Reviewing recent (mainly post-1950) changes in nature and extent of shallow-water, soft-seafloor biological communities of New Zealand's Bay of Islands:
causes, consequences and persisting threats

The remarkably biodiverse shallow-water soft seafloors of the eastern Bay of Islands must entice anyone interested in the living ocean. (Image: Salt Air)

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An unpublished report to Bay of Islands Maritime Park Inc.

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This review was originally submitted to the Ministry for Primary Industries for publication in their *New Zealand Aquatic Environment and Biodiversity Report* series. It brought together in one place all published and unpublished work on changes in the nature and extent of shallow-water, soft-seafloor biological communities of New Zealand's Bay of Islands – and it also included the supporting data that would otherwise have lain buried in the supplementary material of the associated papers. In so doing it has provided a baseline, additional to that of the (mainly) 2009 *Bay of Islands Ocean Survey 20/20* (marinedata.niwa.co.nz; http://www.os2020.org.nz/), from which future ecological change can be gauged. The report also incorporated my research into the physical impact of fishing on the biodiversity of the Bay of Islands shallow-water, soft-bottoms. This study was undertaken in support of Bay of Islands Maritime Park's 2021 appeal to the Environment Court under Clause 14 (1) of the First Schedule of the Resource Management Act 1991 in the matter of the proposed Northland Regional Plan. A draft of my full report was provided in an earlier form to the expert witnesses to this case ahead of the July 2021 Onerahi court hearings.

The Ministry for Primary Industries eventually declined to publish this review, stating that it repeated material that had previously been published (something that reviews are obliged to do, I would have thought).

Nevertheless, a lot of mahi has gone into bringing this material into one place, and I cheerfully offer it to readers and researchers alike. All I ask is that if you use information you acknowledge the source.

I trust that this has been a useful contribution to our understandings around the ever-changing ecological state of my home-waters of Pēwhairangi, the Bay of Islands.

John Booth
28 October 2021

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Booth, J.D. (2021). Reviewing recent (mainly post-1950) changes in nature and extent of shallow-water, soft-seafloor biological communities of New Zealand's Bay of Islands: causes, consequences and persisting threats.

'Marine environmental histories' that provide critical insight into baseline states-of-nature before human modification require information around changes in ecosystems over time. This contribution reviews the variations observed in shallow (<10 m deep), soft seafloors, and their associated biological communities, in the Bay of Islands, New Zealand. The temporal focus is post-1950, but changes in certain communities have their baseline before European colonisation (from about 1800 AD). The main driver has been human-induced, land-derived sedimentation which has led to an ongoing ecological cascade. Mangrove spread has impinged on threatened habitats such as saltmarsh, uppershore coarse-sand/shell beaches and spits, and (probably) intertidal seagrass, and, simultaneously, previously-productive shellfish beds have been destroyed through deposition of fine silt.

It appears likely that in pre-human times **mangroves** (*Avicennia marina*) – although widespread – were much-more restricted to points of freshwater inflow than they are today. Major expansion in the mangrove footprint onto other soft shores took place over many decades of the twentieth century as levels of land-sourced sedimentation escalated. It seems that physical and biological conditions/events coincided in around 1900 to result in widespread mangrove recruitment low on sheltered soft shores, the recruits in turn bringing about higher rates of silt accrual that led to gradual shoreward spread. Mangrove cover by catchment increased 54–267% (overall 128%) between the early-1950s and 2009, the wave of shoreward-infill now essentially complete. Upper sheltered shores will almost certainly continue to accrue sediment in certain parts of the Bay of Islands, inevitably leading to further *alongshore*-expansion of mangroves that can potentially fill every void.

Saltmarsh areal cover reduced by around 12% between 1978 and 2009 as mangroves extended shoreward, but *total* loss over the longer term will have been far greater. Upbeach mangrove expansion, together with saltmarsh being essentially locked against landward expansion by infrastructure such as roads, ensures that for as long as mangrove cover continues to expand, saltmarsh cover will reduce.

Mangrove expansion has also overwhelmed **uppershore coarse-sand/shell beaches and chenier spits** – recently ranked among the most-at-risk marine ecosystems in the country – that had, at least until the early-1950s, comprised the margin of many soft, upper shores of Bay of Islands estuaries and sheltered embayments. Almost certainly intertidal **oyster reefs** (originally the rock oyster *Saccostrea glomerata* but now the Pacific oyster *Crassostrea gigas* too) were once prominent in Bay of Islands estuaries. They are now highly restricted.

In pre-human times, **cockles** (*Austrovenus stutchburyi*) – with pipi (*Paphies australis*) – would have been the prominent estuarine shellfish of the Bay of Islands, as they are today. Significant proportions and quantities of large cockles (40–55 mm long) continued to be available for harvest in the Bay during late pre-Contact times (pre-1800), and into the early post-Contact era on an apparently enduring basis. Yet today, even under low fishing pressure, they are barely harvestable on most shores. Indeed, it appears that recently – possibly within the last couple of decades – there has been substantial decline in the status of the Bay of Islands cockle stocks. Cockles today are abundant (except in the Waikare and Waikino waterways), but seldom reach large sizes. Multiple stressors underpinned by chronic levels of fine terrigenous-silt accumulation – a well-known inhibitor of cockle vigour – are the likely explanation. Indeed, significant scatters of 20–35 mm long surfaced *living* cockles present at many localities may indicate high parasite infestation, and/or the effects of other contagion.

The yellow-green alga ***Vaucheria*** periodically appears as dense and extensive beds in the low intertidal of beaches in the eastern Bay of Islands. Apparently, the way it accumulates silt means, once established, shores can – at least temporarily – become unsuitable for seagrass.

Intertidal **seagrass** (*Zostera muelleri*) beds appear not to have been particularly extensive or notable in living memory within the Bay of Islands, and they may also have been of little significance even as far back as the early-nineteenth century. Although 50 y ago more widespread around the Bay, today's *subtidal* seagrass appears to be largely confined to 12 significant and recovering beds (some extending into the low-intertidal), as well as several smaller, more-ephemeral patches, around the islands of Ipipiri and on adjacent shores in the eastern Bay of Islands. The first aerial images were from the 1930s, yet widespread beds were not evident until the late-1950s. Indeed, some of today's most spectacular beds did not establish until the early-1970s, more than 30 y after the first significant seagrass was observed. This suggests that, at least for recent historical times, significant subtidal seagrass may be a relatively recent biome here. Decadal-scale changes in surface cover of subtidal seagrass since the 1960s/1970s are likely linked to changes in sedimentation rates and turbidity, and ocean-climate factors.

The **shallow soft seabeds around the islands of Ipipiri** – referred to here as the Ipipiri Platform and essentially defined by the 10 m depth contour – stand out in having apparently been much-less affected by land-sourced sedimentation than most other parts of the Bay of Islands. Ipipiri Platform is today characterised by large areas of apparently time-stable red-algal turf interspersed with more-time-varying subtidal-seagrass cover. The algal turf fields appear in turn to be differentiated into a mosaic of patches of biogenic growth familiar in the soft-bottom ecology of other parts of New Zealand that include beds of morning star shells (*Tawera spissa*) and robust dog cockles (*Tucetona laticostata*).

So far, essentially all large-scale changes observed in the biological communities of shallow, soft seafloors in the Bay of Islands have had their origins – directly or indirectly – in human activity, rather than being part of any inherent progression in nature. The expansion in mangroves and concomitant loss of saltmarsh, coarse-sand/shell beaches and spits, intertidal seagrass and cockle beds are attributable primarily to high levels of anthropogenically-generated, land-sourced sediment. Ongoing threats to these ecosystems include continuing sedimentation, damaging fishing practices, and establishment and spread of non-indigenous organisms – in particular, the proliferation of possibly-novel viruses.

Physically small yet ecologically diverse, the Bay of Islands has provided a tractable location for this unfunded, community-science project concerning changes in nature and extent of shallow-water, soft-seafloor biological communities in a northern-New Zealand embayment.

1. INTRODUCTION

1.1 Background

Progressing our understanding of ecosystem functioning at the time of first human arrivals, and through settlement and population growth, can assist coastal managers in developing the 'marine environmental histories' that allow critical insight into baseline states-of-nature before its human-mediated modification (e.g., Manez et al. 2014; Klein & Thurston 2016; MacDiarmid et al. 2016). Drawing on published and unpublished material, this report brings together and addresses in one place the nature of ecological change in representative shallow-water (mainly ≤10 m depth) soft seafloors of the Bay of Islands (35° 12′ S, 174° 10′ E), on the northeast coast of New Zealand (Figure 1). Principally concerned with the past seven decades, but on occasions going back to pre-European times, it considers likely main-drivers of those transformations, and ecological consequences and risks into the future.

All marine ecosystems have inherent natural dynamism, driven by such processes as non-anthropogenically-derived sea-temperature change and varying patterns of storminess. This variation is manifested in significant change over short time-frames, through to little or no perceivable shift over the scale of decades. Superimposed on these are transformations resulting directly from human activities (e.g., seafood harvesting that leads to the overfishing of particular stocks), together with those indirectly brought about by anthropogenic influences such as increased levels of terrigenous sedimentation derived from land clearance, and rising sea temperatures associated with human-mediated climate change.

The paramount driving force for *natural* ecological change in recent geological times has been climatic variation. Briefly, for the past millennium, the 'Polynesian Warm Period', from 1150 to 1450/1500 AD, was followed by the Little Ice Age between 1500 and 1900. In the thirteenth century, average annual air temperatures may have been 0.3–0.5 °C above today's; and during the eighteenth century about 0.8 °C lower (Anderson et al. 2014). But because the inexorable biological and ecological changes brought about by climate variation over this period seem so far to have been small in terms of the environmental tolerances of most taxa (apart from those living at the edge of their geographic range), it is human presence that has had greater *appreciable* ecological impact. Beginning with East-Polynesian arrivals in the Bay of Islands in about 1300 AD (Robinson et al. 2019), and rapidly-growing populations with European arrivals from about 1800 (Booth 2017), human presence wrought immense, conspicuous and enduring change to the local shallow soft-seafloor marine ecology. This came about particularly from increased levels of land-derived sedimentation.

Soft-bottom habitats are those of mud, sand and gravel. But they also include biogenic substrates such as seagrass and shellhash occurring on their own or on top of mud, sand or gravel, and soft-sediment veneers over rocky reef. Biogenic habitats encompass both a) those living species that form emergent three-dimensional structures that distinguish areas in which they occur from surrounding lower vertical-dimension seafloor habitats, and b) non-living structure generated by living organisms, such as infaunal tubes and burrows (Morrison et al. 2014a: 8). Biogenic habitats can exist over extensive areas of seafloor and support higher biodiversity than adjacent habitats, and are often hotspots of living diversity (e.g., Anderson et al. 2019: 13–14).
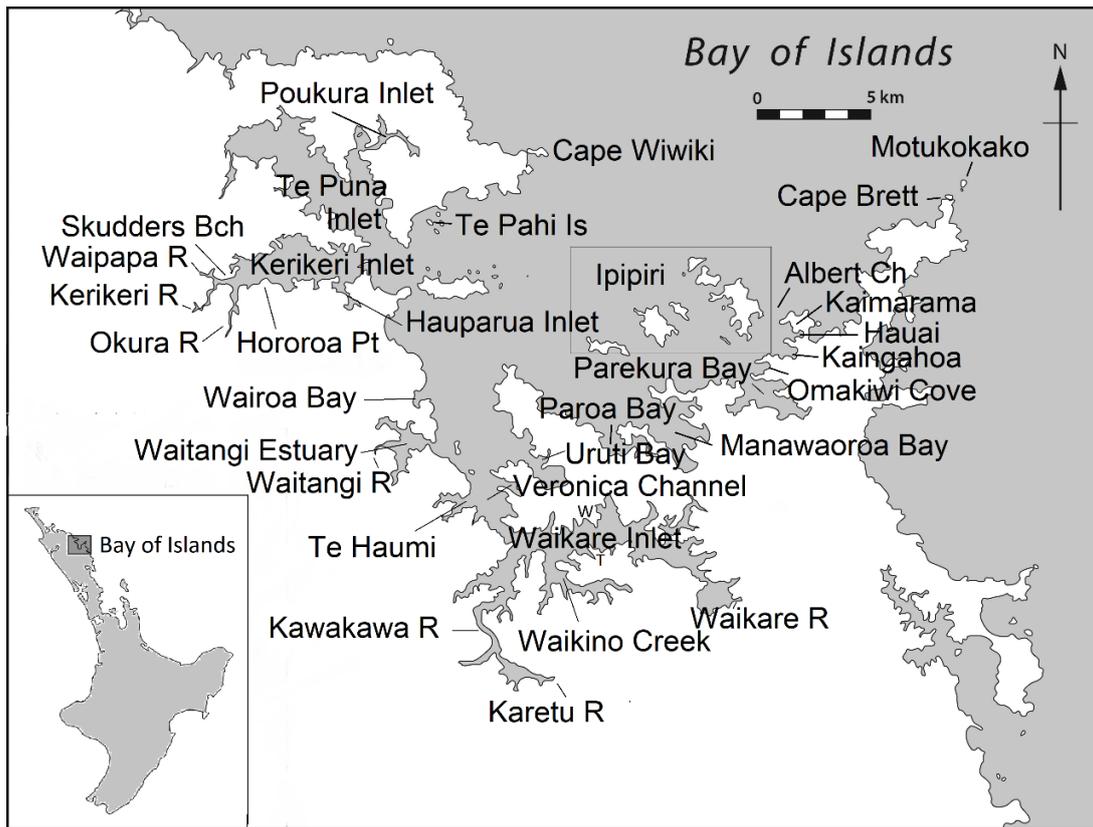
Figure 1: Bay of Islands, on the northeast coast of the North Island (inset), and locations mentioned in the text. T, Tangitu; W, Waiaruhe (Map: author)

In numerous places around New Zealand land-derived sediment inundating nearshore marine substrates is of immense ecological concern (e.g., Morrison et al. 2009), as it is globally (e.g., Gray 1997). This is especially concerning when it involves the soft habitats that often dominate the seabed of estuaries and coastal embayments. This is because soft seafloors in sheltered locations are typically biologically diverse and important to nutrient budgets and the global carbon cycle (e.g., Gray 1997; Snelgrove 1999; Lohrer et al. 2006). Presence in the water column of, and smothering of the seafloor by, land-sourced silt can alter the structure and functioning of these ecosystems, particularly as sedimentation rates rise (e.g., Gray 1997; Thrush et al. 2004). Further, depressed condition among filter feeders such as cockles *Austrovenus stutchburyi*, in particular, is common under elevated levels of suspended terrigenous sediment. The silt particles abrade, clog and smother; reduce interstitial spaces; and reduce food supply and quality through decreased light attenuation (e.g., Norkko et al. 2002; Thrush et al. 2004; Morrison et al. 2009; Adkins et al. 2016).

Although land-sourced sediment deposition pre-dates human settlement in New Zealand, land-use practices – especially over the past 200 y – have greatly increased sediment accumulation rates (SARs) in coastal ecosystems (Swales et al. 2012). Moreover, greater storminess associated with a warming climate means species must cope with greater suspended-sediment loads and increased accumulations of sediment-per-storm, together with concomitant longer-term changes in habitats. Storm events increase turbidity and sedimentation over short time-frames, but repeated turbidity and sedimentation events can have even-more-significant negative impacts (Lohrer et al. 2004; Norkko et al. 2006). Critical thresholds for benthic species are therefore exceeded more frequently, with less time to recover between events and greater chance for gradual degradation in benthic community structure and function.

Inundation of seafloors by silt resulting from land run-off is not, however, the only potential agent of appreciable change in the nature and extent of shallow-water, soft-seafloor biological communities of the Bay of Islands. Others include the physical and ecological impacts of human activities such as

seafood harvesting and boating, and – potentially – the arrival of non-native species of plants and animals and novel viruses (e.g., Harvell et al. 1999; Guo & Ford 2016). Establishment and spread of non-indigenous species (NIS) bringing about far-reaching change in communities and ecosystems is well illustrated in the Bay of Islands in the colonisation of many hard-intertidal surfaces by the Pacific oyster *Crassostrea gigas*.

Soft-bottom marine ecosystems of New Zealand have, overall, been less-well studied than ecosystems associated with rocky reefs (e.g., Anderson et al. 2019). As a contribution to redress this for northeast-North Island, this unfunded, community-science contribution compiles and reviews published and unpublished material concerning changes in, and persisting threats to, the ecology of the shallow soft-seafloors of the Bay of Islands. After addressing the hydrological, sedimentological and biological context of the Bay of Islands, changes (mainly post-1950) among representative intertidal and shallow subtidal soft-shore ecosystems are explored: 1) expansion in the mangrove (*Avicennia marina*) footprint, associated with increasing levels of sedimentation taking place from the late-1800s; 2) concomitant contraction in the extent of saltmarsh and loss of critically-endangered uppershore coarse-sand/shell beaches, and the chenier-like spits (Wiser et al. 2013) that form elongate barriers at freshwater outflows; 3) sedimentation of oyster reefs (originally the rock oyster *Saccostrea glomerata* but now the Pacific oyster too); 4) loss and/or degradation of harvestable beds of shellfish (particularly cockles and pipi [*Paphies australis*]); 5) changes in areal cover of intertidal and subtidal seagrass *Zostera muelleri* and, intertidally, the yellow-green alga *Vaucheria*; and 6) changes – apparently small – in the nature and extent of the red-algae-dominated shallow soft seafloors (<10 m depth) of Ipipiri in the eastern Bay of Islands. Data-sources include published and archived historical and scientific accounts, pictorial records and research documents, the contents of middens, aerial imagery, interviews with locals, and field sampling.

1.2 Hydrological setting

Bay of Islands (Figures 1 and 2) is a 180 km^2 embayment of drowned river valleys, many of its numerous islands being the summits of what were once hills. The Bay lies in a warm-temperate zone with strong subtropical and tropical influences, particularly during summer, surface waters reaching 20–22 °C in late-summer and dropping to 13–16 °C in late-winter (Booth 1974). Extensive estuarine and tidal reaches feed into the mainly 30–50 m deep main basin of the Bay, with depths reaching 80 m near the entrance (Figure 2). Overall, the Bay is reasonably well-mixed, with one estimate of the residence time for waters being 19 tidal periods (Heath 1976). The semi-diurnal tides have amplitudes of 2.0 and 1.5 m for spring and neap highs respectively. The north-flooding tidal stream that turns west into the Bay at Motukokako (the sequence reversing during the ebb; MacDiarmid et al. 2009) ensures waters in the eastern Bay of Islands, in particular, are regularly and extensively renewed. But the tidal streams are generally weak, except at the restricted mouths of estuaries, and particularly between the eastern islands where ebb velocities reach 1.25 m^{-1} (MacDiarmid et al. 2009: 173). The main *oceanic* influence on the waters of the Bay of Islands is the southeast-flowing East Auckland Current. The Cape Brett Peninsula protrudes into this flow, thereby initiating a weak countercurrent across the mouth of the Bay (Booth 1974; Mitchell et al. 2009). This oceanic intrusion is seen in the high abundance (and for some taxa, breeding) of tropical and subtropical species (particularly fishes) especially in the Bay's southeast. Catchment land-use today is mainly agricultural, the low levels of industrial activity (the only mining being rock-quarrying) around the Bay of Islands resulting in generally-low levels of chemical contamination of aquatic systems (Griffiths 2011, 2014, 2015).
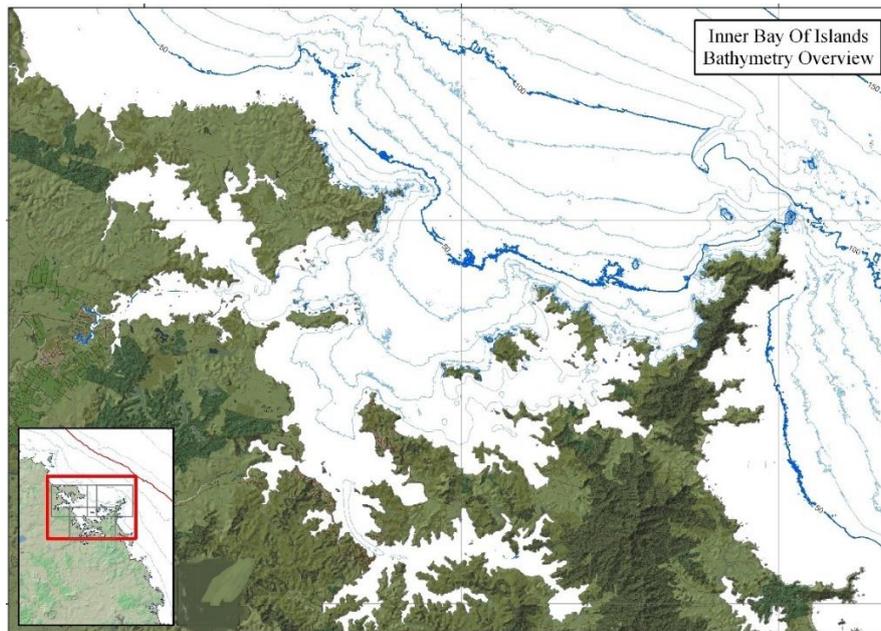
Figure 2: Bay of Islands' bathymetry (Mitchell et al. 2009). Outermost bold contours are 100 m and 50 m, with finer contours at 10 m depth intervals.

1.3 Sedimentological setting

The underlying geology is predominantly greywacke, resultant soils and clays being prone to erosion and aquatic leaching. Land cores show that early Polynesians had devastating impact on the vegetation around the Bay of Islands, particularly through use of fire (e.g., Elliot et al. 1997) to promote growth of starch-rich bracken *Pteridium esculentum*. But erosion from these catchments was minimal. The soil structure was maintained by networks of bracken roots (up to 0.5 m deep, and relatively unaffected by fire), and protected from raindrop impact and slope wash by a dense plant canopy (Wilmshurst 1997). Accordingly, marine-sediment cores around the Bay showed these early firings resulted in only modest increases in SARs (Swales et al. 2012).

With European settlement, however, soil erosion increased markedly. Key land-use changes included widespread land clearances for pastoral farming, beginning in the late-1800s, and, later, plantation-pine planting and, in places, citrus-orcharding (Swales et al. 2012). Extensive replacement of soil-stabilising vegetation with pasture, in particular, left soft-rock hill-country soils vulnerable to erosion and landslides (Wilmshurst 1997), with resultant runoff to the sea (e.g., Figure 3).

Figure 3: Silt-laden surface flood waters flow east out of Kerikeri Inlet which lies just beyond the headland to the right; Te Puna Inlet is to the left; and the Black Rocks and Moturoa Island can be seen in the upper middle distance. (Image: Dean Wright Photography, with permission)

10

Inner-bay sedimentation rates Our most-detailed understandings around sources, rates and impacts of land-derived sedimentation come from the Bay of Islands Ocean Survey 20/20 (marinedata.niwa.co.nz; http://www.os2020.org.nz/) seabed sediment cores and associated observations. Sampling took place mainly during 2009–10: Bostock et al. (2010; Seafloor and subsurface sediment characteristics); Gibbs & Olsen (2010; Determining sediment sources and dispersion in the Bay of Islands); Pritchard et al. (2010; TRANS – Sediment transport model); and Swales et al. (2010, 2012: Recent sedimentation rates, updated in 2012). Other information concerning recent sedimentation in the inner Bay of Islands comes from investigations and sampling by Northland Regional Council (Cornelisen et al. 2011; Griffiths 2011, 2013, 2014, 2015; Bamford 2016), Booth (2017, 2019, 2020) and Booth & Edwards (2020).

Using sediment traps (some nearshore, away from main channels, which is where tidal currents slowed through friction can be expected to have brought about highest silt-deposition rates), Gibbs & Olsen (2010) showed that November/December 2009 SARs were very high in Waikare Inlet, moderate in Kerikeri and Te Puna inlets, and low elsewhere (including – surprisingly – Kawakawa River, possibly because there was no heavy rain just before or during the sampling) (Figure 4).
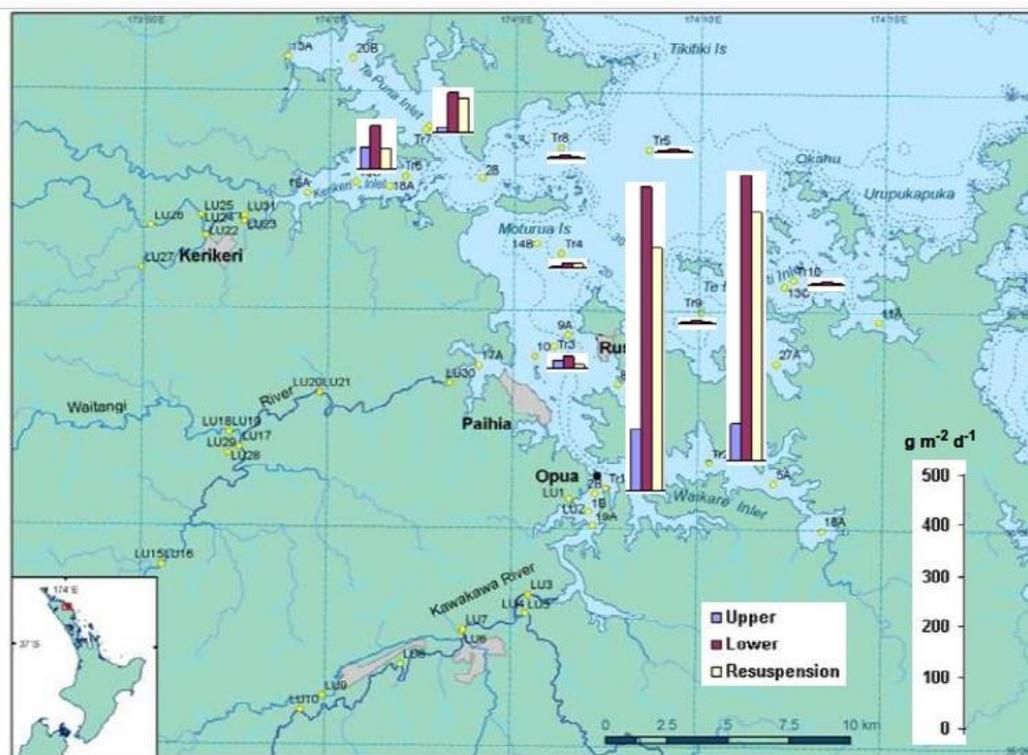
Figure 4: Relative proportions of sedimentation and resuspension fluxes across the Bay of Islands in November/December 2009 (Gibbs & Olsen 2010: 18).

Considering the longer term, the Ocean Survey 20/20 modelling indicates that average annual sediment deposition over the past ~150 y has been ~509 000 t (95% CIs 299 000–719 000; Swales et al. 2012), the largest source being Kawakawa River, with almost 340 000 t. The average annual sediment loads of the other main rivers are Waipapa 4300 t, Kerikeri 12 100 t, Waitangi 62,700 t, and Waikare 9100 t. The associated time-averaged SARs have been 1.0–4.9 mm y^{-1}, except near the entrance to Kawakawa River where the rate has been 14.2 mm y^{-1} (Swales et al. 2012) (Figure 5). These SARs are 10–20 times higher than before European settlement (Swales et al. 2012), with values typically greatest in upper estuaries (Oldman et al. 2009). Most of this terrestrial material enters the sea after heavy rainfall on steep and erosion-prone terrain, increasing suspended sediments in the water column and depositing fine sediments within channels and on their margins.
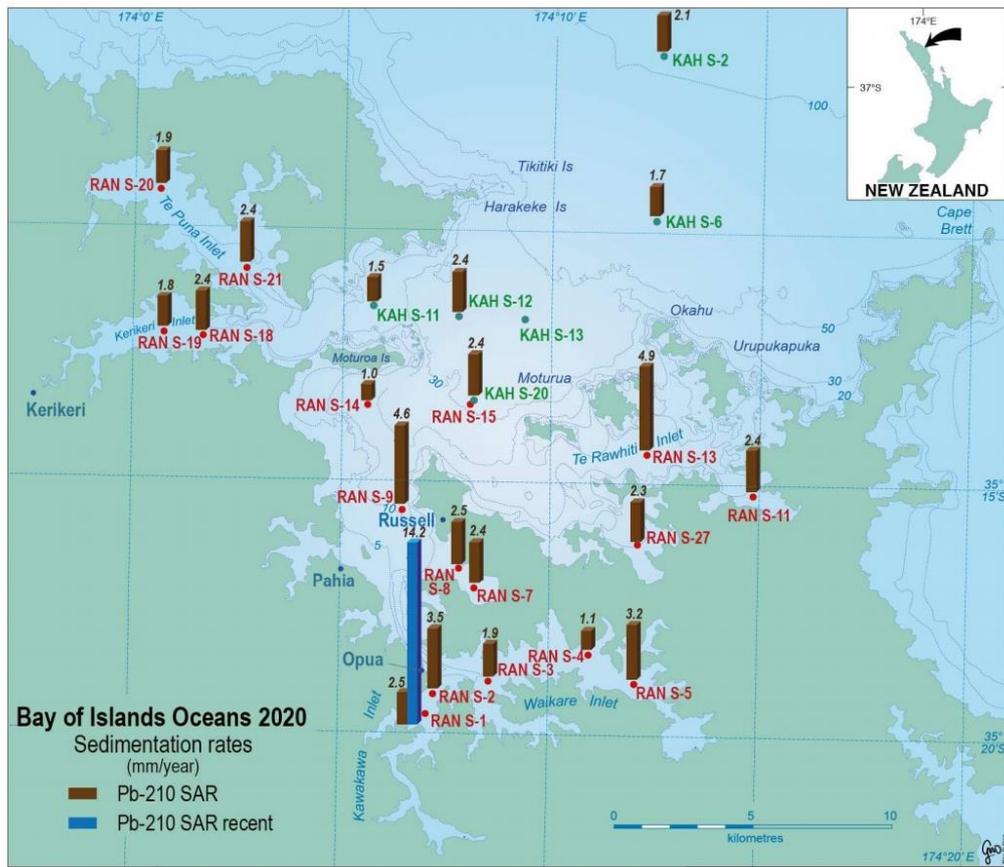
Figure 5: Time-averaged sediment accumulation rates over the last 100–150 y in the Bay of Islands based on sediment cores (Swales et al. 2012: 47).

However, it should be noted that almost all inner-Bay of Islands sediment cores were taken *near mid-channel*, where flood scour would be expected to ensure among-the-lowest silt-deposition rates in the entire system. For example, for Kerikeri Inlet's two stations (RAN S-18 and RAN S-19), SARs were relatively low (2.4 and 1.8 mm y^{-1} respectively), but both stations were well-removed from the shore (Figure 6). In line with this, rock-oyster rock groynes near the edge of the main (Pickmere) channel, apparently set out in the 1920s (Booth 2017), have remained visible (e.g., in 1939 and ~1955; Watkins 1974) to this day (Appendix 1). This indicates little or no sedimentation here over the past 100 y.
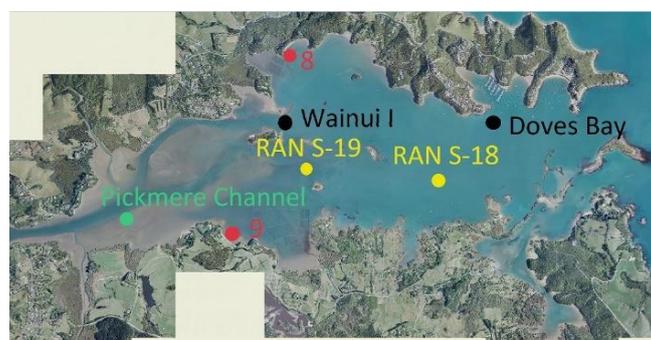
Figure 6: Recent surface benthic grain-size determinations for mid-Kerikeri Inlet. 1) Green dot, Northland Regional Council sampling site 2008–10 (43–46% <63 μm; Griffiths 2011); 2) Yellow dots, Ocean Survey 2020 (2009) RAN S-19 (15.9% mud) and RAN S-18 (48.1% mud) (Swales et al. 2012); 3) Red dots, Ocean Survey 20/20 Sites 8 and 9 (Hewitt et al. 2010), with significant proportions of mud and fine sand; and 4) Black dots, Northland Regional Council sampling sites 2012–16 (~75% mud [<63 μm], the remainder fine sand (Griffiths 2014; Bamford 2016) (from Booth 2020). Marine chart NZ 5124 indicates widespread fine-mud and fine-sand substrates in this region.

12

In contrast, in shallower parts of Kerikeri Inlet, particularly towards and at its margins, SARs have been much higher. This is evidenced in the shallowing of Middle Passage (no longer navigable at low tide) between 1849 and the present, and the presence today of mud extending tens to hundreds of metres away from the Inlet's shores. This mud is bereft of macrofauna such as cockles and is so deep as to be risky to enter on foot (Figure 7).
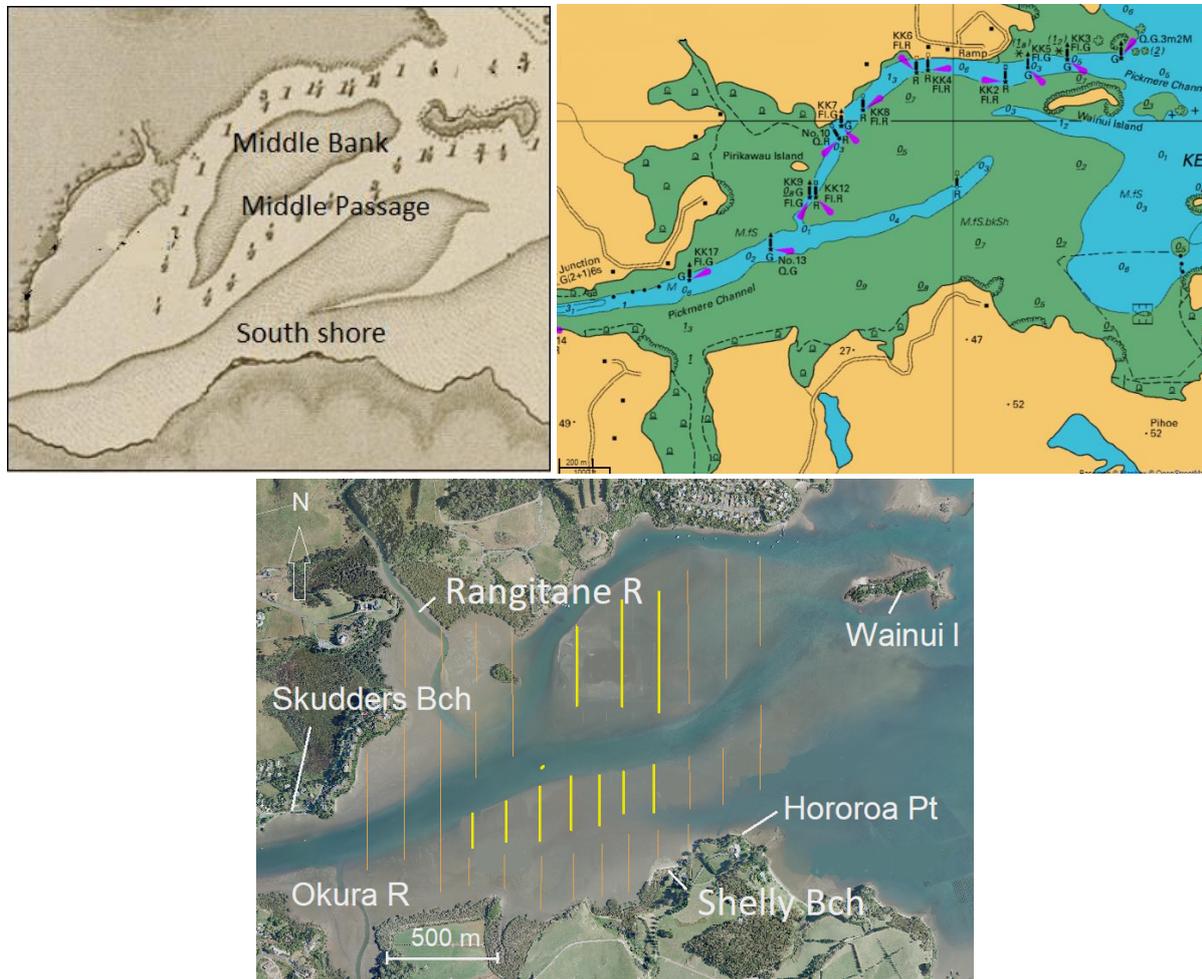
Figure 7: Kerikeri inlet's Middle Passage was navigable in 1849 (upper left; Stokes 1849, depths in fathoms) but is now obstructed (upper right; depths in metres), and large areas of nearby shore are now deep mud that is without shellfish (vertical orange lines, main cockle beds being shown as vertical yellow lines; 2020; lower) (from Booth 2020).

