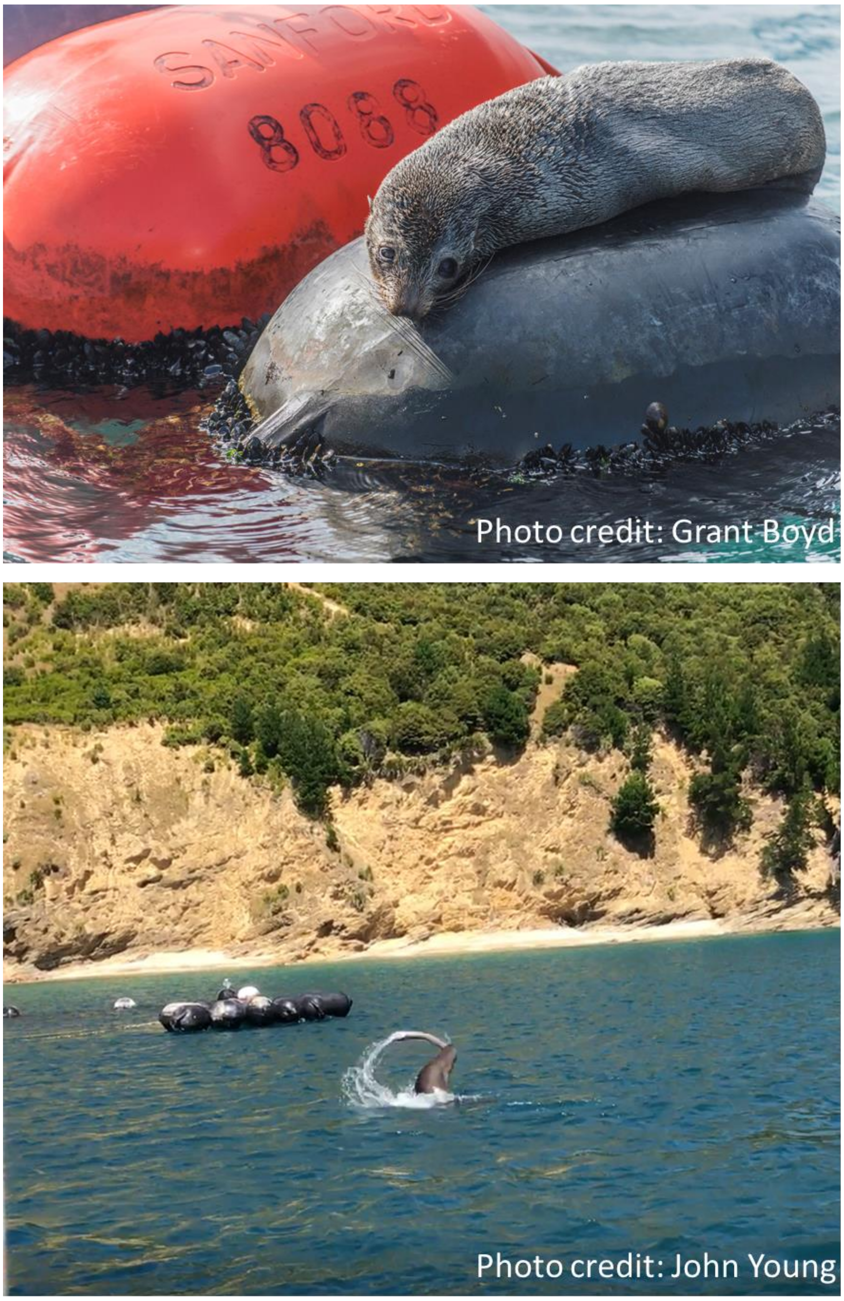

Photo credit: Grant Boyd

Photo credit: John Young

Figure 3-33: Seals interacting with mussel farms. Top image, resting on a mussel buoy and bottom image, a seal flipping a conger eel.

Photo credit: MFA

Figure 3-34: Dolphins herding fish between longlines on a mussel farm.

Figure 3-35: Orcas in Queen Charlotte Sound.

Service provision relating to marine mammals

Marine Mammals: ecological services: (EcolS)	Marine Mammals: ecosystem services (ES)
Provide haul-out for seal pups and foraging opportunities for seals and common and bottlenose dolphins	Habitat provision: haul-out sites

3.7 Equivalency of suspended cultured mussels as benthic habitats

By 1980 much of benthic filter feeding population of the sounds' ecosystem had been destroyed leaving behind an extensive muddy substrate and few of the former biogenic reefs. Wild green-lipped mussels have not regenerated since the muddy substrate is not suitable for mussel larvae settlement (Paul 2012; Handley 2015).

We pose the question: Can mussel farms serve to replace some of the lost benthic habitats? We attempt to answer this question by calculating (1) how much water is filtered by cultured mussels and (2) the area that would be covered if we placed all mussel droppers on the seabed to represent the destroyed mussel beds.

For each hectare farmed, green-lipped mussels filter approximately 8,000 m^3/hr or 192,000 m^3/day[71] (Table 3-4). If the droppers holding these filtering mussels were placed on the seabed, the area covered would be 0.8 seabed ha / farm ha.

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[71] These numbers are only very approximate. Mussel filtration rates vary with body size, seston and sediment content of the water and water temperature. Even when all of these are standardised in laboratory experiments, different experiments have yielded substantially different estimates of the per-capita filtration rate. Similarly, the densities of mussels of any given size (mussels/m of dropper) can vary substantially along the length of a dropper, amongst droppers, with depth, across seasons and years, from the inner to the outer sounds.

These data were multiplied by the area of mussel farms in each of five Marlborough Sounds Zones (MSZ) listed in Table 3-5. In a day, mussels filter 6.3% of the total volume of the Pelorus Sound, 0.8% of the QCS volume and for Port Underwood, 4.1% of the volume in a day.

