A 1,000 year history of seabed change in Pelorus Sound/Te Hoiere, Marlborough

Prepared for Marlborough District Council, Ministry of Primary Industries and the Marine Farming Association

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Executive summary

Marlborough District Council (MLDC), the Marine Farming Association Inc. (MFA) and the Ministry for Primary Industries (MPI) co-funded this study to reconstruct historical changes to seabed ecosystems in Pelorus Sound, Marlborough, New Zealand. Pelorus Sound is the centre of New Zealand's shellfish aquaculture industry and regionally important for farmed and wild finfish and shellfish fisheries. Sediment cores were taken from Beatrix Bay and Kenepuru Sound within the inner Sound. The cores collected preserve records of environmental change over the last several thousand years, including the effects of large-scale catchment deforestation and subsequent conversion to land-uses such as pastoral agriculture for sheep and production forestry, since the 1860s.

The specific objectives of the present study were:

- Determine the sources of eroded soils and their relative contributions to the sediment deposition in the inner Pelorus Sound (by land-use);
- Determine how sedimentary contributions have changed by source over the recent past (present to 1,000 years before present, BP);
- Identify how shellfish communities inhabiting the seabed changed over that period;
- Test the hypothesis that human land-based disturbance triggered the widespread establishment of green-lipped mussel (GLM) beds on soft sediment habitats after the 1860s.

Sediment sources were analysed using the compound specific stable isotope (CSSI) method recently developed by the National Institute of Water & Atmospheric Research (NIWA). A mollusc (shellfish) death assemblage analysis was also undertaken to investigate factors contributing to the lack of recovery of green-lipped mussel beds in Kenepuru Sound. These beds likely supported abundant fish life before being harvested beyond recovery in the 1960s.

For the first time, rates of sediment deposition from different land-uses have been quantified over time in the Marlborough Sounds. The results show profound changes to sedimentation 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.

The 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 to today.

Prior to European settlement, time-averaged sediment accumulation rates were in the order of 0.2 to 1.2mm/yr throughout the Kenepuru Sound. The main sources were the inflow from the Pelorus and Kaituna Rivers ('Havelock inflow'), subsoils from natural slips, and sediment generated from bracken, beech forest, and ponga/podocarp forest. The ecosystem had co-evolved with the fluctuations of sediment from periodic storms and episodic disturbances.

Post-European settlement, sediment accumulation rates have increased to 1.8 to 4.6mm/yr with the contribution of the 'Havelock inflow' to the volumes of sediment deposited on the seabed increased

well above historic levels, reflecting pastoral catchment practices as land was cleared and pastures maintained. This has continued to the present time. Slips associated with farming and roading also rose above historic levels. Pine-derived sediment was detected from the early 20th century, periodically was the dominant contaminant source, and has risen at most coring sites in both Kenepuru and Beatrix Bay since the 1990s. This is despite pine plantations representing less than 15% of the study region. Pine-derived sediment was also detected in samples taken from underneath mussel farms.

Ironically, the extensive land clearance from the 1860s appears to have led to significant productivity increases in shellfish communities, including the probable widespread establishment or expansion of the green-lipped mussel beds. An analysis of mollusc shells buried in sediments (mollusc death assemblage) from cores collected close to shore showed productivity peaked during the period leading up to maximum historic sheep numbers, associated with farming subsidies and application of superphosphate fertiliser. Between 1975-2016 mollusc productivity on the seabed has reduced, following cessation of farming subsidies, removal of mussel beds and the development of green-lipped mussel aquaculture. However, because the productivity estimates from the last 40 years were greater than pre-human levels, there is evidence that the system is now more productive than benchmark – pre-human – conditions. The present day difference in productivity above benchmark conditions is likely derived from increased discharge of nutrients from the catchment associated with changing land-uses resulting in the 10x increase in sediment accumulation at the seabed.

These results reflect that in an unmodified state, the inner Pelorus Sound formerly 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. What has changed since European settlement has been the significant increase in annual or chronic sediment inputs, which have caused significant ecosystem effects and contributed to a decline in benthic biodiversity. This adds weight to the argument that an integrated range of improved land-use controls, particularly for forestry, in the Marlborough Sounds and the Pelorus and Kaituna River catchments, are required to mitigate chronic sediment inputs to benefit the health of the ecosystem and assist future restoration efforts.

As mussel shells were poorly represented in cores we could not draw direct causal linkages between modifications of the Pelorus catchment with changes in mussel populations back through time. In other words, no single land-use practice could be directly linked with the lack of mussel bed recovery following closure of the wild mussel fishery in the early 1970s. The factors that have prevented the intrinsic recovery of mussel beds in Pelorus Sound likely involve complex interactions and feedback mechanisms. Negative drivers implicated include: ongoing effects from sedimentation, reduced nutrient availability, historic overfishing reducing mussel standing stocks, and lack of seabed plants, which in their absence potentially form a bottleneck to wild mussel recruitment. This will make restoration of mussel beds challenging without mitigation measures, such as better land management and control of dredging to reduce sedimentation and disturbance of soft sediment habitats.

1 Introduction

Marlborough District Council (MLDC) is a unitary authority with boundaries that extend out to the edge of the territorial sea in the Marlborough Sounds, Tasman Bay, and Cook Strait. As such, MLDC has Regional Council responsibilities for Resource Management Act functions in these extensive areas, and in particular for safeguarding the life supporting capacity of the water and ecosystems. The New Zealand Coastal Policy Statement (NZCPS) 2010 must be given effect to by regional councils through their policy statements and plans. Objective 1 of the NZCPS requires protection of the integrity, form, functioning and resilience of the coastal environment in particular biological systems, and coastal water quality with reference to natural (historical) condition. Policy 22 requires that the sedimentation levels and impacts on the coastal environment be assessed and monitored, as well as managed. There are other policies pertinent to this project. MLDC is currently developing the second generation of its resource management plan. This includes, amongst other things, the identification and protection of significant marine biological sites (Policy 11 Indigenous Biodiversity), and the development of marine farming provisions (Policy 8 Aquaculture). Te Hoiere/Pelorus Sound (hereinafter Pelorus Sound) is a key location for both significant sites and aquaculture activities. Pelorus Sound is a 50km long, relatively deep (c. 40m) drowned river type estuary, and is the centre of New Zealand's $200 million per annum mussel aquaculture industry.

This project provides a valuable historic context for understanding how the Pelorus has changed, and will assist in the development of planning provisions to ensure beneficial environmental outcomes for seabed habitats. Benthic mussels that historically formed reefs over soft sediments in many parts of New Zealand have been shown to be ecosystem engineers; providing structures which facilitate biodiversity in marine invertebrate communities, and habitat for fish populations which are up to 10 times higher than adjoining muddy seabed (Morrison et al. 2014, Handley & Brown 2012). However, mussel reefs have been severely reduced in Pelorus Sound due to historic dredging and extensive hand-picking of mussels in the 1960s and 1970s (Dawber 2004, Handley 2015).

Recent literature reviews of seabed change in both the Pelorus Sound and Tōtaranui/Queen Charlotte Sound have shown dramatic ecosystem changes over the last 150 years, which have not been widely recognised in the community or appreciated by managers (Handley 2015, 2016). This may be related to the concept of 'sliding environmental baselines'. Sliding baselines essentially reflect diminishing expectations of what is natural in marine environments (and terrestrial – e.g., the pasture/tussock Wither Hills are now commonly seen as natural but were once mixed podocarp forest with kaka and other forest birds). Sliding baselines arise as historical human impacts may be forgotten over generations, and/or gradual change occurs to seafloor habitats such that what exists today does not accurately represent historic benthic communities and sediment composition (Morrison et al. 2014, Handley 2015). This has significant implications for building community support for better management of coastal ecosystems, including protection and restoration initiatives.

1.1 Study objectives

The specific objectives of the present study are:

- Determine the sources of eroded soils and their relative contributions to the sediment deposition in Kenepuru Sound and Beatrix Bay, Pelorus Sound.
- Determine how sedimentary contributions have changed by source over the recent past (present to 1,000 years before present, BP).

- Identify how shellfish communities inhabiting the seabed changed over that period.
- Test the hypothesis that human land-based disturbance triggered the widespread establishment of green-lipped mussel (GLM) beds on soft sediment habitats after the 1860s.

This information will then be used to provide:

- A comprehensive understanding of long-time ecological change in Pelorus Sound.
- Improved ability to contextualise the effects of marine farming and fishing on ecological health and provision of ecosystem services.
- An underpinning contribution to assist in enabling sustainable management of the coastal marine area.
- A baseline for state of the environment reporting and for contributing to future protection and restoration goals.
- A more-informed basis for considering the return of empty mussel shells to the seabed, thereby potentially turning waste into a resource for habitat restoration.

To achieve these objectives, this project uses the Compound Specific Stable Isotope (CSSI) method developed by NIWA scientist, Max Gibbs, which can identify and apportion, by land-use on a catchment scale, the sources of soil contributing to the sediment at a location of an estuary (Gibbs 2008). The CSSI method has been used in over 20 estuaries throughout New Zealand, tested in the Environment Court, has been elevated to the status of being usable as a compliance monitoring tool, and adopted by the international Atomic Energy Agency (IAEA) and Food and Agricultural Organisation (FAO) and used in over 40 overseas countries. The results are given as a “best estimate”, within definable limits, of the proportional contribution of each potential source soil. Information obtained using this method will allow development of management strategies to alter land-use practices to reduce the sediment load to rivers and from land directly coupled to the coast, and thus, the impact on the aquatic ecosystem downstream in estuaries and in sheltered coastal waters.

The CSSI method uses compound-specific isotopic analysis of naturally occurring biomarkers (fatty acids) derived from plants to link source soils to land-use within a single catchment (Gibbs 2008). For identification and apportionment of source soils in the estuarine samples, the method uses a stable isotopic mixing model (SIMM), such as “IsoSource” (Phillips & Gregg 2003) or “MixSIAR” (Stock & Semmens 2015). The feasible proportions obtained from the SIMM are then scaled to allow for the percent organic carbon in the source soils. With this approach, the estimation of each source soil contribution to a location in the Pelorus Sound is independent of any degradation of the biomarkers through microbial or biogeochemical processes. Identification relies on the evaluation of the sediment sample relative to a “library” of reference source soils from different land-use within the surrounding catchments. Selection of potential sources is geographically constrained by the requirement for a natural linkage between each source soil and the sediment site sampled.

As human alteration to land and marine habitats and ecosystems is recognised in the Marlborough Sounds (McKnight & Grange 1991, Handley 2015, 2016), in the absence of long-term observational monitoring, it is difficult to attribute specific changes that have occurred resulting from anthropogenic related disturbance. One way to do this is by the analysis of the molluscan (shellfish) death assemblages (DA, i.e., buried set of taxonomically identifiable, dead or discarded organic remains) within sediment core profiles. This approach is being used increasingly as a useful tool for detecting such changes (e.g., Ferguson 2008, Armenteros et al. 2012, Martínez et al. 2013).

This will enable us to test the hypothesis that human land-based disturbance triggered the establishment of GLM beds formed on soft sediment habitats in Kenepuru Sound after 1860s. The mechanism for the bed formation could be that settlers, in repeatedly burning the land, generated nutrients and woody debris, the latter of which became colonised by GLMs that drifted and sunk in the Kenepuru – 'kick starting' the benthic beds. The hypothesis would be rejected if GLM shell is found throughout the cores. If this is the case, then known large Alpine Fault and Hikurangi Trench subduction earthquakes over the last 1,000 years may have resulted in similar bursts of marine productivity as a consequence of widespread land-sliding delivering significant pulses of sediment and vegetation (Clark et al. 2015). This would provide support for the possibility that Pelorus Sound, when formerly fully afforested under native vegetation, received low nutrient inputs from land. While GLMs may have been formerly present on hard and soft substrata, the European colonisation period may have accelerated terrestrial nutrient release into the marine environment by way of fire, leading to expansion of GLM populations. If we do not find GLM beds throughout the cores, this may suggest that regional earthquakes and intense localised storms did not have the same effects on the ecosystem over the last millennium as widespread human-induced changes did.

1.2 Study area: physical, biological and human context

1.2.1 Geological setting and soils

The Marlborough Sounds consist of a series of narrow river valleys that have been submerged by the sea due to sea-level rising some 140 metres higher than during the last ice age 14,000 years ago, and the subsidence of the Marlborough Sounds area north of the Wairau Fault (Davidson & Wilson 2011). The rock substrata of the Sounds is composed of metasedimentary rocks that vary in texture, with the lowest being most metamorphosed (Lauder 1987). The rock type has been described as the Haast or Marlborough Schist Group which are aligned in bands to the northeast. Weathering of weaker mineral bands in the schist produces planes of weakness prone to deep and surficial slippage with sediment detritus of characteristically flat (platy) form. Overlying the schist is a layer of hardened sandstones and siltstones as greywacke and argillite atop the Pelorus Group (Lauder 1987). Sediments derived from the Pelorus Group are more blocky than platy. Soils of the Sounds are generally steepland yellow-brown earth soils, which are prone to slips, and sheet and rill erosion once the vegetation cover is removed. These soils are primarily silt and silt-clay loams with up to approximately 45% clay, formed by weathering of the parent material and some loessal deposition (DSIR 1968, Laffan & Daly 1985).

1.2.2 Potential historic drivers of sediment accumulation and disturbance

Human habitation and land-use change: Māori and European historians recount early occupation of the Marlborough Sounds with modification of the land for dwellings and for agriculture. Pit dwellings, later excavated by Europeans, show changes to the landscape. *Pa* and *kainga* scattered the top of the South Island-Te Tau Ihu o Waka (Mitchell & Mitchell 2008). Archaeological evidence shows that Māori were active in modifying the environment in Kenepuru and Beatrix, Clova and Crail Bays (Challis 1991, Handley 2015, 2016), and many bays throughout the Marlborough Sounds.

Mining: Although Picton was an active settlement in 1854, it wasn't until 1860 that Havelock at the head of the Pelorus Sound was established where it became a service centre for nearby gold mining developments and later for milling and shipping of timber.

Gold was first discovered in the Wakamarina River that flows into the lower Pelorus in the 1860s with a significant claim developed in 1864 (Ponder 1986). Gold was also discovered at Mahakipawa in 1888, between Havelock and Linkwater, which supported the town of Cullensville occupied by over 1,000 miners (Lauder 1987) (Figure 1-1). A two-mile section of Cullens Creek bed in the Mahakipawa Arm was worked for a short period but suffered from periodic flooding and associated debris which had to be cleared to continue the workings. The Wakamarina mine likely contributed significant sediment discharge to the upper Pelorus Sound via the lower Pelorus River, migrating down-river over a period of years. Gold prospecting likely took place at other sites in Pelorus including Nopera and Kenepuru (Handley pers. observ.). Gold-dredging also took place in Mahakipawa Arm (Handley 2015).

Havelock channel and marina dredging works: The Havelock Harbour has a long history of diversions, deepening and widening to cater for various shipping needs dating back to before 1910 that have been captured by legacy files held at Marlborough District Council[1]. The Kaituna River formerly (ca.1873) used to flow along the western side of Cullen Point, which now forms the Cullen Point blind channel. Around 1910 the "Launch Channel" was cut using a Priestman Grab Dredge to 6 ft (1.8 m) depth connecting the Kaituna in a more direct line with Cullen Point and with a side-cut to the north west to the wharf formerly situated at the end of Cook Street (Figure 1-2). This channel lasted 20 years, kept relatively clear by tidal scour. In 1930, the channel from the wharf directly out to Cullen Point was cut using a suction dredge to 4 ft (1.2 m) depth, lasting approximately 5 years.

Alternatives to keeping the Havelock Harbour channel open were mooted in 1953, including: cutting a channel or tunnel to connect Pelorus with the Queen Charlotte Sound (£200,000); building a new wharf and diverting the highway to Cullen Point (£110,000), or continued dredge works (ca.£4,000). "It must be recognised that at present this wharf serves the only means of transport available to many settlers in the Pelorus Sound area, and replacement of launch transport by a roading system would involve a very heavy expenditure by the State and Local authorities", "the harbour is its highway".

At some stage during the 1950s, the blind channel leading directly from Cullen Point to the Harbour Wharf was deepened with a combination of suction dredging, blasting of hard ground, and the side cut from the Kaituna River channel was closed off using "manuka walling" and infilling with the dredge spoils[2] (Figure 1-2, Figure 1-3). This diversion of part of the Kaituna to run past the wharf was referred to as a "disaster" as it apparently silted up the shipping channel after flooding in the Kaituna. The deepened channel running from the wharf toward Cullen Point, now forms the current entrance to Havelock Harbour. Aside from the infilling of the man-made channel to the Havelock wharf from the Kaituna River channel, no mention of the fate of dredge spoils was made. The dredging works that developed the marina and deepened the Harbour and channel in the 1980s (M. Gibbs, NIWA, pers. observ.) created an island using the spoil, sited off the north eastern end of the Harbour break wall (Figure 1-3). More recent maintenance dredging was carried out in 1995, and spoil dumped on a farm at Twiddles Island, Havelock[3].

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[1] Marine Department – Harbours- Havelock, File No. 43-31-9, DOC19, 10/10/1961.
[2] Marlborough Express, 2 November 1960.
[3] Havelock maintenance dredging 950435/U150829, MLDC, 1995.

Figure 1-1: **Pelorus Sound, rivers and historic sites mentioned herein.**

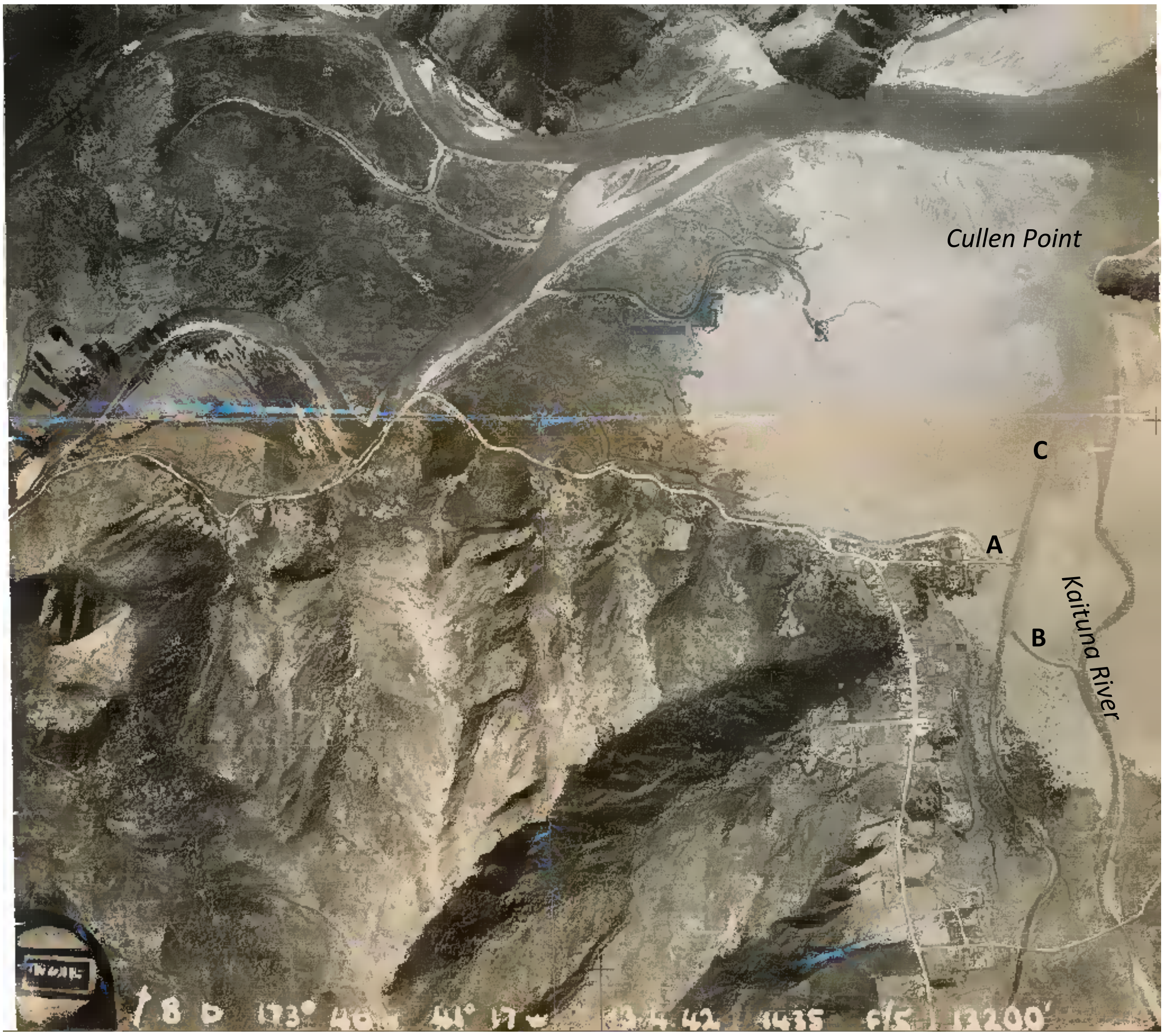


Figure 1-2: Havelock Estuary, 13 April, 1942 showing: A, the wharf at the end of Cook Street; B, the man-made channel connecting the Kaituna River channel with the wharf; and C, the channel that now forms the entrance to Havelock Harbour.

Figure 1-3: **Havelock Harbour, 2010 (Google Earth).**

Timber milling and agriculture: Land clearance, including felling and milling of timber was a common part of these early developments. Timber extraction was the usual method of financing the development of pastoral farming (Walls & Laffan 1986, Clarke 2014). Many timber mills sprang up in Pelorus between 1900 to 1960 with nearly two thirds of the 1,480km^2 native bush catchment of the Marlborough Sounds estimated to have been logged from the flatter lands by 1910 (Bowie 1963, Laffan & Daly 1985, Lauder 1987). The hills were also burned to develop into pasture. Mill sites included Kaituna, Havelock, Nydia Bay, Kenepuru, Kaiuma, Manaroa, and Tennyson Inlet. The population of the Sounds is thought to have peaked at the turn of the century, with pastoral farming peaking by about 1910. By 1880, the hill slopes up to 100 and 300 m elevation were cleared of bush (Bowie 1963). After heavy rains, surface slips were common; with more than 30 large slips observed along a 10 km stretch of hillside between Broughton Bay and Portage in Kenepuru in 1930s (Lauder 1987). From a study of erosion of similar steep slopes in Reefton, a disproportionate sixty percent of the sediment discharged from clear-felled land originated from track surfaces or the loose soil and gravel accumulations which were sidecast onto the steep slopes below forestry tracks during their construction (O'Loughlin et al. 1980, Lauder 1987). In contrast, the use of fire following bush clearance, created ash and wood debris that filtered the water, encouraging rapid growth of grass, fireweeds and liverwort which restricted sediment transport on lower slopes (O'Loughlin et al. 1980). It is thought that the fertility for pastoral farming initially came from the burning the bush (Clarke

2014, Figure 1-4). Soil stratigraphy and composition predisposes the Marlborough Sounds to increased erosion from track construction as the subsoils are more erodible, and the clays more dispersive, than the upper soil layers (McQueen et al. 1985). The range of grain sizes delivered to the coast (from fine to coarse) increased the closer the erosion takes place to the shore, and also the steeper the land adjacent to the coast (Lauder 1987). By the 1950s the fertility of the land had declined necessitating the addition of artificial fertilizers to maintain farming productivity, otherwise land was abandoned and left to revert to native bush (Clarke 2014). Accelerated siltation from the land clearance caused dramatic changes in the sea.

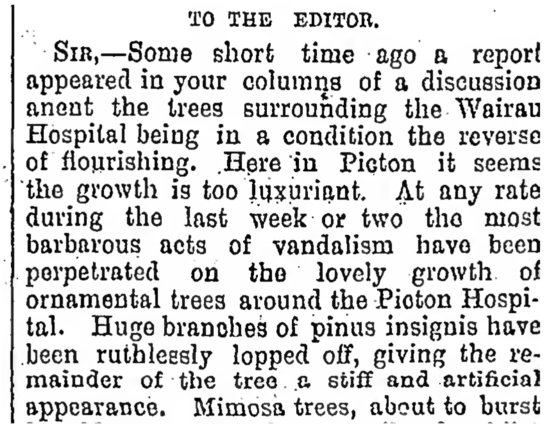
Figure 1-4: Large fire on Taranui peninsula, south west Crail Bay, late 1800s (Kindly supplied by K. Gerard).

Landcare Research's Land Cover Database (LCDB v.4, 2014) showed that in 2012 native and regenerating forest dominated land cover (72.2%) of the Pelorus watershed (the study region), with exotic forest (14.2%), and high and low producing pasture (13.1%) being less significant (Table 1-1).

Table 1-1: Landuse statistics extracted from Land Cover Database (LCDB v.4), Landcare Research. For watershed covered, see Appendix A.

Landuse	Total	Percent (%)
Native forest (ha)	93,205	63.6
Native scrub/regenerating forest (ha)	12,619	8.6
Exotic forest (ha)	20,829	14.2
High producing grassland (ha)	13,822	9.4
Low producing grassland (ha)	5,402	3.7
Tussock/Alpine vegetation (ha)	378	0.3
Built-up Area (settlement, ha)	213	0.1
Other (ha)	18,519	12.6
Total	**146,469**	**100**

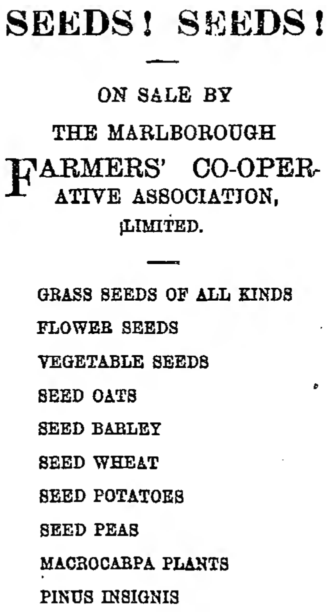
Pinus radiata forestry: Following land clearance for pastoral farming, it was estimated that 5,000 ha of land has been planted with exotic plantation forest since 1920 - mainly radiata pine (*Pinus radiata*) - with the potential for 40,000 ha of afforestation (Johnston et al. 1981, Laffan & Daly 1985). In 2015, MLDC identified 17,440 hectares were planted in pine forest (Urlich 2015). It appears pine was introduced well before the 1900s indicated by: early photographs (Figure 1-5), an account of damage to a large pine outside the Picton Hospital in 1891, and seeds were available for sale in 1893:



TO THE EDITOR.

SIR,—Some short time ago a report appeared in your columns of a discussion anent the trees surrounding the Wairau Hospital being in a condition the reverse of flourishing. Here in Picton it seems the growth is too luxuriant. At any rate during the last week or two the most barbarous acts of vandalism have been perpetrated on the lovely growth of ornamental trees around the Picton Hospital. Huge branches of pinus insignis have been ruthlessly lopped off, giving the remainder of the tree a stiff and artificial appearance. Mimosa trees, about to burst

[4]



SEEDS! SEEDS!

ON SALE BY
THE MARLBOROUGH
FARMERS' CO-OPERATIVE ASSOCIATION,
LIMITED.

GRASS SEEDS OF ALL KINDS
FLOWER SEEDS
VEGETABLE SEEDS
SEED OATS
SEED BARLEY
SEED WHEAT
SEED POTATOES
SEED PEAS
MACROCARPA PLANTS
PINUS INSIGNIS

[5]

Pine was used for shelter, firewood, and praised for its potential for manufacturing fruit and butter boxes, building timber and paper pulp[6]. Re-planting of a cut over pine plantation was evident in Nelson district circa 1910[7].

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[4] Marlborough Express, 8 August 1891 Damage to mature pines in Picton Hospital grounds

[5] Marlborough Express, 1893.

[6] Marlborough Express, 11 September, 1913.

[7] http://mp.natlib.govt.nz/detail/?id=17091&l=en

Figure 1-5: Evidence of large pine trees, presumably planted in mid-late 1800s: Top: Large pines as shelter around houses, Pohuenui Station, Richmond Bay 1920s (National Library ref Pan-1017-F); Bottom: Pines and macrocarpa as shelter in background and around homestead (insert), Elie Bay, early 1900 (J. Denniston, Courtesy of K. Gerard).

John and Hylton Harvey started milling pine in 1957 in Clova Bay producing excellent timber (J. Harvey, pers. comm.). Timber from dense shelterbelts (e.g., 6 trees wide by 3-440 yards) from around Sounds homesteads was milled until the 1970s. The first batches came from North West Bay and Titirangi and were used for construction in Blenheim and Wellington. A newspaper article recorded 236 m3 pine milled at the Manaroa mill in 1960 (Harvey 2008). The brothers planted 70,000 pine in Crail Bay around 1960.

Total nitrogen concentrations in the topsoils of the Marlborough Sounds are low, and critically low below the top 10-20 cm, meaning if the top layer of soil is eroded, then the soil becomes deficient for exotic forest growth (Laffan & Daly 1985). Similarly phosphorous levels are universally limited. The soils formed from greywacke and schist have moderate nutrient limitations, especially in the upper slopes of the Sounds, and soils formed from serpentine generally have moderate to severe physical and nutrient limitations for growing exotic forest (Laffan & Daly 1985). A number of factors influence the profitability of forestry in the Marlborough Sounds, including; market forces, isolation and environmental costs. Environmental issues arising from forestry include impacts on water quality, smothering of benthic habitats, transport and visual landscape issues (MLDC 2016). Although forested catchments generally have lower rates of sediment discharge to the marine environment, forestry can increase erosion of soils during track construction and development, and during harvesting (Davidson et al. 2011). It was estimated that up to 218 tonnes of sediment per square km could be eroded from roadways during logging operations in the Sounds each year (Fahey & Coker 1992) with sediment discharge increasing as much as five times following logging truck movements over roads consisting of weathered schist (Coker et al. 1993). Sediment in the adjacent waters could climb to 1,000 milligrams per litre compared to background levels of 15-20 milligrams per litre (Fahey & Coker 1992) where it quickly settles out on the seafloor (O'Loughlin 1979, Davidson et al. 2011). Increased sediment loading may have profound effects on marine biota (Schiel & Foster 1986, Estes et al. 1989, Cole & Babcock 1996, Airoldi & Virgilio 1998). Recent observations following Easter 2014 storm-related damage from well-managed and well-maintained forestry blocks in the Marlborough Sounds, demonstrated that even under good management, operators cannot protect the environment from rain storm damage (MLDC 2014a).

Public roading and storm events: Roads can be a substantial source of sediment runoff into waterways (Motha et al. 2003; 2004). Although forestry roads may contribute disproportionately to erosion and slips, maintained public roadways constructed over unstable slopes bordering the Marlborough Sounds can also contribute significantly to sediment entering waterways and the sea. To illustrate this, a report by D. Miller, the former MLDC Assets Manager for Roading, recounted 12 slips along the ca.21 km stretch of road connecting Picton and Linkwater between 1985 - 2010 (Miller 2015) (Table 1-2, Figure 1-6). The slips were predominantly caused by the road being inundated by uphill material slipping down-slope, sometimes causing the roadway to subside. Sidecast material and blocked culverts also contributed. When many of these roads were built Miller was advised that the standard was "12 feet wide on solid with grades less than 1:8" meaning there was considerable sidling fills (sidecasting), unbenched and uncompacted. Estimated volumes of the smaller slips ranged from 300-3,000 m^3 (Figure 1-7), with an average slip volume of approximately 1,250 m^3 and a total of 67,100 m^3. However, these smaller slips were dwarfed by a large natural slip estimated at over 55,000 m^3 and located 14 km from Picton at the Linkwater end of the road. This slip appears to have been on the move since at least 1960, with the road having been re-surfaced in this location at least 10 times. Miller (2015) also noted that large weather events like a 'weather bomb' storm that affected parts of the Sounds in 1992 affected D'Urville Island, French Pass, Waitata area, Anakoha and Titirangi roads, with an estimated 500,000 m^3 of material involved in slips.

Table 1-2: Slips recorded along the ca.21 km stretch of road between Picton and Linkwater between 1985 - 2010 (Miller 2015). Y = yes, sidecasting was a likely contributor to the slip.

Date	Distance from Picton (km)	Volume (m3)	Sidecasting	Potential cause
1990	3.5	400	Y	Slip inundating road
1990	6.1	600	-	Road widening
1995	6.3	600	-	Slip inundating road, undercutting?
1998	6.8	500	Y	Road widening
1996	7.2	1500	Y	Road widening
2000	7.55	800	Y	Slip inundating road, undercutting?
2003	9.2	300	Y	Private access-way collapse
1990	11.25	1200	Y	Slip inundating road, undercutting?
1993	11.5	3000	Y	Culvert blockage, rebuilding atop old road
1996	12.15	1200	Y	Slip inundation, blocked culverts, natural erosion
1994	13.7	2000	Y	Slip inundation, collapsed road/sidecasting?
1960-2004	14	55000	-	Uphill water conduits lubricating slip face, natural slip
Total:		**67100**		

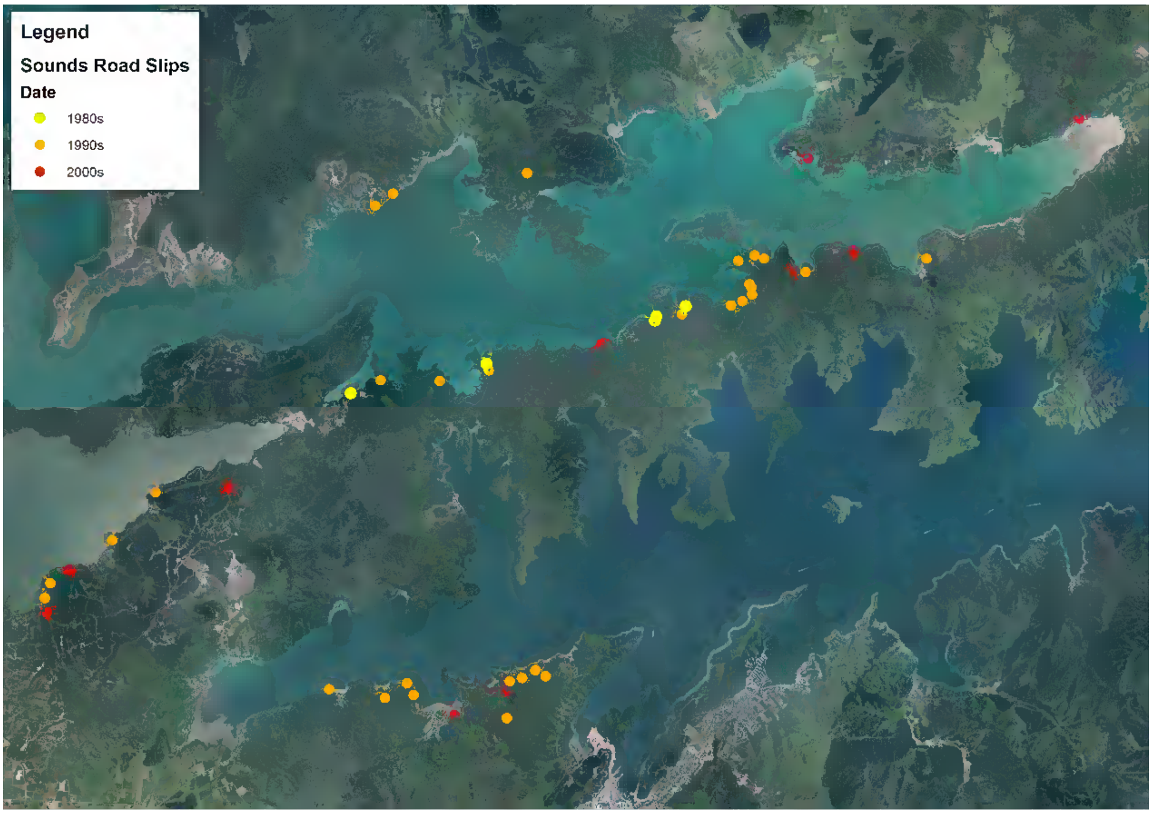

Figure 1-6: Slips that entered coastal waters associated with the transport road network on Queen Charlotte Drive (bottom centre – 12 dots) and the Kenepuru Road. Source: Miller (2015).

Figure 1-7: Estimated volume of slip material associated with the slips identified in Figure 1-6. Source: Miller (2015).

Large disturbances and sediment supply: New Zealand's natural ecosystems are characterised by large, infrequent disturbances such as earthquakes, tsunamis, and storms. These can result in significant mortality to terrestrial and subtidal species as landslides, floods and waves, bury habitats, and often open the way for regeneration of different suites of species to those previous there (e.g., McKnight 1969, Urlich et al. 2005). In the last 1,000 years, severe quakes along the Hikurangi trench were detected in the Wairau lagoon, approximately 40km southeast of Kenepuru Sound and ~55km from Beatrix Bay (Clark et al. 2015) (Figure 1-8). These events coincided with either other fault movements 880-800 years ago in Wellington and Wairarapa, or tsunami deposits dated 520-470 years ago which were contemporaneous with palaeo-tsunami deposits from Kapiti Island and Abel Tasman (Figure 1-8, Clark et al. 2015). The inner Marlborough Sounds are the location of a number of fault lines that run south-west to north-east indicating areas of past tectonic activity (Begg & Johnston 2000) (Figure 1-9). Goff and Chagué-Goff (1999) identified two clear tsunami events recorded in sediment cores from the Abel Tasman National Park estuaries in Nelson: during ~1220 AD, ~1440 AD, and two other potential events in ~1600 BP and 1855. Earthquakes in South America reportedly generated tsunami affecting New Zealand in 1868 and 1869 of 2-3 m[8]. These disturbance events are likely to have affected Pelorus Sound and the surrounding catchments through ground-shaking and/or elevated wave action, resulting in increased deposition of sediment from landslides and beach scour or resuspension of sediments from the seabed. Intense storms can also elevate sediment supply, although the effects are often more localised due to orographic patterns and land-use compared to regional-scale earthquakes and tsunamis.

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[8] GNS New Zealand Tsunami Database: http://data.gns.cri.nz/tsunami/dataDetails.html?id=150

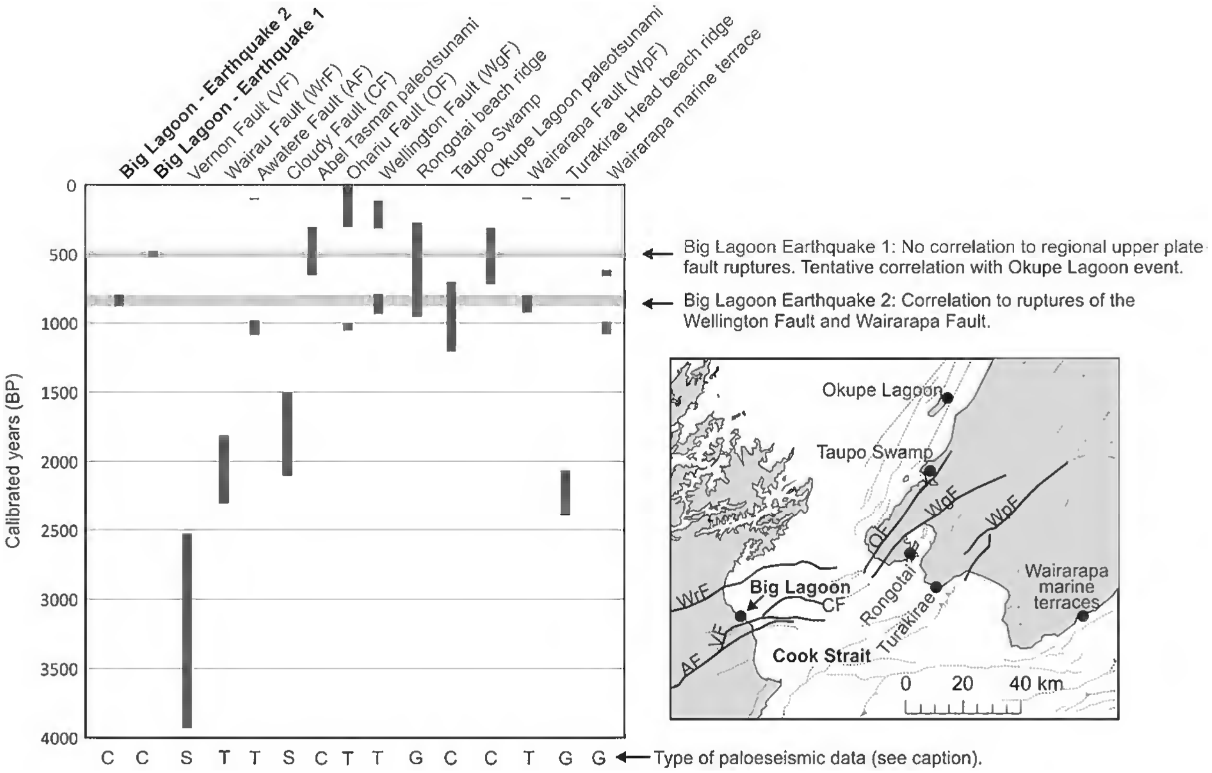

Figure 1-8: History of regional earthquakes and tsunamis from Clark et al. 2015 (Figure 13). Note the apparent synchronous earthquake approx. 800 years ago detected from the Wairau lagoon, Wellington Fault and Wairarapa Fault; and tsunami deposits from approx. 500 years ago at Wairau Lagoon, Okupe Lagoon on Kapiti Island, and Abel Tasman.

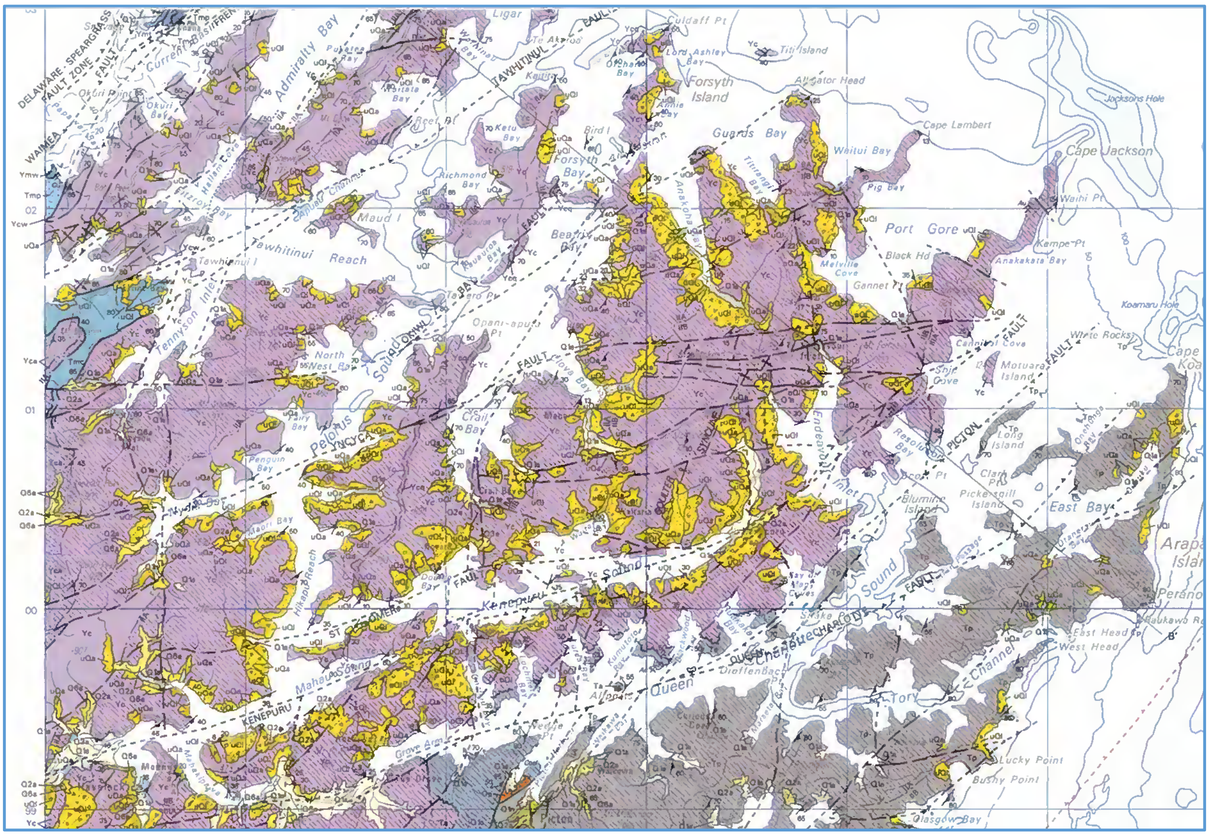

Figure 1-9: Fault lines running through Pelorus Sound (dashed lines). Including: Kenepuru, St Omer, Yncyca, Okiwi, Tawhitinui faults and minor faults in between. Excerpt from Begg & Johnston (2000).

Sediment transport and deposition: Fine sediments washed off the land derives disproportionately from small rivers draining small and steep catchments during storm events (Milliman & Syvitski 1992, Thrush et al. 2004). The resulting fine silts and clay sediment loads are orders of magnitude higher than average (Hicks et al. 2000). Sediment particles are mostly highly charged particles which flocculate on contact with seawater and are rapidly deposited, smothering estuarine and marine sediments (Thrush et al. 2004). The deposition of clay-rich soils, stained yellow-orange by the presence of iron-rich minerals, in the Sounds occurs rapidly upon contact with seawater according to laboratory tests (O'Loughlin 1979, Coker 1994). Those tests on Kenepuru series soils, which underlie many forestry areas in the Sounds, showed rapid flocculation and settlement of suspended sediment. The conclusion from that study was that sediment from coastal erosion was likely to settle out in close proximity to the shoreline, due to the chemical reaction of charged particles of clay reacting with seawater (O'Loughlin 1979, Urlich 2015). Another mechanism for sediment deposition nearshore environments is by transport in tidal currents alongshore (O'Loughlin 1979) or via dilution by tidal currents. Sediments are more likely to be suspended and widely dispersed in fast flowing locations like Hikapu Reach and then settle out in slower flowing side bays (Hadfield et al. 2014, Broekhuizen et al. 2015) where the bottom stress from a tidal current is below a typical resuspension threshold of 0.1 newton m^2, (0.1 pascal) for clay-rich sediments (Hadfield in Urlich 2015). Therefore, the deposition of eroded sediment on the seabed depends somewhat on the hydrodynamics at a bay- and reach-scale (Urlich 2015).

There are complex tidal, estuarine and wind-driven circulation systems in the Pelorus. The mean residence time for the Pelorus channel is approximately 50 days, compared with approximately 60 days in Kenepuru (Broekhuizen et al. 2015). Embayments off the side of the main channel tend to flush more readily, as opposed to the longer residence times of embayments that are affected by local circulation patterns that alter tidal circulation. The Pelorus Sound is frequently characterised by stratified estuarine circulation, especially during winter and under high river flow events (Carter 1976, Vincent et al. 1989, Gibbs et al. 1991, Broekhuzien et al. 2015). Under high freshwater flows, sediment is transported seaward, whereas under low flows sediment is transported with the ebb and flood tides predominantly landward to the head of the Sounds. Sediment thickness in channel profiles is not considered a useful index of sub-regional sedimentation rates due to the role of hydraulic scour (Lauder, 1987). Pre-human mean sedimentation rates, were estimated at 1.24 mm/yr, in Nydia Bay at 1.17 mm/yr, and in nearby Tennyson Inlet at 1.83 mm/yr (overall mean: 1.41 mm/year, Lauder, 1987). Carter (1976) reported that due to hydrodynamics, the Pelorus acts as a double-ended sediment trap, with sedimentation greatest at the head of the Sounds, and at the entrance where seston (live and dead particulate matter) is delivered from the Cook Strait on flood tides. However, Lauder (1987) cautioned that as the mean sedimentation rate calculated for the inner Pelorus profiles is 0.96 mm/year, which he considered significant, meant that as the sub-bottom (i.e., original river valley) lies close to present sea-level in the inner Sound, it offers limited scope for thick sediment accumulation in the presence of tidal scour. The seabed mud layer follows the sub-bottom profile, suggesting a balance in control between the morphology of the original river valleys and tidal processes of sediment redistribution. Also, the significance of embayment trapping may exceed the importance of Sound-head trapping of fine sediments delivered to the coast. At the head of the Pelorus, there is an extensive shallow delta built by sediment from the Pelorus and Kaituna rivers covering 18 km^2 (Carter 1976).

