Advice for mussel restoration trials in Pelorus Sound/Te Hoiere, Marlborough

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Prepared by:
Sean Handley

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
PO Box 893
Nelson 7040

Phone +64 3 548 1715

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1 Introduction

Marlborough District Council (MLDC) has requested advice to support the restoration of extant mussel beds, which were historically a biogenic (or 'living') habitat in the inner Pelorus Sound. This request came from the Marlborough community expressing interest in the possibility of restoring naturally occurring green-lipped mussel (GLM) beds in Pelorus Sound. Restoration is aimed at improving biodiversity outcomes and improving ecosystem services such as water quality. This is in response to a widely discussed NIWA report on the history of benthic change (Handley 2015) and a report on 1,000 years of benthic change in in Pelorus Sound /Te Hoiere (Handley, Gibbs et al. 2017a).

A previous short-advice grant discussed the benefits of mussel restoration in Tasman Bay for Nelson City Council (NCC) (Handley and Brown 2012), so the potential benefits of restoration will not be repeated herein, rather this advice report aims to discuss the findings of recent historic research and how that may inform future restoration efforts. This report is in partial fulfilment of an Envirolink grant that also included attending meetings with MLDC and stakeholders to discuss and provide advice on GLM restoration (Handley and Ellis 2016)[1].

[1] A mussel reef restoration meeting was also attended at MLDC, 1 August 2016.

2 Summary of historic review and sediment coring study outcomes

The Pelorus historic review (Handley 2015) reported that mussel reefs were severely reduced in area during the subtidal dredging of the 1960s and intertidal hand-picking in the 1970s. Collectively, historic changes in Pelorus Sound affected components like water quality and clarity (sedimentation, nutrients), seabed habitat change (loss of shell and biogenic structure), and loss of shellfish (fishing, sedimentation, habitat loss). Mussel beds likely provided essential ecosystem services in the form of water quality amelioration, feedback to primary production and nutrient cycling, as well as habitat for biodiversity including important fish species, such as snapper.

The subsequent sediment coring study (Handley, Gibbs et al. 2017a), showed profound changes to sediment accumulation rates and shellfish composition since European settlement. Sediment accumulation rates were found to have accelerated to an order of magnitude (10x) difference to those of pre-human, benchmark conditions in Kenepuru Sound, and to a lesser extent in Beatrix Bay. These results reflect the history of changing land-use from forest clearance in the 19th and early 20th centuries, followed by extensive sheep farming with regular burning of scrub and application of superphosphate through the middle years of the 20th century, widespread regeneration of native forest as pastures were abandoned over the last 30-40 years, and increasing areas and density of pine plantings from the turn of the 20th century that are being harvested in pockets up to today.

2.1 Factors potentially hindering successful restoration outcomes

As extant mussel reefs have failed to recover, the hypothesis was raised that the ecology of Pelorus Sound had somehow changed to an alternate state, which some in the Marlborough community had previously voiced as being on a deteriorating downward trajectory (Handley 2015). Before the sediment coring study was carried out, the factors that have prevented the intrinsic recovery of mussel beds in Pelorus Sound following closure of the wild mussel fishery in the early 1970s were considered likely to involve complex interactions between stressors involving feedback mechanisms. This prediction was supported by the results of the coring study which failed to directly link a single causal factor to failure of Pelorus mussel beds to recover (Handley, Gibbs et al. 2017a). Potential negative drivers preventing their recovery include: ongoing effects from sedimentation, reduced nutrient availability (nutrients bind to fine sediments in the water column), historic overfishing reducing mussel standing stocks, and lack of seabed plants (shaded by suspended sediment), which in their absence potentially form a bottleneck to wild mussel recruitment.

Because factors preventing recovery of biogenic habitats including mussel reefs are likely to be interrelated and the relationship between individual factors non-linear (e.g., Kemp, Adolf et al. 2005), efforts at restoration are encouraged because overseas restoration efforts indicate that once restoration is initiated (e.g., shellfish restoration), benefits flow to other components (like seagrass and benthic microalgae), which in-turn reinforce and enhance broader restoration goals including stabilisation of soft sediments that help maintain water clarity (Greening, Janicki et al. 2014; Kemp, Adolf et al. 2005). Feedback mechanisms can thus either reinforce a degradation trajectory, or once initiated, provide feedback to reinforce restoration (*sensu* Kemp, Adolf et al. 2005).

While it may be the hope and desire of the Marlborough community to successfully restore mussel beds in Pelorus Sound, it is cautioned that there may be challenges and barriers to restoration success and maintenance of intertidal and subtidal populations of GLMs. This is because shellfish restoration efforts in New Zealand and overseas have demonstrated that although shellfish can be returned to former habitats, they can sometimes fail to become established and/or become self-sustaining populations. This could be due to lack of adequate scale of restoration efforts to be effective in supporting restoration-positive feedback mechanisms, or because there are multiple factors acting on one or many necessary biological requirements of the shellfish. For example: lack of suitable settlement habitat for juvenile shellfish to colonise; and/or smothering of vulnerable juvenile shellfish by fine sediments preventing them surviving to adults.