Further, the impression is that much of the areal expansion of near-shore sedimentation in Kerikeri Inlet is relatively recent. Long-time locals recount how siltation of upper-Kerikeri Inlet shores ramped-up after the 1970s, places like Skudders Beach, Ōkura River and Shelly Beach, and the mouth of Rangitane River, becoming unswimmable and bereft of harvestable cockles. And today, ~50% of the cockle habitat – much of it nearshore – is deep mud (Booth 2020: 11–12). In line with this, the boat-launching ramp at Skudders Beach, a concrete slab extending seaward across the upper 15 m of the 70-m wide intertidal and believed to have been constructed in the 1960s, is useable today only at the top of the tide because it now terminates in deep mud at about half tide level (Appendix 1).

Levels of nearshore sedimentation in the Waikare and Waikino waterways appear to have been even greater, even though SARs at the channel coring sites were only 1.1–3.2 mm yr^{-1} (Figure 5). Nearshore oyster farms have been overwhelmed by mud over the last few decades, and in early-2019 Booth (2020: 13–14) found it difficult to locate significant cockle beds in an area where the presence of huge cockle middens indicated shellfish had been historically abundant (Figure 8). Indeed, the extent and depth of

fine mud apparently precludes cockle establishment on most shores of Waikare Inlet and Waikino Creek today, this now being the long-term condition according to local residents. These observations are in line with Swales' et al. (2012) conclusion that large quantities of terrigenous silt derived from Kawakawa River are transported to and deposited in the Waikare and Waikino waterways.

Figure 8: Only the upper intertidal of even the most-open of beaches in Waikare Inlet and Waikino Creek (upper pair; author's images) support cockles today, lower parts of the beach being deep, fine mud. Oyster farms established late in the twentieth century near the entrance to the Waikare have long since silted-up (lower; Ocean Survey 20/20 image).

In the absence of synoptic sediment corings for many *shallow* (<10 m) parts of the Bay of Islands, insight into regional variation in SARs was obtained by comparing the bottom-depth contours shown on the 1849 *Acheron* chart (Stokes 1849) with various charts since, culminating in the most-modern (mainly 2010s) ones. The approach is crude, it not necessarily taking into account, for example, episodes of major accretion followed by major erosion. Nevertheless, the location of contours – particularly the 10 m/5 fathom lines – suggest significant near-shoreline shallowing within estuaries and near their approaches between 1849 and today. Even if the *absolute* depths at the time of the surveys are debateable, the *pattern* of shallowing across the entire chart – taken to reflect *relative* rates of accretion of sediment by location – are informative.

For example, in the Kerikeri and in the context of little or no tectonic activity, the 3 m depth contour upstream from the inlet's mouth had migrated ~500 m seaward between 1849 and 2017 (Figure 9).

What was once the 3-fathom contour is now 3 m, giving a nominal average annual SAR of 17.9 mm y^{-1} (1849–2017) at certain points.
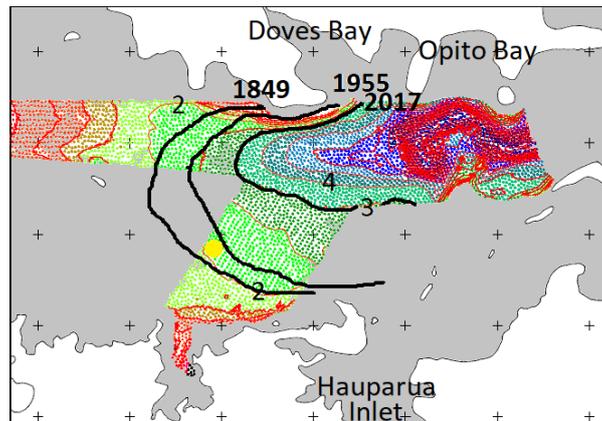
Figure 9: Position upstream from the mouth of Kerikeri Inlet of the 3-m depth contour in 1849 (Stokes 1849) and 1955 (Watkins 1974) superimposed on the depth contours (m) of 2017 (Northland Regional Council's map kerishoalinterp1mgrid).

Growing awareness over the past few decades of the impact of terrigenous silt on the marine environment has seen local-government regulations around the control of silt runoff becoming increasingly stringent (e.g., www.nrc.govt.nz; www.lawa.org.nz), with some evidence for declining levels of siltation in estuaries and other sheltered habitats in certain parts of the Bay of Islands. For example, SARs appear to have recently stabilised in upper parts of Kerikeri Inlet (Richard Griffiths, Northland Regional Council, pers. comm. 2019).

Outer-bay sedimentation There is no evidence of sedimentation to this extent on the margins of Ipipiri Platform. Here, the 2.5 fathom line in 1849 appears to be physically close to the 5 m contour of today, 170 y on (Figure 10, and apparently steady over intervening years). This suggests resuspension and seaward transport of silt, with nominally little or no enduring build-up.
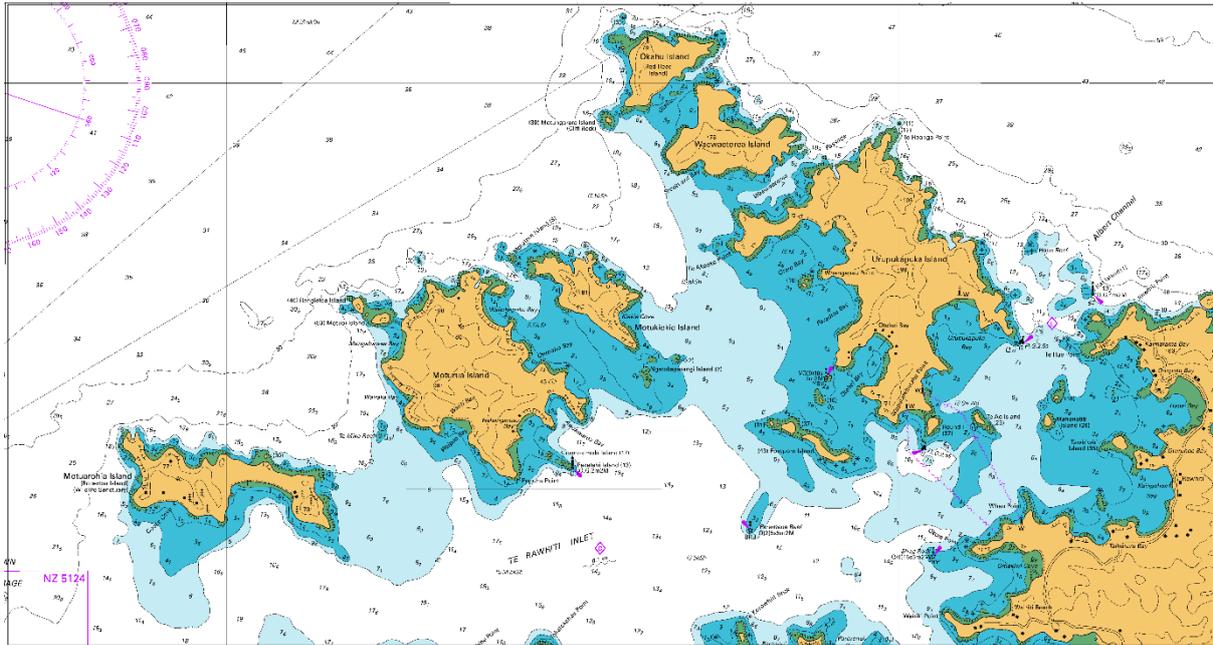
Figure 10: Depth contours for Ipipiri Platform in 1849 (upper, the dotted isoline being 2.5 fathoms, and the continuous black line the 5 fathom contour) and in 2013 (lower, the isoline between dark blue and light blue being the 5 m contour, and with the 10 m contour separating light blue and white).

1.4 Biological setting

Habitat maps, which combine water depth with information on physical variables of the seafloor, and sometimes with biological distributions, provide broad-brush understanding of benthic habitats and communities. For the Bay of Islands as a whole, Kerr (2009) has provided a generalised habitat map, with regional updates for the areas around Waewaetorea Island and Maunganui Bay by Kerr & Grace (2015) and Kerr (2016) (Figures 11–13). These show how soft seafloors predominate in shallow inner parts of the Bay of Islands and around the islands of Ipipiri, often with steep rocky shores further seaward. Various of the biologically-focussed research (much of it directed towards waters >10 m) from Ocean Survey 20/20 includes Bowden et al. (2010; Seafloor assemblage and habitat assessment using DTIS); Hewitt et al. (2010; Soft-sediment habitats and communities); Jones et al. (2010; Fish communities); Nelson & D'Archino (2010; Attached benthic macroalgae); and Parsons et al. (2010; Shallow rocky reefs) are referred to later.
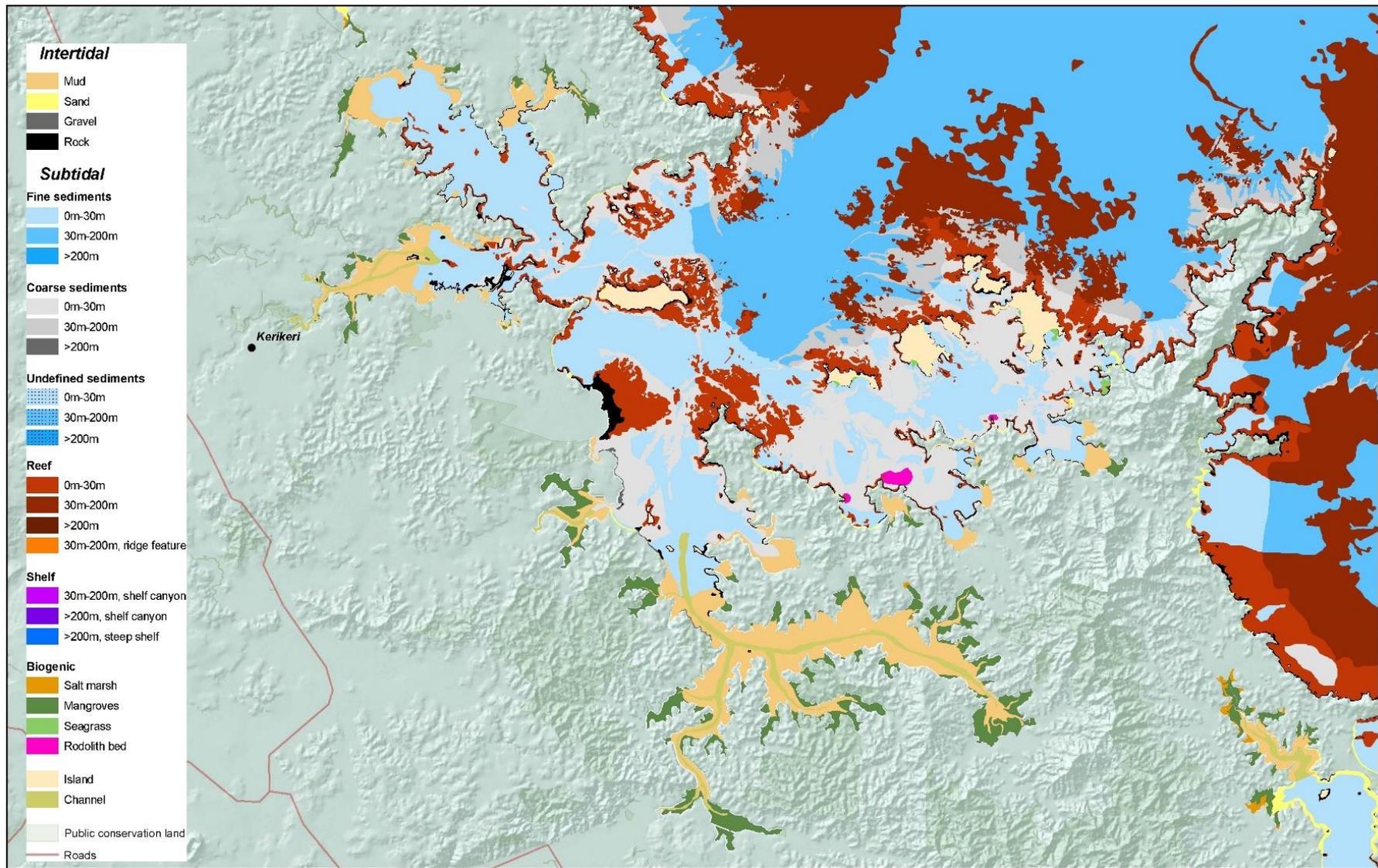
Figure 11: Habitat map of the seafloor of the Bay of Islands, with distribution of physical variables (Kerr 2009).

Legend:

Intertidal
- Mud
- Sand
- Gravel
- Rock

Subtidal

Fine sediments
- 0m-30m
- 30m-200m
- >200m

Coarse sediments
- 0m-30m
- 30m-200m
- >200m

Undefined sediments
- 0m-30m
- 30m-200m
- >200m

Reef
- 0m-30m
- 30m-200m
- >200m
- 30m-200m, ridge feature

Shelf
- 30m-200m, shelf canyon
- >200m, shelf canyon
- >200m, steep shelf

Biogenic
- Salt marsh
- Mangroves
- Seagrass
- Rodolith bed

- Island
- Channel

- Public conservation land
- Roads

Kerikeri

Figure 12: Habitat map of the seafloor in the vicinity of Waewaetorea Island, with distribution of physical variables (Kerr & Grace 2015).
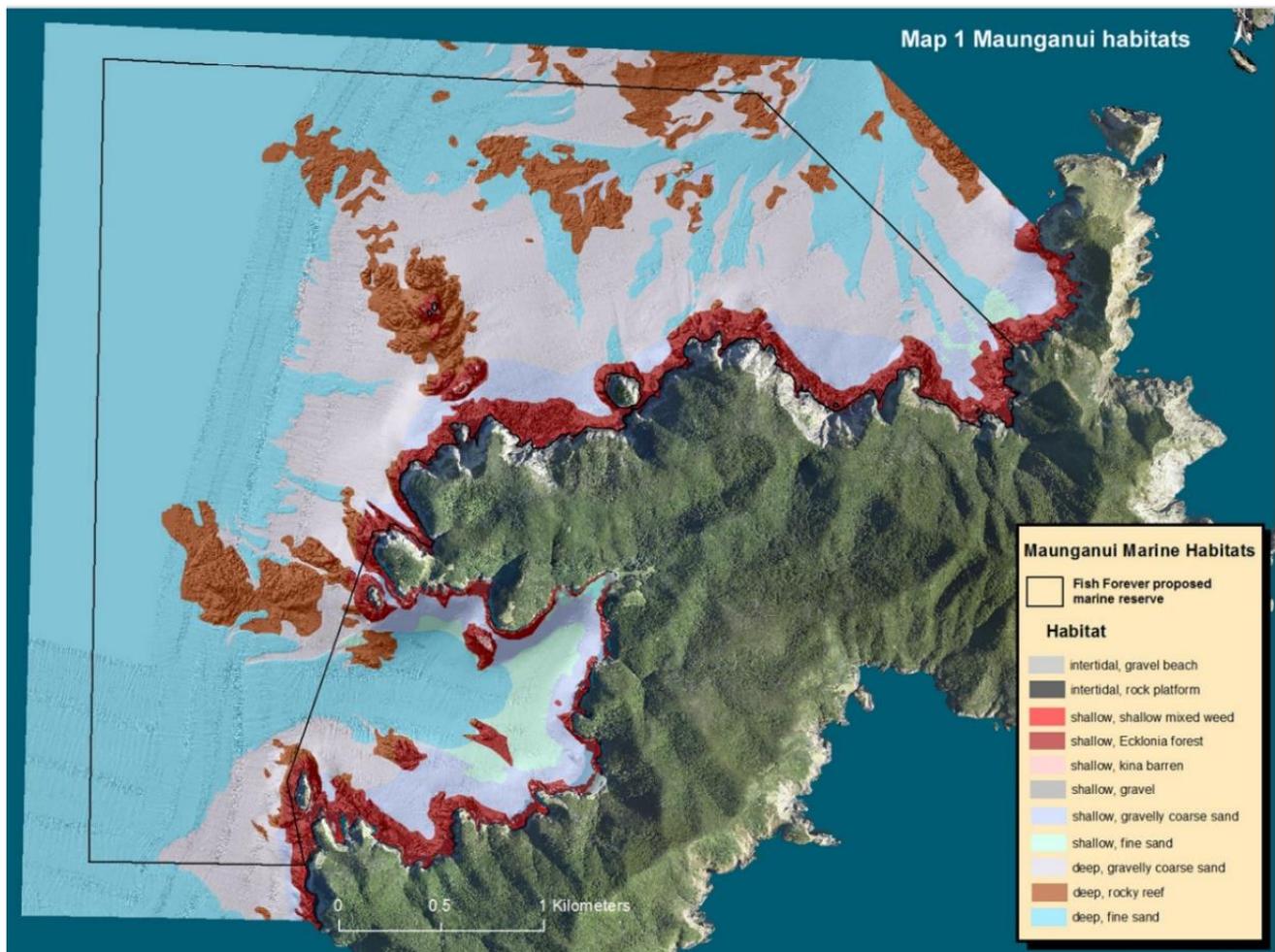
Figure 13: Habitat map of the seafloor in the vicinity of Maunganui Bay, with distribution of physical variables (Kerr 2016).

2. EXPANSION IN MANGROVE FOOTPRINT

Mangroves are well known for the breadth and complexity of their ecological roles (e.g., Morrison et al. 2014a; Anderson et al. 2019). Mangrove forests are defined as areas of continuous tree occurrence, often forming a canopy, extending alongshore for at least 200 m, and across-shore for at least 50 m (Anderson et al. 2019: 45). Smaller areas are typically referred to as mangrove 'patches', and here the term 'grove' refers to mixes of forests and patches of mangroves.

Two main perspectives prevail concerning the biogeomorphic development of recent New-Zealand forests (Swales et al. 2015). Either mangroves are opportunistic, forest development being primarily driven by physical processes; or biophysical feedbacks strongly influence sedimentation and the resulting geomorphology. In order to determine which of these applied most widely in the Bay of Islands, changes in mangrove distribution were derived from mainly early- to mid-twentieth century maps, plans and commentaries, and synoptic aerial imagery that began in the early-1950s. The aerial imagery additionally allowed estimates around changes in individual tree-size and density. Most observations from the Bay of Islands point to biophysical feedbacks strongly influencing sedimentation and the resulting geomorphology, and leading to mangrove spread (Booth 2020).

2.1 Early accounts

Accounts of Bay of Islands mangrove cover (e.g., Chapman 1978; Walls 1987; Hackwell 1989; MacDiarmid et al. 2009; Swales et al. 2012; https://data.linz.govt.nz/layer/50296-nz-mangrove-polygons-topo-150k/) focussed on relatively recent (post-1968) cover, yet baselines concerning mangrove extent are available as far back as the mid-1800s. For the earliest observations, whereas some localities have since shown little change in areal cover, most have expanded (Figure 14).
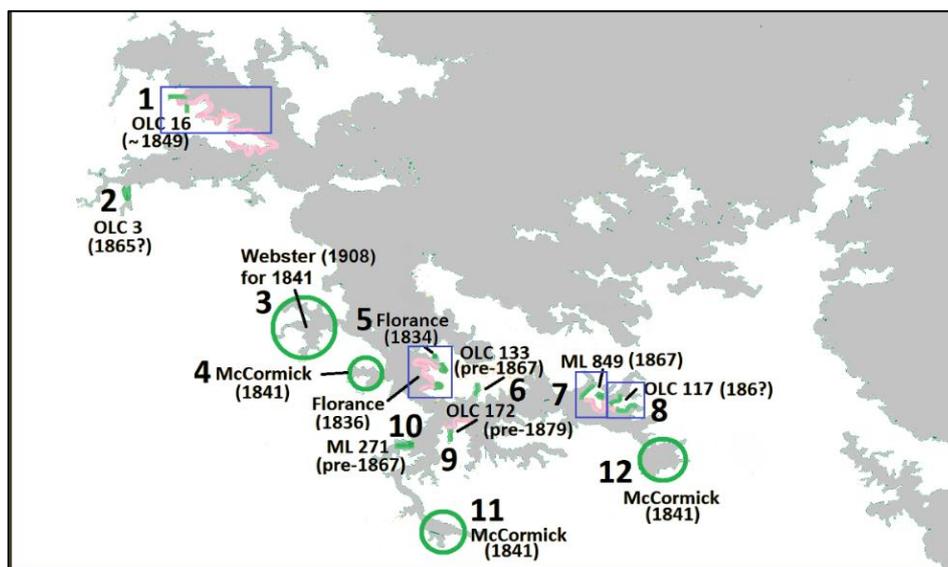
Figure 14: Old land claims (OLC), Māori land surveys (ML) and written accounts from the mid-1800s, indicate where mangroves existed (green shading) or were referred to (green circles); pink indicates shorelines where, on any one plan explicitly showing mangroves, no mangrove cover was indicated. Shores without shading may or may not have supported mangroves. Whereas some localities have shown little change in areal cover since the mid-1800s (blue boxes) (1 and 5 [6 and 8 were already at full-extent]), others have expanded (2, 7 and 9) (Booth 2020).

The first *Bay of Islands-wide* assessment of mangrove presence/absence appears to be that of Ferrar & Cropp (1922), followed by the 1939 hydrographic chart and the 1942 inch-to-mile plans. Between 1922 and 1942, mangroves had spread significantly, especially into areas beyond the uppermost estuaries (Figure 15).
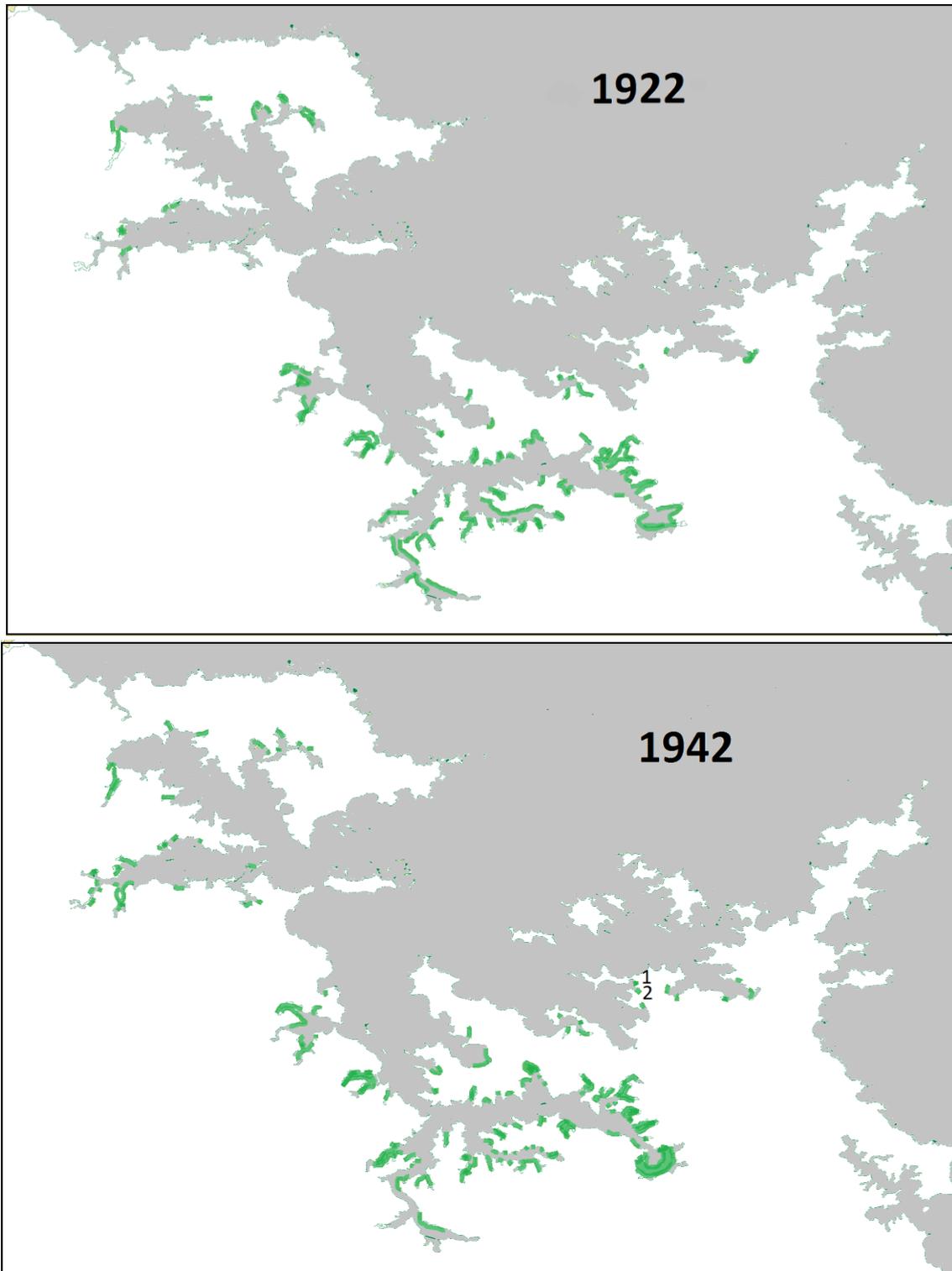
Figure 15: Presence of mangroves (green) in the Bay of Islands in the early-1900s (Ferrar & Cropp 1922) (upper) and in 1942 (Department of Lands and Survey topographical maps) (lower; omission of mangroves at sites 1 and 2 is almost certainly oversight) (Booth 2020).

2.2 Aerial imagery

The first *synoptic* aerial imagery for the Bay of Islands was from the early-1950s, when mangrove cover throughout most of the Bay (Appendices 2–4) was characterised as follows (Figure 16) (Booth 2020). There were reasonably extensive areas of large (and almost certainly old) trees associated with tidal creeks and river mouths, the largest trees occupying seaward fringes. Presumably these mangroves represent those present at the beginning of European colonisation, and probably much earlier. There were also reasonably extensive areas or bands of trees on inlet- and river-flats, the largest individuals occupying seaward fringes (again, likely long-established forests). Conspicuously, on many sheltered, soft shores until then clear of mangroves, one row (but up to three) of reasonably-large trees (most ≥5 m crown diameter) had established well below high-water level, and, occasionally, similar rows of new trees had established seaward of bands of older trees.
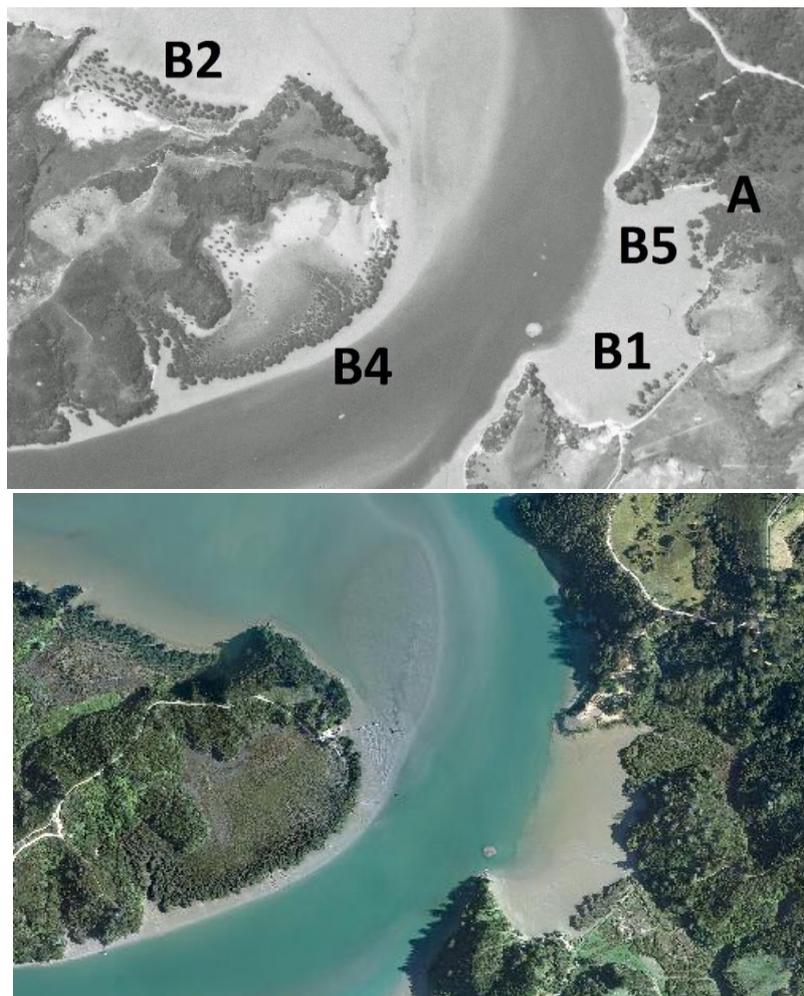
Figure 16: Examples of the categories of mangrove cover in the Bay of Islands in the early-1950s given in Appendix 2 ('River Bend' in Kawakawa River) (upper, NZ Aerial Mapping Ltd. 548-68), with the same location in 2009 (lower, Ocean Survey 20/20) (Booth 2020). A, a significant forest of established trees associated with stream mouth(s); B1, away from stream mouths, one main row, the trees being of similar size; B2, away from stream mouths, 2–3 rows, the trees being of similar size; B3, away from stream mouths, 2–3 rows, the trees within rows being of similar size, but different to those in other row(s); B4, away from stream mouths, wide band (equivalent in width to at least five rows) of large trees; B5, away from stream mouths, wide band of large trees with one main row to seaward; B6, away from stream mouths, wide band of large trees with 2–3 rows to seaward; C1, trees referred to in Columns A–B6 of Appendix 2 remain – almost universally – the lowest on the shore (and in most instances individually identifiable through their pattern of distribution); C2, many or all trees referred to in Columns B1–B3, B5 and B6 are well below mean high water, based on such features as upper-beach form and presence of saltmarsh.

About-decadal follow-up aerial photography, culminating in the 2009 Ocean Survey 20/20 imagery (NZ Aerial Mapping Ltd SN50765X), shows how this mangrove cover evolved. The lines of low-beach recruitment evident in the early-1950s remained the lowest on the shore in 2009 (individual trees often still identifiable), and most of the expansion had been shoreward (e.g., Figure 17). Although grazing of mangroves by cattle had taken place in certain parts of the Bay of Islands (e.g., Chapman 1978), it does not adequately explain this pattern of mangrove presence: 'Grazing results in stunted growth and damage to branches and pneumatophores' (Hackwell 1989), not – except among seedlings – entire removal; and it is unlikely cattle would have left only the lowest lines of trees ungrazed. Today, the wave of shoreward-infill has consolidated. Mangrove cover by catchment increased by 54–267% (overall 128%) between the early-1950s and 2009, with rates higher pre-1978 than post-1978 (Table 1 and Appendix 3). Greatest expansion (≥100%) during 1950s–2009 took place in Te Puna/Poukoura and Kerikeri inlets, Veronica Channel, the Waikare/Waikino waterways, and especially Parekura Bay.

Table 1: Surface area (ha) of mangroves in the Bay of Islands in 1950–53 (orthorectified images given in Appendix 2) compared with 2009 (Booth 2020). Grey indicates estimates of mangrove cover by Swales et al. (2012) for 1978 and 2009, with close alignment between the two independent estimates for 2009 (1 154 ha [present study] and 1 169 ha (which includes the two values below in the column). Italicised entries reflect different geographical groupings. *, incomplete data; –, uncalculable. Rounding has led to minor inconsistencies.

Waterway	Present study					Swales et al. (2012)				
	1950–53	2009			Increase	1978	2009			Increase
	ha	ha	ha	%	% y^{-1}	ha	ha	ha	%	% y^{-1}
Te Puna & Poukoura inlets	34	101	67	197.1	3.3	85	103	18	21.2	0.7
Kerikeri Inlet	48	96	48	100.0	1.7	80*	97	-	-	-
Veronica Channel	119	260	141	118.4	2.0	222*	245	-	-	-
Kawakawa & Karetu rivers	85	131	46	54.1	0.9	-	-	-	-	-
Waikare Inlet & Waikino	197	508	311	157.9	2.7	-	-	-	-	-
Paroa & Manawaora bays	14	25	11	78.6	1.3	-	-	-	-	-
Parekura Bay	9	33	24	266.7	4.5	-	-	-	-	-
ALL Bay of Islands	**506**	**1 154**	**648**	**128.1**	**2.2**	**-**	**1 169**	**-**	**-**	**-**
Kawakawa, Karetu, Waikare & Waikino	*282*	*639*	*357*	*126.6*	*2.1*	615	666	51	8.3	0.3
Paroa, Manawaora & Parekura	*23*	*58*	*35*	*152.2*	*2.6*	40	58	18	45.0	1.5

The predominant biophysical-feedback pattern of mangrove expansion in the Bay of Islands is well-exemplified by an embayment in southeastern Parekura Bay (Figure 17, with other examples listed in Appendix 4). Mangroves were present in the early-1920s. A distinct line that was well-established by the time of the first aerial image (1951) was followed by rapid infilling of new recruits and consolidation during the late-1970s to the 1990s. Meagre knowledge concerning mangrove age and growth means that the period of propagule recruitment that had led to the initial line of mangroves is difficult to judge. However, based on an average crown diameter in 1951 of 7.5 m (SD 1.8 m, from the orthorectified imagery), and using the aerial imagery to estimate time for a new recruit to reach 7.5 m diameter (~55 y), 1890–1910 may be a reasonable estimate.
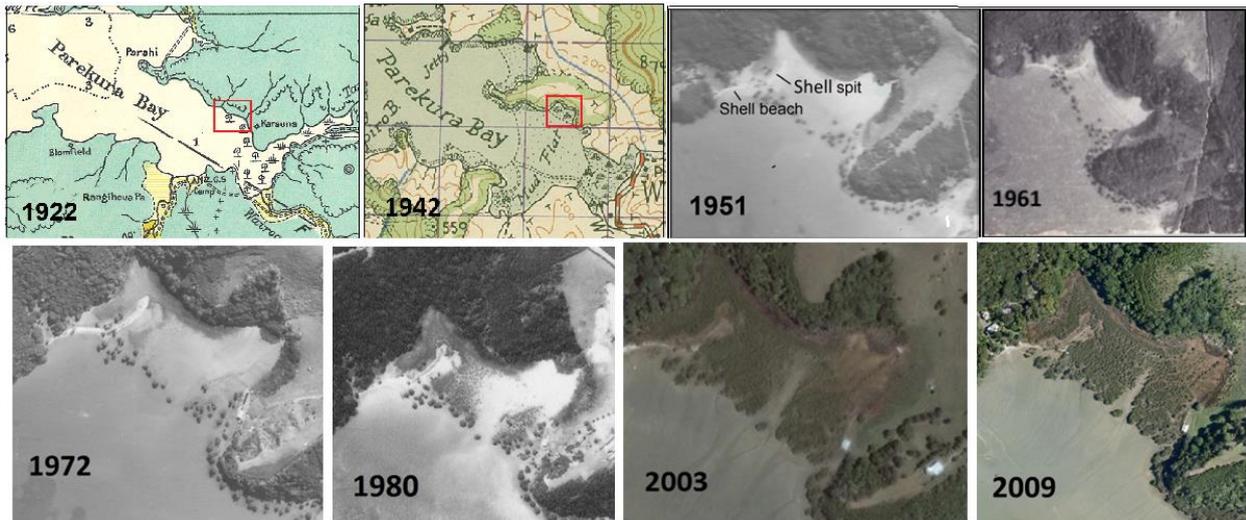
Figure 17: Changes in mangrove cover in Parekura Bay, 1922–2009, the red-boxed mangroves in 1922 and 1942 presumably representing the tree-line visible by 1951 (Booth 2020). During rapid infilling and consolidation of new recruits, individual initial trees remained discernible.