The sediments of Pelorus comprise terrigenous (land-based), biogenic (once living), and indeterminate components (Carter 1976). Mean shell content in the coarse fraction of offshore samples was 22% and lower (20%) in Pelorus samples. Nearshore shell content of sediments was lower at 10.7% (Lauder 1987). The fine biogenic component is mostly derived from individual and colonial diatoms, which constitute up to 20-33% of the seston at the entrance of Pelorus indicating higher diatom productivity there (Carter 1976). The terrigenous and indeterminate components transported in bottom waters are greatest at the head of the Sounds, tapering off rapidly to about a third of the way down the Sound, then tapering more slowly to the entrance. Grain-size evidence shows that Pelorus Sound sites have lower sand contents and Kenepuru Sound sites higher clay contents, but that marginal bays were found to contain a full range of the sediment sizes - sand, silt, and clay.

Nutrient supply: It has been found that the supply of particulate nitrogen (N) material or seston from Cook Strait differs by season (Zeldis et al. 2013, Broekhuizen 2015, Broekhuizen et al. 2015), being driven by climatic factors affecting supply of N off the West Coast (Zeldis et al. 2013). The patterns in seston supply, which comprises important food for invertebrates like greenshell mussels, can be predicted using physical factors. In summer a negative Southern Oscillation Index (SOI), north-north-west winds (NNW), and cool sea surface temperature (SST) were correlated with offshore upwelling of nitrate-nitrogen rich water off the entrance to Pelorus Sound which is pushed into Pelorus under NNW winds (Zeldis et al. 2013). As nitrate-nitrogen is a limiting nutrient, this supply stimulates increased growth of phytoplankton and zooplankton (particulate nitrogen production) resulting in greater farmed green-lipped mussel (*Perna canaliculus*) growth inside Pelorus Sound (Zeldis et al. 2013). In winter however, particulate nitrogen is not related to offshore upwelling, but instead is related to the Pelorus River flow, where the river creates estuarine circulation with the less-dense freshwater flowing over the top and drawing in deeper seawater containing nitrate nitrogen at the head of the entrance of the Sound (Gibbs et al. 1991, Broekhuizen et al. 2015). Vertical stability of the water column can have a major influence on nutrient supply, phytoplankton growth, and light levels, with year to year variability linked to variability of stratification of the water column (Inglis et al. 2000). Therefore, the supply of particulate nitrogen material potentially available as a food source, or destined for deposition to the sediments has the potential to vary seasonally and inter-annually depending on climate driven differences in rainfall in winter, and fluctuations in the SOI affecting wind stress (Zeldis et al. 2013).

Shellfish fisheries and mussel reefs: Reports of early fishing in Pelorus are scant. Shellfish including mussels: the green-lipped mussel, the blue mussel (*Mytilus galloprovincialis*), fan mussel (Pinnidae), and the horse mussel (*Atrina zelandica*) were an important component of the diet of Māori (Best 1929, Smith 2011). Early accounts of shellfish exploitation in Pelorus are rare, but intertidal mussels were likely a first meal for the first European Harvey family on arrival in Clova Bay (Ponder 1986). Reports of oyster bars in Nelson and Blenheim suggest shellfish sales were part of a thriving local economy from 1859 until over-fishing took its toll by the early 1900s (Wright 1990, Handley 2015; 2016).

The extent of early shellfish beds can only be conjectured. Early accounts indicate that mussel beds covering soft-sediment and rocky intertidal were present in many harbours throughout New Zealand (Chisholm 2005, Handley & Brown 2012, Paul 2012). 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 20h century (Anderson 2008, Smith et al. 2009, Handley & Brown 2012, Handley 2015; 2016). Mussels appeared to be over-exploited near the turn of the 20th century in Tasman Bay, Nelson, with effects on sponge beds presumably from dredging (Handley 2015).

Despite this early period of exploitation in Nelson, the first official fisheries records for greenshell mussels was 21 sacks harvested from Tasman/Marlborough in 1958 (Paul 2012). The first scallop (*Pecten novaezelandiae*) dredging license was issued in 1961 (Dawber 2004), although Nelson mussel beds appeared to have been exploited before the scallop fishery took precedence. It is unclear whether mussels were a preferred culinary delicacy over scallops in the early days of dredging, or that the scallop beds and their markets developed after the removal of the more abundant and accessible mussels. A preliminary survey of mussel stocks in the Pelorus in 1968-‘69 reported that the Pelorus was first commercially dredged in 1962 by a boat from Havelock (Stead 1971b). Dredging removed the “crust” of mussels in Kenepuru exposing the underlying mud bottom (Clarke 2014).

Demand for wild Marlborough mussels came from the Greek population in Australia and the Auckland markets faced with dwindling mussel stocks in the Hauraki Gulf - Firth of Thames (Dawber 2004; Paul 2012). Similarly, indicating the fragile nature of the Marlborough mussel beds, Stead’s (1971b) preliminary survey reported that the commercial sized beds off Skiddaw and Weka Point in Kenepuru Sound already showed signs of depletion (Figure 1-10). Large “old-growth” mussels were also harvested from the outer Pelorus at Forsyth Reef and transported to the North Island via Paremata (Dawber 2004). Catches from grounds off Skiddaw (Figure 1-10) in 1967 declined, but boats continued to fish at Weka Point. The mussel beds were never thick in the more coarse “dirty” grounds off Skiddaw, but formed a very thick carpet in the upper Kenepuru Grounds, especially in Waitaria Bay (Chris Guard, pers. comm.). By 1968 up to eleven boats were dredging for mussels in Pelorus. Some boats would wait until extreme high tide and fish with their 4 ft dredge so close to shore that their masts would get ensnared in overhanging tree branches. Stead (1971b) commented that conservation of the stock 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.” To conserve mussel stocks, in 1968 the area within harbour limits (Tawero Point to Whakamahawahi Point) was closed to dredging, with only hand gathering of mussels permitted apart from during a closed season between 30 November to 1 March. Hand picking produced prolific hauls, with 28 wooden boxes (70-80 lb each) in a single low tide in Waitaria Bay (Chris Guard, pers. comm.). These mussels were never a particularly prized product, and Nelson sales were poor, with the majority being sold in Marlborough via Wairau Fisheries or Tom Reeves Fisheries. Otherwise the mussels were sent to Picton to be shipped to the North Island. Green-lipped and blue mussels were found scattered throughout the inner Pelorus out to Beatrix Bay in the late 1960s (Figure 1-10).

It was in 1968 that the first experiments with mussel farming rafts were undertaken in conjunction with Victoria University in Wellington. A follow-up mussel survey in December 1969 confirmed that most of the areas holding commercial densities of wild mussels in Pelorus had already been dredged and exhibited signs of depletion (Stead 1971a). The two main areas of dredged mussel beds consisted of mud, broken shell and coral substrate off Skiddaw, and an area of mud bottom north-east of Weka Point in Kenepuru Sound (Stead 1971b). Mussel distribution was considered patchy, and more dense close inshore. Large mussels often exceeded 70 m^{-2} in density. A conservative estimate of the area covered by the mussel grounds surveyed by Stead (1971b) (and calculated herein), is approximately 350 ha, but this excludes the intertidal distribution recorded on most headlands in the inner Pelorus (Figure 1-10), so an upper estimate could be in the order of 2000 ha. Size distribution of greenshell mussels differed between sites, and from intertidal to subtidal. All very small mussel recruits (<5 mm) were found amongst adults in intertidal beds on rock substrate, with no <5 mm recruits found on mud, stony, or shell-coral substrate in the subtidal. Stony and mud substrate appeared to hold the largest mussels, and Kenepuru dredged beds had the highest meat to shell ratio. Dredging of the beds was considered by John Greenway of Fisheries Management Division as the equivalent to harrowing a field, with the subsequent collapse of the Pelorus beds, a natural result of such exploitative harvesting (Dawber 2004). Even though intertidal mussel stocks dwindled, the hand picking of mussels continued well into the 1970s during the early development of mussel farming (Chris Guard, pers. comm.).

The first recorded surveys of scallops in Pelorus were by Mike Bull during his studies as a Doctoral Student at Victoria University between 1973 and 1974. His study had the aim of providing "a contribution to better management of the fishery for this species" (Bull 1976). Bull described and mapped the preferred habitat, spawning cycle, larval recruitment and growth rates of the scallop mainly from the outer Pelorus Sound area (Bull 1976, Unpub. map) (Figure 1-11). Scallop landing statistics in the early days of the fishery were lumped together with Nelson Bays production, so it is difficult to determine yields from Pelorus (Francis & Paul 2013). The history of the Nelson/Marlborough scallop fishery was highlighted by a maximum production of 1,000 tonnes meat weight recorded in the 1970s (Francis & Paul 2013, Handley 2006). This production subsequently crashed, leading to the closure of the fishery between 1981 and 1982 (Francis & Paul 2013). In 1983 enhancement trials proved very successful (Arbuckle & Metzger 2000) 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. 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 & 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.). There is strong similarity in modern distribution of scallop biomass estimates (Handley, pers. observ, Challenger Unpub. data, 2013) with historical beds recorded by Bull (Figure 1-11) except for the beds in the Mahau Sound that are no longer present.

Dredge oysters (*Tiostrea chilensis*), whilst present in mussel reefs in Pelorus, were small and rare (Stead 1971b), and did not appear to be targeted by fishers. Like Pelorus, Tunbridge (Tunbridge 1962) noted that as much of the seabed in Tasman and Golden Bay is mud, dredge oyster and mussel settlement was probably limiting, and that in order to enhance both fisheries for commercial exploitation "thought could be given to the deposition of a suitable substance on the grounds prior to settlement" (Tunbridge 1962, Handley 2006). Similarly, Greenway (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 as a mechanism to provide cultch for settlement, because laboratory experiments showed that dredge oyster larvae settle equally on weathered oyster, scallop or mussel shells (Brown 2011). However, 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 (Paul 2012, Scott 1963).

Potentially overlooked, horse mussels (*Atrina zealandica*) dominated most dredge tows in preliminary green-lipped mussel surveys by Stead (1971b).

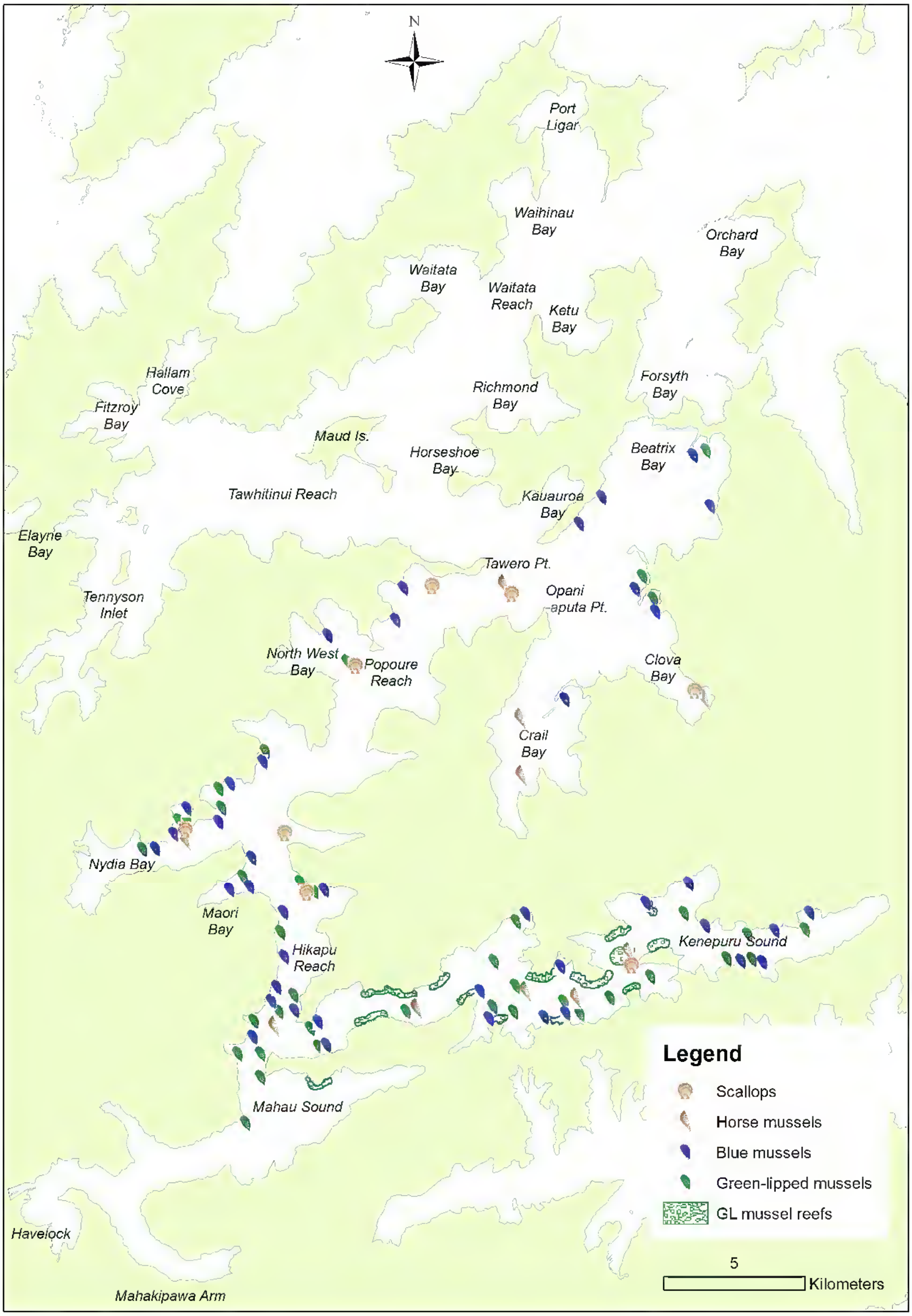

Figure 1-10: Historic shellfish beds from Pelorus Sound (excluding large scallop beds). Sources from: (Stead 1971a, b) and Davidson et al. (2011). GL = green-lipped mussels.

Figure 1-11: Historic scallop beds in Pelorus Sound. Sources from: Bull (Unpub.); (Stead 1971a, b)

Finfish fisheries: The historical spatial extent of bottom-contact fishing methods in the Pelorus Sound are important as an agent of disturbance to the seabed. Bottom trawling and dredging for shellfish have been shown to cause physical disturbance to the seabed homogenising sediment structure and benthic assemblages which results in reduced habitat complexity and species diversity (Gray et al. 2006, Thrush & Dayton 2002, Jennings & Kaiser 1998, Kaiser et al. 2006, Handley et al. 2014). This disturbance is expected to have an effect on the radioisotope aging methods used herein, and also damage live and dead molluscs, potentially confounding death assemblage (DA) analyses.

Biogenic habitats brought about by living organisms, are in many respects 'self-structuring' (Reise 2002), as they are contingent on settlement, growth and death of the likes of large bivalves at the sediment water interface (Handley et al. 2014). Because biogenic species are often large and fragile, they can only persist in the absence of high disturbance. As biogenic habitats are one of the keys to increased biodiversity in the Marlborough Sounds, benchmarking pre-impact sediment composition is important for management (Handley et al. 2014) and informing potential restoration efforts (Handley 2016, MLDC 2016).

Large fishes are also important bioturbators (mixers of sediments), that is, their feeding activities at the sediment water interface, can mix surficial and underlying sediment layers. A great variety of fish have been recorded in the Marlborough Sounds, and early settlers advocated for the establishment of fishing stations to exploit the early abundance (Handley 2015, 2016)

Species in order of abundance netted at Te Mako estuary, Duncan Bay over a 33 year period (1971-2004) included: kahawai (*Arripis trutta*), warehou (*Seriolella brama*), yellow-eyed mullet (*Aldrichetta forsteri*), yellow-belly flounder (*Rhombosolea leporina*), snapper (*Pagrus auratus*), blue mackerel (*Scomber australasicus*), rig (*Mustelus lenticulatus*), barracouta (*Thyrsites atun*), spotty (*Notolabrus celidotus*), dab or sand flounder (*Rhombosolea plebeia*), grey mullet (*Mugil cephalus*), jack mackerel (*Trachurus novaezelandiae*), blue cod (*Parapercis colias*), trevally (*Pseudocaranx georgianus*), red mullet (*Upeneichthys porosus*), elephant fish (*Callorhynchus milii*), gurnard (*Chelidonichthys kumu*), red cod (*Pseudophycis bachus*), eagle ray (*Myliobatis tenuicaudatus*), red snapper (*Centroberyx affinis*), skipjack tuna (*Katsuwonus pelamis*), carpet shark (*Cephaloseyllium isabella*), spotted stargazer (*Genyagnus monopterygius*), leatherjacket (*Meuschenia scaber*), porcupine fish (*Tragulichthys jaculiferus*), ihi or garfish (*Hyporhamphus ihi*), short-tailed stingray (*Dasyatis brevicaudatus*), and sunfish (*Mola mola*) (Bray & Struick 2006). Pilchards or sardines (*Sardinops neopilchardus*) were also recorded in Tennyson Inlet as very abundant in the early days and suitable for bait and canning, and in deeper water groper (hapuku) (*Polyprion oxygeneios*) were also common (Archer 2010).

Fish populations in Duncan Bay recorded by intertidal netting over a 33 year study have fluctuated over time in relation to season, temperature, rainfall, day/night and moon state (Bray & Struick 2006). The population variables measured declined between 1971-1986 and 1987-2002 especially in the former period where declines were recorded as 71% decline in weight per fish, 48% length per fish, 70% number of fish caught per tide and 91% decline in weight of fish caught per tide. These declines were thought to be a result of: a large increase in unregulated Foreign Fishing Vessels (FFV) between 1968 (20,000 t) and 1977 (500,000 t); a rapid increase in domestic commercial and recreational fishing and the use of new technology; destruction of nearby benthic communities by trawling and dredging, and; an increase in farmed mussels and wild Pacific oysters (*Crassostrea gigas*) in Pelorus Sound which feed on the plankton base of the food chain (Bray & Struick 2006). A collapse in the dominant species, rig, from 1971-1974 (58% and 65% of the biyearly percent weight per tide) to no rig present from 1979-80 to 1987-88 was followed by the occasional appearance of rig with a low total weight per tide after 1990. The rig appeared to be replaced by kahawai. Increases in abundance recorded more than once were for short-lived species like flounder and grey mullet.

Bray & Struick (2006) noted that FFV were observed in Tennyson Inlet until 1978 when the Exclusive Economic Zone (EEZ) was declared.

> "In 1978 in Tennyson Inlet, Mr R. Winstanley (P.c.1978) saw three FFV trawlers working near Maud Island and Dr E. Twose (p.c.1978) saw a Japanese purse seiner near Maud Island with a net stretched to Richmond Bay [ca.4 km]. One possible effect of the FFVs was noted by Mr N. Andrews (p.c.) of Tuna Bay, who had fished the area since 1955. He stated that before the early to mid 1970s you were guaranteed a snapper meal whenever you went fishing, but not thereafter."

As fish stocks became depleted, not all the pressure on the fish resource of Tennyson Inlet was from FFVs as confirmed by Bray & Struick (2006) and by Chris Guard (pers. comm.) whom recounted of people illegally fishing the area. Anecdotally, illegal practices included trawling at night, fishing in closed areas, the use of dynamite, and nets stretching from Maud Island to the mainland. The deregulation of the inshore fisheries in 1963 led to depletion of inshore fisheries especially between 1965-1975 until recovery in the early 1980s following the introduction of the Quota Management System. The effects of trawling and dredging are thought to have altered benthic habitats:

> "Mr J.H. King-Turner of Canoe Bay, Tennyson Inlet has told us (p.c. 1993) he observed a long term decline in the bottom flora and fauna, including some fish species, of his bay over the previous 30 years. He thought the decline might be due to scallop dredging, bottom trawling, over fishing and the increased number of boats with anti-fouling chemicals on their hulls." (Bray & Struick 2006).

At present Danish seining is prohibited in and around the entire Marlborough Sounds (Baxter 2012). Bottom trawling is prohibited in Queen Charlotte Sound, Tory Channel and inner Pelorus Sound; inside Tawero Point and within Tennyson Inlet and neighbouring Fitzroy Bay and Hallum Cove. Commercial scallop dredging occurs throughout suitable grounds in Waitata Reach down to Maud Island and especially in Ketu Bay. There is relatively little trawling undertaken within the enclosed parts of the Marlborough Sounds (Baxter 2012). The great majority of effort in the Marlborough Sounds is in the outer Sounds from eastern D'Urville Island through to Cape Lambert. As fishers want to avoid ensnaring their trawl gear on emergent rocks and reefs, trawling is unlikely to take place on the steeper sloping bottoms found closer to shore or along the sides of the main channels, thus fishing which is generally located a reasonable distance offshore where the bottom begins to shelve out (Baxter 2012).

Biogenic[9] habitats in Pelorus: The first published shellfish surveys were carried out by Stead (1971a; b) over the summer of 1968-'69 using a shellfish dredge and SCUBA. He reported finding broken shell and "coral" offshore from Skiddaw in the lower Kenepuru consisting of several hundred square yards 45 to 90 metres in ca. 10 m depth. This habitat was commercially dredged for green-lipped mussels. Densities of large mussels in the intertidal exceeded 70 m^{-2} on some exposed rocky headlands in Kenepuru and Nikau Bay, but also occurred individually or in clusters along cobble and boulder-strewn beaches. It is unclear what the "coral" habitat reported by Stead (1971b) was, but it is likely that it may have been formed by rhodolith beds. Rhodoliths are calcified red coralline algae that can form large beds, like those that still occur in Picnic Bay, in the outer Pelorus (Davidson et al.

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[9] Produced from living organisms or biological processes

2011) and off Rock Point, Catherine Cove, D'Urville Island (Handley pers. Observ; Davidson & Richards 2016). Rhodoliths or maerl are thought to be important in providing complex three dimensional structures and habitat for other invertebrates and fishes, and are vulnerable to shellfish dredging (Hall-Spencer et al. 2006). Today, intertidal blue mussels are relatively common covering up to 80% cover in Queen Charlotte Sound when measured as part of Ferry Wake monitoring, whereas in Pelorus green-lipped mussels are almost absent intertidally and blue mussels only achieve as little as 10% cover at some sites (Rob Davidson, pers. comm.). Pacific oysters (*Crassostrea gigas*) also invaded the inner Pelorus after being first recorded in the Marlborough Sounds in 1979 (Jenkins & Meredyth-Young 1979). Pacific oysters became abundant in Kenepuru Sound during the 1970-'80s on stony beaches and rock outcrops, but recently have declined and appear restricted to soft sediment intertidal habitat where they likely cannot be easily predated by oyster borers (*Haustrum* sp.) (J. Jenkins, pers. comm., Handley, pers. observ.).

Other biogenic habitats have been noted in the Pelorus including the headlands of Tapapa Point, Tawero Point and Kauauroa Bay which contain habitat forming bryozoans, sponges, ascidians, horse mussels and hydroids fed by strong tidal currents (Davidson et al. 2011). Horse mussel beds are also found in Clova Bay and in the Bay between Elie Bay and Wet Inlet in Crail Bay, and a tiny sea pen species *Virgularia gracillima* is found in Little Nikau Bay (Davidson et al. 2011). Horse mussels (*Atrina zelandica*) appeared relatively common in Pelorus around the time of early mussel fishing (Stead 1971b). Large surface dwelling shellfish like horse mussels have been described as important ecosystem engineers as they provide settlement surfaces for other species, filter large amounts of water sequestering sediment and nutrients, and modifying neighbouring macrofaunal communities (Hewitt et al. 2002, Norkko et al. 2001, Norkko et al. 2006).

Although seagrass beds may be patchily distributed in the smaller estuaries and bays of Pelorus, for example in Duncan Bay (Bray & Struick 2006), extensive seagrass beds are now only present in the well flushed areas of the lower Havelock estuary between Cullen Point and Shag Point (Stevens & Robertson 2014). At Havelock, saltmarsh extent, consisting mostly of rushlands (95%), has been reduced by 15% since 1999 largely from historic estuary drainage (Lauder, 1987), the removal of ca.50 ha of introduced *Spartina*, reclamation and channelization with ongoing activities such as that in the upper tidal reaches between the Pelorus River channels where drainage and infilling is apparent (Stevens & Robertson 2014).

With the development of scuba diving in the 1960s, the resulting drastic decline in rock lobster (*Jasus edwardsii*) appeared to cause kina (*Evichinus chloroticus*) populations to "explode resulting in major habitat changes to the exposed shores of the outer Sounds" (Clarke 2014). Availability of cheap outboard powered boats later resulted in overfishing of blue cod (Clarke 2014), presumably having other, unmeasured food-chain effects.

History of aquaculture in Pelorus: The artificial culture or aquaculture of shellfish has a long history in Pelorus, much longer than formerly realised. The following newspaper accounts depict the introduction of rock oysters from the North Island to Pelorus Sound for intertidal cultivation in the late 1800s (Handley 2015).

Today, there are well over 500 marine farm sites in Marlborough, most of them within the Marlborough Sounds (MLDC 2014b). The early development of the mussel industry has been well reviewed by Dawber (2004) and will not be elaborated on herein. There is a perception by some farmers that have been involved in the industry from its outset that some of the changes relating to marine farming have been positive. For example, in the later 1970s water clarity was only a few feet, and the seasonal krill blooms, and red and green algal blooms were common, whereas today ‘the water is always clear’ (Clarke 2014). However, sea lettuce (*Enteromorpha* sp.) blooms were only recorded twice in a 33 year intertidal fish netting study (1971-2004) in Duncan Bay, Tennyson Inlet (10% cover) occurring for a sustained period in September 1980 and January 1981 (Bray & Struick 2006). Clarke (2014) commented that farmed mussel stocking densities and growth rates have reduced over time, perhaps reflecting reduced productivity on the land and in the sea. Unfortunately, there are no published data on mussel growth rates prior to 1997 to verify long term changes. There has however been a steady increase in the area of mussel farm development in Pelorus over time (Handley 2015). Analysis of mussel growth rates between 1997 and 2005 however show measured meat yield declined and then recovered, and that yield could be predicted based on modelled particulate nitrogen production data which indicated that the long term changes in mussel growth during that period appeared driven by climate variability rather than overstocking (Zeldis et al. 2013).

Development of early aquaculture and forestry were shaped by various management and legislative processes that sometimes conflicted. For example, in the 1970s the Forest Service had a plan to turn the Sounds into a pine forest, whereas the Lands and Survey Department wanted it to be a National Park (Clarke 2014, Handley 2015). Today, the Sounds landscape may reflect a random mix of decisions made by these various bodies resulting in “pockets of pastoral farms, pine forests, regenerating bush, a ribbon of buildings, with the degraded virgin bush on the tops, and mussel farms along the shore” (Clarke 2014).

2 Methods

2.1 Sediment core collections

CSSI cores: On 11 and 12 March, 2015 sediment cores were collected for Compound Specific Stable Isotope (CSSI) analysis to a depth of approximately 2 m using a vibra-corer developed and operated by Diving Services Ltd., Nelson (Figure 2-1). Sediment cores were collected at two locations: Kenepuru Sound and Beatrix Bay. Within each location, 3 sites were chosen, and at each site, 4 replicate sediment cores were collected (Figure 2-2, Appendix B). These cores were targeted as low-flow, high deposition sites between the 5-10 m bathymetric contours, away from the influence of tidal currents, terrestrial land-slides, and marine farms (Figure 2-2). One core from each site was analysed first to quantify age stratigraphy and sediment accumulation rates (see Section 2.5), and the remaining cores were analysed for CSSI signatures (see Section 2.6).

Mollusc death assemblage (DA) cores: During the collection of the CSSI cores, and subsequent analysis of cores in Kenepuru Sound revealed a lack of green-lipped mussel *Perna canaliculus* (GLMs) shells in the cores initially collected – an interim result that appeared incongruous with reported mussel distribution in the 1960s, that supported a former dredge fishery (Stead 1971a, 1971b). To increase the interpretive power of the CSSI cores and enable a Kenepuru Sound-wide picture of long-term ecological change, on 16 November 2015, 4 replicate cores were collected at each of 3 sites closer to the shoreline, where former mussel beds were reported to occur (Figure 2-2, Appendix C). The location of DA cores were targeted at ca.5 m depth near the base of the subtidal slope descending from the shoreline, where the seafloor levels off. The rationale for this approach was to sample soft sediments as close as possible to the hard shoreline where dense GLM beds historically occurred (Stead 1971a, 1971b). One core from each site was analysed first to quantify age stratigraphy and sediment accumulation rates (see Section 2.5.3) and the remaining cores were analysed for mollusc death assemblage (see Section 2.7)[10].

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[10] Note: as the inshore coring site in Beatrix Bay (BT1-4) proved unsuitable for CSSI analysis due to very low fine mud content, one of the cores from Poison Point was analysed for CSSI signatures, leaving only 2 cores from PP to be analysed for mollusc DA.

Figure 2-1: Sediment core being retrieved at the side of the vessel showing soft sediment on the outer core (left). A core from the upper Kenepuru that extruded on the vessel deck after failure of the 'core-catcher'. The top of the core is in the foreground (right)**.**

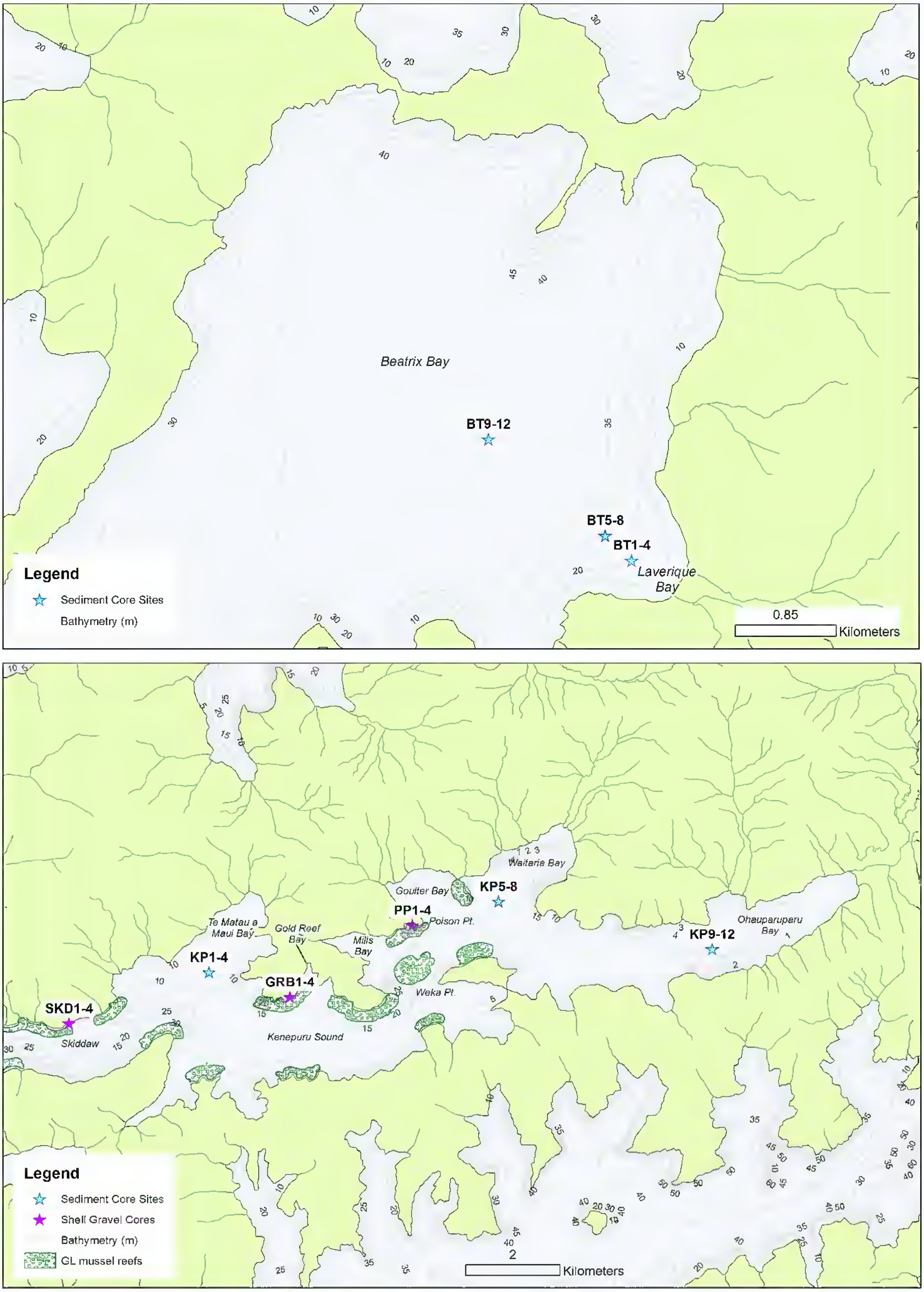

Figure 2-2: Location of core collection sites in Beatrix Bay (top) and Kenepuru Sound (bottom), Pelorus Sound. Blue stars denote CSSI coring sites (Appendix B), pink stars are shell gravel coring sites (Appendix C), and green polygons are historic mussel reef sites mapped by Stead (1971a, b).

2.2 Core processing

The sediment cores are processed in two stages: a ‘first-cut’ analysis of top layers (0 - 60 cm) and a ‘second-cut’ analysing lower down the cores (and/or intermediary layers), once the dates of the upper layers had been established, with a total of 15 layers in each core analysed.

The ‘first cut’ or top 60 cm of the cores from CSSI were sampled by cutting the downpipe casing and splitting each core longitudinally. One-centimetre increments of sediment were then sampled at each of nine levels (0, 2, 4, 10, 20, 30, 40, 50, and 60). During this sampling, a smear of fine sediment was retained for later laser size analysis (see Section 2.4). These samples were then dried to a constant weight, weighed, and the shell material sieved from the sample using a 2 mm sieve. A portion of the fine fraction was sent to the Institute of Environmental Science and Research (ESR) for lead (Pb^{210}) and caesium (Cs^{137}) radiometric dating analyses. The remaining portion was sent to University of California, UC Davis for CSSI fatty acid analysis. The shell portion of the samples of the representative layers (e.g., pre-human, early European colonisation, post-mussel fishing, post-mussel aquaculture development, and modern including forestry effects) was sent to NIWA Nelson laboratory for weighing and identification to lowest practical taxonomic level.

Once the results of the radiometric dating by ESR were obtained, further samples were extracted down-core for CSSI analysis at a maximum of 15 levels per core/site (i.e., 15 levels x 3 sites per Pelorus location). For the DA cores, the number of levels was reduced to a total of 9 levels.

To estimate the maximum age of the sediments at the base of the cores, during the ‘second-cut’ of the cores (ca. September 2015), 2 shells from near the base of each core collected were sent to the University of Waikato’s Radio Carbon Dating Laboratory for dating using Accelerator Mass Spectrometry (AMS) radiocarbon dating of C^{14}.

Unused cores from each site were stored, as a backup.

2.3 Contaminant source sediments collections

Thirty source soil/sediment samples were collected across a range of land and marine contaminant sources between 21 April and 5 May 2015, to identify and constrain the sediments in the cores (Figure 2-4, Appendix D). Where possible, to better inform the analysis of the sediments using CSSI, 3 replicate samples of each soil/sediment were collected across a range of sites from inner to outer Pelorus Sound to provide some spatial resolution and information on the natural variation of the resulting contaminant source CSSI signatures. A Van-Veen grab was used to collect marine surface sediment samples (Figure 2-3). Where samples could not be readily collected (e.g., recently milled *Pinus* forest[11]), samples were collected in nearby catchments (Figure 2-4).

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[11] Forestry Health and Safety guidelines dictated that to enter recently milled areas in Pelorus, NIWA staff would have to be escorted on and off site, a timeframe/logistical constraint that would have hindered progress on sample analyses. Instead, sites were accessed on public, road reserve, and private land in neighbouring catchments under the assumption that the milled *Pinus* signatures are very distinct as compared with other land-use practices, and any difference derived from catchment would be minimal. This was later confirmed to be the case (see Section 2.6.3).

Figure 2-3: Example of marine sediment grab sampling beneath a mussel farm, inner Kenepuru.

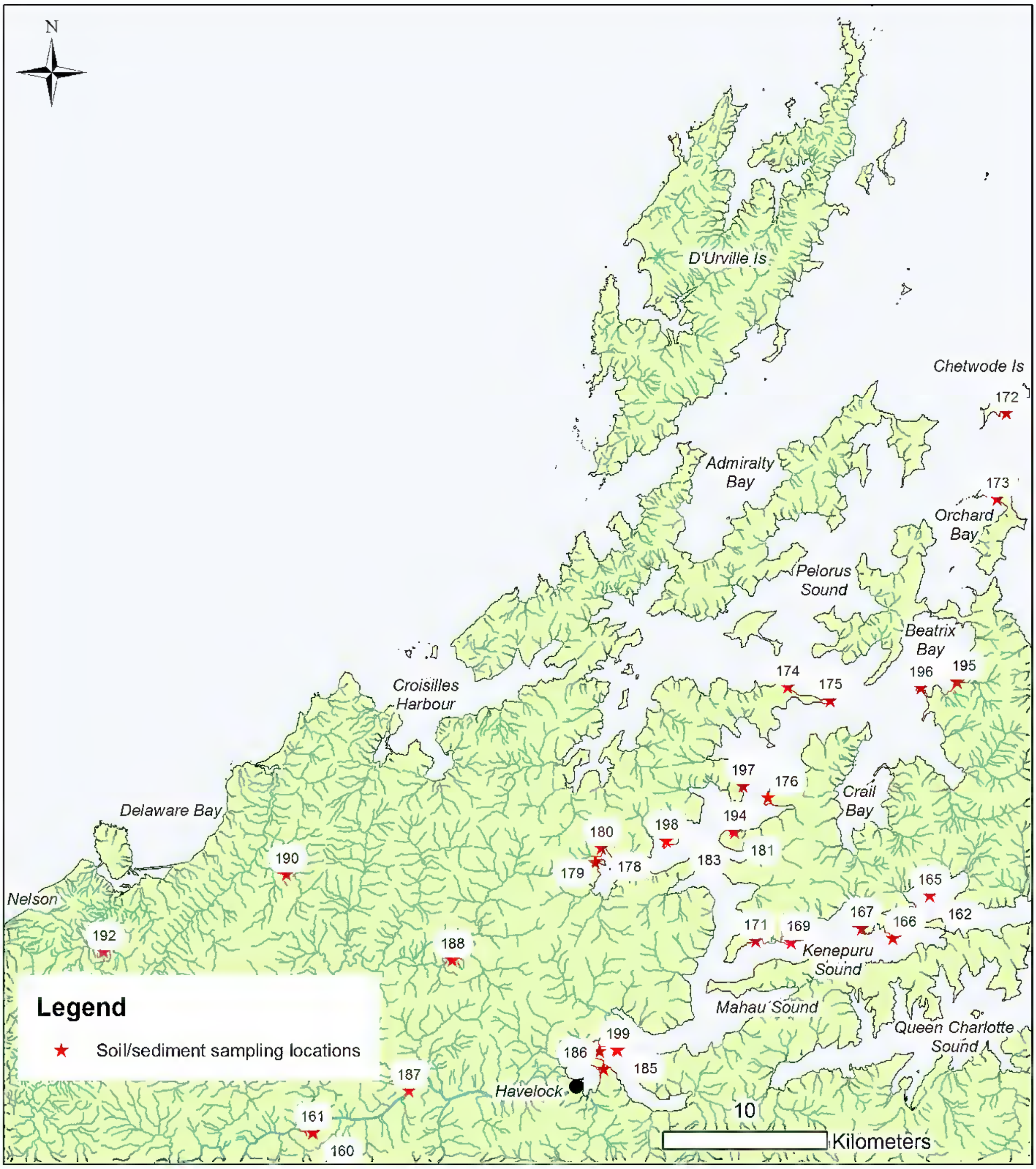

Figure 2-4: Location of contaminant sediment/soils labelled by waypoint (see Appendix D).

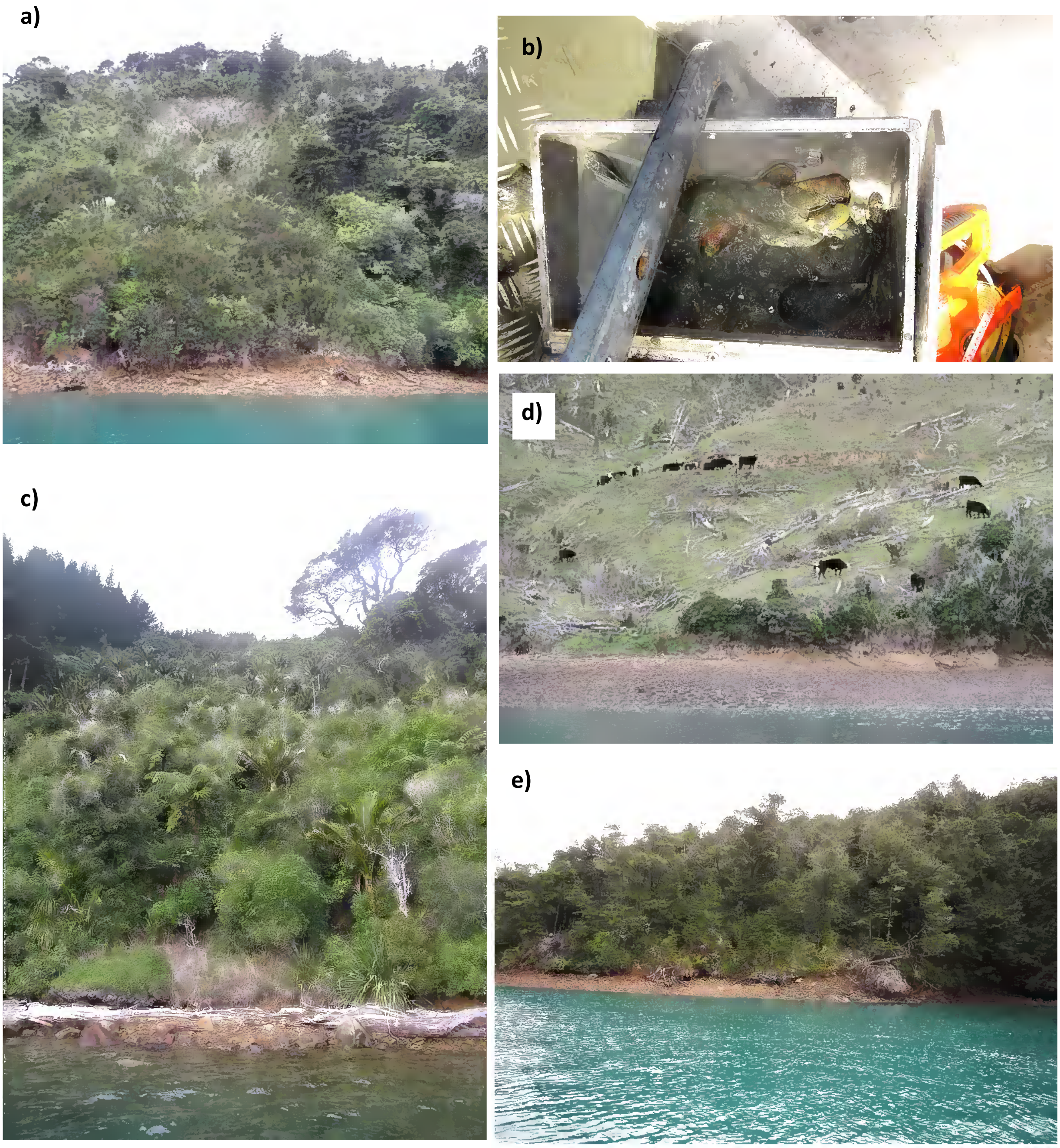

Figure 2-5: Examples of sites sampled for contaminant source soils/sediments: a) regenerating slip; b) marine sediment grab sample from beneath spat farm, Orchard Bay; c) regenerating nikau grove Yncyca Bay; d) Sounds foreshore reserve bordering farmland-used for beef grazing, Skiddaw, Kenepuru; e) virgin Beech forest, north west of Schnapper Pt., Kenepuru (for locations, see Appendix D, Figure 2-2).

2.3.1 Soil CSSI sample analyses

Soil and Source samples and sediment samples were subsampled, freeze dried and (depending upon sample) sieved prior to CSSI processing (see Section 2.6). Between 9 and 74g of sample was weighed and the fatty acids (FA) extracted with the solvent dichloromethane. FA's extracted were converted to methyl esters, then shipped to University of California, UC Davis for CSSI analysis. A subsample of the source soils/sediments were treated with 1N HCl to remove carbonates, and rinsed with reverse osmosis water and shipped to NIWA Wellington's isotope lab for bulk C ($\delta^{13}C/^{12}C$) isotope analysis.

2.4 Sediment composition

The Kenepuru and Beatrix Bay CSSI sediment cores were processed at NIWA's Hamilton campus, where they were prepared for x-ray imaging and sub-sampling for dating, stable isotope analysis and determination of basic sediment properties as described below. Sediment cores collected from the locations of historical mussel reefs were sub-sampled at NIWA Nelson, with processing for dating and source determination conducted at NIWA Hamilton.

Sediment cores selected for radioisotope dating were cut open length-wise using a skill saw with a 125 mm diameter blade. After cutting the core barrels along their entire lengths on both sides, thin stainless steel sheets were pushed through the sediment to split the core into two separate halves. The cores were first logged, including description of any obvious sediment layers before sub-sampling for radioisotope, particle size and bulk density analyses.

Information on the composition and stratigraphy of the sediment cores was provided by x-ray imaging (Figure 2-6). An x-ray image or x-radiograph provides information on the fine-scale sedimentary fabric of sediment deposits. Density differences (due to particle size and composition, porosity) between layers of silt and sand or animal burrows that are infilled with mud make these often subtle features easily recognisable in the x-ray image even though they may not be visible to the naked eye.

Figure 2-6: NIWA digital x-ray system, with a sediment slab mounted on the detector plate ready for imaging. (Photo: Ron Ovenden, NIWA Hamilton).

X-radiographs were made of each sediment core prior to dating. To do this, each core was first split lengthways and sectioned into 40 cm long and 2 cm thick longitudinal slabs. These slabs were then imaged using a Varian PaxScan 4030E amorphous silicon digital detector panel (Figure 2-6). X-rays were generated using an Ultra EPX-F2800 portable x-ray source with a typical exposure of 25 mAs (milliamp seconds) and 50–60 kiloelectron Volts (keV). The raw x-ray images were post-processed using the Image-J software package.