2.2 How history may inform future restoration

In the following, I discuss historical findings from Pelorus Sound considering what can be learnt from mussel restoration trials in the Hauraki Gulf.

2.2.1 Were pre-human mussel beds present in Pelorus Sound?

Although the coring study failed to collect sufficient quantities of GLM shells in the cores, we collected evidence to suggest that the Pelorus Sound may have been less productive historically, meaning GLMs may have occupied a narrower range or been present in lower densities than at their peaks prior to being fished below sustainable levels in the 1970s. The results of the sediment coring study revealed that GLM shells were poorly represented in sediment cores, precluding drawing any direct linkages with historical changes in the Pelorus catchment with lack of mussel bed recovery. That result may however be an artefact of the 100 mm wide sediment core tubing being a poor apparatus from which to collect mussel shells buried in the sediments. That is, the mussels could have been very patchy, or GLMs were less prevalent at the coring sites on the soft sediment in deeper water below the rocky substratum adjoining the shoreline, as compared with on the rocky shoreline and subtidal fringe as recorded by Stead (1971b). Analysis of proportional content of shells from other mollusc species from the sediment cores showed that in pre-human times, mollusc shell (carbonate) deposition was much lower by proportion, than after human arrival, indicating that the Pelorus Sound supported greater mollusc productivity during human times consistent with large-scale changes occurring to the catchment and fisheries resources following colonisation, especially during European habitation post-1860. That increase in productivity was shown to especially benefit suspension feeding bivalves and to a much lesser extent deposit feeding molluscs. These changes were hypothesised to be in response to increases in the supply of nutrients released from forest clearance on land by fire and later farming fuelling phytoplankton and marine plant production. Peak mollusc production was consistent with peaks in superphosphate application during the 1950-1974 period associated with land development and fertiliser subsidies. From this evidence, and because GLMs are also filter feeding bivalves, we hypothesised that GLM populations increased in size and/or expanded in range during that period in history. Stead's (1971b) surveys showed that mussels were present in greatest density in the intertidal with population density decreasing but mean size of mussels increasing with increasing depth down the subtidal slope out onto soft sediments.

2.2.2 Where and how do mussels recruit?

Analysis of the former depth and density distributions of GLMs in the inner Pelorus Sound reported by Stead (1971b) suggest juvenile recruitment was solely intertidal and that mussels having largest glycogen reserves[2], came predominantly from the middle of their range between the intertidal and the deeper beds. In experimental GLM restoration plots in the Firth of Thames, McLeod, Parsons et al. (2012) found that mussel condition was greatest at sites with lowest turbidity, and attributed the lack of recovery of the Firth of Thames mussel beds was due to low recruitment and lack of survival

[2] Most of the GLMs were in pre-spawning condition during Stead's survey in January, with spawning reported to occur predominantly in January-February.

of juvenile mussels. Similarly, low recruitment success was experienced in experimental seabed trials further out in the Hauraki Gulf that also experienced periodic inundation of silt, despite larval supply evident on collectors suspended above mussel beds (Wilcox 2017). Another parallel study in the Hauraki Gulf concluded that soft sediment composition had no effect on adult GLM survival, but may have affected survival of juvenile mussels reseeded on provisioned substrates including coir bags and shell (van Kampen 2017).

While adult GLMs were historically found in Kenepuru Sound attached to rock in the intertidal or sub-littoral or to dead shells (including GLMs), other live mussels, horse mussels *Atrina zelandica* and sunken branches, bottles and other live shellfish by Stead (1971b), most of the small mussels (ca. 4 mm in length) were seen attached and growing in the spaces between larger mussels in the intertidal zone. It is highly likely that fine silt could smother newly settled juvenile mussels attached to either hard substrate or byssal threads in the interstitial gaps between clumps of adult mussels. Adult GLMs have been reported to attract mud within clumps by fisherman, which may be an observation supporting the hypothesis that build-up of faecal and pseudofaecal material occurs amongst clumps in low-wave climate sites armoured from resuspension by the mussels. If this is the case, then the armouring of the seabed by adult mussels allowing sediment accumulation, may hinder recruitment of mussel larvae. Thus, recruitment of mussels in sheltered locations, in deeper water not exposed to resuspension of sediments from waves, will be limited to supply and availability of filamentous settlement substrates.