2.3 Synthesis

It appears likely in pre-human times that mangroves, although widespread on sheltered shores of the Bay of Islands, were much-more restricted to freshwater sources such as rivers and streams than they are today (Booth 2020). Major expansion in footprint onto other soft shores then took place over many decades of the twentieth century.

Key to explaining this spatial explosion of mangroves in the Bay of Islands was establishment by the early-1950s of narrow lines of trees near and slightly above half-tide level on sheltered shores. The general similarity in size suggests a reasonably-discrete recruitment episode (Booth 2020). It seems likely some 'window of opportunity' (Balke et al. 2011) involving climatic, biological and geomorphic events coincided to ensure establishment of this early wave of recruitment along kilometres of sheltered soft shore. (A possible sequence is offered in Table 2.) Decades later, from the 1970s, the silt accumulating among the roots and pneumatophores of the founding trees had become sufficient to sustain the infilling and consolidation of mangroves *upshore*.

This biophysical-feedback interpretation is similar to that applying in parts of southeast Australia (Saintilan et al. 2014), but contrasts with the Firth of Thames (250 km south of the Bay of Islands). In the Firth of Thames, mangroves occupied mudflats once the shore had reached sufficient elevation in the intertidal (Lovelock et al. 2007; Swales et al. 2015). Bay of Islands' upper sheltered shores with soft substrates will almost certainly continue to accrue sediment in a manner similar to the Firth of Thames, potentially leading to further *alongshore* expansion of mangroves that can potentially fill every void (author's unpubl. obs.). Apparently therefore, very-different establishment regimes apply in different parts of the country. Possibly, in constricted places like the estuaries and sheltered shores of the Bay of Islands, overarching driving mechanisms such as severe flood events have had greater impact than is possible in morphologically less-constrained places like the Firth of Thames, this leading to biophysical feedbacks strongly influencing sedimentation and the resulting geomorphology.

Table 2: Possible sequential contributors leading to the establishment (likely around 1900), and subsequent consolidation, of mangroves on sheltered soft shores of the Bay of Islands.
:

1	Warming air and sea temperatures associated with the end of the Little Ice Age had led to increased plant vigour;
2	Vast volumes of soil destabilised as a result of the land clearances of the late-1800s/early-1900s reach the marine environment;
3	Particularly bountiful propagule production occurs;
4	One or more exceptionally wet and fierce storms result in wholesale deposition of silt along shorelines (e.g., Swales et al. 2012: 54–55);
5	Calm conditions ensue, allowing propagules to establish;
6	This is followed by a quiescent period of years (in propagule-production, silt-delivery and/or wave-action) when few further mangroves are added to the now-established line of recruitment;
7	Mangrove growth is facilitated by substantial quantities of nitrogen and phosphorus emanating from farming activities (e.g., Lovelock et al. 2007);
8	Finally, seedlings spread alongshore and fill remaining niches.

2.4 Persisting threats

Mangrove forests in New Zealand are potentially affected by 25 significant threats (MacDiarmid et al. 2012: 43): two are extreme (rise in sea-level due to climate change, and reclamation); one is major (causeway construction); and another 14 are moderate. Of all, sea-level rise appears to be the immediate significant threat to Bay of Islands' mangroves.

Ironically, it seems that mangroves today present a greater threat to other native biodiversity than they are themselves threatened. In an ongoing ecological cascade, the enormous expansion in mangrove cover that has taken place in the Bay of Islands over the past century or so has impinged on threatened/rare habitats such as saltmarsh, uppershore coarse-sand/shell beaches and spits, and (probably) intertidal seagrass. Simultaneously, previously-productive shellfish beds have been destroyed through deposition of fine silt.

3.   LOSS OF SALTMARSH

Saltmarsh is the biodiverse buffer between fully terrestrial vegetation and the intertidal flats lower down the shore. Its areal cover has reduced as mangroves have spread shoreward (e.g., Figure 18). Swales et al. (2012) estimated ~12% loss of Bay of Islands saltmarsh between 1978 and 2009 (Table 3), but *total* loss over the longer term will have been far greater. For example, there was 78% loss of saltmarsh in Whangaroa Harbour (40 km north) between 1909 and 1981 (Morrison et al. 2014a).
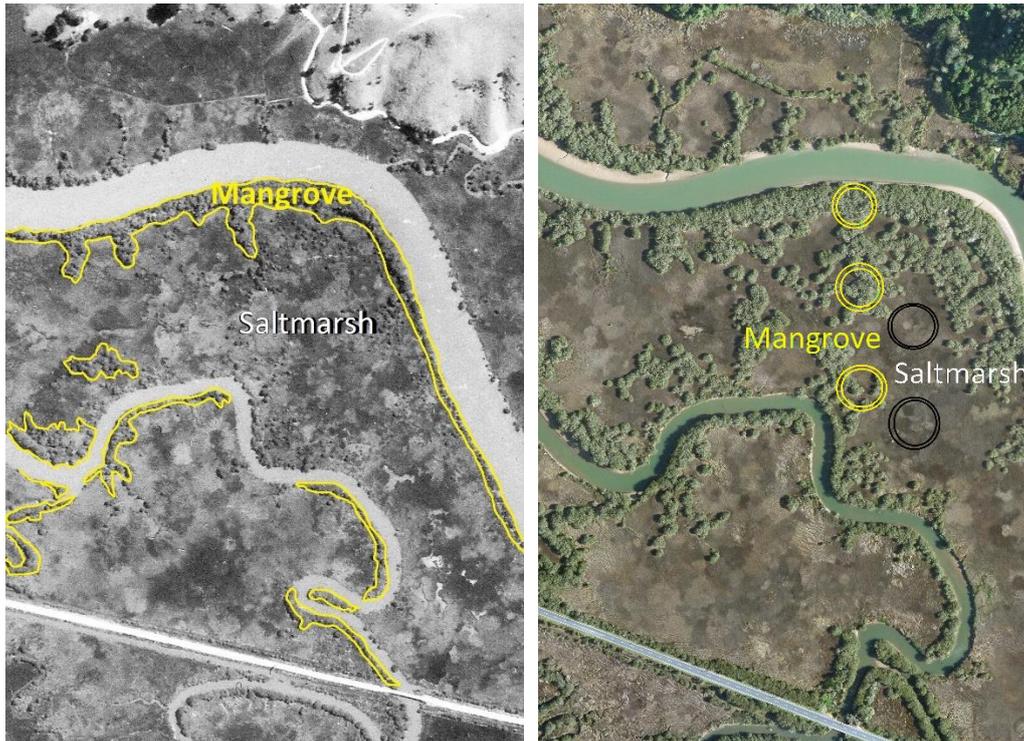
Figure 18: An example of mangroves advancing into saltmarsh habitat. The mangroves (indicated in yellow) lining the edges of these tidal reaches of Karetu River appeared thicker and more continuous in 2009 (right; Ocean Survey 20/20) than in the early-1950s (left; NZ Aerial Mapping Ltd image 549-76).

Table 3: Estimates of surface area (ha) of saltmarsh in the Bay of Islands in 1978 (NZ Aerial Mapping Ltd images) compared with 2009 (Ocean Survey 20/20) (Swales et al. 2012, using their individual tables rather than their Table 3-12) (Booth 2020). *, incomplete data; -, cannot be calculated

	Compartment	1978	2009	% change since 1978	Habitat change (% yr^{-1})
1	Te Puna & Poukoura	15.6	14.0	-10.5	-0.3
2	Kerikeri	19.4*	12.7	-	-
3	Veronica Channel	18.3*	21.4	-	-
4	Kawakawa, Karetu, Waikare & Waikino	254.4	219.7	-13.6	-0.44
5	Paroa, Manawaora & Parekura	9.2	10.1	9.4	0.3
	TOTAL BAY OF ISLANDS (indicative)	**316.9**	**277.9**	-	-

3.1 Persisting threats

Saltmarsh habitats are affected by 23 significant threats (MacDiarmid et al. 2012: 43), with two extreme (reclamation and rise in sea level caused by climate change). Major threats are the effects of causeway construction, increased sediment loading of rivers, and oil pollution, and a further 10 are moderate. For the Bay of Islands, mangrove expansion is probably the predominant immediate threat, the saltmarsh being essentially locked from landward expansion by infrastructure such as roads and stopbanks (e.g., Figure 18).

4. LOSS OF UPPERSHORE COARSE-SAND/SHELL BEACHES AND SPITS

Mangrove expansion has overwhelmed the now-rare uppershore coarse-sand/shell beaches that had, at least until the early-1950s, comprised the margin of many soft, upper shores of Bay of Islands estuaries and sheltered embayments (e.g., Figure 19) (Booth 2020).
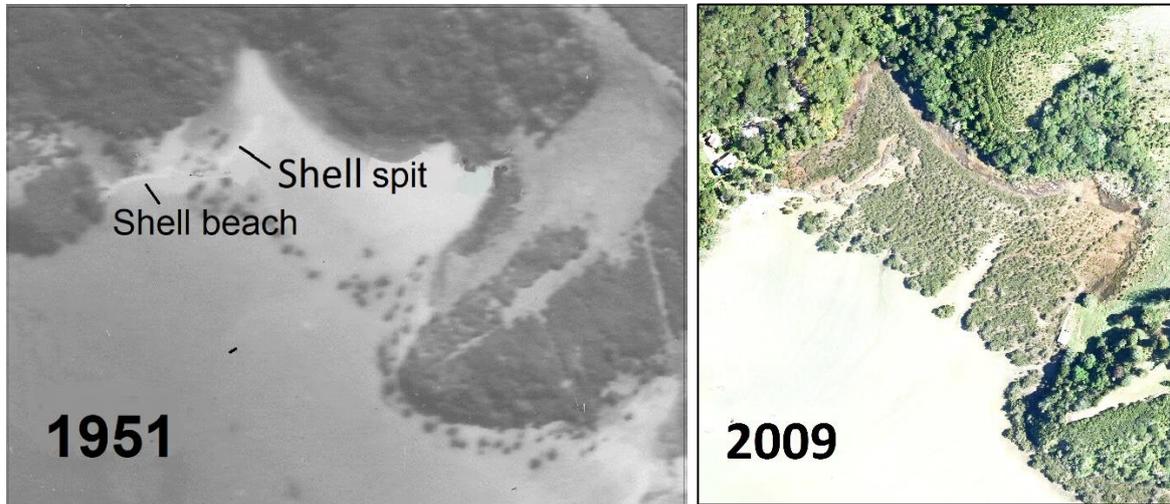
Figure 19: Much of the coarse-sand/shell beach, and the entire spit, in this embayment in the eastern Bay of Islands has been obliterated in the course of shoreward expansion of mangroves, between 1951 and 2009 (images from Figure 17).

These high-shore beaches and spits associated with essentially every place where fresh-water streams flow out onto soft sheltered shores (e.g., Figures 19 and 20) were most readily distinguished in the earliest (mainly early-1950s) synoptic aerial imagery. But, even then, most of the small spits (<50 m long) were already too overgrown with terrestrial vegetation and mangroves to be obvious (Booth 2020). Nevertheless, these images formed the baseline from which to estimate the extent of subsequent loss of this biome, with Kerikeri Inlet being considered representative of the entire Bay of Islands.

Figure 20: A typical coarse-sand/shell spit, in Waikino Creek, with freshwater marsh to the left, and mangroves invading from estuarine waters to the right. (Image: author)

In mid-Kerikeri Inlet, 2.04 km of the sand/coarse-shell beaches (58% of the total length of such shore that was still relatively intact in the 1951 images) had been overwhelmed by mangroves by 2009, and all of the nine obvious, ecologically-distinctive spits overrun (with other smaller, essentially unperceivable spits invaded too) (Appendix 5).

The *intertidal* of such shores today are often feeding grounds for birds like the endangered NZ dotterel *Charadrius obscurus* and variable oyster catcher *Haematopus unicolor*. But the shoreward expansion of mangrove cover means there are no longer nesting opportunities for them above high-water level on these beaches. Instead, birds must nest in ever-diminishing areas of intact sand/shell uppershore elsewhere, which is often where people with their pets gather.

4.1 Persisting threats

Few coarse-sand/shell beaches and spits remain intact, and, accordingly, they are considered among the most-at-risk marine ecosystems (Clement Lagrue, Department of Conservation, pers. comm. 2020). Threats to them are similar to those affecting saltmarsh. Mangrove expansion (now mostly alongshore) appears to be the main *immediate* threat to this biome in the Bay of Islands: terrestrial vegetation invading these beaches and spits is usually easily managed and presents far-less long-term menace than do mangroves.

5. INUNDATION OF OYSTER REEFS

There has been ~85% loss globally of natural oyster reefs and beds (Beck et al. 2011), many of them intertidal. Northern-New Zealand oyster reefs today are comprised of both the native rock oyster and the Pacific oyster. Rock oysters extend furthest up the shore and Pacific oysters furthest down (Morrison et al. 2014a: 49-51), at least native rock oysters apparently being excluded from the subtidal through infestations of spionid polychaete (mud) worms (e.g., Handley & Bergquist 1997). The oysters can be present on stony surfaces amid mudflats, or form reefs on top of mud.

Oysters (pre-1970, the rock oyster alone) have formed intertidal biogenic reefs in the Bay of Islands (e.g., Figure 21). The oyster reefs tend not to show well in aerial imagery through there being little colour-contrast with surrounding substrates and because the reefs have often been small (<50 m^2). Nevertheless, aerial images (from the early-1940s onward), early charts and recent field observations provide a sense around changes in the presence and extent of intertidal oyster reefs of the Bay, the main focus having been Kerikeri Inlet.

Figure 21: The largest oyster reef in Kerikeri Inlet today (~1 000 m^2) lies off Hororoa Point (Figure 22). (Image: author)

Human-made rock-oyster rock reefs associated with an oyster-enhancement initiative in the first half of the twentieth century were prominent on various intertidal shores of the Bay of Islands, and remain visible in many places (Booth 2017). They tend to show well in aerial imagery because of the mainly dark, basaltic rock used, and the ordered lines or groups of rocks.

5.1 Natural oyster reefs

Almost certainly, oyster reefs would have been far more prominent in Bay of Islands estuaries in the past than in recent times. The two significant areas of oyster reef in Kerikeri Inlet today are associated with the extensive mudflats off Hororoa Point/Skudders Beach (Figure 22; Appendix 6). Comprised of tightly-packed, mainly-large (>80 mm long), dead but still-articulated individuals, the proportions of rock versus Pacific oysters are unknown. These two areas appear to have also been the only significant beds visible in the earliest images (1942; Appendix 6 – possible-others being difficult to distinguish with confidence). The larger bed (~1 000 m^2; '1' in Figure 22) is alongside Middle Channel. The smaller one ('2') is upstream of Hororoa Point and is comprised of a number of small patches that are probably supported by shingle (Watkins 1974).

Figure 22: The two significant oyster reefs (1 & 2) remaining in Kerikeri Inlet (left) are of tightly-packed, mainly-large (>80 mm long) individuals, many dead but still articulated (right). (Map and image: author)

5.2 Persisting threats

Intertidal reefs in harbours and estuaries are affected by 51 significant threats (MacDiarmid et al. 2012: 44), they being extremely vulnerable to the effects of ocean acidification, sedimentation, invasive species and reclamation. Major threats include rise in sea-level, increased sea temperature, shellfish gathering, increased storminess, altered rainfall, UV increase, change in currents, and causeway construction. A further 28 threats were considered moderate. For Kerikeri Inlet, it is remarkable that any of the oyster reefs persist beyond the main channels, given the levels of sedimentation along the inlet's margins; possibly ongoing spat settlement on top of older oysters maintains these beds. Continuing sedimentation is the immediate threat likely to lead to further losses of reefs.

5.3 Human-made rock-oyster reefs

These were established along various intertidal shores of the Bay of Islands in the early- to mid-1900s in what was the first serious attempt at marine fishery enhancement in New Zealand (e.g., Figures 23 and 24). Rocks for oyster spat to settle on were accessed mainly from Te Puna Inlet and distributed widely on soft-bottom seafloors around the Bay of Islands (Booth 2017). Further, by 1916, local and imported high-level oyster rocks were being moved down to half-tide level, with kilometres of rock wall established (Marine Department 1916) on what had previously been soft shores.

Figure 23: Large area of newly-laid-out rocks in the lower reach of Kerikeri Inlet in 1922. (Photograph: Sir George Grey Special Collections, Auckland Libraries, Auckland Weekly News AWNS-19210224-40-4)
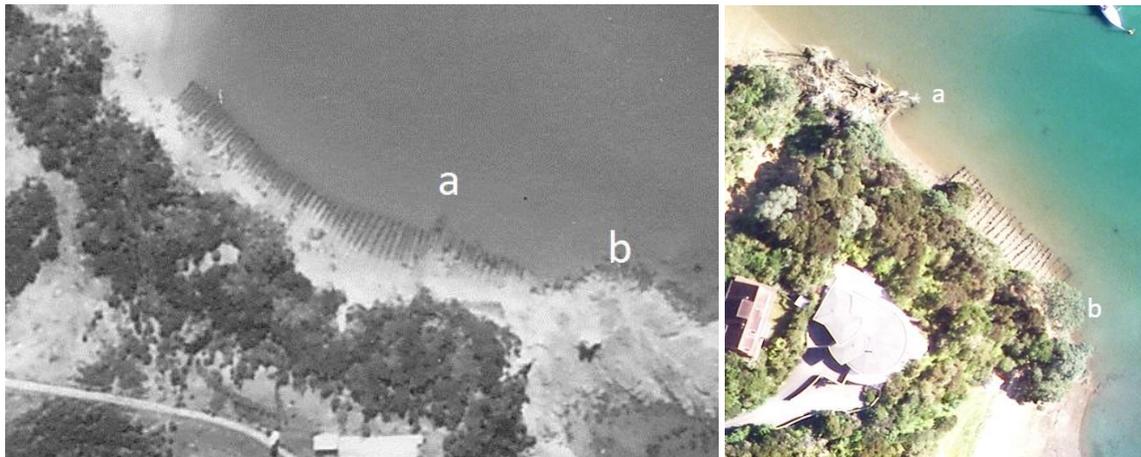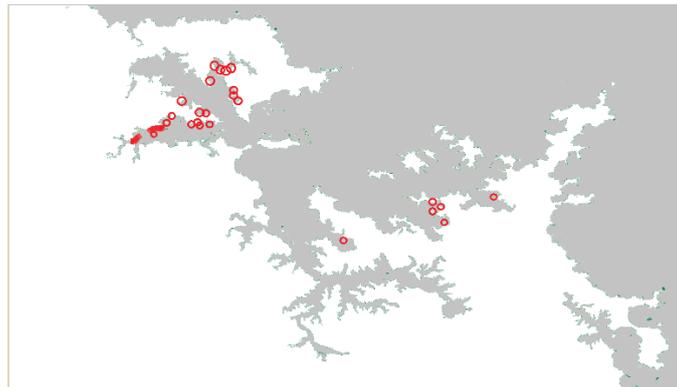
Figure 24: Upper: Places where intertidal oyster groynes, or groynes and rocks, established early in the twentieth century were still clearly identifiable in the 2009 Ocean Survey 20/20 aerial images, most having been established on soft bottom (Booth 2017). Lower pair: Extensive areas of oyster groyne clearly visible in 1971 in Kerikeri Inlet (left image: NZ Aerial Mapping Ltd 4476-5, part of S.N. 3406) had been greatly reduced by 2009 (right image: Ocean Survey 20/20 AV29_3021).

6. CHANGES IN COCKLE DISTRIBUTION AND SIZE

Cockles – with pipi – are the prominent estuarine shellfish of the Bay of Islands (Booth 2020). Cockles are ubiquitous, shallow-burrowing bivalves of soft estuarine and sheltered shores (Morton & Miller 1968) that live from near high-water mark to the lowest intertidal. They are found most abundantly (up to 4500 m^{-2}) in sediments with ~11% mud (Anderson 2008; MPI 2018). Cockles are ecosystem engineers, creating, modifying and maintaining habitats (Gutiérrez et al. 2003). (For essential-other biology, *see* Booth 2020: 9.) Kerikeri Inlet and Waikino Creek/Waikare Inlet were the main focus for detailed assessment of changes in the characteristics of cockle populations over the past two centuries,

but cockles in the broader Bay are also considered. Shellfish beds are where 'large' (interpreted here as 'adult' and breeding individuals, and so ≥20 mm long) cockles at densities of at least 30% cover populate an area of ≥100 m^2 (Anderson et al. 2019: 118). Cockles are 'harvestable' when individuals at least 30 mm long are present at at least 25 m^{-2} (Pawley & Smith 2014).

Some of our most useful, early insights into the characteristics of the cockles of the Bay of Islands are found within middens, the midden-cockle size, abundance and ubiquity pointing to extensive and particularly rich resources of this clam in at least late pre-Contact (pre-1800) times (Booth 2016a: 78). Māori middens are records of human harvests rather than being reflections of natural abundance of taxa in an environment (Anderson 1981). Nevertheless, their analysis can provide critical insight into ecological change. Moreover, with a documented history going back to the early-1800s, information around the early-post-Contact cockle resources of the Bay of Islands (and in particular Kerikeri Inlet), by which time cockles were a dietary staple in the north (Allen 2012; Smith 2013), may be among the most detailed available. Yet today, local cockle populations appear degraded, no longer achieving the same sizes or ages they once did.

6.1 Cockles in Kerikeri Inlet

This example demonstrates how cockle beds significant in mid-Kerikeri Inlet 200 y ago have declined markedly in areal extent as a result of terrigenous sedimentation, and that key biological characteristics have changed. Even though essentially unfished, the beds now contain generally low proportions of harvestable individuals (Booth 2020).

Kerikeri Inlet (biologically and physically illustrative of most Bay of Islands estuaries) is an 8 km, shallow drowned valley that narrows near Skudders Beach into two tidal rivers, the Kerikeri (upstream catchment area 99 km^2) and Waipapa (34 km^2). Tidal mudflats occupy around half the surface area. Whereas the ecology of the upper third of the Inlet is dominated by freshwater, the lower third is influenced by fully-saline waters. Mid-Inlet hydrological conditions appear suitable for cockle recruitment and at least early growth: (1) during low river discharge, near-surface salinities vary between 28 and 35 psu according to the tide (Cornelisen et al. 2011); (2) dissolved oxygen values are typically ≥90% percent saturation (Griffiths 2015); and (3) although transparency tube [Secchi disk] readings the length of the Inlet in summer after little rain were low in mid- and upper-parts (<0.6 m [~1.0 m]; Booth 2020), over longer periods mid-Inlet turbidities have typically been 4–5 NTU [mainly 1.3–1.6 m Secchi depth] (Griffiths 2015). Today, however, deep fine mud prevents cockles establishing in many parts of Kerikeri Inlet, particularly along the margins of its mid- and upper-reaches (e.g., Griffiths 2011), and, elsewhere, cockles may be abundant but are rarely harvestable. Yet, at least during early-Contact times (starting in ~1800), the Hororoa beds enduringly provided enormous quantities of medium-to-large cockles.

Pre-Contact/early post-Contact cockles Mid-Kerikeri Inlet presents an archaeologically-rich landscape: the density of recorded shoreline middens approaches 4 km^{-1} of coast, this being among the highest in the Bay of Islands (Booth 2016a, 2017; Appendix 7). Cockles dominate these middens, and essentially all shells recorded on the Site Record Forms (SRFs, downloaded from ArchSite, New Zealand Archaeological Association's Site Recording Scheme website in 2014) have been 30–55 mm and opened (Appendix 8). Further, middens were still conspicuous in the early-1900s when Ferrar & Cropp (1922) indicated two 'Huge pipi [=cockle]-shell middens' associated with Hororoa Point (Appendix 9), at least one of which remains.

Two middens directly associated with Hororoa Point, the 300 m long midden complex P05/464 and the smaller P05/465 (Figure 25), were recorded on SRFs by archaeologist Glenis Nevin, in 1984. At that time, P05/464 had an estimated volume of 1660 m^3 (Booth 2020). The western-most portion of P05/464 was a low-lying cockle-shell spit (cockles 35-51 mm long). To the east, on the face of the bluff, was a midden-scree remnant, where cockles were predominantly 29–47 mm (SRF) (Booth 2020). Later, at least one kiln produced burnt lime. The shell for this agricultural dressing came not only from the area

of the spit, but possibly too from huge (now covered/excavated) middens on the banks of Ōkura River (NAR 2004: 11,16). Many tonnes of both whole cockles and machine-crushed cockles were trucked from here to nearby properties in the mid-1900s.

The spit appears to have been both natural and anthropogenic in origin. Degrading whole, dead cockles over the entire size-range, as well as shell fragments, accumulate naturally on the margins of cockle beds (e.g., Morrison et al. 2014a: 58), transported and sorted by the nearshore hydrodynamics. Nevertheless, mainly large cockles were once present on the spit in enormous quantities. In the early-1960s, remnant faces of previously-quarried deposits were 2–3 m high and comprised of opened but otherwise whole cockles, interspersed with organic material (Greg Imms, Kerikeri, pers. comm., 2019). Almost certainly, therefore, this spit represents a midden (as suggested in the SRF), which was subsequently mined and which, as a result, had become much smaller (Figure 25). However, because of potential mixing of natural and midden cockles, it was not sampled for this study.
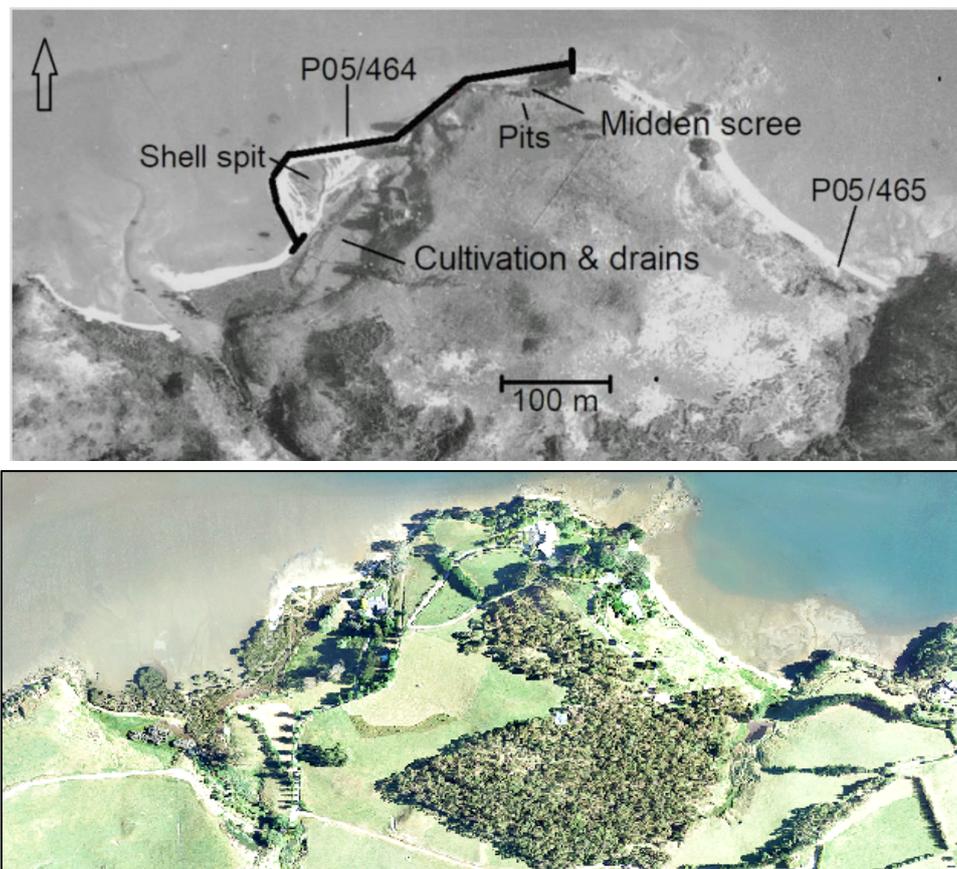

Figure 25: Orthorectified February 1942 image (Air Force Museum of New Zealand: enlNZAMtin109frameA3) of Hororoa Point with the location of middens P05/464 (solid black line, before mining of the shell spit) and P05/465 (upper). Hororoa Point in 2009, showing much reduced spit (lower).

The midden-scree (35° 12′ 30.0" S, 173° 59' 50.0" E), almost certainly one of the middens referred to by Ferrar & Cropp (1922) (Appendix 9), was not mined. In 2018–19, its eroding face, taking in much of the 10-m height of the bluff, was without evidence of layering, was comprised almost solely of 'clean', often tightly-packed, disarticulated but whole and unburnt, medium to large (30–50 mm long) cockle valves. Each cubic metre contained ~134,000 valves (Booth 2020). Almost no other shellfish were present, they most commonly being an occasional pipi. Similarly, parts of nearby P05/465 (~330 m^3) remain, up to 3 m high with densely-packed cockles. Few of the stones and little of the charcoal normally associated with day-to-day cooking were apparent within either midden. Midden cockles (P05/465 and P05/464) averaged 38 and 37 mm shell length respectively (N = 126, 150), reached 56 and 54 mm, and lived to a considerable age (at least 12 y). The second full-years' average increments

were 4.2 and 3.9 mm shell height respectively, and the third full-years' growths 3.7 and 3.6 mm shell height (Figure 26). (The first full-year's growth was not estimated because of difficulties in determining the first winter depression, laid down shortly after settlement, it lying close to the umbo and often faint.)

Arguments justifying the associating of P05/465 and P05/464 cockles with the Hororoa beds, and of examining only surface cockles from the middens, were presented by Booth & Edwards (2020: 5–6). First written records concerning a significant cockle fishery near Hororoa Point (and upstream to at least Skudders Beach) emerge from the early-nineteenth century. Around then, the south side of Kerikeri Inlet, and particularly near Ōkura River, was where people of (or closely allied to) Taiamai (near Ohaeawai, 18 km inland) had land, access and fishing rights (e.g., Sissons et al. 2001: 28). Summer months were spent here fishing, including the harvesting and preparation of cockles for transport inland. Typically at such shellfishing camps, shellfish were steamed open, threaded on flax string, then hung to harden before transport/storage (Best 1929: 58), large individuals presumably being preferred. It appears, however, that by about 1830 the area was being little used any longer for summer fishing (Shawcross 1967: 210–212).
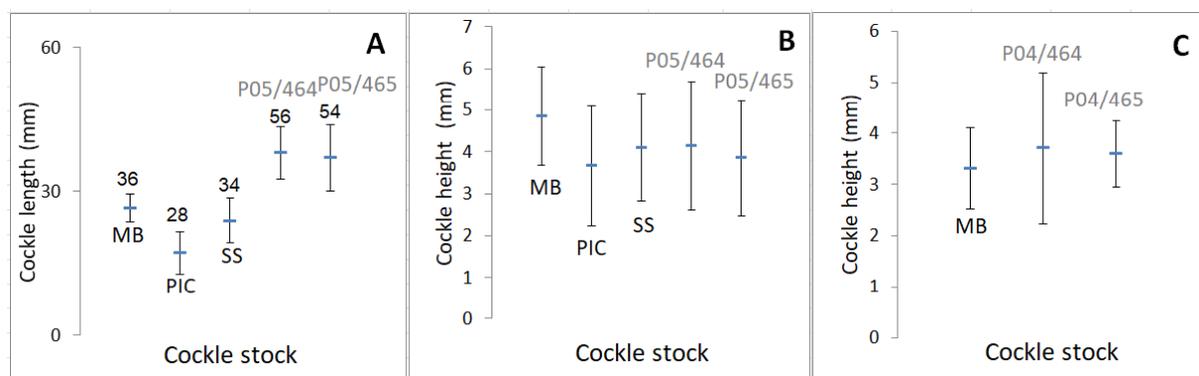

Figure 26: For Hororoa cockles in 2018–19, mean size (mm length ± 1 SD; 2 mm sieve), with largest cockle-size given above each (A); mean second full-year's growth (mm height ± 1 SD) (B); and mean third full-year's growth (mm height ± 1 SD) (C). MB, Middle Bank; PIC, Pickmere Channel; SS, South Shore (*see* Figure 27). Midden (P05/465 and P05/464) growth increments were for cockles 25–35 mm long (Booth & Edwards 2020).

For 1819–26, there are three independent commentaries around significant cockle stocks apparently being present. Early in 1819, missionary Samuel Marsden found, in the middle of Kerikeri Inlet, a very large cockle bed dry at low water where 'about a hundred women were busy collecting cockles for food' (Elder 1932: 180). In August 1823, also near Hororoa, missionary Henry Williams was 'struck with the appearance of vast quantities of wild duck.... but upon drawing nearer, we discovered that it was a considerable quantity of children in the water collecting cockles' (Easdale 1991: 22). And in 1826, 'opposite Skudders Beach', Colonial Botanist of New South Wales Alan Cunningham found '…whilst we were passing the narrows bounded by mudflats covered with a Cockle (Cardium) which the natives & more especially those often females were gathering together in baskets for food.' (Easdale 1991: 22).

Recent cockles Although the immediate shores of Hororoa Point are now of deep, fine mud that is essentially bereft of shellfish, small live cockles are numerous today on the tidal flats further offshore (Figures 7 and 27) (Booth 2020). There has been no significant harvesting of cockles in mid-Kerikeri Inlet for decades now according to residents with expansive views over the tidal flats (e.g., Adrian Walker, Department of Conservation, Kerikeri, pers. comm., 2019). Yet long-time local Richard Civil (21 Rangitane Rd, Kerikeri, pers. comm., 2018) recalled high proportions of plentiful, *large* cockles being harvested here in the 1940s–1950s; Booth (1972: 100, 224) recorded living bivalves present on the nearshore intertidal and shallow-subtidal flats at Shelly Beach (and Skudders) in 1971–72 to include abundant cockles and pipi, as well as wedge shells *Macomona liliana* (those at Shelly Beach being biologically-sampled monthly); and locals reported harvestable cockles being present at Skudders Beach until the early-1970s but not later.
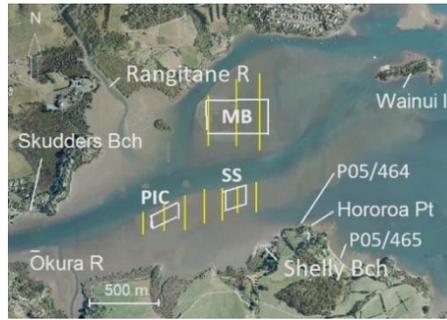
Figure 27: Sampling of living cockles in mid-Kerikeri Inlet in 2018–19 (MB, Middle Bank; PIC, Pickmere Channel; SS, South Shore), the yellow vertical lines indicating the main beds. (Map: author)

Cockles were widespread and abundant (up to 2400 m^{-2}) at and near the surface at Middle Bank (MB), South Shore (SS) and Pickmere Channel (PIC) – but were barely harvestable. Averaging 24 mm in length across all 18 samples, the largest individual was 36 mm (Figures 26 and 28 and Appendix 10). Cockles (MB, SS and PIC) averaged 26.6, 24.0 and 17.3 mm length respectively (N = 392, 142, 108), reached 36, 34 and 28 mm, and lived only 3–5 y (Booth 2020). (The largest recently-dead cockles in the samples were no larger than the living ones.) Growth rates were similar to the midden cockles of the same size (overlapping SDs): the second full-year's average increments were 4.9, 4.1 and 3.7 mm shell height for MB, SS and PIC respectively; and the third full-year's growth 3.3 shell height for MB (Figure 26). Moreover, cockles >30 mm long have been rare at PIC since at least 2009, when sampling began there (Figure 28). Indeed, a decade now of sampling of PIC cockles suggests successful (albeit annually variable) recruitment, but with essentially none surviving to exceed 30 mm (Figure 28), die-off apparently being more age/size-related than episodic. Furthermore, significant numbers of the live cockles at all three sampling areas were not completely buried in the substrate; instead they appeared as scatters entirely atop the sediment surface, or only partially buried (*see* Figure 30), all in the context of no recent flood scour or similar.
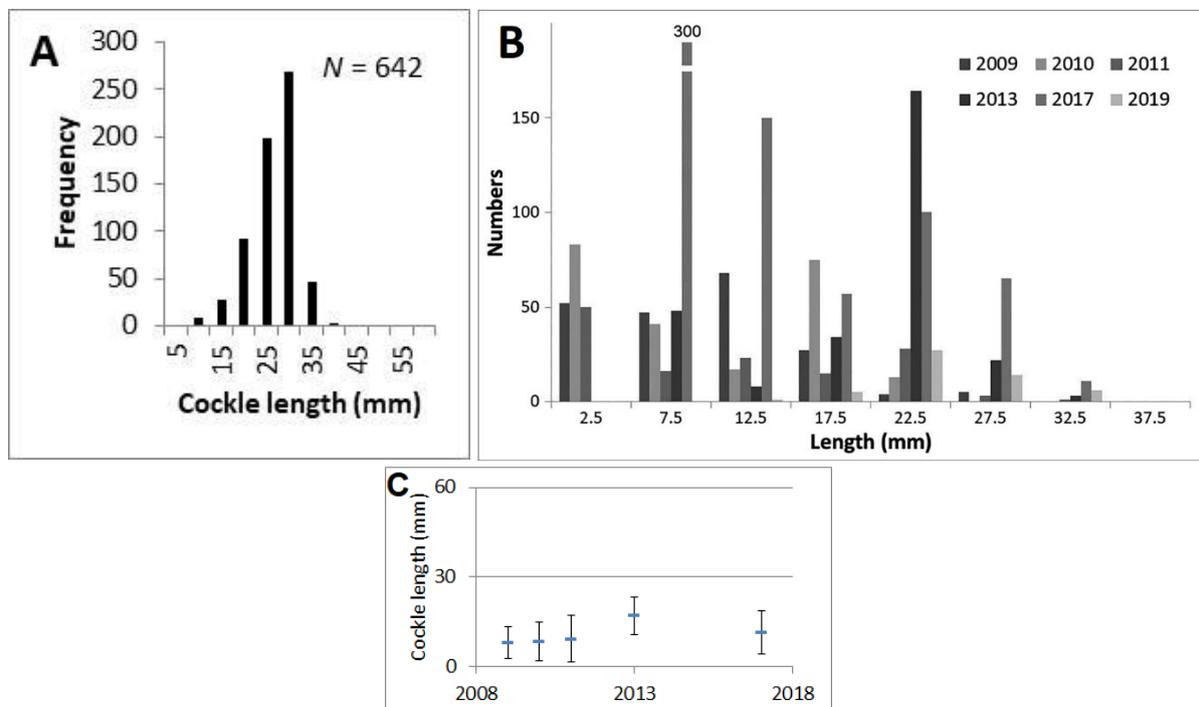

Figure 28: 2018–19 length-frequency distribution of living Hororoa cockles from Middle Bank, Pickmere Channel and South Shore combined (2 mm sieve; A). Length frequencies of Pickmere-Channel cockles sampled during April (0.5 mm sieve), by year, 2009–19 (B) and their summary size-statistics (mm length ± 1 SD; C) (Richard Griffiths, Northland Regional Council, pers. comm. 2019).

