Feasibility of restoring Tasman Bay mussel beds

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Authors/Contributors:
Sean Handley
Stephen Brown

For any information regarding this report please contact:

Sean Handley
Marine Ecologist
Nelson Marine Ecology and Aquaculture
+64-3-548 1715
sean.handley@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
217 Akersten Street, Port Nelson
PO Box 893
Nelson 7040
New Zealand

Phone +64-3-548 1715
Fax +64-3-548 1716

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Executive summary

Green-lipped mussels *Perna canaliculus* historically were a significant component of soft-sediment habitats in regions like Tasman Bays, the Marlborough Sounds, the Firth of Thames, and potentially the Kaipara Harbour. Historical newspaper accounts and catch-landing statistics indicate populations of mussels in Nelson/Marlborough region potentially have been over-exploited twice; in the late 1800s and between 1960 and 1982 when an estimated 20,534 tonnes were landed. Tasman Bay mussel beds have since failed to recover. Nelson City Council is interested in testing the feasibility of restoring mussel beds in Tasman Bay.

Evidence from studies of remnant soft-sediment mussel populations, bivalve ecological studies, and restoration research here and overseas demonstrate that shellfish living on soft-sediments are an integral part of soft-sediment ecosystems, and provide significant ecosystem services as live aggregations and by providing dead calcareous shell. These services include:

- Filtration capacity: clarification of the water-column of suspended sediments and phytoplankton, potentially mitigating eutrophication and soil erosion;
- Deposition of particulate matter and excretion of nutrients which fertilise benthic primary production (micro-phytobenthos and macro-algae);
- Aggregations stabilise sediments, provide settlement surfaces for other species (including species potentially important to mussel and scallop settlement), and interstitial habitat complexity. These factors increase species diversity, secondary-producer biomass and productivity, potentially enhancing supported biomass of fishes;
- Feedback mechanisms that enhance restoration of benthic primary producers like diatoms, macro-algae and submerged aquatic vegetation (e.g. seagrass);
- Sequestration of nutrients including carbon and nitrogen;
- Dead shells contributing to the carbonate budget of coastal sediments, sequestering nitrogen and carbon, potentially mitigating eutrophication, and buffering coastal waters from acidification arising from climate change.

Factors that have prevented the intrinsic recovery of soft-sediment mussel beds in Tasman Bay and elsewhere are likely to be complex, potentially involving:

- Over-exploitation of stocks preventing sufficient larval provision, or conspecific settlement surfaces;
- Habitat change from various effects: sediment from terrestrial sources, bottom-contact fishing methods (e.g. dredging, trawling, seining), climate change;
- Poor water quality from high suspended sediments suffocating mussels, or preventing efficient feeding;
- Food chain effects, such as the loss of top predators that formerly controlled small predators of mussel spat.

Green-lipped mussels require filamentous substrata on which to settle and metamorphose for primary settlement - a role once thought to be provided for by benthic filamentous algae, bryzoans, hydroids and seagrass. Filamentous red algae and bryozoans have been previously recorded present in Tasman Bay shellfish beds, but are likely now to be scarce or absent, potentially as the result of siltation, concomitant loss of water clarity for photosynthesis, and bottom-contact fishing methods. For these reasons, we suggest that recruitment failure due to habitat change appears to be the most likely reason for lack of mussel bed recovery. We hypothesise that a regime shift has occurred whereby recovery of benthic mussels is prevented because of a lack of filtration capacity brought about by the collapse of shellfish beds in the system. Shellfish including mussels help clarify the water column and create water column and seabed conditions conducive to the growth of filamentous species including bryozoa, hydroids and benthic algae, which in turn become settlement substrata for shellfish re-colonisation.

Regardless of the mechanisms preventing recovery of mussel beds, there appear to be ecological benefits in returning waste shell to the seabed in Tasman Bay, especially for providing settlement habitat for species that may facilitate shellfish larval settlement, or recruitment of other filter-feeders (e.g. sea-squirts) that will help improve water quality and clarity at the seabed. To help restore mussel beds, intervention by placing live juveniles on the seabed or on shell piles is also suggested. Appropriate experimental design and monitoring methods are proposed to test the feasibility of mussel bed restoration.

1 Introduction

Nelson City Council (NCC) is interested in testing the feasibility of restoring green-lipped mussel *Perna canaliculus* beds in inner Tasman Bay. This project, while not linked with Tasman District Council or Marlborough District Council, has relevance to all three authorities as regional boundaries bisect the bay. It is also relevant to other regions with extant mussel fisheries (e.g. Waikato and Rodney).

Historically, green-lipped mussel beds were an abundant component of many shallow soft sediment coastal environments in New Zealand (McLeod 2009, McLeod et al. 2012, Paul 2012, Morrison et al. in review). Most of these mussel beds have been lost or severely reduced in size due to historic over-harvesting, habitat change and possibly terrestrial derived sedimentation. In the Nelson/Marlborough region, mussels, oysters and scallops were worth ca.$90M per annum at their peaks of harvest (K. Michael, NIWA unpub. data.). Now these fisheries have collapsed, with unknown ecological effects. National and international research shows that large benthic filter-feeders are vital ecosystem engineers, playing a significant role in the maintenance of benthic (seafloor) food webs, water quality and clarity, and provide feedback mechanisms supporting benthic primary production. So, regardless of economic imperatives, the restoration of mussel beds should provide ecological resilience to soft sediment habitats that are dominant in Tasman Bay.

Recent research in the Firth of Thames shows that restoration of mussel beds there was hampered by poor recruitment and low survivorship related to high sediment loads (McLeod 2009, McLeod et al. 2012). Experiments with shell deployment in outer Tasman Bay to restore flat oysters showed that oysters will not settle on soft sediments, but will recruit to waste shell (Brown 2011). The present report uses the results of those studies as the basis of a literature review of historical mussel beds in Tasman Bay.

This report comprises:

1) A literature review related to ecosystem services provided by mussel beds and their use in ecosystem restoration.

2) A proposed experimental design to test the feasibility of utilising waste green-lipped mussel shells and juvenile mussels as a tool for habitat restoration.