2.2.3 A model of historic Pelorus mussel recruitment

A potential model for mechanisms controlling larval recruitment of juvenile mussels can be developed if we also consider the role of plants as filamentous habitat. In the U.S.A., mussels *Mytilus edulis* first settle as larvae on taller reproductive shoots of eelgrass (*Zostera marina*) that provide a refuge from predators during metamorphosis (Newell, Short et al. 2010; Disney, Kidder et al. 2011). They subsequently raft or drift away from eelgrass beds to settle amongst mussel beds when they are of a size that prevents them being cannibalised by adult mussels. In the absence of similar studies here in New Zealand linking recruitment to our seagrass species, we have good evidence that GLMs similarly recruit to fine filamentous substrates including seaweeds and hydroids (Buchanan and Babcock 1997). For example, the beach-cast seaweed that enables the Ninety-Mile Beach spat collection industry. Seagrass beds are in decline in Pelorus Sound (Stevens and Robertson 2014) and it is likely that seaweed densities and distributions are also in decline due to 10x increase in sediment accumulation rates in Pelorus Sound (Handley, Gibbs et al. 2017a) since European colonisation in the 1860s. If seabed plants including seagrass historically provided essential settlement substrate enabling GLM larvae to undertake primary metamorphosis to be followed by a secondary settlement phase (drifting to adult beds), then the order of magnitude sediment accumulation rates and decline of seagrass beds in the Kenepuru Sound (c.f. Bull 1976), may explain the lack of recovery of mussel beds in Pelorus Sound. Our model would thus include:

- primary settlement of GLM larvae on filamentous substrates including seaweeds and seagrass;
- migration (mucus drifting, e.g. Buchanan and Babcock 1997) or dislodgement (e.g. attached to seaweeds) allowing secondary settlement amongst adult mussel preventing cannibalism;
- slow migration of adults (self-thinning) to deeper water.

For such a recruitment model to function in perpetuity, the Pelorus system would need:

- healthy reproductive seaweed or seagrass communities (or similar filamentous primary settlement substrate);
- adult GLM stocks in an area exposed to wave action to minimise the build-up of soft sediments to prevent smothering of secondary GLM settlers (e.g. intertidal mussel beds);
- adult GLM stocks at a density to provide adequate refuge from predation (e.g. starfish, predatory gastropod snails, flatworm predators, and/or fish);
- adequate supply of nutrition (phytoplankton, zooplankton) to feed adult and juvenile mussels.

By proposing this hypothetical but potentially realistic model, it is possible to see how interrelated biological and physical factors could become and how feedback systems mentioned previously can either support or diminish the success of restoration trials. It also adds to the appreciation of the importance of reducing stressors like suspended sediment loads within Pelorus Sound. To illustrate how feedback mechanisms may operate, suspension feeding bivalves benefit submerged plants like benthic diatoms and seagrass in two ways. First, they exert 'top-down' control by grazing on phytoplankton improving water clarity and light penetration (Everett, Ruiz et al. 1995; Carroll, Gobler et al. 2008; Wall, Peterson et al. 2008), and secondly, seabed shellfish fertilize the bottom with their bio-deposits and excretion of bioavailable nutrients (Dame and Libes 1993; Reusch, Chapman et al. 1994; Everett, Ruiz et al. 1995; Peterson, Bruce J 1999; Peterson, B. J. and Heck 2001a; Peterson, B. J. and Heck 2001b; Carroll, Gobler et al. 2008). Seabed plants in turn provide important environmental services including providing food and nursery habitat for many commercially important fish, crustaceans, and molluscs (Heck, Hays et al. 2003; Francis, Morrison et al. 2005; National Research Council. 2010). Aquatic plants also help trap and stabilise sediments, and remove nutrients (Yallop, de Winder et al. 1994; Underwood 1998; Disney, Kidder 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, Adolf et al. 2005). Thus, if seabed plant production is dependent on an unknown level of bivalve standing-stock on the seabed to maintain water clarity and excrete nutrients bioavailable to seabed plants, then GLM dredging and the subsequent hand picking of remaining intertidal GLM stocks in the early 1970s may have reduced densities to levels also precluding seabed plants surviving (e.g., during summer stratified low nutrient conditions) – creating a bottleneck to mussel recruitment.