In summary, if shells on the surface of the Hororoa-Point middens today represent large-scale, more-or-less sustained harvests of Hororoa cockles over many years of the early-1800s (presumably managed, healthy and productive stocks, with sizeable proportions of large individuals); and the much smaller cockles off Hororoa today represent the current, more-or-less steady state (a depressed stock, with barely harvestable cockles, despite little gathering), then there has been significant change in fishery status of this resource. On inlet margins today, terrigenous silt appears to prevent cockles establishing altogether, while further offshore presumably compromised cockles succumb within ~4 y (and ~35 mm length).

6.2 Cockles in Waikino Creek and Waikare Inlet

Although their densities in the Waikino/Waikare waterways are lower (~1.3 km^{-1}; Booth 2016a) than in Kerikeri Inlet, there are nevertheless many recorded shoreline middens (102). Several are huge and dense with cockles. Associated with midden Q05/937 in Waikino Creek '…..there was an old boiler [kiln?] lying on the beach which was used for the lime burning of the midden shells to produce agricultural fertiliser' (1984 SRF). (Other kilns operated nearby too, in the Waikare Inlet; Peter Clark, Waikino Creek, pers. comm., 2019.) Remnants of this enormous midden in 2005 formed a terrace 30 m long and up to 3.5 m thick (Turner 2006), and contained mainly large opened cockles (Appendix 11). The surface cockles of this midden today are mainly 30–45 mm long (Booth 2020).

Long-time local resident Peter Clark stressed the importance of cockles (and pipi) as food for families here during the 1950s–60s in particular, with high proportions of large individuals being widely available. But today, deep fine mud means abundant beds are essentially absent from the Waikare and Waikino waterways. Where living cockles in 2019 were found, they were typically as sparse individuals beneath numerous dead valves (up to ~35 mm) on the surface (Booth 2020).

6.3 Cockles in the broader Bay of Islands

Cockles are the most abundant and conspicuous shallow-water shellfish in the Bay of Islands, as a whole, prone to high levels of terrigenous sediment. And the trajectories of many or most of the individual populations appear to be similar to those of Hororoa: high proportions of large individuals archaeologically, with cockles today absent in the widespread, deep nearshore-mud, and with essentially-unharvestable – or barely-harvestable – beds further offshore. This transformation has taken place in the context of long-term, time-averaged, post-Contact (post-1800) SARs having been similar among Bay of Islands' estuaries (mainly 1.8–3.5 mm y^{-1}; Swales et al. 2012) (Figure 5), but with apparently-higher recent rates having essentially eliminated cockle habitat from much of the Waikino/Waikare.

Cockles dominate middens throughout the Bay of Islands. Most middens are almost certainly the result of many years of harvesting during late pre-Contact/early post-Contact times (some dated; Booth 2016a: 80), rather than being ancient and derived entirely from pristine stocks. Despite large local human populations capable of intense fishing pressure being present by late-pre-Contact times (Booth 2017), and strong dependence by Māori on estuarine shellfish (e.g., Smith 2013), most middens with associated size data contain large to very large cockles (≥40 mm) (Figure 29A).

Maximum cockle sizes throughout the Bay of Islands today are typically much lower (usually ≤33 mm; Figure 29B–C, this being a common refrain too among long-term locals) than the midden cockles, even though the beds are essentially unfished. (The sole bed in the Bay recognised as having been significantly fished in recent times, Te Haumi, has length frequencies similar to the essentially-unfished beaches; *see* Berkenbusch & Neubauer 2015.) Moreover, valves located among the living cockles do not suggest significant proportions of larger cockles having been recently present (Booth 2020). Dearth of cockle-size data from the twentieth century means it is unknown precisely when mean cockle-size declined, the one length frequency located (Figure 4.32 in Larcombe 1971) showing that large cockles (>40 mm) were still present in 'Parekura Bay' in the mid-1900s.
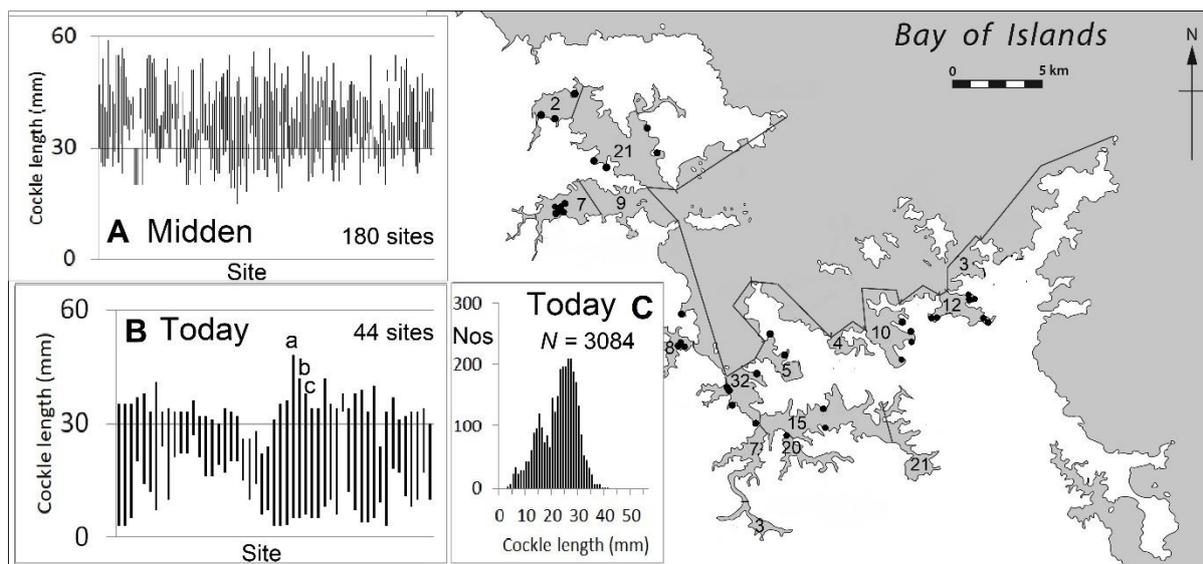
Figure 29: Length-ranges of midden cockles reported on archaeological site record forms (A, with numbers of middens shown on the map according to Booth's [2016a] archaeological compartments), and recent (since 2009) living cockles (B and C, with sampling sites indicated by dots on the map, the author sieving to 2 mm, but others' mesh sizes varying) for the Bay of Islands (Appendix 10); each vertical line in A and B denotes maximum and minimum cockle lengths for a particular locality (Booth 2020). In B, designations a, b and c are beach-wide maximum and minimum values.

Scatterings of living, surfaced individuals were both common and widespread on Bay of Islands cockle beds during the recent sampling on which Figure 29B–C was largely based. Without any recent storm or other-such event, the shellfish sat proud of the substrate surface or they lay on their sides atop the sediment (e.g., Figure 30). Large numbers of surfaced, live cockles in the populations may have been recent because neither Larcombe (1971) nor Hewitt et al. (2010; pers. comm., 2019) seem to have encountered them during their studies of Bay of Islands cockles. Further, because surfacing is disadvantageous, it appears significant proportions of the cockles are compromised. Indeed, large-scale surfacing events may account for recent widespread mass mortalities in the Bay of Islands, each mortality evidenced by waves of what appeared to be uniformly-fresh and articulated 20–35 mm long cockles on the mud surface. Such events appear to have taken place at Crowles and Wharengaere bays (Te Puna Inlet), Waitangi, Whiorau Bay (Parekura Bay) and outer Waikino Creek, among others (Booth 2020).

A notable 'surfacing event' recently played out on a beach 1 km south of Te Haumi. Here, thousands of living cockles formed low ridges on the beach's mid- and low-intertidal, from early in December 2019 (although it is unknown when the cockles became surfaced), and were still present alive (albeit at much lower densities) in late-February 2020 (Figure 30, although it is unknown if they were the same group of individuals throughout). (A similar event appears to have recently taken place among the pipi at Te Haumi; Berkenbusch & Neubauer 2015: 111.)

Figure 30: High proportions of Middle Bank (Hororoa) live cockles (mainly 25–30 mm long) in 2019 were partly or fully exposed at the surface, rather than being completely buried; although those buried were dense, by no means was all space taken (left). Low ridges of 20–30 mm cockles, first observed in early December 2019, were still alive – although less numerous – in late-February 2020 on the (apparently unnamed) beach 1 km south of Te Haumi (right). There had not been any flood or other relevant weather immediately before or during either event. (Images: author)

6.4 Synthesis

Significant proportions and quantities of large cockles (40–55 mm) continued to be available for harvest throughout much of the Bay of Islands into recent historical times on an apparently enduring basis. Today, however, they are barely harvestable on most shores. This suggests a massive diminution in fishery status of the resource.

Size-range is an extremely coarse metric, and although the archaeologists' observations (Figure 29A) necessarily stand, sizes of the living cockles of the Bay of Islands in recent times (Figure 29B–C) can be examined more perceptively. Although the recent sampling was necessarily limited (in both size and numbers of samples), it was nevertheless widespread, and the length-frequency distributions and other data (Appendix 10) support the notion that cockles are much smaller on average today than in late pre-Contact/early post-Contact times.

It appears that recently – probably over the course of the past half-century, and possibly within the last couple of decades – there has been substantial decline in the status of the Bay of Islands cockle stocks. Cockles today are *widespread* and *abundant* (except in the Waikare and Waikino waterways), but seldom reach large sizes. There are many competing and/or compounding potential explanations for significant and enduring reduction in the size of Bay of Islands cockles today compared with earlier times, with the Hororoa beds in Kerikeri Inlet being the example location underpinning the following analysis of possible causes. 1) Recent suboptimal seawater temperatures associated with ocean-climate variation: *however*, although the Hororoa middens probably derive from times when average air temperatures were up to 1 °C cooler than today (Little Ice Age; Anderson et al. 2014: 121), cockles, until at least the 1960s, reached large sizes (~50 mm) in warm northern waters (Larcombe 1971: 43; author's and others' unpubl. obs.), and, anyway, northeast-New Zealand coastal sea temperatures have risen little since the 1970s (Shears & Bowen 2017). 2) Game-changing rises in sea level: *however*, northern-New Zealand sea-level rise has averaged only ~1.3 mm yr^{-1} since 1899 (Hannah 1990), and the intertidal of mid-Kerikeri Inlet today appears geomorphologically similar to that of the mid-1800s (Figure 7). 3) Diminished growth rates today: *however*, at least early annual-growth increments are indistinguishable from midden cockles of similar size (overlapping SDs; Figure 26). 4) Recent overharvesting: *however*, according to locals there has been no significant harvesting here for decades.

5) Previous heavy exploitation of large individuals has profoundly altered population genetics: *however*, this seems most unlikely, based on the international literature reviewed. 6) Māori translocated and manipulated cockles on such a scale that natural size-distributions were supplanted: *however*, evidence for transplantation of cockles *at large scale* has proved elusive. 7) Loss of interest in cockles as seafood has led to overcrowding and slower growth: *however*, early growth increments are indistinguishable from midden cockles, and we know densities can reach values much higher (~4500 m^{-2} ; MPI 2018: 233) than the maximum of ~2400 m^{-2} (average ~1100 m^{-2}) found in this study. 8) Chronic and intolerably-high levels of organic or inorganic contaminants: *however*, at least since 2008, enrichment in the water column and surficial sediments in Kerikeri Inlet has been at most low to moderate, with no lethal levels of bivalve toxins reported (Cornelisen et al. 2011; Griffiths 2011, 2014; Bamford 2016). 9) Chronic food-limitation brought about by low productivity: *however*, tidal flushing is fulsome, and conditions are not unproductive (Griffiths 2011). 10) Greater populations of large-cockle predators, and/or fewer predators of small cockles: *however*, there is no evidence for noteworthy changes in abundance of these. 11) Chronically insufficient larvae: *however*, breeding-sized cockles are still numerous in the broader Kerikeri Inlet. 12) Highly-variable recruitment success, with long intervals between cohorts of large cockles: *however*, there is no evidence for quantities of *large* dead-shells present on the beds or adjacent shores. 13) Periodic and damaging environmental episodes (e.g., eutrophication, harmful algal-blooms, viral outbreaks) have led to mass mortalities of large cockles: *however*, no quantities of recently-dead, *large* cockles are known here. 14) Greater prevalence of parasites and disease-causing organisms, with parasite impact typically positively age-related: this is a strong possibility. 15) Chronic stress, probably brought about by persistent, and at times catastrophic, deposition of terrigenous silt, has left cockles less-resistant to parasites and disease: this is also a strong contending explanation for much smaller cockles off Hororoa Point cockles today compared with 200 or so years ago. In summary, generally-low densities of harvestable cockles in Kerikeri Inlet today probably result from multiple stressors possibly including infestations, underpinned by chronic levels of fine terrigenous-silt accumulation – a well-known inhibitor of cockle vigour (e.g., Lohrer et al. 2004).

Given the waves/low ridges of uniformly-fresh, 20–35 mm long mortalities – and sometimes living cockles of similar size – seen on many beaches in the Bay of Islands, *mass surfacing events* may well be a major source of mortality. This possibly suggests – combined with the high levels of fine silt – high parasite infestation, or the effects of some other contagion. Surfacing can be characteristic of trematode infestation: cockles serve as second intermediate host for several echinostome species, some of which prevent cockles from burrowing, with infection rates being positively cockle-size-dependent. Indeed, such parasites infect (albeit at low individual densities) all cockles in certain parts of the Bay of Islands (Studer et al. 2013). Accordingly, new parasites and/or novel disease-causing organisms, or greater prevalence of existing ones, with impacts positively age/size-related, may be a primary explanation for cockles surfacing. It is even possible that some as-yet undefined ecological tipping point (environmental changes having set in motion mutually reinforcing feedback loops that have propelled the ecosystem on a new course [e.g., Selkoe et al. 2015]) has been breached whereby significant proportions of large cockles, are unlikely to emerge in the near future. This may involve some level of prevalence and persistence of disease/parasite having been breached (e.g., Harvell et al. 1999), whereby re-attainment of a full size range, with substantial proportions of older cockles, is presently not possible. Accordingly, even *if* SARs have, in places, recently begun to stabilise – or even decline – we may not necessarily shortly be seeing cockles once again reaching large sizes in the Bay of Islands.

The length-frequency distributions by sampling site and by region provide insight into the current status of the Bay-of-Islands cockle stocks, in the context of essentially all stocks being unharvested or only lightly harvested. Throughout, most cockles were 12–33 mm long, with smaller cockles being only moderately-well represented, and larger ones poorly represented (Appendix 10). These patterns are consistent with one or more possible explanations: 1) poor recent larval recruitment; 2) larval recruitment taking place elsewhere, juveniles migrating onto the bed within a year; 3) high mortality/predation of very small cockles; 4) particularly high larval recruitment ~2 y earlier, with good survival; and 4) death after ~4 y or sooner. Poor recent larval recruitment, and high mortality once the shellfish reach round 30 mm, appear to be the most likely explanations for these size distributions. The impression is that although levels of larval recruitment may be spatially and temporally variable, the

one constant is that cockles seem to no longer achieve even 40 mm length, let alone the larger sizes of earlier times.

6.5 Persisting threats

Cockle beds are affected by 38 significant threats. They are extremely vulnerable to the effects of ocean acidification; there are five major threats (sedimentation, increased intertidal temperature, rise in sea level, shellfish gathering and causeway construction); and 15 others are moderate (MacDiarmid et al. 2012: 44). For the Bay of Islands cockles in particular, continuing sedimentation will lead to further loss of cockle habitat, and possibly to increased stress on remaining beds.

7. INTERMITTENT APPEARANCE OF LOW-INTERTIDAL *VAUCHERIA*

Possibly four species of the mainly freshwater/terrestrial yellow-green alga *Vaucheria* found in New Zealand are marine (Wilcox 2012: 285). Almost certainly *Vaucheria velutina* (*see* Wilcox 2012), an internationally-widespread
(https://www.algaebase.org/search/species/detail/?species_id=529&distro=y#distro) yet apparently-native yellow-green alga has occurred periodically during winter and spring in the low intertidal of parts of the eastern Bay of Islands. Observations here began in 2006, and the bloom at Omakiwi Cove in winter 2020 was the first to take place when abundant seagrass was also present (Figure 31).

Figure 31: *Vaucheria* patches (foreground) interspersed amongst low-intertidal seagrass (beyond) at Omakiwi Cove, June 2020. (Image: author)

V. velutina (the provisional determination here based on Bingham 2011 and Figure 1A of Wilcox 2012) has from time to time heavily colonised low intertidal parts of bays in the eastern Bay of Islands. Its growth characteristics (prominent erect tufts on top of the mud surface and extensive subsurface siphons and deep-reaching roots which bind and stabilise the sediment) can give a braided appearance to the intertidal (Figure 32; Appendix 12).
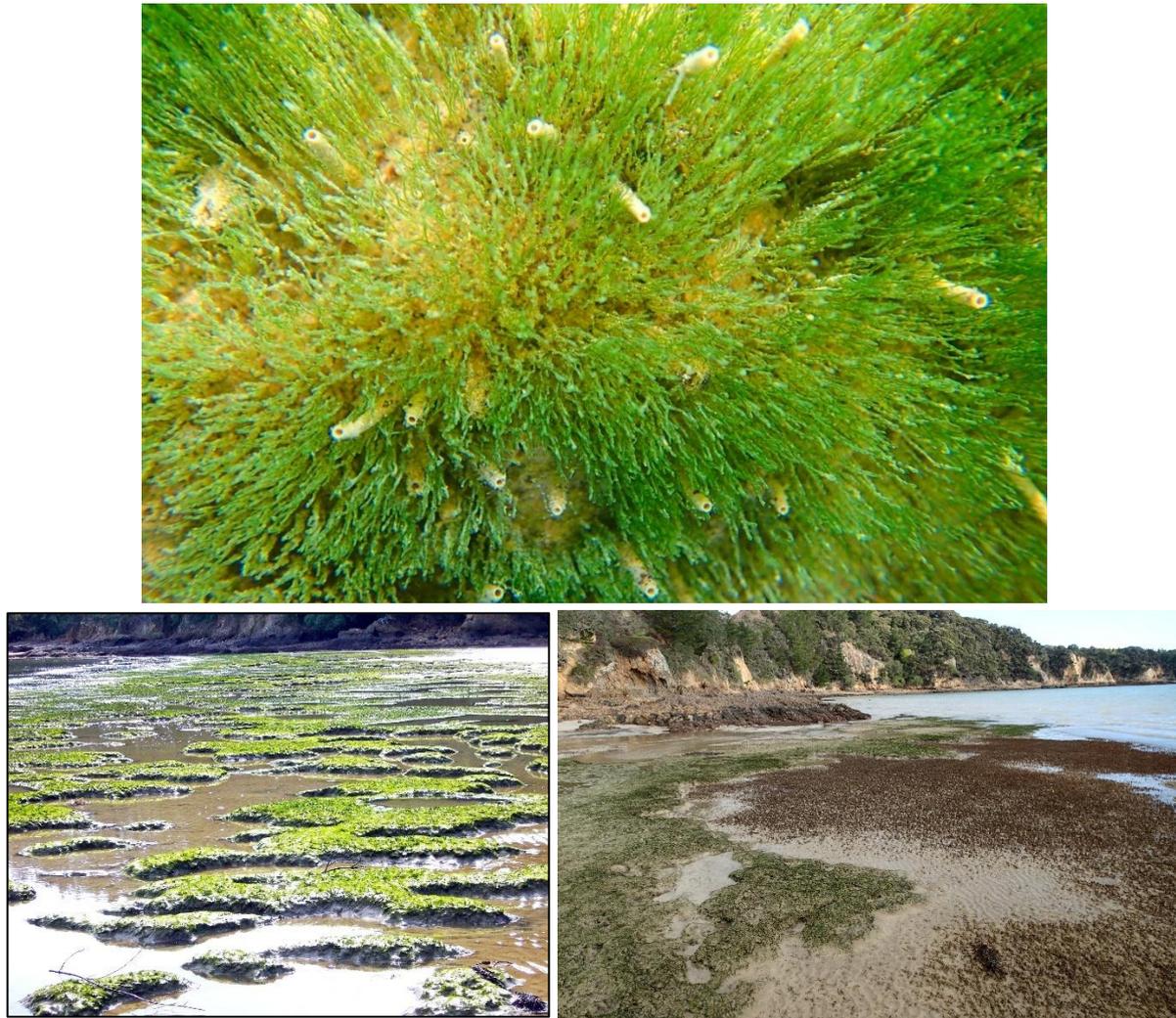
Figure 32: *Vaucheria* interspersed with worm tubes, from Omakiwi Cove in 2020 (upper). Differential growth/erosion in the beds can lead to patchy accumulation of fine silt in Omakiwi's low intertidal (lower left, 2013, when no seagrass was present), as well as loss of seagrass cover (lower right, 2020). (Images: author)

All of the several records of this alga from the intertidal of east Auckland have been on protected soft shores away from major freshwater sources. With manifestations between April and October, visible expression centred on winter is clearly suggested (Wilcox 2012) – although it is not clear whether any plant parts persist unseen at other times of the year. *Vaucheria* near Auckland typically grew 'on fine, grey mud towards and just below the low tide mark in sheltered embayments….', but in the eastern Bay of Islands it appears that the fine, grey mud is what had been *trapped* by the plant, rather than it being the parent substrate (author's unpubl. obs.).

Little is known of the ecology and recruitment of this alga in the eastern Bay of Islands, it possibly remaining unnoticed for years before reappearing. Since 2006, *Vaucheria* has been prominent in eastern-Bay of Islands' low intertidal in late-winter 2011 (Omakiwi and Hauai, but not Kaingahoa or Kaimarama), and winter 2013 and winter–spring 2020 (Omakiwi only). Only Kaingahoa has an essentially-permanent (and then most of the time trivial) freshwater source.

At Omakiwi Cove in winter 2020, *Vaucheria* was observed (perhaps for the first time in New Zealand) associated with the low-intertidal parts of dense beds of mainly subtidal seagrass. First noticed in early-June and observed about-monthly, the *Vaucheria* bloom led to localised silt build-up manifested as humps and bumps in the beach surface (Figures 32 and 33). Increased siltation in turn resulted in

fragmentation and mortality among the seagrass, the leaves browning and taking on the appearance of having been cropped (Figure 33; Appendix 12). In turn, considerable amounts of seagrass-leaf fragments accumulated higher on the beach. Meantime, the *Vaucheria* itself aged and all surface expression had disappeared by December.
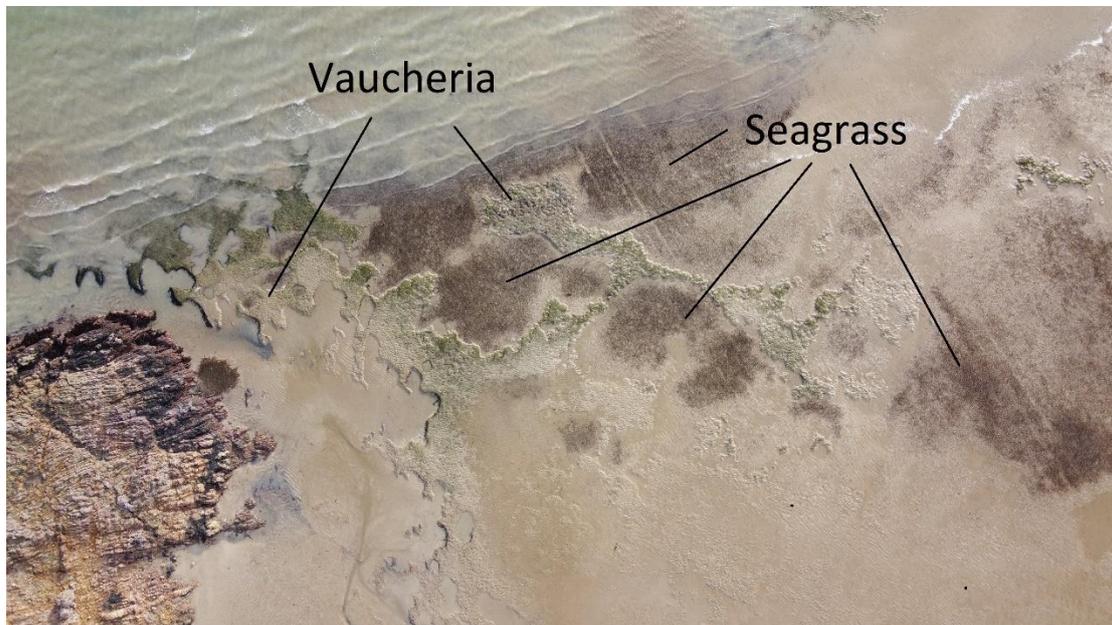

Figure 33: *Vaucheria* and seagrass (browning as it deteriorates) in Omakiwi Cove, July 2020; parallel lines are vehicle wheel tracks. (Image: Tim Booth)

7.1 Persisting threats

Physical damage to it and to the associated seagrass from vehicle movements lasts for months or more (Figure 33). Intuitively, invasive species, boat anchoring, sedimentation, and pollution – in addition to the general effects of climate change – are the main-other threats to the eastern Bay of Islands *Vaucheria* beds.

8. CHANGES IN INTERTIDAL AND SUBTIDAL SEAGRASS COVER

Seagrass beds/meadows are well-known for the breadth and complexity of their ecological roles (e.g., Morrison et al. 2014b; Anderson et al. 2019). In contrast to mangroves, no reference to seagrass was located among the many written accounts by nineteenth-century explorers of the Bay of Islands that might provide insight into the plant's historic distribution. Significant seagrass in the Bay of Islands today – and, apparently over at least the past half-century – occurs mainly subtidally around the islands of Ipipiri and on adjacent mainland shores in the eastern Bay, but also in a handful of other localities such as Hauparua Inlet. In contrast, intertidal seagrass has seemingly been represented over the same period only by small and often-transient patches on sheltered soft shores, although they have been fairly widely distributed throughout the Bay.

Seagrass meadows/beds are areas of continuous/dominant (>60%) plant cover within an area of at least 1 ha (10,000 m^2), and patches are <1 ha (Anderson et al. 2019: 30). In the Bay of Islands, beds and patches are 1) medium to high in the intertidal (often among mangroves); 2) low in the intertidal and not extending below extreme low-water spring (ELWS); 3) in the low intertidal at ELWS but also extending into deeper waters, to 6 m or so; and 4) entirely subtidal, to 6 m or more, and not visible intertidally even at ELWS (Figure 34). Here the plant's upbeach presence is most-often constrained by the nature of the substrate, in turn mainly a product of the level of exposure to winds and swells, together

with the size of the beach-surface particles (e.g., Turner & Schwarz 2006). However, results are reported here as 1 and 2 combined ('intertidal seagrass'), and 3 and 4 combined ('subtidal' seagrass).

Figure 34: Categories of seagrass cover, with 1 and 2 (upper pair, the left one among mangroves) combined as 'intertidal seagrass', and 3 (lower, the low-intertidal seagrass at Hauai extending to depths of about 4 m) as 'subtidal' seagrass. (Images: upper left – Chris Richmond, with permission; remainder – author)

Although the recall of long-time residents concerning the presence and persistence of seagrass is potentially a valuable source of information, the results of in-depth interviews made in the early-2000s concerning marine life in the eastern Bay of Islands were found not specific-enough to be instructive concerning *subtidal* seagrass cover (Mountain Harte et al. 2010). Instead, aerial imagery provided best insight, with field confirmation (ground-truthing) undertaken at various times by the author from 1980 to the present, and in 2009–10 (Matheson et al. 2010; Booth 2019). For *intertidal* seagrass, however, long-term memories seem to have been more reliable: on occasions, these could be confirmed through the aerial imagery, but because intertidal beds tend to show less-well than those subtidal, their full extent may have been underestimated.

8.1 Intertidal seagrass

Intertidal seagrass – as meadows or patches – appears not to have been of any particular note in recent living memory on Bay of Islands' mud/sand flats. This is surprising for it might be expected to have flourished in the same way it still does today in other northeastern embayments such as Houhora Harbour, 100 km to the northwest (MacDiarmid et al. 2009). Indeed, intertidal seagrass may have been of little overall significance in the Bay of Islands even as far back as the early-nineteenth century. For example, explorers of Kerikeri Inlet in 1826 included not only the missionaries referred to in Section 6.1, but also the Colonial Botanist of New South Wales Alan Cunningham and the naturalist Samuel Stutchbury (after whom the cockle is named), but it seems neither mentioned seagrass (Easdale 1991). Both men were struck by the scale of the cockle beds, and would surely – given their backgrounds –

have mentioned seagrass had it been prominent at the time. Nevertheless, almost certainly intertidal seagrass would have been – at least at times – widespread in a pristine Bay of Islands, mangroves having since come to occupy vast areas of the intertidal and leading to sedimentation of shores.

Based on long-term memories and aerial images, about 30 sites of intertidal seagrass provisionally identified Bay of Islands-wide for the 1950s had declined to nine by the 1970s (Figure 35, Appendix 13). In a Bay of Islands-wide survey in 1987, the single significant intertidal seagrass bed was in Parekura Bay (14.7 ha, none of which remains today; Appendix 14) (Walls 1987). And for the Ocean Survey 20/20 imagery, in 2009, only three small likely areas were identified (although they were not recorded by Hewitt et al. 2010).
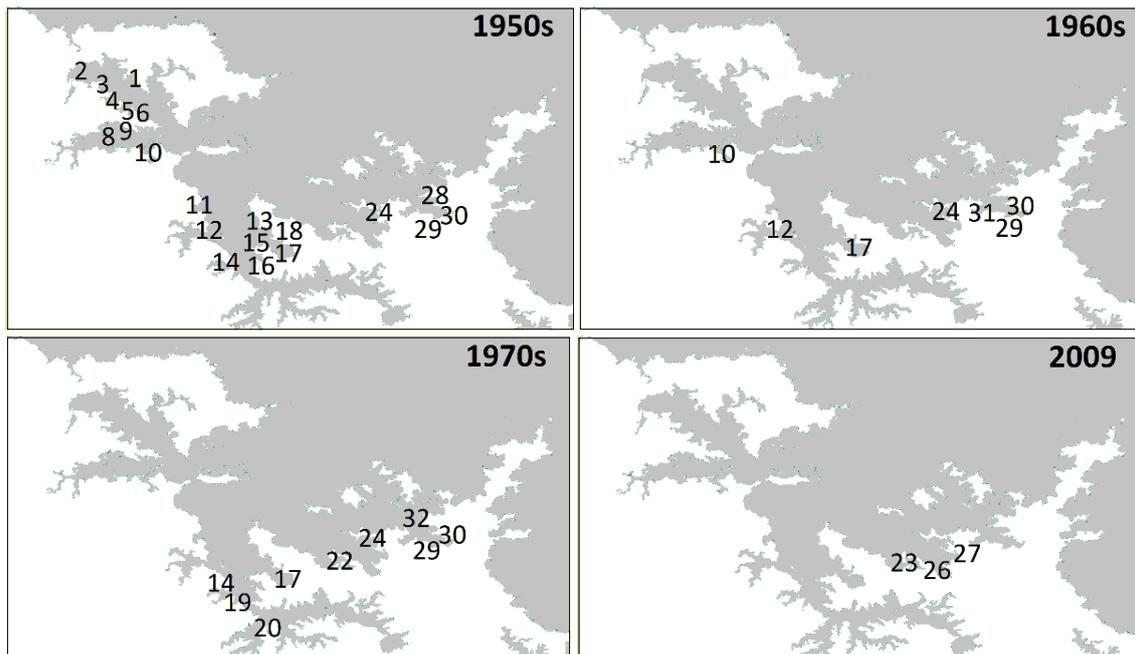

Figure 35: Early (1950s–70s), and 2009, possible and/or probable intertidal/shallow-subtidal seagrass patches in the Bay of Islands (but not including impingement into the low intertidal of the subtidal beds of the eastern Bay; *see* **Appendix 13 for details). (Maps: author)**

Today, apart from the subtidal beds of the eastern Bay of Islands that extend upbeach into the low midlittoral, intertidal seagrass appears largely confined to a few, mainly-small patches among mature mangrove forests, and on certain low shores (including Uruti Bay, the broader Wairoa Bay [near Waitangi] and Hauparua Inlet). Low-intertidal seagrass patches can be particularly transient: for example, significant patches (each ~30 m^2) that had established in Waipiro and Whiorau bays in January 2019 disappeared within 6 mo (author's unpubl. obs.). It is unclear how widespread seagrass among mangroves used to be (e.g., Morton & Miller 1968 apparently did not mention it), but because mangrove cover has been expanding and consolidating, this may represent a significant prospect for expansion intertidally of seagrass cover.