1.1 The case for restoration

1.1.1 History of Tasman Bay mussels – what has been lost?

Historically, shellfish including green-lipped mussels were an important component of the diet of Māori (Best 1929, Smith 2011). Early accounts of shellfish exploitation in Tasman Bay are rare, but reports of oyster bars in Nelson suggest shellfish sales were part of a thriving local economy from 1859 until over-fishing took its toll by the early 1900's (Wright 1990). The extent of early mussel beds can only be conjectured. Early accounts indicate that mussel beds were present at the entrance to Nelson Harbour in 1862 (Nelson Examiner and NZ Chronicle 1862):

> ACCIDENT TO THE HEBE.—An accident occurred to the brig Hebe on Wednesday morning last, but which, luckily, was not of serious consequence. While the pilot was bringing her into harbour it appears that her bottom touched a mussel bank, but, after a short delay, the rising tide floated her off. The tide, which was running strongly, with a head wind, again caught her, and she was forced on to the Boulder Bank, where she had to remain until the night's tide. On being examined while in this position, it was found that a few sheets of copper were damaged, and a small portion of her false keel forward had been broken away. When again floated the Hebe was taken alongside the wharf, and is now making but very little water.

Mussel beds were perhaps common at the entrance to many of New Zealand rivers and ports as the following Mokihinui West Coast account portrays, where mussels appear to have provided a necessary food source for settlers and gold prospectors (Nelson Examiner and NZ Chronicle 1887):

> We have a very pretty spot for a township ; you could scarcely tell the difference between this and the Grey river—the same entrance, gorge, with the islands above. One great boon the boys have here is first-rate fishing and mussel ground. I don't know what some of them would have done only for that blessing.

Either by necessity or for profit, shellfish were clearly targeted by early settlers, hand-picked from foreshore, or dredged from the seabed. Little is known regarding the structure of the marine environment during European settlement, but there is increasing evidence that overexploitation of fisheries resources was apparent by the turn of the 19th century (Anderson 2008, Smith et al. 2009). The following excerpt from the Nelson Mail (1896) illustrates that mussels were being over-exploited near the turn of the century, and that sponge beds were common around the coast, and appeared to be regarded as worthy of protecting along with mussels. Because of the associated concern regarding sponge beds, we assume that mussels were being harvested by dredge.

> The Sea Fisheries Act Amendment Bill was read a second time on the motion of Mr Walker, who explained that some of the mussel beds are getting exhausted. The measure was introduced with a view to giving them periodical rests for recovery as well as to protect sponge beds around the coast.

Over 70 years later, shellfish resources and associated habitats targeting scallops were surveyed (Choat 1960). This survey reported large green-lipped mussels being abundant over the greater part of the dominant “fine silty mud” substratum of Tasman Bay, with some patches in great abundance (Figure 1-1).

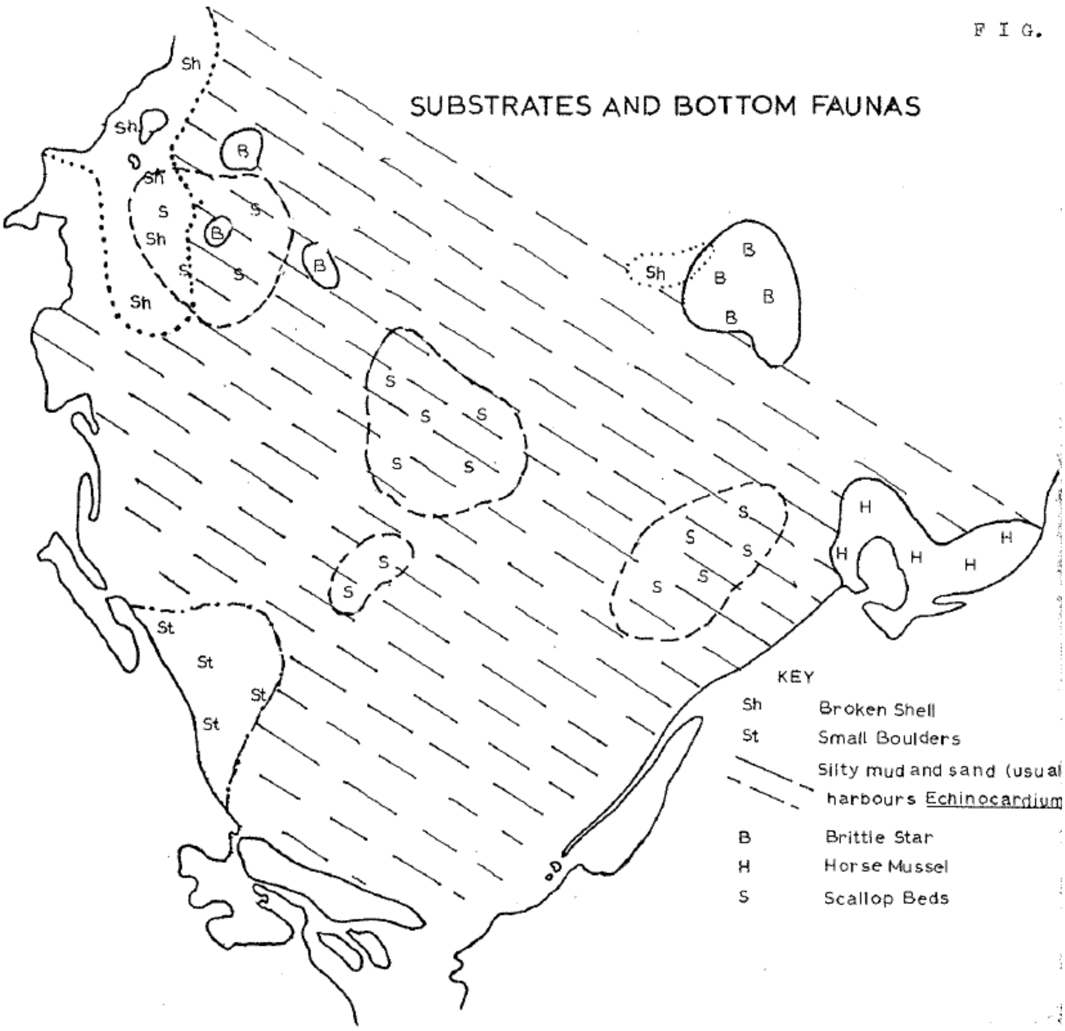

Figure 1-1: Substrata and bottom faunal map of Tasman Bay showing the dominance of silty mud where mussels were reported abundant (Choat 1960).

A subsequent quantitative dredge oyster survey in 1962 by Tunbridge (1962) mapped the distribution and density of mussels and scallops. Two dense mussels beds were reported, the largest directly offshore from the Boulder Bank between 10-30 m depth, and another smaller bed at about 10 m depth offshore from Kina Peninsula (Figure 1-2).