For each of these areas, the benthic coverage of droppers was ca. 80% of the consented areas for suspended mussel culture. When the area of mussel-culture derived reefs below the longlines was added, this increased to ca. 88%.

Mussel farming in the Marlborough Sounds thus provides some degree of equivalency to lost benthic habitats that is approximately 88% of all consented areas presently farming mussels, i.e. 4196 X 0.88 = 3693 ha. In terms of area, we do not know how much of the lost mussel beds this represents. An upper estimate of area covered by mussels in pre-European times could have been in the order of 2000 ha (Handley 2015) in the Pelorus Sound. The benthic equivalent of the mussel farms in Pelorus Sound is approximately 2964 ha (

Table 3-5).

In terms of biota community composition and FFGs (Functinal Feeding Groups) some parallels can be drawn with the biogenic reefs described in Table 2-1, Section 2.2.5. Beside the green-lipped mussel, dropper communities are comprised of 61% suspension feeders which add an unknown volume of filtered water to that filtered by mussels. We do not know the quantitative community composition of biogenic reefs in the Marlborough Sounds but anecdotal information indicates a prevalence of suspension feeders (sponges, ascidians, tube worms, bryozoans) that are also found on droppers. The remaining 40% of the dropper fauna comprised of scavengers, detritivores and predators, have their equivalent on biogenic reefs (Table 2-1).

Green-lipped mussel shell and live mussel drop-off return some of the lost hard biogenic structures to areas that are now unstructured muddy soft-sediment habitat because of past trawling, dredging and elevated rates of sedimentation. The three-dimensionality of these mounds is like that provided by biogenic reefs, but the difference lies in the faunal community being exposed to a regime of sedimentation and biofouling discards at reseeding and harvest. Although we have no quantifiable data at hand, this regime appears to suppress the abundance and diversity of suspension feeders in favour of detritivores, scavengers and predators.

This type of habitat could be partially akin to the soft bottom tubeworm mounds recorded in soft-sediment bays throughout the Marlborough Sounds (Anderson, Morrison et al. 2018). These tubeworms have been initial described as *Spiochaetopterus* spp intertwined within *Acromegalomma suspiciens* and support a wide range of flora (most red algal species) and fauna that appear to be predominately detritivores, scavengers and predators (5-armed starfish, holothurians, ophiuroids, and small fishes, such as triplefins and spotties) (Figure 3-36). Like the mussel culture derived reefs, these are exposed to sedimentation through resuspension of bottom sediments by strong tidal currents in the central parts of the sounds.

Table 3-4: For each hectare farmed, the volume of water filtered by mussels and the equivalent benthic occupation by mussel droppers. All base data were provided by MFA; we used 10 longlines (160 m each) per 3 ha farm (3.33 lines / ha) with a dropper length of 4000 m / longline except for spat lines where we used a dropper length of 6000 m. Mussel filtration rates (FR) per size class (NIWA unpubl. data). Approximately 10% of a dropper is assumed to be devoid of mussels.

	MUSSEL FILTRATION RATE									**BENTHIC AREA EQUIVALENT**		
Mussel size class (mm)	**Shell length (mm)**	**Mussels /m**	**DL (m) dropper length / longline / mussel size class**	**DP dropper portion occupied at any one time**	**DPL (m) dropper portion length occupied at any one time (m)**	**Mussels / DPL occupied at any one time**	**FR (L/h) /mussel**	**FR (m3/h) / DPL occupied at any one time**	**FR (m3/h/ha) (x 3.3 longlines /ha)**	**DC (m) Dropper circum-ference**	**DPL x DC (m^2) “benthic” area equivalent**	**Benthic DL m^2 / ha**
No mussels	0	0	6000	0.1	600	0	0	0	0	0.09	54	179.82
spat nursery	<35	1000	6000	0.09	540	540000	0.5	270	891	0.16	86.4	287.71
intermediate seed	35 - 50	500	4000	0.15	600	300000	0.9	270	891	0.31	186	619.38
young final seed	50 - 70	165	4000	0.22	880	145200	2	290	958	0.47	413.6	1377.29
half adult	70 - 90	165	4000	0.22	880	145200	4	581	1917	0.94	827.2	2754.58
harvest adult	90 - 110	165	4000	0.22	880	145200	7	1016	3354	0.94	827.2	2754.58
TOTAL									8011m^3/hr/ha			7973.35

Table 3-5: For each area of the Marlborough Sounds, the volume of water filtered by mussels per day and the equivalent benthic occupation. *Volume from Broekhuizen, Hadfield and Plew (2015) and # from Hadfield, Broekhuizen and Plew (2014). Areas for the Marlborough Sounds Zones (MSZ)s were provided by MDC. Depths for Anakoa Bay, Port Gore and Port Underwood were estimated from charts at http://fishing-app.gpsnauticalcharts.com. Benthic equivalent drop-off (ha) was calculated as 3.33 (longline / ha) x 160 m (longline length) x 1.5 m (average spread of drop-off beneath each longline) = 800 m^2 / ha = 0.08 ha drop-off per ha farm

MUSSEL FILTRATION RATE							BENTHIC AREA EQUIVALENT			
Marlborough Sounds Zone MSZ	Mussel farms (ha)	Vol filtered by mussels x 10^6 m^3 /day	MSZ area (ha)	Depth (km)	MSZ Volume x 10^6 m^3	% MSZ volume filtered by mussels	Benthic equivalent droppers (ha)	Benthic equivalent drop-off (ha)	Benthic equivalent droppers + drop-off (ha)	% MSZ benthic equivalent
Pelorus Sound	3378	649.47	38477	-	*10300	6.31	2693.28	270.24	2963.52	7.70
Anakoa Bay	116	22.30	3510	0.07	2457	0.91	92.49	9.28	101.77	2.90
Port Gore	77	14.80	9530	0.085	8101	0.18	61.39	6.16	67.55	0.71
QCS and Tory	401	77.10	21557	-	#9990	0.77	319.72	32.08	351.80	1.63
Port Underwood	224	43.07	2347	0.045	1056	4.08	178.60	17.92	196.52	8.37