8.2 Subtidal seagrass

Almost all recent (post-1960s), confirmed subtidal seagrass beds of significance in the Bay of Islands have been confined to eastern parts. Here, there are 12 significant and recovering beds (some extending up into the low intertidal) around the islands of Ipipiri and along adjacent mainland shores, with several smaller, more-ephemeral patches (Hayward et al. 1981; Walls 1987; Hewitt et al. 2009; Matheson et al. 2010; Mountain Harte et al. 2010; Kerr & Grace 2015; Booth 2019, 2020) (Figure 36, Appendices 15–17). ('Seagrass habitat' in subtidal regions of the eastern Bay of Islands on the Northland Regional Council website is a mix of subtidal seagrass and algal turf; *see* Figure 41.) However, there is strong

evidence for significant subtidal seagrass, extending into the low subtidal, once occupying one or two other parts of the Bay of Islands – particularly Hauparua Inlet, near the entrance to Kerikeri Inlet (Figure 37, but not examined further here).
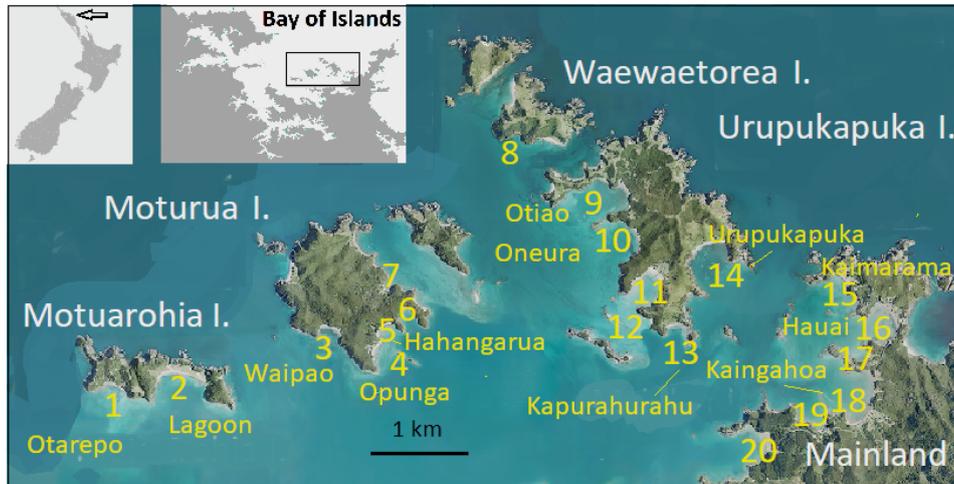

Figure 36: Seagrass beds of the islands and adjacent mainland shores in eastern Bay of Islands (Booth 2019). Major beds are 1, Otarepo; 3, Waipao; 9, Otiao; 14, Urupukapuka; 15, Kaimarama; 16, Hauai; and 18, Kaingahoa. Other smaller, but nevertheless enduring, beds are 2, Lagoon; 4, Opunga; 5, Hahangarua; 10, Oneura; and 13, Kapurarahurahu. More ephemeral/smaller beds and patches include 6, Awaawaroa; 7, Otupoho; 8, Otawake; 11, Otehei; 12, Sunset; 17, Oruruhoa; 19, Taiharuru; and 20, Omakiwi.

Because seagrass within a bed is typically patchy, in the analyses of change in areal extent over time in seagrass cover in relation to environmental parameters *density* of each bed was taken into account by using Area*% (Booth 2019). For each major subtidal seagrass bed there were 14–19 aerial observations, the earliest from the 1930s and spanning up to nine decades. Although plant-condition is important in the dynamics of seagrass, this is not readily assessed from aerial imagery. As it turned out, almost all images were from spring and summer, when this seagrass is typically most lush (Turner & Schwarz 2006; Matheson et al. 2009; Bulmer et al. 2016).
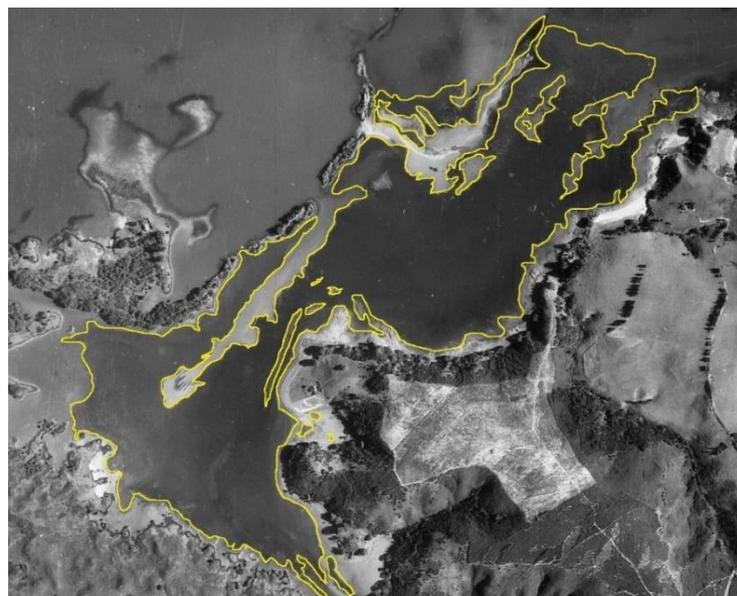

Figure 37: Subtidal (and low-intertidal) seagrass appeared to be extensive in Hauparua Inlet near the mouth of the Kerikeri in 1942 (Air Force Museum of New Zealand reference Tin 109 frame C3), although it is noted that in certain ways at least parts appear atypical.

The areal extent of footprint of the subtidal seagrass of eastern-Bay of Islands, as estimated from aerial imagery, has varied over time for both the island (from the 1930s) and the mainland beds (from the early-1950s) (Booth 2019). Subtidal seagrass was apparently largely absent until the mid- to late-1950s, rapid expansion in cover took place during the mid- to late-1960s, cover peaked in the late-1960s to early-1980s, many beds were at a nadir in the 1990s to early-2010s, and all beds have shown recovery since. Most are now at their maximum historical coverage (Figures 38 and 39; Appendices 15–17).
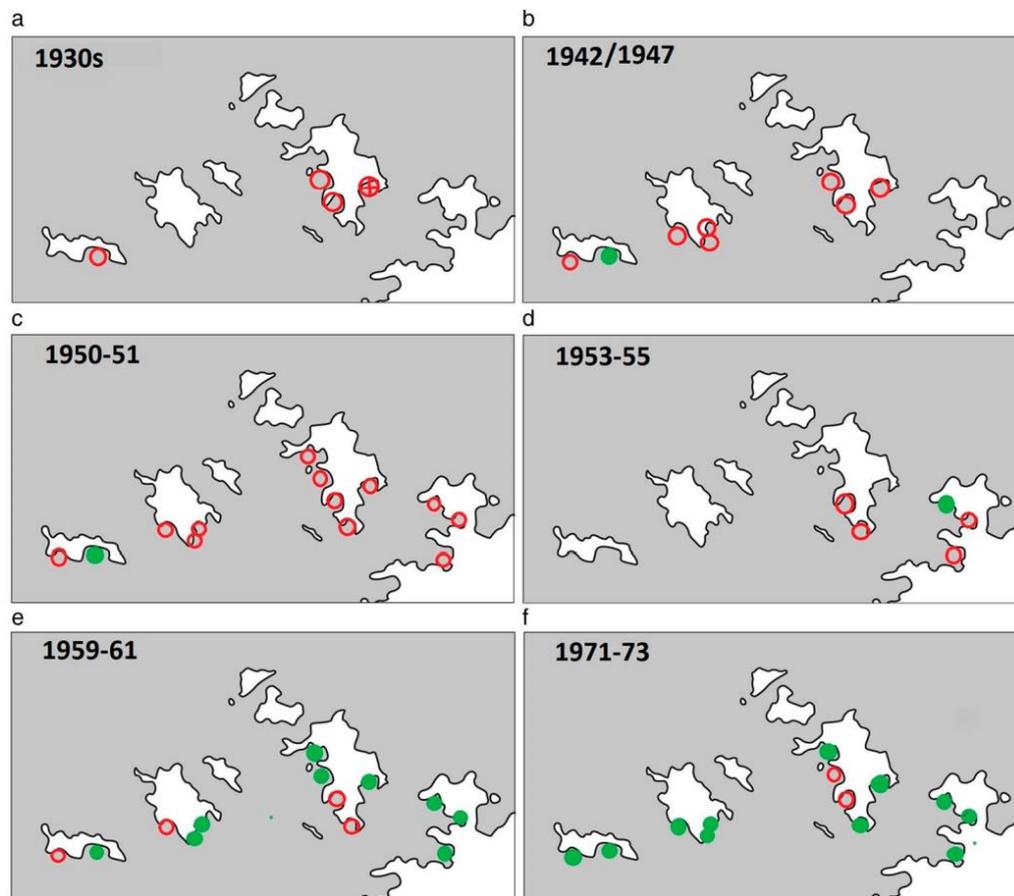

Figure 38: Apparent sequence of expanding spread of subtidal seagrass beds in the eastern Bay of Islands from the 1930s to early-1970s (this sequence also showing 11 Otehei Bay, for which – additionally – there was no subtidal seagrass visible in April 1952 or January 1958 [Appendices 15–17]) (Booth 2019). Red circle, no seagrass observable; red circle with cross, seagrass possibly present; green-filled circle, seagrass cover ≥ 20% of maximum; no symbol means no observation

For the islands, there were moderate levels of positive correlation in cover among south-facing beds (often P <0.10; Appendix 18), and higher levels for east-facing beds. In contrast, seagrass cover for the two west-facing beds was poorly correlated. For both, however, coverage rose from being low at the beginning of the time-series, to peak in the 2010s. For the mainland, there was significant positive correlation in coverage (all positive, P ≤0.10) among the three beds (Booth 2019).

The shapes of the curves of areal coverage for both the islands and the mainland were consistent with what were generally steady changes in surface manifestation of the seagrass over time once plants had become established (Figure 39). The first bed to show significant subtidal seagrass cover, in 1942, was Lagoon Bay (21% of maximum) on Motuarohia, which remains today one of the most enigmatic of all in that its typically small, multiple patches usually cover small portions of the bay and are often difficult to distinguish from areas of riddled pebbles. In contrast, nearby Otarepo Bay – today a prominent bed – was clear-cut: subtidal seagrass was not evident there until the early-1970s, and the same was true of Waipao and Kapurarahurahu bays on Moturua.
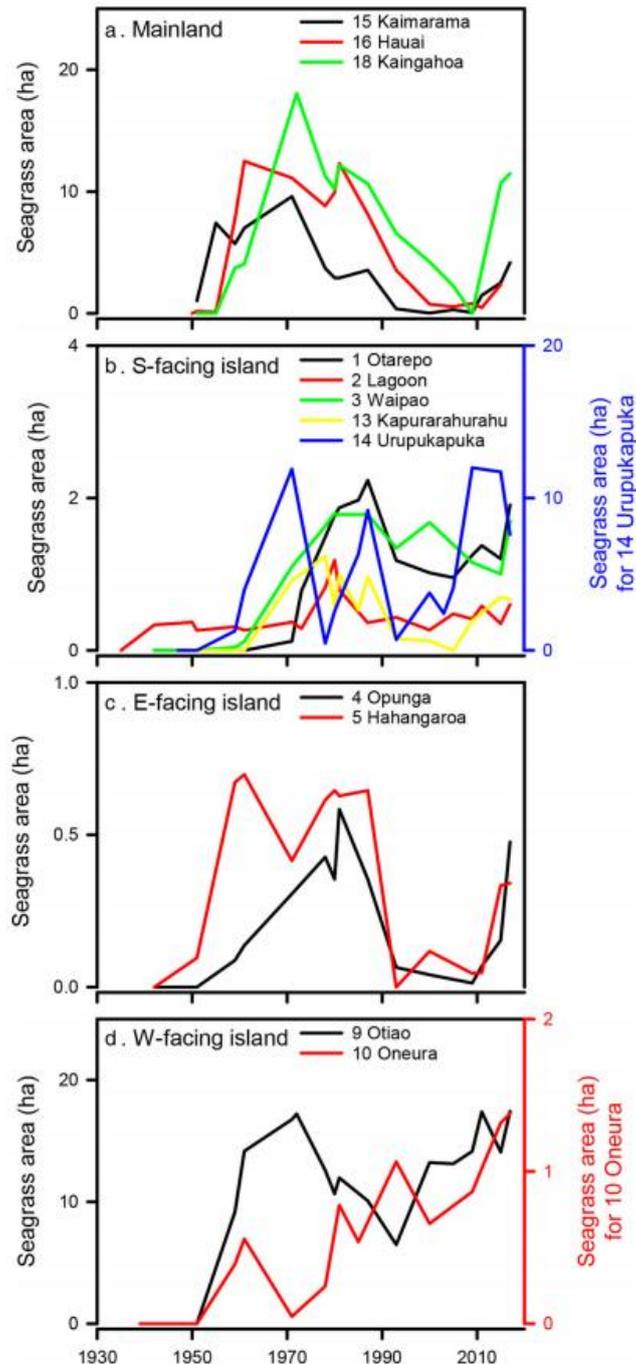
Figure 39: Graphs of subtidal seagrass Area*% cover (ha) for the Mainland beds (a), and beds on the islands south facing (b), east-facing (c) and west-facing (d) (*see* Appendix 16 for data) (Booth 2019). Seagrass areas should be read off the left vertical axes, except for 14 Urupukapuka and 10 Oneura which should be read off the right vertical axes.

Phases in the environmental history of the Bay of Islands likely to have had most bearing on this pattern of establishment and persistence of subtidal seagrass locally include (1) the periodic landscape burnings, starting around 1400 AD, led to only modest increases in levels of sedimentation (Swales et al. 2010, 2012); but (2) annual sedimentation rates increased enormously from the mid- to late-1800s and into the early-twentieth century following European settlement (Swales et al. 2012); and (3) water-clarity today is improving as land cover is re-established and silt-generating activities are better managed. Also pertinent are that (1) both the islands and adjacent mainland of the eastern Bay of Islands had little forest-cover from before the time of James Cook (late-1769) through into the early-twentieth century

45

(Salmond 1991; Alexander 2006), and twentieth-century human populations were small (Booth 2017); and (2) the construction of a coastal road in the 1960s, and its extension past Hauai (location 16 in Figure 36) in the early-1970s, brought about high levels of siltation (e.g., Alexander 2006: 308–315), which largely ceased with the sealing of the road in the early-2000s (Booth 2019).

During the 1960s to 2010s, there were significant positive correlations between the average planar extent of the three Mainland beds with air temperature, Southern Oscillation Index, rate of increase in forest-cover, and snapper spawning biomass (a potential proxy for predatory pressure on herbivores that keep seagrass clear of epiphytes). Also there were significant negative correlations with sunshine hours and the rate of increase in house-building (Table 4; Appendices 18 and 19). For mean seagrass cover on the five major South-facing beds on the islands, there were significant positive correlations with air temperature, the Interdecadal Pacific Oscillation Index, and snapper fishing-intensity; and significant negative correlations with mean sea level and snapper spawning-biomass (Booth 2019).

8.3 Synthesis

The observations strongly suggest that significant subtidal seagrass was not prominent in the waters of the eastern Bay of Islands between the first aerial images, in the 1930s, and the early-1950s (Figures 38 and 39). (This also applied to the ephemeral/small beds shown in Figure 36.) Some of today's most spectacular beds had not established until the early-1970s, more than 30 y after the first significant seagrass was apparent in the aerial imagery. Absence of seagrass in the early period may have been the legacy of highly turbid waters and high rates of sedimentation associated with the land clearances of the late-1800s (Booth 2019). Once subtidal seagrass had established, in the late-1950s to early-1970s, changes in sedimentation rates and sources, and variations in the ocean climate, appear to have had major parts to play in changes in areal extent.

The validity of the suggestion that there was little or no subtidal seagrass present in the eastern Bay of Islands from the 1930s until after the early-1950s is contingent upon accurate interpretation of sufficiently-high-resolution images taken under good lighting and water-clarity conditions. The early images available in which seafloor features are clearly visible (e.g., Appendix 17) indicate that little or no subtidal seagrass was present. The remarkable insight provided by the first systematic and extensive imagery, from the early-1950s – taken on the same days using the same cameras – gives confidence that little surface expression of subtidal seagrass was indeed present in the eastern Bay of Islands at that time (Appendix 17).

Possible explanations behind the notion that today's subtidal seagrass in the eastern Bay of Islands is recent (essentially post-early-1950s) include (1) freed from centuries of sporadic yet debilitatingly low levels of water clarity brought about by things like the presence of tannin-coloured waters in pre-human times, and combinations of tannin and silt – and high rates of sedimentation – in later times, seagrass has only fairly recently been able to establish in quantity; (2) seagrass was present until persistently-turbid waters associated with the late-nineteenth century/early-twentieth century forest-clearing and land disturbance, together with high levels of resulting sedimentation, meant that beds disappeared for decades, improved water clarity and lower levels of sedimentation having only recently led to their re-establishment; or (3) subtidal seagrass has essentially been present throughout, but there have been episodic and catastrophic changes in its surface manifestation because of things like disease outbreaks and periods of debilitatingly discoloured water, leading to scarcities lasting decades. On balance, it seems most likely that a combination of high levels of turbidity and heavy sedimentation associated with the late-1800s land-clearances brought about loss of much of the subtidal seagrass in the eastern Bay of Islands which has only recently – since the 1950s – been reversed.

Table 4: *rho* values for Spearman Rank Correlation Coefficient comparison of the mean % maximum cover of the Mainland and of the major South-facing beds on the islands (Figure 39) with various factors, for long and shorter time-series, with level of significance (*, P<0.1; **, P<0.05; ***, P<0.01; ns, not significant) (*See Booth 2019 for source references and for the methodology used to digitise the data*). Graphs given in Appendix 19 illustrate the associations. Location, site closest to the Bay of Islands for which data were available; East Northland, East Northland Substock of snapper; B_0, virgin biomass

	Factor	Proxy (at least in part) for:	Location	Source	Years	Correlation with Mainland beds (shorter period)	Correlation with S-facing beds (shorter period)
A	Air temperature	Sea surface temperature	NZ	Mullan et al. (nd)	1939-2004 (1959-2004)	0.63*** (0.48*)	0.66*** (0.45*)
B	Extreme wet day magnitude	Intolerably low salinities	Tauranga	Griffiths (2006)	1939-2004 (1959-2004)	ns (ns)	ns (ns)
C	Interdecadal Pacific Oscillation index	Wind strength & direction	NZ	Mullan et al. (nd)	1939-2000 (1959-2000)	ns (ns)	0.70*** (0.46*)
D	Southern Oscillation index	Wind strength & direction; water temperature	Auckland	Goring and Bell (1999)	1939-97 (1959-97)	ns (0.81***)	ns (ns)
E	Mean sea level	Extent of the shallow subtidal	Auckland	Goring and Bell (1999)	1939-97 (1959-97)	ns (ns)	-0.55** (-0.42*)
F	Sunshine hours	Optimum growing conditions	Whangarei	Anon (nd)	1972-2016	-0.42*	ns
G	Rate of increase in house-building	Silt/nutrient inflow; human population	Eastern Bay of Islands	Author's analysis of aerial images	1939-2015 (1959-2015)	-0.68*** (-0.86***)	ns (ns)
H	Rate of increase in forest cover	Silt inflow	Eastern Bay of Islands	Author's analysis of aerial images	1939-2015 (1959-2015)	0.47*** (0.35*)	ns (ns)
I	Snapper spawning biomass (%B_0)	Reduced abundance of keystone predators	East Northland	MPI (2017)	1939-2013 (1959-2013)	ns (0.68***)	-0.55** (ns)
J	Intensity of snapper fishing	Seafloor-damaging fish-harvesting practices	East Northland	MPI (2017)	1939-2013 (1959-2013)	ns (ns)	0.61*** (0.40*)

If significant subtidal seagrass is indeed a relatively recent biome then its spread was rapid – often achieved in years rather than decades. This is most likely due to the persistence of small and somewhat isolated – and from aerial images, undetectable – patches of surviving subtidal seagrass. Indeed, rapid development in the coverage of seagrass once environmental conditions improved has been observed in several recent overseas studies (Robert Orth, Virginia Institute of Marine Science, pers. comm. 2018). The rate of spread could have also been helped along by the transport of vegetative parts linked to the increasing numbers of vessels anchoring in the sheltered bays of the Bay of Islands over summers from the 1960s onwards, transporting rhizomes on their anchors.

Similarities in the curves of subtidal-seagrass cover over time on the mainland, and according to direction faced for the islands, are consistent with the mechanisms driving establishment and persistence of the seagrass affecting shorelines at reasonably broad scales. Both abiotic and biotic factors may have influenced this pattern (Table 4). Based on exploratory correlations, the most plausible explanations for the temporal pattern of seagrass cover for the Mainland beds include the rate of establishment of housing, together with the rate of increase in forest cover, presumably – respectively – increasing and reducing sediment-load from run-off. For the major South-facing beds on the islands, changes in the ocean climate (particularly air temperature and the Interdecadal Pacific Oscillation Index) appeared crucial. These associations might be further explored bay-by-bay using local climate data.

8.4 Persisting threats

Seagrass meadows are affected by 39 significant threats. Major threats include sedimentation, reclamation, benthic accumulation of debris from marine farms, causeway construction, and nitrogen and phosphorus loading (MacDiarmid et al. 2012: 44; Morrison et al. 2014b; Anderson et al. 2019); and 23 others have moderate impacts. For the eastern Bay of Islands specifically, land-derived siltation – probably in combination from time to time with anthropogenically-derived enrichment of waters – has been invoked as the major factor in the trajectory in extent of the subtidal beds (Matheson et al. 2010; Booth 2019). Boat anchoring and propeller-wash damage can also be damaging (Figure 40), the impression being that persisting propeller-wash has greater and longer-lasting effects than anchoring. For example, thousands of boat-anchor nights take place every summer in Otiao Bay yet the beds – although scarred – remain vibrant. Vehicle movements over intertidal seagrass has direct and lasting impacts, remaining visible for months or longer (e.g., Figure 33). The Bay of Islands beds are probably not under significant threat from recreational scallop-dredging: the thick meadows would quickly foul dredges. However, regenerating tufts and patches adjacent to the main beds may be prone to dredge damage.

Figure 40: Anchor-drag damage at Otiao Bay (left – straight whitish lines arrowed) and propeller-wash damage at Otarepo Bay (right – area clear of seagrass at wharf-end). (Images: Ocean Survey 20/20)

9. CHANGES IN BIOLOGICAL CHARACTERISTICS OF SHALLOW SOFT SEAFLOORS OF IPIPIRI PLATFORM

This section summarises current understanding around present and recent-past distributions of biological communities on the shallow (≤10 m deep) soft seafloors of Ipipiri Platform in the southeast of the Bay of Islands (Figure 10). This understanding is underpinned by exploratory snorkel observations in Poroporo Channel in February 2020. The shallow waters of Ipipiri Platform stand out in being visually dominated (underwater and in aerial imagery) by 1) meadows of red-algal turf (a reasonably-common [although rarely-characterised; Anderson et al. 2019]) soft-sediment biome that is physically stable; interspersed with 2) subtidal seagrass patches that have, in contrast, shown considerable variability in planar cover over time; together with 3) areas of apparently-featureless sand and sand/shell mix. Algal meadows are defined as stands of one or more key species growing over sand, shell or cobble substrates which may or may not be attached to the substrate, and which provide ≥35% cover over an area of ≥10 m^2 in seabed imagery (Anderson et al. 2019: 68). They provide low-lying three-dimensional structure that can stabilise sediments and also low-lying canopy cover for a variety of invertebrates and fishes (e.g., Anderson et al. 2019: 68).

Although similar algal-turf seafloors appear to exist elsewhere in the Bay of Islands (being particularly associated with the mainland from Paroa Bay to Albert Channel, and including Manawaora Bay – Figure 1; Ocean Survey 20/20 imagery), none is as extensive as those on Ipipiri Platform. Indeed, the Platform today probably contains the highest diversity and concentration of subtidal biogenic communities within the entire Bay of Islands. This diversity is presumably brought about by the relatively-shallow and silt-free seafloors, the gradients of sea exposure and associated seafloor types, the clear and clean waters, and – in many places – reasonably-strong tidal currents. In turn, these waters underpin what is probably the most-widely-promoted tourist representation and allure of the Bay of Islands today whereby not only people on boats and from the air draw wonderment, but swimmers, kayakers and divers are inspired too.

Although no Ocean Survey 20/20 (or other) bottom-sediment cores or sediment-settlement-plate observations for Ipipiri Platform were located, it seems that this area has undergone far-less shoaling than have the margins of inner parts of the Bay of Islands. On Ipipiri Platform, the 2.5 fathom line in 1849 appeared to be spatially close to the 5 m contour of today, 170 y on (Figure 10, intervening charts being consistent). With no significant tectonic activity, and a mean annual sea-level rise of ~1.4 millimetres, this indicates little or no accumulation of silt on shore margins, and suggests resuspension and transport seaward of silt that does arrive.

9.1 Distribution of habitats

Aerial imagery confirms a great deal of physical and biological complexity among the shallow soft seafloors of Ipipiri Platform today, as well as in the recent past (e.g., *see* Figure 45 [2020]). Although there has not yet been extensive, in-depth analysis of this diversity, sufficient observations have been undertaken in the past, and recently, to allow broad characterisation of these ecosystems. Sediments at depths ≤10 m on the Platform today are predominately coarse sand with shell hash through to fine sand and mud (e.g., Hayward et al. 1981; Morley & Hayward 1999; Hewitt et al. 2010; Kerr & Grace 2015; Froude 2016; recent nautical charts; author's unpubl. obs.), and this seems to have been the situation since at least the 1950s according to what can be inferred from the aerial imagery (author's analyses, not shown).

The generalised habitat map for the Bay of Islands (Figure 11; Kerr 2009), and the more-detailed map focusing on Waewaetorea Island (Figure 12; Kerr & Grace 2015), provide broad overviews of the seafloor characteristics and communities by depth zone for Ipipiri Platform. Among the soft substrates identified by Kerr & Grace (2015) were biogenic seafloors – particularly subtidal seagrass and an extensive red-algal turf zone. And, based on the 2009 Ocean Survey 20/20 imagery, Northland Regional Council's   Richard   Griffiths

(https://localmaps.nrc.govt.nz/localmapsviewer/?map=55bdd943767a493587323fc025b1335c) showed that 'Seagrass habitat' – a combination of algal turf and subtidal seagrass – occupied significant proportions of Ipipiri-Platform waters <10 m deep (Figure 41).
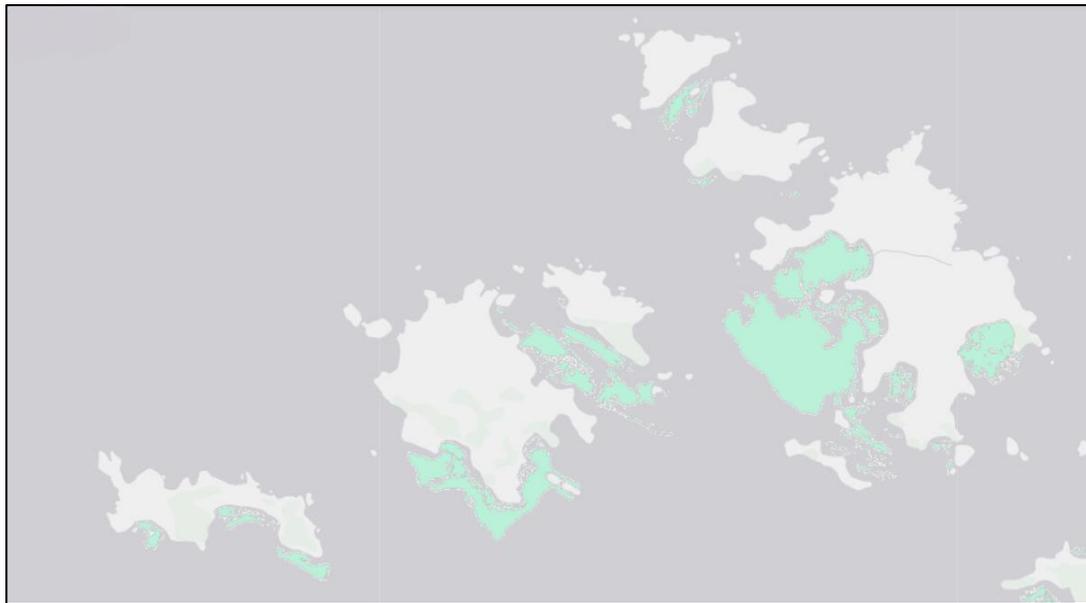
Figure 41: Distribution of 'Seagrass habitat' (algal turf and subtidal seagrass, combined) on and near Ipipiri Platform interpreted from the 2009 Ocean Survey 20/20 imagery. (Map: Northland Regional Council)

An area off southern-Urupukapuka Island was, in 1980, the focus of relatively fine-scale studies of seafloor habitats and communities (Hayward et al. 1981; Appendices 20 and 21), particular combinations of co-occurring taxa being assigned to specific community assemblages. It appears that the distribution of various sediment types (and presumably the accompanying biological communities) has changed little over the following 30–40 y, based on seafloor features and depth contours of the modern chart and seafloor features visible in the 2009 Ocean Survey 20/20 imagery (Appendix 21).

Ocean Survey 20/20 observations of soft-seabed biodiversity on Ipipiri Platform were limited (Figure 42) but did include 1) about a dozen soft-sediment, biological point-samples, these being dominated by patchy algae, rhodoliths and subtidal seagrass (Hewitt et al. 2010); 2) a handful of macroalgal reef point-sampling sites (Nelson & D'Archino 2010); and 3) dive, baited underwater video, and deep-water video assessments of fish communities (Jones et al. 2010).
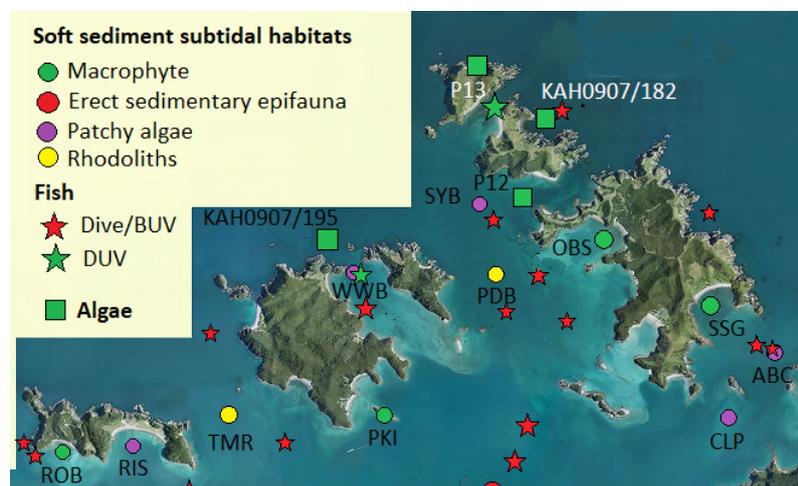
Figure 42: Ocean Survey 20/20 biological sampling of Ipipiri Platform was limited (see text). (Map: author)
Biological communities associated with the shallow waters of Ipipiri Platform observed by previous workers are summarised as follows.

Attached algae Attached algae living on soft substrates have been quite-widely reported in the Bay of Islands, albeit in a very general manner. On Ipipiri Platform, Hewitt et al. (2010) reported patches of red algae (also sparse *Codium fragile*, *Caulerpa flexilis* and *Carpophyllum* sp.) to be reasonably widespread. Later, Morrison et al. (2014: 35, 117) reported red algae in Te Rawhiti Passage; Kerr & Grace (2015: 32) found widespread red-algal turfs dominated by small foliose red-algae species on soft bottoms inshore of Waeweatorea and Urupukapuka islands (Figure 12); and Froude (2016) reported corallines and *Caulerpa* at sampling station 623 in Albert Channel. Indeed, Hewitt et al. (2010) surmised that an apparent algal-turf ubiquity meant fewer subtidal soft-sediment habitats defined by beds of suspension-feeding bivalves and sponges being present in the shallow soft seafloors of the Bay of Islands than in many other parts of New Zealand.

Unattached algae Unattached algae of note on Ipipiri Platform include living and dead rhodoliths, and detached calcareous algal debris. Rhodoliths (maerl) are free-living non-geniculate (lacking uncalcified joints) coralline algae (Farr et al. 2009) found subtidally in areas where coarse sand, gravel or shell debris dominate – often in areas with strong currents – and are known for their high diversity and numerous ecological services (e.g., MacDiarmid et al. 2013: 44). Rhodoliths have been reported in many places on and near Ipipiri Platform: Albert Channel (Hayward et al. 1981: 113); Te Rawhiti Inlet (Appendix 20); Te Miko Reef and off Kahuwera (Appendix 22, mainly *Lithothamnion crispatum* [previously *L. indicum*] and *Sporolithon durum*: Hewitt et al. 2010; Nelson et al 2012; Neill et al. 2015; and Froude's 2016 stations 632 & 633); inside Waewaetorea Island (Kerr & Grace 2015: 33); and in Poroporo Channel (Appendix 23).

Morning star shells (Tawera) The morning star shell *Tawera spissa* is a defining species in certain northern waters, forming beds up to 1.5 km^2 or more, and reaching densities of at least 3500 m^{-2} (Taylor & Morrison 2008; Morrison et al. 2014a). It is also a species that can exhibit large population changes over time (e.g., Hayward et al. 1997). Beds of abundant Tawera have been reported on Ipipiri Platform off Urupukapuka Island (Hayward et al. 1981, where they were the characterising species of one particular community); in Okahu Channel (Kerr & Grace 2015); and more generally (Hewitt et al. 2010).

The abundant Tawera valves cast-up on the shores of Ipipiri, and the widespread Tawera-shell hash in shallow waters there, point to this bivalve being a major component (numerically and in biomass) of the shallow-water, soft-bottom biodiversity of Ipipiri Platform.

Robust dog cockles The robust dog cockle *Tucetona laticostata* is often associated with rhodoliths (e.g., Morrison et al. 2014a: 59), and their shells may collect in large post-mortem deposits (Dewas & O'Shea 2012), which in turn become important long-lived biogenic features of the seafloor. For Ipipiri Platform and nearby, they have been reported live off Urupukapuka Island (Hayward et al. 1981); generally over the Platform (Hewitt et al. 2010); at Te Miko Reef/Kahuwera (Nelson et al 2012; Neill et al. 2015); southwest of Urupukapuka Island; and in Albert Channel (Froude's [2016] Station 623; author's unpubl. obs.).

Valves of this shellfish are commonly encountered in shallow waters of Ipipiri, and in places form large drifts on the shore (Figure 43). It is almost certainly abundant in places, but the robustness and longevity of the shell means its abundance as living bivalves may be prone to overstatement.

Figure 43. Robust dog cockles valves – many appearing reasonably fresh – have for at least the past decade formed extensive swathes of shell hash on certain shores of Manawaora Bay. (Image: author)

Scallops Scallops *Pecten novaezelandiae* can be important biogenic components of subtidal soft bottoms, providing structural habitat for other epifauna. They are also well-known for their high interannual variability in population size (e.g., MPI 2019: 410–411). Overall, Bay of Islands scallops are heavily fished, and appear to occupy in any significant quantities a much-reduced geographic distribution compared with 20–30 y ago (Booth 2017: 53). Early reports of scallops on or near Ipipiri Platform include Hayward et al. (1981) and Morley & Hayward (1999) (Appendix 20).

The principal scallop beds in the Bay of Islands over the past 12 y have been in the area of Ipipiri, mainly 1) Albert Channel between Urupukapuka Island and the Rawhiti mainland (including Urupukapuka Bay); 2) the area between Paramena Reef, Poroporo Island and Ngatokaparangi Islands/reefs to the south of Motukiekie; and 3) Motukiekie Channel between Urupukapuka and Motukiekie Islands (Pacific Eco-logic Ltd. 2016). Population and other surveys of these beds indicate high interannual and spatial variability in abundance (Williams et al. 2008; Williams 2009; Hewitt et al. 2010). However, the impression today is that scallops are a minor component of the biodiversity of Ipipiri Platform.