Particle size distributions (PSD, 0.1–300, 10–2000 µm) of sediment-core samples were determined using an Eye-Tech stream-scanning laser system, employing the time-of-transition (TOT) method to measure the diameters of individual particles (e.g., Jantschick et al. 1992).

Dry-bulk sediment density (ρ_b) profiles were determined for each core. The ρ_b was calculated as the dry mass per unit volume of sediment in each 1-cm thick core slice prepared for radioisotope dating. The slice volume was 78 cm^3 for the 10-cm diameter cores. Samples were processed by first weighing on a chemical balance to the nearest 0.01 g, dried at 70°C for 24 hours and reweighed to obtain the dry-sample weight. The ρ_b is expressed in units of grams per cubic centimetre (g cm^{-3}) and was calculated from the dry sample weight and sample volume.

The ρ_b reflects the bulk characteristics of the sediment deposit, in particular sediment porosity (i.e., proportion of pore-space volume) and particle characteristics, such as size distribution and mineralogy. For example the ρ_b of an estuarine sand deposit is of the order of 1.5–1.7 g cm^{-3}, whereas a mud deposit with high water content can typically have a ρ_b of ~ 0.5 g cm^{-3}.

2.5 Radioisotope dating and sediment accumulation rates (SAR)

Sediment accumulation rates (SAR) were estimated from dated sediment cores based on the radioisotope activities of lead-210 (^{210}Pb), caesium-137 (^{137}Cs) and beryllium-7 (^{7}Be) in the sediments, as well as radiocarbon dating (^{14}C) of shell material preserved in the cores. These SAR estimates, expressed as time-averaged values in millimetres per year (mm yr^{-1}), are used in the present study to: (1) quantify changes in the rates of estuary infilling over the last several thousand years, which includes the human settlement of New Zealand around ~1,300 AD (Wilmshurst et al. 2008); and (2) correct the $\delta^{13}C$ stable isotope values of the bulk carbon and fatty acid biotracers. These dating methods are described below.

2.5.1 AMS ^{14}C dating

Pre-human sediment accumulation rates (SAR) were estimated by atomic mass spectrometry (AMS) radiocarbon (^{14}C) dating of marine/estuarine carbonate shell valves preserved in the sediment cores. Individual and articulated valves of *Mactra* sp. (estuarine trough shells), *Cyclomactra ovata* (Oval trough shell), *Saccostrea* sp. (NZ oyster), *Talochlamys* sp. (fan shell), *Austrovenus stutchburyi* (cockle) were collected from the Kenepuru cores. The Beatrix Bay cores did not contain shell material suitable for AMS dating. Shell valves of *Dosina* sp., *Zygochlamys delicatula* (southern queen scallop), *Perna* (green-lipped mussel: GLM) and *Ruditapes largillerti* were also collected from the mussel reef cores for dating (Table 2-1). Two samples of whole shell valves collected from individual animals in each of the Kenepuru cores were dated to ensure robust dating of sediment layers.

Suspension feeding bivalves, including the New Zealand cockle are particularly suitable for radiocarbon dating as ^{14}C concentrations in cockles are similar to those found in shellfish previously used in accounting for marine reservoir effects (Hogg et al. 1998) using the marine ^{14}C calibration curve (Petchy et al. 2008).

Table 2-1: Summary of bivalve shell sub-sampled from the Kenepuru Sound cores and submitted for AMS ^{14}C dating.

Core	Depth increment (cm)	Sample type	Wk number
KP-4	136–137	*Mactra* sp. shell valve	Wk-42186
	138–141	*Saccostra* sp. shell valve	Wk-42187
KP-6	199–200	*Talochlamys* sp. shell valve	Wk-42188
	204–206	*Talochlamys* sp. shell valve	Wk-42189
KP-10	76–80	*Cyclomactra ovata* shell valve	Wk-42190
	77–81	Cockle (*Austrovenus stutchburyi*) shell valve	Wk-42191
	137–138	*Talochlamys* sp. shell valve	Wk-42192
	137–138	*Cyclomactra ovata* shell valve	Wk-42193
PP2	132–133	*Dosina* shell valve	Wk-43477
	136–137	*Zygochlamys deliculata* shell valve	Wk-43476
GRB2	79–80	*Perna* shell fragments	Wk-43479
	118–119	*Zygochlamys deliculata* shell valve	Wk-43478
SKD1	117–118	*Ruditapes largillierti*	Wk-43841
	120–121	*Dosina*	Wk-43480

Shell samples were acid-washed in 0.1 N hydrochloric acid, rinsed and dried prior to AMS analysis. The AMS dating results are expressed as conventional ages in years before present (B.P., 1950 AD, Stuiver & Polach 1977). Duplicate samples were analysed from the same depth interval in several cores to evaluate the likelihood of shell material being reworked from its original stratigraphic position.

2.5.2 ^{210}Pb, ^{137}Cs and ^{7}Be dating

Sediment accumulation rates (SAR) were estimated from radioisotope activities measured in each core. Radioisotopes are strongly attracted to the surfaces of clays and silt particles and this makes them particularly useful as "mud meters" (Sommerfield et al. 1999).

The sediment cores collected from the Pelorus Sound were dated using the radioisotopes caesium-137 (^{137}Cs, ½ life 30 years) and lead-210 (^{210}Pb, ½ life 22.3 years). Sediment accumulation rates were calculated from the vertical activity profiles of ^{210}Pb and ^{137}Cs. The activities of the cosmogenic radioisotope beryllium-7 (^{7}Be, $t_{1/2}$ 53 days) were also measured in the core samples. ^{7}Be is particle reactive, binding to fine sediment, which tends to be concentrated in aquatic systems, making it a useful sediment tracer in fluvial-marine systems at seasonal timescales (Sommerfield et al. 1999). In the present study, ^{7}Be is used to provide information on the depth and intensity of sediment mixing in the surface-mixed layer (SML).

Sediment dating using two or more independent methods offsets the limitations of any one approach. This is important when interpreting sediment profiles from estuaries because of the potential confounding effects of sediment mixing by physical and biological processes (Smith, 2001). Sediment mixing by physical and biological processes in the surface mixed layer (SML) results in uniform radioisotope activities. Because of differences in ^{7}Be and ^{210}Pb decay rates, these radioisotopes provide quantitative information about the depth and rate of sediment mixing. This is important when considering the fate of fine-sediments in estuaries or coastal waters.

Radioisotope activities expressed in S.I. units of Becquerel (disintegration s^{-1}) per kilogram (Bq kg^{-1}) were determined by gamma-spectrometry. Dry samples (~50 g) were counted for 23 hrs using a Canberra Model BE5030 hyper-pure germanium detector. The unsupported or excess ^{210}Pb activity (^{210}Pb$_{ex}$) was determined from the ^{226}Ra ($t_{1/2}$ 1622 yr) assay after a 30-day ingrowth period for ^{222}Rn ($t_{1/2}$ 3.8 days) gas in samples embedded in epoxy resin. Gamma spectra of ^{226}Ra, ^{210}Pb and ^{137}Cs were analysed using Genie2000 software.

The uncertainty ($U_{2\sigma}$) of the ^{210}Pb$_{ex}$ activities was calculated as:

$$U_{2\sigma} = \sqrt{({}^{210}\mathrm{Pb}_{2\sigma})^2 + ({}^{226}\mathrm{Ra}_{2\sigma})^2} \qquad (1)$$

where ^{210}Pb$_{2\sigma}$ and ^{226}Ra$_{2\sigma}$ are the two standard deviation uncertainties in the total ^{210}Pb and ^{226}Ra concentrations at the 95% confidence level. The main source of uncertainty in the measurement of radioisotope activities relates to the counting statistics (i.e., variability in the rate of radioactive decay). This source of uncertainty is reduced by increasing the sample size.

The ^{210}Pb$_{ex}$ profiles in cores are used to determine the time-averaged SAR from regression analysis of natural log-transformed data and validated using independent SAR estimates derived from ^{137}Cs profiles. The ^{137}Cs SAR was based on the maximum depth of ^{137}Cs in each core and included a correction for sediment mixing in the surface layer based on the maximum depth of the ^{7}Be profiles. In NZ, ^{137}Cs deposition from the atmosphere was first detected in 1953 (Matthews 1989).

2.5.3 Sediment accumulation rates (SAR)

Time-averaged SAR were estimated from the unsupported ^{210}Pb (^{210}Pb$_{ex}$) concentration profiles preserved in cores. The rate of ^{210}Pb$_{ex}$ concentration decrease with depth can be used to calculate a net sediment accumulation rate. The ^{210}Pb$_{ex}$ concentration at time zero (C_0, Bq kg^{-2}), declines exponentially with age (t):

$$C_{\mathrm{t}} = C_0 e^{-kt} \qquad (2)$$

Assuming that within a finite time period, sedimentation (S) or SAR is constant then $t = z/S$ can be substituted into Eq. 2 and by re-arrangement:

$$\frac{\ln\left[\frac{C_t}{C_0}\right]}{z} = -k/S \qquad (3)$$

Because ^{210}Pb$_{ex}$ concentration decays exponentially and assuming that sediment age increases with depth, a vertical profile of natural log(C) should yield a straight line of slope $b = -k/S$. We fitted a linear regression model to natural-log transformed ^{210}Pb concentration data to calculate *b*. The SAR over the depth of the fitted data is given by:

$$S = -(k)/b \tag{4}$$

An advantage of the ^{210}Pb-dating method is that the SAR is based on the entire ^{210}Pb$_{ex}$ profile rather than a single layer, as is the case for ^{137}Cs. Furthermore, if the ^{137}Cs tracer is present at the bottom of the core then the estimated SAR represents a minimum value.

The ^{137}Cs profiles were also used to estimate time-averaged SAR based on the maximum depth of ^{137}Cs in the sediment column, corrected for surface mixing. The ^{137}Cs SAR is calculated as:

$$S = (M - L)/T - T_0 \tag{5}$$

where S is the ^{137}Cs SAR, M is the maximum depth of the ^{137}Cs profile, L is the depth of the surface mixed layer (SML) indicated by the ^{7}Be profile and/or x-ray images, *T* is the year cores were collected and T_0 is the year (1953) ^{137}Cs deposition was first detected in New Zealand.

Radiocarbon dates (^{14}C) were also obtained from cores KP-4, KP-6 and KP-10 from various bivalve shells from different individuals to obtain independent dates for the sample depth horizon (e.g., 136–137-cm), using AMS dating

The conventional ages BP estimated by ^{14}C AMS dating for the two shell samples from each core are very similar (within 20-80 years), with small potential errors, so that we can have confidence in the ages at the respective sampling depths. These dates were used to: (1) calculate time-average SAR from the dated horizon to the base of the excess ^{210}Pb-dated (i.e., early 20th century) sediments; and (2) date sediment samples previously analysed by NIWA for bulk δ^{13}C and (CSSI) FAME stable isotope tracers.

The time-averaged ^{14}C SAR for the two samples were 0.13 and 0.14 mm/year respectively. These values largely reflect pre-human rates, given that substantial catchment deforestation did not begin until the mid-1800s (Handley 2015).

2.6 Source apportionment

The general concepts of CSSI sediment source tracing are summarised in Section 1 and described in detail in Appendix E. There are two fundamental decisions required in any sediment source tracing study:

- **Which tracers to use**? This decision should be based on the ability of a suite of tracers to discriminate potential sediment sources. In the present study, the δ^{13}C values of Fatty Acids (FAs) are used to inform which FA to include.
- **Which potential sources to include**? Where possible, the definition of sources should include a statistical evaluation of the differences in the δ^{13}C FA values of each potential source. Individual sources should be combined if they cannot be distinguished from each other on the basis of parametric (e.g., difference of means, median %ile) and/or non-parametric tests. A further key requirement for the selection of tracers and potential sources is that they must conform to the isotopic polygon principle, which is the basis of isotopic mixing models. Specifically, the δ^{13}C values of the mixture samples

must be enclosed with a polygon (two tracers) or hyper-volume (three or more tracers) defined by the $\delta^{13}C$ values of potential sources.

Decisions on both varied between fluvial and estuarine mixtures in line with analytical good practice (e.g., Phillips et al. 2014). The methods employed in the present study to make these decisions on which tracers and sources to include in the isotopic modelling are described below.

2.6.1 CSSI methodology

The CSSI technique uses two different sets of stable isotope signatures — the bulk $\delta^{13}C$ values and percentage carbon (%C) of the whole soil, after acidification to remove inorganic carbonates, and the $\delta^{13}C$ values of individual FAs bound to soil particles after these have been extracted from the unacidified soil samples. Because the FAs are highly polar, they cannot be analysed directly as they will bind to the gas chromatograph (GC) column during analysis. Consequently, they must be derivatised into their methyl esters, which are non-polar, using a catalyst such as boron trifluoride (BF_3) in methanol (MeOH). Each FA methyl ester (FAME) consists of the FA carbons plus one carbon from the MeOH used for the derivatisation step. The analytical values from the GC-combustion-isotope ratio mass spectrometer (GC-C-IRMS) were corrected for the added carbon in a methyl-group from methanol to obtain the CSSI value for each FA using the equation:

$$\delta^{13}C_{FA} = (\delta^{13}C_{FAME} - (1-X) * \delta^{13}C_{Methanol})/X \qquad (6)$$

where FA is the fatty acid and *X* is the fractional contribution of the FA to the FAME. *X* can be calculated from the number of carbons in the FA molecule divided by the number of carbon atoms in the FAME derived from the FA. For example, the FA stearic acid (C18:0) has 18 carbon atoms whereas the FAME produced, methyl stearate, has 19 carbon atoms, including one added carbon from the methanol and thus has an *X* value of 18/19 or 0.9474. $\delta^{13}C_{FA}$ is the FACSSI value corrected for the methyl- group, $\delta^{13}C_{FAME}$ is the uncorrected isotopic value for the FAME and $\delta^{13}C_{Methanol}$ is the isotopic value for the methanol used in the derivatisation step.

The CG-C-IRMS analysis uses FA standards, both internal and external, of known CSSI $\delta^{13}C$ value for the calibration of the soil FAMES and uses the retention times of the standards to confirm the identity of each FA being measured. The methyl-group correction was applied to all FAMEs.

Several corrections were applied to the raw data to enable direct comparison of data between batches and for samples of varying ages (in the case of the sediment cores):

- Methyl-group (MeOH, FAME only) corrections to the $\delta^{13}C$ signature of each batch.
- Inter-batch corrections for individual FAs were applied relative to the main batch containing soil samples using a NIWA FAME standard analysed with each batch.
- These inter-batch and methyl-corrected $\delta^{13}C$ data were finally adjusted for the Suess Effect to the year 2015 AD (i.e., sediment cores only). The Suess Effect describes the progressive depletion of the atmospheric CO_2 $\delta^{13}C$ signature, which is largely due to the combustion of fossil fuels since the early 1700s. This process also results in a depletion of soil $\delta^{13}C$ signatures as plants utilise CO_2 in photosynthesis and subsequently label potential soil sources (Verburg 2007, Gibbs et al. 2014). The annual rate of $\delta^{13}C$ CO_2 depletion in New Zealand is -0.025‰ (per mil) per year (source: NIWA).

This Suess Effect correction is critical to enable direct comparison of sediment deposits with sources of varying ages, which has resulted in a ~2.15‰ depletion in $\delta^{13}C$ values since 1700. Full details of the CSSI method are included in Appendix E.

2.6.2 Modelling of sediments sources using the SIMM "MixSiar"

MixSIAR was used to model the spatial surface data and the temporal data from the sediment core slices. MixSIAR is a recently developed Bayesian isotopic mixing model, which incorporates advances in mixing model theory and builds on the earlier MixSIR and SIAR models (Stock & Semmens, 2015, 2016). Model-fitting to the observed data is based on a Markov Chain Monte Carlo (MCMC) method whereby the isotopic proportions of potential sources are estimated by repeated random sampling and discarding those which are not "probabilistically consistent with the data" (Phillips et al. 2014). Subsequent estimates are required to be similar to previous ones, thereby creating a Markov Chain (Phillips et al. 2014). The model output consists of a sample of the posterior proportions derived from the MCMC simulation. The outputs represent true probability distributions of source proportions that can be summarised by various descriptive statistics, including the 95% credible interval.

MixSIAR includes two diagnostic tests to determine convergence of the MCMC on the posterior distributions for all variables in the model:

- Gelman-Rubin test requires more than one MCMC to be calculated (default = 3), with a value of 1 at convergence. A value of less than 1.1 is generally acceptable. In the present study, most model variables had G-R values of less than 1.05 (Stock and Semmens 2015).
- Geweke test. A two-sided z-test comparing the means of chain segments. At convergence these means should be the same, with large z-scores indicating rejection (Stock and Semmens 2015).

In the present study the MCMC settings in MixSIAR were: three chains, chain lengths of 300,000, "burn in" of 200,000 and "thin" value of 100. This generated model output containing 3000 samples of posterior source proportions (sum = 1). A continuous effects model, with a process only (i.e., $n = 1$) error structure, was employed to estimate the posterior distributions of sources for each individual sediment mixture sampled from the dated cores. The process-only error structure implements the MixSIR model (Moore & Semmens 2008) within the MixSIAR suite, so that uncertainty includes the source variance only and no distinction is made from sources of variance associated with the trophic discrimination factors (TDF) (Stock & Semmens 2015, 2016). Specification of TDF to account for differences in the isotopic values of consumers' tissues and diet is a major source of uncertainty in estimating source contributions in food-web applications (Phillips et al. 2014, Stock & Semmens 2016). In the context of the present study, the fact that TDF are not required for sediment tracing studies, as well as the application of historical information to constrain potential sources, are key advantages.

Bayesian estimates of source proportions can be informed by reliable priors based on data and thereby constrain the model and reduce uncertainty. For example, in food web studies, the gut contents of fish (i.e., prey species and relative abundance) can be used to construct priors in MixSIAR. In the present study, reliable/semi-quantitative information on the relative contributions of various sediment sources was unknown so that an "uninformative prior" was applied. An uninformative prior is one where all combinations of isotopic proportions (sum = 1) are equally likely (Stock & Semmens 2015).

2.6.3 Selection of sources and tracers

The selection of sources to be used in the SIMM is critical to the credibility of the results obtained. Best practices for the use of SIMM are reviewed by Phillips et al. (2014). Key recommendations include: (1) selecting potential sources in an informed way, based on prior information using three replicates; (2) use of isotopic biplots to ensure that mixtures fall within potential source polygons; (3) combine sources if sample variability is such that different sources cannot be distinguished based on parametric tests (e.g., difference of means, median %ile) and non-parametric statistical tests. Statistical analysis can also be used to determine the level of discrimination of each different source provided by each tracer (e.g., FA); (4) incorporate uncertainties; and (5) report distributions of source proportion estimates. Ultimately, whatever methods are used, the selection of potential sources and tracers must conform to the isotopic biplot polygon principle, where the mixture must be enclosed with the polygon area (two tracers) (Figure 2-7) or hyper-volume (three or more tracers) defined by the isotopic values of potential sources and the range of the standard deviations of the three replicate values.

In this study, the selection of sources and tracers were achieved using an array of polygon biplots (two tracers) to test conformity of the sediment mixtures. In all cases the best compliance with the isotopic biplot polygons was achieved with FA isotopes from C18:0 to C24:0, a total of 6 potential isotopes. On a site-by-site basis, choice of these isotopes was found to vary slightly such that any one of these isotopes, if included, would cause the polygon test to fail (i.e., the mixture lay outside the polygon). In each case, the isotope that caused the biplot failure was excluded while the rest were used in the modelling.

The same set of isotopes tracers were used on all core mixtures at that site. Surface spatial mixture samples were individually assessed by the polygon test for the best range of isotopes, as above.

The selection of potential sources was also based on the polygon tests along with test modelling.

For this study, the request was made to use as many potential sources as possible / practical in the modelling. Unfortunately, that approach can compromise the model output where the tracer isotopic signatures for some sources are similar or there are ‘distant’ source signatures that are obscured from the mixture by ‘closer’ source signatures (e.g., Figure 2-7A), and it is better to reduce the number of potential sources focussing on the major sources or specific sources that may be important or of particular interest.

In the example polygon below (Figure 2-7A) there are 11 potential sources contributing soil to the sediment mixture. Some of these have similar tracer signatures and can be combined as indicated by the red rings (Figure 2-7B). The logic behind combining these sources is that, first, in this isotope pair biplot, beef/dairy and manuka sources have almost identical isotopic signatures and are therefore indistinguishable. In different isotope pairs tested, there were small degrees of separation but not enough to warrant using these sources separately. Secondly, the beef/dairy farms may be running stock through land recently cleared of manuka bush (e.g., Figure 2-5D). That could be the reason these two source soils have such similar isotopic signatures.

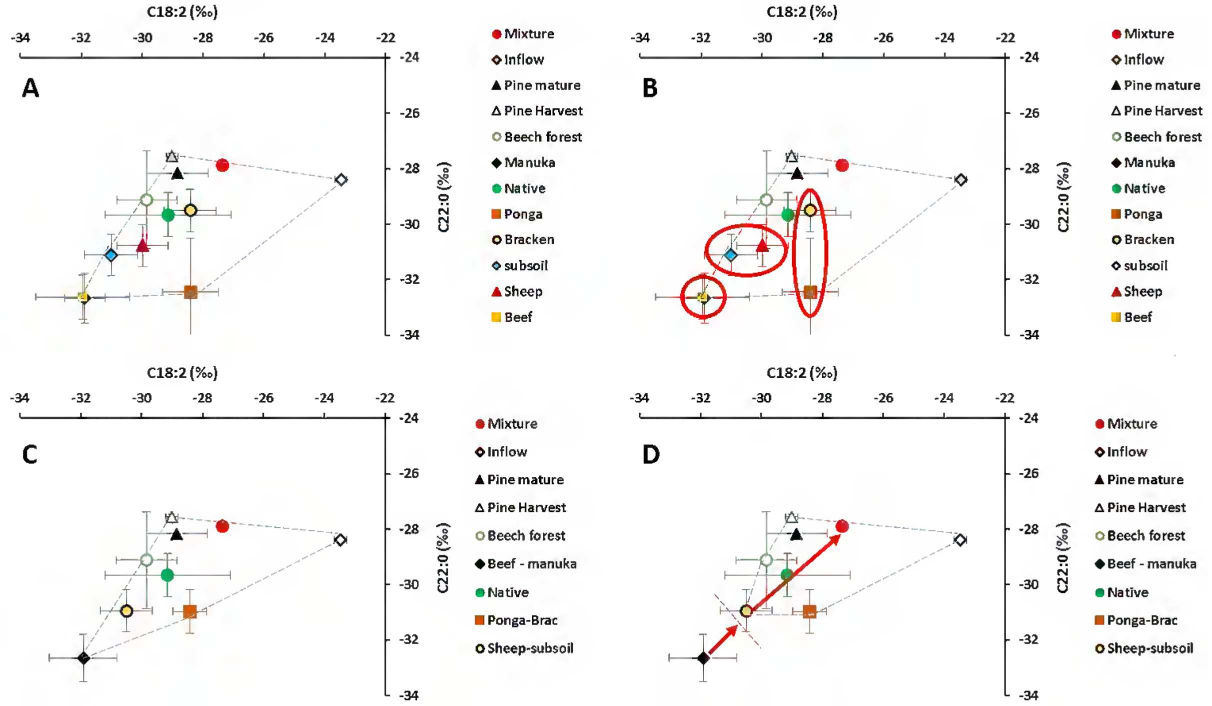

Figure 2-7: Example of the use of polygon testing to identify usable sources for different isotope tracers. A) All sources relative to the mixture (Kenepuru Top) enclosed in a polygon (dashed line), B) circles enclose sources that can be combined, C) The resultant set of sources enclosed in a polygon, and D) the reduced polygon that excludes the dairy source. (See text for logistics behind these actions).

Information about the Pelorus Sounds (section 1.1) indicates that clearance of the native forest by logging and "match farming" each summer leaving bare, burnt, steep hillsides which, along with road slips, were probably the main source of the subsoil source signature. Land clearance was followed by establishment of pasture for sheep farming in the 1900s. Because of this, it would be reasonable to combine sheep and subsoil data (Figure 2-7B). It would also be reasonable the combine ponga and bracken as these are both 'ferns' that colonise disturbed ground. However, it is clear that ponga can easily be distinguished from bracken (Figure 2-7A), so that combination should not be made.

Once the combinations have been made, they would be tested in a new polygon (Figure 2-7C). Here it is apparent that there is a phenomenon where the more distant sources are obscured from the mixture by sources closer to the mixture. The beef-manuka combined signature has no direct line of influence to the mixture, as indicated by the arrows, and therefore that source can be excluded from the modelling (Figure 2-7D).

The preliminary test modelling using beef/dairy and manuka as individual sources demonstrated that land-use associated with beef/dairy was not a substantial source of sediment in any mixture. Consequently, the beef/dairy source was not included in any subsequent modelling run[12]. As a prior for the MixSIAR modelling, is only a relatively recent (10s of years) land-use in the Pelorus Sound compared with sheep farming, which has been present since the land was first cleared in the mid- to late- 1800s. There will be some sediment from the dairying/beef source in the Pelorus Sound but it is hasn't become a substantial source, yet.

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[12] The low contribution from beef pasture is consistent with dairy farming typically occupying low sloping land, which experiences minimal erosion.

Consequently, the sheep pasture source, although minor, was retained in the modelling along with all native forest and indigenous plant species e.g., beech forest, non-beech native forest, ponga, bracken and manuka to accommodate the request to use as many sources as practical.

Another possible combination for use in the modelling would be pine mature with pine harvested However, while the isotopic values of these two sources are sufficiently close to allow combination (Figure 2-7A), prior knowledge is that only harvested pine produces substantial amounts of sediment (i.e., up to 20 times as much as from mature pine). Consequently, only the harvested pine signature was used in the MixSIAR modelling.

Pine forestry was introduced in the 1900s and is potentially a major source signature in the surface samples during, and for the 3-5 years after harvest, until canopy closure. At all other times it will be a minor source signature. Consequently, there is an expectation to find high proportions of pine in different layers in the sediment cores corresponding with periods when pine harvesting has occurred in the past.

Because both sheep farming and pine forestry were not part of the natural landscape in Pelorus Sound before European settlers arrival, these two sources were excluded from the modelling of historical changes in land-use down the sediment cores before the mid-1860s.

Because Pelorus Sound is a drowned river valley system, it has a large river system with the inland end flowing along the main channel to the sea, a distance of about 22 km. The hydrodynamics in Pelorus Sound has been described by Carter (1976) and Gibbs et al. (1991) who allude to the surface low salinity water layer flowing out of the Sound while the more saline oceanic water moves into the Sound along the bottom in a “conveyer belt” type of flow pattern (see also Broekhuizen et al. 2015). Under storm conditions, the surface freshwater layer carries a substantial load of terrigenous sediment from the Pelorus River system out of the Sound, depositing that material along the length of the Sound and into the side embayments such as Kenepuru Sound at the inner end, the Beatrix Bay-Clova Bay-Crail Bay complex in the middle and to the Chetwode Islands at the sea entrance to the Sound. This results in an inflow sediment signature which occurs throughout Pelorus Sound. Consequently, the CSSI signature of the surface sediment samples collected at the Chetwode Island were not significantly different from the CSSI signature of the inflow sediment collected in the Havelock Estuary and the Chetwode site was regarded as a sink rather than a source. For modelling purposes, the Havelock Estuary sample characterised by the sediment trapped in seagrass beds, was always used as the inflow source sediment in the modelling. This Havelock Estuary sediment source, originating from the Pelorus and Kaituna Rivers was hereafter referred to as ‘Havelock inflow’. This ‘Havelock inflow’ therefore represents a unique source in its own right, as it represents the portion of sediment derived from the sum total of all sources deposited at the Havelock Estuary delta, that was remobilised by flood scour, waves and tidal currents and transported and deposited at our coring sites over time.

2.7 Mollusc death assemblage (DA) analysis

2.7.1 Beatrix and Kenepuru CSSI cores

The material remaining on the 500 µm sieve processed from the 1 cm slices of sediment sampled from the cores for the CSSI analyses (above), was oven dried (70°C) and weighed. Large mollusc shells were identified to lowest practical taxonomic level, and weighed, with the remainder of the shell gravel material also weighed.

2.7.2 Kenepuru mussel reef cores

The shallow Kenepuru cores that targeted historic mussel reef sites, contained a greater quantity of shell and rock gravels, due to their close proximity to reef habitat and potential supply of terrigenous gravels from the adjacent subtidal slope and land above high tide.

To analyse the mollusc (shellfish) death assemblage present in mussel reef cores, the age stratigraphy of the sediment profiles was first obtained via bomb radionuclide and carbon radioisotopes (Section 2.5) so that the 3 additional cores collected at each site (Skiddaw, Gold Reef Bay West, Poison Point; Figure 2-2) could be partitioned into arbitrary historic time periods of interest (Table 2-2). To maximise the quantity of shell available for analysis, it was decided to process whole sections of the cores, as compared with the approach used to section cores for CSSI which use only 1 cm slices (Section 2.2). Each core section was analysed by volume between predicted sediment depth/age ranges (Figure 2-8).

To quantify fine sediment composition, a small ca.5 g fraction was retained for grain-size analysis (below) by compositing 3 subsamples of sediment haphazardly sampled from the top, middle and bottom of each section of core. To extract shell and gravels, the remainder of each core section was gently washed through a 1 mm sieve. The shells and gravel were weighed after air drying to constant weight at 60°C. We quantified all shells to lowest practical taxonomic level, we also weighed all shell fragments. Shell fragments were included in our analyses under the assumption that bottom-contact fishing methods (e.g., dredging, trawling) and feeding from large fishes would damage molluscs, creating fragments of whole live and dead mollusc shells. Some samples, especially from Gold Reef Bay West, contained a higher proportion of rock (schist) gravel. Large (>1 g) clasts of gravel were removed by hand and weighed, leaving small gravel and shell fragments. To estimate the proportion of carbonate from smaller rock fragments, a ca.15-30 g subsample was pre-weighed, and then the carbonate was dissolved by repeated immersion in 10 mM HCl acid until all bubbling ceased. The remaining rock gravel component was then washed, re-dried and weighed, to estimate the proportion of carbonate shell from the original sample.

Table 2-2: Arbitrary time periods used to section and process sediment cores sampled at sites formerly containing mussel reefs.

Time period (AD)	Description
500-1299	Pre-human period
1300-1859	Māori period
1860-1949	European colonisation, mining, forest milling, farming period
1950-1974	Commercial fishing, chemical agriculture period
1975-2015	Recent period, post-green-lipped mussel fishery

Percent weight of shell and gravel were calculated from the volume of the core analysed per time period, after conversion to equivalent volume. Rock gravel was converted to volume based on 1.52 tonne/m^3, and mollusc shells were converted to volume based on regression of oyster shell weights to volume calculated from unpublished data collected during a study of Pacific oyster *Crassostrea gigas* condition indices (Handley 1998) from which the regression equation: $y = 0.47x + 2.10$ ($r^2 = 0$ 82) was established. This conversion was used under the assumption that carbonate volume of oyster shells does not differ significantly to those of other mollusc species. As pre- and post-human sediment accumulation rates differed for each coring site (see Section 3.1.1) the shell and gravel estimates were standardised to percent material accumulating per year, by back calculating the number of years each core section represented, and dividing the percent volume of material deposited in each core section by the estimated years that deposited them.

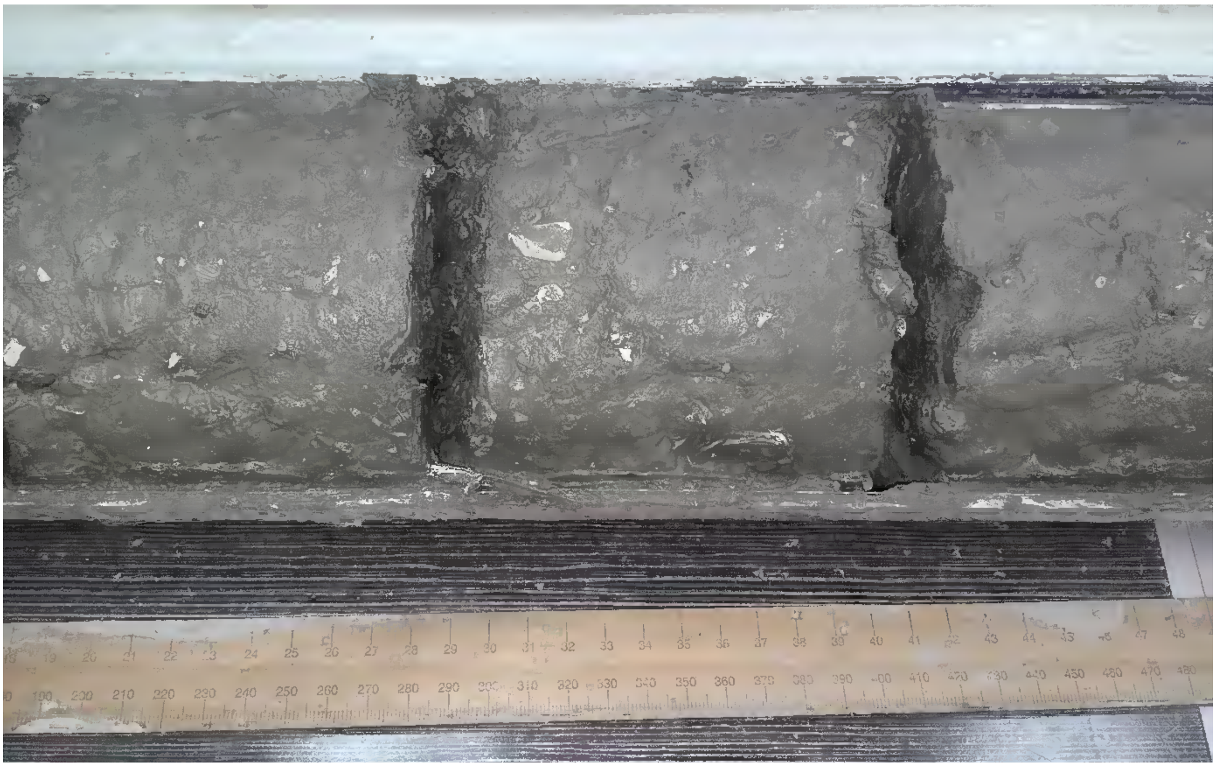

Figure 2-8: Section of core in preparation for removal and washing to extract shell gravels.

2.8 Sediment grain size

Particle size distributions (0.5–300 µm) based on particle volume were determined using a ‘Galai CIS-100 time-of-transition stream-scanning-laser’ following ultra-sonic dispersion. To investigate role of fine sediments the 0-300 µm were correlated against mollusc assemblage data. Estimates are presented as percent size fraction by volume.

2.9 Statistical methods

2.9.1 Multivariate analyses

Exploratory analyses and relationships among DA and sediment characteristics were assessed using non-metric multidimensional scaling (nMDS, Kruskal & Wish 1978). Differences between time periods (mussel reef cores) or date ranges (CSSI cores) were examined using canonical analysis of principal coordinates (CAP), a constrained ordination technique that finds the best means of separating *a priori* chosen groups, which in this case were those time periods arbitrarily chosen to delineate periods in history (Table 2-2) (Anderson & Willis 2003). The CAP procedure also generates correlations between the canonical axes and the original variables to help explain which variables (in this case, mollusc species and sediment characteristics) are correlated with the between-group differences that were shown as biplots. Such comparisons however should be interpreted under the assumption that correlation does not infer causation (Anderson et al. 2008). In the case of the CSSI core data for carbonate and gravel content where there were many core slices containing zero gravel, a constant (1) was added to the transformed data prior to matrix construction (Clarke et al. 2006). nMDS and CAP multivariate analyses were completed using the procedures in PERMANOVA+ for PRIMER (Anderson et al. 2008).

2.9.2 DA functional feeding analysis

To investigate changes to the mollusc community over time, we analysed functional feeding traits. To achieve this, an index was derived by multiplying the percent volume represented by each mollusc species by a score assigned to each of five functional feeding traits: suspension feeders, deposit feeders, scavengers, grazers, and predators (e.g., Handley et al. 2014). A diagram outlining the feeding traits using examples of species sampled in DA cores is in Figure 2-9.

To investigate temporal trends in the result, data (e.g., sediment characteristics including carbonate content) were averaged and plotted with 95 percent confidence intervals to meaningful simple comparisons on statistical significance (Jones 1984). Data points were plotted linked with dashed lines to extrapolate trends, but these dashed lines should be interpreted with caution in relation to the confidence intervals and the size of the intervals between data points.

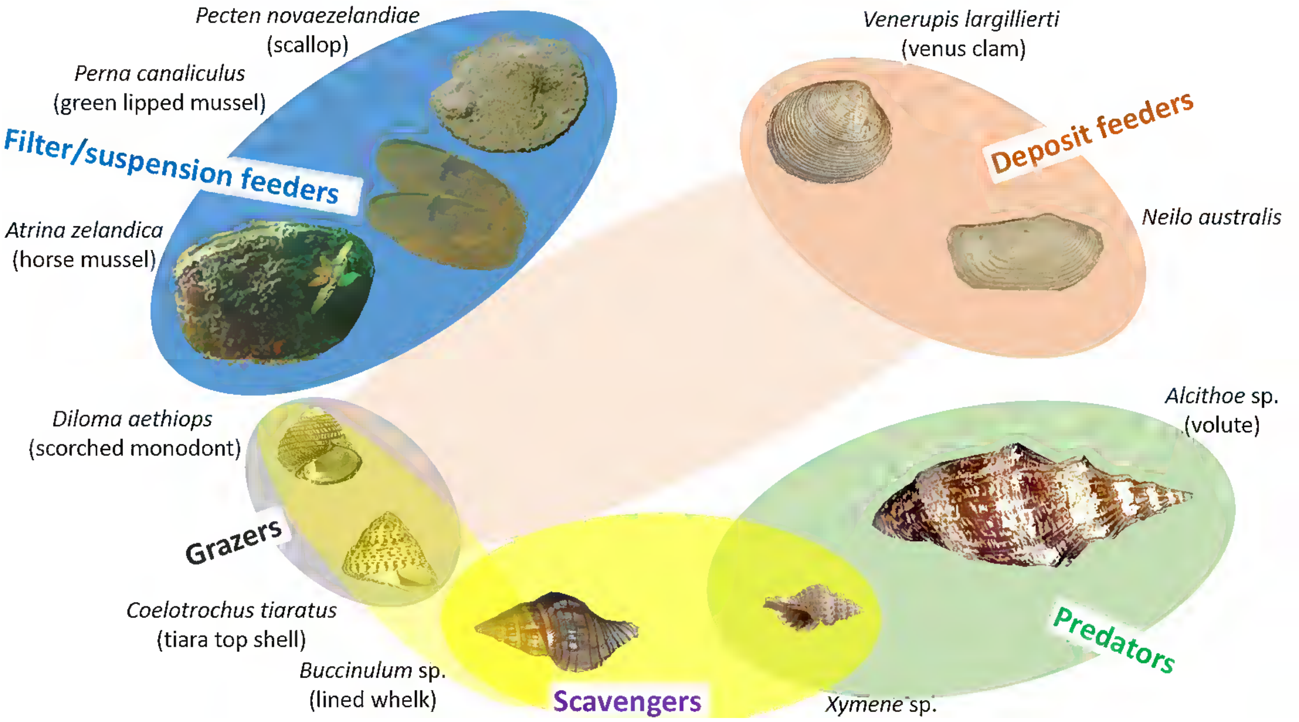

Figure 2-9: Functional feeding traits of species sampled in the mollusc death assemblage: Filter or suspension feeders take food from the water column (e.g., phytoplankton); deposit feeders ingest food from the surface of sediment around them; predators consume other animals; scavengers consume carrion (dead animals); and grazers eat plants and organisms that can be scraped off hard surfaces. Note: some species use multiple feeding modes, depending on food availability indicated by overlapping polygons.

3 Results

3.1 Sediment core geochronology and sedimentation

3.1.1 Summary of sediment accumulation rates

Results from dated cores collected in Kenepuru Sound and Beatrix Bay show that sediment accumulation rates (SAR) have increased by as much as ten-fold following European settlement (Table 3-1). The Kenepuru Sound cores preserve sedimentation records extended back over 1,000 years, with the oldest dated sediment layer deposited about 3,400 years ago. The Beatrix Bay sedimentation records only extend back ~100 years as they did not contain shell material that could be dated. In Kenepuru, cores collected from near the mouth to near the head of the sound (sites KP-4, KP-6, KP-10) had similar SAR (0.63–0.86 mm yr^{-1}) over 1,600–1,900 years prior to the 20th century. ^{210}Pb dating provides SAR estimates of 1.8 to 8.9 mm yr^{-1} since the late-1800s, which are 4–20 times long-term rates derived primarily from radiocarbon dating (Table 3-1). The timing of this historical increase in SAR sometime after the mid-1800s cannot be determined because the excess ^{210}Pb profiles in this study do not date sediments back to that time. Details of sediment properties and sediment accumulation rates in each of the sediment cores are presented below.

The geochronology of the sediment cores collected in the present study has been reconstructed from analysis of sediment core properties, x-radiographs and radioisotope dating. The results of the radioisotope dating of the sediment cores is summarised in Table 3-1 and presents estimates of time-averaged SAR in the system over the last 820 to 3,360 years. These estimates are based on ^{137}Cs and ^{210}Pb dating of sediments and ^{14}C dating of carbonate shell valves preserved in discrete sediment layers below the excess ^{210}Pb profiles. The ^{14}C SARs represent the time-averaged value for sediments deposited above the dated shell layer to the base of the excess ^{210}Pb and includes the pre-deforestation, Māori (1300–1859) and European (post-1860s) periods.

Comparison of the time-averaged ^{137}Cs SAR with the ^{210}Pb estimates showed poor agreement in several cores (KP-4, KP-10 and BT-9), but reasonable agreement between these two dating techniques in the majority of the cores (Table 3-1). The maximum depth of ^{137}Cs penetration in the cores, and resulting ^{137}Cs SAR estimates, could not be corrected for vertical mixing within the surface mixed layer (SML) using beryllium-7 (^{7}Be, ½ life ~53 days) as this short-lived radioisotope was not detected in the cores.

Several factors complicate the application of ^{137}Cs dating in estuarine[13] sediments: (1) ^{137}Cs activity has substantially reduced even since the early-1960s ^{137}Cs deposition peak (i.e., $t_{1/2}$ = 30 years) so that ^{137}Cs activities are below detectable levels in deeper deposits and the maximum ^{137}Cs is increasingly under-estimated; (2) the ^{7}Be SML, when present, is assumed to be constant over time, when in fact deeper mixing over annual–decadal time scales is often indicated ^{210}Pb profiles, with the result that the maximum ^{137}Cs is over-estimated; (3) the early-1960s ^{137}Cs deposition peak observed in New Zealand wetland deposits (Gehrels et al. 2008), and the most reliable ^{137}Cs time-horizon for dating, is typically absent in New Zealand estuarine and coastal marine sediments.

It should be noted that the maximum age of sediments dated using ^{210}Pb profiles depends on the maximum depth of excess ^{210}Pb in each core. The maximum depth of excess ^{210}Pb in turn varies depending on the SAR, surface activity of excess ^{210}Pb, particle size and degree of sediment reworking after deposition (i.e., radioisotope activity generally increase with mud content). Small

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[13] Pelorus Sound is considered an estuarine system.

amounts of excess ^{210}Pb may occur below the apparent maximum depth but are below detectable levels.

Table 3-1: Summary of sediment accumulation rates (SAR), Kenepuru Sound (KP) and Beatrix Bay. Time-average SAR (mm yr-1) estimated from ^{137}Cs, excess ^{210}Pb and ^{14}C dating from historical to pre-human periods. Information on linear regression fits to log-transform ^{210}Pb$_{ex}$ data included. The ^{137}Cs SAR is estimate assuming deposition since 1953.

Core site	^{137}Cs max (cm)	^{137}Cs SAR	^{210}Pb and ^{14}C depth and age ranges (cm, AD)	^{210}Pb SAR (r^2, n)	^{14}C SAR	Time span (Years)
KP-4	25	4.0	0-31 (*2015–1908 AD*)	2.9 (*0.95, 6*)		107
			31–137 (*1908–270 AD*)		0.64	1,745
			31–140 (*1908–250 AD*)		0.65	1,765
KP-6	35	5.6	0–35 (*2015–1939 AD*)	4.6 (*0.67, 8*)		76
			35–200 (*1939 AD– 6 BC*)		0.84	2,021
			35–206 (*1939 AD– 47 BC*)		0.86	2,062
KP-10	21	3.4	0–21 (*2015–1991 AD*)	8.9 (*0.95, 8*)		24
			21–80 (*1991– 1194 AD*)		0.72	821
			21–80 (*1991– 1063 AD*)		0.63	952
			80–138 (*1129– 632 AD*)		1.18	1,383
			80–138 (*1129– 551 AD*)		1.14	1,464
PP2	21	3.4	0–41 (*2015–1898 AD*)	3.5 (*0.79, 9*)		117
			41–133 (*1898 AD – 657 BC*)		0.36	2,672
			41–137 (*1898 AD – 759 BC*)		0.34	2,774
GRB2	27	4.4	0–41 (*2015–1912 AD*)	4.0 (*0.78, 8*)		103
			41–80 (*1912 AD – 873 BC*)		0.13	2,888
			41–119 (*1912 AD – 935 BC*)		0.27	2,950
SKDI	24	3.9	0–43 (*2015–1896 AD*)	3.6 (*0.89, 7*)		119
			43–118 (*1896 AD – 1,377 BC*)		0.23	3,392
			43–121 (*1896 AD – 1,342 BC*)		0.24	3,357
BT-1	18	2.9	0–25 (*2015–1911 AD*)	2.4 (*0.86, 7*)		104
BT-6	13	2.1	0–21 (*2015–1898 AD*)	1.8 (*0.46, 7*)		117
BT-9	13	2.1	0–25 (*2015–1941 AD*)	3.4 (*0.95, 11*)		74

3.1.2 Radiocarbon dating results

The time-averaged ^{14}C SAR for the sediment cores range from 0.1 to 1.2 mm yr^{-1} (mean: 0.59, s = 0.34 mm yr^{-1}) and spanning time periods of ~750 to 3,300 years prior to the late 1800s– early 1900s (Table 3-2). These time periods incorporate background sedimentation rates prior to human arrival in ~1300 AD as well as the effects of deforestation by Māori and European settlers. Most of the ^{14}C SAR estimates integrate sedimentation during the period of Māori occupation and the early–mid-European period (i.e., as recently as late-1930s), as well as the 1,000–2,600 years prior to human arrival. These ^{14}C SAR are typically less than 1 mm yr^{-1} and suggest that forest clearance by Māori had a minimal impact on sedimentation rates in the Kenepuru Sound. However, these ^{14}C SARs are averaged over centuries and do not capture sedimentation peaks that may have occurred over annual–decadal time scales, associated with shorter periods of forest clearance or infrequent natural disturbance events, such as landslides in hill country generated by high intensity rainstorms or seismic activity.

Conventional radiocarbon ages (AMS ^{14}C) obtained for shell samples taken from similar depths (i.e., within several cm) in the Kenepuru cores are presented in Table 3-2. The calibrated ^{14}C ages of the shell samples taken from these sediment layers and resulting SAR estimates show a high level of agreement.