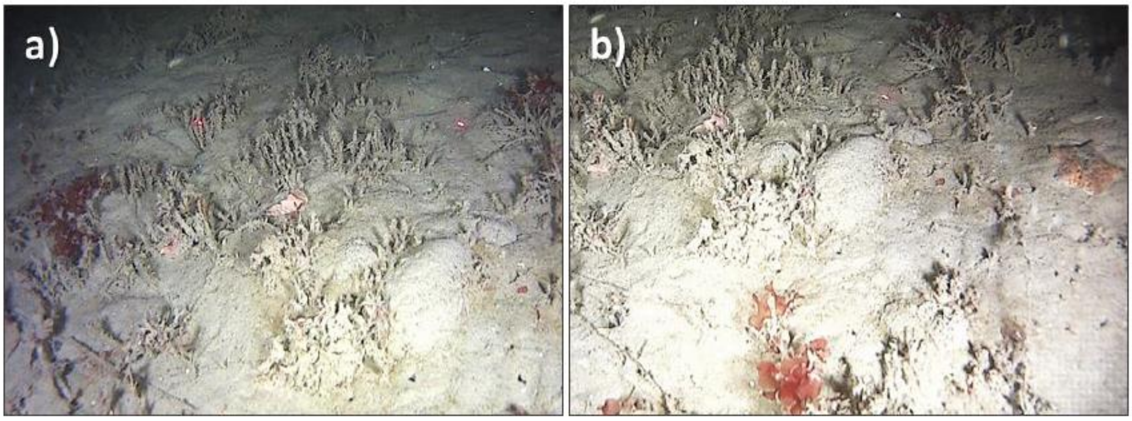

Figure 3-36: Wire-weed like Chaetopterid tubeworm beds, *Spiochaetopterus* spp. From Figure 3-54 in Anderson, Morrison et al. (2018). This habitat is common throughout the Marlborough Sounds as mono-specific beds and intertwined within *Acromegalomma* fields. a-b) Port Gore, Marlborough Sounds. Images (a-b) taken during NIWA's-MBIE Bottlenecks programme (C01X1618) using NIWA's CBedcam (END17101-MSCB17 survey).

Can mussel farms serve to replace some of the lost benthic habitats?

Existing mussel farms provide an equivalent spatial benthic habitat of 3693 ha versus around 2000 ha of historical beds (but we acknowledge that at least some of the activity arises in the water-column rather than at seabed – so not strictly equivalent in this sense)

Cultured green-lipped mussels filter approximately 192,000 m^3/ ha / day which is 2.5% of the entire Marlborough Sounds volume – so if our spatial equivalency to historic beds is realistic, cultured mussel would filter the same volumes of water filtered by lost wild stocks.

Non-mussel suspension feeders on droppers filter an unknown volume of water in addition to that filtered by mussels;

Mussel dropper communities are akin to those of biogenic reefs composed of algae meadows, rhodoliths, bryozoan thickets and calcareous tube worms;

Mussel-culture derived benthic reefs are perhaps akin to soft bottom tubeworm mounds that attract a predominance of scavengers, detritivores and predators.

4 Discussion

4.1 Assessment of services

In this review it was important to benchmark the State of the Environment (SOE) of the Marlborough Sounds (Pelorus and Queen Charlotte Sounds) for two reasons: (1) to contextualise both perceived and quantified environmental impacts of mussel farming, with respect to the SOE, and (2) to assess services of mussel farming with respect to (a) ecological services (EcolS - services to the ecosystem) and (b) provision of ecosystem services (ES - services for human wellbeing) within the context of the present day SOE of the sounds.

By the time the first mussel raft was towed into Kenepuru Sound in 1969 (Dawber 2004) the natural resources of the Marlborough Sounds had been heavily overexploited. Biogenic reefs succumbed to indiscriminate bottom trawling for demersal fish and dredging for scallops and mussels, leaving behind a degraded benthic ecosystem in which we surmise filter feeders once dominated. One of the top key predatory fish, rig, was overfished and stocks have never recovered, being replaced by short-lived species such as kahawai, flounder and grey mullet. Demersal fish juveniles, like blue cod, are associated with biogenic reefs and damage to these complex heterogenous habitats has had a knock-on effect for fisheries stocks in the sounds. The loss of hard biogenic reef surfaces upon which many invertebrate species settled directly and indirectly impoverished the communities preyed upon by several ecologically and economically important finfish species. Accounts of substantial reductions in the abundance of pilchard, blue cod, flatfish, gurnard, kahawai, groper, snapper and crayfish (Handley 2015, 2016 and references therein) have led to the view (Clarke 2014 in Handley 2015) that the Marlborough Sounds ecosystem has experienced a top-down trophic cascade[72] (Forest, Petrie et al. 2005).

Besides the removal of top predators (rig, fur seals) the Marlborough Sounds has also undergone a bottom-up ecosystem step-change with the removal of benthic suspension feeders from the lower food web (mussels, scallops, horse mussels, bryozoans, sponges, ascidians and tubeworms). The removal of shellfish beds go beyond impacts on the food web (van de Geer 2011) because these are hotspots of biodiversity and biogeochemical transformations (Vaughn and Hoellein 2018). They are bioengineers, transforming energy and elements through their capacity for filtration (from the water column) and biodeposition (to the seabed) (i.e., benthic–pelagic coupling) (McKindsey, Archambault et al. 2011). They also determine sediment characteristics and landscape heterogeneity; its likely green-lipped shell middens provided coarse substrata similar to the dog cockle shells that are a present feature of multispecies biogenic clumps in the sounds (Davidson, Richards et al. 2010; Davidson, Baxter et al. 2016). Because bivalves provide multi-faceted ECoIS their loss from an ecosystem is likely to have wider and more far reaching food-web effects than the change in balance caused by a different predation pressure when removing a top predator.