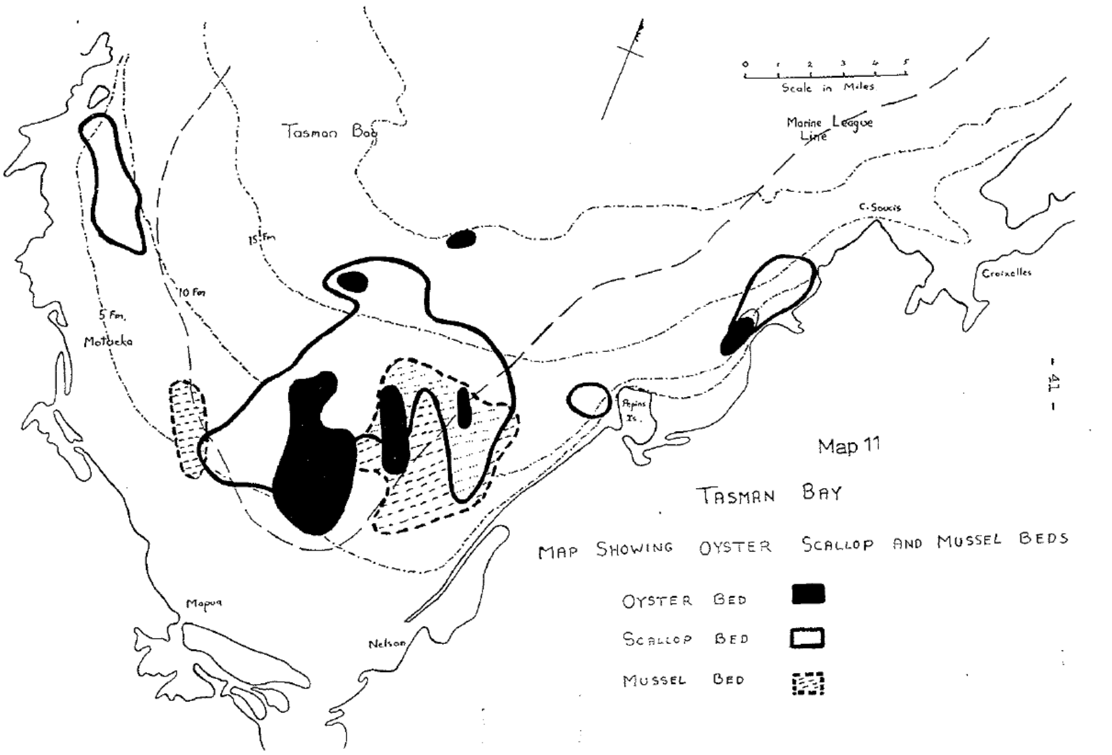

Figure 1-2: Map of dredge oyster, scallop and mussel beds in Tasman Bay (Tunbridge 1962).

It is not clear whether initial declines of shellfish near the turn of the 19th century reported in a newspaper article led to complete collapse of these fisheries in Tasman Bay. It appears that following the scallop surveys conducted by Choat (1960) and dredge oyster surveys by Tunbridge (1962) mussels were again harvested, most likely as bycatch as part of the oyster and scallop fisheries. Tunbridge (1962) noted that crew members of his survey vessel "Ikatere" said the mussels during his survey were in good condition and compared favourably with the Auckland mussels, but local fishermen stated that they were in poor condition for much of the year.

Recorded landings of mussels began with 21 sacks in 1953 from the Tasman/Marlborough region (Paul 2012). Mussels did not figure again in reported landings (apart from 3 sacks in 1957), until the 1960s, presumably after the surveys for scallops and dredge oysters by Choat (1960) and Tunbridge (1962) established the presence of commercial densities. Harvesting of mussels during this period peaked with annual landings of 40,149 sacks in 1971 (ca. 2,731.7 t[1]), which was near equivalent to the peak of production harvested in the early 1960's from the Hauraki Gulf (ca. 2,750 t, Paul 2012). The decline and collapse of the stocks in the Hauraki Gulf, which were thought to have been brought about by serial depletion of beds after de-licensing of the fishery (Chisholm 2005, McLeod 2009, Paul 2012), appeared to precede the peaks of Nelson mussel production which, no doubt were fuelled by the doubling of the price paid per sack for Auckland mussels between 1958 and 1960 (Paul 2012). The decline of the Hauraki Gulf stocks which collapsed towards the end of the 1960's (Paul 2012) also may have led to increased demand for mussels from other regions. Between 1963 and 1981, Annala and Sullivan (1997) reported that oysters were taken as

[1] Sacks of mussels were converted to greenweight landings (tonnes) using the conversion of 1 sack = 150 lb (Paul 2012).

bycatch, firstly by the revived mussel fishery and subsequently by the scallop fishery, which suggests local fishermen switched target species depending on price, demand, and supply of stocks in the Nelson region.

Harvesting of mussels after the decline of mussel stocks in the 1970's appeared largely reliant on the scallop and dredge oyster fisheries, but by that stage wild mussels would likely have had to compete with superior farmed mussels with the development of mussel aquaculture (Dawber 2004). Maximum scallop fishery production of 1,000 tonnes meat weight was recorded in the 1970's (Handley 2006). This production subsequently crashed, leading to the closure of the fishery between 1981 and 1982. In 1983 enhancement trials proved very successful leading to large scale seeding of juvenile scallops with landings peaking by the late 1980s. The enhanced fishery was managed by the Challenger Scallop Enhancement Co., and by 1992 the Southern Scallop Fishery was introduced into the Quota Management System (QMS). Under the QMS an Annual Allowable Catch is set for the fishery each year, contingent on a pre-season biomass survey. Reseeding of spat collected in both Tasman and Golden Bays is followed by a two year growing period, and harvesting of scallops in a rotational cycle among nine statistical reporting fishing areas (Arbuckle and Metzger 2000). The scallop fishery was managed spatially by rotational fishing of sectors annually until 2005/06 when the Tasman Bay stocks declined and enhancement of juvenile stocks also failed. After 2007, commercial harvest of scallops was largely restricted to Golden Bay, west of the exclusion zone, and the Marlborough Sounds (Mitch Campbell, Challenger Scallop Enhancement Co., pers. comm.). Since the mid 2000's dredge oyster populations were most abundant in Tasman Bay to the south east of Separation Point (Brown 2011) but the fishery is currently closed waiting the rebuilding of biomass levels (Mitch Campbell, pers. comm.).