Horse mussels The horse mussel *Atrina zelandica* occurs from extreme low water down to depths of at least 45–70 m. They can form densely-packed beds extending over hundreds of metres that typically support diverse species assemblages (Morrison et al. 2014a: 53–55). Recruitment is typically highly variable between years, leading to beds appearing and disappearing over decadal time-scales (e.g., Hayward et al. 1997; author's unpubl. obs.). Stations in the Bay of Islands from which Morley & Hayward (1999) recorded horse mussels in the 1990s were confined mainly to the southeast, as were those during the Ocean Survey 20/20 sampling (Figure 44; Hewitt et al. 2010: 35-37); Nelson et al. (2012: 22) found scattered individuals among the Kahuwera rhodoliths; and Froude (2016) reported horse mussels east of Motukiekie Island, at Station 622. Overall, it appears that horse mussels have in recent years been a minor component of the biodiversity of Ipipiri Platform itself, the greater densities occupying the deeper waters of Te Rawhiti Inlet (Figure 44). Even embedded dead shells are rarely encountered on the Platform.
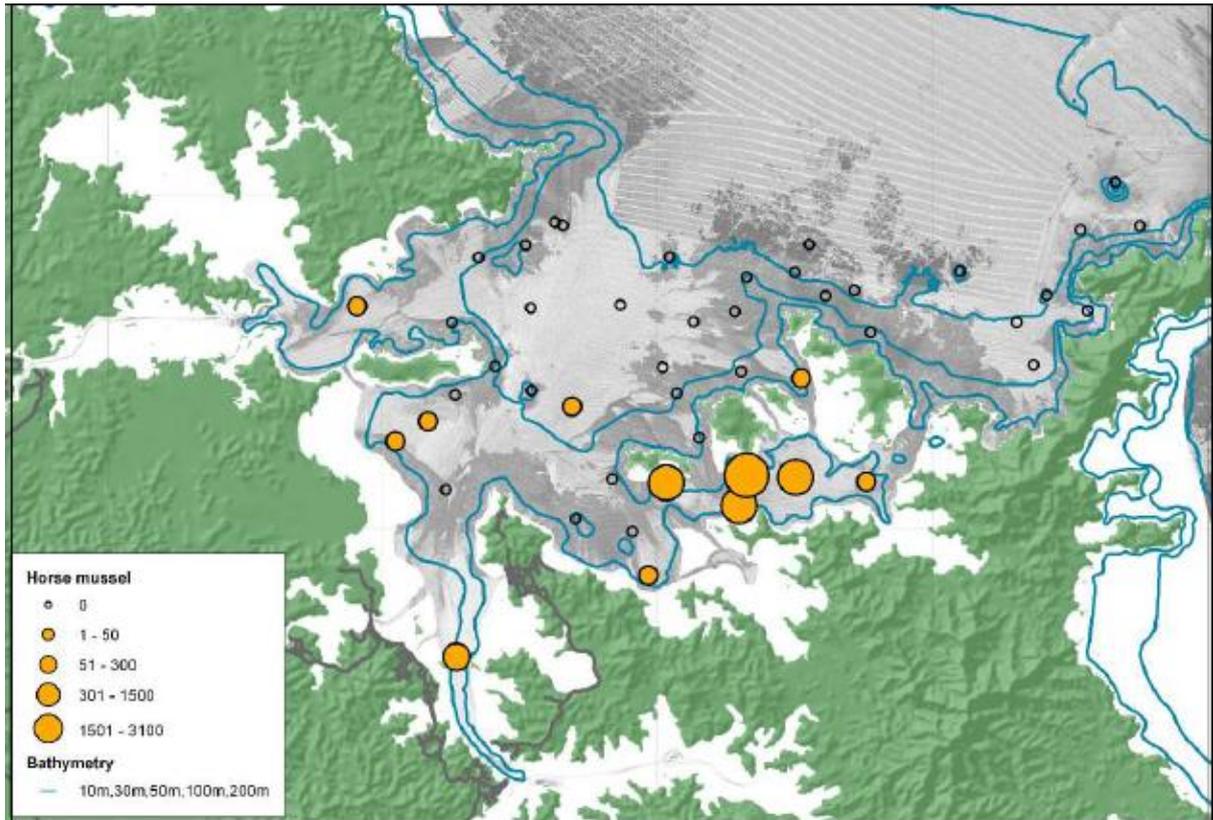
Figure 44: Distribution of horse mussels in video transects within the Bay of Islands during the 2009 Ocean Survey 20/20. The highest densities were in Te Rawhiti Inlet, and associated with sediments consisting of accumulations of shell hash and rhodoliths (Bowden et al. 2010).

9.2 Case study: soft-bottom biological communities of Poroporo Channel today

Preliminary ecological observations of waters 2–5 m deep in Poroporo Channel in February 2020 showed that soft seafloors were dominated by red-algal turf (mostly corallines), the beds of which typically appeared fragmented/dissected in the aerial imagery (Figures 45 and 46), and patches of subtidal seagrass, over areas of apparently-featureless coarse sand (Appendix 23) (Booth & Booth 2020). Most-obviously amongst the red-algal turf were patches of shell hash (especially the valves of Tawera, but also robust dog cockles, these presumably representing incumbents recently/presently living in the area). Unattached algae were dominated by small living and dead rhodoliths, coralline-algal hash, and accumulations of *Hydroclathrus* (presumably *clathratus*) (Appendix 23).
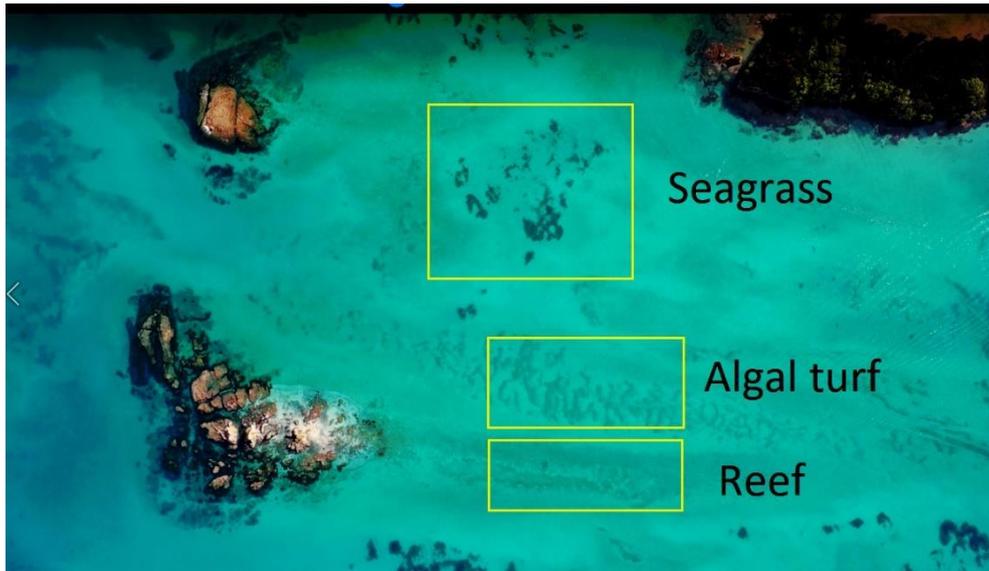
Figure 45: Shallow soft seafloors of Poroporo Channel, 2020. (Image: Tim Booth, with permission)

Worms, evidenced by mounds, holes and depressions in the sand, as well as protruding siphons and remnant casts, were abundant, particularly among the turf (Appendix 23). 'Leathers' of the chaetopterid polychaete *Chaetopterus* were common, particularly in areas associated with seagrass. Sponges seemed noticeably absent.

Distribution of the three main habitats (algal turf/subtidal seagrass/sand) in Poroporo Channel appears to have remained remarkably stable over the past 40 y. The most conspicuous change was in the extent and distribution of the seagrass. In 1980, seagrass occurred more-widely than in 2009, being similar to that suggested in 2020; and in all years the signature of the algal turf showed strongly in essentially the same parts of the channel (Appendix 24).

Figure 46: Representative image of shallow (to 5 m depth), soft-bottom red-algal-dominated biome in Poroporo Channel in February 2020 (also *see* Appendix 23). (Image: Tim Booth, with permission)

9.3 Persisting threats

Shallow (2–9 m) areas of sand on sheltered coasts are affected by 36 significant threats, they being particularly vulnerable to the effects of ocean acidification (MacDiarmid et al. 2012: 46). Threats with major impact are sedimentation, bottom trawling, shellfish dredging, increased sea temperature, sand and gravel abstraction, and increased turbidity. A further 16 were judged to be modest. Threats were similar for shallow areas of gravel, pebbles and shell habitat on sheltered coasts (MacDiarmid et al. 2012: 46). For Ipipiri Platform, sedimentation and increased turbidity are probably the key immediate pressures on biodiversity.

Algal meadows and associated communities may be impacted in particular by invasive species, boat anchoring, sedimentation, fishing and pollution, together with the general effects of climate change (Anderson et al. 2019: 72). Scallop dredging could be extremely destructive in the Bay of Islands, should it become more intense and/or widespread. Because they are subsurface, Tawera and dog cockles may be less-affected by light recreational dredges than surface-living biota. In contrast, species that emerge above the seabed, such as horse mussels, may be very vulnerable to being removed, dislodged, broken or knocked sideways *in situ* by dredging. Further, removal of dog-cockle shell debris may significantly reduce the biodiversity associated with relict-shell habitats (Anderson et al. 2019: 126).

The greatest physical threat to rhodolith beds comes from dredging (Nelson et al 2012: 66–67, although damage caused by anchoring of vessels can also be significant), and because they are long-lived and slow-growing they have limited ability to respond to or recover from damage or burial (Neill et al. 2015: 63). But at least the beds at Kahuwera Bay and Te Miko Reef appear not, so far, to have been unduly impacted by dredging or other fishing (Nelson et al. 2012).

Although there has been no commercial dredging of any sort for years in the Bay of Islands (and then, apparently, only at low levels; Booth 2017) – scallops have been, and still are, dredged recreationally. Although it is thought to be presently undertaken almost entirely in the southeast among the islands of Ipipiri and near adjacent mainland shores, dredging is spatially and temporally unrestricted.

Dredging involves towing a mesh-socked frame across the ocean floor to sift out targeted species and is typically more-invasive and less-selective than most other bottom-trawl-type operations (Beentjes & Baird 2004). The effects of commercial scallop-dredging on the benthos are relatively-well studied, including for the northern-New Zealand scallop grounds (e.g., Thrush et al. 1995; Ministry of Fisheries 2007; MPI 2019: 413), with examples of the variety of bycatch given by Williams et al. (2010). Generally, with increasing fishing intensity there are decreases in the density and diversity of benthic communities and, especially, the density of emergent, often-fragile epifauna that provide structured habitat for other fauna. Further, habitat complexity is reduced as sediment is blended to become similar over large areas, rather than there being pockets of different sediment types.

The physical seabed impacts of *recreational* scallop dredging are believed to be essentially the same as for commercial dredging, even though the dredge is much smaller and lighter (typically ~5 kg, with a mouth-width of about 60 cm; Figure 47). NIWA's mid-1990's study of the impact of recreational scallop dredging in the Hauraki Gulf concluded that "experimental dredging using standard northern "box" type recreational dredges failed to demonstrate any adverse effects on scallop incidental mortality, growth rates, or fecundity…." (Ministry of Fisheries 2007: 35), but – remarkably – the study seems not to have considered the *impacts* of recreational dredging on the seafloor biodiversity. Although the bycatch of epibenthic species such as sponges, ascidians, and starfish was noted, and there was 'extensive raking of the seafloor', the report simply speculated that the potential loss of habitat structure and non-target species might be significant in areas heavily dredged by recreationalists. Such impacts are likely to have been ongoing for several decades or more, and the animal and plant assemblages present seen now may not be representative of what used to be there (Morrison et al. 2010). Since then, however, more definitive statements have been forthcoming: 'There is no doubt that [recreational dredges] damage seafloor assemblages – some heavily fished gravel areas in Kawau Bay

look like bare Zen gardens from all the dredge passes' (Mark Morrison, NIWA, pers. comm. January 2020).
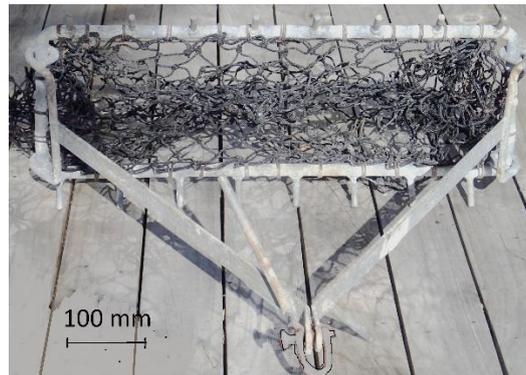

Figure 47: A typical recreational scallop dredge of the type used in the Bay of Islands, weighing ~5 kg. (Image: author)

Information on recreational dredge-use for scallops in New Zealand, in general, is sparse, and the proportions of scallops harvested using dredges, against diving, appear to vary considerably by region (e.g., Ministry of Fisheries 2007: 35; Wynne-Jones et al. 2019). Korero with Bay of Islands-local scallop fishers, and with members of *Fish Forever* (a local community group focussed on conservation of marine biodiversity in the Bay; https://www.fishforever.org.nz/), suggest that free diving and scuba diving are by far the most-used methods to recreationally harvest scallops. Apparently no physical indications of dredging were noted in the DTIS survey (Bowden et al. 2010), and the author was unable to find any signs of it in the November 2009 Ocean Survey 20/20 aerial imagery. However, other images point to dredging potentially having had some, possibly limited, impact on the nature of the seafloor in certain parts of the eastern Bay (e.g., Figure 48). The presumed dredge paths typically take the form of a narrow line passing through dark-coloured biogenic seafloor features, in situations where there seems to be no other plausible reason for the marks. In such instances, the dredge would have fairly-soon filled and become unmanageable. Tows over sand, however, are less likely to have left an aerially-visible signature so use of this imagery is likely to be underestimating recreational dredging effort and impact. The time required for damage to Bay of Islands' biogenic seafloor features to reverse is unknown, but the nature of the seafloor biota suggests it is likely to be months, if not years.
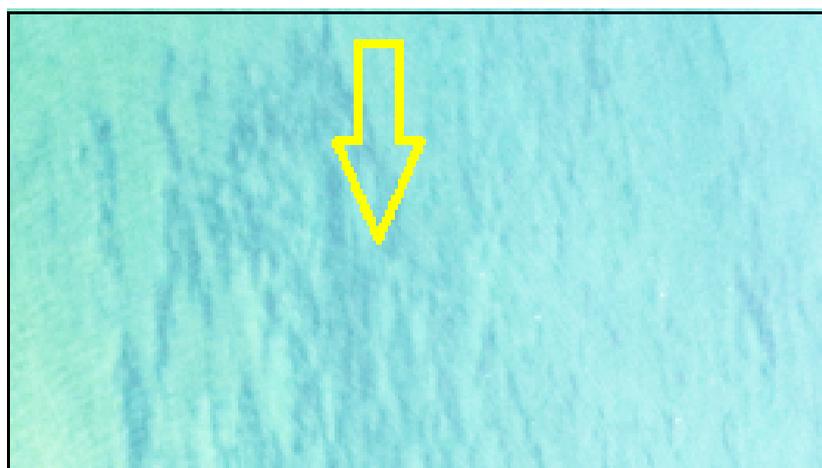

Figure 48: Likely example of recreational scallop-dredge track through biogenic seabed in Motukiekie Channel. (Image: Lara.Kay Photography, with permission)

10. GENERAL DISCUSSION

Drawing on data little-used in ecological studies, such as the contents of middens, together with more-mainstream approaches like analysis of aerial imagery, this review has characterised shallow soft-bottom communities of a northern-New Zealand embayment, and the ecological changes in them over time. The analyses point to dynamism – rather than stability – over recent decades for most shallow soft-bottom communities of the Bay of Islands, human-induced runoff of terrigenous silt being the main driver. Because sedimentation can be seen as essentially irreversible, it trumps the impact of seafood overharvesting (as seen for example in the widespread development of shallow-reef sea-urchin barrens in the Bay) that is often thought of as being reversible (e.g., Ballantine 2014). There will also have been ecological shifts in response to natural cycles in the climate, but these have been imperceptible under current technologies and knowledge – as have been any changes brought about by human-induced climate change (warming waters, rising sea levels and ocean acidification). High and chronic levels of sedimentation have, accordingly, been the most important and enduring contributors to ecological degradation here, a situation apparently replicated widely throughout similar water bodies in northeast-New Zealand.

Most changes in the Bay of Islands brought about by sedimentation are ecologically adverse, having destroyed ecosystems, reduced biodiversity, and threatened uncommon habitats. Impacts of fluxes of terrigenous sediment have been catastrophic (far-reaching, persistent, and seemingly irreversible) on its shallow-water ecology, with remarkably long lags between stressor emergence and realisation of impact. Just as it took decades of heavy fishing pressure on keystone predators for the sea-urchin barrens on the shallow rocky reefs of the Bay of Islands to become the obvious biome of today (e.g., Booth 2016b, 2017; Froude 2016), and apparently a century or so for seabed conditions to improve sufficiently for the subtidal seagrass beds in the eastern Bay of Islands to recover (Booth 2019), so it has taken more than a century for mangroves to establish on many sheltered soft shores after the land clearances beginning in the late-nineteenth century. In an ongoing ecological cascade, mangrove spread has impinged on threatened habitats such as saltmarsh, uppershore coarse-sand/shell beaches and spits, and (probably) intertidal seagrass. Simultaneously, previously-productive shellfish beds have been eliminated by deposition of fine silt. The extent of expansion, and the continuing spread, of mangroves in the Bay of Islands is such that – unless urgent action is taken – naturally-rare ecosystems such as coarse-sand/shell upper beaches and cheniers will be lost altogether. Indeed, it is arguably indefensible to allow mangroves to take over essentially all sheltered soft shores, obliterating other native biodiversity and ecological functioning. Allowing – even requiring – removal of seedlings in certain situations might be the appropriate management approach. Afterall, landscape-scale manipulation of terrestrial native biodiversity is commonplace in New Zealand, for instance in the purposeful planting of native trees in order to encourage use by native birds and invertebrates.

Some of our most useful insights into the status of the cockle stocks of the Bay of Islands derive from Māori middens, midden-cockle size, abundance and ubiquity pointing to extensive, enduring and particularly rich resources of this bivalve in at least late pre-Contact times (Booth 2016: 78). Moreover, with a documented history going back to the early-1800s, information around the early-post-Contact period cockle resources of the Bay of Islands (and in particular Kerikeri Inlet), when cockles had become a dietary staple in the region, may be among the most detailed available. Yet today, local cockle populations appear degraded, individuals no longer achieving the same sizes or ages they once did.

Productivity and vigour in living bivalves is typically assessed using multiple lines of evidence, including data concerning age and size attained, growth rate, condition index (mass of tissue relative to shell), biochemical composition, and levels of parasites and disease – but only the first two can be applied to archaeological cockles. Not only has recent sedimentation in Kerikeri Inlet (apparently since the mid-1900s; Booth 2020) led to ~50% loss of cockle habitat, mostly nearshore, but also the cockles present today are small, even though the shellfish are apparently as productive over the first few years of their lives as they were 200 y ago (their early annual growth-increments being indistinguishable). On the margins of Kerikeri Inlet today, deep, fine silt appears to altogether prevent cockles establishing, while presumably-compromised cockles further offshore succumb within ~4 y (and a size of ~35 mm).

Further, the significant numbers of surfaced cockles present possibly suggest high parasite infestation, or the effects of some other contagion or debilitating phenomenon. These presumably-challenged cockles may be less-resilient to other infection, leading most to succumb when they are small and young. Novel viruses (or degraded conditions that can lead to incumbent viruses taking greater hold) cannot be discounted as possible contributors to cockles apparently dying young in at least parts of the Bay of Islands.

Moreover, a drastically-reduced mean shell size seems to apply to many if not most of Northland's significant cockle beds, with some size declines recent and rapid (e.g., Cummings & Hatton 2003; Marsden & Adkins 2010; Berkenbusch & Neubauer 2015, 2016; Tricklebank et al. 2020; Griffith, pers. comm. 2019). Ironically, asymptotic length for Snake Bank cockles (Whangarei Harbour, 70 km southeast) today is only 35 mm (even though little fished recently; MPI 2018), contrasting starkly with nearby midden cockles that frequently exceed 50 mm (Nevin 1984). And despite potential remedies (e.g., reduced fishing pressure, thinning, transplanting; Marsden & Adkins 2010), no reference was found for a recovered (e.g., ≥20% of cockles ≥40 mm), or an unambiguously recovering, cockle stock in northern New Zealand. This contrasts with invertebrate populations in other rehabilitation contexts (for instance, paua *Haliotis iris* and red rock lobsters *Jasus edwardsii* in no-take marine reserves; e.g., Ballantine 2014) which have bounced back towards 'normal' size-distributions.

With little or no evidence for significant ongoing sedimentation, Ipipiri Platform appears to be the main area of exception to an ever-degrading habitat, the most-obvious recent change here being *expansion* in the cover of subtidal seagrass. Although divers with long connection to this area report increasing levels of sedimentation in certain places (e.g., Vince Kerr, pers. comm. 2020), this has not been obvious in the aerial imagery or in the sampling that supported the present study. To summarise for Ipipiri Platform, 1) there appears to have been little net shallowing along land margins or in deeper waters since the surveys of 1849, in contrast to many inner parts of the Bay of Islands; 2) aerial imagery suggests surprising stability over both short and long terms in the extent and appearance of seafloor communities (apart from variability in subtidal-seagrass cover); and 3) the (limited, so far) underwater imagery does not suggest significant recent sedimentation. Confirmatory sediment cores are required, but it appears that the Ipipiri Platform has remained essentially silt-free through it's being refreshed with oceanic waters each flood tide, and the high-velocity tidal flow – particularly on the outgoing tide (MacDiarmid et al. 2009) – that helps disperse silt particles.

The main threat to the relatively-pristine state of shallow Ipipiri Platform waters seems to lie with Te Rawhiti Inlet. This inlet is the major sink for the largest source of sediment for the entire Bay of Islands. Te Rawhiti Inlet, with a depositional area of ~46 km^2, accounts for 30% of the total annual sedimentation deposition into the Bay (Swales et al. 2012: 62), with sediment cores showing SARs of around 4.9 mm y^{-1} (Station RAN S-13 in Figure 5; Swales et al. 2012: 52) over the past 80–120 y. Stable-isotope data suggest that these sediments are derived largely from the Kawakawa and Waitangi rivers, later to be dispersed by river plumes and tidal currents out into the Bay and particularly into Te Rawhiti Inlet (Swales et al. 2012: 66). Does there come a point when the silt burden of Te Rawhiti Inlet spills onto Ipipiri Platform at such a rate that even shallow waters and shorelines are overwhelmed?

Other main threats to the shallow soft-bottom biodiversity of the Bay of Islands are attributable to fishing and boating activity. Almost certainly recreational fishing effort today significantly (perhaps by an order of magnitude) exceeds that commercial (Booth 2017: 50): this intensive and extensive fishery is likely to continue to expand and intensify further, mainly through more and more vessels visiting the Bay, particularly from Auckland during the summer. Although the direct physical impacts of fishing on shallow soft-bottom biodiversity – beyond that of a likely-small recreational-dredge effort – are probably insignificant (e.g., MacDiarmid et al. 2012), the effects of overharvesting of particular cohorts of certain ecologically-keystone species can be instrumental in difficult-to-perceive human-induced changes in shallow soft-bottom biodiversity. Such transformations may not be nearly as recognisable as, for example, loss of kelp through urchin overgrazing.

General boating activity, which typically involves manoeuvring and anchoring in shallow waters, intuitively can bring about long-term modification. However, there have been few confirmatory studies of such impacts in New Zealand waters. Indeed, in a study at Kawau Island near Auckland, with a setting similar to Ipipiri, anchoring scars on grounds dominated by horse mussels persisted for up to 3 mo, but had diminished in area and depth after a further 1 mo (Backhurst & Cole 2000). Accordingly, despite protracted usage, popular anchoring places were not ecologically distinct from less-popular sites. This probably had something to do with anchoring being localised and intense in a few bays over a short period, the macrobenthos recovering over the remainder of the year. Nevertheless, subtidal seagrass is demonstrably affected negatively by propeller wash when it is frequent and strong enough (Figure 40).

Perhaps one of the more notable revelations of this report has been the extent of the red-algal-turf-dominated biome associated with the shallow soft bottoms of Ipipiri Platform. Only recently for New Zealand as a whole has it become apparent that algal turf can be an important component of soft-seafloor biodiversity (e.g., Rowden et al. 2012: 51; Anderson et al. 2019: 68, 70). And although red-algae turfs are often viewed locally (e.g., Alestra et al. 2014) and world-wide (e.g., Filbee-Dexter & Wernberg 2018) as being a recent, stable, degraded state, many kelp forests globally having disappeared and been replaced by turf algae over the last decade, the evidence is that coralline turf on the *soft substrates* of Ipipiri Platform is a long-existing state. These algal turfs – and their embedded mosaic of communities – appear to be a particularly extensive, ecologically-distinctive and nationally-important biome. Their significance appears to have been largely overlooked in the Ocean Survey 20/20 studies because most of the more-synoptic 2009 observations were made at depths >10 m. Almost certainly a vast amount of ecological attention will in course accrue to the accessible and visually- and ecologically-remarkable Ipipiri Platform, with many exciting results likely. By way of example, once algal communities in Whangarei and Otago harbours were examined in detail, the recognised flora for each region increased by a third (Neill et al. 2012). The widespread biological sampling undertaken in the 1990s in the Bay of Islands by Morley & Hayward (1999) (Appendix 20, which is still being worked up; Bruce Hayward, pers. comm. 2020), is also likely to be a rich source of baseline information concerning spatial patterns of taxa and a springboard for insightful investigation of temporal changes in distributions and abundances.

Non-indigenous species (NIS) appear not to have had significant ecological impact on native subtidal biodiversity of the Bay of Islands. Although a long list of subtidal marine NIS are reported for the Bay of Islands in the Marine Biosecurity Porthole (https://www.marinebiosecurity.org.nz/sources-of-data/), many associated with the international port of Opua, few appear to have become ecologically-conspicuous. *Codium flexilis* and *Hydroclathrus* may not be native, but no deleterious impacts are immediately apparent. *Chaetopterus* may also be foreign, but its presence is rarely obvious until quantities wash ashore after storms. For molluscs, Morley & Hayward (1999) reported the Asian date mussel *Musculista senhousia* to exist in small transient thickets in Otehei, Parekura, Manawaora and adjacent bays; the small Asian semele *Theora lubrica* living in large numbers in shallow muddy sediment throughout most of the Bay (and also reported for Kerikeri Inlet in the 2010s; Richard Griffiths, Northland Regional Council, pers. comm. 2019); and the file shell *Limaria orientalis* is widespread in subtidal shallows in many parts of the Bay of Islands. But none appears to be exerting much ecological pressure.

The Bay of Islands, although spatially quite small, is a physically- and ecologically-diverse location representing east-Northland's rich marine biodiversity. It has provided a tractable location for this unfunded, community-science project concerning changes over time in nature and extent of shallow-water, soft-seafloor biological communities. So far, essentially all identified threats to this biodiversity, and the changes observed, have had their origins – directly or indirectly – in human activity, rather than being part of any inherent progression in natural cycles. Sedimentation appears to be the single-most important and enduring contributor to ecological degradation in shallow waters of this northern harbour, with time lags between stressor-onset and realisation of impact (decades to centuries) that only now are becoming clear.

11. ACKNOWLEDGEMENTS

My highlights? 1) Significant subtidal seagrass appears to be a relatively new biome in the eastern Bay of Islands, at least in terms of recent-historical times. 2) An opportunity to draw to the attention of ecologists the almost complete loss of coarse-sand/shell upper beaches and spits in the Bay – a biome guaranteed extinguishment if mangrove expansion continues uncontrolled. 3) Observing *Vaucheria* in stand-off with *Zostera*. 4) The value of *midden* cockle-size data: not routinely used in marine ecology, it is these data that have been the foundation of my case that today's *Austrovenus* stocks of the Bay of Islands are highly degraded. 5) But perhaps the most satisfying new insight – and then only briefly touched on here – is the sheer extent, and the stability over time, of the nationally-significant soft-bottom red-algal turf biome of the shallow waters of the Ipipiri Platform. In these clear waters of the Platform, the algal-turf meadows, together with their associated subtidal seagrass and near-white shell sand, underpin what is probably the most-widely promoted tourist representation and allure of the Bay of Islands today. Not only do people on boats and from the air draw wonderment, but swimmers, kayakers and divers are inspired too.

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APPENDICES

Appendix 1: Sedimentation in Kerikeri Inlet. Rock oyster rock groynes laid possibly as early as 1920 remain clearly visible directly alongside Pickmere Channel (left; Ocean Survey 20/20), indicating little silt build-up here over the past century. Further upstream, and on the margin of the Inlet, the boat-launching ramp at Skudders Beach is now of little use, it terminating in deep mud at about half tide level (right; author's image).


Appendix 2: Grove characteristics of mangroves of the Bay of Islands in the early-1950s. Images based on NZ Aerial Mapping Ltd photography, with examples of the categories given in Figure 16 (Booth 2020). √, mangroves present; -, not applicable. A, a significant forest of established trees associated with stream mouth(s); B1, away from stream mouths, one main row, the trees being of similar size; B2, away from stream mouths, 2–3 rows, the trees being of similar size; B3, away from stream mouths, 2–3 rows, the trees within rows being of similar size, but different to those in other row(s); B4, away from stream mouths, wide band (equivalent in width to at least five rows) of large trees; B5, away from stream mouths, wide band of large trees with one main row to seaward; B6, away from stream mouths, wide band of large trees with 2–3 rows to seaward; C1, trees referred to in Columns A–B6 of Appendix 2 remain – almost universally – the lowest on the shore (and in most instances individually identifiable through their pattern of distribution); C2, many or all trees referred to in Columns B1–B3, B5 and B6 are well below mean high water, based on such features as upper-beach form and presence of saltmarsh.

Catchment Location	Image (date)	A	B1	B2	B3	B4	B5	B6	C1	C2
Te Puna										
Redcliffs	1366-74 (Mar 51)	√			√				√	√
West Te Tii	1366-75 (Mar 51)								√	-
East Te Tii	1366-76 (Mar 51)	√	√	√					√	√
Poukoura	1366-79 (Mar 51)	√	√						√	√
Opete	1366-81 (Mar 51)	√	√			√			√	√
Napia	540-88 (Mar 51)	√	√						√	√
Kerikeri										
Okura	542-2 (Mar 51)	√				√			√	-
Shelly Beach	542-3 (Mar 51)			√					√	√
Hauparua	542-6 (Mar 51)	√	√			√			√	√
Rangitane River	541-61 (Oct 50)	√							√	-
Aroha Island	541-623 (Oct 50)	√				√			√	-
Blacksmiths	541-64 (Oct 50)	√	√		√				√	√
Wairoa Bay	544-8 (Mar 51)					√			√	-

Waitangi									
North	544-7 (Mar 51)	√		√	√			√	√
South	545-50 (Mar 51)	√			√			√	-
West	545-50 (Mar 51)						√	√	√
Te Haumi	545-53 (Mar 51)	√			√			√	-
East Veronica									
Te Wahapu to Pipiroa	546-77 (Oct 53)	√	√		√			√	√
Orongo Bay	545-56 (Mar 51)	√	√	√				√	√
Uruti Bay	545-56 (Mar 51)	√						√	-
Kawakawa & Karetu									
Te Raupo	547-70 (Oct 53)	√		√	√			√	√
East Te Raupo	547-71 (Oct 53)	√	√	√	√	√		√	√
River Bend	548-68 (Oct 53?)	√	√	√	√		√		√
Upper	548-68 (Oct 53?)		√		√			√	-
Karetu	548-68 (Oct 53?)	√	√		√			√	x
Upper Karetu	549-76 (Oct 53?)		√		√			√	x
Opposite Opua	547-72 (Oct 53)	√		√	√			√	√
Waikare									
N entrance	546-77 (Oct 53)	√						√ , x	-
East N entrance	546-79 (Oct 53)	√			√			√	-
Outer north	546-80 (Oct 53)	√	√		√			√	√
Frenchmans Swamp	546-81 (Oct 53)	√	√	√	√			√	√
Paroa turnoff	546-82 (Oct 53)	√	√	√	√			√	√
Man o War Creek	546-84 (Oct 53)	√			√			√	-
Throat	546-84 (Oct 53)	√	√	√	√			√	√
Head	547-79 (Oct 53)	√			√			√	-
Mid South	546-81 (Oct 53)	√		√	√	√		√	√
Outer South	546-80 (Oct 53)	√	√		√	√		√	√
Waikino									
East	547-74 (Oct 53)	√			√			√	-
West	547-73 (Oct 53)	√	√	√	√	√	√	√	√
Paroa	544-16 (Mar 51)	√		√	√			√	√
Te Hue	544-18 (Mar 51)	√	√		√	√		√	√
Manawaora	545-62 (Mar 51)	√						x	-
Te Huhuri	544-19 (Mar 51)	√	√					√	√
Waipiro	544-20 (Mar 51)	√	√		√			√	√
Whiorau	543-23 (Mar 51)	√	√	√				√	√
Parekura	544-22 (Mar 51)	√	√	√				√	√
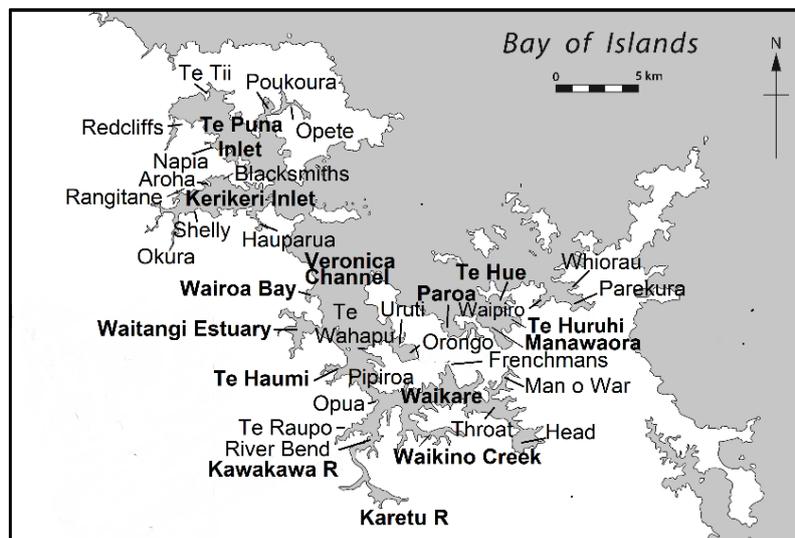
Appendix 3: Present distribution of mangroves in the Bay of Islands (https://www.seasketch.org/#projecthomepage/5357cfa467a68a303e1bb87a) and changes in the main categories of mangrove cover between the early-1950s (indicative, based on aerial images in Appendix 2) and 2009 (Ocean Survey 20/20; https://marinedata.niwa.co.nz/bay-of-islands-coastal-surveyproject/) (Booth 2020). Dark green represents the distribution of large trees in the early-1950s (believed to essentially reflect the distribution of mangroves at first European contact – and probably much earlier); light green represents the presence of small trees in the early-1950s; pink indicates the landward expansion that has taken place between the early-1950s and 2009; and red is significant alongshore expansion between the early-1950s and 2009. Blue is appropriated ('reclaimed') mangrove habitat; black is mangrove habitat now a farm pond.