Bottom up effects of bivalve removal depend mostly on the way bivalves are removed from the system: when given the chance, some bivalve communities (e.g. mytilid species) will spring back in very short times indeed (Beukema and Cadée 1996). When resettlement is impaired by changes to the sediment due to the fishing technique being used the recovery will be much harder. This is complicated by the fact that most mytilid bivalves serve as ecosystem engineers by forming beds that hold the silt together, and thereby facilitate their own settlement. Thus, removing the bivalves themselves may be enough to prevent resettlement. The lack of recovery of green-lipped mussel beds in the sounds may be due, in part, to past harvesting methods – i.e., indiscriminate dredging that removed the entire top layer of the seabed leaving behind no hard substrata (or even patches of adult mussels) for subsequent mussel recruitment and recovery. Habitat destruction caused by the

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[72] **top-down cascade** is a trophic cascade where the top consumer/predator controls the primary consumer population. In turn, the primary producer population thrives. The removal of the top predator can alter the food web dynamics. In this case, the primary consumers would overpopulate and exploit the primary producers. Eventually there would not be enough primary producers to sustain the consumer population. Top-down food web stability depends on competition and predation in the higher trophic levels.

dredging when fishing for filter feeders can constitute the bigger risk of ecosystem collapse (van de Geer 2011).

This has been evident in the Hauraki Gulf which has the second highest density of inshore green-lipped mussel farms in New Zealand (Hauraki Gulf Forum 2018, Seachange[73]). Here mussel beds, believed to have covered 50,000 ha of the soft bottom seabed (Paul 2012, 2014), were removed by dredging 50 years ago with no regeneration to date. This lack of recovery is generally thought to be due to the complete destruction of adult beds, which are used by larval mussels as a settlement substrate (McLeod, Parsons et al. 2012; Hauraki Gulf Forum 2018) and the high sediment accumulation rates in the Firth of Thames (Zeldis, Swales et al. 2015). These subtidal mussel reefs would have had the highest secondary productivity of any marine habitat every recorded in New Zealand with high abundances of attached fauna (e.g. sponges, ascidians, bryozoans and cnidarians), invertebrates (e.g. gastropods, starfish, crabs), and small fishes (McLeod, Parsons et al. 2014). It is conservatively estimated that on top of the loss of the mussels, up to 33,000 tons of small invertebrates would have been lost, which could have supported an additional biomass of up to 16,000 tons per year of predatory fish (McLeod 2009). As found in the Marlborough Sounds, the mussel community has now been replaced with a soft-sediment community of moderately low species diversity and richness that is adapted to the very muddy conditions present today (Morrisey, Keeley et al. 2016). The change in status that has occurred in the Hauraki Gulf over the last two centuries has been so great that even if catchment sediment inputs were immediately stopped, it is unlikely the Firth benthic ecosystem would undergo a natural recovery to a pre-reef-collapse state (Zeldis, Swales et al. 2015; Hauraki Gulf Forum 2018).

The regime shifts in both the Gulf (Hauraki Gulf Forum 2018) and the Marlborough Sounds (Ulrich 2015) have resulted in dramatic changes in the EcolS and ES provided by the previous unmodified ecosystems and this presents a challenge for coastal resource managers. Effective integrated coastal management of both these areas requires an understanding of these regime shifts together with “new” services such as that provided by mussel culture. However, to date the traditional approach to managing coastal regions that incorporate mussel aquaculture is focused on assessing aesthetic and environmental impacts at the base of the food chain rather than creating synergies with wider goals that consider the overall SOE. Research and regulatory monitoring have focused on potential adverse benthic effects from biodeposition (biogeochemical and biological processes) (Keeley, Forrest et al. 2009; Keeley and Morrisey 2013) and depletion of plankton resources (concentrations of phytoplankton, zooplankton, chlorophyll-*a* and particulate and dissolved nutrients). These data have been used to develop production carrying capacity models (Inglis, Hayden and Ross 2000; Broekhuizen, Ren et al. 2004; Broekhuizen, Oldman et al. 2005; Grant and Filgueira 2011; Stenton-Dozey 2013) but again without regard for the overall SOE.

Accounting for marine regime shifts in resource management decisions clearly requires integrative, cross-sectoral ecosystem-based management (EBM) approaches (Levin and Möllmann 2015) that incorporate aquaculture services. This review provides the first inventory of service provision by cultured green-lipped mussels in the Marlborough Sounds and as such “opens the door” to a new viewpoint gaining momentum internationally: that aquaculture can be managed in such a way that it enhances ecosystems and supports the communities that depend on these ecosystems (Gentry, Alleway et al. 2019 and references therein). This view still incorporates potential negative effects of aquaculture to provide an integrated and balanced assessment of ecosystem service potential. Measuring the intrinsic ability for the natural environment to provide goods and services (Ecols + ES)

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[73] http://www.seachange.org.nz/read-the-plan/

is a largely novel method for investigating the potential ecosystem-enhancing aspects of aquaculture. Ecosystem services (ES) are usually applied to natural environments and, by quantifying the value of nature, can create a strong incentive for conservation (e.g. Geange, Townsend et al. 2019; Appendix A). While conservation of wild species and habitats has the potential to preserve and restore these services, it is important to understand if and when human modified systems and infrastructure, such as those presented by mussel farming in the sounds, can provide the same or similar services as the natural ecosystem.

We have shown that cultured green-lipped mussels in the Marlborough Sounds do have some degree of equivalency with the previous unmodified wild mussel beds and that there are parallels in biodiversity with benthic biogenic reefs. This then implies that mussel farming provides some of the EcolS and ES that once existed before degradation by humans. However, since (i) we do not know the spatial scale of the previous unmodified benthic habitats and (ii) we have not been able to fully assess the degree to which suspended rope mussels (usually operated in the surface, mixed layer) can adequately duplicate each of the functions of a more natural benthic shellfish community, we cannot quantify the full extent of service "substitution" provided by mussel culture.