Tunbridge (1962) noted that much of the substrate in Tasman and Golden Bay is mud, so settlement was probably limiting for both oysters and mussels, and that to work these areas commercially "thought could be given to the deposition of a suitable substance on the grounds prior to settlement" (Tunbridge 1962) to enhance these fisheries (Handley 2006). Similarly, Greenway (1969) stated that dredging of the Hauraki Gulf left an unstable muddy substrate unsuitable for mussel attachment, precluding natural bed regeneration (Paul 2012). The return of mussel shells or heavier oyster shells was suggested to provide cultch for settlement. Although Brown (2011) demonstrated that shell return could increase dredge oyster densities in Tasman Bay, there is some doubt as to whether returning shells alone will lead to recovery of mussel beds, as observations from the Firth of Thames (Hauraki Gulf) in 1961 suggested that mussels preferentially attach to other live mussels (conspecific settlement) or recently dead shells, rather than old shells (Scott Report 1963, Paul 2012). Spat catching experiments in the Firth of Thames by McLeod (2009) caught very few spat on shells and on hairy spat ropes, although uncertainty around methods could render this work inconclusive[2].

Despite dredge fisheries for green-lipped mussels once operating in the Kaipara Harbour, the inner Hauraki Gulf and Firth of Thames, and in Tasman Bay (Morrison et al. in review.) soft-sediment mussel reefs are now commercially and ecologically extinct over much of their

[2] Spat ropes were reported as being agitated in fresh water to detach spat (McLeod 2009). The spat counting procedure used by NIWA (N. Davey unpub. data.,) and Buchanan and Babcock (1997) used dilute hypochlorite solution to dislodge the spat from spat ropes.

historic range (McLeod 2009). Remnant subtidal populations of green-lipped mussels are known from Whangapoua Estuary, Great Barrier Island; Ohiwa Harbour in the eastern Bay of Plenty; in association with one of the mussel farms, Waimangu Point in the Firth of Thames; and potentially at the entrance to the Kaipara Harbour (McLeod 2009, Morrison et al. in review.).

1.1.2 Ecosystem services provided by soft-sediment mussels

The loss of extensive mussel beds has significantly altered the benthic ecosystem in many parts of New Zealand, removing hard surfaces upon which many invertebrate species settled, thus directly and indirectly impoverishing the communities preyed upon by several ecologically and economically important finfish species (Paul 2012, Morrison et al. in review).

All suspension-feeding bivalves filter particles, including phytoplankton, zooplankton, particulate organic matter, inorganic particles from the water column (Peterson et al. 2010). These particles are bound up with mucous produced on the gills of the bivalves and any particles not ingested, are discharged as pseudofaecal deposits, a process that clarifies the water column, and transfers organically rich particulates to the seabed (Dame 1996, Newell 2004, Zeldis et al. 2004, Dumbauld et al. 2009, Peterson et al. 2010). The ability to reduce turbidity and deposit organic material depends on how densely concentrated the individuals are (Peterson et al. 2010). Mussels, although not typically forming reef structures that project up into the water column, provide complex interstitial and outward-projecting structural habitat for many marine invertebrates and modify the community composition, especially crustaceans and fish (Paine & Suchanek 1983, Reusch et al. 1994, Buschbaum et al. 2009). Suspension-feeders help buffer shallow waters against developing and sustaining excessive phytoplankton blooms in response to anthropogenic loading of nitrogen (Officer et al. 1982) and by removing particulates from the water column they can mitigate soil erosion from catchments (Landry 2002). Dense aggregations of shellfish can baffle water flow (Lenihan 1999) potentially reducing scour and resuspension of sediments. Overseas, intertidal mussel reefs have been trialled to provide coastal protection and stabilise intertidal flats in front of dikes, with variable success, but demonstrated their ability to attenuate wave energy and accumulate muddy sediment (De Vries et al. 2007, Borsje et al. 2011).

Suspension feeding bivalves benefit submerged plants like benthic diatoms and seagrass in two ways. First, they exert ‘top-down’ control by grazing on phytoplankton which allows greater water clarity and light penetration (Everett et al. 1995, Carroll et al. 2008, Wall et al. 2008), and secondly, they fertilize the bottom with their bio-deposits and excretion of nutrients (Dame and Libes 1993, Reusch et al. 1994, Everett et al. 1995, Peterson & Heck 1999, 2001a, b, Carroll et al. 2008, Peterson et al. 2010). Soft sediment plants in-turn also provide important environmental services including providing food and nursery habitat for many commercially important fish, crustaceans, and molluscs (Heck et al. 2003, Francis et al. 2005, Peterson et al. 2010). Aquatic plants also help trap and stabilise sediments, and remove nutrients (Yallop et al. 1994, Underwood & Smith 1998, Disney et al. 2011), further maintaining water quality allowing more light to reach the seabed, again enhancing benthic photosynthesis. These interactions between filter-feeders and soft sediment plants are thought to reinforce the restoration process by enhancing water quality improvements once they have been initiated (Kemp et al. 2005).

McLeod (2009) made estimates of lost secondary small invertebrate productivity following mussel biogenic reef loss in the Firth of Thames, and found the associated small mobile invertebrate assemblages had four times the average density, seven times the biomass, six times the productivity, and greater species richness than bare sediment areas. Morrison et al. (in review) concluded that based on these estimates, a strong cascading effect to epibenthic carnivores such as fish (including fisheries species such as snapper) was highly likely. McLeod (2009) estimated that the pre-1958 mussel reefs could have supported an additional fish biomass of between 200 to 16,000 T y^{-1} of small predatory fish above that supported by bare sediment. It was also estimated that the remnant mussel population in the Firth of Thames would take more than two years to filter the entire volume of the Firth of Thames as compared with less than two days for historic populations (McLeod 2009), with historic reports of sailors being able to see the seabed sailing into Coromandel Harbour (Morrison et al. in review).

In terms of sequestration of nitrogen and carbon, *Mytilus edulis* mussel tissue (excluding gametes) is approximately 33% to 68% nitrogen and mussel tissue carbon can range between 32% to 70% dry weight (Rodhouse et al. 1984). The shells comprise approximately 12% to 15% nitrogen and 8% to 11% carbon by dry weight. We are not aware of any economic evaluations attributed to the ecosystem services of benthic shellfish. However, an estimate from the Gulf of Mexico pertaining to the flow-on cost of a 20% loss of submerged aquatic vegetation attributed to eutrophication from land-based nitrogen estimated a \$56USD/kg/N_2 loss to crab and shellfish production (Compton et al. 2011). As mussels can mitigate nitrogen inputs through sequestration (Rodhouse et al. 1984), and also provide important feedback mechanisms helping maintain benthic primary production by increasing nutrient utilisation and exchange at the seabed (Kemp et al. 2005), their economic value as ecosystem engineers is likely to be significant. However, assigning economic value, or the “commodification” of ecosystem services – thus creating ‘fictitious commodities’ (Polanyi 2001) - deserves some critical evaluation (Brockington 2011).