Kawakawa River

Waikare & Waikino inlets

Paroa & Manawaora bays

Parekura Bay
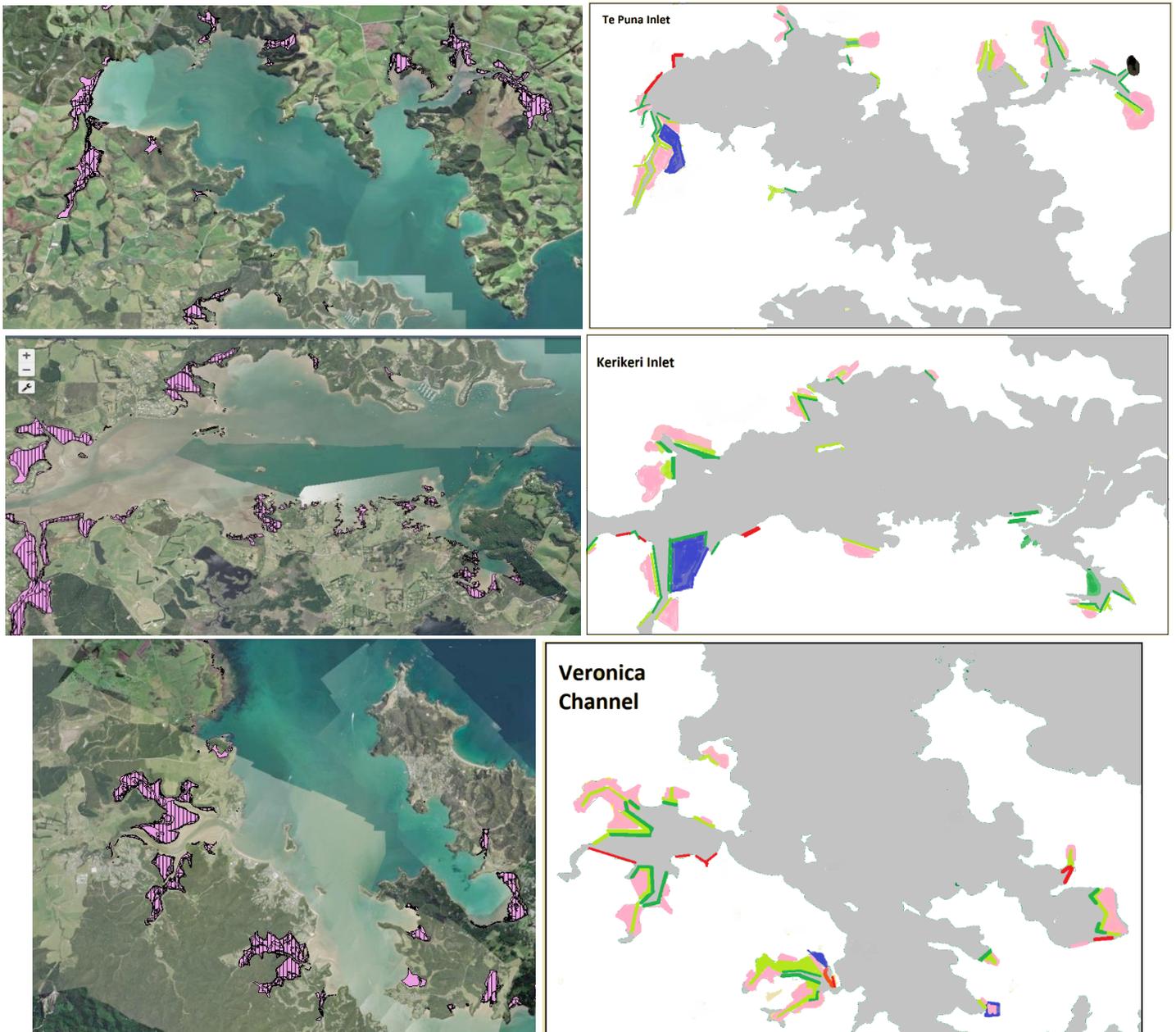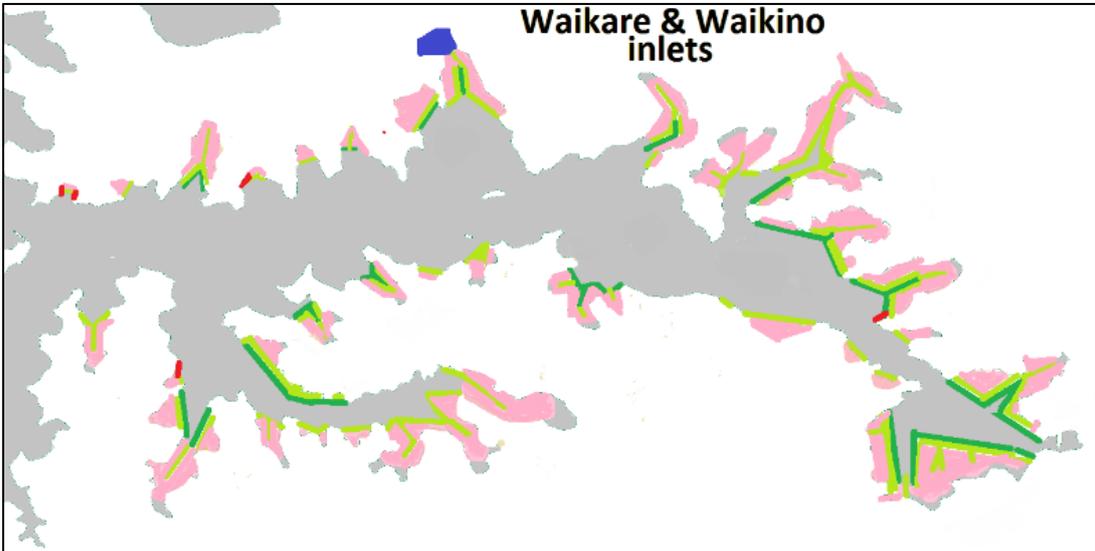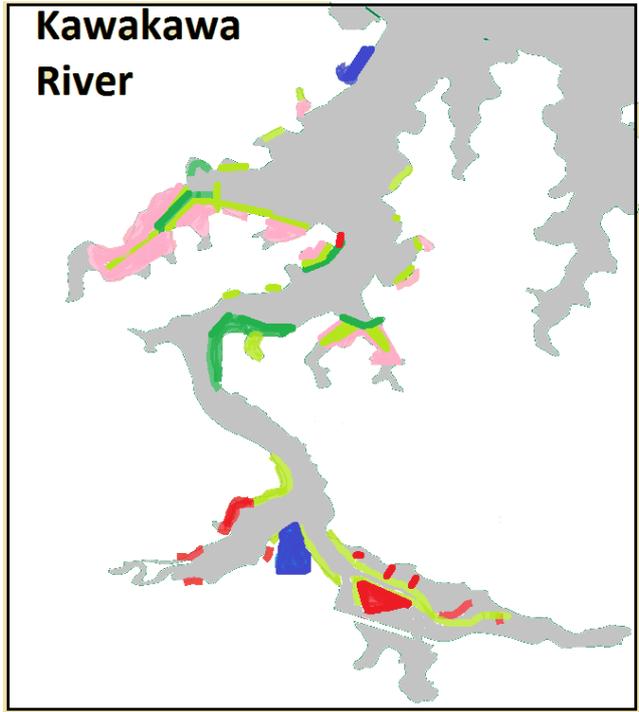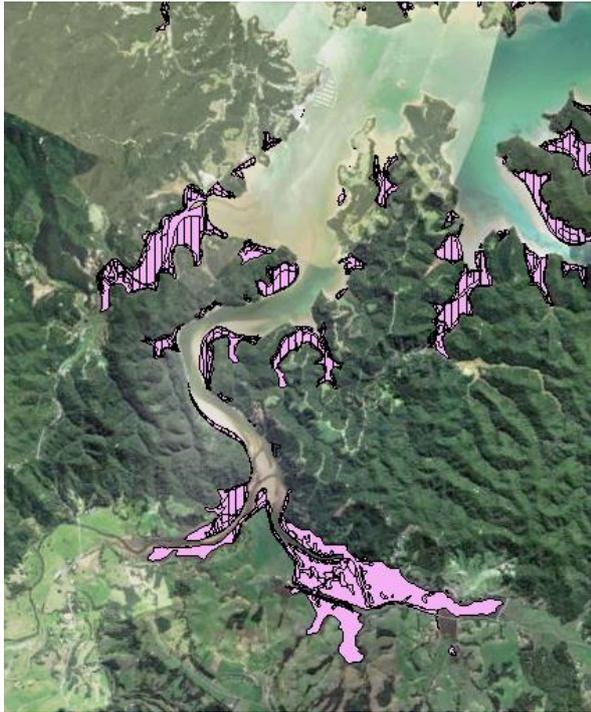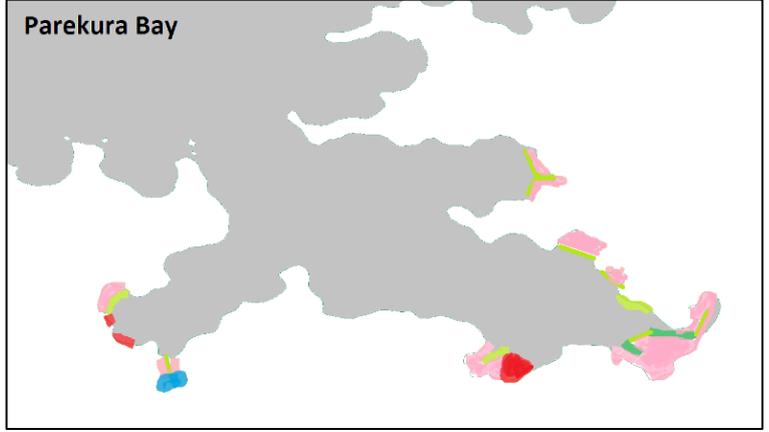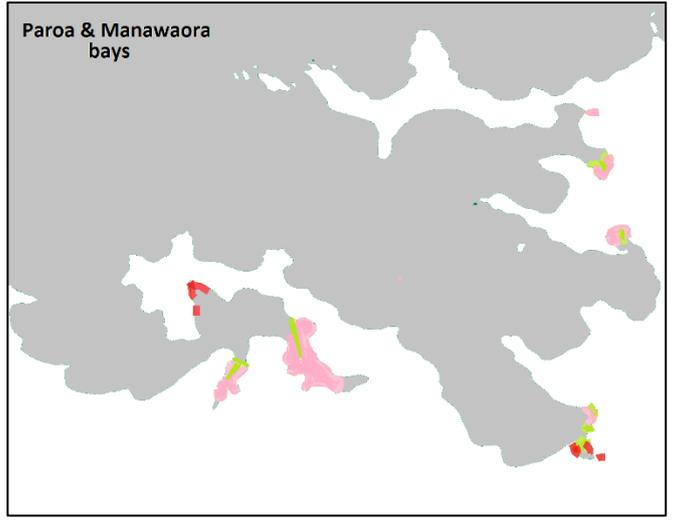
Appendix 4: Other particularly instructive, representative examples of shoreward expansion in mangrove cover in the Bay of Islands. These are based on NZ Aerial Mapping Ltd and other images (all but last column, with more than one entry where at least 8 y separated images) and November 2009 Ocean Survey 20/20 aerial images (NZAM SN50765X; last column) (Booth 2020). Coordinates are from Google Earth. For all sites, the 1942 Lands and Survey map indicated the presence of mangroves (although for Redcliffs, they were confined to the creek). -, no suitable image for that decade. For all catchments, there was typically a single initial line (less frequently, up to three lines) of mangrove recruitment; almost everywhere, these lines remain to this day the seaward extent of the mangrove cover, with individual trees usually discernible. The decades in which rapid infilling of mangroves took place, inferred from the time series of images and assessed subjectively, are shaded.

Catchment	Example site	1950s	1960s	1970s	1980s	1990s	2009
Te Puna	Redcliffs 35° 9'23.02"S; 173°59'0.68"E	1951 (1366-74)	1961 (2604-5)	1971 (4474-1) Late 70s (5006_N4_C(1)1)	1981 (5932A G39)	1993 (NRC)	2311, 2312, 2411, 2412
Kerikeri	East of Shelly 35°12'45.51"S; 174° 0'39.23"E	1951 (542-3)	1961 (2604-7)	1971 (4477-3)	1980 (SN5651 C7)	-	3217, 3317
Veronica	Orongo Bay 35°17'8.56"S; 174° 8'36.08"E	1951 (545-56)	1961 (2605-1)	1972 (4481-17)	1981 (SN5932A J39)	1993 (Kerr)	4343, 4443
Kawakawa	Te Raupo 35°19'49.61"S; 174° 6'47.64"E	1953 (547-71)	1961 (2605-1)	1976-79 (5006_HII_D(2)(1)1)	1981 (5932A L37)	1993 (NRC)	0136, 0137
Waikare	West of Lane's Rd 35°18'23.21"S; 174° 8'40.29"E to 35°18'15.53"S; 174° 9'12.98"E	1953 (546-80)	1961 (2605-1)	1976-79 (5006_I3_C)	1981 (5932A K38)	1993 (NRC)	4742, 4743, 4744
Parekura	North Te Kauri 35°15'7.63"S; 174°15'27.50"E	1951 (543-23)	1961 (2607-1)	1972 (4479-23)	1980 (5932A J44)	-	3914
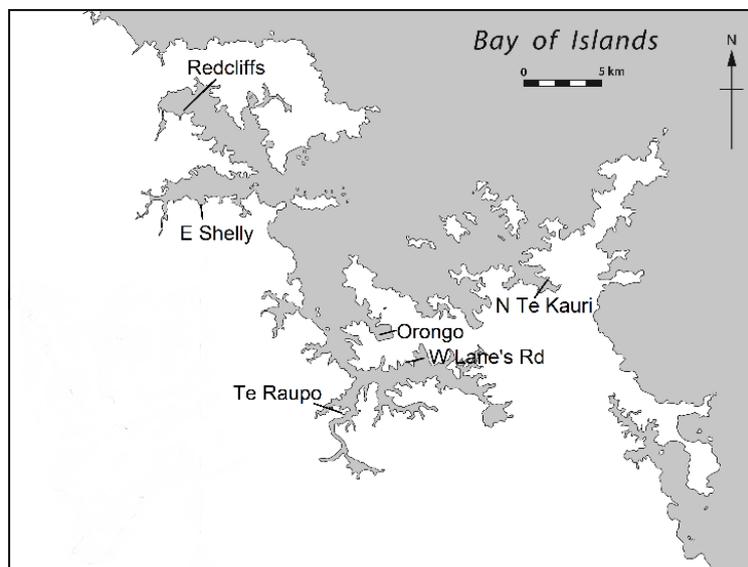
Appendix 5: Uppershore coarse-sand/shell beaches and spits of Kerikeri Inlet in 1951. Many of the uppershore coarse-sand/shell beaches and spits that had, at least until the early/mid-1900s, comprised the shores of much of the sheltered soft margins of the Bay of Islands, had by 2009 been overrun by mangroves, this 1951 example being the upper mid-Kerikeri Inlet (upper; NZ Aerial Mapping Ltd image 542-2, orthorectified over the Ocean Survey 20/20 image [http://www.os2020.org.nz/]) and the lower northern mid-Kerikeri Inlet (lower; NZ Aerial Mapping Ltd orthorectified image 541-63) (Booth 2020).

80 m shell spit now overwhelmed by mangroves

50 m shell beach now overwhelmed by mangroves

60 m shell spit now overwhelmed by mangroves

300 m shell beach still intact

110 m shell beach, most now engulfed with mangroves

50 m shell spit now overwhelmed by mangroves

250 m long shell beach, but the outer (E) section now overwhelmed by mangroves

120 m shell beach still largely intact

60 m shell beach still intact

50 m shell beach still largely intact

120 m of this shell beach still largely intact - but loss of shell at each end

60 m shell beach still intact

Appendix 6: Oyster reefs in Kerikeri Inlet. Oyster reef 1 (*see* Figures 21 and 22) appeared to be much more extensive in 1942 than in 2009 (upper pair: Air Force Museum of New Zealand, 109FrameA3; Ocean Survey 20/20), and with no evidence for other oyster reefs being present (intervening imagery was consistent). Oyster reef 2 appeared more extensive in 1942 (lower foursome: Air Force Museum of New Zealand, 109FrameA3; Retrolens 542_2, March 1951; Retrolens 5651 C4, January 1980; 2009 Ocean Survey 20/20).
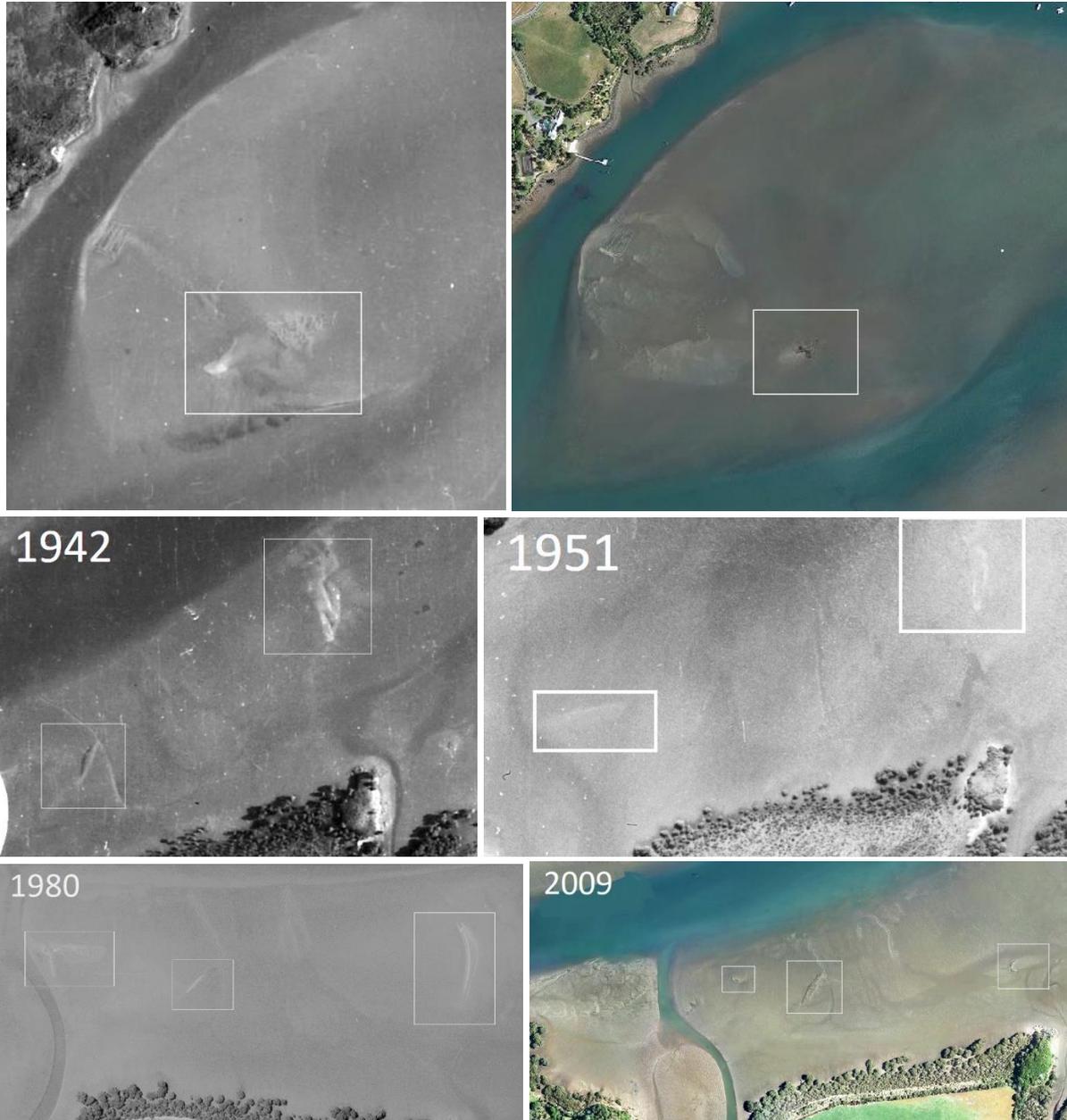
Appendix 7: Indicative distribution & volume (minimum m³) of Kerikeri Inlet middens. Assumes 1 m width and 0.2 m depth for each metre-length of midden, from archaeological Site Record Forms. All middens were dominated by cockles (Booth 2020).
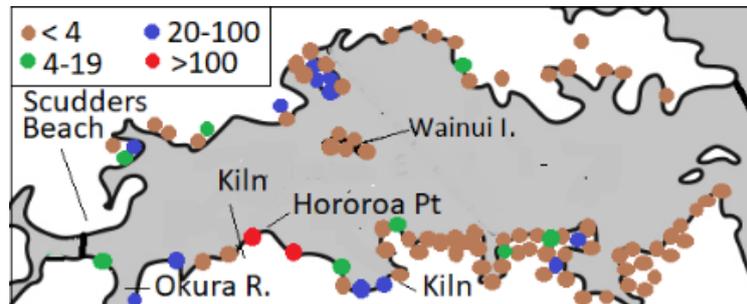
Appendix 8: Kerikeri Inlet midden-cockle sizes. Recorded middens at and near Hororoa Point that have associated cockle-length information provided on Site Record Forms (Booth 2020). Percentage is proportion of midden material that is cockle shell; Pred, predominantly

	Location	Site	Cockle (%)	Size range (mm)
1	Blacksmiths	P05/477	99%	34-46
1	Blacksmiths	P05/476	?100%	27-54
1	Blacksmiths	P05/475	?100%	35-55
2	Rangitane Peninsula	P05/474	?100%	33-55
3	Rangitane R	P05/944	Pred.	Medium to large
3	Rangitane mouth	P05/468	?100%	34-53
4	Rangitane trig	P05/18	Pred.	34-54
5	Kerikeri entrance	P05/458	100%	30-49
6	Okura	P05/460	Pred.	27-38
6	Okura	P05/993	?100%	Small to medium
6	Okura	P05/459	95%	26-36
7	Above Okura bridge	P05/759	100%	up to 47
8	Hororoa	P05/461	?100%	30-39
8	Hororoa	P05/462	100%	30-40
8	Hororoa	P05/464	Pred.	35-51
8	Hororoa	P05/465	Pred.	34-54
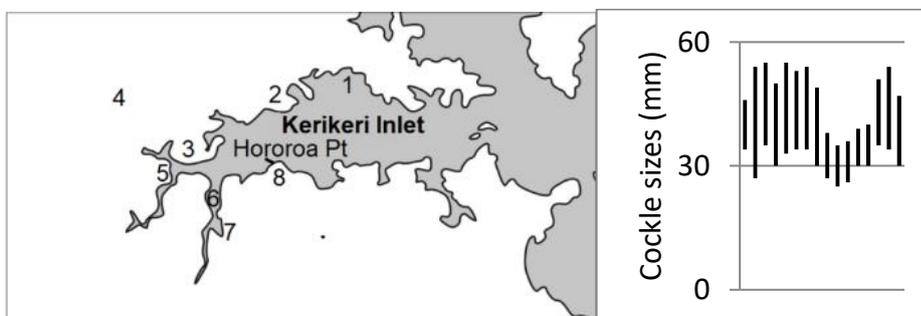
Appendix 9: Huge middens in Kerikeri Inlet, 1922. Geological map of mid-Kerikeri Inlet (Ferrar & Cropp 1922). Note the similar form of the intertidal flats to the situation today, and reference to middens at Hororoa Point. The tree-like symbols represent mangroves.
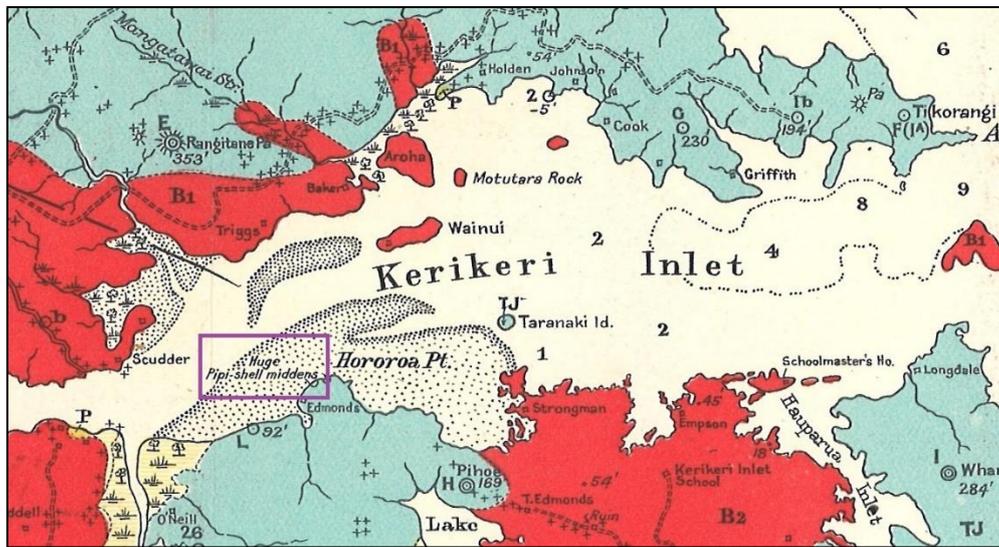
Appendix 10: Characteristics of Bay of Islands-wide recent (since 2009) live cockles. For some samples, maximum/minimum sizes were centre-points of ranges provided, rounded to nearest whole digit (Booth 2020). In the author's sampling, beds were $\geqslant 100$ m^2, near low-tide level, close to open water, and cockles appeared plentiful. Usually, three replicates perpendicular to the shore and separated by 20–30 m were sampled, each with 0.03 m^2 of substrate sieved to 2 mm, and the counts combined. replics, replicates; LFD, length-frequency distribution; na, not applicable, or not available in combatable format. The length-frequency distributions by sampling site and by region provide insight into the biological status of the cockle stocks, essentially all stocks being unharvested or only lightly harvested. Throughout, most cockles were 12–33 mm, smaller cockles being only moderately-well represented, and larger ones poorly represented.
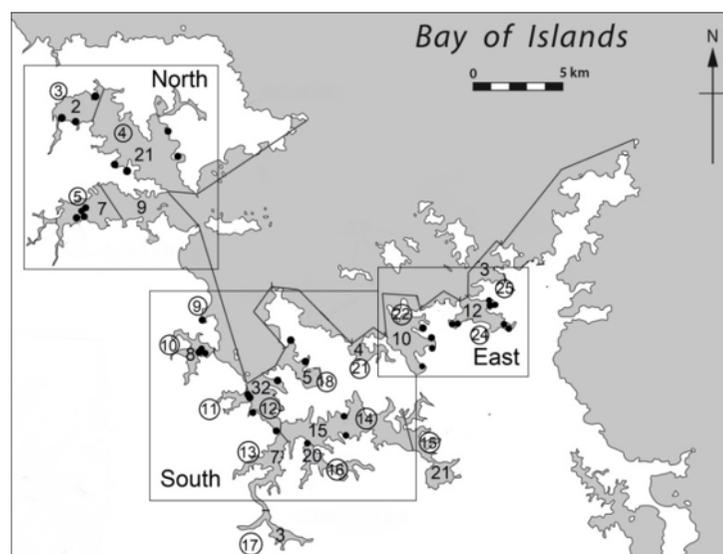
Map shows compartment nos (circled), no. of middens by compartment, and recent sampling sites (filled circles).
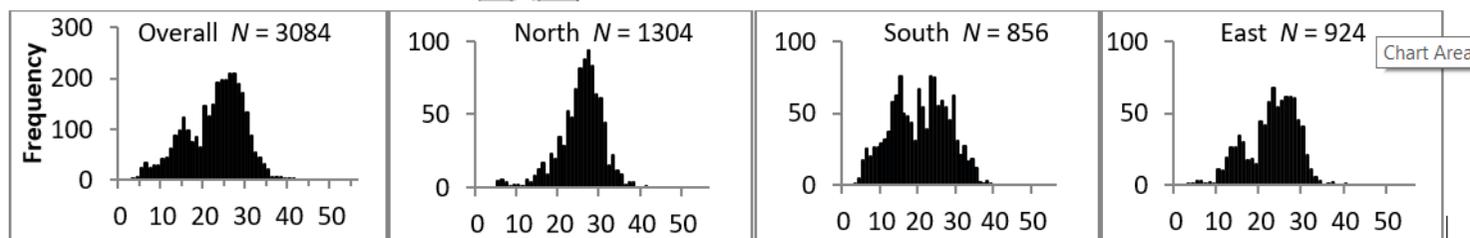
Cockle length-frequencies (mm).

Compartment	Station	Replics	Date	Latitude S	Longitude E	Density (m²)			Med	Length (mm)		N	Source	LFD
						All	≥30 mm	Av (± SD)		Max	Min			
Upper Te Puna 3	Te Tii 5	1	? 2009	35 8.50868	174 0.58984	na	na	~8.5 (na)	na	35	3	24	Hewitt et al. (2010)	na
	Redcliffs 6	1	? 2009	35 9.40271	173 59.23981	na	na	~16.1 (na)	na	35	3	128	Hewitt et al. (2010)	na
	Redcliffs 30	3	Apr-19	35.159028	173.995639	533	178	25.3 (9.4)	28.5	35	5	48	Author	
Te Puna 4	Kahikatoa 29	3	Apr-19	35.181528	174.019528	878	233	27.5 (3.2)	28	37	20	79	Author	
	Crowles	3	Nov 19	35.183165	174.025457	1233	111	24.4 (4.6)	24	38	14	111	Author	
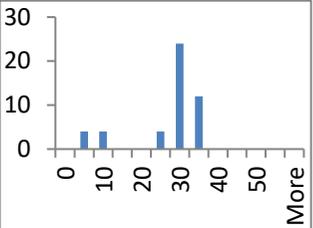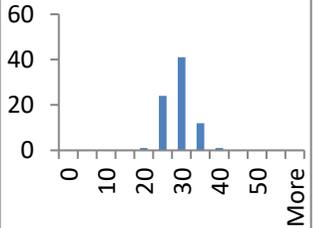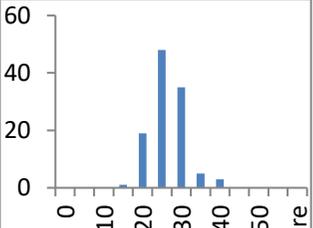
Compartment	Station	Replics	Date	Latitude S	Longitude E	Density (m²)			Med	Length (mm)		N	Source	LFD
						All	≥30 mm	Av (± SD)		Max	Min			
	Oneroa	3	Nov 19	35.160363	174.050598	144	111	29 (5.4)	30.5	33	12	13	Author	
	Whare-ngaere	3	Nov 19	35.174558	174.056202	500	300	30.1 (5.3)	31	41	7	45	Author	
Mid-Kerikeri 6 (Main Bank)	2	1	Dec-18	35.20262	173.99686	1700	267	27.5 (2.0)	27	33	24	51	Author	
	5	1	Dec-18	35.20281	173.99491	1867	300	27.5 (3.4)	27.8	34	10	56	Author	
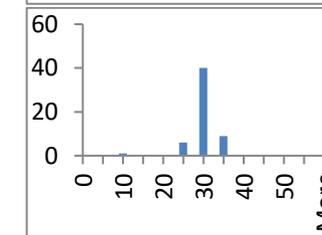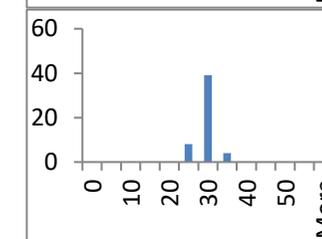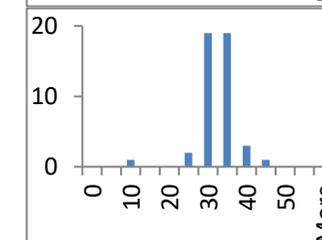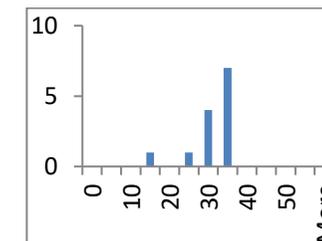
Compartment	Station	Replics	Date	Latitude S	Longitude E	Density (m²)			Med	Length (mm)		N	Source	LFD
						All	≥30 mm	Av (± SD)		Max	Min			
	6	1	Dec-18	35.20241	173.99439	2433	267	25.2 (2.8)	25	33	21	73	Author	
	8	1	Dec-18	35.20186	173.99412	1867	133	24.9 (2.4)	24	33	22	56	Author	
	10	1	Dec-18	35.20118	173.99514	2267	233	27.1 (1.9)	27	33	22	68	Author	
	12	1	Dec-18	35.20176	173.99496	800	633	30.6 (1.9)	30	36	27	24	Author	
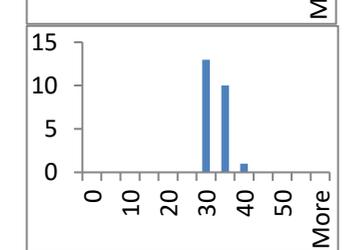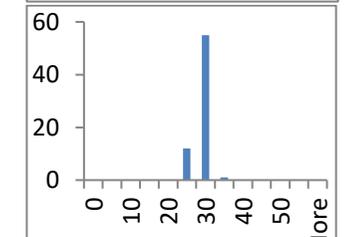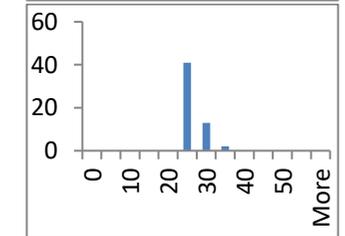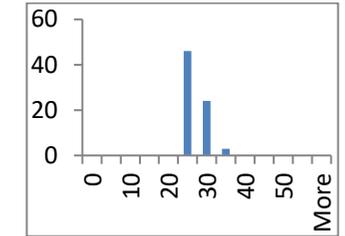
81

Compartment	Station	Replics	Date	Latitude S	Longitude E	Density (m²)			Med	Length (mm)		N	Source	LFD
						All	≥30 mm	Av (± SD)		Max	Min			
	14	1	Dec-18	35.20239	173.99539	2133	200	25.9 (2.3)	26	32	21	64	Author	
(South Shore)	1/1	1	Jan-19	35.005278	173.297778	1000	33	20.6 (3.7)	20	32	16	30	Author	
	4/1	1	Jan-19	35.205753	173.997928	500	67	21.7 (5.1)	20	31	16	15	Author	
	1/2	1	Jan-19	35.20577	173.997819	833	67	24.9 (3.4)	25	30	19	25	Author	
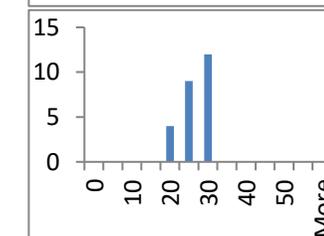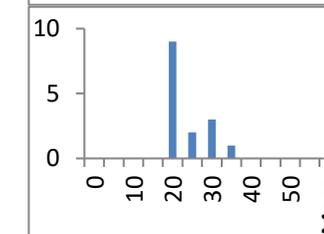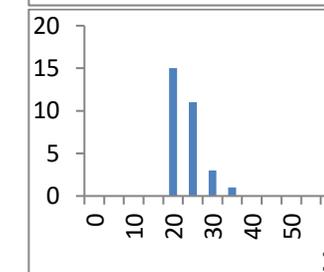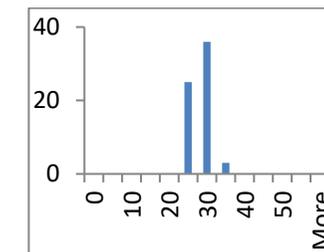
Compartment	Station	Replics	Date	Latitude S	Longitude E	Density (m²)			Med	Length (mm)		N	Source	LFD
						All	≥30 mm	Av (± SD)		Max	Min			
	4/2	1	Jan-19	35.205906	173.997786	1000	167	24.1 (5.0)	23	34	17	30	Author	
	1/3	1	Jan-19	35.205872	173.997764	867	267	27.2 (3.7)	26.5	33	20	26	Author	
	4/3	1	Jan-19	35.206178	173.997181	533	33	25.5 (3.0)	25.5	32	20	16	Author	
(Pickmere Channel)	WP019	1	Apr-19	35.207639	173.988917	267	0	20.9 (3.6)	21.9	26	15	12	Author	