With these constraints in mind, our summarised assessment of the provision of services by mussel farming in the Marlborough Sounds follows:

Regulatory

In our consideration of the *regulatory* ES cultured mussels can provide in the removal of suspended sediment from the water, we found no evidence to indicate that the farms are having a substantial influence upon concentrations of suspended sediment measured in the upper parts of the water-column. Mussel farming therefore does not serve to reduce the amount of suspended sediments that arise from land-based activities such as farming and forestry. Mussels do provide EcolS in benthic-pelagic coupling by (temporarily) moving suspended particles (in their faeces and pseudofaeces) to the seabed to be reworked by benthic processes before being resuspended.

However, in terms of nitrogen removal the Pelorus mussel harvest may remove nitrogen equivalent to about 45% of the annual riverine nitrogen-load to Pelorus Sound (Knight 2012). For the Firth of Thames, the figure is closer to 1% (based upon figures by Zeldis 2008). In Pelorus Sound, there is some evidence to suggest that, if the entire mussel crop were to mature synchronously, the denitrification flux may amount to approximately 50% of the annual-scale riverine nutrient loads to the sound around harvest time. The ES provided by mussels amounts to the removal of some of the anthropogenic nitrogen loading of the sounds. The EcolS provision is manifested through nutrient regeneration in the water column and on the seabed.

Even though mussel shells are rich in inorganic carbon (as calcium carbonate), it is unlikely that shell formation acts as a sink for CO_2 (no carbon sequestration ES through shell formation). However, shells discarded in the sea will dissolve in an (even mildly) acidic aqueous environment and through this process aqueous CO_2 will be consumed. Returning harvested shell to aqueous, acidic environments (e.g. surficial soils and surficial seabed sediments that contain sufficient supply of rotting organic matter) will tend to compensate for the prior CO_2 enrichment that arose when the shell was formed. Shell that remains in the sea contributes to the carbon cycle of the sounds' ecosystem, thereby providing EcolS whereas mussel shell discards from processing that are stored on land equate to approximately 2-5 $x10^3$ tonne inorganic carbon being immobilised from the sounds each year.

Habitat and supporting

Suspended mussel culture provides a suite of *habitat and supporting* EcolS to the sounds' ecosystem. We estimated from the literature that suspended mussel structures provided habitat for approximately 139 taxa of which ascidians contributed the most, followed by macroalgae, sponges, crustaceans - amphipods, isopods and crabs, cnidarians – hydroids and sea anemones, bryozoans and annelids - tube worms, feather-duster worms and carnivorous polychaetes. Most of the species were suspension feeders (ca. 61%) followed by scavengers and predators. The species composition on droppers changes with depth, season and location in the sounds (inner, middle or outer Pelorus).

The dominance of suspension feeders is an important contribution to the food web considering the extensive destruction of this functional feeding group (FFG) from the sounds' ecosystem by past overharvesting. This biofouling FFG together with the cultured green-lipped mussels, contribute a substantial standing biomass to the bottom-up trophic level that extracts suspended plankton and particulate organic matter from the water column, and that returns this material in its dissolved and particulate inorganic form through excretion. This stimulates the remineralisation pathways in the water column and on the seabed.

The seabed beneath mussel farms is dominated by patchy mounds of mussel shells and clumps of live green-lipped mussels to which is added episodic biofouling discards and regular biodeposits. These mussel-culture derived reefs form three-dimensional heterogenous habitats that provide food, shelter, protection and resources for other marine flora and fauna and help to stabilise bottom sediments. In these mounds biogeochemical processes and nutrient cycling is more akin to that of biogenic habitats - increases in oxygen exchange, nitrate fluxes, and overall benthic regeneration – rather than to the near-featureless open muddy areas outside farms.

Local mobile epifauna such as sea cucumbers, starfish, sea urchins and gastropods are attracted from outside farms to the food supply afforded by the mussel-culture derived reefs. Other sedentary species (sponges, ascidians and bryozoans) are more likely to have originated from biofouling discards or incidental drop-off from mussel structures. Overall species diversity appears marginally higher under farms but there is a clear indication of a greater abundance of these species in association with mussel-culture derived reefs.

In a spatial context mussel farms do provide an equivalency of 3693 ha versus around 2000 ha of historical wild mussel beds. We calculated that for this area green-lipped mussels filter approximately 192,000 m^3/ ha / day which is 2.5% of the entire Marlborough Sounds volume – so if our spatial equivalency to historic beds is realistic, cultured mussel would filter the same volumes of water filtered by lost wild stocks. In addition, mussel dropper flora and fauna communities are akin to those found associated with present day benthic algae meadows, rhodolith beds, bryozoan thickets and calcareous tube worms. Thus, to some degree mussel farms compensate for the loss of both wild mussel beds and biogenic reefs by providing renewable mussel stocks and habitats that increase the abundance of organisms that once would have been plentiful among the now-destroyed benthic habitats.

Habitat and supporting ES provision is manifested through primary production (colonising diatoms and macroalgae), nutrient regeneration and habitat for species.

Provisioning

Mussel farming provides *provisioning* ES through food, raw material and medicinal / neutraceutical materials for human wellbeing. Since 2003 the annual production of mussels from the Marlborough Sounds has ranged from 40 000 to 70 000 tonnes green weight. Most of this production is consumed as mussel meat, but a small proportion provides neutraceutical products (powder and mussel oil) for the treatment of inflammatory diseases and general health benefits. The industry is seeking uses for a large quantity of discarded mussel shell with suggestions ranging from land mulch, stabilisation of seabed sediments in the sounds and substrate for benthic reef restoration. Crushed shell is now being used in the wine industry as mulch around vines in the Marlborough Sounds.

By-products of mussel farming are emerging providing ES: *Undaria pinnatifida* is now being used in a land fertiliser and blue mussels are being harvested for exploratory market. There is significant potential provision of a wide variety of bioactives from macroalgae and sponges that grow on mussel farms.