1.1.3 The importance of the mollusc shell component in coastal marine sediments

The loss of bivalve populations and their contribution of calcareous shell to the sediments in Tasman Bay could potentially have far-reaching ecological effects. Bivalve shells act as ecosystem engineers in the succession of biogenic (produced by living organisms) habitats as shells provide substratum for the recruitment of plants and animals that bind the shell fragments together (Powell & Klinck 2007). This stabilises the sediments (Hewitt et al. 2005), provides refugia from predation, physical or physiological stress, and controls transport of solutes and particles in the benthic environment (Choi 1984, Guitiérrez et al. 2003, Powell & Klinck 2007). Biogenic structure, in turn, may frequently provide recruitment habitat and shelter for small fish (Thrush et al. 2002, Kaiser et al. 2003) or invertebrates (Kamenos et al. 2004). Habitats that are less modified are suggested to contribute more recruits to fisheries (Auster et al. 1996, Carbines et al. 2004), and to contain greater diversity than disturbed habitats (Thrush et al. 1998, Auster & Langton 1999). Loss of soft sediment habitat heterogeneity has the potential to reduce species diversity and ecological function (Hewitt et al. 2008). Recent studies have shown that increased habitat heterogeneity and biodiversity promote greater stability among species assemblages, and increased resilience of biotic populations subjected to disturbance, invasions or long-term stresses such as climate change (Walker 1992, Hooper et al. 2005, Stachowicz et al. 2007, Palumbi et al. 2008, Oliver et al. 2010)

On the north-western side of Tasman Bay, the Separation Point fisheries exclusion zone, an area that has been preserved from the effects of bottom contact fishing methods, dead bivalve shells are an important feature of the sediments (Handley et al. 2010, Handley et al. in review. 2010). In a comparison of infauna inside and outside the exclusion zone, this shell component in the sediment at Separation Point is correlated with greater biomass and productivity of infauna, with the functional composition of the species dominated by filter-feeders and a grazer. Outside the exclusion zone, the disturbed habitats were dominated by fine mud, were comparatively depauperate in biomass and productivity and were dominated by scavengers, predators and deposit feeders (Handley et al. 2010, Handley et al. in review). Not only do molluscan shells provide habitat when they are alive (Dame et al. 1997, Cummings et al. 1998, Thrush & Dayton 2002) but they are also vital to successional processes allowing biogenic habitats to become established and persist (Hewitt et al. 2005, Powell & Klinck 2007). Biogenic structure, in turn, may provide recruitment habitat and shelter for small fishes (Thrush et al. 2002, Kaiser et al. 2003) or invertebrates (Kamenos et al. 2004). Habitats that are less damaged are suggested to contribute more recruits to fisheries (Auster et al. 1996, Carbines et al. 2004).

The calcium carbonate component of mollusc shells can last on the seafloor for hundreds of thousands of years (Smith 1993). Carbonate storage in sediments has a role in preserving environmental information, sequestering carbon (Smith et al. 2010). Carbonate storage is at risk in coastal areas from dredging, land reclamation shoreline construction, shellfish dredging, natural erosion and dissolution (Smith et al. 2010). Smith et al. (2010) estimated that, with projected increases in human impacts in Otago Harbour, carbonate storage would cease within 100 years. A cessation of carbonate deposition in coastal areas could impinge on these sediments' ability to buffer effects of acidification resulting from global warming and to sequester carbon (Peterson et al. 2010, Smith et al. 2010).

1.1.4 Community effects of depositing shell on soft sediment habitat

A study conducted in Tasman Bay demonstrated that habitat enhancement via the deposition of waste scallop shell on the seabed increased densities of oyster *Ostrea chilensis* spat and adults (Brown 2011, Brown et al. in prep.). That study also concluded that habitat enhancement is likely to confer benefits to ecosystem function associated with community level effects on benthic diversity. They found that deposition of shell material over soft sediment habitat caused increased macrofaunal densities and a shift in dominance from mobile deposit feeders toward sessile suspension-feeding taxa. These trends parallel results of comparisons of complex biogenic habitat compared to simple mud habitat inside and outside Tonga Island Marine Reserve, Tasman Bay (Hewitt et al. 2008); and inside and outside Separation Point exclusion zone, Tasman and Golden Bays (Handley et al. in review), and those demonstrated by Rodney and Paynter (2006) in a comparison of macrofaunal assemblages on restored and non-restored oyster reefs in Chesapeake Bay. In Tasman Bay shell habitat enhancement increased measures of biodiversity including taxonomic richness, beta diversity among patches, and functional richness and redundancy (Brown 2011, Brown et al. in prep.).

The increase in macrofaunal densities on shell-enhanced habitat may also facilitate transfer of energy from the benthos to higher trophic levels by providing improved foraging for predatory fishes. Peterson et al. (2003) estimated that restoration of $10m^2$ of oyster reef in the southeast United States generates an additional 2.57 kg $10m^{-2}$ $year^{-1}$, of fish biomass. There was evidence for a similar type of effect in Tasman Bay in the greater numbers on enhanced habitat of Grahams gudgeon, *Grahamichthys radiata*, a predatory fish (Brown 2011, Brown et al. in prep.). Heterogeneous biogenic habitat that was once widespread, but is now distributed in relict patches and protected areas in Tasman Bay provides habitat for organisms including polychaetes and crustaceans that are important in the diets of commercially important predatory fish including snapper, *Pagarus auratus*, tarakihi, *Nemadactylus macropterus* and blue cod, *Parapercis colias* (Bradstock and Gordon, 1983). The greater density of macrofauna on the enhanced habitat is likely to provide improved foraging for these fish species in a similar manner.

1.1.5 Factors preventing recovery of soft-sediment mussel reefs

Following cessation of commercial fishing in areas like Tasman Bay and the Firth of Thames, mussel populations have failed to recover to their former biomass. Factors that may limit their recovery are most likely linked to loss of settlement surfaces (McLeod 2009, Paul 2012) and potentially lack of larval supply in regions where adult densities are too low to prevent effective reproduction (e.g. Dare et al. 2004). Green-lipped mussels prefer to settle on filamentous material such as red algae and hydroids (Buchanan and Babcock 1997), and have even been settled on submerged gorse (*Ulex europaeus*) in aquaculture (S. Handley NIWA, pers. observ.).