Table 3-2: Atomic Mass Spectrometry 14C dating results and sediment accumulation rates for the Kenepuru Sound cores. Age is the conventional age BP (Before Present, 1950 AD), with one standard deviation error shown. Note: Wk number is the Waikato University Radiocarbon Dating Laboratory sample identification

Core	Depth (cm)	Wk number	Age (years BP)	(± years)	^{14}C SAR (mm yr^{-1})	Time period
KP-4	136–137	Wk-42186	1,680	20	0.64	*1908–270 AD*
	138–141	Wk-42187	1,700	20	0.65	*1908–250 AD*
KP-6	199–200	Wk-42188	1,956	20	0.84	*1939 AD– 6 BC*
	204–206	Wk-42189	1,997	20	0.86	*1939 AD– 47 BC*
KP-10	76–80	Wk-42190	756	20	0.72	*1991– 1194 AD*
	77–81	Wk-42191	887	20	0.63	*1991– 1063 AD*
	137–138	Wk-42192	1,318	22	1.18	*1129– 632 AD*
	137–138	Wk-42193	1,399	22	1.14	*1129– 551 AD*
PP2	132–133	Wk-43477	2,607	20	0.36	*1898 AD – 657 BC*
	136–137	Wk-43476	2,826	20	0.34	*1898 AD – 759 BC*
GRB2	79–80	Wk-43479	2,823	20	0.13	*1912 AD – 873 BC*
	118–119	Wk-43478	2,885	20	0.27	*1912 AD – 935 BC*
SKDI	117–118	Wk-43841	3,327	20	0.23	*1896 AD – 1,377 BC*
	120–121	Wk-43480	3,292	20	0.24	*1896 AD – 1,342 BC*

These ^{14}C dating results suggest that substantial reworking of older sediments and shell, and subsequent re-deposition in more recent deposits has not occurred in the Kenepuru cores. The small sigma errors in the radiocarbon ages of about ±20 years, as well as the similar ages of shell sampled from the same sediment layers provide confidence in these data and derived estimates of long-term SAR.

In the following sections the sedimentation history at each core site in the Kenepuru Sound and Beatrix Bay, including changes in sediment accumulation rates and sediment physical properties, are described in detail. The locations of the core sites are presented in Figure 2-2.

Core KP-4

Core KP-4 was collected from subtidal flats in Te Matau a Maui Bay, located on the northern shore of Kenepuru Sound (Figure 2-2). X-radiographs for core KP-4 show that sediments are largely composed of homogenous, poorly laminated muds (Figure 3-1). Evidence of bioturbation by infauna is indicated by vertical and sub-vertical traces of mm to cm-scale burrows identified by their lower-density (i.e., black). Shell valves and fragments are rare. Fragments of scallop shell are present in the top 10 cm of the core. The shell layer at 131–137 cm depth dated to 250-270 AD can be clearly seen.

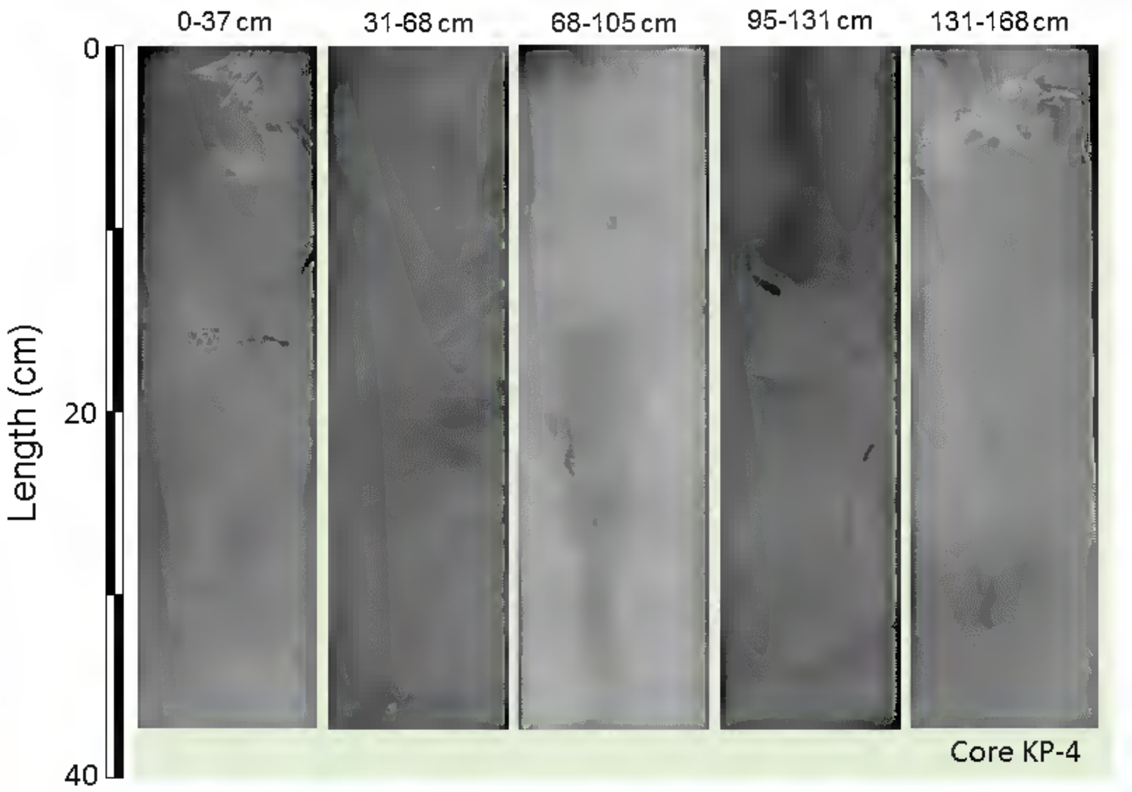

Figure 3-1: Core KP-4 (subtidal: lower Kenepuru Sound) X-radiographs. (0–168 cm)[14]. These images have been inverted so that relatively high-density objects appear white (e.g., shell valves) and low-density materials such as muds or organic material appear as darker areas (format: 8bit tiff, export: 256 greyscale, scale 400%, png).

Figure 3-2 summarises the radioisotope dating and physical properties of sediments preserved in core KP-4. Sediments deposited over the last century occupy the upper 25-cm of the sediment record, with ^{210}Pb SAR averaging 2.9 mm yr^{-1} during this period (Figure 3-2a). The presence of ^{137}Cs-labelled (i.e., post-1950s) sediments at the base of the ^{210}Pb$_{ex}$ profile is indicative of down-core sediment mixing, so that ^{210}Pb dating cannot be validated by ^{137}Cs dating. The ^{210}Pb SAR, however, is

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[14] Note: the depths overlap because the core slabs are more than 37 cm long but the digital detector plate only has a 37 cm long window. The overlap is useful as it provides continuity between cores.

based on regression fit ($n = 6$, $r^2 = 0.95$) to the radioactivity of discrete down-core samples whereas ^{137}Cs dating is based on detecting the maximum depth of this radioisotope in the sediment column. As described in section 3.1.1, several factors can complicate the application of ^{137}Cs dating to estuarine sediments. The ^{210}Pb dating also provides a more conservative SAR estimate (2.9 mm yr^{-1}) at site KP-4 than does the ^{137}Cs (4 mm yr^{-1}).

Radiocarbon dating of *Mactra* and *Saccostrea* valves from a shell layer at 136–141 cm depth yield an average ^{14}C SAR of 0.65 mm yr^{-1} over at least a ~1,750 year time period. These radioisotope data indicate an apparent four-fold increase in time-averaged SAR over the last century in comparison to the long term ^{14}C SAR. Although this substantially lower long-term rate includes the period of occupation by Māori (i.e., post-1300 AD) and the first ~50 years of European settlement, the ^{14}C SAR also reflects background (i.e., pre-human) sedimentation rates over a ~1,000 year period.

Dry-bulk sediment density (ρ_b) profiles for the cores provide information on the composition of the sediment deposits. For example, ρ_b values for estuarine sand deposits are typically of the order of 1.5–1.7 g cm^{-3}, whereas a mud deposit with high water content can typically have a ρ_b value as low as 0.4–0.5 g cm^{-3}. Core KP-4 displays a gradual increase in ρ_b values with depth, from~ 0.75 g cm^{-3} in near-surface sediments to 0.9–1 g cm^{-3} in sediments at 75 cm depth (Figure 3-2b), which is consistent with sediment compaction. Particle size profiles are highly uniform with depth, with a narrow range of mean and median particle diameters (range: 14–21 µm) (Figure 3-2c) for sediments that are composed of clay-rich muds (i.e., 4–6% by volume, Figure 3-2d).

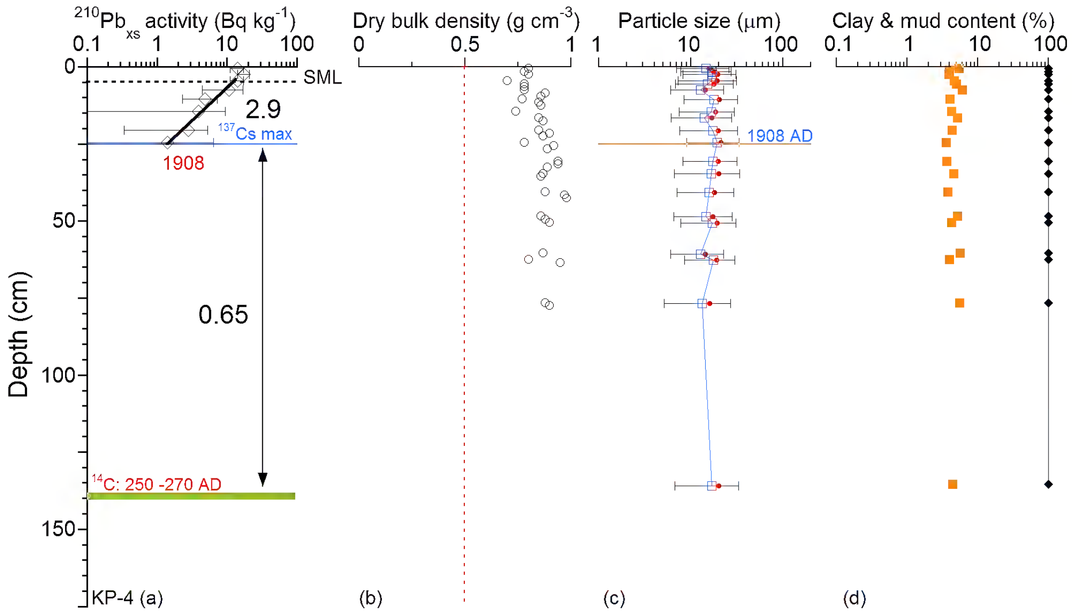

Figure 3-2: Core KP-4 (Kenepuru) - ages of sediment layers and sediment accumulation rates (SAR), and sediment properties. (a) Excess ^{210}Pb activity profiles with 95% confidence intervals shown. Time-averaged SAR (Black text) derived from regression fit to natural log-transformed ^{210}Pb data and ^{14}C ages of bivalve shells. Estimated ages of depth horizons (red text). Surface mixed layer (SML) inferred from excess ^{210}Pb profiles. Maximum depth of caesium-137 (^{137}Cs) indicated. Radioisotope activity expressed in units of Becquerels (Bq). (b) Sediment dry bulk density; (c) mean (red) and median particle diameters with standard deviation; (d) clay and mud content as percentage of sample by particle volume.

Core KP-6

Core KP-6 was collected from Waitaria Bay, located in the upper reaches of Kenepuru Sound. The x-radiographs for core KP-6 show that sediment deposits are similar to those described for core KP-4, being composed of homogenous, poorly laminated muds (Figure 3-3). Differences in water content, indicated by darker areas particularly in the upper one metre of the core may be artefacts of the vibracoring methodology employed to collect the cores. Evidence of bioturbation by infauna is limited and shell valves and fragments are very rare although less so below 150 cm depth.

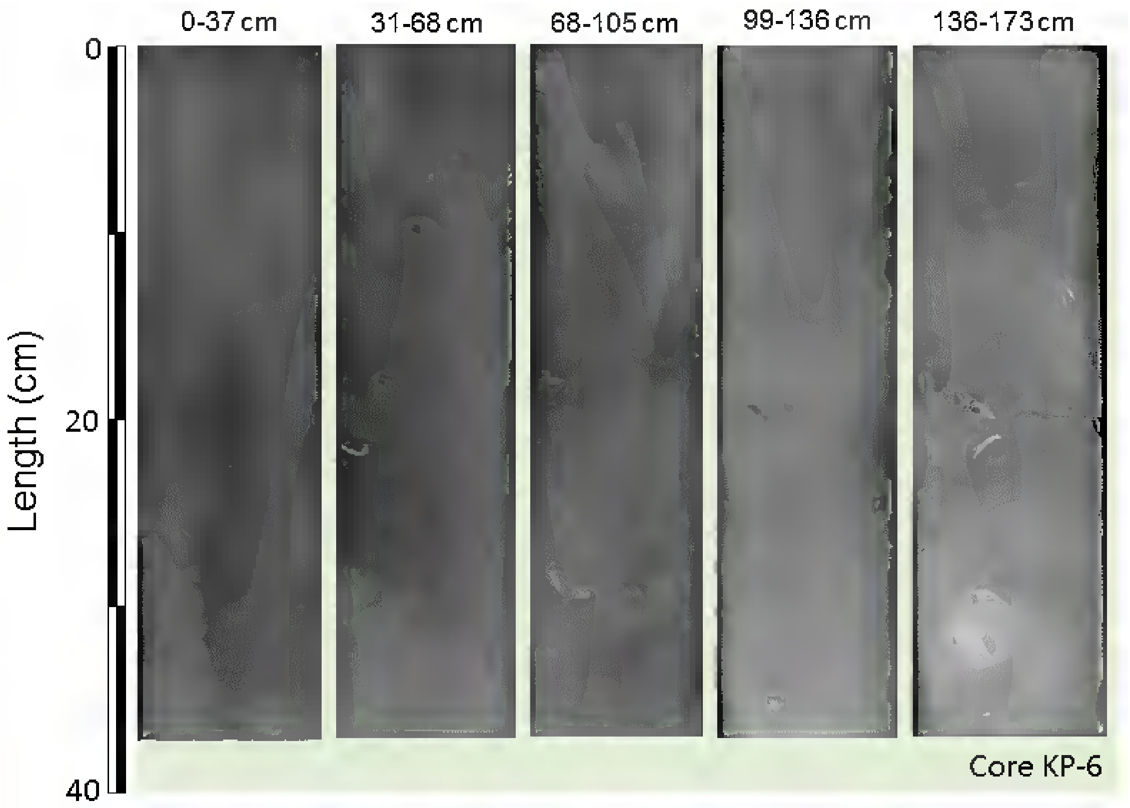

Figure 3-3: Core KP-6 (subtidal: mid Kenepuru Sound) X-radiographs. (0–173 cm). These images have been inverted so that relatively high-density objects appear white (e.g., shell valves) and low-density materials such as muds or organic material appear as darker areas (format: 8bit tiff, export: 256 greyscale, scale 400%, png).

Figure 3-4 summarises the radioisotope dating and physical properties of sediments preserved in core KP-6. Sediments deposited over the last ~75 years occupy the upper 35 cm of the sediment record, with ^{210}Pb SAR averaging 4.6 mm yr^{-1} during this period (Figure 3-4a). The ^{210}Pb SAR is in reasonable agreement with dating based on the maximum depth of ^{137}Cs (i.e., post-1950s) in core KP-6. Radiocarbon dating of *Talochlamys* sp. shell valves from 200–206 cm depth yield an average ^{14}C SAR of 0.85 mm yr^{-1} over a ~2,000 year time period prior to the 1940s (1939 AD – 47 BC). These radioisotope data indicate a more than five-fold increase in time-averaged SAR over the last ~75 years in comparison to the long term ^{14}C SAR. The pre-1940 ^{14}C SAR includes ~1300 years of background sedimentation prior to human settlement. Dry bulk sediment densities in KP-6 gradually increase with depth due to compaction, from~ 0.55 g cm^{-3} in near-surface sediments to a maximum of 0.9 g cm^{-3} at ~60 cm depth (Figure 3-4b). As described for core KP-4, particle size profiles are highly uniform with depth, with a narrow range of mean and median particle diameters (range: 8–14 µm) in the fine-silt size range (Figure 3-4c). Clays account for 7–14% by volume of these estuarine muds (Figure 3-4d).

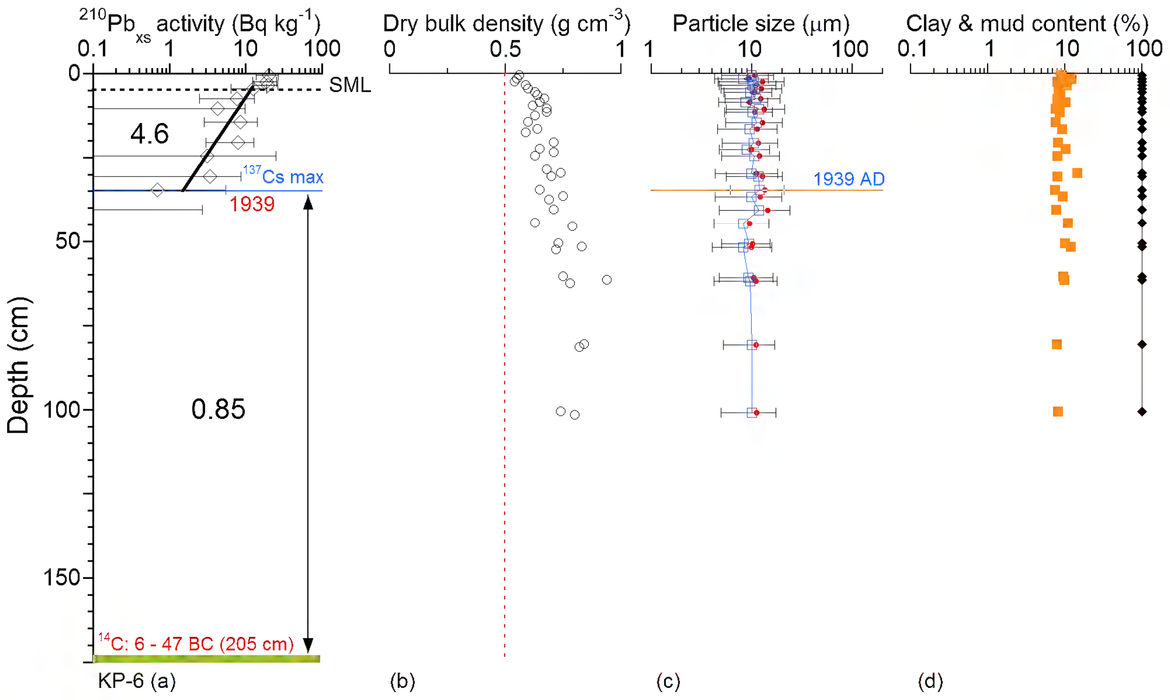

Figure 3-4: Core KP-6 (Kenepuru) - ages of sediment layers and sediment accumulation rates (SAR), and sediment properties. (a) Excess ^{210}Pb activity profiles with 95% confidence intervals shown. Time-averaged SAR (Black text) derived from regression fit to natural log-transformed ^{210}Pb data and ^{14}C ages of bivalve shells. Estimated ages of depth horizons (red text). Surface mixed layer (SML) inferred from excess ^{210}Pb profiles. Maximum depth of caesium-137 (^{137}Cs) indicated. Radioisotope activity expressed in units of Becquerels (Bq). (b) Sediment dry bulk density; (c) mean (red) and median particle diameters with standard deviation; (d) clay and mud content as percentage of sample by particle volume.

Core KP-10

Core KP-10 was collected from Ohauparuparu Bay, located at the head of Kenepuru Sound. The x-radiographs for core KP-10 show that the upper metre of these homogenous low-density estuarine muds contain abundant shell valves of cockle, *Talochlamys*, trough shells (*Cyclomactra*) and *Dosina* (Figure 3-5). A low-density fluid-mud surface-mixed layer (black) occupies the upper several centimetres of the core, indicating that sediment resuspension by waves may occur at this site.

Figure 3-6 summarises the radioisotope dating and physical properties of sediments preserved in core KP-10. Excess ^{210}Pb and ^{137}Cs is limited to the upper 21-cm of the core, with the ^{210}Pb$_{xs}$ data indicating relatively rapid sedimentation since the early 1990s, averaging 8.9 mm yr^{-1} (Figure 3-6a). The apparent high ^{210}Pb$_{x}$ SAR and very poor agreement with ^{137}Cs dating and low bulk density of sediments in the SML, suggests reworking of these estuarine muds, most likely by physical rather than biological processes. Radiocarbon dating of shell valves from two layers at 76–80 and 137–138-cm depth enable ^{14}C SAR to be estimated for two (pre-1990s) time periods. Notably, time-averaged SAR over the last 1,000 years (1991– ~1,100 AD) of 0.7 mm yr^{-1} were substantially lower than background rates averaging 1.2 mm yr^{-1} during the 500 years prior to ~1,100 AD. Dry bulk sediment densities in KP-10 gradually increase with depth due to compaction, from~ 0.55 g cm^{-3} in near-surface sediments to ~0.75 g cm^{-3} at 60 cm depth (Figure 3-6b). As described for cores KP-4 and KP-6, particle size profiles are highly uniform with depth, with a narrow range of mean and median particle diameters (range: 7–12 µm) in the fine-silt size range (Figure 3-6c). Clay-sized particles account for 9–17% by volume of these homogenous estuarine muds (Figure 3-6d).

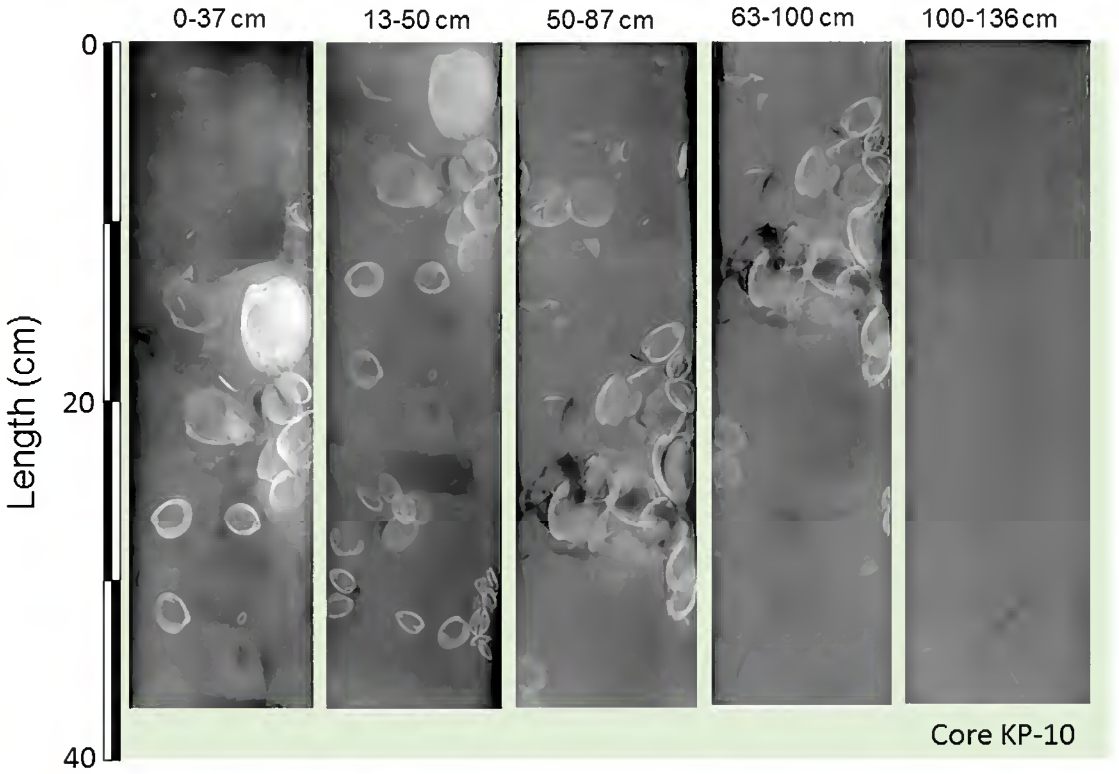

Figure 3-5: Core KP-10 (subtidal: upper Kenepuru Sound) X-radiographs. (0–136 cm). These images have been inverted so that relatively high-density objects appear white (e.g., shell valves) and low-density materials such as muds or organic material appear as darker areas (format: 8bit tiff, export: 256 greyscale, scale 400%, png).

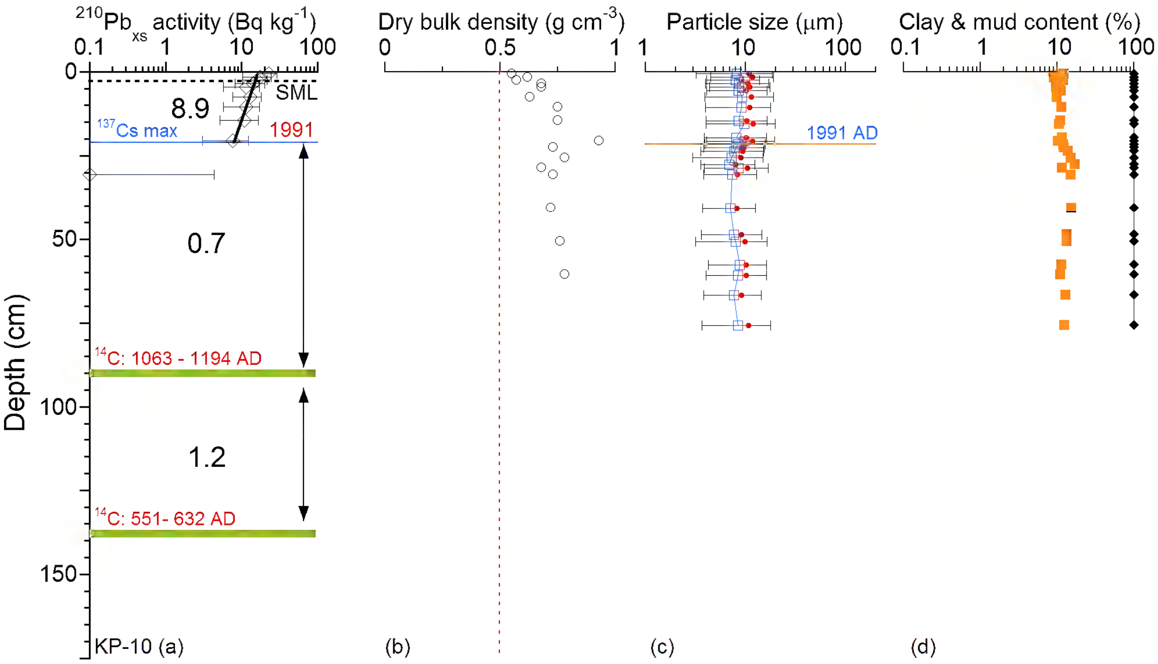

Figure 3-6: Core KP-10 (Kenepuru) - ages of sediment layers and sediment accumulation rates (SAR), and sediment properties. (a) Excess ^{210}Pb activity profiles with 95% confidence intervals shown. Time-averaged SAR (Black text) derived from regression fit to natural log-transformed ^{210}Pb data and ^{14}C ages of bivalve shells. Estimated ages of depth horizons (red text). Surface mixed layer (SML) inferred from excess ^{210}Pb profiles. Maximum depth of caesium-137 (^{137}Cs) indicated. Radioisotope activity expressed in units of Becquerels (Bq). (b) Sediment dry bulk density; (c) mean (red) and median particle diameters with standard deviation; (d) clay and mud content as percentage of sample by particle volume.

Kenepuru mussel-reef cores

Sediment cores collected at three locations (SKD-1, GRB-2, PP-2) immediately inshore of former wild green-lipped mussel reefs that existed until being harvested during the early 1960s to mid-1970s. Thus, these cores provide information on sedimentation in areas of the Kenepuru Sound that were previously biogenic habitats.

Core SKD-1

Figure 3-7 summarises the radioisotope dating and physical properties of sediments preserved in core SKD-1 that was collected close to the entrance to Kenepuru Sound and west of site KP-4. Apparent ^{210}Pb SAR averaging 3.6 mm yr^{-1} over the last ~120 years occupy the upper 25 cm of the sediment core. The presence of ^{137}Cs-labelled (i.e., post-1950s) sediments at the base of the ^{210}Pb$_{ex}$ profile, however, suggests sediment reworking, so that younger sediments have been mixed down into the sediment column (Figure 3-7a), so that ^{210}Pb dating may not be reliable. Radiocarbon dating of shell valves from 133–177 cm depth yield an average ^{14}C SAR of 0.23 mm yr^{-1} over a ~2,600+ year time period (i.e., from 1,342–1,377 BC). These mussel reef sediments are composed of muddy-sand matrix with mean particle sizes in the coarse silt to very-fine sand range (Figure 3-7b-c).

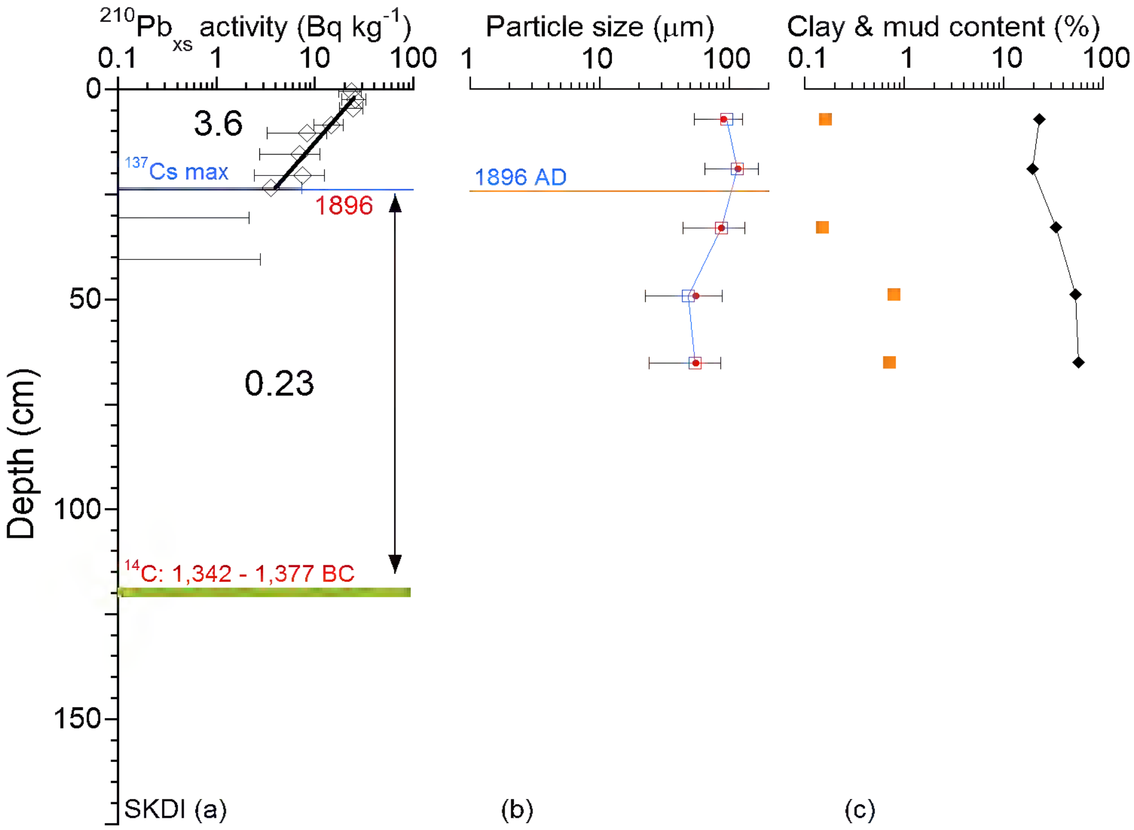

Figure 3-7: Core SKD-1 (Skiddaw, Kenepuru) - ages of sediment layers and sediment accumulation rates (SAR), and sediment properties. (a) Excess ^{210}Pb activity profiles with 95% confidence intervals shown. Time-averaged SAR (Black text) derived from regression fit to natural log-transformed ^{210}Pb data and ^{14}C ages of bivalve shells. Estimated ages of depth horizons (red text). Surface mixed layer (SML) inferred from excess ^{210}Pb profiles. Maximum depth of caesium-137 (^{137}Cs) indicated. Radioisotope activity expressed in units of Becquerels (Bq). (b) Sediment dry bulk density; (c) mean (red) and median particle diameters with standard deviation; (d) clay and mud content as percentage of sample by particle volume.

Core GRB-2

Figure 3-8 summarises the radioisotope dating and physical properties of sediments preserved in core GRB-2 that was collected immediately west of Mills Bay, Kenepuru Sound. Apparent ^{210}Pb SAR averaging 4 mm yr^{-1} over the last ~100 years occupy the upper 41 cm of the sediment core. The maximum depth of ^{137}Cs-labelled (i.e., post-1950s) sediments at 27 cm is in close agreement with the ^{210}Pb age of 67 years (i.e., ~1948 AD) (Figure 3-8a). Thus, we can have some confidence in the ^{210}Pb geochronology at this site. Radiocarbon dating of shell valves at 79–80 and 117–118 cm depth yield 14C SARs of 0.13 and 0.23 mm yr^{-1} (average ~0.2 mm yr^{-1}) respectively over ~2,900 years (i.e., from 837–935 BC). These mussel reef sediments are primarily composed of muddy-sand matrix with mean particle sizes in the coarse silt to very-fine sand range (Figure 3-8b-c). An increase in mud content since the 1950s is suggested by the sedimentological data, although the temporal resolution is limited by the sparse data.

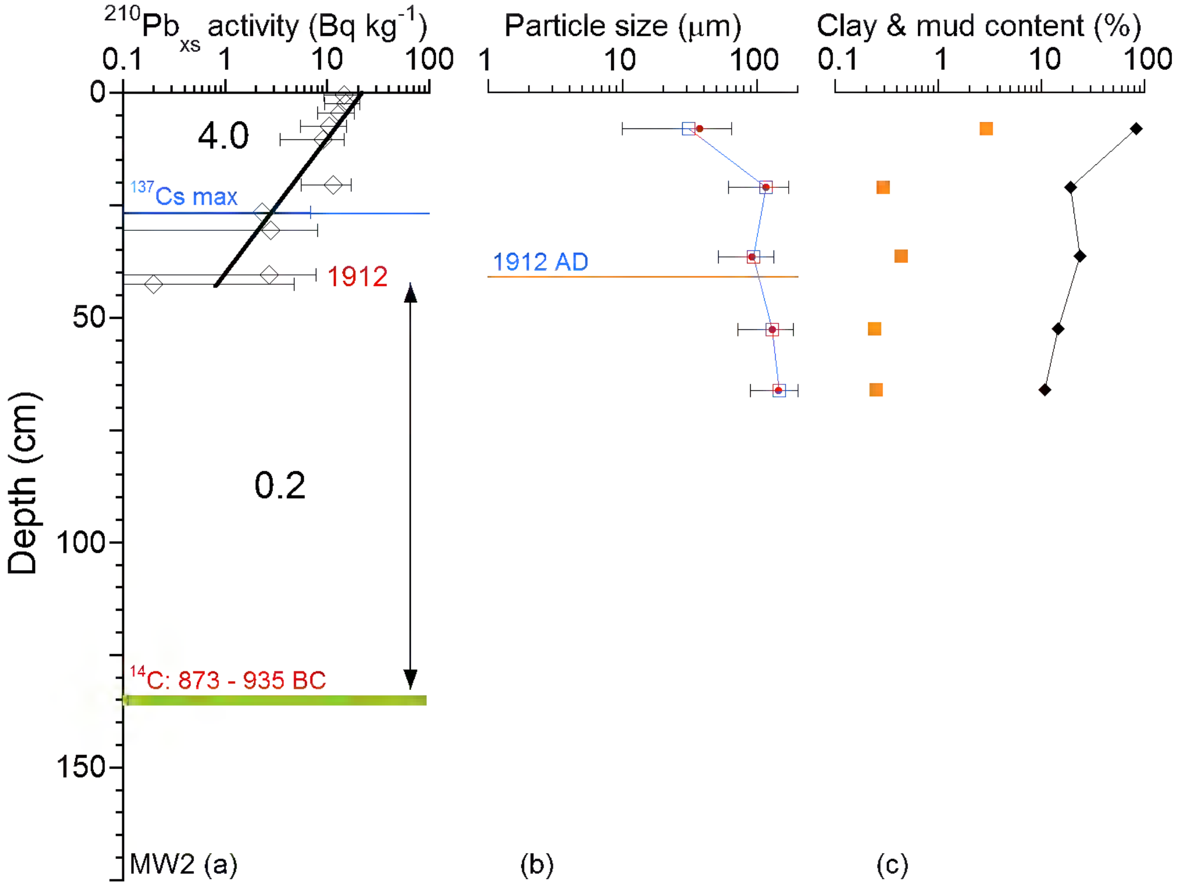

Figure 3-8: Core MW2 (Gold Reef Bay, Kenepuru) - ages of sediment layers and sediment accumulation rates (SAR), and sediment properties. (a) Excess ^{210}Pb activity profiles with 95% confidence intervals shown. Time-averaged SAR (Black text) derived from regression fit to natural log-transformed ^{210}Pb data and 14C ages of bivalve shells. Estimated ages of depth horizons (red text). Surface mixed layer (SML) inferred from excess ^{210}Pb profiles. Maximum depth of caesium-137 (^{137}Cs) indicated. Radioisotope activity expressed in units of Becquerels (Bq). (b) Sediment dry bulk density; (c) mean (red) and median particle diameters with standard deviation; (d) clay and mud content as percentage of sample by particle volume.

Core PP-2

Figure 3-9 summarises the radioisotope dating and physical properties of sediments preserved in core PP-2 that was collected immediately south of Goulter Bay, Kenepuru Sound. Apparent ^{210}Pb SAR averaging 3.5 mm yr^{-1} over the last ~117 years occupy the upper 41 cm of the core. The maximum depth of ^{137}Cs-labelled (i.e., post-1950s) sediments at 21 cm is in close agreement with the ^{210}Pb age of 60 years (i.e., ~1955 AD) (Figure 3-9a). Thus, as observed at site GRB-2, we can have some confidence in the ^{210}Pb geochronology at the Poison Point site. Radiocarbon dating of shell valves at 133 and 137 cm depth yield a time-averaged ^{14}C SAR of 0.35 mm yr^{-1} over a ~2,700 year period, which is an order of magnitude lower SAR than since the late-1800s. These relict mussel reef sediments at site PP-2 are more similar to the Kenepuru (KP) core sites. Dry bulk sediment densities in PP-2 gradually increase with depth due to compaction, from~ 0.5 g cm^{-3} in near-surface sediments to a maximum of ~0.75 g cm^{-3} at ~30 cm depth (Figure 3-9b). Sediments are substantially more fine-grained than at GRB-2 and SKD-1, being composed of low-density, clay-rich muds with mean particle sizes of 10–26 µm (i.e., fine–medium silt) (Figure 3-9d). Mud deposition has characterised this site since at least ~900 AD and for ~400 years prior to human arrival

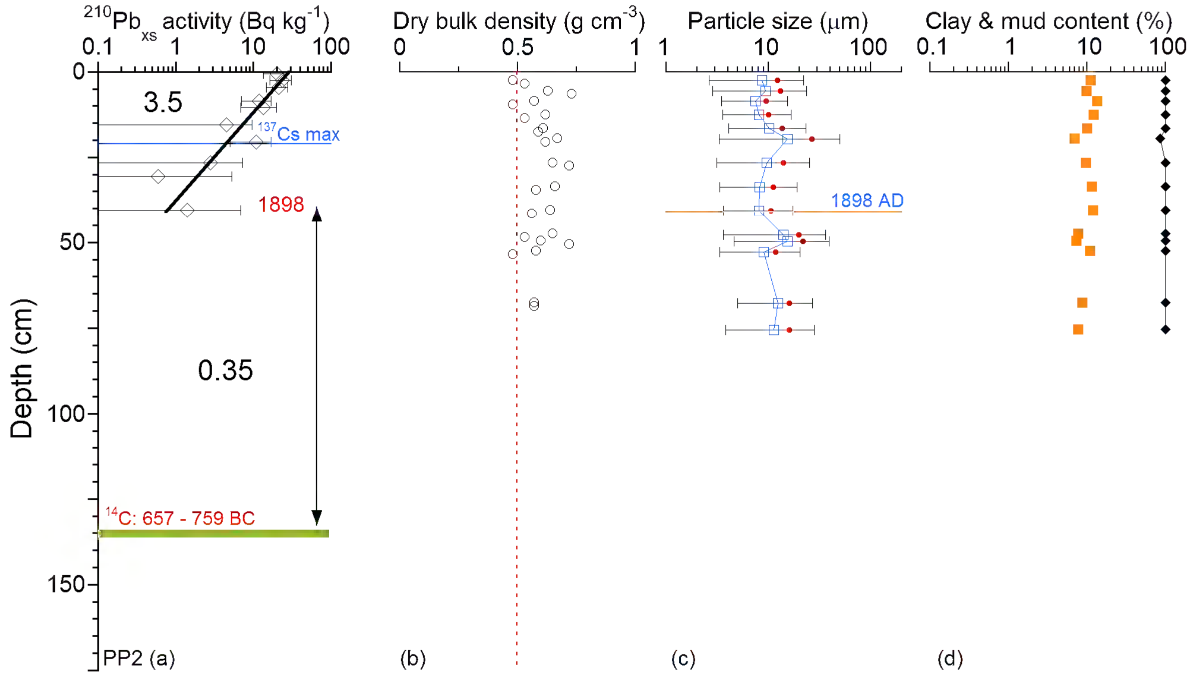

Figure 3-9: Core PP-2 (Poison Point, Kenepuru) - ages of sediment layers and sediment accumulation rates (SAR), and sediment properties. (a) Excess ^{210}Pb activity profiles with 95% confidence intervals shown. Time-averaged SAR (Black text) derived from regression fit to natural log-transformed ^{210}Pb data and ^{14}C ages of bivalve shells. Estimated ages of depth horizons (red text). Surface mixed layer (SML) inferred from excess ^{210}Pb profiles. Maximum depth of caesium-137 (^{137}Cs) indicated. Radioisotope activity expressed in units of Becquerels (Bq). (b) Sediment dry bulk density; (c) mean (red) and median particle diameters with standard deviation; (d) clay and mud content as percentage of sample by particle volume.

Core BT-1

The Beatrix Bay cores were collected along a depth gradient between the relatively shallow inshore and the central mud basin of the bay, below 40 m water depth (refer to map Figure 2-2). Core BT-1 was collected in Laverique Bay in ~20 m water depth.

Figure 3-10 summarises the radioisotope dating and physical properties of sediments preserved in core BT-1. Apparent ^{210}Pb SAR averaging 2.4 mm yr^{-1} over the last ~100 years occupy the upper 25 cm of the core. The maximum depth of ^{137}Cs-labelled (i.e., post-1950s) sediments at 18 cm is in relatively close agreement with the ^{210}Pb age of 73 years (i.e., ~1942 AD) (Figure 3-10a) so that we can have reasonable confidence in the ^{210}Pb geochronology at this site. Visual inspection of this core shows that it is composed of coarse gravels and shell material with a sandy-mud matrix (Figure 3-11). Dry bulk sediment densities in BT-1 vary around 1.5 g cm^{-3}, reflecting the high sand content of these deposits and do not display a clear trend with depth (Figure 3-10b). Laser particle-sizing shows that the sediment matrix is composed of slightly-muddy very-fine to fine sand, with mean particle sizes of 155–180 µm (Figure 3-10d).

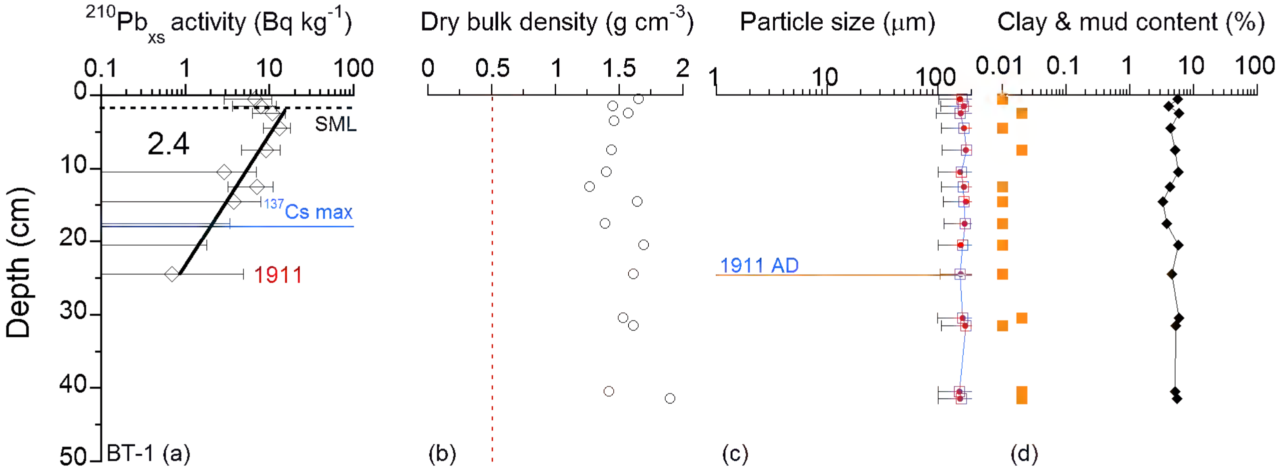

Figure 3-10: Core BT-1 (Beatrix Bay) - ages of sediment layers and sediment accumulation rates (SAR), and sediment properties. (a) Excess ^{210}Pb activity profiles with 95% confidence intervals shown. Time-averaged SAR (Black text) derived from regression fit to natural log-transformed ^{210}Pb data. Estimated ages of depth horizons (red text). Surface mixed layer (SML) inferred from excess ^{210}Pb profiles. Maximum depth of caesium-137 (^{137}Cs) indicated. Radioisotope activity expressed in units of Becquerels (Bq). (b) Sediment dry bulk density; (c) mean (red) and median particle diameters with standard deviation; (d) clay and mud content as percentage of sample by particle volume.

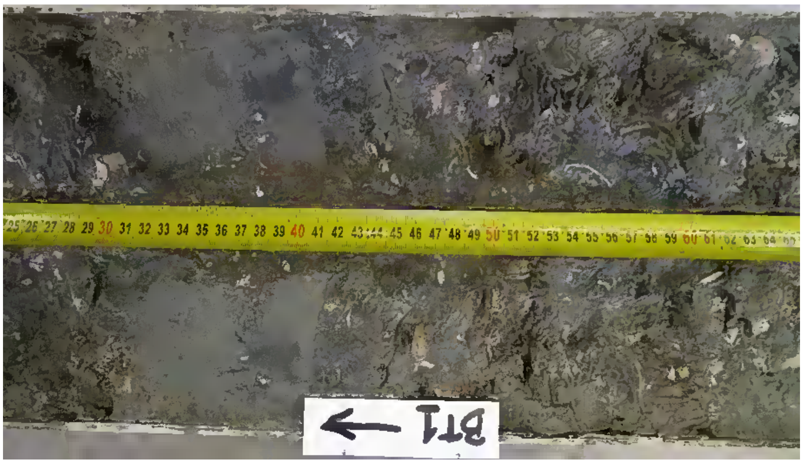

Figure 3-11: Core BT-1 (Beatrix Bay) – photo of split core (25–65 cm interval).