Seabirds, Fish and Marine mammals

Mussel droppers, mussel-culture derived reefs and block anchors provide habitat EcolS (food and shelter) for spotties and triplefins throughout the year. The occasional leatherjackets, stargazers, blue cod, mullet and flatfish have also been observed around mussel-cultured derived reefs. Pelagic species (snapper, kingfish, kahawai and yellow-eyed mullet) pass through the farms and there are anecdotal accounts of snapper feeding off mussel droppers. ES is demonstrated through food and habitat provision for species (snapper and blue cod) that are of interest to fishermen.

Mussel farms provide an EcolS to the sounds' ecosystem by providing feeding and roosting opportunities for some seabirds. Buoys on mussel farms provide EcolS haul-out for seals and at harvest foraging opportunities are afforded for seals. The common and bottlenose dolphins use farms to herd their prey.

4.2 Knowledge gaps

The lack of underpinning data precludes quantifying most of the EcolS provided by mussel farming that have been identified in this review. Key areas that require investigation are:

1. associated biofoulers (e.g. macroalgae) and the seabed below farms;
2. a better understanding of denitrification and nutrient cycling;
3. measurements of the contribution of discarded biofouling biomass to the benthic environment and the fate of this material;
4. biodiversity – measures of the full scale of species diversity and abundance on mussel farm structures and mussel-culture derived reefs;
5. assessment of functional feeding group energetics and contribution to food web; and
6. sound scientific studies on the interactions between mussel farms and fish, seabirds and mammals.
7. refined measurements of particulate, nitrogen and carbon sequestration by mussels,

In terms of quantifying and refining our understanding ES provision of mussel farming, a scoring matrix approach could be useful like the one developed by Geange, Townsend et al. (2019) for New Zealand benthic marine habitats (see Appendix A). To score the matrix the authors used the best available information, which included New Zealand-focused peer-reviewed scientific literature that verified a service score; support from non- peer-reviewed scientific literature with a New Zealand focus; peer-reviewed literature external to New Zealand; and expert opinion. They used a numeric indicator within the matrix to demonstrate confidence in the assessment. An important provision not included in this study was cultural, an ES that should form part scoring of a mussel farming ES matrix.

We are cognisant that this review may also be the first step towards sourcing more funds in the future to undertake field research to deliver evidence-based knowledge to fulfil the gaps listed above.

4.3 Way forward

We understand that the MFA intends to submit this review to inform the emerging chapter on aquaculture in the Marlborough Environment Plan (MEP) which will govern the rules around Marlborough's marine farming for the next ten years. Even though this review does not fully quantify the services of mussel farming, it does provide the first step towards developing a service-approach that can underpin future aquaculture regulatory and monitoring requirements. The review goes a step further by framing the service inventory within the present SOE of the Marlborough Sounds (1) to contextualise both perceived and quantified environmental impacts of mussel farming, with respect to the SOE, and (2) to assess services of mussel farming with respect to (a) EcolS and (b) provision of ES within the context of the present day SOE of the sounds.

At some point into the future (once key services provided by mussel farming have been better quantified (see section 4.2)) the provision of these services can be incorporated into a knowledge-based approach leading onto an ecosystem-based approach, and an integrative management framework that includes economic, environmental and social considerations. The ecosystem-based management approach has been defined as '*a comprehensive integrated management of human activities based on the best available scientific knowledge about the ecosystem and its dynamics, in order to identify and take actions on influences that are critical to the health of ecosystems, thereby achieving sustainable uses of ecosystem goods and services and maintenance of ecosystem integrity*' (Rice et al. 2005 in Cranford, Kamermans et al. 2012).

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6 Glossary of abbreviations and terms

biodeposit	A deposit of biological origin
biota	living organisms
Diversity index	A diversity index is a quantitative measure that reflects how many different types (such as species) there are in a dataset (a community), and simultaneously takes into account how evenly the basic entities (such as individuals) are distributed among those types.
Ecosystem services (ES)	ES are the benefits people obtain from ecosystems. There are four broad categories for classifying ES: (1) *Regulating*, which encompasses services that regulate the environment such as improving water quality through sequestering suspended particulates, nitrogen and carbon; (2) *Habitat and Supporting*, which includes physical creation of habitats, habitat provision for species and maintaining diversity; (3) *Provisioning*, meaning the production of food, water or other goods and (4) *Cultural*.
Ecological services (EcolS)	EcolS are services that are a benefit to the marine ecosystems and in this review, we have used the same defining categores as used for ES.
epibiota	The organisms that live on the surface of another one.
epifauna	Animals living on the surface of the seabed or attached to submerged objects or aquatic animals or plants.
ESMS	Ecologically Significant Marine Sites: Scientific criteria (https://www.cbd.int/ebsa/about): ▪ Uniqueness or Rarity ▪ Special importance for life history stages of species ▪ Importance for threatened, endangered or declining species and/or habitats ▪ Vulnerability, Fragility, Sensitivity, or Slow recovery ▪ Biological Productivity ▪ Biological Diversity ▪ Naturalness
FRIA	Fisheries Resource Impact Assessment
infauna	the animals living in the sediment matrix (below the surface)
nMDS	Non-metric MDS plots examine the similarity of different ecological communities based on their species composition. In those analyses, the abundance of all species within samples is recorded and the raw data takes the form of a matrix of species (the variables) by samples.

r-strategists	r-selected species are those that emphasize high growth rates, typically exploit less-crowded ecological niches, and produce many offspring, each of which has a relatively low probability of surviving to adulthood
seston	suspended dead and living organic particulates
SOE	State of the Environment: relates to an analysis of trends in the environment of encompassing aspects such as water quality, air quality, land use, ecosystem health and function, along with social and cultural matters.
sounds	This refers to the Marlborough Sounds inclusive of Pelorus Sound, Queen Charlotte Sound, Tory Channel, and some of the outer bays: Croisilles Harbour, Admirality, Catherine Cove, Anakoa, Titirangi, Port Gore and Port Underwood (see Figure 2-2).