Mussels can go through multiple settlement phases. The “primary settlement” phase occurs when the larvae (<0.5 mm) attach and metamorphose to a filamentous substrata like the hydroid *Aphisbetia bispinosa* and the tufting algae *Corallina officianalis*, *Champia laingii* and *Laurencia thyrsifera* (Buchanan and Babcock 1997). However, size frequency data from mussel beds investigated on the West Coast of Auckland indicated that the majority of recruitment came from “secondary settlement” whereby post settlement larvae (<6 mm) can drift by extruding mucous, and then reattach to other substrata. Significant differences in settlement preference were observed for mussels of different size classes (Buchanan and Babcock 1997). The presence of secondary settlement as a dispersive phase implies that larvae choose not to settle in adult aggregations, perhaps to avoid predation (Bayne 1964), but recruitment patterns may merely reflect post-settlement recruitment and mortality from conspecific predation (Buchanan unpub. data, Alfaro 2006), and secondary settlement patterns (Buchanan and Babcock 1997). In the U.S.A., mussels *Mytilus edulis* settle as larvae especially to taller reproductive shoots of eelgrass (*Zostera marina*) that provide a refuge from predators during metamorphosis (Newell et al. 2010, Disney et al. 2011). Successful recruitment of *M. edulis* to seabed populations is thought to depend on availability of suitable primary settlement substrate provided by eelgrass. A hypothesis for the lack of mussel bed recovery in New Zealand could be related to the loss of subtidal seagrass beds in areas like Tasman Bay (Robertson and Stevens 2009) and the Firth of Thames (Graeme 2006) estuaries driven by declining water quality potentially preventing effective settlement of green-lipped mussels. Scallop, which also attach themselves as larvae using byssus threads, were found in areas of the Pelorus Sound attached to brown alga *Cystophora retroflexa,* red algae attached to horse mussels *Atrina zelandica*, and drift seagrass *Zostera* debris, however sand, mud and broken shell in the area was not colonised by spat (Bull 1976).

Notably, Tunbridge (1968) reported red algae and bryozoans on the historic scallop beds of Tasman Bay.

One hypothesis for the initial formation of the mussel beds in the Firth of Thames was that they arose during land clearance following European settlement that provided a critical mass of brushwood debris on which mussel spat settled (Greenway 1969). Demonstrating how this may have worked, early trials in mussel aquaculture in the Hauraki Gulf successfully used bundles of green manuka (*Leptospermum scoparium*) as spat settlement surfaces (Greenway 1969). Interestingly, pre-European Māori burnt significant volumes of manuka on the Nelson Waimea Plains to add to the soils for kumara cultivation, with over 1,000 acres once in production (Rigg and Bruce 1923). Manuka ash is high in phosphates and potash salts, which was thought to add nutrients and regulate soil acidity. Māori kumara soil when analysed matched exactly the soil characteristics recommended by the U.S.A. Department of Horticulture for sweat potato cultivation (Rig & Bruce 1923). It was estimated that several hundred tons of vegetable matter must have been burnt on each acre of the Waimea Plains. It is conceivable, that if a fraction of the manuka burned by Māori, or cleared by European settlers, was washed down streams and rivers, this brushwood may have provided the settlement substrate that created or facilitated large populations of soft-sediment mussels, once the brush became settled with mussels and sank in the bay under their weight.

Regardless of whether the mussel populations were created or enhanced by forest clearance during Māori and European settlement, the lack of suitable settlement substrate is likely to be a significant factor limiting the recovery of benthic shellfish populations. Factors that are likely to exacerbate the loss of suitable settlement substrate for mussel primary settlement are: contact fishing gear that will remove, erode or bury hard and soft settlement surfaces (Paul 2012, Handley et al. *in review*), and siltation which can smother or bury mussel beds, and settlement surfaces, and interfere with efficient suspension feeding (McLeod 2009, Thrush 2004). Excessive fishing pressure removing critical biomass of adult mussels required for effective reproduction (e.g. Dare et al. 2004) and settlement success and perpetuation of benthic populations (McLeod 2009, Paul 2012). It however seems unlikely that larval supply is limiting in Tasman Bay, as ropes and structures held off the bottom in the bay become colonised by green-lipped mussel spat (Handley & Brown, pers. observ.) and commercial spat catching occurs offshore from Motueka. A compounding effect of both siltation and the use of contact fishing gear (which creates re-suspension) is that these factors can also reduce light levels at the seabed, reducing the depth that photosynthetic algae can grow (McLeod 2009), or in the case of seagrass, preventing the establishment or persistence of subtidal seagrass beds (Turner and Schwarz 2006) potentially of benefit to mussel and scallop settlement (Bull 1976). Loss of benthic primary production also reduces the amount of energy processed and carbon stored at the benthos. For example, seagrass beds are globally important habitats and storage areas of carbon that are currently under threat from water pollution, dredging and sea level rise resulting from climate change (Fourqurean et al. 2012).

An alternative hypothesis for the lack of recovery of soft-sediment mussel beds in New Zealand could be lack of large predators like snapper *Pagrus auratus* and coastal sharks, which may have once exerted top-down control of small predatory fish that prey on juvenile mussels. Morrison et al. (in review) noted that large adult snapper and coastal sharks were more abundant in the greater Hauraki Gulf in the past. Those larger predators may have helped regulate numbers of smaller fish like spotty *Notolabrus celidontus,* banded wrasse *Notolabrus fucicola,* and snapper that prey upon mussel spat in the intertidal and on mussel farms (Rilov & Schiel 2006, Hayden 1995). As the average size of snapper in the Hauraki Gulf has declined since Māori and European settlement (Parsons et al. 2009), it is conceivable that the diminishing size and abundance of once dominant predators could have changed the size structure of small predatory fish, resulting in more mussel spat predation. In support of this hypothesis, illustrating the complexity of trophic cascades in food webs, a study in Sweden found that decadal scale declines in seagrass beds were linked to overfishing of top predatory fish (Baden et al. 2012). An 80% decline in predatory fish resulted in an 8-fold increase in intermediate predatory fish, which decimated herbivorous amphipods, which control fouling filamentous algae that reduces seagrass growth. Fouling algal growth is further exacerbated by eutrophication from land-based nutrients.

2 Aims

There are two questions about soft-sediment green-lipped mussel restoration that we propose answered with experiments:

1. What are the key ecological benefits of returning mussel shell to the seabed of Tasman Bay?

The rationale for this being; if the biomass of mussels landed from the Nelson/Marlborough region between 1960 and 1982 totals 20,534 tonne greenweight[3], then the Nelson/Marlborough region currently has a deficit of shell carbonate in its sediments (excluding scallops and dredge oysters). The mussel industry produces large volumes of shell that would be suitable for return to the seabed, but are currently either land-filled, or a sold in small volumes for landscaping, and fertiliser.

2. Will green-lipped mussels survive on the mud substratum, or will mussels require hard substratum, for example shell, on which to survive above the surface sediments?