Core BT-6

Core site BT-6 is located at the entrance to Laverique Bay between the~20 and 30 m isobaths. The x-radiograph for core BT-6 indicates that the sediments depositing at this site are primarily biogenic, composed of abundant shellfish valves and fragments (Figure 3-12). Figure 3-13 summarises the radioisotope dating and physical properties of sediments preserved in core BT-6. Apparent ^{210}Pb SAR averaging 1.8 mm yr^{-1} over the last ~117 years occupy the upper 20 cm of the core. The maximum depth of ^{137}Cs-labelled (i.e., post-1950s) sediments at 13 cm is in relatively close agreement with the ^{210}Pb age of 72 years (i.e., ~1943 AD) (Figure 3-13a) so that we can have reasonable confidence in the ^{210}Pb geochronology at this site.

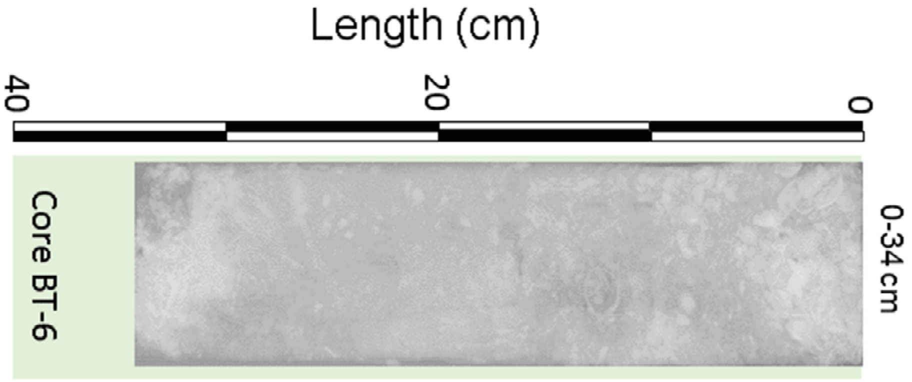

Figure 3-12: Core BT-6 (subtidal: inner Beatrix Bay) X-radiographs. (0–34 cm). These images have been inverted so that relatively high-density objects appear white (e.g., shell valves) and low-density materials such as muds or organic material appear as darker areas (format: 8bit tiff, export: 256 greyscale, scale 400%, png).

Dry bulk sediment densities in BT-6 gradually increase with depth due to compaction, from ~1 g cm^{-3} in near-surface sediments to a maximum of 1.4 g cm^{-3} at ~31 cm depth (Figure 3-13b). Particle size profiles show that the sediment deposits are composed of poorly-sorted muddy sands, with a wide range of mean and median particle diameters (range: 46–160 µm) in the coarse silt to fine-sand range (Figure 3-13c). Clay-sized particles typically account for less than 2% by volume of these sediments (Figure 3-13d).

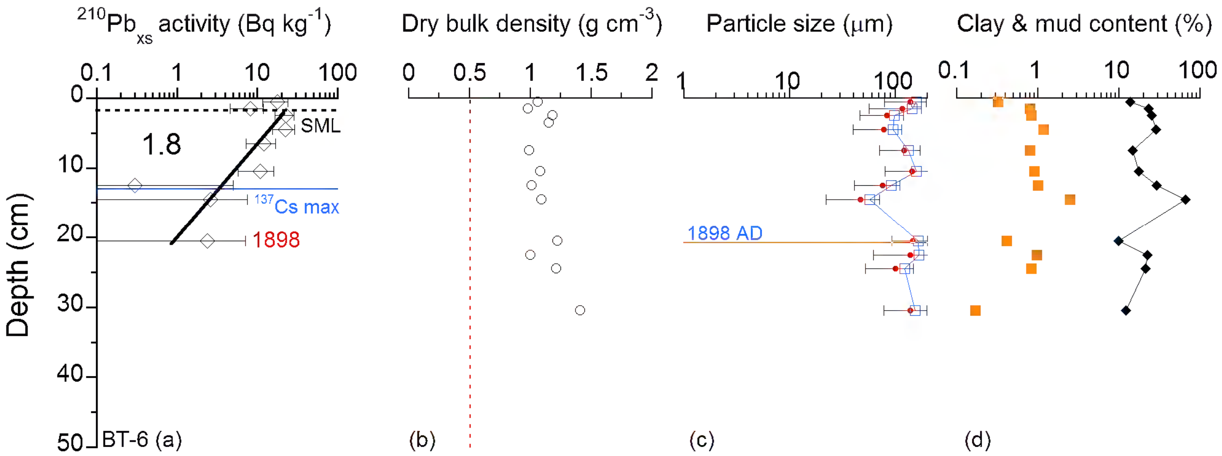

Figure 3-13: Core BT-6 (Beatrix Bay) - ages of sediment layers and sediment accumulation rates (SAR), and sediment properties. (a) Excess ^{210}Pb activity profiles with 95% confidence intervals shown. Time-averaged SAR (Black text) derived from regression fit to natural log-transformed ^{210}Pb data. Estimated ages of depth horizons (red text). Surface mixed layer (SML) inferred from excess ^{210}Pb profiles. Maximum depth of caesium-137 (^{137}Cs) indicated. Radioisotope activity expressed in units of Becquerels (Bq). (b) Sediment dry bulk density; (c) mean (red) and median particle diameters with standard deviation; (d) clay and mud content as percentage of sample by particle volume.

Core BT-9

Core site BT-9 is located in the central mud basin of Beatrix Bay between the 35 and 40 m isobaths. The x-radiograph for core BT-9 indicates that the sediments depositing at this site are primarily composed of fine-grained muds, with traces of mm-scale burrows associated with the feeding and/or burrowing activities of animals being common. Shellfish valves and fragments are rare (Figure 3-14). The ^{210}Pb SAR averaging 3.4 mm yr^{-1} over the last ~74 years occupy the upper 25 cm of the core. The maximum depth of ^{137}Cs-labelled (i.e., post-1950s) sediments at 18 cm is in relatively close agreement with the ^{210}Pb age of 53 years (i.e., ~1962 AD) (Figure 3-15a) so that we can have reasonable confidence in the ^{210}Pb geochronology at this site. Dry bulk sediment densities in core BT-9 vary between 0.6 and 0.8 g cm^{-3} and do not display a trend of increasing bulk density with depth (Figure 3-15b). Particle size profiles are highly uniform with depth, with a narrow range of mean and median particle diameters (range: 7–12 μm) (Figure 3-15c) for sediments that are composed of clay-rich muds (i.e., 13–16% by volume, Figure 3-15d).

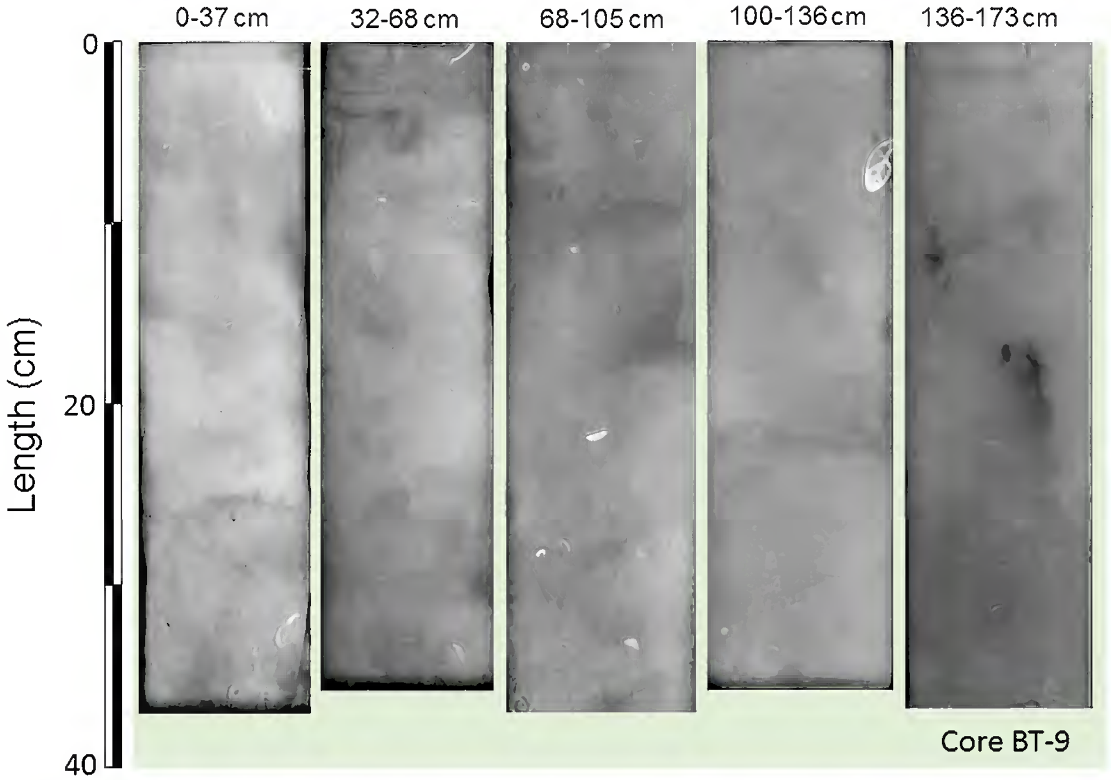

Figure 3-14: Core BT-9 (subtidal: central basin - Beatrix Bay) X-radiographs. (0–173 cm). These images have been inverted so that relatively high-density objects appear white (e.g., shell valves) and low-density materials such as muds or organic material appear as darker areas (format: 8bit tiff, export: 256 greyscale, scale 400%, png).

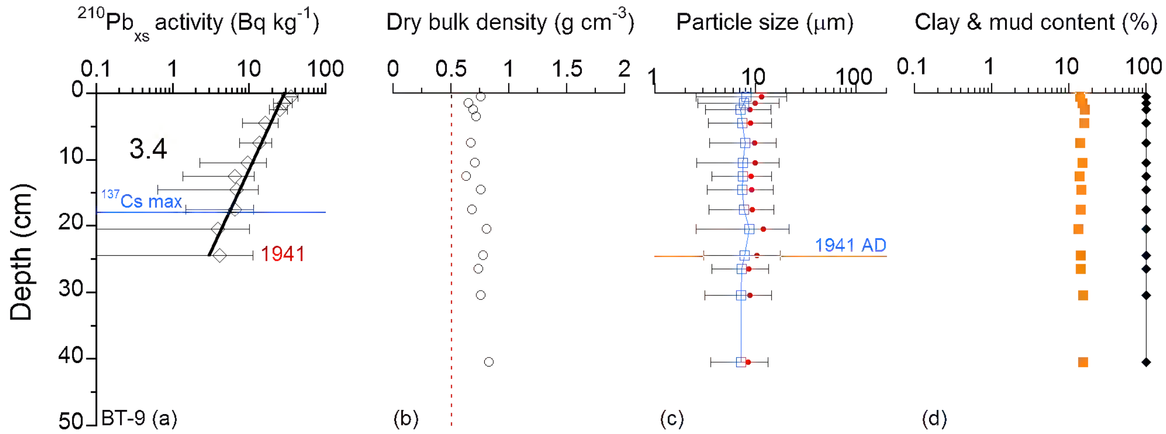

Figure 3-15: Core BT-9 (Beatrix Bay) - ages of sediment layers and sediment accumulation rates (SAR), and sediment properties. (a) Excess ^{210}Pb activity profiles with 95% confidence intervals shown. Time-averaged SAR (Black text) derived from regression fit to natural log-transformed ^{210}Pb data. Estimated ages of depth horizons (red text). Surface mixed layer (SML) inferred from excess ^{210}Pb profiles. Maximum depth of caesium-137 (^{137}Cs) indicated. Radioisotope activity expressed in units of Becquerels (Bq). (b) Sediment dry bulk density; (c) mean (red) and median particle diameters with standard deviation; (d) clay and mud content as percentage of sample by particle volume.

3.2 CSSI sediment modelling results

Surface sediment mixture samples were collected from 9 sites (Table 3-3, Appendix F).

Table 3-3: Site information for surface samples collected in March and April 2015 at selected locations within the Pelorus Sound. (See Figure 2-2 for relative positions of sampling sites by core ID).

Core_ID	Sample	Site description	Lat	Long	Depth (m)	Comments
BT-1	BT1	Inner Laverique Bay	41 03.086	174 02.636	16	Hard packed sand mud shell gravel
BT-5	BT5	Outer Laverique Bay	41 02.975	174 02.474	25	Sand mud shell gravel
BT-9	BT9	Offshore Laverique Bay	41 02.541	174 01.764	36	Soft mud
KP-1	Kenepuru	Te Matua a Maui Bay	41 11.294	173 57.452	6	Soft mud
KP-6	Ken-Mid	Waitaria Bay	41 10.417	174 01.836	9.5	Soft mud
KP-10	Ken-Top	Upper Kenepuru	41 10.950	174 05.088	6	Soft mud
SKP3	MF-Kenepuru	Mussel farm sediment,	41 10.413	174 01.296	5	soft mud
SYNC5	MF-Yncyca Bay	Mussel farm sediment,	41 08.194	173 52.860	25	live mussels
SORCH	MF-Orchard Bay	Mussel farm sediment,	40 57.273	174 04.032	28.7	live spat

The major sediment sources were found to be derived from the ‘Havelock inflow’, pine, subsoil and bracken (Figure 3-16), with beech forest, ponga, native forest (other than beech), and sheep being only minor components. At most sites, there were substantial proportions of sediment with a pine signature in the upper 2 cm (Figure 3-16).

This is consistent with the large areas of pine plantation forestry in the Pelorus Sound catchment and the potential for sediment relocation with the complex hydrodynamics associated with the large freshwater inflow at the head of the Sound and saline oceanic bottom water intrusions into the Sound.

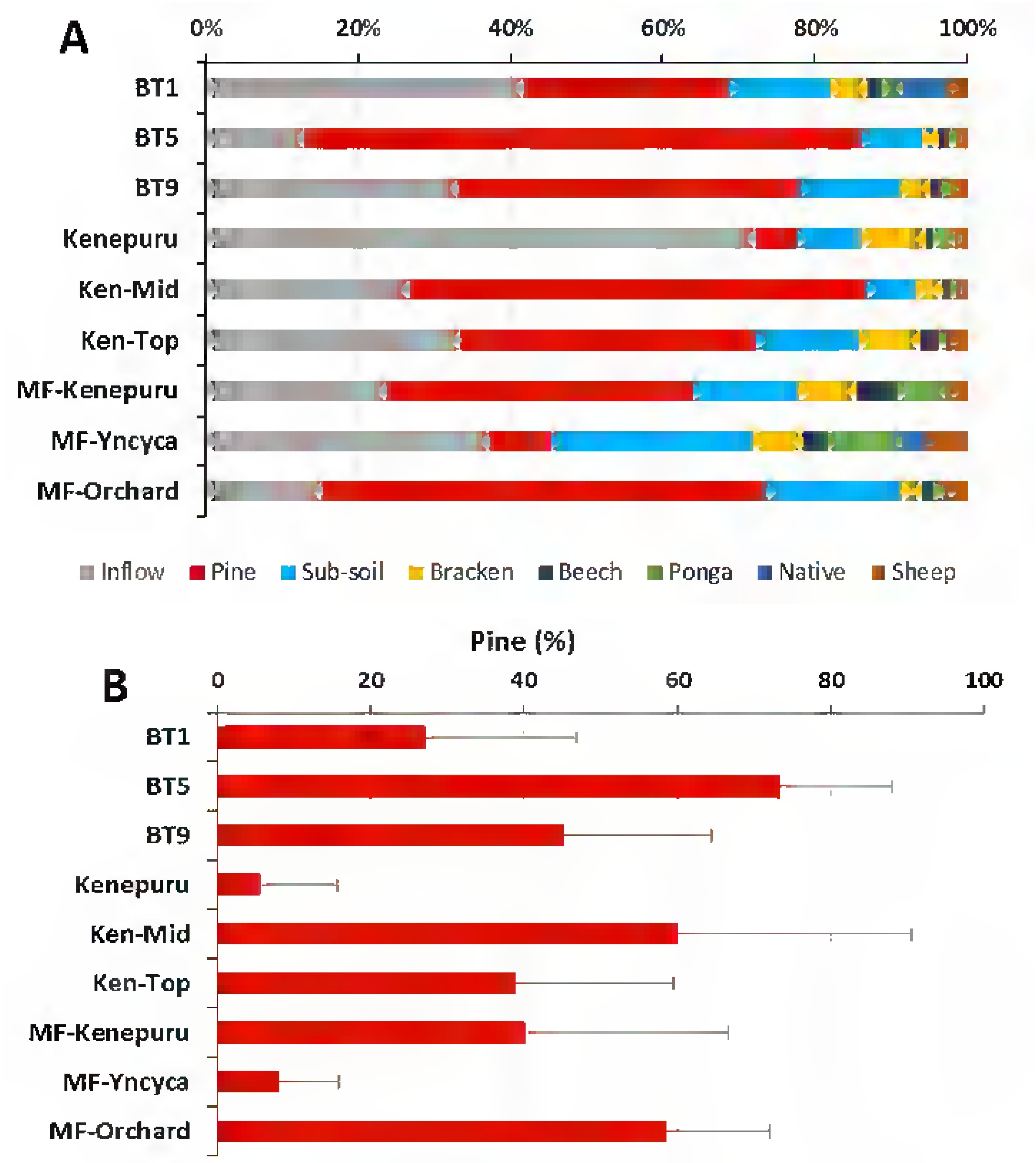

Figure 3-16: A) Proportional soil contributions from surface sediments from each of 8 sources and B) pine sediment only to the sediment mixture at each sampling site listed in Table 3-3.

Beatrix Bay cores: Sediment cores were taken from 6 sites: two in Beatrix Bay (BT-8 and BT-11) and four in Kenepuru Sound (KP-4, KP-6, KP-11 and PP-2) to look at changes in land-use over time (see Figure 2-2 for exact locations and relative positions of the core sites to each other). The core location in Beatrix Bay present a short transect from the shallow inshore site to a deeper off-shore site corresponding with the surface sediment samples BT-1, BT-5 and BT-9 (Figure 3-17).

The mid-depth core at BT-8 had lower proportions of the inflow source sediment (~20%) than the deep-water core at BT-11 (~50%) but higher proportions of sub-soil at 23-45% compared with 15-24% at BT-11. While both cores had sediment from native vegetation, bracken and ponga were present in highest proportions in core BT-8 consistent with this site being closer to shore. Sediment from native forest/bush was minimal at both sites and there was a higher proportion of sediment from sheep pasture at BT-8 than BT-11. This is consistent with native bush clearance in the 1800s and conversion to pasture before the 1990s.

A general interpretation of these data is that sediment was being carried from the 'Havelock inflow' and out of the sound also intruding into the side arms and embayment depositing the sediment load in the middle of the bay. Near-shore current generated by tidal action is more likely to resuspend sediment (Gibbs et al. 1991) and thereby reduce the amount of fine sediment depositing from this source. Conversely, fresh terrigenous sediments would have a higher clay content (sub-soil) and be more granular thereby flocculating and settling locally more rapidly in the inshore waters. Consequently, soil erosion from the Laverique Bay catchment is likely to deposit within the bounds of Laverique Bay and diminish with distance from shore (Figure 3-17).

Contributions of sediment with a pine signature ranged from ~8% up ~40% at different depths in the sediment cores at both sites (Figure 3-17). As there was less pine forestry in the Laverique Bay catchment, the pine signature sediment may have been transported around the Beatrix Bay, Clova Bay and Crail Bay forest areas. This would also be consistent with more elevated pine proportions in the offshore site BT-11. The elevated proportion of pine signature in the offshore site around 1946, 1972 and the present are indicative of production forest activity such as harvesting and land clearance for replanting locally within the Beatrix Bay, Clova Bay and Crail Bay complex. It may also indicate sediment from the timber mill at the head of Clova Bay (Benny 2015).

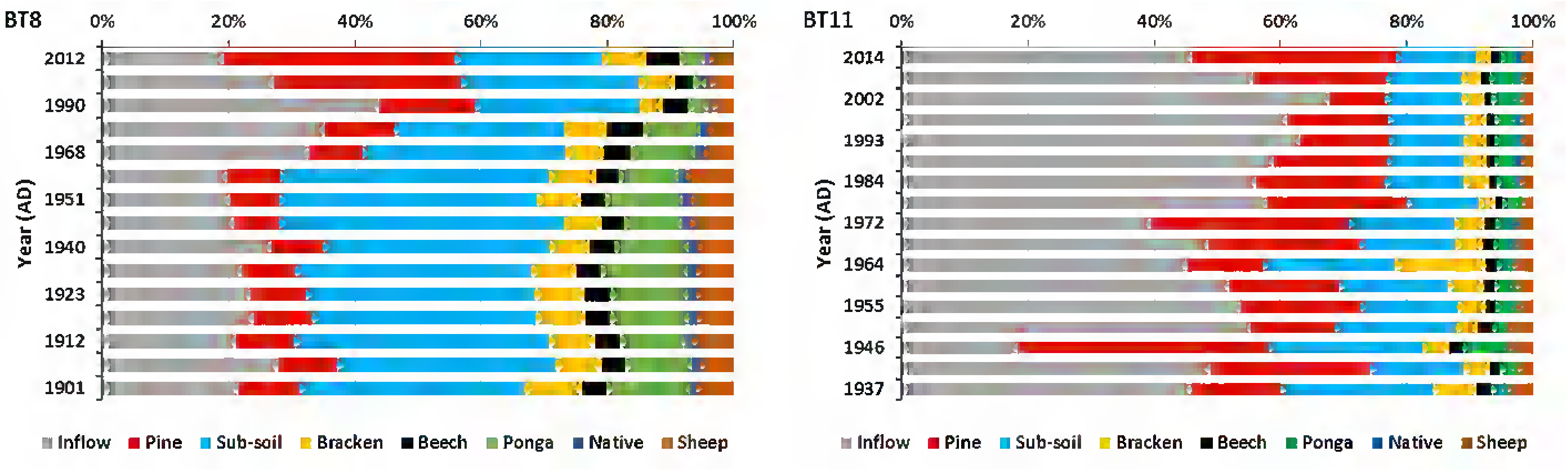

Figure 3-17: Relative sediment source proportions through the 1900s to present in sediment cores collected in Beatrix Bay. Core BT-8 was from the outer Laverique Bay site and core BT-11 was from the offshore Laverique Bay site (Figure 2-2).

Kenepuru Sound cores: The four sediment cores collected in Kenepuru Sound also showed temporal differences in the relative proportion of different source soil contributions at each site (Figure 3-18). As with the Beatrix Bay core, a general interpretation of these data is that sediment from the Pelorus River inflow was also being dispersed into the Kenepuru arm of the Sound. The relative proportion of the inflow sediment at these sites has been increasing since the late 1800s (Figure 3-18), which is consistent with the beginning of European settlement and the clearance of the native bush to produce sheep pasture and mining. It is also consistent with the requirement to keep a clear navigable passage for shipping. Brownlee's wharf was used by sailing ships about 1914 for loading logs (National Library Data).

About the same time, the proportion of sub-soil in the sediment began to decrease, which may be related to a change in vegetation cover and a reduction in slips, through human intervention. Bracken is typically associated with land slips as it is the first plant to colonise the disturbed poor quality soil exposed. Bracken rhizomes can also survive fire, allowing for rapid regeneration (McGlone et al. 2005). There appeared to be a step-wise increase in inflow sediment in the 1980s to 1990s which may indicate disturbance of the sediment in the Havelock estuary during Port Marlborough's developed of the navigable shipping passage (M. Gibbs pers. observ. 1984-1985). The mussel industry needed the Havelock Harbour channel to be maintained by dredging to allow larger mussel barges access to the Havelock wharf. It is unlikely that that this increase in inflow sediment can be attributed to eradication of the invasive cord-grass, *Spartina* (ca. 42 ha cover) that did not begin until after 2002 (Brown 2002) with aerial spraying taking place in 2004-05.

The sheep pasture sediment proportion decreased slightly after the 1960s. This was possibly associated with an early peak in sheep production recorded nationally in the late 1960's followed by another in the early 1980's with decline in sheep production following abolition of development loans for marginal lands by the fourth Labour government (e.g., superphosphate fertiliser) in 1984 (StatsNZ 2012) and the conversion of the steep land to pine forestry.

The pine signature sediment was typically around 10% by proportion at the four sites in Kenepuru Sound. There were exceptions which appear to be related to local forest harvesting. For example, the high pine sediment proportion at site KP-4 in the 2010 layer (68%) was most likely associated with harvesting operations on the adjacent headland at Koutuwai Point at that time (Figure 3-19). Similar harvesting events are likely to be the cause of elevated pine signature sediment proportions at site KP-11 around 1993 (20%) and at Poison Point site PP-2 around 1999 (48%).

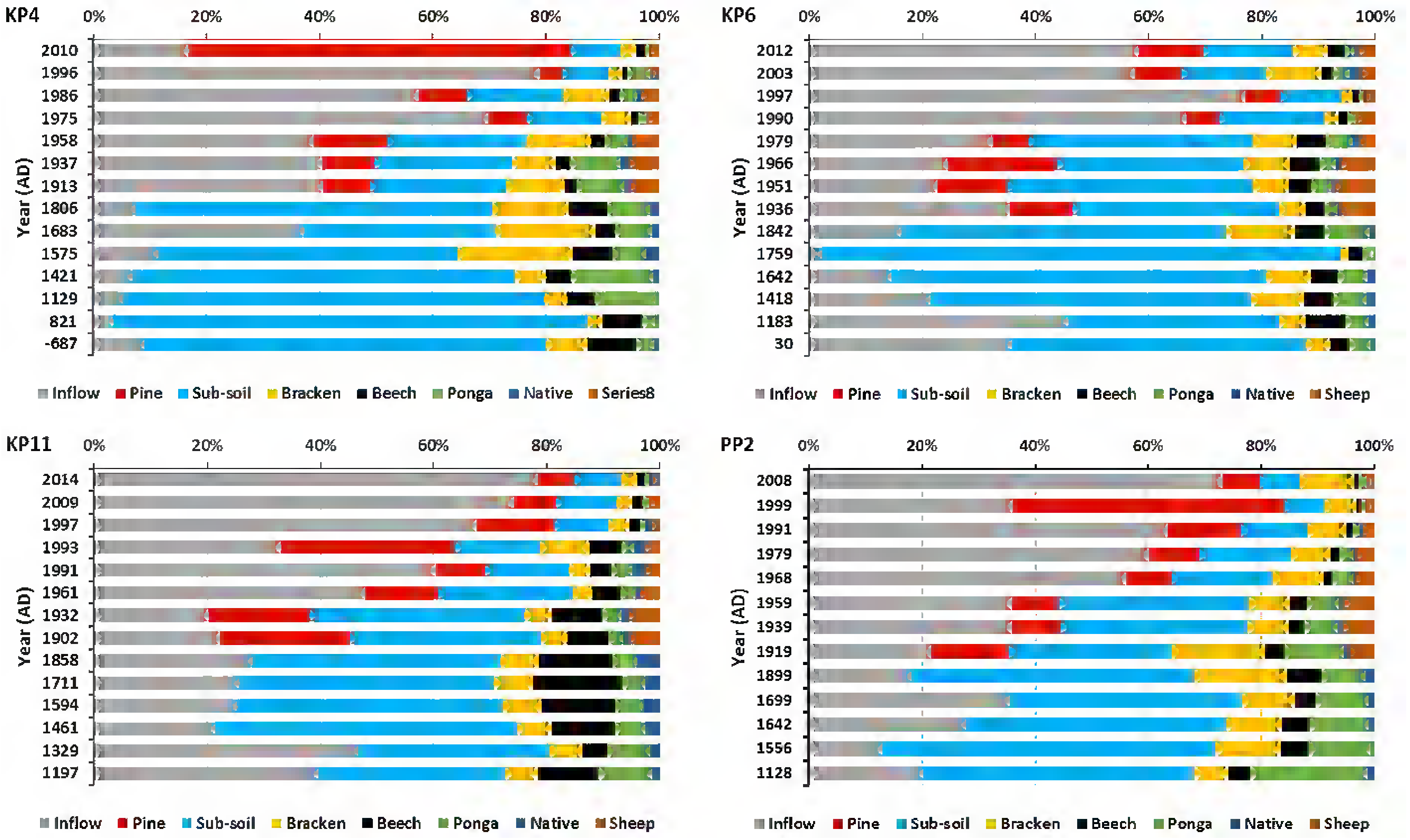

Figure 3-18: Temporal changes in source soil contribution in the four cores from Kenepuru Sound. (See Figure 2-2 for exact location of each core site).

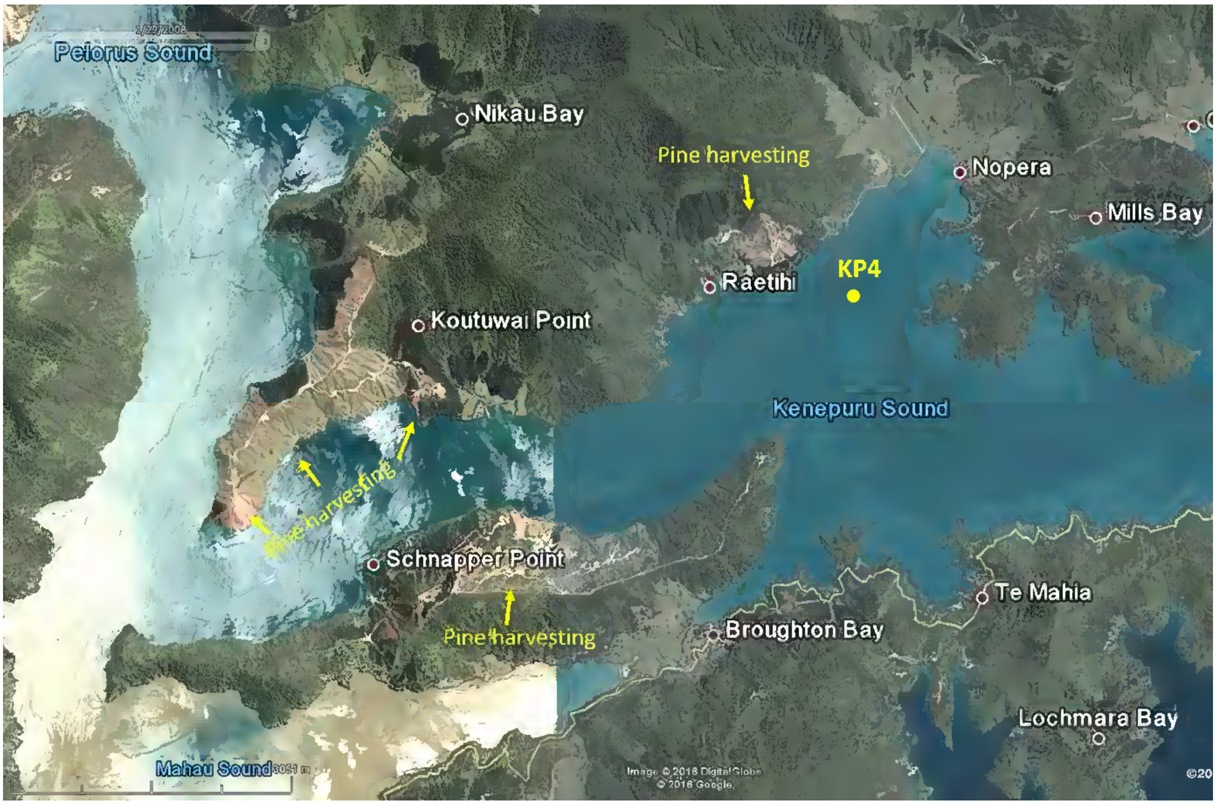

Figure 3-19: Google Earth image (22 January 2008) showing the extent and proximity of pine forest harvesting to core site KP4.

3.3 Mollusc death assemblage (DA)

3.3.1 Former mussel reef DA

Multivariate canonical analysis of principal coordinates (CAP) analysis of the percent carbonate content of the sediments revealed an interesting separation of the samples by time period that delineated pre-European settlement (<1860s) sediments from modern-day sediments (Figure 3-20a). Plotting of the data points as bubble plots (% volume of carbonate/year) showed early sediments (<1850) contained low levels of shell derived carbonate content compared with the European period. Labelling of the sample points by site showed that this relationship was present across all three Kenepuru mussel reef sites that were exploited during the 1960-70s (Figure 3-20b). The Pearson correlation biplot shows that although the dominant correlate was carbonate content, rock gravel was also strongly correlated but only one of the eight laser particle size fractions included in the model (125-250 µm) was moderately correlated with the CAP2 axis.

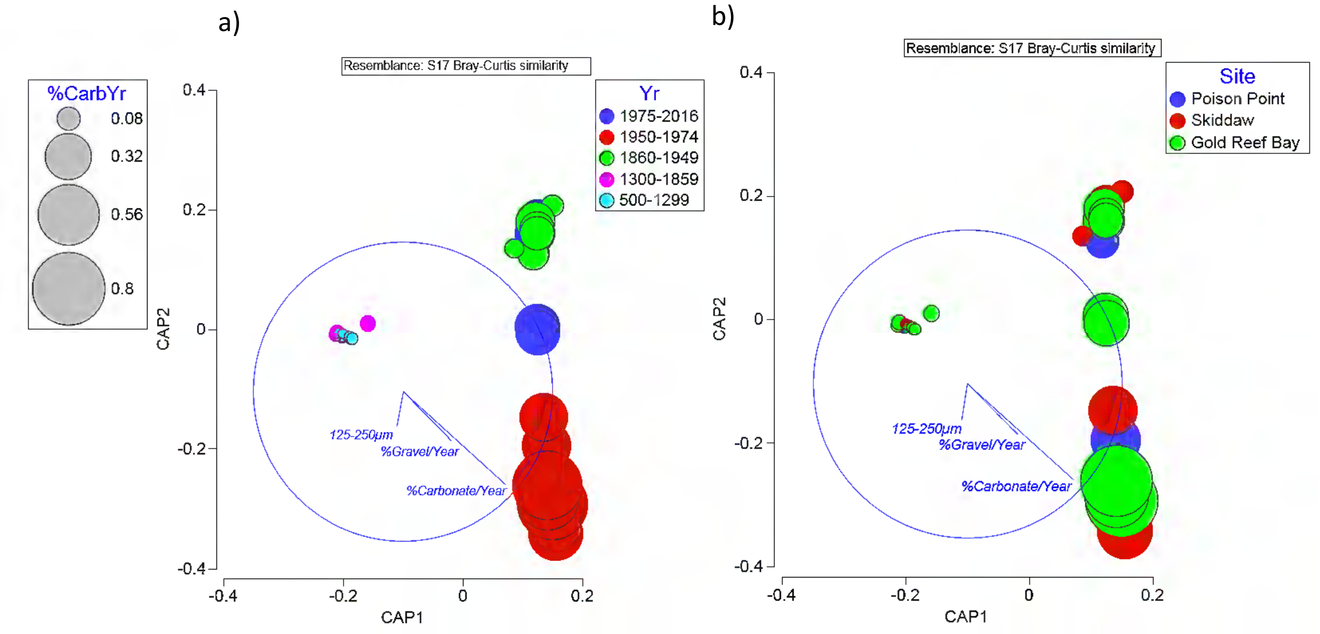

Figure 3-20: a) CAP plot attempting to discriminate mussel reef core sections by time period (Yr), and b) the same samples labelled by site. The biplot overlay shows the Pearson correlation coefficients (>0.3) of sediment characteristics.

Analysis of the sediment characteristics averaged across replicate cores collected at each coring site confirmed there was an increase in carbonate deposition after European colonisation and that deposition peaked in 1950-74 then decreased again in recent sediments (Figure 3-21a). The Gold Reef Bay West carbonate levels were notably greater than the other sites, and the small confidence intervals indicate high precision of the estimates, showing that within sites there was low variation between cores, thus they accurately recorded conditions at each site. Plotting of rock gravels showed that Gold Reef Bay West site had much higher levels of schist rock gravel present in cores than the other sites (Figure 3-21b). The peak in rock gravel deposition was during 1950-74. Interestingly, the supply and accumulation of schist rock gravel mirrored the trend in the mollusc shell deposition (Figure 3-21a).

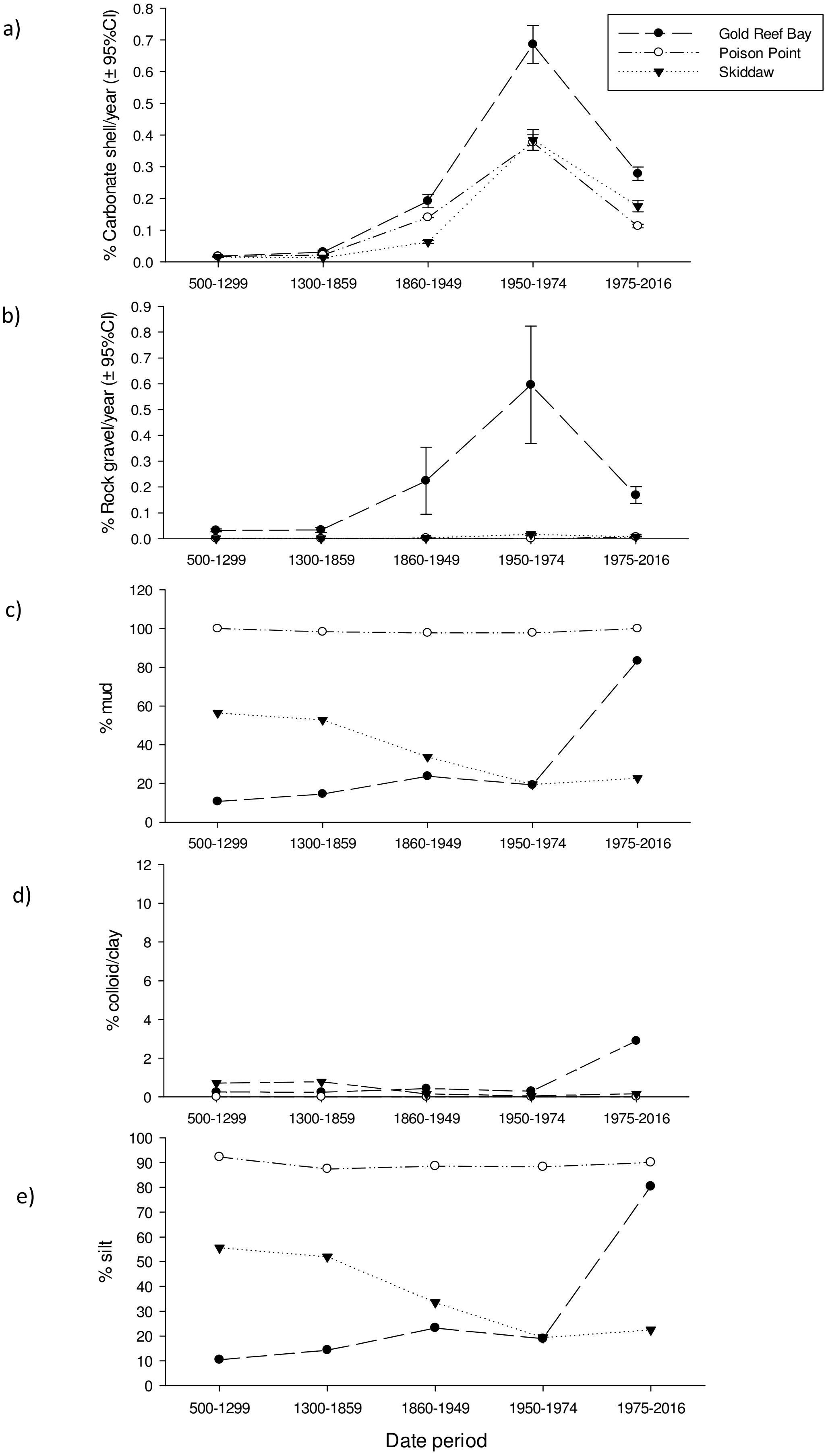

Figure 3-21: Sediment characteristics derived from mussel reef cores plotted by time-period. Percent content of: a) carbonate shell, b) rock gravel, c) mud (0-62.5 µm), d) colloid clay (0-3.9 µm) and e) silt (3.9-62.5 µm).

We hypothesise that the high levels of rock gravel at Gold Reef Bay West were due to localised post-European land-based disturbance activities or unstable substrata up-slope of the coring site supplying terrigenous gravel. As this site-specific effect may confound system-wide comparisons, it was decided to exclude samples from this site from further multivariate analyses.

Analysis of the different sediment grain sizes measured by the laser analyser and plotted as mud, silt, and colloid classes showed that Poison Point closest to the head of Kenepuru contained the greatest volume of mud and silt, but interestingly Skiddaw, closest to Havelock, was the next muddy and silty site (Figure 3-21c, e). During the decline in the peak in carbonate shell deposition after 1974, mud, silt and colloid content all rose at the middle Kenepuru site at Gold Reef Bay West (Figure 3-21c-e).

A repeat of CAP analysis, after excluding the post-European Gold Reef Bay West samples, more-clearly discriminated pre-1860 samples from later sediments (Figure 3-22a, b). However, the 1950-1974 period was also markedly different to the 1860-1949 and the 1975-2016 periods. Possible hypotheses for these differences are either physical disturbance from fishermen dredging for mussels during that period increased the deposition of mollusc shells thus killing more molluscs, and/or mollusc productivity was enhanced during that period (Hypothesis 1, Ho:1). It was also interesting that the post-European periods contained elevated quantities of deposited mollusc shells compared with pre-1860 sediments (Figure 3-22a). We raise a second hypothesis that this may be due to enhanced productivity of the benthos resulting from land-based disturbance elevating nutrient supply to the Pelorus system (Ho:2).

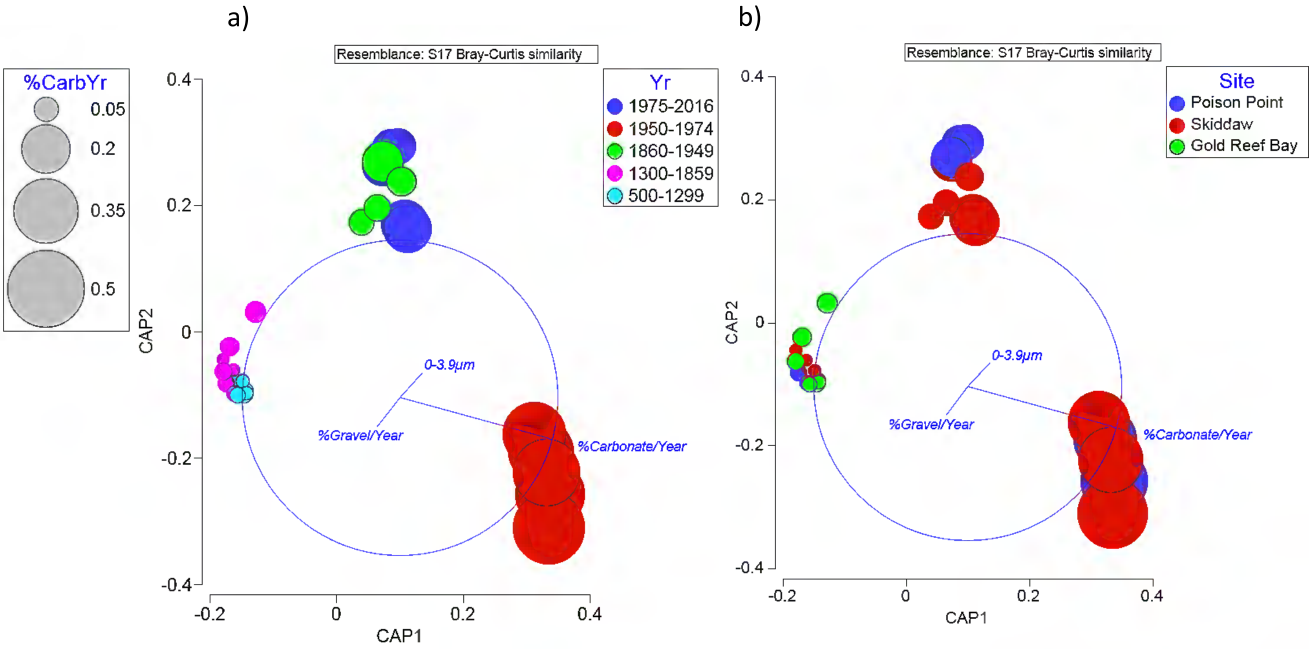

Figure 3-22: a) CAP plot attempting to discriminate mussel reef core sections by time period (Yr), and b) the same samples labelled by site. The biplot overlay shows the Pearson correlation coefficients (>0.3) of sediment characteristics. Note: the CAP analysis excludes samples from Gold Reef Bay West between: 1860-2016.

3.3.2 Death assemblage (DA) species composition

To investigate Ho: 1, we analysed species represented in the mussel reef core DA by overlaying Pearson correlations coefficients of the mollusc species from the DA (Figure 3-23). These correlations show some changes in the species composition over time. The mollusc macrofauna shells deposited during early and most recent European time-periods (CAP1 axis) were most correlated with the suspension feeding gastropod *Sigapatella novaezelandiae*, the veneroid bivalve *Pratulum pulchelleum*, the pinnid bivalve *Atrina zelandica*, the deposit feeding mud snail *Amphibola crenulata*, the deposit feeding bivalve *Leptomya*, and calcareous tubeworms (Figure 3-23). In contrast, the macrofauna between 1950-1974 (CAP2 axis) were more-strongly correlated with suspension feeding: oysters *Ostrea chilensis*, turret shells *Māoricolpus roseus/Stiracolpus* sp., *Venerupis largillierti*, the scallop *Pecten novaezelandiae*, *Corbula zelandica*, the cockle *Austrovenus stutchburyi*, and the deposit, grazing and scavenging *Diloma aethiops* and *Coelotrochus tiaratus*.

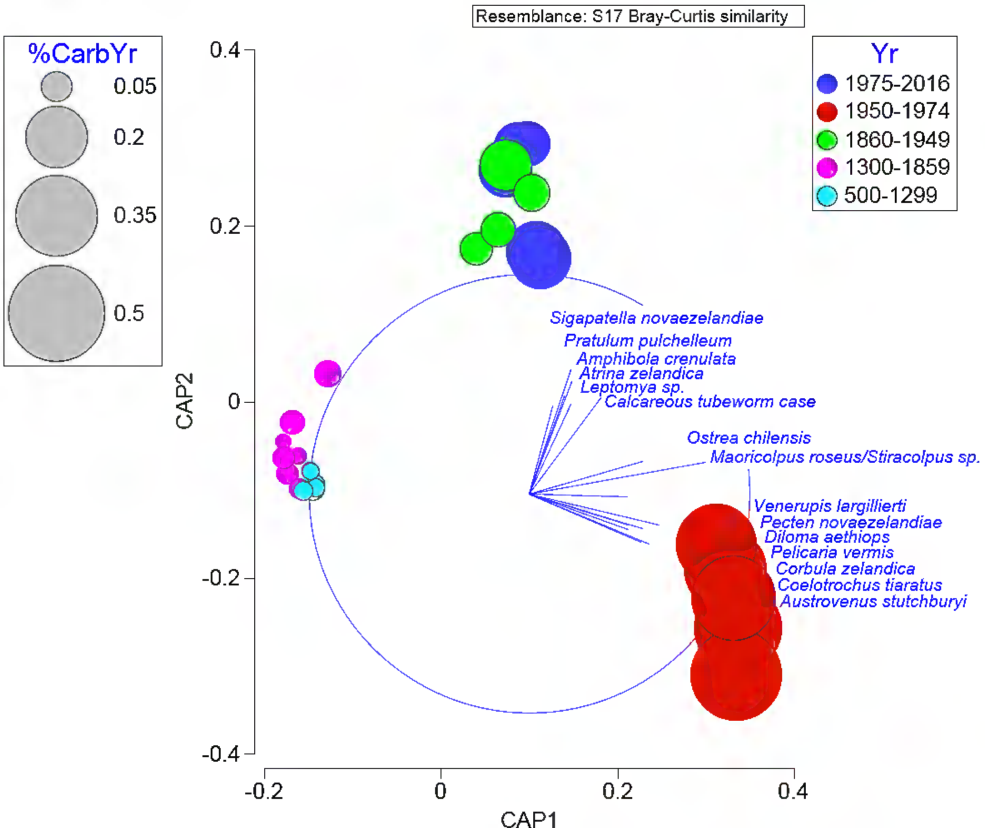

Figure 3-23: CAP plot attempting to discriminate mussel reef core sections by time period (Yr). The biplot overlay shows Pearson correlations of (P>0.4) species represented in the death assemblage (% by volume) correlated with the CAP plot. Note: the CAP analysis excludes samples from Gold Reef Bay West between: 1860-2016.