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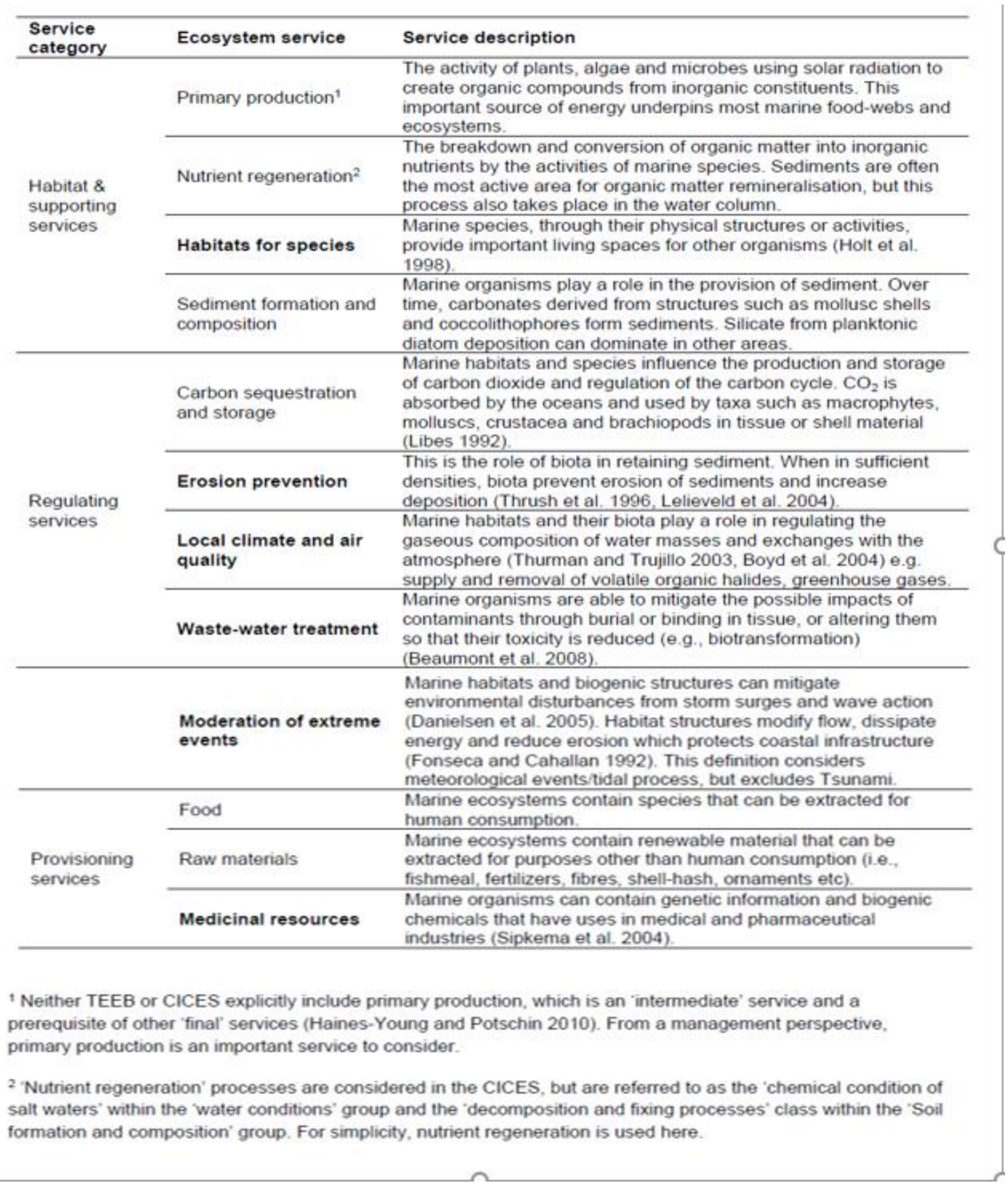
Appendix A ESP matrix for natural biogenic reefs

Geange, Townsend et al. (2019) constructed an Ecosystem Service Potential (ESP) matrix for natural biogenic reefs that incorporated 12 services divided into three broad categories: Habitat and supporting services; Regulating services; and Provisioning services based predominately on The Economics of Ecosystems and Biodiversity (TEEB) classification (TEEB 2010), with the addition of primary production and nutrient regeneration as important ‘intermediate’ services, and the addition of ‘sediment formation and composition’ from the Common International Classification of Ecosystem Services CICES classification (Haines-Young and Potschin 2013) (Table 2-1).

Table 1: Description of ecosystem servies incorporated in an ecosystem service matrix. Based on TEEB and CICES ecosystem service classificaitons.