The restoration of mussel beds via secondary settlers or spat may require augmentation of habitat and perhaps seeding. This is because primary settlement surfaces are likely to be scarce or absent in Tasman Bay, as trawling is common at depths where mussels historically were once common (Tuck et al. 2012), and the sediments of Tasman Bay appear unstable and easily re-suspended (Chris Cornelisen, Cawthron pers. comm., Handley & Brown, NIWA pers. observ.).

3 Methods

3.1 Experimental design

In GIS (ESRI ® ArcMap ™ 10.0) two 90 m x 90 m areas were established outside the eastern and western boundary of the Horoirangi Marine Reserve, approximately 150 m south east of each corner marker. These sites were chosen in an attempt to protect them from potential effects of trawling, while not being inside the marine reserve. Each area was divided into 9 sectors, where the following treatments were randomly assigned:

[3] This value was calculated by summing number of sacks landed during this period reported by Paul (2012; Appendix 2) and assuming a sack equals 150 lb

1. 3 sectors with a pile of mussel shells
2. 3 sectors with a pile of mussel shells stocked with mussel spat
3. 3 sectors with no mussel shell and stocked with mussel spat

3.2 Study site

The Horoirangi marine reserve was gazetted in 2006 and is situated on the north eastern end of the Nelson Boulder Bank. The dominant substratum of the reserve is soft sediments, ranging from sand, inshore; to soft mud offshore (Grange et al. 2006). To minimise the potential risk from trawling, we propose to deploy piles of shell along the western and eastern boundaries of the reserve, inshore of the buoy markers (Figure 3-1).

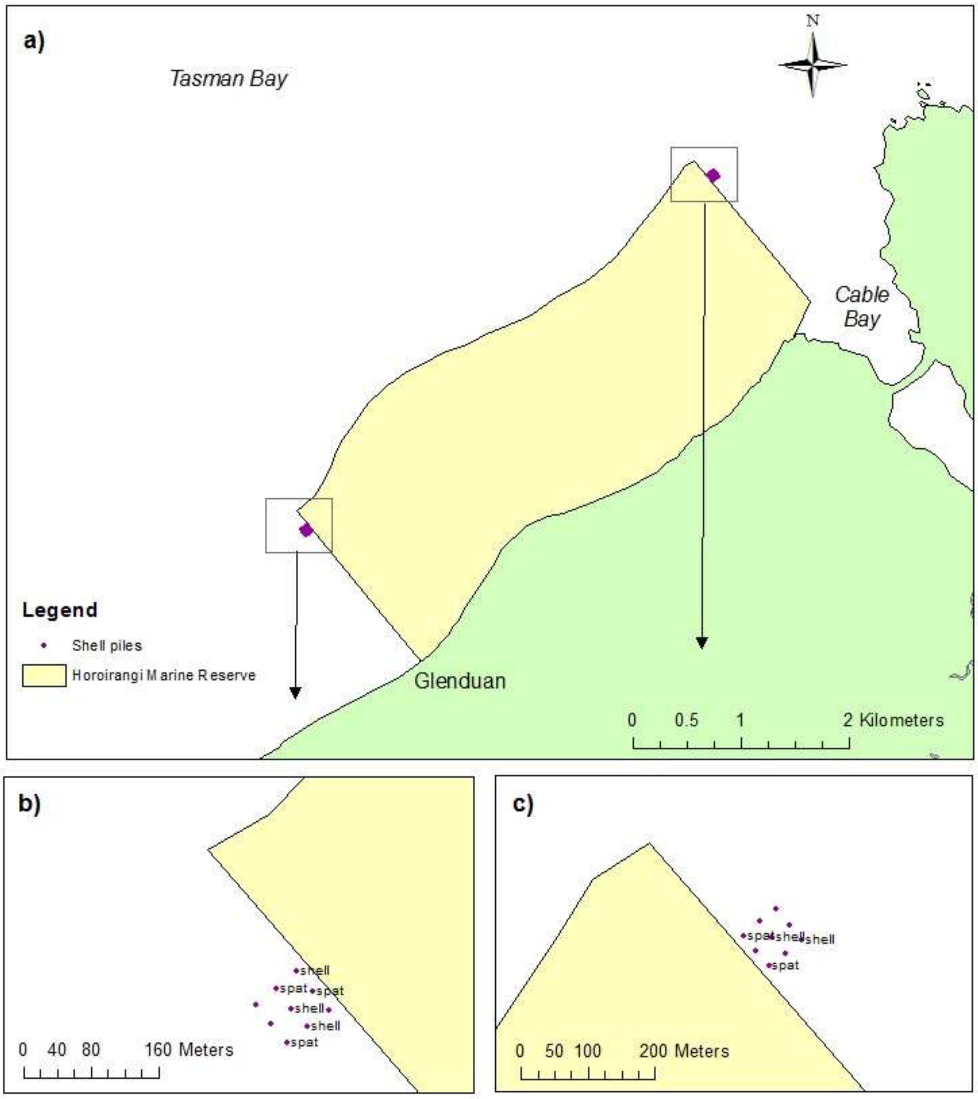

Figure 3-1: Map showing proposed shell deployment sites either end (west - east) of the Horoirangi Marine Reserve. Within each area b) Glenduan and c) Cable Bay, 6 areas will have mussel shell placed, 3 of which will have spat placed on top, and the remaining 3 sites will have spat placed on bare mud.

3.3 Suggested monitoring methods

Ideally, comparisons should be made between control sites (bare mud) mussel spat on the mud, mussel spat on shells, and unstocked shell piles using SCUBA. To investigate survivorship, mussel spat could be surveyed by remote camera/ROV, but if recruitment of juveniles is to be monitored, then sampling by SCUBA would likely be warranted.

To investigate key ecological benefits of shell return and mussel aggregations, samples of infauna by grab or core is recommended. Estimates of secondary biomass and productivity could then be compared between mussels and shell versus shell alone to determine what benefits live mussels provide in structuring soft sediment communities. Sampling should ideally be carried out over several years. To determine the potential food chain benefits to fishes, a baited underwater video (BUV) system (Willis and Babcock 2000) could be deployed to compare fish aggregations inside the polygon of shell piles versus control sites over bare mud[4].

4 Discussion

From scant newspaper records, and the catch landings reported by Paul (2012) it appears that there may have been two periods of historic over-exploitation of green-lipped mussels in Tasman Bay; in the late 1800's and by the end of the 1970's with some 70 years recovery in between. Early fishing of shellfish (oysters, mussels and scallops) in the 1800's was based on inshore beds accessible at low tide, with exploitation with some dredging in Tasman Bay (Drummond 1994). These shallow water beds no longer exist, and the fishery has progressively worked grounds moving out into deeper water over time (Handley 2006). New Zealand is not unique in having a history of over-exploitation of shellfish fisheries around the world including Australia (Olsen 1994) and U.S.A. whereby fishers exploited stocks close to urban centres and then moved further afield to distant estuaries as each fishery collapsed (Kirby 2004).