3.3.3 DA commercial bivalve species

Of significant note to one of the main aims of this study, mussel shells were not common in the mussel reef cores sampled close to shore in areas formerly surveyed to contain mussels living atop reef and soft sediment habitats (Figure 3-24c, (Stead 1971a, Stead 1971b). Analysis of the remains of commercial species (scallops, dredge oysters and mussels), revealed scallops then oysters were more abundant in the DA than mussels. There appeared to be a significant increase in scallop shell deposition at Skiddaw and Poison Point after European occupation, and dredge oysters at all sites (Figure 3-24 a, b, c). Mussel shells were poorly represented in the DA and indicated a trend (note: 95% confidence intervals overlapped so differences are not statistically significant) at Poison Point and Skiddaw of an increase in deposition during the Māori period (1300-1859) and the early European period (1860-1950), that appeared to decrease after 1950. However, the low counts of mussel shell, giving rise to large within- and between-site variability, limited comparisons.

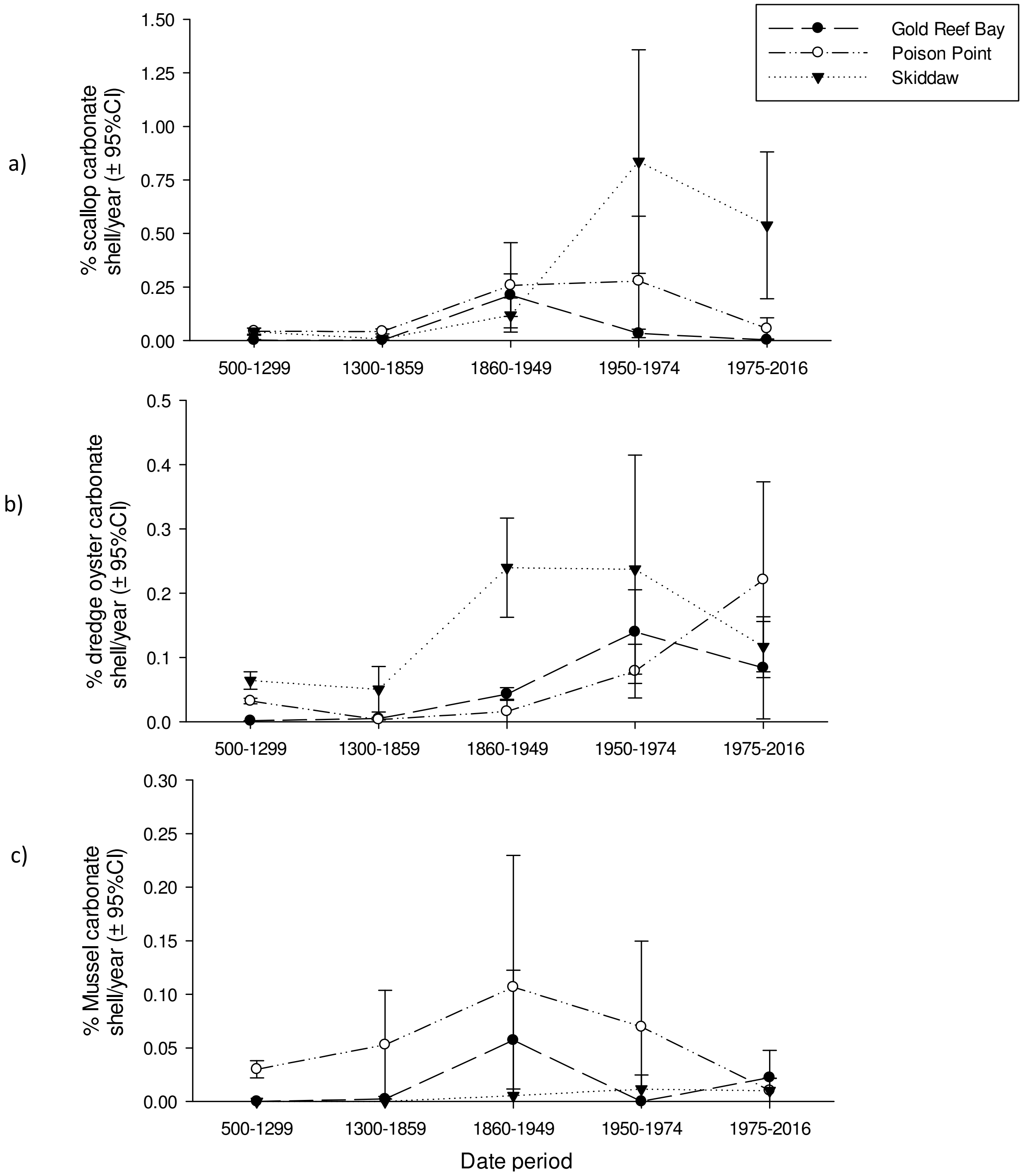

Figure 3-24: Percent volume of carbonate deposited from commercial shellfish species derived from shell gravel cores sampled in Kenepuru. a) scallop *Pecten novaezelandiae*, b) dredge oyster *Tiostrea chilensis*, and c) mussel (unknown species).

3.3.4 DA functional feeding traits

Analysis of the total functional feeding trait indices as a biplot over the CAP plots from Figure 3-22 and Figure 3-23 indicates a correlation of increased importance of suspension and deposit feeders along the CAP1 axis (Figure 3-25). Plotting of the data points as bubbles depicting total functional trait index values indicated that the DA functional feeding scores were reduced during the 1950-1974 period (Figure 3-25). Plotting of each individual feeding trait by site and time period showed that overall suspension feeders followed by deposit feeders were the most common feeding mode represented by the DA at Gold Reef Bay. Despite there being patchy and sometimes high variation in the role of the feeding traits between cores within sites, indicated by the size of the 95% confidence intervals, there appeared to be a downward trend in the importance of scavengers, grazers and predators in the most recent time period (Figure 3-26c, d, e). There was also a notable decline in suspension and deposit feeding, and scavengers during 1950-1974 (Figure 3-26a, b, d), potentially indicating reduced functional diversity.

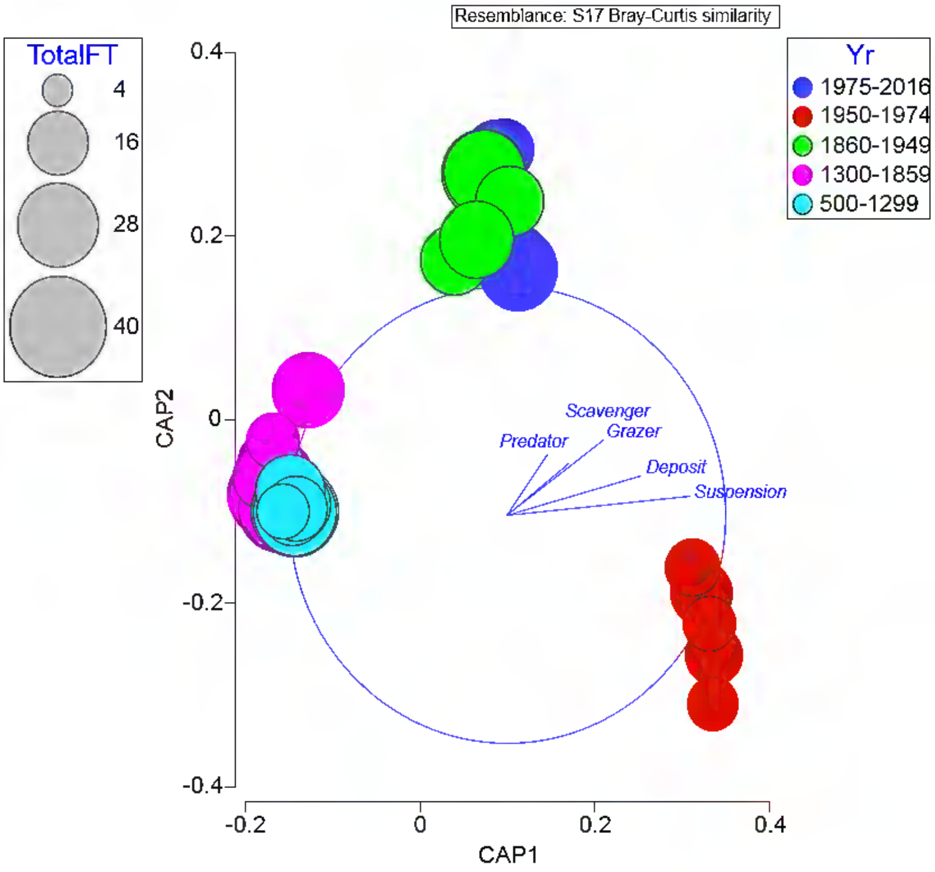

Figure 3-25: CAP plot attempting to discriminate core sections by time period, expressed with bubble plot showing the total number of functional feeding trait scores from core samples of the faunal death assemblage from the shell gravel cores sampled in Keneperu. The biplot overlay shows the Pearson correlations (P>0.2) of the total functional trait index scores from each time period (Yr). Note: the CAP analysis excludes samples from Gold Reef Bay West between: 1860-2016.

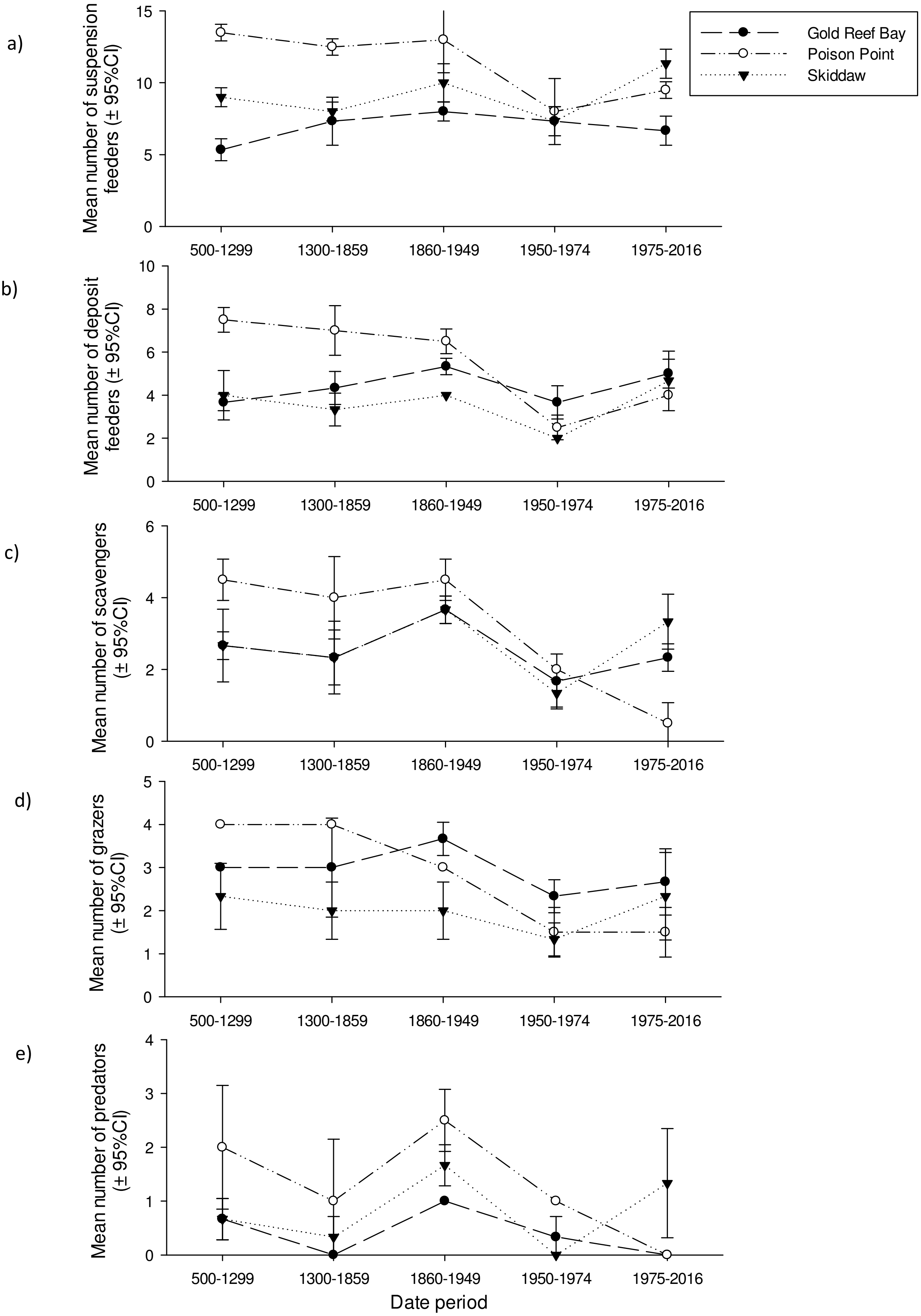

Figure 3-26: Functional trait scores expressed as percentage of total, derived from the death assemblage extracted from shell gravel cores collected in Kenepuru Sound.

By multiplying the proportion of each feeding traits by the total shell volume of all identifiable species collected in each date period, we see that suspension feeders were the dominant feeding trait by shell volume, and these greatly increased from 1860-1949 with peak in their abundance during 1950-1974, and then declining (Figure 3-27). These were represented by the turret shell *Maoricolpus roseus/Stiracolpus sp*., scallops *P. novaezelandiae*, the dredge oyster *Ostrea chilensis*, and the bivalve *Dosina mactracea*. The deposit feeders: *Venerupis largillierti, Diloma aethiops* and *Coelotrochus tiaratus* were less abundant, but have continued to increase. Grazers, predators and scavengers were far less abundant in the cores. Despite the large increase in volume of suspension feeders, the total number of species with each core section appear to decrease during 1950-1974 (Figure 3-28).

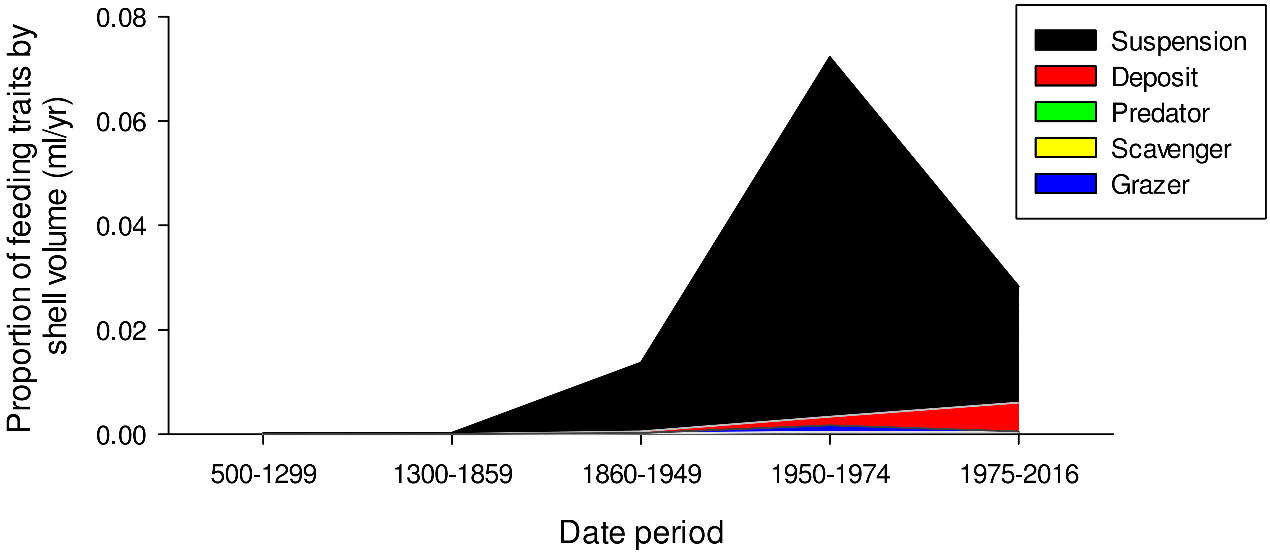

Figure 3-27: The mean proportion of feeding traits calculated from all cores expressed by shell volume (ml/yr). Note: predators and scavengers are not visible at this scale.

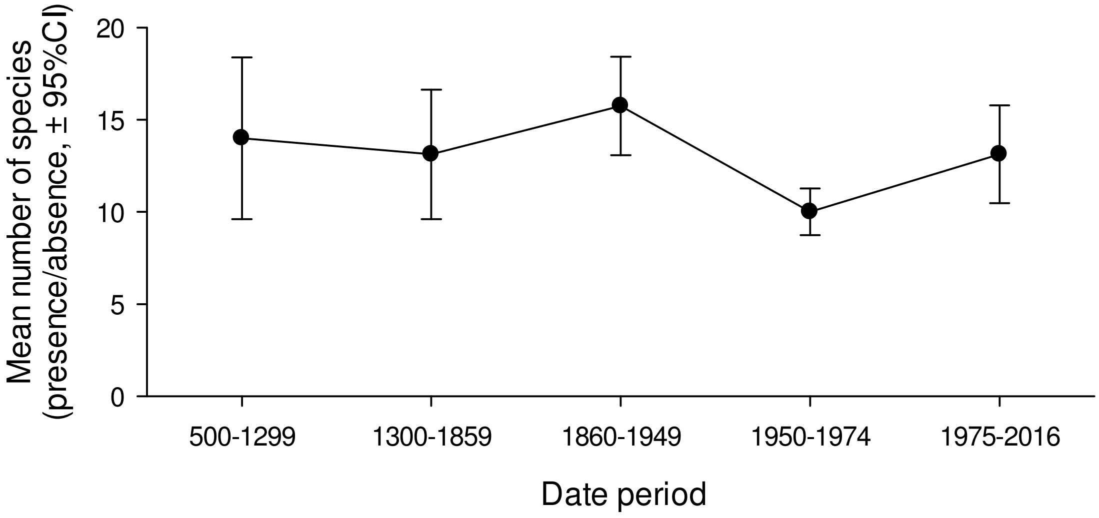

Figure 3-28: Mean number of species calculated from presence/absence from each date period across all shell-gravel cores.

A non-metric multidimensional scaling (nMDS) analysis of percent volume of carbonate overlaid by Pearson correlations of sediment grain size characteristics and C and N isotopes extracted from neighbouring CSSI sampling cores (i.e., shell gravel-SKD1 c.f. CSSI-KP4, shell gravel-PP1 c.f. CSSI-KP6; Figure 2-2), showed that core sections with the greatest shell deposition were correlated with sediment grains larger than mud (125-250 µm) and greater δ^{13}C levels. This was in contrast to the pre-European sediments being correlated with greater C:N ratios and finer grained sediments 15.6-62.5 µm; Figure 3-29). Correlation of the same plot with the CSSI soil signatures, show that sediments derived from sheep farming, pine harvest and the 'Havelock inflow' were correlated with the highest rate of mollusc shell deposition during 1950-74 (Figure 3-30). In contrast, the low levels of carbonate deposited before European settlement was correlated with beech forest, ponga and subsoils.

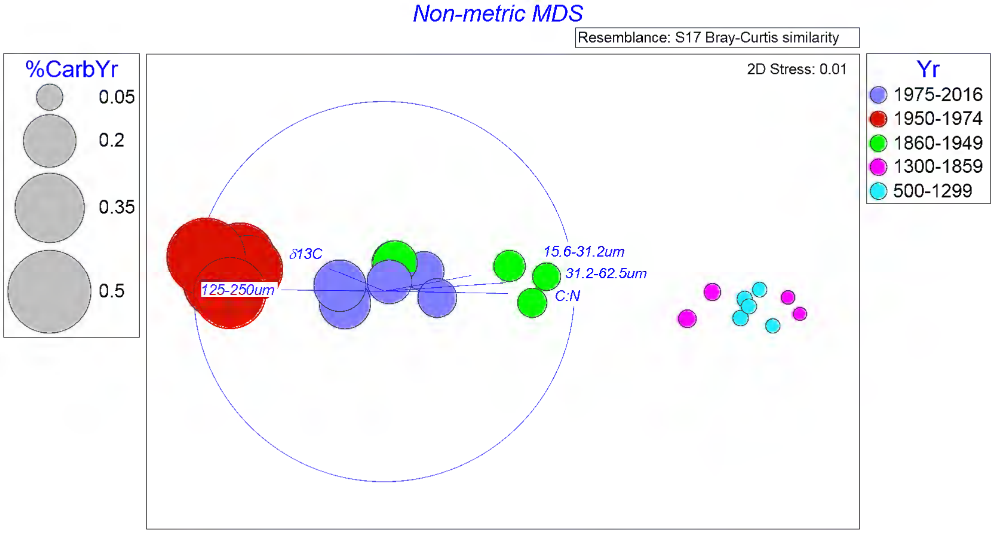

Figure 3-29: An nMDS analysis of percent volume of shell gravels from core samples of the faunal death assemblage from the mussel cores sampled in Keneperu plotted as bubbles (%CarbYr, excluding Gold Reef Bay cores). The biplot overlay shows the Pearson correlations (P>0.3) of the sediment grain size classes and δ^{13}C, δ^{15}N and the C:N ratio.

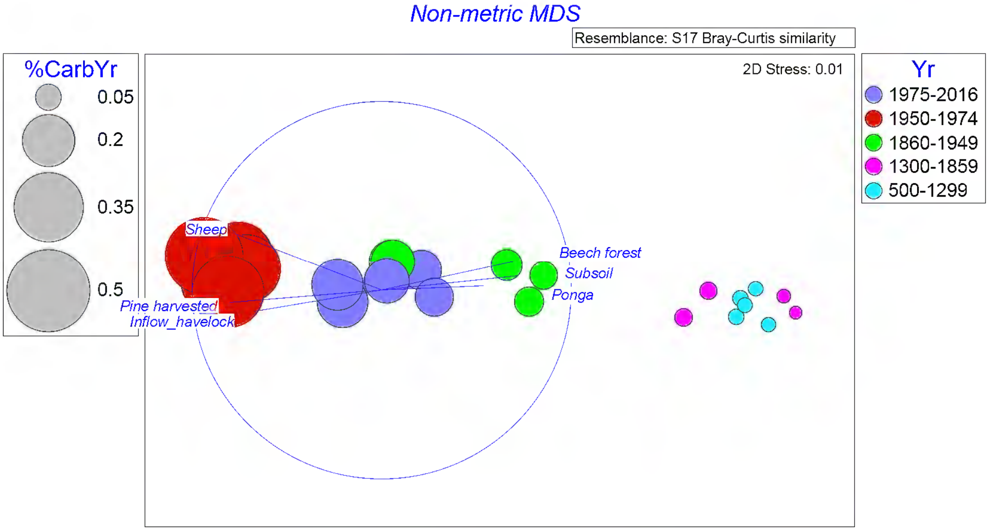

Figure 3-30: An nMDS analysis of percent volume of shell gravels from core samples of the faunal death assemblage from the shell gravel cores sampled in Keneperu plotted as bubbles (%CarbYr, excluding Gold Reef Bay cores). The biplot overlay shows the Pearson correlations (P>0.3) of the percent sediment contribution by land-use cover calculated from CSSI signatures (Section 3-2).

3.3.5 Temporal changes in sediment isotopes and soil sources

To give context to the temporal changes in the DA deposited close to shore over former mussel reef habitat, an analysis of the N and C isotopes stored in the sediments showed large variation in preservation of these signatures between the CSSI cores sampled in deeper water in the Kenepuru (Figure 2-2). Large differences within cores were especially evident in nitrogen signatures in KP-6 after 1905 in KP-10, and 1930s in KP-6 and KP-10 (Figure 3-31a). Similar fluctuations were evident in the δ^{13}C signatures, which resulted in reductions in the C:N ratio early in the 1900s, with some recovery, then a large decrease after 1975 (Figure 3-31b,c).

A comparison of the timing of these changes with the CSSI soil source contributions, shows a decline in the proportion of the dominant sediment type derived from subsoils after the 1800s, with small peaks in the late 1930s, 1950s and 1980s (Figure 3-32a). During this time, there are peaks and an increase in the proportion of sediment originating from 'Havelock inflow' evident especially in KP-4 which was sampled closest to the entrance to Kenepuru (Figure 3-32b, Figure 2-2). This showed a small peak in the early 1900-1930s, followed by a larger peak in 1975, and the largest in 1996. From early 1900s onwards soils originating from pine harvest and sheep farming become evident in the sediments, with spikes in bracken and ponga content starting from 1935 to 1960s followed by another peak in 1985 (Figure 3-32c-f). However, as sediment mixing appeared to have taken place in KP4 and KP10 these early dates where pine was first detected are considered approximate (see Discussion). In contrast in KP6, which had strongest agreement between ^{210}Pb and ^{137}Cs SAR estimates, we detected pine first in 1930.

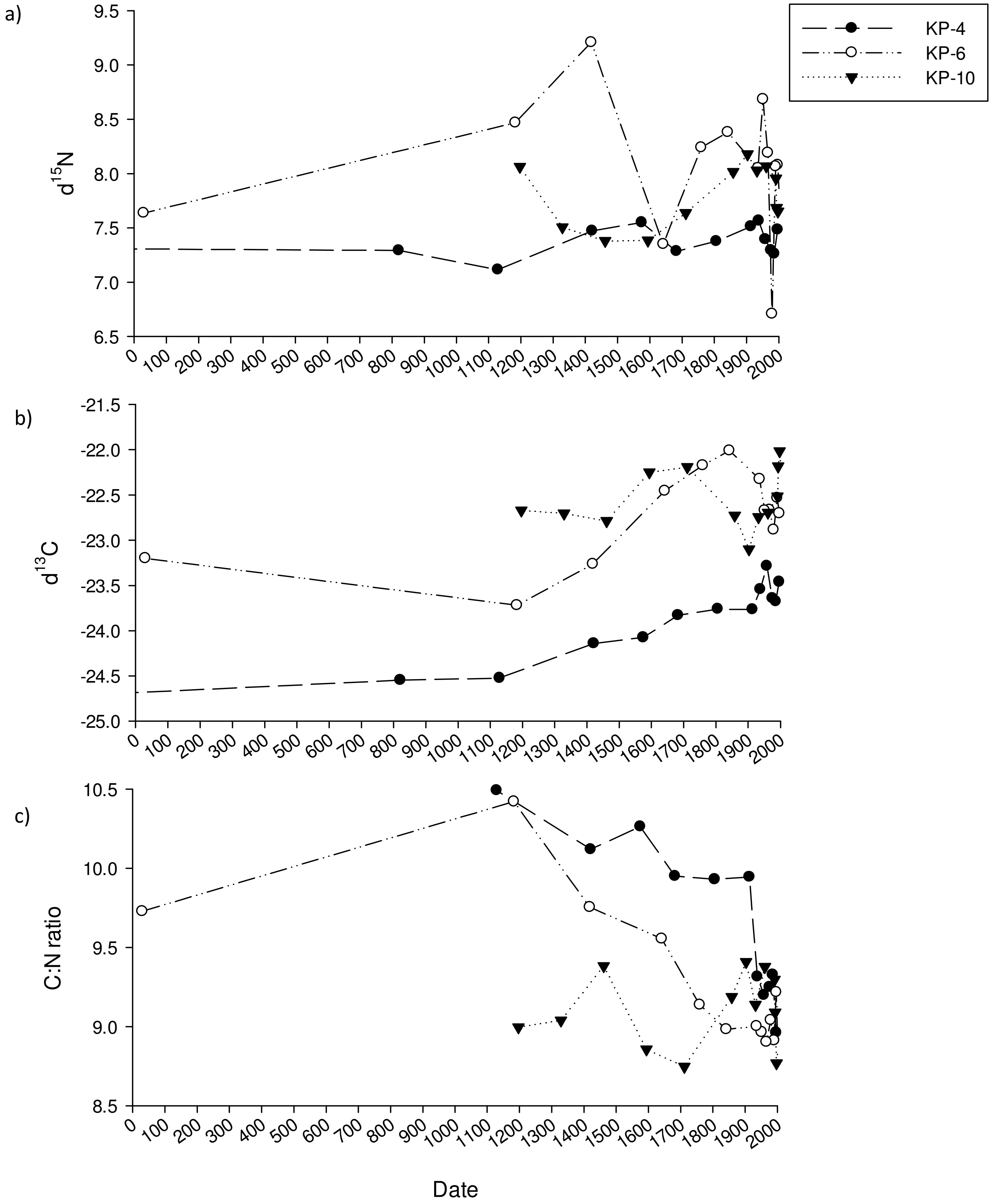

Figure 3-31: δ^{15}N, δ^{13}C and C:N stable isotope ratios analysed from CSSI sediment cores: KP-4, KP-6 and KP-10.

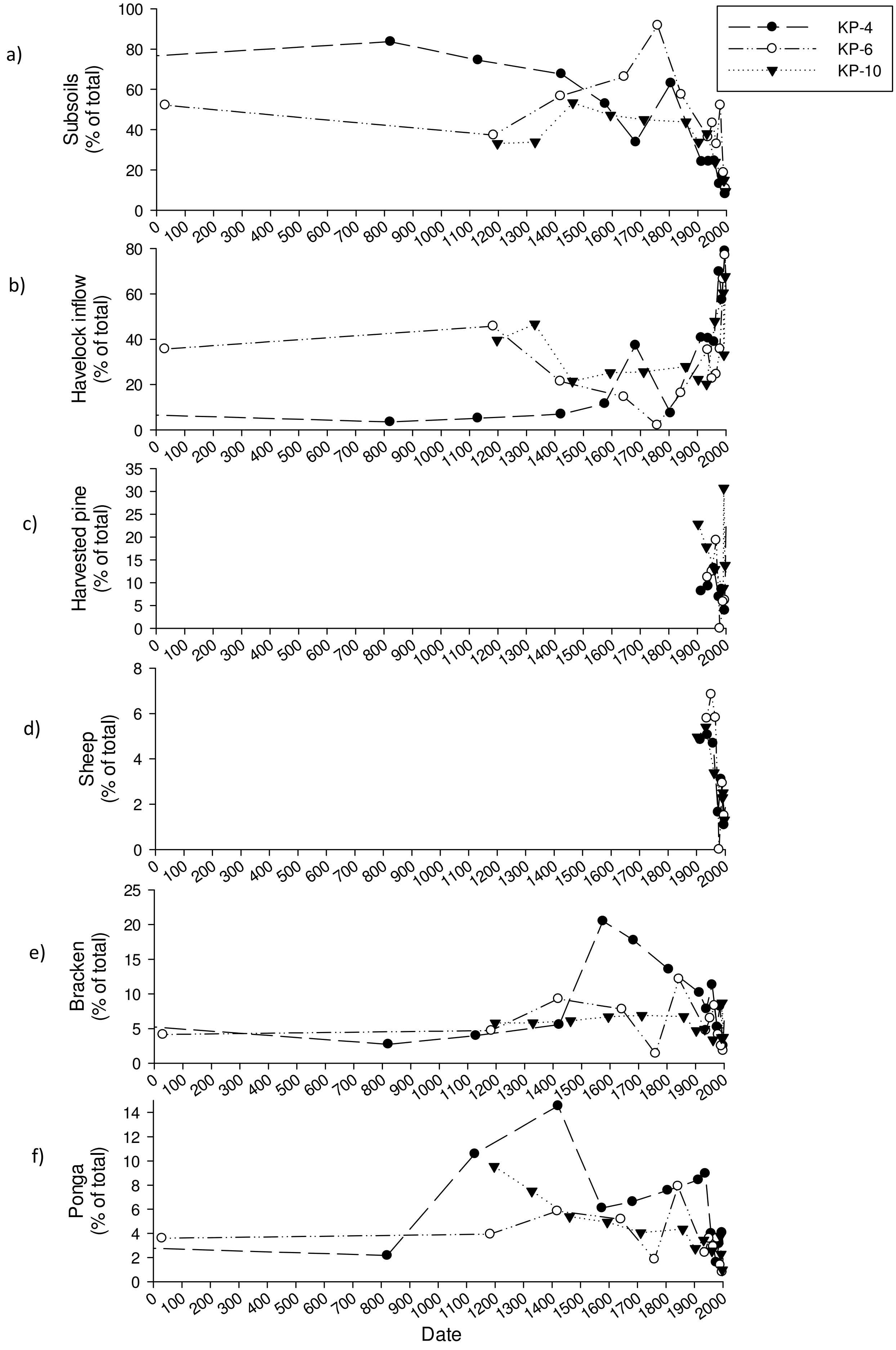

Figure 3-32: Percent of source soils derived from CSSI analysis of Kenepuru cores: KP-4, KP-6 and KP-11.

3.3.6 Offshore DA from CSSI cores

To explore Ho:2 that European land-based disturbance had contributed to nutrient discharge and increase in Pelorus productivity we analysed the CSSI shell gravel data from cores collected offshore in the middle of bays, away from the mussel beds mapped by (Stead 1971a) (Figure 1-10). The aim was to test if mollusc shell deposition was similarly elevated at offshore sites away from the influence of historic mussel dredging during 1950-1974. Unfortunately, as there were no intact shells in the Beatrix Bay cores near the base of the cores that could be aged by ^{14}C methods to constrain pre-human SAR's, pre-human SAR could not be accurately predicted. Thus, beyond 40-42 cm dating using ^{210}Pb constrained maximum quantified dates of 1911, 1899, and 1941 (BT-1, BT-6, BT-11 respectively). Dates younger than those calculated by ^{210}Pb are therefore only approximate estimates, but are likely to be under-estimates of the age of the sediments which likely accumulated more slowly before 1960s European settlement as shown in the Kenepuru cores (Section 3.1.1).

The shallow BT-1 core and the mid-depth BT-6 core contained 10-fold more volume of carbonate accumulated per year (Figure 3-31) as compared with the Kenepuru CSSI cores (Figure 3-33). However, the results of the deepest BT-9 and all of the Kenepuru CSSI cores (KP-4, KP-6 & KP-10) contained very low levels of carbonate. There was no indication of any increase in depositional rates during post-European colonisation periods. Further, an attempt to discriminate between different time periods using a CAP analysis of the CSSI shell-gravel data from the Kenepuru core sections too, failed to cluster samples (Figure 3-34) as compared the separation evident in the inshore mussel reef cores (Figure 3-22).

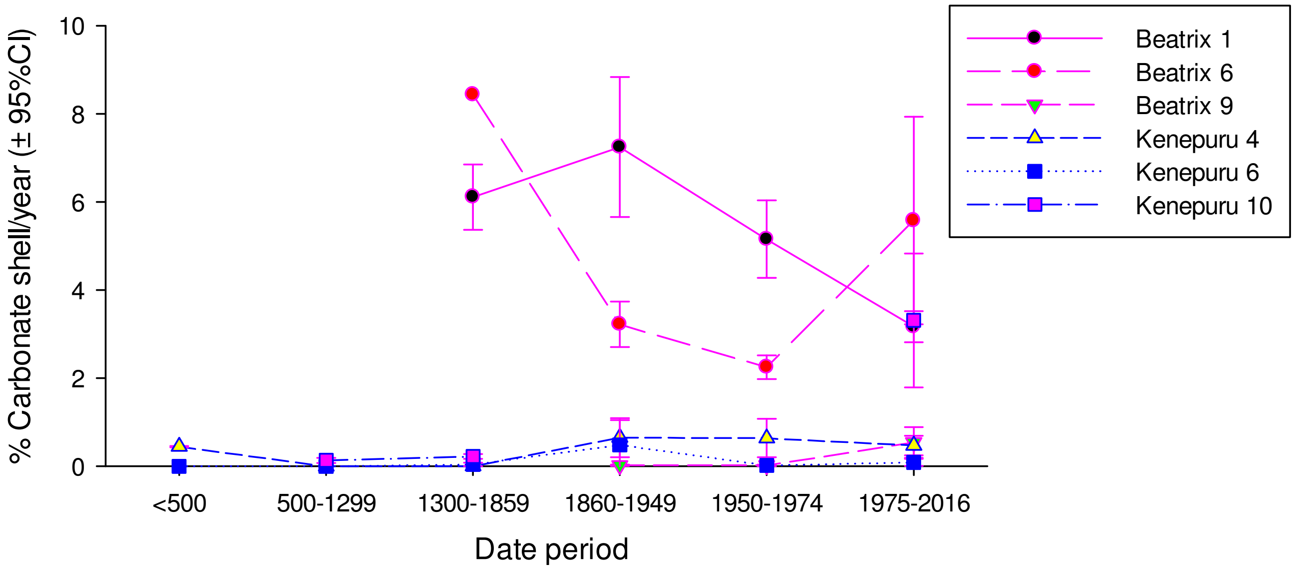

Figure 3-33: Percent carbonate accumulated by volume of sediment per year from cores collected for CSSI analysis from Beatrix and Kenepuru Sound. Core sample locations as per Figure 2-2.

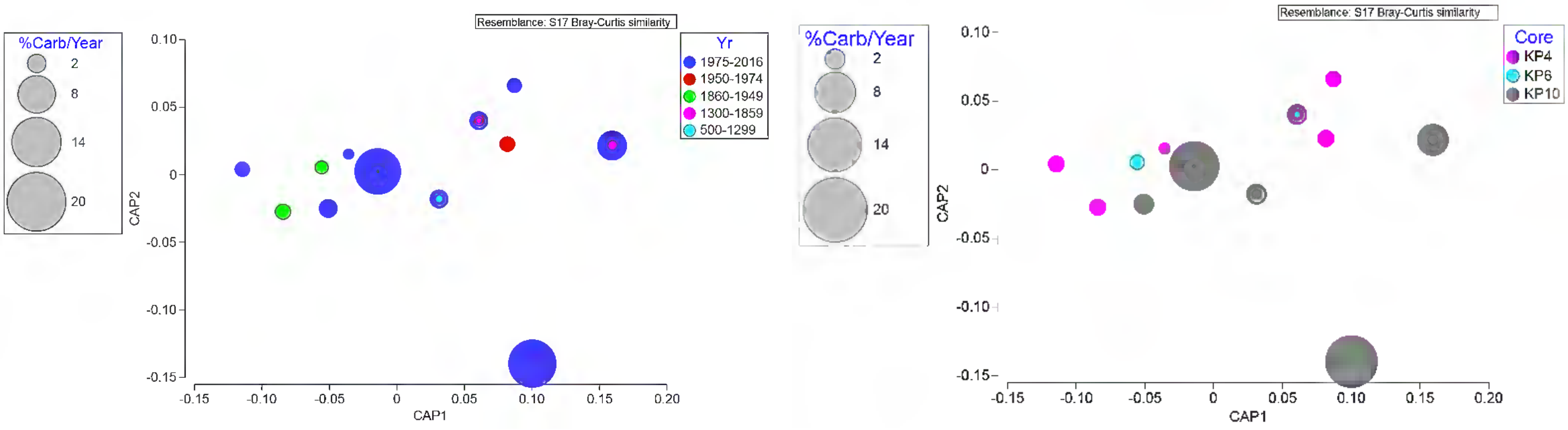

Figure 3-34: CAP plot attempting to discriminate percent carbonate accumulated by volume of sediment per year from Kenepuru CSSI core sections (KP-4, KP-6, KP-10). Labelled by time period (Yr, left), and the same samples labelled by core (right).

4 Discussion

4.1 Changes in sediment accumulation rates (SAR)

For the first time, rates of sediment deposition from different land-uses have been quantified over time in the Marlborough Sounds. The results show profound changes to sedimentation rates and shellfish composition since European settlement. Sediment accumulation rates (SAR) 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.

Reconstruction of the sedimentation history of Kenepuru Sound and Beatrix Bay over the last 800 to 3,400 years indicates that sediments accumulated at a relative low rate in Kenepuru Sound (0.1–1.1 mm yr^{-1}) to the late-1800s/early 1900s. The core data show a progressive increase in SAR from the entrance (west) to the head (east) of the Kenepuru Sound. Long-term pre-20th century SAR are also higher in the bays (0.6–1.1 mm yr^{-1}) than inshore of the relict mussel reefs (0.2–0.35 mm yr^{-1}). The long-term SAR measured in the present study are of the same order as pre-human rates measured in Nydia Bay (1.2 mm yr^{-1}) and Tennyson Sound (1.4 mm yr^{-1}, Lauder 1987), tributary arms of Pelorus Sound and are consistent with the results of previous coring studies conducted in Northland, Auckland and Waikato estuaries (Hume & McGlone 1986, Oldman & Swales 1999, Sheffield et al. 1995, Swales et al. 1994, 1995, 1997, 2002a, 2002b, 2005a, b, 2007, 2012, 2013).

Comparison of maximum ^{137}Cs penetration depth with ^{210}Pb age estimates indicated that ^{210}Pb dating for several cores are not reliable (KP-4, KP-10 and SKDI), most likely due to post-depositional sediment mixing. The maximum depth of ^{137}Cs penetration in the cores, and resulting ^{137}Cs SAR estimates, could not be corrected for vertical mixing within the surface mixed layer (SML) using beryllium-7 (^{7}Be, ½ life ~53 days) as this short-lived radioisotope was not detected in these cores. As the coring sites investigated were dredged for GLMs, it is possible that dredging may have caused some of the mixing observed in these cores. However, bioturbating species that live and move at the sediment-water interface 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 (Lohrer et al. 2004).

Excluding cores with poor agreement between dating methods, ^{210}Pb dating of European period sediments show that time-average SAR over the last 74–120 years of 1.8–4.6 mm yr^{-1} are as much as an order of magnitude (10x) higher than the pre-European period. These ^{210}Pb SAR estimates are less than the ^{137}Cs-validated ^{210}Pb SAR of 5.7 mm yr^{-1} (post-1950s) measured at a single core site in Opua Bay (Queen Charlotte Sound) (Mackenzie et al. 2016). That area is surrounded almost exclusively by pine forestry.

Evidence of land clearance by Māori preserved in the sedimentary record, such as increased SAR or changes in sediment physical properties, were not detected in the present study. This apparent absence of evidence of Māori land-use activities reflects: (1) the coarse resolution of the core sampling; and (2) low SAR so that Māori to early-European era sediments (i.e., 1300–1800s AD) are represented by sediment layers only 8 to 50 cm thick (i.e., SAR ≤ 0.69 mm yr^{-1}), or (3) perhaps low impact from Māori activity.

Prior to European settlement, the main sediment sources were the subsoils from natural slips, inflow from the Pelorus and Kaituna Rivers ('Havelock inflow'), and sediment generated from bracken, beech forest, and ponga/podocarp forest (Figure 4-2). The ecosystem had co-evolved with the fluctuations of sediment from periodic storms and episodic disturbances. The 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 to today.

The order of magnitude higher ^{210}Pb SAR over the last century in comparison to long-term background rates is consistent with sediment records from a number of North Island estuaries. These large increases in SAR over the last century or so coincide with large-scale catchment deforestation and conversion to pastoral agriculture during the mid–late 1800s. Figure 4-1 compares weighted-average ^{210}Pb SAR measured in Kenepuru Sound and Beatrix Bay with sediment accumulation rates in a number of North Island estuaries. The weighting of ^{210}Pb SAR values is based on the length of record (years) represented by each SAR estimate. Weighted-average ^{210}Pb SAR of 4 and 2.4 mm yr^{-1} in Kenepuru Sound and Beatrix Bay respectively are within the range of values measured for the post-European period in a number of other North Island estuaries (range: 2.3–5.5 mm yr^{-1}, Figure 4-1). The variability in the weighted-average SAR is highest in the Kaipara Harbour, Auckland's east Coast Estuaries and Firth of Thames, which partly reflects the size of these systems and range of sedimentary environments. The relatively low weighted-average SAR in Beatrix Bay, located in the outer Pelorus Sound, is consistent with the Bay's relative distance from major inputs of fine fluvial sediments.

In many North Island estuaries, an increase in SAR following deforestation has been accompanied by a shift from sand- to mud-dominated systems (e.g., Swales et al. 2002a, 2002b, 2012, 2013). In contrast the results of the present study indicate that mud-rich sediments have accumulated in the Kenepuru Sound for at least the last 3,400 years. For the first time, the rate of deposition of these fine sediments and their sources has been quantified in Pelorus Sound, showing an order of magnitude increase over the last century in comparison to long-term background rates. To illustrate the scale of the temporal changes in SARs including the proportion of source contaminants during historic time periods, we can scale up the soil source proportion data. To achieve this we: used the time periods chosen to section the shell-gravel DA cores sampled close to shore in Kenepuru Sound (above); we averaged the proportion of sediment source estimates within each time period; and then we multiplied the mean proportion of source sediments by the SARs calculated (above) for each core {(source %/100) x SAR} and multiplied x10 to get a 10 year accumulation estimate for each soil source (Figure 4-2). This was implemented for the early 1300-1859 and 1975-2016 periods where we considered we had some replication of slices within each time period and high precision in SAR's calculated from carbon dated shells and radio isotopes, respectively. The resulting plot depicts the large increases in sediment accumulation above historic baselines (see also Table 3-1) increasing from sites at the entrance up to sites at the head of Kenepuru Sound (west-east : KP4-KP11, Figure 4-2). Between 1975-2016, the remobilised 'Havelock inflow' was consistently the dominant source comprising more than 50% of the sediment followed by pine soils in all cores except KP6 where subsoils were the next greatest contributory source. This contrasts with the earlier period 1300-1859 where subsoils were the dominant source. This order of magnitude increase in SARs necessitates measures to address erosion from the dominant sediment sources (e.g., the setback and retirement mitigation measures for forestry set out in MLDC's review of sedimentation (Urlich 2015) and the riparian plantings and stream crossings for dairy farms required under the Government's National Objectives Framework for Freshwater), as well as further investigation into the contemporary and historic sources contributing to the 'Havelock inflow' from the Kaituna and Pelorus River catchments.