Service category	**Ecosystem service**	**Service description**
Habitat & supporting services	Primary production[1]	The activity of plants, algae and microbes using solar radiation to create organic compounds from inorganic constituents. This important source of energy underpins most marine food-webs and ecosystems.
	Nutrient regeneration[2]	The breakdown and conversion of organic matter into inorganic nutrients by the activities of marine species. Sediments are often the most active area for organic matter remineralisation, but this process also takes place in the water column.
	Habitats for species	Marine species, through their physical structures or activities, provide important living spaces for other organisms (Holt et al. 1998).
	Sediment formation and composition	Marine organisms play a role in the provision of sediment. Over time, carbonates derived from structures such as mollusc shells and coccolithophores form sediments. Silicate from planktonic diatom deposition can dominate in other areas.
Regulating services	Carbon sequestration and storage	Marine habitats and species influence the production and storage of carbon dioxide and regulation of the carbon cycle. CO_2 is absorbed by the oceans and used by taxa such as macrophytes, molluscs, crustacea and brachiopods in tissue or shell material (Libes 1992).
	Erosion prevention	This is the role of biota in retaining sediment. When in sufficient densities, biota prevent erosion of sediments and increase deposition (Thrush et al. 1996, Lelieveld et al. 2004).
	Local climate and air quality	Marine habitats and their biota play a role in regulating the gaseous composition of water masses and exchanges with the atmosphere (Thurman and Trujillo 2003, Boyd et al. 2004) e.g. supply and removal of volatile organic halides, greenhouse gases.
	Waste-water treatment	Marine organisms are able to mitigate the possible impacts of contaminants through burial or binding in tissue, or altering them so that their toxicity is reduced (e.g., biotransformation) (Beaumont et al. 2008).
	Moderation of extreme events	Marine habitats and biogenic structures can mitigate environmental disturbances from storm surges and wave action (Danielsen et al. 2005). Habitat structures modify flow, dissipate energy and reduce erosion which protects coastal infrastructure (Fonseca and Cahallan 1992). This definition considers meteorological events/tidal process, but excludes Tsunami.
Provisioning services	Food	Marine ecosystems contain species that can be extracted for human consumption.
	Raw materials	Marine ecosystems contain renewable material that can be extracted for purposes other than human consumption (i.e., fishmeal, fertilizers, fibres, shell-hash, ornaments etc).
	Medicinal resources	Marine organisms can contain genetic information and biogenic chemicals that have uses in medical and pharmaceutical industries (Sipkema et al. 2004).

[1] Neither TEEB or CICES explicitly include primary production, which is an ‘intermediate’ service and a prerequisite of other ‘final’ services (Haines-Young and Potschin 2010). From a management perspective, primary production is an important service to consider.

[2] ‘Nutrient regeneration’ processes are considered in the CICES, but are referred to as the ‘chemical condition of salt waters’ within the ‘water conditions’ group and the ‘decomposition and fixing processes’ class within the ‘Soil formation and composition’ group. For simplicity, nutrient regeneration is used here.

Appendix B Water trends- statistical methods

The water-quality data alluded to in this report stem from Marlborough District Council and five other sources Table 3-1. Most water samples were gathered using a hose-pipe that was lowered (open) to 15 m depth then sealed and recovered (ie the samples were depth-averages of the upper 15 m) but some early studies collected water at discrete depths using a bottle-sampling devices. Water-samples were transported to a laboratory within an ice-filled chilly container. They reached the laboratory within 24 hours.

Validity of concatenating time-series

We have concatenated time-series data from sampling stations that were often not exactly co-located. This raises the possibility that any 'trends' that we might detect arise from underlying temporally invariant spatial differences amongst the individual time-series from which the composite time-series was constructed. To guard against this, we sought to determine whether there is any evidence that salinity characteristics differ across the individual time-series from which each composite one was built. We used the Kruskall-Wallis test to determine whether study is a predictor of salinity. Where differences are absent, we argue that this provides some evidence that the differing sampling locations that form each component of the composite were indeed, located within the same, homogenous water mass/region. Where salinity differences do arise, and all of the component series span several years (such that year-to-year flow fluctuations may be averaged out), the difference may indicate that it is inappropriate to generate a composite time-series.

It transpires that the salinity is unrelated to study at the Kenepuru and Beatrix Bay sites, but at the outer-Pelorus region, study is a predictor of salinity. This latter influence probably reflects that fact that the MDC data are gathered at a more seaward (hence, more saline) location than the earlier (NIWA) data. Accordingly, we conclude that any trends evident in the outer-Pelours composite time-series may be artefacts arising from the fact that later (MDC) data were collected at a more seaward location than the earlier (NIWA and Cawthron) data. Thus, we perform no further analyses on the data from the outer Pelorus region.

Trend detection

We sought to determine whether there is evidence of long-term change in the of turbidity, and concentrations of total suspended solids.

Firstly, the raw-data were deseasonalized. This was achieved by calculating the multi-year month-of-year medians and subtracting the appropriate monthly median from the values in the raw-time-series. Subsequently, the Sen slopes of the deseasonalized data. The Sen slope of each deseasonalized time-series were calculated using the zyp.sen function out of R's zyp package (Bronaugh and Werner 2013). Whilst the NIWA 1997 data had weekly resolution, other data had monthly, or bi-monthly resolution (or comprised only short-term studies). The Sen slope is a median of the slopes calculated from all possible pair-wise sampling dates. The Sen-slope is a measure of linear-slope. It provides an estimate of the net (or average) rate of change over the entire time-span. The Sen-slope method is robust against missing values. Nonetheless, since different sub-intervals of a time-series were sampled with differing frequencies, care was taken to ensure that none of the sub-intervals carry a disproportionate weight when calculating the median slope (Helsel and Hirsch 2002). Thus, only one datum was selected from each month within the time-series. Furthermore, data were extracted only for the calendar months which were sampled during the DSIR1984 study (February, April, June, August, September, December).

Even in samples drawn from a genuinely stationary distribution, the sample Sen-slope is vanishingly unlikely to be exactly zero – no matter how long the time-series that is generated. The standard ‘two-sided’ slopes test adopts a null-hypothesis that the slope is exactly zero. Almost inevitably, this null hypothesis becomes ever more likely to be rejected as the sample size increases – even if the samples are drawn from a stationary distribution. Thus, rather than aiming to determine whether our realised Sen slopes ‘are significantly different from zero’, we adopted a new approach proposed in Larned, Snelder et al. (2015) and now published in an international scientific journal (McBride in press). Specifically, we undertake two one-sided tests corresponding to the null hypotheses: (a) the slope is not less than zero and (b) the slope is not greater than zero. If neither null hypothesis is rejected, we conclude that the direction of any trend cannot be reliably determined (rather than concluding ‘there is no trend’). It is not possible for both null hypotheses to be rejected but if one is, we conclude that the direction of trend can be confidently determined. We use a 95% confidence level for each of the two tests. When one or other of the null hypotheses are rejected, the implication is that the sign of the underlying true (cf sampled) linear trend-slope has been correctly identified with 95% probability. We will refer to such trends as having been ‘confidently identified’.