Green-lipped mussel beds in Tasman Bay do not appear to be recovering in the absence of shellfish dredging, and the same is true for other extant populations around New Zealand (McLeod 2009, 2012, Paul 2012, Morrison et al. in review). Large scale recovery of soft-sediment mussel populations in Tasman Bay seems unlikely without provision of suitable settlement substrata for primary settlement, for example filamentous hydroids and/or submerged aquatic vegetation. It is our hypothesis that a regime shift has occurred, whereby the over-exploitation of shellfish in areas like Tasman bay has created a tipping point in terms of ecosystem function. As mussels require filamentous settlement substrata on which to settle (primary and secondary phases), the lack of such substrata has created a barrier to recovery of soft-sediment populations. Unfortunately, because of the non-linear feedback mechanisms described by Kemp et al. (2005), adequate water quality and clarity may be required for species like hydroids and benthic macro-algae to survive at historical depths and locations. Ironically, ecosystem services once provided for by the presence of abundant soft-sediment shellfish (mussels, scallops and oysters), could help clarify the water column of suspended sediments, stabilise surface sediments, and provide deposited nutrients to fertilise benthic filamentous algae. Concomitantly, top down control from large predators may be lacking, resulting in recruitment failure of juvenile mussels which are eaten by elevated

[4] To avoid spatial confounding, BUV controls would need to be deployed inside and outside the marine reserve as the shell piles are on the edge of the marine reserve.

numbers of intermediate size predatory fishes, similar to the trophic cascade described in Sweden where loss of seagrass beds has been linked to overfishing of large predators, which is now reinforced by eutrophication (Baden et al. 2012).

Regardless of the complex mechanisms involved in the recruitment failure of mussel populations, there appears to be a sound argument for the return of bivalve shells to the seabed. These shells can provide significant ecosystems services including; providing settlement surfaces, complex three-dimensional habitat and heterogeneity at the sediment surface, provide sediment structure, and contribute to the carbonate budget in the sediments potentially helping buffer coastal waters from acidification arising from climate change. Aside from whether mussel recruitment and benthic population restoration is achievable, waste shells from aquaculture and also shellfish fisheries provide a potentially valuable resource to address the apparent carbonate deficit in Tasman Bay sediments. From the catch-landings reported by Paul (2012), we estimate that 20,534 tonne greenweight of green-lipped mussels were harvested from the Nelson/Marlborough region from 1960 until the collapse of the fishery by 1982. This estimate does not take into account regeneration of the beds, or potential losses from poor dredge efficiency and mussels being crushed or buried (Paul 2012). It is encouraging that the associated changes in macrofauna and functional diversity associated with live green-lipped mussel reefs reported in the Firth of the Thames (McLeod et al. 2012, McLeod 2009), appear similar to those provided for by shell piles in Tasman Bay (Brown et al. 2008, Brown 2011), and shell component of sediments at Separation Point (Handley et al. in review), providing supportive evidence of the vital role mollusc shells provide in allowing biogenic habitats to become established and persist (Hewitt et al. 2005, Powell & Klinck 2007). An increase in species richness, functional richness, or in other facets of biodiversity is likely to affect the function of marine communities and ecosystems (e.g. Gutierrez et al. 2003, Hooper et al. 2005, Stachowicz et al. 2007, Palumbi et al. 2008). The increase in dominance of filter feeders and a grazer correlated with a high proportion of shell in soft sediments (Handley et al. in review) may also help clarify the water column enhancing succession of benthic primary producers and hydroids.

Stressors from inputs of terrestrial sediment via rivers, on-going contact fishing methods like trawling and seining, and increased storms resulting from climate change are all likely to exacerbate the lack of mussel bed recovery by smothering, burying, or directly removing filamentous species necessary for in-situ settlement of byssally attaching mussels and scallops. Light levels at the seabed are also likely to be diminished from suspended sediments or from resuspension during contact fishing or storm events (Cornelison, Cawthron, pers. com.). Subtidal algae are unlikely to survive at historic depths in Tasman Bay without concomitant improvement in water quality, which will likely only occur with restoration of historic levels of shellfish, stabilisation of sediments (again achieved through shellfish restoration facilitated by subtidal algae) and reductions in land-based sediment inputs. Hydroids can be a significant component of trawl bycatch (Kaiser et al. 1998), and we would expect shellfish dredging to eliminate both hydroids and benthic algae in their path. Concomitantly, contact fishing gear is likely to reduce the surface shell component of the seabed, reducing the settlement surfaces for other shellfish, hydroids and seaweed (Handley et al. in review). Although we are not aware whether mussel primary larval settlement may occur on the reproductive shoots of seagrass in New Zealand (Mark Morrison, NIWA, pers. comm., c.f. *Mytilus edulis* Newell et al. 2010), seagrass habitat in Nelson/Marlborough region is depauperate, with declines reported in the Waimea Inlet and Nelson Haven (Gillespie et al.

2009, Robertson and Stevens 2009, Stevens and Robertson 2010, Leigh Stevens, Wriggle Coastal Management, pers. comm.).

Given the lack of natural recovery of green-lipped mussel beds, the greater than 70 years it appears to have taken for mussel beds to recover from initial over-exploitation at the end of the 1900's, intervention appears required to restore mussel beds in Tasman Bay. The proposed experiment will address whether green-lipped mussel can be returned as juveniles directly to the mud substratum, or whether, as is the case for oysters (Brown 2011), providing a shell substratum on which to aggregate is beneficial to their survival and growth.

4.1 Recommendations

Future research should investigate:

- the role of top-down predation in the recovery of species likely to be important for primary settlement surfaces, and also predation of spat.
- direct comparisons of dead mussel shell piles versus live mussel aggregations over soft-sediment habitats to determine their relative role in providing ecosystem services.

If green-lipped mussels can survive on soft-sediments or on shell piles, managers and stakeholders (e.g. Regional Councils, MPI, DoC, Finfish quota holders, NGO's) collectively should consider the potential benefits to restoring mussel stocks for:

- conservation or historical values,
- ecosystem services,
- providing buffers to man-made stressors,
- "bottom-up" benefits to higher value finfish species that may benefit from increased secondary productivity of invertebrates likely from the return of mussel-reef habitats,
- future sustainable exploitation of shellfish, preferably by non-contact harvest methods.

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