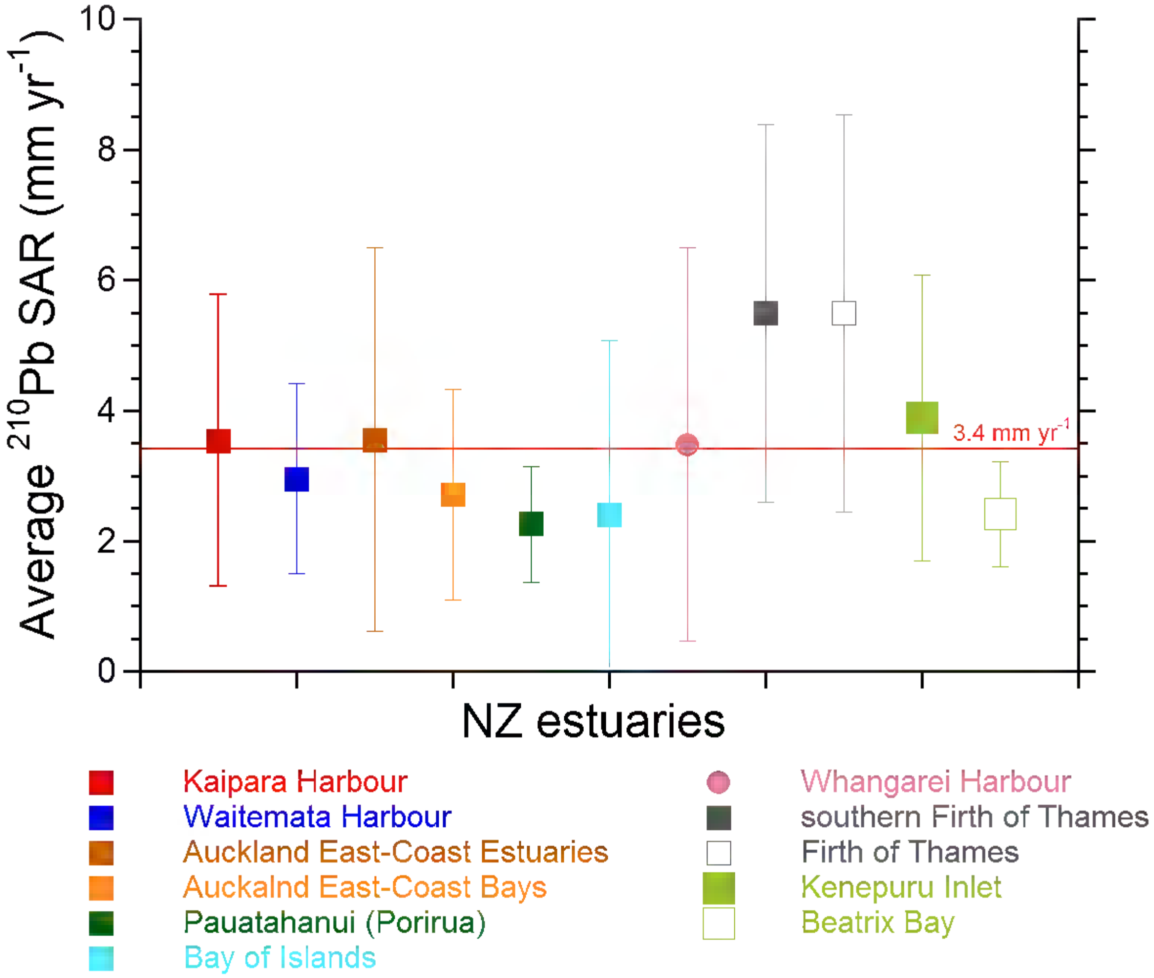

Figure 4-1: Comparison of estuary weighted-average ^{210}Pb sediment accumulation rates (SAR) in North Island estuaries (mid-1800s to present including the Firth of Thames. Comparison of estuary weighted-average ^{210}Pb sediment accumulation rates (SAR) in North Island estuaries (mid-1800s to present), including the Firth of Thames. Notes (1) total number of estuaries (16) and cores (99); (2) standard deviations shown; (3) southern Firth –present study and (4) including De Baere (2006) data. Source: NIWA.

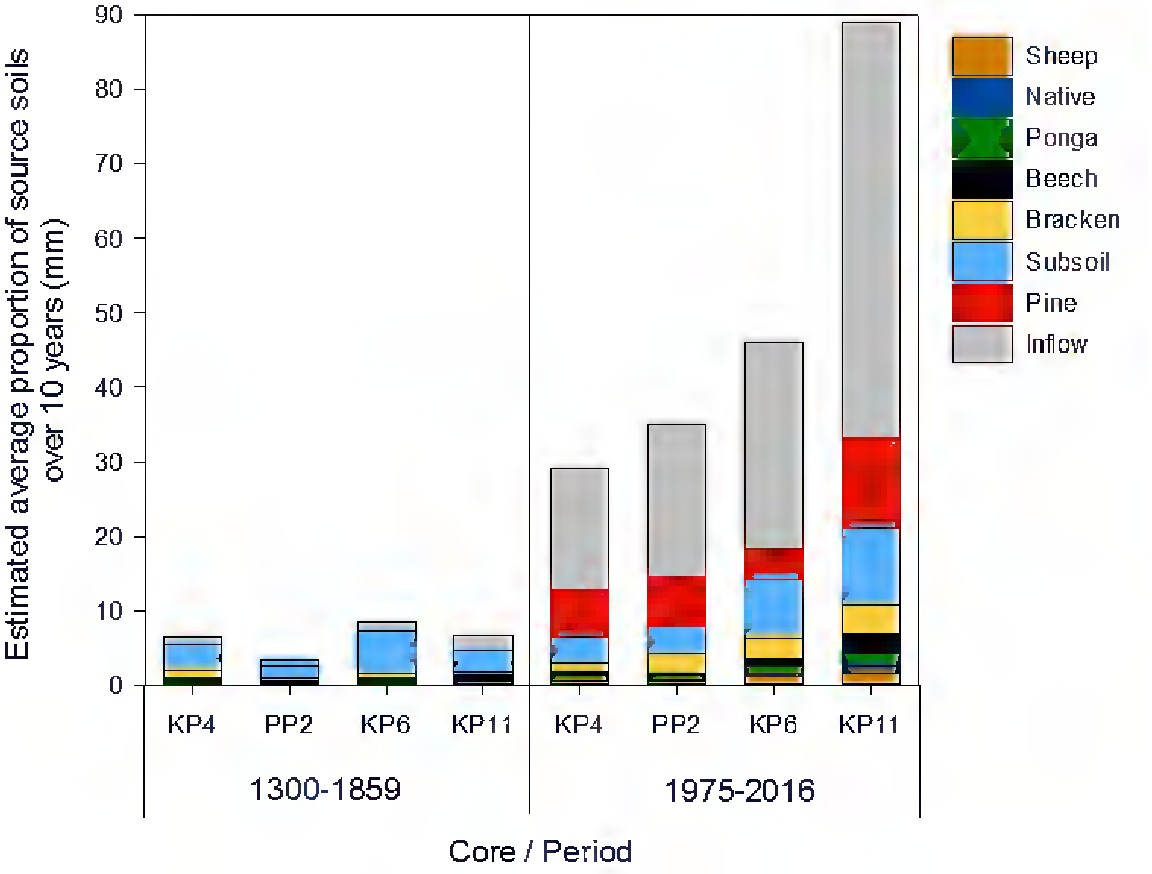

Figure 4-2: **Estimated average proportion of source soils (Figure 3-18 above) scaled by the SAR over 10 years.**

4.2 Interpretation of DA drivers

In the following discussion, we use SARs, CSSI soil source, and stable isotope data to interpret and discuss causal mechanisms for marked changes in mollusc shell deposition rates in the DA. In doing so, we present truncated plots of previous data focussing on the period since 1900. Changes in percent carbonate derived from total weight of molluscan death assemblages were used herein as a proxy for shellfish productivity.

DAs have been used to detect historic changes and have been identified as reliable palaeo-environmental indicators as they were able to record decadal-scale changes, with comparisons of live-dead assemblages having strong similarity (Poirier et al. 2010). This is because DAs constitute the direct empirical evidence of the former existence of mollusc populations on some spatial scale and within some past time frame (Kidwell 2013). Mollusc DAs have been used to detect species composition changes between unaltered and anthropogenically altered sites in Florida, USA (Ferguson et al. 2008), and reduced species diversity with a shift to dominance of deposit feeders in response to eutrophication from nutrient release derived from urbanisation and pollution in a Cuban Archipeligo (Armenteros et al. 2016). Exceptions to accurate DA representation can occur close to river mouths and intertidal mudflats that can supply terrestrial and intertidal species to subtidal death assemblages (Poirier et al. 2010). Dispersal of shells at low bottom shear stress (ca.10s to 100s of meters), demonstrated that death assemblages preserved environmental gradients even at a fine spatial scale (Poirier et al. 2010). Sediment budget can significantly influence DAs with sites of deposition (c.f. erosion) favouring the colonisation, rapid burial and preservation of thin-shelled infaunal species.

Our analysis of the DA demonstrated a clear increase in the deposition of mollusc shell carbonate after European settlement at all three coring sites (Skiddaw, Gold Reef Bay, and Poison Point) chosen to overlap with former mussel reefs that were exploited in the 1960s to mid-1970. There was a distinct peak in deposition during the arbitrary time period of 1950-74 which was chosen to represent the period in history when the GLM beds were fished, before the advent of longline mussel farming. The site that consistently exhibited the highest rates of shell deposition west of Gold Reef Bay, interestingly also had unusually high levels of schist rock gravel deposition that accumulated at rates mimicking the deposition rates of mollusc shells. The high precision of the within-site DA data indicates that the response measured from the cores are an accurate representative of past conditions at these sites. To try and understand what factors might have contributing to increased mollusc shell deposition, which we interpret as a proxy for mollusc productivity, the concomitant accumulation of rock gravels in GRB1-4 may give clues. We speculate that this rock gravel was deposited from land-based disturbance west of Gold Reef Bay, which persisted throughout the European occupation period. This land-based disturbance, evidenced at Gold Reef Bay by the supply and deposition or rock gravels deposited in the sediment strongly suggested terrigenous erosion was involved, but this disturbance was consistent with an almost doubling of mollusc productivity, as compared with lesser productivity at adjoining sites during the 1950-74 period. Further, the consistent trends of enhanced mollusc shell deposition at all three sites shows that whatever terrigenous disturbance was responsible for elevating productivity at Gold Reef Bay, it was also affecting the wider Kenepuru system.

Figure 4-3: Google Earth image (2/18/2007) of the coring site (GRB1-4) west of Gold Reef Bay, showing regenerating seral species in the steep gullies (pale green colour), and evidence of old slip on the north-west face (circle).

The factor that most likely led to Kenepuru-wide increase in mollusc carbonate deposition from 1860 onwards was the assumed accelerated release of nutrients from land due to removal of native vegetation by early European settlers for timber and agriculture developments. However, prior to the 1900s it can be seen that the deposition of $\delta^{15}N$ at CSSI coring sites fluctuated the most at KP-6 in Waitaria Bay, whereas the other two sites remained relatively constant with some gradual increase in $\delta^{15}N$ at KP-11 after 1700 (Figure 3-31). The elevated levels of $\delta^{15}N$ and enriched $\delta^{13}C$ at Waitaria Bay (KP-6) are not a measure of total N- or C-loading, rather they are indicative of land-based origin. Historically, Waitaria Bay was recorded as a site containing multiple Māori oven sites (Challis 1991) (Figure 4-4 & Figure 4-5), and these signatures are consistent with land-clearance by Māori occupation in the two valleys surrounding the bay (Figure 4-5) indicated by the largest peak in $\delta^{15}N$ (Figure 3-31) during that period (~1418 AD).

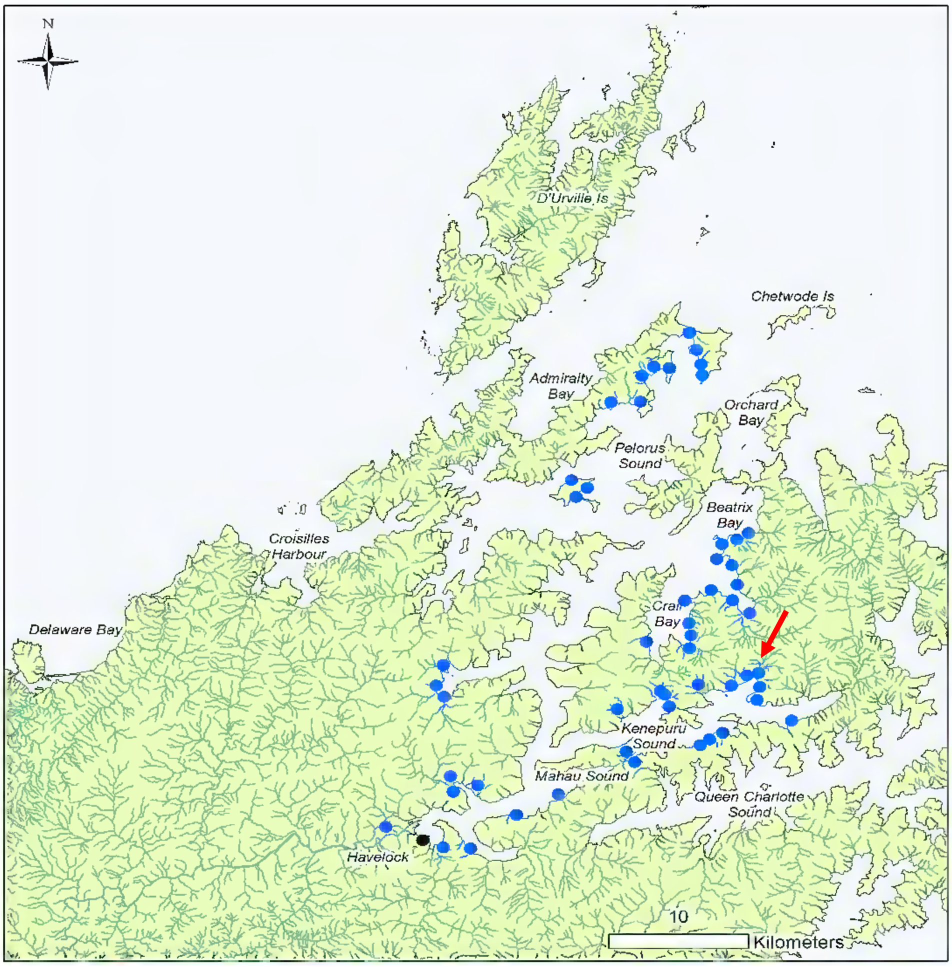

Figure 4-4: Distribution of Māori oven sites (blue circles) in Pelorus Sound, digitised from (Challis 1991). Waitaria Bay indicated by red arrow.

Figure 4-5: Google Earth image (2/18/2007) Wataria Bay, Kenepuru Sound. Image shows two valleys cleared of vegetation and developed as farmland, formerly occupied by Māori during the pre-European period. Pine plantations (dark green) can also be seen on some of the adjoining steep slopes above the farmland.

Corroborative evidence supporting the source of elevated $\delta^{15}N$ levels being due to human clearance of the land, comes from analysis of CSSI soil sources which showed increasing proportions of subsoils and bracken soils at Waitaria Bay (ca.1418 AD), and Ponga at Te Matau a Maui Bay (ca.1420, KP-4) (Figure 3-32). Bracken is a successional species that became more abundant in New Zealand following use of fire by Māori (McGlone et al. 2005). Bracken rhizomes are resistant to fire, and help stabilise soils from erosion. This seral species accumulates large amounts of inflammable dead fronds, persists with the use of fire as it outcompetes woody competitors, and became a troublesome weed during the European agricultural period. During the early European period (1860-1950) the levels of bracken soils, indicative of land clearance and perhaps repeated burn-off, were consistent through time, with some low peaks in the 1950-1965 period from Skiddaw (KP-4) and Waitaria Bay (KP-6, Figure 4-6). Jim Jenkins, a resident of Gold Reef Bay since the early 1970s, recalls "the farming was still match farming, each summer burning an area. I remember DC-3's flying over top dressing. Then the subsidy ended and the burning ended." Fire was a major tool employed in removal of forest and scrub during European settlement and development of farming (Walls & Laffan 1986). There was a more-rapid pulse of bracken soils in the mid-1990s which matched a similar peak in pine harvest at Ohauparuparu Bay (KP-10), possibly indicating land clearance following or during harvest of pine in that area. The presence of the peak in ponga soils at Te Matau a Maui Bay at ca.1149 AD and ca.1435 AD potentially indicate destabilisation of land behind this catchment following large slips during cyclonic events (McFadgen 1985) and/or felling of ponga by Māori for whare building. Archaeological sites are scattered throughout this area, including the peninsulas either side of Gold Reef Bay (Challis 1991).

Other possible explanations for enhanced nutrients entering the Pelorus are from seismic disturbances including large earthquakes and tsunami creating pulses of erosion and associated nutrient discharge. Recent modelling of tsunami evacuation zones in Marlborough by GNS Science predicted that for waves generated off the coast, maximum tsunami heights inside the sounds are of approximately the same size as those on the coast outside (Heron et al. 2015)[15]. Tsunami hazard was however assessed as higher from earthquake source tsunamis (which were used to create the evacuation zones); submarine landslides and landslides from the hills surrounding Cook Strait and within the Marlborough Sounds (from quakes and intense rainfall) are likely to have more localised effects. Landslides within the sounds of as little as a few thousand cubic metres could generate a tsunami that may locally have a run-up above 5m in height in susceptible embayments. There is therefore the potential that the large tsunami events recorded in sediment cores, oral history and historic newspaper accounts (Section 1-2-2) could have also had widespread effects on sedimentation through landslides and wave run-up on the coast and inner Pelorus Sound. Supporting this, the peaks in ponga soils at Te Matau a Maui Bay at ca.1149 AD and ca.1435 AD are in close accordance with the tsunami signature dates estimated from sediment cores from the Abel Tasman National Park in Nelson at ~1220 AD and ~1440 AD (Goff & Chagué-Goff 1999). In the Canterbury region, monitoring of the Waimakariri sewage outfall in 2012 following the earthquake activity in the area (2010 Darfield 7.1 magnitude quake & 2011 Christchurch 6.3 magnitude quake and aftershocks) revealed unexplained increase in seabed productivity at reference stations. Changes in infauna were characterised by unusually large recruitment event of juvenile heart urchins *Echinocardium cordatum*, spionid and oweniid polychaete worms and the ostracod *Scleroconcha* sp. (Handley et al. 2012). This observation suggests that seismic activity can stimulate seabed productivity perhaps by releasing stored nutrients from within sediments or from increased supply of terrestrial nutrients.

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[15] For example: https://maps.marlborough.govt.nz/smaps/?map=61a36a29276b4d4888306321f4448b83

The second largest depositional increase in $\delta^{15}N$ in 1950 and then again in 1990 at Waitaria Bay may have been due to the periodic discharge of stored nutrients in the catchment following further use of fire for land clearance or storm events during the 1960s to mid-1970s (Figure 4-7).

As European's developed saw mills, gold mining, and farming (1860-1950; Handley 2015) there was accelerating deposition of sediment from the 'Havelock inflow', and soils from sheep farming appeared in the sediments for the first time in the early 1900s (Figure 4-6). As sheep farming and bracken soils were relatively constant or increasing in the Kenepuru cores during the early European period, we hypothesise that land clearance and farming activities aided by the application of chemical fertilisers like superphosphate were responsible for the increase in mollusc productivity measured in cores sampled close to shore. "Superphosphate went on sale in England in 1843, the very time that British farmers began settling in New Zealand[16]". Superphosphate greatly enhanced the productivity of sheep farming especially on hill country when applied by aerial top dressing since the late 1940s[17]. As a result, sheep numbers nationally increased 40% between 1951-61. Supporting these observations, there was a peak in $\delta^{15}N$ in 1950 that matched a similar peak in sheep soils at Waitaria Bay (KP-6, Figure 4-6). We deduce that because there was no similar increase in $\delta^{15}N$ either side of Waitaria Bay in Te Matau a Maui or Ohauparuparu Bays during that period, that the source of the $\delta^{15}N$ was localised to Waitaria Bay. As nitrogenous fertilisers would cause the $\delta^{15}N$ to be depleted, the enriched N signature suggests 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 (McGlone1989, McGlone et al. 2005) or "A-horizon" soils. Alternatively, it was the constant "match farming" that produced a steady supply of nutrients in the form of N from burning of scrub, thus stimulating productivity. Waitaria Bay is still an area important for local sheep farming due to the low-lying valleys behind the bay (Figure 4-5).

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[16] http://www.teara.govt.nz/en/superphosphate

[17] http://www.teara.govt.nz/en/sheep-farming/page-7

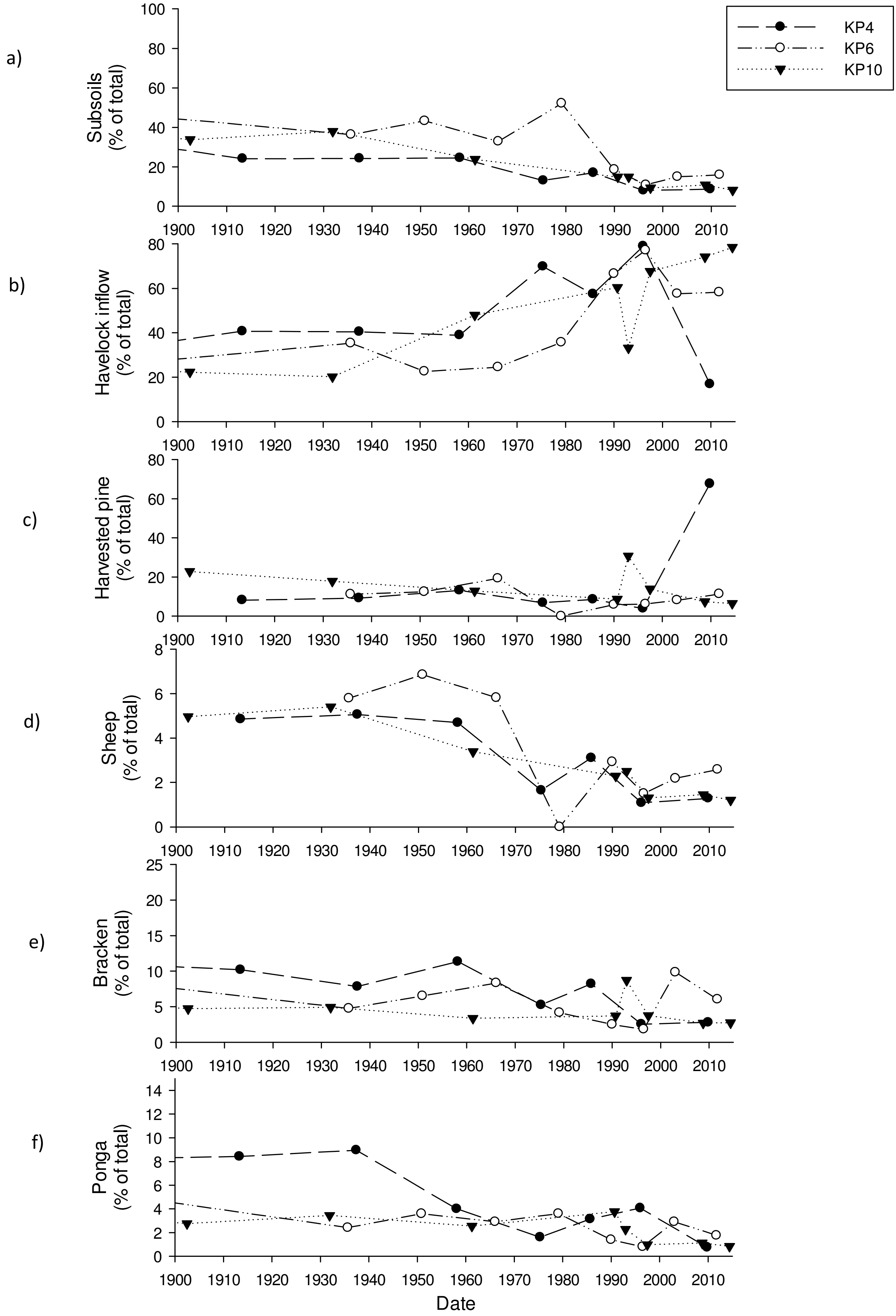

Figure 4-6: Percent of source soils derived from CSSI analysis of Kenepuru cores: KP-4, KP-6 and KP-11. Note, this figure is a truncated version of Figure 3-32 showing the period 1900-2015 AD.

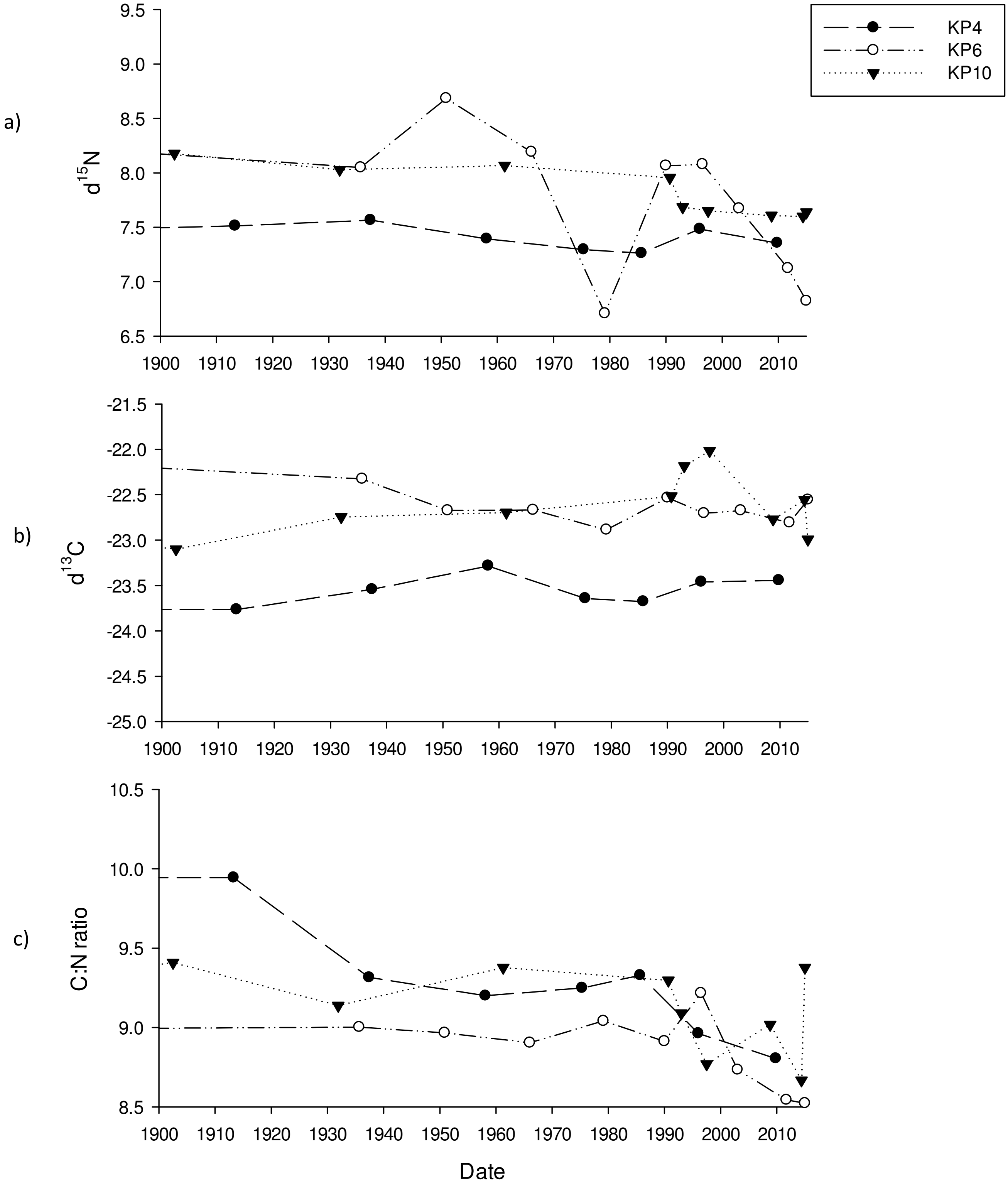

Figure 4-7: δ15N, δ13C and C:N stable isotope ratios analysed from CSSI sediment cores: KP-4, KP-6 and KP-10. Note, this figure is a truncated version of Figure 3-31 showing the period 1900-2015 AD

We hypothesise that steep gullies in the embayment west of Gold Reef Bay were the source of schist gravel and that this indicates elevated nutrient discharge stimulating the benthos below. This is because the greatest mollusc shell deposition measured at Gold Reef Bay (Figure 3-22a) also contained anomalously high, but matching, levels of schist gravel (Figure 3-22b). The peaks in supply of schist gravel suggests elevated levels of erosion. The peninsula in question was farmed, but the farm was largely abandoned in the '50s as it was too steep to farm profitably (Jim Jenkins, pers. comm., Figure 4-3). The site where our cores were taken consists of a schist formation that was explored for gold with multiple test diggings and an abandoned gold mine (1884) on the Jenkins' property at the head of Gold Reef Bay. There is evidence from a small slip on the north western side of the embayment that the land is susceptible to slipping. The land behind this bay is steep in aspect, with the slope from the shore to the 100 m elevation contour estimated at 40°[18]. The land on the ridges is regenerating seral kanuka and manuka with pockets of beech, whereas the steep gullies appear to be covered with broadleaf species (Handley, pers. observ.).

Since 1860, the DA in the subtidal sediments in this bay contained the greatest number of grazers, and during 1950-74 this site had the greatest proportion of shells derived from deposit feeding species (Figure 3-26). Grazers like *Micrelenchus* sp. and *Diloma aethiops* may have taken advantage of the gravel present on the surface of the sediment as it was laid down following storm events, and deposit feeders like *Venerupis largillierti, Neilo australis,* and *Linucula hartvigiana* could have taken advantage of terrigenous particulate matter similarly washed into this bay and deposited. Also of note, the functional feeding trait scores (Handley et al. 2014) reduced at all sites between 1950-74 suggesting an overall reduction in species diversity, which was in strong contrast to the elevated productivity measured during that period. Reductions in functional diversity have been measured in Crail Bay in response to nutrient discharge from a salmon farm (Handley, unpub. data), supporting the hypothesis that the benthos during that period in history was enriched, chiefly from effects associated with sheep farming. Studies investigating benthic effects from salmon farm developments in the Marlborough Sounds have suggested that in many situations, reference seabed conditions can be 'naturally' enriched and/or disturbed (Keeley et al. 2014). If this 'natural' enrichment is the result of a legacy of land clearances and farming activities, this raises important questions for coastal regulators and managers regarding the setting of baseline conditions or benchmarking (e.g., Handley et al. 2014, Saunders & Taffs 2009), from which to evaluate the magnitude of changes from impacts derived from anthropogenic effects including aquaculture, especially when shifting baselines may have occurred (e.g., Pauly 1995, Handley 2015).

The greatest DA productivity measured at the Gold Reef Bay site may however also be due to the site being geographically centred near the middle of Kenepuru Sound thus receiving greater pelagic productivity from increased residence times of water parcels containing phytoplankton that pass backwards and forwards with tidal movement up and down the Kenepuru (Gibbs et al. 1992). However, filter-feeders were not dissimilar in the DA to the other sites, potentially discounting this theory. Another theory is that disturbance from dredging for GLMs somehow stimulated productivity, but fishing disturbance generally increases the abundance of scavengers, predators and deposit feeders at the expense of filter feeders and grazers (Handley et al. 2014). In support of rejecting this theory, the increased supply of schist gravel at the Gold Reef Bay did not appear to be related to dredging for mussels, as gravel inputs were elevated during 1860-1949 and 1950-2015, levels of deposition above the pre-European period (500-1859), periods in history when dredging for mussels was absent. Further, we can also likely discount any influence of productivity increases

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[18] The distance to the 100 m contour was measured at ca.230 m using MapToaster Topo maps software (http://www.integrated-mapping.com/)

resulting from large seismic events triggering land-slides or tsunami increasing erosion. This is because as pre-human productivity estimates were low. Also, the reported tsunami events (~1220 AD, ~1440 AD; Goff & Chagué-Goff 1999) appeared consistent only with increases in the proportion of ponga soils at Skiddaw (KP-4), the latter of which was also consistent with Māori occupation.

Perhaps the most intriguing findings at Gold Reef Bay were the very similar trend in the supply of schist gravel after European colonisation that mimicked the trend in the mollusc shell deposition at this site. This trend potentially indicates a causal link between discharges of nutrients from the steep land above following disturbance from farming that is consistent with farming activity in the area that ceased after the land was retired, and later purchased by the Crown in the 1960s (Jim Jenkins, pers. comm.). Another potential contributory factor, increasing nutrient discharge resulting in high mollusc productivity, which is also consistent with the timing of highest productivity at this site, is the effects of the liberation of wild game animals (deer, goats and pigs). Ponder (Ponder 1986) noted game animals were likely used to advantage by early settlers in the Marlborough Sounds as a welcome food source. The most destructive in terms of increasing erosion (Handley, pers. observ.), feral pigs (*Sus* sp.) were first introduced to New Zealand in 1769, and had spread widely by the early 1800s, to become the most abundant wild ungulate at the top of the South Island (Clarke & Dzieciolowski 1991). Pig densities were reported to be the most abundant in the Marlborough Sounds and Murchison districts where they predominantly inhabit native forest and scrubland. Interesting in terms of historic timing, pig numbers only began to decline in the district since the 1970s after the Game Meats Industry started buying wild pork for export in ca.1967, with recreational hunting in 1985 providing the principal means of harvest and population control (Clarke 1985, Clarke & Dzieciolowski 1991). Jim Jenkins recalls: “there must have been periods of pig numbers up and down on this property but in more recent times they are not in big numbers”.

To further elucidate causal drivers of high mollusc productivity measured during 1950-74, other palaeoecological measures of productivity like phyto-pigment signatures sequestered by macroalgae, phytoplankton, and benthic diatom communities could be used (e.g., Petersen et al. 2004, Schüller et al. 2015). Similarly, genetic tools could be used to investigate terrestrial agents of soil disturbance like sheep and feral pigs (e.g., Corinaldesi et al. 2008).

4.3 Contemporary sedimentation versus extant mussel beds

As mussel shells were poorly represented in DA cores we could not draw direct causal linkages between modifications of the Pelorus catchment with changes in mussel populations back through time. We therefore discuss changes in SAR and CSSI soil contributions before and after 1975 to discuss theories as to why GLM populations have not recovered following cessation of fishing in the early 1970s.

Pine harvest soils: Concerns about the effects of accelerating sedimentation from plantation forestry degrading seabed habitats and the reducing productivity of the developing marine farming industry were first published in 1981 (Johnston et al. 1981). More recently, forestry related sedimentation effects were raised again in Queen Charlotte Sound, when surveys in the Hitaua Bay Estuary showed fine sediment from the logged forestry catchment causing a build-up over and around intertidal cobbles and a disappearance of some intertidal species compared to a baseline survey conducted in 2003 (Davidson & Richards 2015). In our study, pine soils were typically around 10% at the four sites in Kenepuru Sound as a proportion of total sedimentation after the first appearance of pine harvest soil in the sediments around the early 1900s (Figure 3-18). In the period between 1975 to 2016, there was a large reduction in δ^{15}N recorded in sediments in 1979 in Waitaria Bay (Figure 4-7). This decrease coincided with replanting of pine and is most likely due to the application of urea fertilizer (contains low $\delta^{15}N$) to trees (e.g., Davis 2005) during the late 1970s and early 1980s (Max Gibbs, pers. observ.). The first noticeable increase of pine harvest soils in Kenepuru Sound was evident in 1992 when it contributed 30% at Ohauparuparu Bay with a spike of 68% in 2009 in Waitaria Bay from an adjacent headland at Koutuwai Point (Figure 3-19, Figure 4-6). In the catchments behind Waitaria Bay, there are at least three areas of pine plantation (Figure 4-5). In the central Pelorus, contributions of pine signatures in Beatrix Bay ranged from ~8% up ~40% and we deduce that as there was less pine forestry in the Laverique Bay catchment, the pine signature sediment may have been transported from plantations in Beatrix Bay, Clova Bay and Crail Bay. The timing of peaks in pine soils in the deepest Beatrix Bay site (BT-11) around 1946, 1972 and the present, are consistent with crop cycling of production forest activity. Although the proportion of pine sediments appeared greater in Beatrix Bay cores, it should be noted that the highest contemporary SARs at the deepest site in Beatrix Bay (3.4 mm yr-1) was approximately a third of that recorded at the head of Kenepuru Sound (8.9 mm yr-1). On average, pine soils were the second largest sediment source after 'Havelock inflow' during the 1975-2016 period (Figure 4-2). As there were no significant peaks in pine as a proportion soils deposited prior, during, or well after the period when mussel beds were exploited, it seems unlikely erosion of sediment from plantation forestry was the sole cause of the lack of recovery of GLM beds, as there was at least a decade between fishing down of the mussel stocks and pine soils contributing greater than 10% proportion in 1992, especially at Ohauparuparu Bay. It should however be noted that surface sediments recorded substantial proportions of pine sediment in the upper 2cm (Figure 2-6) which could, if it continues, hinder future restoration efforts.

Subsoils: The contribution of subsoils, typically derived from large storm and slip events, were the dominant sources of sediment to the unmodified system. The first changes in Kenepuru Sound were the increases in subsoil and bracken soils in 1418 at Waitaria Bay and 1461 at Ohauparuparu Bay which are consistent with Māori occupation of the area. The increase in the relative proportion of the subsoils since the late 1800s that was dispersed into the Kenepuru arm of the Sound (Figure 3-18) was consistent with the timing of European settlement, clearance of the native bush, and sheep pasture development. However our CSSI plots do not reflect the order of magnitude (10x) increase in sedimentation that accelerated after Europeans arrived. From 1979 onwards, the proportion of subsoil in the sediment began to decrease. This contemporary reduction in subsoils perhaps reflects reductions of major slips on slopes that had been cleared for farming that had adjusted to changes in vegetative cover, or overall reductions in sedimentation rates followed regeneration of vegetation cover stabilising slopes following the cessation of farming subsidies. Again, looking for causal linkages with lack of recovery of mussel stocks in the 1970s, subsoils do not appear implicated as they were only elevated significantly at one coring site, Waitaria Bay in 1979 that may have been caused by a localised storm. Interestingly, an extreme slip ca.35,000 m^3 recorded by Miller (2016) above Mills Bay in the mid-1990s did not appear in our sediment profiles associated with subsoils, potentially indicating that this slip did not discharge significant subsoils and rather contained bracken and pine soils which were evident as small peaks at that time off Ohauparuparu Bay.

'Havelock inflow' soil: The dominant sediment type to increase by proportion in contemporary times is the 'Havelock inflow' that showed a step-wise increase between 1860-present. This phenomenon is consistent with catchment-wide increase in sediment discharge from land following deforestation, agriculture developments, and later plantation forestry development and harvesting activities. This is because the 'Havelock inflow' represents the sum total of all catchment sediments from the Pelorus and Kaituna rivers accumulating together at the delta in the Havelock Estuary. This sediment is periodically resuspended and discharged during high rainfall events causing riverine scour, and also during high wind and wave events. It represents a distinct sediment source in its own right, and was analysed and classified as such. As the question being addressed is: "what are the different sources contributing sediments to our coring sites?", it is then problematic to try and deconstruct the components of the inflow sediment. This is because it is important to know the proportion of the total sediment the 'inflow' represents when transported and deposited throughout Pelorus Sound, especially in relation to management of the Havelock Estuary, and downstream effects. For example, management and protection of seagrass and salt-marsh flora and fauna will be important in reducing mobilisation of this sediment. This is because in its pre- European state, we expect that the Havelock Estuary and other shallow areas or embayment's like the upper Kenepuru would have had more-intact and extensive wetlands serving the role of reducing sediment loads by filtering and settling out fine sediment. Another factor likely contributing to the 'Havelock inflow' was the periodic discharges likely to have come from historic and contemporary dredging to allow navigable shipping passage to and from Havelock Harbour, as "the Harbour is its highway" (see Introduction, M. Gibbs pers. observ.). As the proportional dominance of 'Havelock inflow' sediments was greatest at the head of Kenepuru Sound, it appears that 'inflow' sediment can be transported during large storm events. We envisage that freshwater flows from the Pelorus and Kaituna rivers would scour these estuarine sediments or resuspend them with wind and waves to be transported by the tides to the top of the Kenepuru. As this sediment has increased in proportion over time, the 'Havelock inflow' could be implicated in the lack of GLM bed recovery.

4.4 Hypotheses regarding lack of GLM bed recovery

As we could not identify any single land-use practice implicated with the lack of GLM bed recovery, we discuss below potential hypotheses that may explain the lack of innate recovery of GLM beds in the inner Pelorus Sound in light of previous research and results presented in this study. These are summarised in:

1. The mussel beds were an aberrant artefact formed after the discharge of fine wood debris to waterways during European settlement, thus creating floating habitat that was colonised by mussel larvae that washed ashore, triggering bed formations. Therefore GLM beds will not re-establish until another such event occurs.

The utilisation of spat catching ropes by the Greenshell Mussel industry's spat monitoring in Pelorus Sound demonstrate that larval supply is not limiting in areas formerly holding GLM beds. Although, numbers of spat retained on ropes has been reported to be in decline more recently for unknown reasons (Vaughan Ellis, pers. comm.). If larval supply is not limiting mussel recruitment, then either settlement substrata or post-settlement survival may be limiting recruitment to seabed habitats. It is conceivable that wood debris during European land clearance triggered the GLM bed formations, but wood debris is common on many intertidal shorelines (Handley, pers. observ.), unless there was a large influx of manuka/kanuka brush historically that was colonised by mussel larvae. The low numbers of mussel shells collected in our sediment cores prevent us confirming if GLMs were present in significant densities prior to human habitation, but given larval supply does not appear limiting, it seems probable that recruitment surfaces are limiting.

2. The fishing down of mussel predators (e.g., snapper and rock lobster) resulted in "predator release" (e.g., Steneck 1998) allowing for the proliferation and expansion of GLMs population beyond pre-human densities and range.

Snapper and rock lobster were formerly more abundant in the Marlborough Sounds (Handley 2015, Handley 2016, Bray & Struick 2006, Clarke 2014) so it is possible that release from predation pressure helped increase GLM populations. However, these predators continue to occur in historically low numbers and as juvenile mussels appeared to settle intertidally in 1971 amongst adult mussels in Kenepuru Sound (Stead 1971b), predation does not appear to be a significant limiting factor. There is however the potential that cryptic predators like platyhelminth flatworms (Handley 2000, 2002), parasites like spiond polychaete worms (mudworm: Handley 1998) could have impacted GLM bed recovery (e.g., Diggles 2013).

3. Changes in the Pelorus Sound ecosystem have created a ‘bottleneck’ limiting essential settlement habitats for wild mussel recruitment. For example, in the U.S.A., mussels *Mytilus edulis* settle as larvae especially on taller reproductive shoots of eelgrass (*Zostera marina*) that provide a refuge from predators during metamorphosis (Newell et al. 2010, Disney et al. 2011). Bull (1976) reported that scallops, which similar to GLMs attach themselves as larvae using byssal threads, were found in areas of the Pelorus Sound attached to brown alga *Cystophora retroflexa*, red algae attached to horse mussels *Atrina zelandica*, and drifting seagrass *Zostera* debris.

If seabed plants including seagrass historically provided essential settlement substrata enabling GLM larvae to undertake metamorphosis and primary and secondary settlement phases, then the order of magnitude SARs and decline of seagrass beds in the Kenepuru Sound (c.f. Bull 1976), may have been causal factors contributing to the lack of mussel bed recovery. The report of phytoplankton stripping available nutrients from the water column under summer thermally stratified conditions in the mid-1980s (Gibbs et al. 1992), suggests there is also the potential for phytoplankton to outcompete seabed plants (macrophytes) for nutrients during such conditions.

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 et al. 1995, Carroll et al. 2008, Wall et al. 2008), and secondly, they fertilize the bottom with their bio-deposits and excretion of bioavailable nutrients (Dame & Libes 1993, Reusch et al. 1994, Everett et al. 1995, Peterson & Heck 1999, 2001a, b, Carroll et al. 2008, Charles et al. 2010). Seabed plants in turn 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, Charles et al. 2010). Aquatic plants also help trap and stabilise sediments, and remove nutrients (Yallop et al. 1994, Underwood 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). 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 available 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 precluding seabed plants surviving (e.g., during summer stratified low nutrient conditions) – creating a bottleneck to mussel recruitment.

4. Increased suspended sediment concentrations adversely affects juvenile and adult GLMs.

This hypothesis is also highly likely as we measured an order of magnitude increase in SARs, and a recent review of the effects of land-based effects on coastal fisheries argued that the most important land-based stressor is sedimentation, including both suspended sediment and deposition effects, and associated decreases in water clarity (Morrison et al. 2009). As little as 26 mg l^{-1} of sediment fed continuously to sponges, oysters, and mussels adversely affected their health after thirteen days (Schwarz et al. 2006). Suspended sediments were also conjectured to have serious consequences at the ecosystem level from indirect effects, through reduced epifaunal abundance, as epifauna are responsible for about 80% of the flow of energy and materials through rocky reef animal communities (Taylor & Cole 1994).

The effects of suspended sediments may also have indirect effects reducing phytoplankton production due to light attenuation (Krause-Jensen & Sand-Jensen 1998) and by affecting the bioavailability of nutrients required by phytoplankton. This is because fine sediments can bind with organic dissolved reactive phosphorous (Viner 1988). This process converts phosphorous to a less bioavailable (inorganic) form hindering its potential bioavailability to phytoplankton as compared with dissolved reactive phosphorus (Owens & Walling 2002). In its bound form, particulate phosphorous can accumulate in river channels, to be resuspended and transported downstream during storm events (e.g., 'Havelock inflow'). But particulate phosphorous in its inorganic form can be deposited with sediments, thus the seabed could become an important sink for particulate phosphorous removing it from the system, especially under conditions of accelerated sediment discharge.

5. Terrestrial nutrient availability is in decline, and as a result phytoplankton production is declining (exacerbated by grazing from cultured mussels), causing newly settled mussel spat to starve before recruiting to adult beds. This could arise if Pelorus Sound, which appeared to formerly have low mollusc productivity, has undergone reductions in the supply of terrigenous nutrients since the early 1970s following cessation of land clearance (milling, fire), farming (fertiliser subsidies), forestry (urea), and human population decline (sewage discharge).

Pelorus Sound is reported to be nitrogen limited (Gibbs et al. 1992, Zeldis et al. 2013, Broekhuizen et al. 2015), and the lowest levels of mollusc productivity as measured in the DA prior to human habitation herein is consistent with the system being formerly low in productivity. This supports the hypothesis that the inner Kenepuru, when fully afforested under native vegetation, received low nutrient input from land. Although we have no absolute measure of historic nitrogen or phosphorus availability from deposited sediments, the recent decline in mollusc shell deposition in the DA from its peak in 1950-74 is consistent with a response to declining nutrient supply. The close agreement between sites (except Gold Reef Bay) suggests these effects are widespread. How this relates to survivorship of mussel spat is unknown. It was interesting that the highest mollusc productivity was measured during the peak of sheep farming when fertilizers were applied by aerial top-dressing. The observation that mollusc productivity was greatest at Gold Reef Bay, and the concomitant supply of schist gravel at that site, suggests that nutrient supply and mollusc response was elevated adjacent to catchments susceptible to erosion of coarse substrate, and the mollusc response can be localised, differing at the scale of our coring sites (ca. 4-5km). A contributing factor in the recent decline in mollusc productivity could have been the cumulative increase in the discharge of fine sediments that smother and choke molluscs, bind to nutrients rendering nutrients less bioavailable, and shading plants. It therefore seems unlikely that nutrient availability is the only factor acting on phytoplankton production and mussel survival, preventing GLM bed recovery.