2.2.4 Where to attempt GLM restoration?

In the sediment coring report, we recommended that mussel bed restoration experiments be tested adjacent to regenerating steep catchments that have adequate current and wave exposure, and that seabed plant restoration should also be encouraged and tested for synergistic effects (Handley, Gibbs et al. 2017a). The rationale for the former recommendation was because the highest rates of historic mollusc productivity were found at the coring site near Gold Reef Bay that was steep in aspect, and experienced an unusually high rate of gravel input, suggesting that elevated erosion levels at that site somehow enhanced mollusc productivity. We hypothesised that the above average mollusc productivity may have been a localised response to the influx of nutrients from erosion of seral plant soils discharged to the sea from the land above. The enriched Nitrogen signatures from that site were consistent with supply from a terrestrial source such as from seral plants fixing N_2 from the atmosphere. Seral plants species like bracken, manuka and kanuka can produce leaf litter high in nutrients that can be lost during burning or discharged during erosion of topsoil (McGlone 1989; McGlone, Wilmshurst et al. 2005) or “A-horizon” soils. The rationale for the latter advice, to maximise current and wave exposure is to reduce the effects of suspended sediments, and maximise supply of food to restored mussels. To reduce on-site suspended sediment concentrations that may affect GLM health and smother newly settled recruits, restoration experiments could also include the use of other bivalve species including horse mussels and sediment tolerant filter-feeders like ascidians and sponges that inhabit marine farm structures currently as fouling organisms. Similarly, seagrass beds restored or enhanced in areas of shallow or intertidal soft sediment will help stabilise soft sediments. Seagrass beds may also provide an important site for primary settlement to allow for drift of juvenile mussels that can then on-migrate once they are of a size preventing them being cannibalised by adult mussels, to experimental mussel restoration plots. As this secondary recruitment appeared important in Kenepuru Sound, experimental GLM plots should extend into the intertidal. Restoration plots would require protection from hand or dredge harvesting.

A critical factor in the future success of GLM restoration will likely be having sufficient scale to be robust to predation and to provide ecosystem services to provide positive feedback enhancing aquatic plants to overcome any recruitment bottleneck. The scale of experimental plots trialled in the Hauraki Gulf by Wilcox (2017) ranged from 24.4 m^2 to 45.2 m^2 and varied little over the 25-month study. Those experimental plots suffered sea star predation which accounted for 30.1% of mortality, and a natural mussel population in Ōhiwa Harbour experienced ca. 88% loss over four years with high densities of sea stars observed (*ibid*. Paul-Burke 2015). Wilcox (2017) concluded that even a small amount of predation can result in the failed establishment or complete removal of recovering mussel beds in the absence of adequate recruitment.

3 Discussion and recommendations

It is unlikely that the apparent reduction of mollusc productivity since 1975 measured in our sediment cores (Handley, Gibbs, et al. 2017a) was the sole result of reduced nutrient supply from reduced input of fertilisers by farmers, as human induced discharge of sediment and nutrients (e.g., from farming, urbanisation, aquaculture processing facilities) continues in the Pelorus catchment. Therefore, it also seems unlikely that reduced productivity is the sole reasons for lack of innate recovery of the mussel beds following cessation of mussel fishing and hand gathering. Rather, the lack of recovery is likely to be complex, but most likely related to legacy effects from changes in the ecosystem and continued discharge and resuspension of fine sediments at levels far exceeding (10x) pre-human levels preventing juvenile mussels surviving.

Because GLMs appear to be relatively robust to high suspended sediment (c.f. scallops), they could be used as a tool to mitigate areas of soft sediments or sites experiencing high sediment loads as mussels can armour soft sediments from resuspension. The use of waste mussel shell could also be used to amour very soft sediments to provide substrate upon which GLMs can grow preventing their burial. There appear to be ecological benefits in returning waste shell to the seabed (Brown 2011; Handley and Brown 2012), especially for providing settlement habitat for species that may facilitate shellfish larval settlement, or recruitment of other filter-feeders (e.g., sea-squirts) that help improve water quality and clarity and armour soft sediments from resuspension. To help restore mussel beds, intervention by placing live juveniles on the seabed or on shell piles has been suggested (Handley and Brown 2012). However, as mussel condition was historically greatest in the shallow sublittoral on hard rock substrate, it is suggested restoration trials may be most successful on a similar habitat. If supply of suitable hard substrate is lacking, the prior application of waste shell could be trialled over soft sediment and condition and survival of GLM monitored and compared to inform future restoration efforts.

To predict where GLM restoration might be best trialled in the Pelorus Sound, the hydrodynamic model of Broekhuizen et al. (2015) could be coupled with assessment of resuspension of fine sediments (e.g., Hadfield 2015). This may require some validation of those models to test their suitability in shallow waters close to the shoreline. For this reason, a combined approach of restoration trials at several sites along a gradient of sheltered to exposed sites in the inner and mid-Pelorus Sound, with *in-situ* hydrodynamic measurements to validate model outputs is recommended.

Significant stressors likely to hinder perpetuation of restored mussel beds will be predation and high sediment loads affecting the health and survivorship of juvenile pre-recruit GLMs, unless recruitment can occur in pockets of high current flow or in the intertidal where wave climates may re-suspend sediment. Potential limiting factors to survival of intertidal mussels will be nutrition during periods of low productivity and/or stress associated with high temperature events which may elevate susceptibility of especially juvenile mussels to mortality from predation or disease. Monitoring of trials is recommended to investigate such stressors.

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