Table 4-1: Summary of potential hypotheses that could explain mechanisms preventing innate recovery of GLM beds in the inner Pelorus Sound.

	Hypothesis:	Likelihood?	Reasoning:
H0: 1	Mussel beds were an aberrant artefact of European settlement.	Probable	• Mussel larval supply and floating debris don't appear to be limited.
H0: 2	Reduced mussel predators allowed for mussel bed formation/expansion.	Unlikely	• Snapper and rock lobster densities likely at historic low levels.
H0: 3	Ecosystem changes created a "bottleneck" for mussel larval settlement substrates (e.g., filamentous algae, seagrass).	Probable	• 10x increase in sedimentation would smother plants and reduced water clarity shading out algae. • Absence of foreshore and seabed mussel beds to clarify water column and fertilize plants (feedback mechanisms).
H0: 4	Increased suspended sediment negatively affects juvenile and adult mussels.	Probable	• Fine sediment is a shellfish pollutant at 20 mg/l concentration. • Sediment can also bind with nutrients reducing their bioavailability to phytoplankton.
H0: 5	Reduced nutrient availability limiting phytoplankton production, causing juvenile mussels at the seabed to starve.	Unlikely	• Mollusc death assemblage results show decline in mollusc productivity following reductions in drystock farming since 1975 and increased SARs. • SARs of fine sediments have increased, potentially shading plants and smothering and chocking mussel spat.

4.5 Conclusions

Sedimentation rates 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. The greatest contributor of sediment since 1975 was the 'Havelock inflow', bracken from repeated land clearance associated with sheep farming and forestry activities, with localised peaks in pine-harvest soils. The proportion of pine-harvest soils was greatest in Beatrix Bay and exceeded 30% in majority of the surface sediment samples taken.

The low abundance of GLM shells sample in cores, even close to shore where historic mussel beds used to occur, precluded drawing direct linkages with factors preventing GLM bed recovery. The DA results however showed that in a pre-human unmodified state, mollusc productivity appeared lower than estimates calculated from shell deposited in the last 40 years. Mollusc productivity increased followed human colonisation. This initial increase is hypothesised to result from elevated discharge of land-based nutrients, consistent with: elevated subsoil discharge associated with land clearances, and elevated deposition of bracken and ponga soils indicative of ongoing clearance or repeated burning of regenerating bush. After 1900 dramatic increase in 'Havelock inflow' soils were seen along with the first records of pine harvest and sheep soils. Mollusc shell deposition peaked during the 1960-1975, the period in history during which fertilizer subsidies were available and near maximum historic sheep production took place.

The factors that have prevented the intrinsic recovery of mussel beds in Pelorus Sound are considered complex. They likely involve interactions and feedback between multiple factors including: historic fishing pressure reducing mussel standing stocks, acceleration of sedimentation affecting availability of nutrients; sediment attenuating light diminishing phytoplankton and seabed plant production, and sediment smothering and choking spat. These factors will be compounded by low densities of mussels and seabed plants that cannot provide positive feedback mechanisms that could enhance and reinforce wild mussel survivorship.

4.6 Recommendations

- As the ‘Havelock inflow’ soils were the dominant source of discharge to the coring sites with the greatest SARs, we recommend that the source of this sediment be determined to evaluate whether the land-use practice contributing that sediment can be mitigated. If farming is found to be significant contributor to sedimentation, riparian planting underway in the Pelorus/Kaituna river catchments since 2013 (Peter Hamill, MLDC, pers. comm.) and also improved farming practices in the Sounds (Kristen Gerard, pers. comm., Benny 2015) should be further encouraged.

- Because pine harvest soils have increased in proportion over time, had strong localised effects in Te Matau a Maui Bay, and also more widespread effects in Beatrix Bay, we recommend that the mitigation measures outlined by (Urlich 2015) be encouraged, especially measures to protect steep slopes and land during windows of vulnerability following harvest.

- We recommend that mussel bed restoration experiments be tested adjacent to regenerating steep catchments that have adequate current and wave exposure (potentially maximising nutrient supply), and that seabed plant restoration should also be encouraged and tested for synergistic effects. Restoration experiments could involve 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, to reduce on-site suspended sediment concentrations.

- Because mollusc productivity estimates from the last 40 years (since 1975) were elevated above pre-human benchmark conditions that we have associated with changes in land-use especially for farming sheep, there is the potential that future mitigation measures to reduce nutrient discharge from the catchment combined with continued discharge of fine clay particles binding with nutrients could partially reduce bioavailability of nutrients and hence productivity in Pelorus Sound. As we have no measure of historic nutrient loadings in the Pelorus, only contemporary estimates based on particulate nitrogen (Zeldis et al. 2013), we suggest that future research should focus on using palaeoecological techniques to estimate historic nutrient concentrations. For example, using additional proxies for system productivity like historic sediment signatures from seabed plants and water-column plants to estimate historic nutrient loadings. These estimates could then be used to model future scenarios of carrying capacity to support planning and management of regionally important sectors including aquaculture and fishing.

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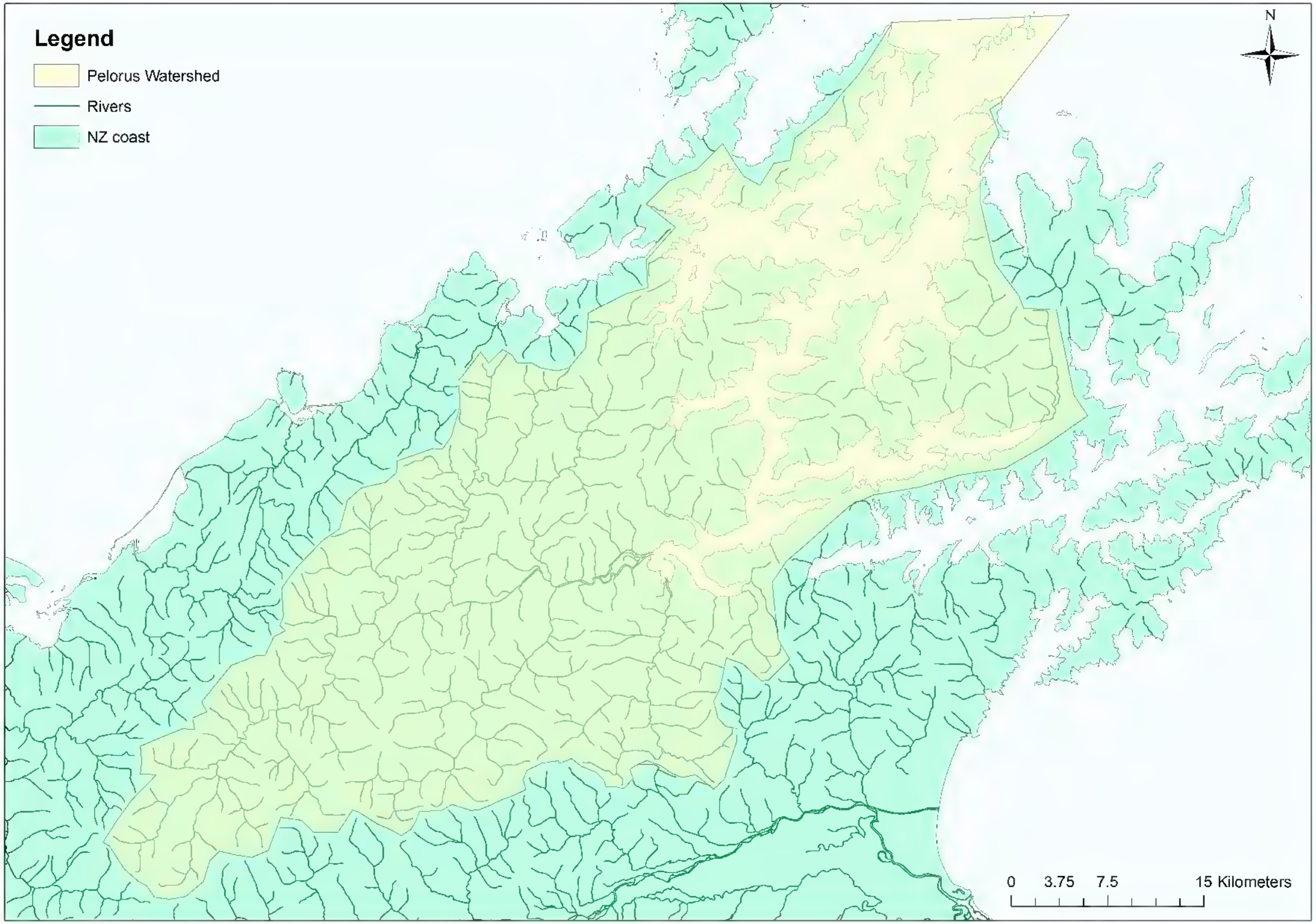
Appendix A Pelorus watershed area used to extract landuse statistics from Land Cover Database (LCDB v.4), Landcare Research (Table A-1)



Appendix B Location of CSSI sediment core collection sites in Beatrix Bay (top) and Kenepuru Sound (bottom), Pelorus Sound

Core ID	Date	Location	Site	Lat	Long	GPS Wpt	Water Depth	Core Depth	Notes
KP1	11-Mar-15	Kenepuru	Te Matua a Maui Bay	41 11.294	173 57.452	151	6	1.9	Soft mud
KP2	11-Mar-15	Kenepuru	Te Matua a Maui Bay	41 11.294	173 57.452	151	6	2.2	Soft mud
KP3	11-Mar-15	Kenepuru	Te Matua a Maui Bay	41 11.294	173 57.452	151	6	1.6	Soft mud
KP4	11-Mar-15	Kenepuru	Te Matua a Maui Bay	41 11.294	173 57.452	151	6	2.4	Soft mud
KP5	11-Mar-15	Kenepuru	Waitaria Bay	41 10.417	174 01.836	152	9.5	2.4	Soft mud
KP6	11-Mar-15	Kenepuru	Waitaria Bay	41 10.417	174 01.836	152	9.5	2.4	Soft mud
KP7	11-Mar-15	Kenepuru	Waitaria Bay	41 10.417	174 01.836	152	9.5	2.2	Soft mud
KP8	11-Mar-15	Kenepuru	Waitaria Bay	41 10.417	174 01.836	152	9.5	2.2	Soft mud
KP9	11-Mar-15	Kenepuru	Upper Kenepuru	41 10.950	174 05.088	154	6	2.3	Soft mud
KP10	11-Mar-15	Kenepuru	Upper Kenepuru	41 10.950	174 05.088	154	6	2.3	Soft mud
KP11	11-Mar-15	Kenepuru	Upper Kenepuru	41 10.950	174 05.088	154	6	2.3	Soft mud
KP12	11-Mar-15	Kenepuru	Upper Kenepuru	41 10.950	174 05.088	154	6	2.3	Soft mud
BT1	12-Mar-15	Beatrix Bay	Inner Laverique Bay	41 03.086	174 02.636	155	16	1.1	Hard packed sand mud shell gravel
BT2	12-Mar-15	Beatrix Bay	Inner Laverique Bay	41 03.086	174 02.636	155	16	0.9	Hard packed sand mud shell gravel
BT3	12-Mar-15	Beatrix Bay	Inner Laverique Bay	41 03.086	174 02.636	155	16	0.4	Hard packed sand mud shell gravel
BT4	12-Mar-15	Beatrix Bay	Inner Laverique Bay	41 03.086	174 02.636	155	16	0.7	Hard packed sand mud shell gravel
BT5	12-Mar-15	Beatrix Bay	Outer Laverique Bay	41 02.975	174 02.474	156	25	0.6	Sand mud shell gravel
BT6	12-Mar-15	Beatrix Bay	Outer Laverique Bay	41 02.975	174 02.474	156	25	0.6	Sand mud shell gravel
BT7	12-Mar-15	Beatrix Bay	Outer Laverique Bay	41 02.975	174 02.474	156	25	0.5	Sand mud shell gravel
BT8	12-Mar-15	Beatrix Bay	Outer Laverique Bay	41 02.975	174 02.474	156	25	0.5	Sand mud shell gravel
BT9	12-Mar-15	Beatrix Bay	Offshore Laverique Bay	41 02.541	174 01.764	157	36	2.1	Soft mud
BT10	12-Mar-15	Beatrix Bay	Offshore Laverique Bay	41 02.541	174 01.764	157	36	2	Soft mud
BT11	12-Mar-15	Beatrix Bay	Offshore Laverique Bay	41 02.541	174 01.764	157	36	2.1	Soft mud
BT12	12-Mar-15	Beatrix Bay	Offshore Laverique Bay	41 02.541	174 01.764	157	36	2.2	Soft mud

Appendix C Location of mussel reef sediment core collection sites in Kenepuru Sound

Core_ID	Date	Location	Site	Lat	Long	GPS_Wpt	WaterDepth	CoreDepth	Notes
PP1	16-Nov-15	Kenepuru	Poison Pt.	-41.1785	174.00884	3	7		shells at surface and muddy lower down
PP2	16-Nov-15	Kenepuru	Poison Pt.	-41.1785	174.00884	3	7	1.4	shells at surface and muddy lower down
PP3	16-Nov-15	Kenepuru	Poison Pt.	-41.1785	174.00884	3	7		shells at surface and muddy lower down
PP4	16-Nov-15	Kenepuru	Poison Pt.	-41.1785	174.00884	3	7		shells at surface and muddy lower down
MW1	16-Nov-15	Kenepuru	Gold Reef Bay West	-41.193	173.9781	6	6		mud, then shell, then mud and gravel + rocks lower down
MW2	16-Nov-15	Kenepuru	Gold Reef Bay West	-41.193	173.9781	6	6	1.13	mud, then shell, then mud and gravel + rocks lower down
MW3	16-Nov-15	Kenepuru	Gold Reef Bay West	-41.193	173.9781	6	6		mud, then shell, then mud and gravel + rocks lower down
MW4	16-Nov-15	Kenepuru	Gold Reef Bay West	-41.193	173.9781	6	6		mud, then shell, then mud and gravel + rocks lower down
SKD1	16-Nov-15	Kenepuru	Skiddaw	-41.1987	173.92228	7	6	1.22	soft mud at surface, sand and shell gravel, and the mud lower down. Band of shell at ~70cm
SKD2	16-Nov-15	Kenepuru	Skiddaw	-41.1987	173.92228	7	6		soft mud at surface, sand and shell gravel, and the mud lower down. Band of shell at ~70cm
SKD3	16-Nov-15	Kenepuru	Skiddaw	-41.1987	173.92228	7	6		soft mud at surface, sand and shell gravel, and the mud lower down. Band of shell at ~70cm
SKD4	16-Nov-15	Kenepuru	Skiddaw	-41.1987	173.92228	7	6		soft mud at surface, sand and shell gravel, and the mud lower down. Band of shell at ~70cm

Appendix D Location of contaminant sediment/soils labelled by waypoint

WPT	Date	Long: WGS84	Lat: WGS84	Label	Notes, description
160	21/04/2015	173.5735733	-41.3067915	PB1	Beech (black) forest, ponga, caprosma, pittosporum. Pelorus Bridge reserve track.
161	21/04/2015	173.5728943	-41.30682851	PB2	Rimu, tawa, mahoe, silver ponga, caprosma. Pelorus Bridge reserve track.
162	21/04/2015	174.0224162	-41.17026486	KP1	Sheep grazing, grass, cocksfoot, clover, pinus overhead nearby. Road reserve, Waitaria Bay,
165	21/04/2015	174.0215632	-41.17356273	SKP3	Mussel farm sediment, Kenepuru head 5m depth
166	21/04/2015	173.9951298	-41.19703781	SKP4	Manuka, Kanuka, ponga, cabbage tree, mahoe - regrowth from old slip
167	21/04/2015	173.9722632	-41.19195289	SKP5	Kanuka, akeake, ponga, mahoe, 5 finger- secondary regrowth -headland off St Omer, Ferndale Campsite
169	21/04/2015	173.9210171	-41.20011431	SKP6	Beech forest, mature, mahoe, ponga - headland reserve west of Double Bay, Kenepuru
171	22/04/2015	173.8950005	-41.19951023	SKP7	Beef grazing grassland- regrassed from milled pine (stumps), east of Koutuwai Pt.
172	22/04/2015	174.0733047	-40.90716804	SCHET	Marine end member sediment sample - Chetwode Island, Nukuwaiata Is, 17m depth
173	22/04/2015	174.0672363	-40.95455835	SORCH	Mussel farm sediment, Orchard Bay (live spat present), 28.7m depth
174	22/04/2015	173.9163858	-41.05952859	STAW1	Sheep farm, Pasture, rush - Foote's farm, Tawhitinui Reach. Sample collected at foot of steep gully
175	22/04/2015	173.9476934	-41.06658644	STAW2	Sheep farm, Pasture, rush - Foote's farm, South of Tawero Pt. Sample collected at foot of steep gully
176	22/04/2015	173.9028796	-41.12058932	SYNC3	Nikau, kiki, brachyglotis, kawakawa, griselinia - headland on north side of Yncyca Bay. Steep aspect
177	22/04/2015	173.7776733	-41.15736821	SNYD1	Mature Pine forrest - Marty's place. Road reserve, Nydia Bay track.
178	22/04/2015	173.7813451	-41.14386168	SNYD2	Beech forest, climbing rata, ponga (silver), crown fern, Nydia Bay track.
179	22/04/2015	173.7813701	-41.14461465	SNYD3	Rimu, kiki, ponga, nikau, Nydia Bay track.
180	22/04/2015	173.7818702	-41.14932447	SNYD4	Kanuka, ponga, mingimingi, crown fern, coprosma, Nydia Bay track.
181	23/04/2015	173.8782642	-41.13819764	SYNC3	Bracken fern, grass - Forrest estate bach track. Retired farm land, ~20 years ago
183	23/04/2015	173.8810362	-41.1365677	SYNC5	Mussel farm sediment, Yncyca Bay - live mussels present, 25m depth.
184	23/04/2015	173.7821487	-41.26082778	WPT184	Havelock seagrass, intertidal bank in middle of channel. Swan grazing nearby.
184	23/04/2015	173.7821487	-41.26082778	WPT184	Havelock seagrass sediment, intertidal bank in middle of channel. Swan grazing nearby.
185	23/04/2015	173.7946014	-41.25966967	WPT185	Havelock Ponga grove, south of Kaiuma Pt. Steep bank above road reserve.
186	23/04/2015	173.7849386	-41.27073246	WPT186	Gorse, broom, bracken, manuka - Havelock view point, Mahikipawa Scenic Reserve
187	23/04/2015	173.6431393	-41.28350467	WPT187	Dairy grazing & transit area, overbridge, Pelorus R., Daltons Rd. Cow tracks and pooh present.
188	23/04/2015	173.674025	-41.21149862	WPT188	Dairy grazing & transit area, overbridge, Opouri river, Opouri Rd. Cow tracks and pooh present.
189	5/05/2015	173.3011328	-41.29239815	WPT189	Recent harvested pine (storm damaged) - skid site, Codgers track, Sharland Hill, Nelson
190	5/05/2015	173.5527907	-41.16522422	WPT190	Recent harvested pine - gully draining into Collins River, Road reserve, Collins Valley Rd, Whangamoa.
191	5/05/2015	173.4192051	-41.20795642	WPT191	Recent harvested pine - skid site, Kanuka Ridge, Hill above Cable Bay Rd.
192	5/05/2015	173.4196251	-41.20818941	WPT192	Mature pine - Kanuka Ridge, Hill above Cable Bay Rd.
194	22/04/2015	173.8789957	-41.13988997	SYN2	Mature Pine forrest - Forrest estate
195	14/10/2015	174.0401	-41.05399	SS1	Scrub - sub-soil from slip
196	14/10/2015	174.01377	-41.05738	SS2	Scrub - sub-soil from slip
197	14/10/2015	173.88499	-41.11254	SS3	Bush- sub-soil from slip
198	14/10/2015	173.82939	-41.14326	SS4	Bush- sub-soil from slip
199	14/10/2015	173.7954	-41.25846	SS5	Scrub - sub-soil from slip

# Appendix E	CSSI sediment source tracing

In this section we describe how stable isotopes are used to identify the sources of catchment sediments deposited in lakes, estuaries and coastal waters and explain how isotopic data are interpreted.

Stable isotopes are non-radioactive and are a natural phenomenon in many elements. In the NIWA Compound Specific Stable Isotope (CSSI) method, carbon (C) stable isotopes are used to determine the provenance of sediments (Gibbs 2008). About 98.9% of all carbon atoms have an atomic weight (mass) of 12. The remaining ~1.1% of C atoms have an extra neutron in the atomic structure, giving it an atomic weight (mass) of 13. These are the two stable isotopes of carbon. Naturally occurring carbon also contains an extremely small fraction (about two trillionths) of radioactive carbon-14 (^{14}C). Radiocarbon dating is also used in the present study to determine long-term sedimentation rates.

To distinguish between the two stable isotopes of carbon, they are referred to as light (^{12}C) and heavy (^{13}C) isotopes. Both of these stable isotopes of carbon have the same chemical properties and react in the same way. However, because ^{13}C has the extra neutron in its atom, it is slightly larger than the ^{12}C atom. This causes molecules with the ^{13}C atoms in their structure to react slightly slower than those with ^{12}C atoms, and to pass through cell walls in plants or animals at a slower rate than molecules with ^{12}C atoms. Consequently, more of the ^{12}C isotope passes through the cell wall than the ^{13}C isotope, which results in more ^{12}C on one side of the cell wall than the other. This effect is called isotopic fractionation and the difference can be measured using a mass spectrometer. Because the fractionation due to passage through one cell-wall step is constant, the amount of fractionation can be used to determine chemical and biological pathways and processes in an ecosystem. Each cell wall transfer or "step" is positive and results in enrichment of the ^{13}C content.

The amount of fractionation is very small (about one thousandth of a percent of the total molecules for each step) and the numbers become very cumbersome to use. A convention has been developed where the difference in mass is reported as a ratio of heavy-to-light isotope. This ratio is called "delta notation" and uses the symbol "δ" before the heavy isotope symbol to indicate the ratio i.e., δ^{13}C. The units are expressed as "per mil" which uses the symbol "‰". The delta value of a sample is calculated using the equation:

$$\delta^{13}C = \left[\left(\frac{R_{sample}}{R_{standard}}\right) - 1\right]1000 \qquad \text{(E-1)}$$

where *R* is the molar ratio of the heavy to light isotope ^{13}C/^{12}C. The international reference standard for carbon was a limestone, Pee Dee Belemnite (PDB), which has a ^{13}C/^{12}C ratio of 0.0112372 and a δ^{13}C value of 0 ‰. As all of this primary standard has been consumed, secondary standards calibrated to the PDB standard are used. Relative to this standard most organic materials have a negative δ^{13}C value.

Atmospheric CO_2, which is taken up by plants in the process of photosynthesis, presently has a δ^{13}C value of about -8.5. In turn, the δ^{13}C signatures of organic compounds produced by plants partly depends on their photosynthetic pathway, primarily either C_3 or C_4. During photosynthesis, carbon passes through a series of reactions or trophic steps along the C_3 or C_4 pathways. At each trophic step, isotopic fractionation occurs and organic matter in the plant (i.e., the destination pool) is depleted by 1 ‰. The C_3 pathway is longer than the C_4 pathway so that organic compounds produced by C_3 plants have a more depleted δ^{13}C signature. There is also variation in the actual amount of fractionation between plant species having the same photosynthetic pathway. This results in a range of δ^{13}C values, although typical bulk values for C_3 and C_4 plants vary around -26 ‰ and -12 ‰ respectively. The rate of fractionation also varies between the various types of organic compounds produced by plants. Thus, by these processes a range of organic compounds each with unique $\delta^{13}C$ signatures are produced by plants that can potentially be used as natural tracers or biomarkers.

The instruments used to measure stable isotopes are called “isotope ratio mass spectrometers” (IRMS) and they report delta values directly. However, because they have to measure the amount of ^{12}C in the sample, and the bulk of the sample C will be ^{12}C, the instrument also gives the percent C (%C) in the sample.

When analysing the stable isotopes in a sample, the $\delta^{13}C$ value obtained is referred to as the bulk $\delta^{13}C$ value. This value indicates the type of organic material in the sample and the level of biological processing that has occurred. (Biological processing requires passage through a cell wall, such as in digestion and excretion processes and bacterial decomposition.) The bulk $\delta^{13}C$ value can be used as an indicator of the likely source land cover of the sediment. For example, fresh soil from forests has a high organic content with %C in the range 5% to 20% and a low bulk $\delta^{13}C$ value in the range -28‰ to -40‰. As biological processing occurs, bacterial decomposition converts some of the organic carbon to carbon dioxide (CO_2) gas which is lost to the atmosphere. This reduces the %C value and, because microbial decomposition has many steps, the bulk $\delta^{13}C$ value increases by ~1‰ for each step. Pasture land cover and marine sediments typically have bulk $\delta^{13}C$ values in the range -24‰ to -26‰ and -20‰ to -22‰, respectively. Waste water and dairy farm effluent have bulk $\delta^{13}C$ values more enriched than -20‰. Consequently, a dairy farm where animal waste has been spread on the ground as fertilizer, will have bulk $\delta^{13}C$ values higher (more enriched) than pasture used for sheep and beef grazing.

There are occasions when the inorganic component of the soil imparts a highly modified $\delta^{13}C$ isotopic signature to the soil such that the $\delta^{13}C$ value cannot be used for modelling of soil sources. This phenomenon occurs in Karst (limestone) soils and as occurs in the upper Whangarei Harbour associated with the Portland sediment.

In addition to the bulk $\delta^{13}C$ value, organic carbon compounds in the sediment can be extracted and the $\delta^{13}C$ values of the carbon in each different compound can be measured. These values are referred to as compound-specific stable isotope (CSSI) values. A forensic technique recently developed to determine the provenance of sediment uses both bulk $\delta^{13}C$ values and CSSI values from each sediment sample in a deposit for comparison with signatures from a range of potential soil sources for different land cover types. This method is called the CSSI technique (Gibbs, 2008).

The CSSI technique is based on the concepts that:

1. land cover is primarily defined by the plant community growing on the land, and
2. all plants produce the same range of organic compounds but with slightly different CSSI values because of differences in the way each plant species grows and also because each land cover type has a characteristic composition of plant types that contribute to the CSSI signature.

The compounds commonly used for CSSI analysis of sediment sources are natural plant fatty acids which bind to the soil particles as labels called biomarkers. While the amount of a biomarker may decline over time, the CSSI value of the biomarker does not change. The CSSI values for the range of biomarkers in a soil provides positive identification of the source of the soil by land cover type.

The sediment at any location in an estuary or harbour can be derived from many sources including river inflows, coastal sediments and harbour sediment deposits that have been mobilised by tidal currents and wind-waves. The contribution of each sediment source to the sediment mixture at the sampling location will be different. To separate and apportion the contribution of each source to the sample, a mixing model is used. The CSSI technique uses the mixing model IsoSource (Phillips & Gregg 2003). The IsoSource mixing model is described in more detail in a following section.

While the information on stable isotopes above has focused on carbon, these descriptions also apply to nitrogen (N), which also has two stable isotopes, ^{14}N and ^{15}N. The bulk N content (%N) and bulk isotopic values of N, δ^{15}N, also provide information on land cover in the catchment but, because the microbial processes of nitrification and denitrification can cause additional fractionation after the sediment has been deposited, bulk δ^{15}N cannot be used to identify sediment sources. The fractionation step for N is around +3.5‰ with bulk δ^{15}N values for forest soils in the range +2‰ to +5‰. Microbial decomposition processes result in bulk δ^{15}N values in the range 6‰ to 12‰ while waste water and dairy effluent can produce bulk δ^{15}N values up to 20‰. However, the use of synthetic fertilizers such as urea, which has δ^{15}N values of -5‰, can result in bulk δ^{15}N values <0‰.

Analyses

An aliquot of each dry sediment sample was acidified with 1 N hydrochloric acid to remove inorganic carbonate before analysing for bulk organic C and N stable isotopes. About 50 mg of each acidified sample was combusted in a helium gas stream in a Fisons N1500 Elemental Analyser coupled via a ConFlo-II interface to a Thermo-Finnegan Continuous Flow Isotope Ratio Mass Spectrometer (CF-IRMS).

For δ^{13}C, CF-IRMS measurements typically have a precision of ± 0.1 ‰ or better and the instrument also provides the proportion of organic C and N (%) in each sample.

Aliquots (20 to 40 g) of the non-acidified dry sediment were extracted with hot dichloromethane (100 ºC) under high pressure (2000 psi) in a Dionex Accelerated Solvent Extractor (ASE 2000) to extract the fatty acids bound to the sediment particles. The fatty acids were methylated using 5% boron trifluoride catalyst in methanol to produce fatty acid methyl esters (FAMEs). These FAMEs were analysed by gas chromatography (GC)-combustion-IRMS to produce compound-specific stable isotope δ^{13}C values i.e., CSSI values. Method details and data interpretation protocols were described previously by Gibbs (2008).

Data processing and presentation

The %C and suite of CSSI values for the extracted FAMEs were assembled into a matrix table and modelled using IsoSource to estimate the number (*n*) of isotopically feasible proportions of the main sediment sources at each sampling location. In successive model iterations, potential sources were added or removed to find an isotopic balance where the confidence level was high (lowest *n* value) and uncertainty was low. The isotopically feasible proportions of each soil source are then converted to soil proportions using the %C of each soil on a proportional basis. That is to that the higher the %C in the soil, the less of that soil source is required to obtain the isotopic balance. In general, soil proportions less than 5% were considered possible but potentially not present. Soil proportions >5% were considered to be present within the range of the mean ± SD.

CSSI Method

The CSSI method applies the concept of using the δ^{13}C signatures of organic compounds produced by plants to distinguish between soils that develop under different land-cover types. With the exception of monocultures (e.g., wheat field), the δ^{13}C signatures of each land-cover type reflects the combined signatures of the major plant species that are present. For example, the isotopic signature of the Bay's lowland native forest will be dominated by kauri, rimu, totara and tānekaha. A monoculture, such as pine forest, by comparison will impart an isotopic signature that largely reflects the pine species, as well as, potentially, any understory plants.

The application of the CSSI method for sediment-source determination involves the collection of sediment samples from potential sub-catchment and/or land cover sources as well as sampling of sediment deposits in the receiving environment. These sediment deposits are composed of mixtures of terrigenous sediments, with the contribution of each source potentially varying both temporally and spatially. The sampling of catchment soils provides a library of isotopic signatures of potential sources that is used to model the most likely sources of sediments deposited at any given location and/or time.

Straight-chain Fatty Acids (FA) with carbon-chain lengths of 12 to 24 atoms (C12:0 to C24:0) have been found to be particularly suitable for sediment-source determination as they are bound to fine sediment particles and long-lived (i.e., decades). In the present study, five types of FA were used to evaluate the present-day and historical sources of terrigenous sediments deposited in the Bay: Myristic Acid (C14:0); Palmitic (C16:0); Stearic (C18:0); Arachidic (C20:0) and Behenic (C22:0). Although breakdown of these FA to other compounds eventually occurs, the signature of a remaining FA in the mixture does not change.

The stable isotope compositions of N and C and the CSSI of carbon in the suite of fatty acid (FA) biomarkers are extracted from catchment soils and marine sediments. It is the FA signatures of the soils and marine sediments that are used in this study to determine sediment sources. Gibbs (2008) describes the CSSI method in detail.

Correction of CSSI signatures for the Suess effect

The reconstruction of changes in sources of terrigenous sediment deposited in the BOI system is derived from dated cores using the FA isotope signatures preserved in the sediments. Before the feasible sources of these sediments could be evaluated using the IsoSource package, the isotope (i.e., input) data required correction for the effects of the release of “old carbon” into the biosphere over the last 300 years, associated with the burning of fossil fuels and deforestation.

Specifically, the release of old carbon with a depleted $\delta^{13}C$ signature has resulted in a decline in $\delta^{13}C$ in atmospheric CO_2 ($\delta^{13}CO_2$). The changing abundance of carbon isotopes in a carbon reservoir associated with human activities is termed the Suess effect (Keeling 1979). This depletion in atmospheric $\delta^{13}CO_2$ is of the order of 2 ‰ since 1700 and has accelerated substantially since the 1940s (Verburg 2007). Thus, the $\delta^{13}C$ signatures of plant biomarkers, such as Fatty Acids have also changed due to the Suess effect. Consequently, the isotopic signatures of estuarine sediments (i.e., the mixture) deposited in the past must be corrected to match the isotopic signatures of present-day source soils.

Figure B1 presents the atmospheric $\delta^{13}C$ curve reconstructed by Verburg (2007) using data collected in earlier studies and includes measurements of material dating back to 1570 AD. These data indicate that the atmospheric $\delta^{13}C$ signature was stable until 1700 AD, with subsequent depletion of $\delta^{13}C$ due to release of fossil carbon.

In the present study, we use this atmospheric $\delta^{13}C$ curve to correct the isotopic values of the FA in sediment samples of varying ages taken from cores to equivalent modern values. This is required because the $\delta^{13}C$ values of the FA from the potential catchment sources are modern (i.e., 2010 AD), and are therefore depleted due to the Suess effect. For example, the $\delta^{13}C$ value of a Fatty Acid derived from a kauri tree growing today will be depleted by -2.15 ‰ in comparison to a kauri that grew prior to 1700 AD (Fig. 8.1). It can be seen that the isotopic correction for the period since 1700 is variable depending on age. Examples of this correction process for isotopic data for sediments taken from core RAN-5B are presented in Table B2.

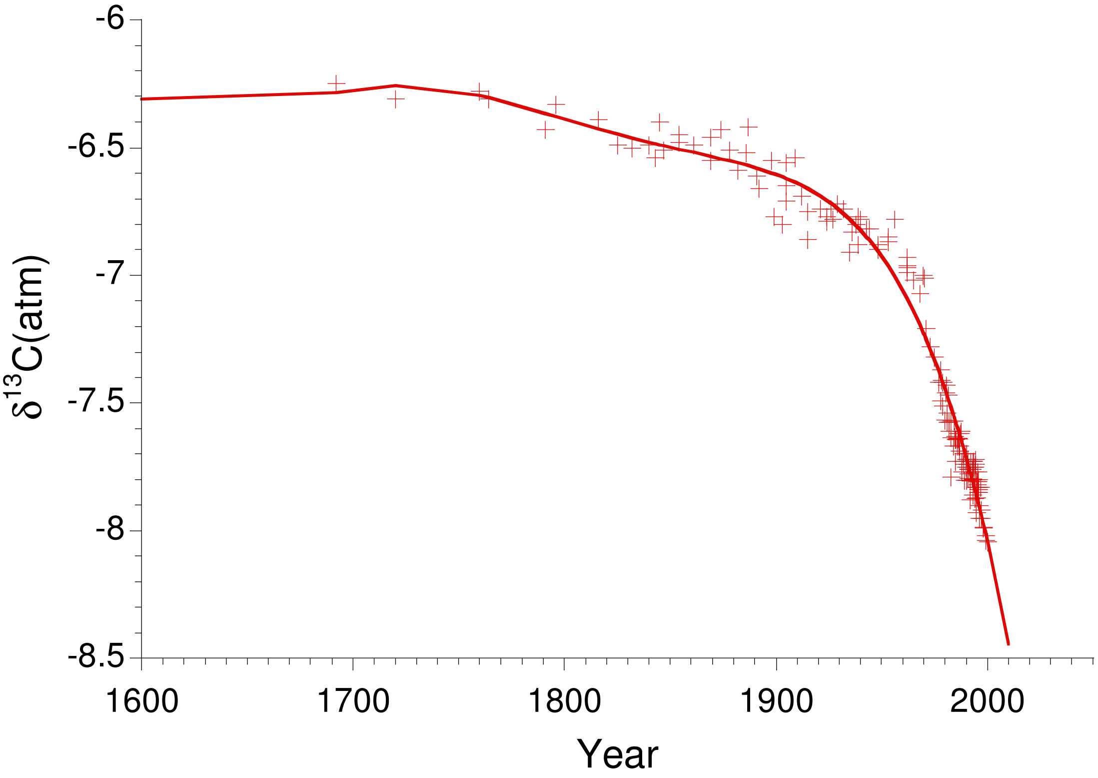


Figure A1: Historical change in atmospheric δ^{13}C (per mil) (1570–2010 AD) due to release of fossil carbon associated with anthropogenic activity (the so-called Suess effect), Source: Verburg (2007).

IsoSources mixing model

The sources of terrigenous sediments deposited on the present-day seabed surface and at various times in the past, that are preserved in cores, were determined from analysis of the CSSI signatures of potential sources (i.e., soils) and mixtures (i.e., marine-sediment deposits). The library of isotopic signatures used included those derived from local (i.e., Bay of Islands) soils as well as other potential sources that were not sampled because (1) they could not be accessed or (2) no longer occur in the catchment (e.g., kumara gardens).

In the present study, the IsoSource mixing model (Phillips & Gregg 2003) was used to evaluate the feasible sources of terrigenous sediments in the estuarine deposits. IsoSource requires a minimum of three sources and two isotopic tracers to run. In the present study, an iterative approach was taken to the selection of potential sediment sources, constrained by the recorded land-cover history. For example, in the Bay of Island's, citrus trees were not planted in large numbers in the Kerikeri catchment until the late 1920s so that citrus is not a valid sediment source for sediments deposited before that time.

IsoSource is not a conventional mixing model in that it iteratively constructs a table of all possible combinations of isotopic source proportions that sum to 100% and compares these predicted isotopic values with the isotopic values in the sediment mixture (i.e., deposit). If the predicted and observed stable isotope values are equal or within some small tolerance (e.g., 0.1 ‰, referred to as the mass-balance tolerance by Phillips and Gregg 2003) then that predicted stable-isotope signature represents a feasible solution. Within a given tolerance, there may be few or many feasible solutions.

The total number of feasible solutions (*n*) provides a measure of the confidence in the result. High values of *n* indicate many feasible solutions and hence there is low confidence in the result. As the value of *n* reduces towards 1 the level of confidence increases until *n* = 1, which represents a unique solution. It is rare to have an exact match or unique solution. In most cases there will be many feasible solutions and these can be statistically evaluated to assess the most likely combination of sources in the sediment sample. These feasible solutions are expressed as isotopic feasible proportions (%) with an uncertainty value equivalent to the standard deviation about the mean.

In practice, the tolerance is reduced by iteration within the IsoSource model to obtain the lowest *n* and therefore the highest confidence in the result. The tolerance required to obtain any feasible solutions will be greater than 0.1 ‰ if the isotopic values of the source tracers differ markedly from those of the sediment mixture in the receiving environment. Together, the tolerance and number of feasible solutions (*n*) for each sediment mixture provide measures of uncertainty in the results in addition to the standard deviation and the range of the isotopic proportions for each soil source. An example result from this analysis for a Bay of Islands sediment sample is shown in Table D-1 below (Swales et al. 2012).

Table D-1: Example of IsoSource model result. Core RAN-5B (Waikare Inlet), 30-31 cm depth (1914 AD). The mean, median and standard deviation (SD) values are shown.

Tolerance	n	Nikau			Kauri			Bracken		
		mean	median	SD	mean	median	SD	mean	median	SD
0.9	3	0.317	0.32	0.006	0.55	0.55	0.01	0.133	0.13	0.006

This sample comes from core RAN-5B, which was collected in the Waikare Inlet. The catchment even today remains largely under native forest and scrub land cover, so that sediments deposited in the inlet should reflect these land cover signatures. The sample was taken from 30—31-cm depth in the core, with radioisotope dating indicating that it was deposited in the early 1900s. The feasible isotopic proportions of the three major sediment sources are shown in the table (range = 0–1, where 1 = 100%). Although mean, median and standard deviation values are shown, minimum and maximum values of the feasible isotopic proportions for each source are also calculated. **The reporting solely of mean values is not adequate** and a measure of uncertainty, such as the minimum, maximum and/or standard deviation should be included in the results (Phillips & Gregg 2003).

The results indicate that the soils that make up the sediment-core sample are largely derived from native forest (kauri and nikau associations), with a small contribution from bracken. The presence of bracken is a key indicator of catchment disturbance/forest clearing. The presence of bracken pollen in sediment deposits has long been used in historical reconstructions of the New Zealand environment (e.g., McGlone 1983). However, bracken pollen reflects the presence of these plants growing in the general area and may or may not be indicative of bracken soils being eroded. By comparison, the presence of a CSSI bracken signature in a deposit positively indicates that some proportion of the sediment sample is composed of eroded bracken soil. The tolerance at 0.9 ‰ is a mid-range value, with values as low as 0.01 ‰ possible in some of the samples that were analysed. The number of feasible solutions (*n* = 3) is low, which also provides high confidence in these results.

Typically less than 5% of most sediment samples is composed of carbon, and the isotopic balance evaluated by IsoSource is only applicable to the carbon content of each source. These isotopically feasible proportions must therefore be converted to soil proportions using a linear scaling factor to estimate the percent contribution of each feasible soil source. This conversion of feasible isotopic source proportions to soil source proportions is described in a following section.

Conversion of isotopic proportions to soil proportions

The IsoSource model provides estimates of the isotopic-proportional contributions of each land-cover (i.e., soil) type in each marine sample. Thus, these results are in terms of carbon isotopic proportions and not source soil proportions. Furthermore, the stable isotope tracers account for a small fraction, typically less than 2%, of total organic carbon (OC) in the soil and OC accounts for typically <10% of the soil by weight. These factors mean that the contribution of each source soil to a sediment mixture will scale with the soil carbon content. Consequently, a linear correction based on the soil OC is required to estimate the proportion of each soil source in a sediment sample from a receiving environment (Gibbs 2008).

To convert the isotopic proportions to soil proportions (S_n%) the simple linear correction equation below: was used:

$$S_n\% = \frac{{}^{I_n}/_{C_n\%}}{\Sigma_n^1\left({}^{I_n}/_{C_n\%}\right)} * 100 \qquad \text{(E-2)}$$

Where I_n is the mean feasible isotopic proportion of source soil *n* in the mixture estimated using an isotopic mixing model and C_n% is the percentage organic carbon in the source soil.

Because this calculation only uses the OC% in the source soils for linear scaling, the proportional contribution of each source soil is not influenced by any loss of carbon (e.g., total carbon, Fatty Acids etc.,) in the sediment mixture due to biodegradation. The level of uncertainty in the mean soil proportion is the same as that defined by the standard deviation about the mean isotopic proportion.

A simple example of this linear correction is illustrated here by considering a solution composed of a mixture of three different sodium (Na) salts which provide equal proportions of Na to the mixture (3 x 1/3 each): sodium chloride (NaCl, molecular weight 58.45); sodium nitrate ($NaNO_3$, mw 85.0); and sodium sulphate (Na_2SO_4, mw 142.0). Consider each of these salts to represent a different source soil, each of which are present in a sediment mixture. The %Na represents the % carbon in each source soil. The %Na in each salt is calculated by dividing the atomic weight of sodium (23) by the molecular weight of each salt compound, but also recognising how many atoms of sodium are present in the molecule.

Table D-2 below presents the calculations required to apply the linear correction equation using the sodium salts example in order to determine how much of each salt is in the mixture. The ratio M%/S% for each salt and sum of this ratio (3.11) represent the numerator and denominator respectively in the conversion equation. Thus, for example the proportion of NaCl salt in the mixture is given by (0.85/3.11)*100 = 27.3%.

In the present study this linear conversion of isotopic proportions to soil source proportions was applied to the present-day surficial sediments. This correction process was not applied to the historical soil-source data from cores because %C data was not available for all soil sources. For example, although kumara and potato cultivation were important land-use types in some sub-catchments in the past, this is no longer the case. In this situation the isotopic signatures of the plants themselves and not the labelled soils were used in the isotope modelling.

Table D-2: Example of the linear correction method to convert the isotopic proportions to soil proportions using sodium (Na) salt compounds as analogies to various soil sources present in a mixture.

Salt type	%Na in salt (S%)	%Na in mixture (M%)	M%/S%	% salt in mixture
NaCl	39.4	33.3	0.85	20.5
$NaNO_3$	27.1	33.3	1.23	29.8
Na_2SO_4	32.4	33.3	1.03	33.1
SUM			3.11	

Appendix F Mean and standard deviations of CSSI source signatures

A) Mean values for percent C (%C) bulk δ^{13}C and the CSSI isotopic values used in the stable isotopic mixing model modelling.

Catchment sources	%C	Bulk δ^{13}C	C14:0	C16:0	C18:0	C18:1	C18:2	C20:0	C22:0	C24:0
Inflow at Havelock	1.90	-24.78	-22.40	-23.76	-22.69	-25.13	-23.48	-28.54	-28.39	-29.47
subsoil	0.72	-27.16	-33.34	-31.48	-29.95	-31.03	-31.02	-32.01	-31.11	-31.23
Beech forest	11.11	-27.57	-33.64	-30.61	-28.34	-29.53	-29.85	-30.14	-29.12	-30.26
Native Forest	33.04	-28.67	-33.79	-27.51	-25.98	-26.96	-29.15	-26.46	-29.65	-30.72
Manuka	8.72	-28.91	-35.20	-32.72	-30.15	-30.33	-31.89	-33.76	-32.65	-32.23
Ponga	10.68	-28.53	-34.13	-30.57	-28.92	-28.59	-28.43	-32.97	-32.44	-32.55
Bracken	7.52	-27.57	-30.42	-27.93	-25.69	-28.30	-28.43	-29.09	-29.50	-30.00
Pine mature	10.66	-28.72	-35.93	-28.84	-26.05	-28.07	-28.85	-28.86	-28.16	-28.31
Pine Harvest	3.91	-27.34	-32.57	-28.52	-26.68	-28.10	-29.02	-28.57	-27.56	-28.17
Sheep pasture	5.80	-27.80	-34.64	-30.05	-27.50	-30.46	-29.99	-31.14	-30.77	-31.09
Beef pasture	8.90	-28.47	-34.31	-31.77	-32.11	-30.68	-31.96	-32.29	-32.63	-33.25

B) Standard deviation about the means in A

Catchment sources	%C	Bulk δ^{13}C	C14:0	C16:0	C18:0	C18:1	C18:2	C20:0	C22:0	C24:0
Inflow at Havelock	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
subsoil	0.44	1.63	1.40	0.52	0.81	1.16	0.87	0.75	0.75	0.41
Beech forest	1.94	0.24	2.37	0.08	0.47	1.74	0.99	0.62	1.75	0.51
Native Forest	5.33	0.42	3.66	0.21	0.34	0.22	2.07	1.53	0.79	0.18
Manuka	1.48	1.41	1.33	0.57	0.23	0.67	0.67	1.34	0.89	0.10
Ponga	0.51	0.53	1.59	0.88	1.00	0.75	0.91	3.19	1.93	1.21
Bracken	0.59	0.11	0.59	0.56	1.47	0.42	0.16	2.36	1.46	1.05
Pine mature	0.29	0.20	0.12	0.02	0.57	1.33	0.19	0.13	0.39	0.01
Pine Harvest	2.55	0.93	3.39	0.26	0.59	1.41	1.00	0.67	0.10	0.62
Sheep pasture	4.10	1.73	1.74	0.89	0.55	0.28	0.84	1.15	0.77	0.61
Beef pasture	0.56	0.04	1.37	1.60	2.76	1.02	1.55	0.27	0.79	0.96

Only one sample was collected for the Inflow at Havelock and the Standard deviation is value for the analysis.