Compartment	Station	Replics	Date	Latitude S	Longitude E	Density (m²)				Length (mm)		N	Source	LFD
						All	≥30 mm	Av (± SD)	Med	Max	Min			
	WP020	1	Apr-19	35.207694	173.989417	356	0	18.6 (4.2)	18.4	26	10	16	Author	
	WP021	1	Apr-19	35.207528	173.989806	556	0	19.5 (4.0)	18.2	28	14	25	Author	
	WP022	1	Apr-19	35.207306	173.990222	467	0	15.7 (4.1)	16	22	6	21	Author	
	WP023	1	Apr-19	35.207194	173.990583	756	0	14.9 (3.6)	15	24	7	34	Author	
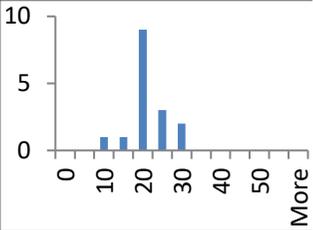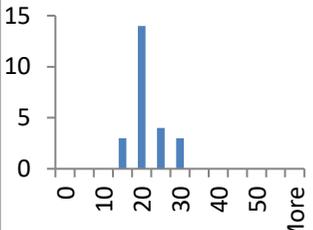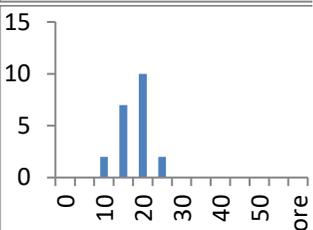
Compartment	Station	Replics	Date	Latitude S	Longitude E	Density (m²)		Length (mm)				N	Source	LFD
						All	≥30 mm	Av (± SD)	Med	Max	Min			
Wairoa 9	Wairoa S	3	Dec 19	35.25808	174.07518	2489	22	15.3 (5.5)	15	31	3	224	Author	
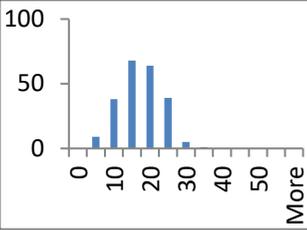
Waitangi 10	11	1	? 2009	35 16.40225	174 4.27140	1582	na	na	na	35	3	62	Hewitt et al. 2010; Griffiths 2013: 27	na
	WAT 4	3	May-13	see source	see source	1094	132	na	na	na	na	na	Griffiths 2013	na
	WAT 5	3	May-13	see source	see source	1320	301	na	na	na	na	na	Griffiths 2013	na
	WAT 6	3	May-13	see source	see source	434	56	na	na	na	na	na	ditto	na
		3	Apr-19	35.272972	174.074222	1567	411	23.3 (9.1)	25.8	36	3.2	141	Author	
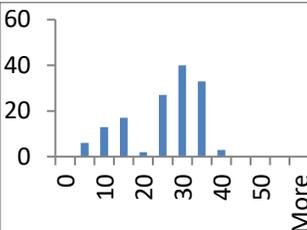
	28	many	2009-10	see source	see source	312	9	19.1 (na)	na	48	5	na	Berkenbusch & Neubauer (2015)	see source, p 70
Te Haumi 11		many	2012-13	see source	see source	427	20	18.7 (na)	na	42	5	na	Berkenbusch & Neubauer (2015)	see source, p 70
		many	2014-15	see source	see source	351	34	20.5 (na)	na	38	6	na	Berkenbusch & Neubauer (2015)	see source, p 70

Compartment	Station	Replics	Date	Latitude S	Longitude E	Density (m²)			Med	Length (mm)		N	Source	LFD
						All	≥30 mm	Av (± SD)		Max	Min			
	North	3	Dec 19	35.294867	174.101148	1600	133	24.8 (4.6)	25	34	5	144	Author	
	South	3	Dec 19	35.296285	174.10148	2244	89	22.1 (5.7)	23	34	5	202	Author	
Veronica 12	Walls Bay	10	May-18	see source	see source	41	11	25.9 (na)	25	42	8	32	4Sight Consulting 2018	See source
	Te Wahapu	3	Dec 19	35.286227	174.117077	1756	211	19.8 (6.6)	17	35	10	158	Author	
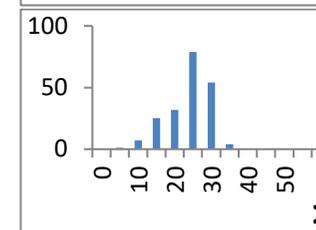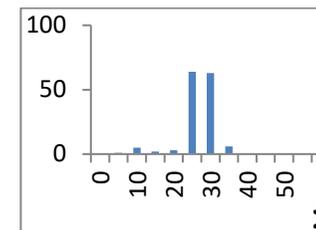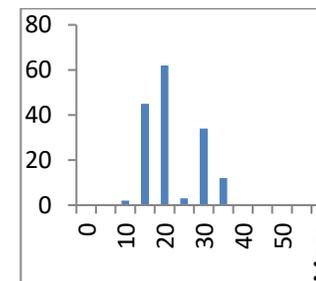
Compartment	Station	Replics	Date	Latitude S	Longitude E	Density (m²)			Med	Length (mm)		N	Source	LFD
						All	≥30 mm	Av (± SD)		Max	Min			
	Smiths	3	Dec 19	35.30082	174.10283	1189	44	22.8 (5.2)	24	34	6	107	Author	
Waikare 14	Waiaruhe 031	3	May 19	35.30478	174.1611	44	44	35.3 (2.1)	35	38	33	4	Author	
	Tangitu 032	3	May-19	35.30039	174.1611	211	33	18.6 (6.6)	17	34	12	19	Author	
Waikino 16	033	3	May-19	35.32025	174.136083	256	167	26.2 (10.6)	32	38	7	23	Author	
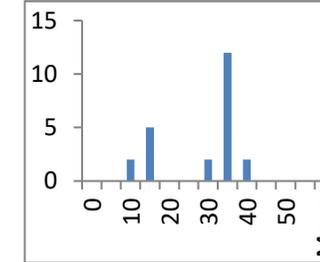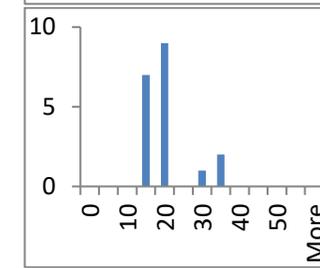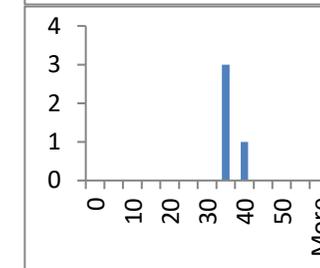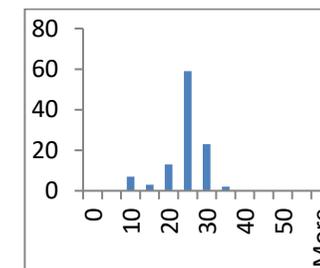
Compartment	Station	Replics	Date	Latitude S	Longitude E	Density (m²)			Med	Length (mm)		N	Source	LFD
						All	≥30 mm	Av (± SD)		Max	Min			
Pomare 18	Uruti	3	Dec 19	35.28611	174.11694	2033	189	17.5 (7.1)	15	39	4	183	Author	
	Matauwhi	3	Nov 19	35.267218	174.128415	1567	89	17.9 (7.9)	20	33	4	141	Author	
Manawaora 22	Mana-waora 21	1	?2009	35 16.70419	174 12.52948	na	na	na	na	35	3	75	Hewitt et al. (2010)	na
	Te Huruhi N	3	Nov 19	35.265285	174.21619	1078	222	25.2 (5.2)	25	40	5	97	Author	
	Te Huruhi S	3	Dec 19	35.268047	174.21778	2400	0	13.9 (2.2)	14	24	9	216	Author	
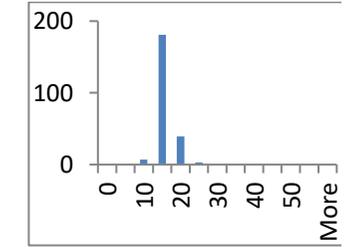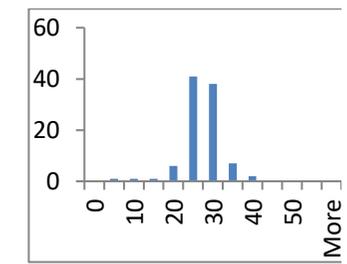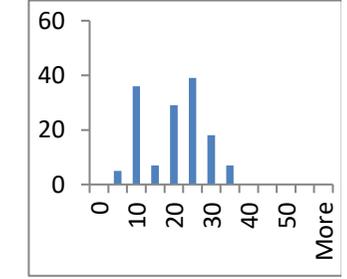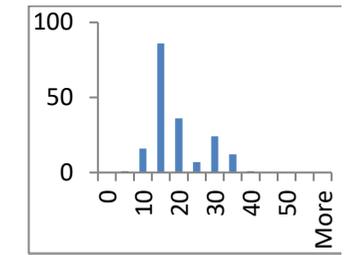
Compartment	Station	Replics	Date	Latitude S	Longitude E	Density (m²)			Med	Length (mm)		N	Source	LFD
						All	≥30 mm	Av (± SD)		Max	Min			
	Opunga	3	Nov 19	35.26173	174.20842	944	67	18.2 (7.7)	16	33	3	85	Author	
Parekura 24	Waipiro N	3	Dec 19	35.258605	174.229995	989	144	25.6 (3.9)	26	37	18	89	Author	
	Waipiro S	3	Nov 19	35.258732	174.230606	1344	111	24.9 (3.3)	25	31	17	121	Author	
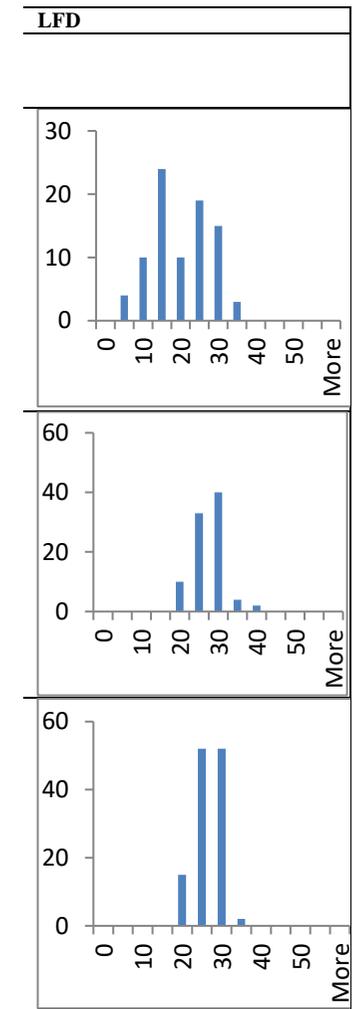
Compartment	Station	Replics	Date	Latitude S	Longitude E	Density (m²)			Med	Length (mm)		N	Source	LFD
						All	≥30 mm	Av (± SD)		Max	Min			
	Parekura SW	3	Nov 19	35.25724	174.2537	1100	56	25.2 (3.3)	26	32	11	99	Author	
	Parekura NE	3	Nov 19	35.25512	174.25558	678	111	25.7 (5.6)	28	33	8	61	Author	
	Whiorau N	3	Nov 19	35.2455	174.25185	867	78	20.6 (5.2)	20	33	10	78	Author	

Compartment	Station	Replics	Date	Latitude S	Longitude E	Density (m²)			Med	Length (mm)		N	Source	LFD
						All	≥30 mm	Av (± SD)		Max	Min			
	Whiorau WH1	3	Nov 19	35.24715	174.2523	856	122	25.1 (3.8)	25	34	17	77	Author	
	Whiorau WH2	3	Nov 19	35.246028	174.252193	467	11	22.7 (4.0)	23	30	10	42	Author	
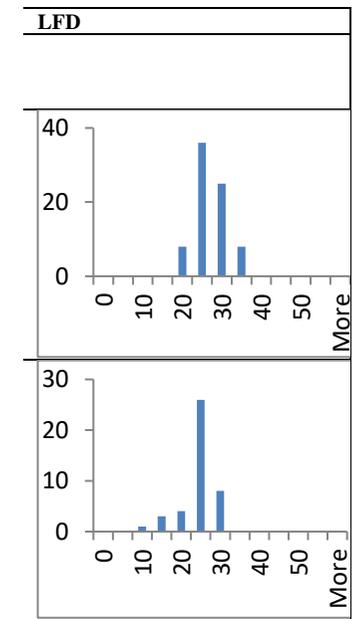
Appendix 11: Part of midden Q05/937 in Waikino Creek in 2005. The midden formed a terrace 30 m long and up to 3.5 m thick, and contained mainly large, opened cockles (Turner 2006). The surface cockles of this midden today are mainly 30–45 mm in length (Booth 2020).

Appendix 12: *Vaucheria* **beds amongst seagrass in Omakiwi Cove, winter 2020.** Examples of distribution and patterns of growth of *Vaucheria*, and 'cropped' leaves of the seagrass. (Images: author)

Appendix 13: Early (1950s–1970s) Bay of Islands intertidal seagrass. Table gives NZ Aerial Mapping Ltd aerial photographs (1951–53, 1959–61, 1971–72, 1976-79, and 1977–78) with *possible* and/or *probable* intertidal/shallow-subtidal seagrass patches (excluding extensions into the intertidal of subtidal patches) (locations shown on Figure 35) (Booth 2020). Place names based on Watkins (1974). Myra Larcombe (Opua, pers. comm. 2015), growing-up on the banks of the Waikare in the 1940s and 1950s, did not recall significant areas of seagrass in either Waikare Inlet or Waikino Creek. (Note that the extensive area of intertidal/subtidal seagrass referenced to near the entrance to Kerikeri Inlet by MacDiarmid et al. 2009: 162 is most unlikely to have ever existed.)

Compartment	Image/other reference	Date	Just where	Location
Te Puna	1366-75 to -81	29 Mar 51	Wrights	1
	Richard Civil, Rangitane, pers. comm. 2016	1950s	Redcliffs, S of Dudley Point	2, 6
	540-87, 88 & 89	29 Mar 51	Between Toatoa & Te Mamaku, Napia, E & W sides of Crowles, N & S of Dudley Point	3-6
	2785-3 & 4	4 Feb 59	Wrights, between Toatoa & Te Mamaku, Napia	1, 3, 4
Kerikeri	541-63	13 Oct 50	Near Wainui Island	8
	Richard Civil, Rangitane, pers. comm. 2016	1950s	W of Blacksmith's	9
	541-67	13 Oct 50	Hauparua	10
	David Manning & Don Starr , Hauparua, pers. comm. 2016	1950s/60s	Hauparua	10
	542-6	29 Mar 51	Hauparua	10
	2604-7	17 Mar 61	Hauparua	10
	2787-1 & -2	17 Mar 61	Hauparua	10
Veronica	544-8 & -9	29 Mar 51	Wairoa & SE of Waitangi	11, 12
	544-12	29 Mar 51	Matauwhi Bay	13
	545-53	29 Mar 51	Te Haumi	14
	545-55	29 Mar 51	Toretore & Wahapu	15, 16
	545-56 & -57	29 Mar 51	Orongo & Uruti	17, 18
	2788-1	4 Feb 59	Orongo	17
	2788-2	4 Feb 59	Te Haumi & Orongo	14, 17
	2604-9, -10 & -11	17 Mar 61	SE of Waitangi	12
	2604-12	17 Mar 61	Orongo	17
	2605-1 & -2	17 Mar 61	Orongo	17
	4481-13	22 Aug 71	Orongo	17
	Alex Clifford, Orongo Bay, pers. comm. 2019	1950s-60s	Orongo	17
	4482-10 & -11	22 Aug 71	Smith's camp	19
	4482-26	22 Aug 71	Smith's camp	19
	4482-27	22 Aug 71	Orongo	17
	4482-29	22 Aug 71	Orongo	17
	4483-11 & -12	22 Aug 71	Te Haumi & Smith's camp	14, 19
	4483-25 & -26	22 Aug 71	Smith's camp	19
	4481-17	6 May 72	Orongo	17
Kawakawa & Karetu	4484-13	11 Jun 72	East side	20
Waikare & Waikino	546-84	23 Oct 53	Side of channel	21
Paroa	5006 J1 C	17 Oct 78	Kaimomote	22
Orokawa	Whites Aviation 1419853	4 Feb 50	Orokawa	24
	4480-17	6 May 72	Orokawa	24
	Jim Frater, Opunga, pers. comm. 2016	1950s-80s	Opunga	24
Parekura	543-22	29 Mar 51	Whiorau	28
	544-21	29 Mar 51	Te Uenga	29
	2791-2	3 Feb 59	Inner Parekura	30
	2607-2	17 Mar 61	Inner Parekura	30
	2607-2	17 Mar 61	Te Uenga	29
	Penny Brothers, Te Uenga, pers. comm. 2016	1960s	Te Uenga	29

	2607-2	17 Mar 61	Waipiro		31
	4480-20	6 May 72	Inner Parekura	30	
	4480-20	6 May 72	Te Uenga	29	
	5006_P3 & P4	22 Nov 78	Inner Parekura	30	
	2607-2	17 Mar 61	Waipiro	31	
Omakiwi	4479-22	6 May 72	South	32	

Appendix 14: Intertidal seagrass in Parekura Bay in 1987. At the time, these intertidal seagrass beds in Parekura Bay were the largest in the Bay of Islands (14.7 ha, labelled 'eelgrass', and apparently even more extensive in previous times; shading also shows saltmarsh and mangroves) (Walls 1987). Also *see* https://www.seasketch.org/#projecthomepage/5357cfa467a68a303e1bb87a.
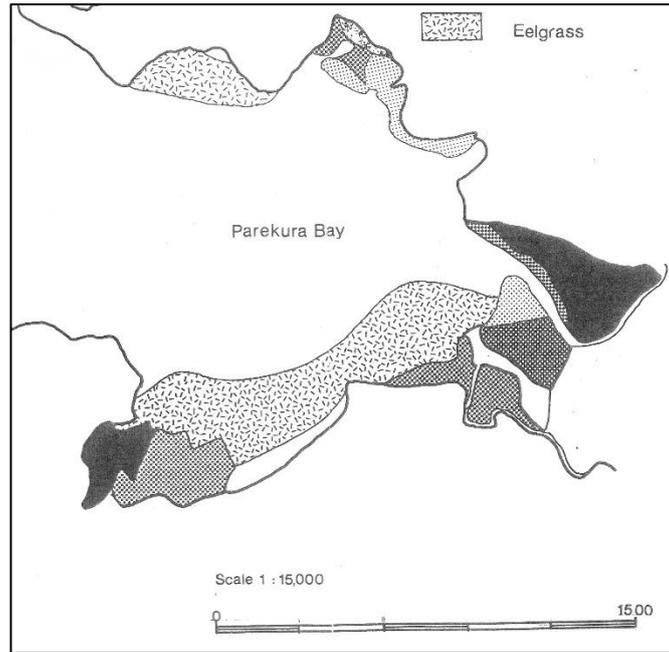
Appendix 15: Sources of aerial images used to estimate the extent of the main subtidal seagrass beds of the eastern Bay of Islands. 'Aerial' images were also taken to include a few from highpoints overlooking beds (Booth 2019). Whi, Whites Aviation Ltd photograph with National Library of New Zealand reference; RNZAF, Royal New Zealand Air Force reference (held by Air Force Museum of New Zealand); 1951 (SN 209), images part of NZ Aerial Mapping Ltd (NZAM) Survey No. 209; 1959 (SN 1223), images part of NZAM Survey No. 1223; 1961 (SN 1223), images part of NZAM Survey No. 1223; 1971 (SN 3406), images part of NZAM S.N. 3406; 1972 (SN 3406), images part of NZAM S.N. 3406; 1978 (SN 5006), images part of NZAM S.N. 5006; 1980 (SN 5651), images part of NZAM S.N. 5651; 1981 (SN 5932A), images part of NZAM S.N. 5932A; Walls, Walls (1987); NRC, Northland Regional Council image; Kerr, image held by Kerr & Associates, Kamo; Salt, image held by Salt Air Paihia; Harte, Mountain Harte et al. (2010); OS 20/20, November 2009 Ocean Survey 20/20 aerial images (NZAM SN50765X); Wri, Dean Wright Photography, Kerikeri. Waipao takes in Wai-iti; Kaingahoa takes in Te Tawa. (Kaing, Kaingahoa; Kaima, Kaimarama; Haha, Hahangarua; Kapura, Kapurarahurahu; Urupuk, Urupukapuka)

Bay	193?/1939 (Whi)	1942/1947 (RNZAF/ Whi)	1950 (Whi)	1951 (SN 209)	1952/53 (Whi)	1955/58 (Whi)	1959 (SN 1223)	1961 (SN 1223)	1971 (SN 3406)	1972 (SN 3406)	1973 (Whi)	1978 (SN 5006)	1980 (SN 5651)
1 Otarepo	-	235 A1	-	543-16	-	-	2789-3	2606-1	4479-15	-	1404906	5006 J2	5651 J2
2 Lagoon	1367622	235 A3	1419850	543-16	-	-	2789-3	2606-1	4479-15	-	1404906	5006 J2	5651 J2+
3 Waipao	-	138 A5	-	542-16	-	-	2789-2	2606-1	4478-16	-	-	5006 J2+	5651 J4+
4 Opunga	-	138 A5	-	542-16	-	-	2789-2	2606-1	4478-16	-	-	5006 J2	5651 J4+
5 Haha	-	138 A5	-	542-16	-	-	2789-2	2606-1	4478-16	-	-	5006 J2	5651 J4+
9 Otiao	-	-	-	542-19	-	-	2789-1	2607-1	4478-19	4477-24	-	5006 J2	5651 J6
10 Oneura	WA-03198-G	WA-04655(&9)-F	WA-23783-F	542-19	-	-	2789-1	2607-1	4478-19	-	-	5006 J2	5651 J6
11 Otehei	WA-03198-G	WA-04655(&9)-F	1419860+	542-19	WA-30579-F/1458962	WA-45131 & 9	2789-1	2607-1	4478-19	-	-	5006 J2+	5651 J6+
13 Kapura	-	-	1419859+	542-19	-	WA-39655-F	2789-1	2607-1	4478-19	-	-	5006 J3+	5651 J6+
14 Urupuk	WA-03198-G	WA-04655(&59)-F	1419790+	542-19	-	-	2789-1	2607-1	4478-19	-	-	5006 J2+	5651 J6+

15 Kaima	-	-	-	542-21	-	1269872	2791-2	2607-1	4478-23	-	-	5006 J2+	5651 J8+
16 Hauai	-	-	1419855	542-21	-	1269872	2791-2	2607-1	4478-23	-	-	5006 J2+	5651 J8+
18 Kaing	-	-	-	543-23	-	1246361	2791_2	2607-1	-	4479-23	-	5006 J2+	5651 J8+

Bay	**1981 (SN 5932A)**	**1985 (Whi)**	**1987 (Whi)**	**1987 (Walls)**	**1993 (NRC/Kerr)**	**2000 (NRC)**	**2003 (Harte)**	**2005/06 (Kerr/NRC)**	**2009 (OS20/20)**	**2011 (Salt)**	**2014-16 (NRC)**	**2017 (Wri)**
1 Otarepo	5932A I42	1429867	1434804+	-	√	√	-	DSC_0686	AV30-3645/46	110+	√	DW80312
2 Lagoon	5932A I42	-	-	√	√	√	-	DSC_0690	AV30-3647/48	102+	√	DW80304
3 Waipao	5932A I44	-	-	√	√	√	-	-	AV30-3501	-	√	DW80293
4 Opunga	5932A I44	-	-	√	√	√	-	-	AV30-3502	093	√	DW80283
5 Haha	5932A I44	-	-	√	√	√	-	-	AV30-3502	093	√	DW80283
9 Otiao	5932A I44	-	-	√	√	√	-	√	AV30-3307/08	066	√	DW80249
10 Oneura	5932A I45	WA-78090-F	1435052+	-	√	√	-	√	AV30-3409	-	√	DW80245
11 Otehei	5932A I45	1429874+	1435053+	-	√	√	-	√	AV30-3409	-	√	DW80239
13 Kapura	5932A I46+	1429875+	-	√	-	√	-	√	AV30-3509/10	-	-	DW80233
14 Urupuk	5932A I45	1429879+	1435050	√	√	√	√	√	AV30-3410/11	-	√	DW80221
15 Kaima	5932A I45+	-	1435064	-	√	√	-	√	AV30-3414	022	√	DW80218
16 Hauai	5932A I45+	-	1435062+	-	√	√	-	√	AV30-3515	022	√	-
18 Kaing	5932A I45+	-	1435057	-	√	√	-	√	AV30-3614	-	√	DW80203

Appendix 16: Area*% (ha) of the 12 major plus enduring (and three other) subtidal seagrass beds in the Bay of Islands by year. Blank, no data (Booth 2019).

MAINLAND	1935	1939	1942	1947	1950	1951	1953	1955	1959	1961	1971	1972	1973
15 Kaimarama						1.0528		7.4173	5.7275	7.004	9.5997		
16 Hauai					0	0.1935		0.108	7.763	12.4887	11.1172		
18 Kaingahoa						0		0	3.7359	4.0584		18.0424	
S-FACING													
1 Otarepo			0			0			0	0	0.1219		0.7854
2 Lagoon	0		0.3344		0.3713	0.2642			0.3111	0.2658	0.3733		0.2878
3 Waipao			0			0			0.0412	0.1164	1.0975		
13 Kapurarahurahu					0.0096	0		0	0	0	0.9171		
14 Urupukapuka				0	0	0			1.2861	3.9795	11.9087		
E-FACING													
4 Opunga			0			0			0.0878	0.1367	0.3057		
5 Hahangarua			0		0.0959				0.6722	0.6976	0.4139		
W-FACING													
9 Otiao						0			9.1783	14.1593	16.7557	17.2063	
10 Oneura		0		0	0	0			0.3911	0.5552	0.0467		
OTHER													
6 Awaawaroa							0.0172	0	0	0.0244	0.051	0	0
7 Otupoho					0.0188				0.1943	0.0973	0.2707		
11 Otehei					0.1955	0	0		0	0	0.0845		

	1978	1980	1981	1985	1987	1993	2000	2003	2005	2009	2011	2015	2017
15	3.7019	2.9312	2.9199		3.5663	0.3834	0.031		0.3084	0.0709	1.493	2.5181	4.1646
16	8.8309	9.9158	12.3179		8.146	3.5578	0.7658		0.5652	0.8278	0.4658	2.3736	
18	11.2821	10.2024	12.1699		10.6438	6.5838	4.2338		2.2721	0		10.6854	11.4694
1	1.4882	1.7732	1.8747	1.9727	2.2334	1.181	1.0208		0.9575	1.2524	1.3773	1.202	1.9094
2	0.8283	1.1852	0.7932		0.3655	0.4346	0.2692		0.4807	0.4142	0.5841	0.3518	0.6036
3	1.6322	1.7997	1.7849		1.7849	1.3445	1.6789			1.1552		1.0034	1.6994
13	1.239	0.5886	0.9976	0.5273	0.9637	0.1577	0.1245		0	0.3904		0.7003	0.6719
14	0.4746	2.5633	3.3454	6.3303	9.2014	0.7154	3.7762	2.4223	4.094	11.9966		11.7153	7.6007
4	0.4266	0.3541	0.5834		0.3541	0.0649	0.0402			0.0131	0.0683	0.1534	0.4759
5	0.614	0.6449	0.6269		0.6449	0	0.1178			0.0447	0.0472	0.3333	0.3406
9	12.5864	10.6633	11.9703		10.0821	6.484	13.2206		13.1215	14.1462	17.3828	14.0725	17.419
10	0.2457	0.5978	0.7777	0.5373		1.0626	0.6575			0.8665		1.3173	1.3789
6	0	0.0572	0	0	0	0	0			0.0059	0.0049	0.0331	0.066
7	0.0641	0.2722	0.2124		0.2722	0.013				0	0	0	0.0019
11	0.7253	0.7336	0.868	0.7755	0.5264	0.162	0		0	0		0	0.0407

Appendix 17: Early aerial images suggest little seagrass in eastern Bay of Islands.

Motuarohia. In the 1930s, Lagoon Bay on Motuarohia appeared bereft of subtidal seagrass (upper, red circle; National Library reference 1367622); by winter 1942, limited seagrass cover (green arrows) was visible in Lagoon Bay, but not in Otarepo (lower; Air Force Museum of New Zealand reference 235 A2). ('Reef' refers to dark kelp-shadows at beach-ends.)
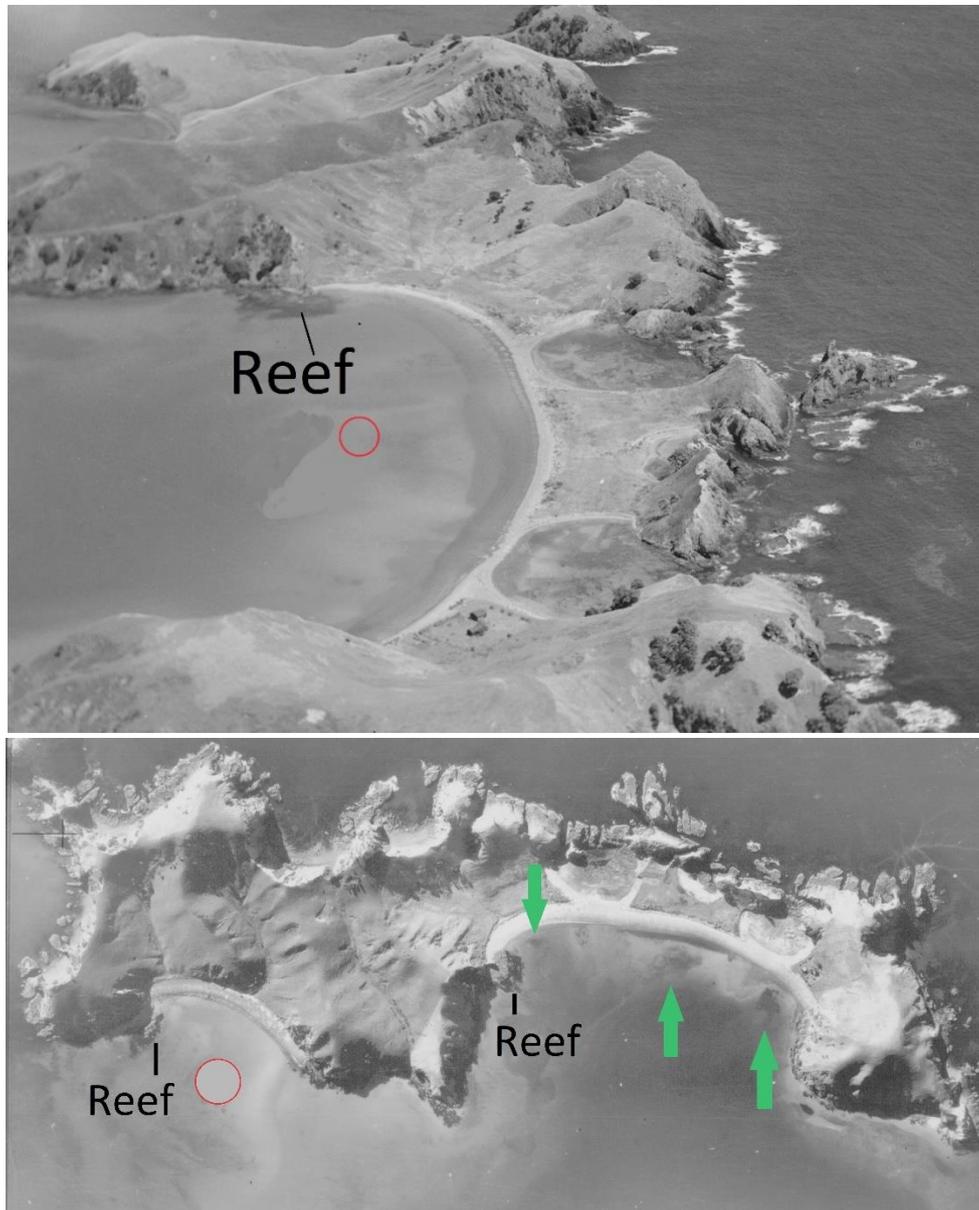
Other oblique one-off images were also useful. Otarepo Bay apparently lacked seagrass in the late-1950s (the dark area on the left of the bay being kelp associated with reef; seagrass had clearly established by January 1973 (National Library reference WA-71219-G); it appears to have expanded by February 1987 (National Library reference 1434804); and to have covered much of the length of the bay by November 2011 (Salt Air Paihia 110, there no longer being subtidal kelp associated with the reef at bottom left).

Late-1950s

Reef

1973

1987

2009
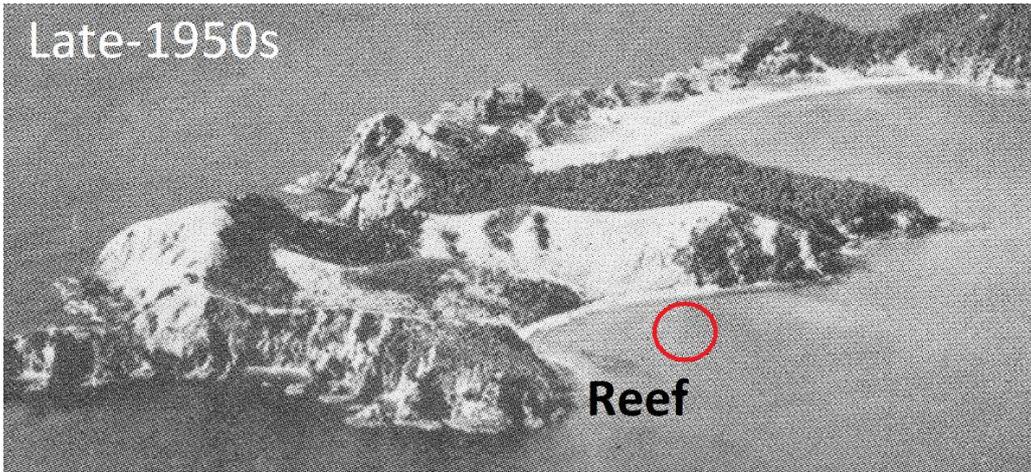
Moturua In winter 1942, bays at the south end of Moturua appeared bereft of subtidal seagrass (Air Force Museum of New Zealand reference 138 A5) (upper), but seagrass in one bay was indicated in the early-1950s (NZ Aerial Mapping Ltd [NZAM] Survey No. 209, 542-16) (lower).
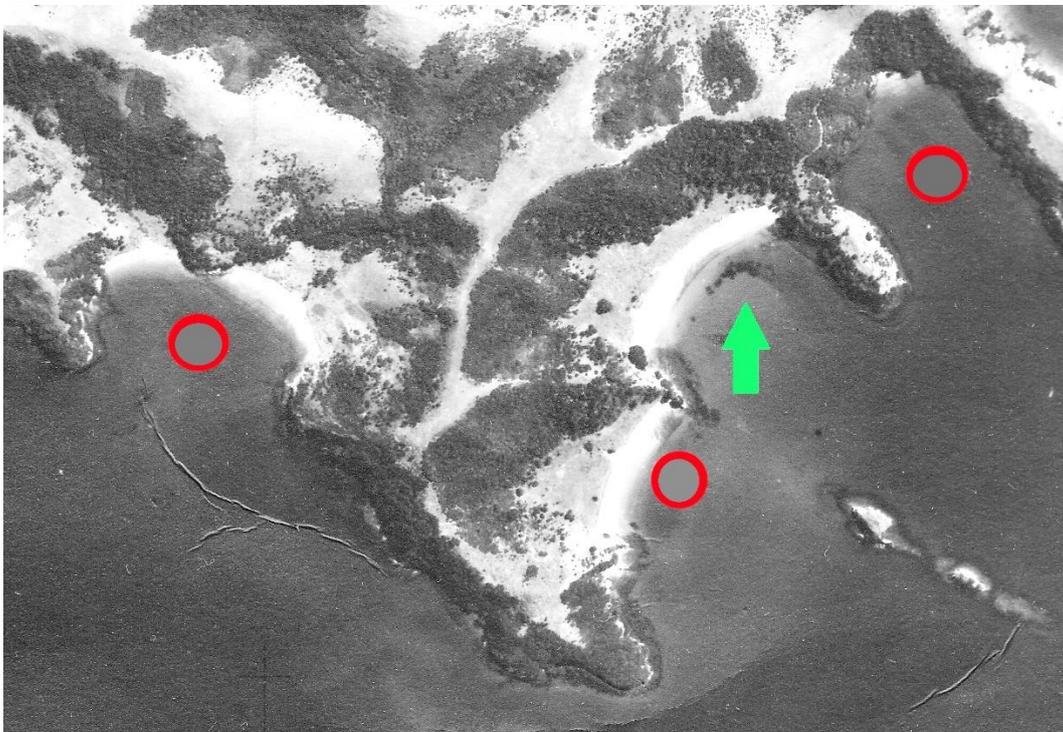
Urupukapuka Island No seagrass was indicated in the early-1950s (NZAM Survey No. 209, 542-19).
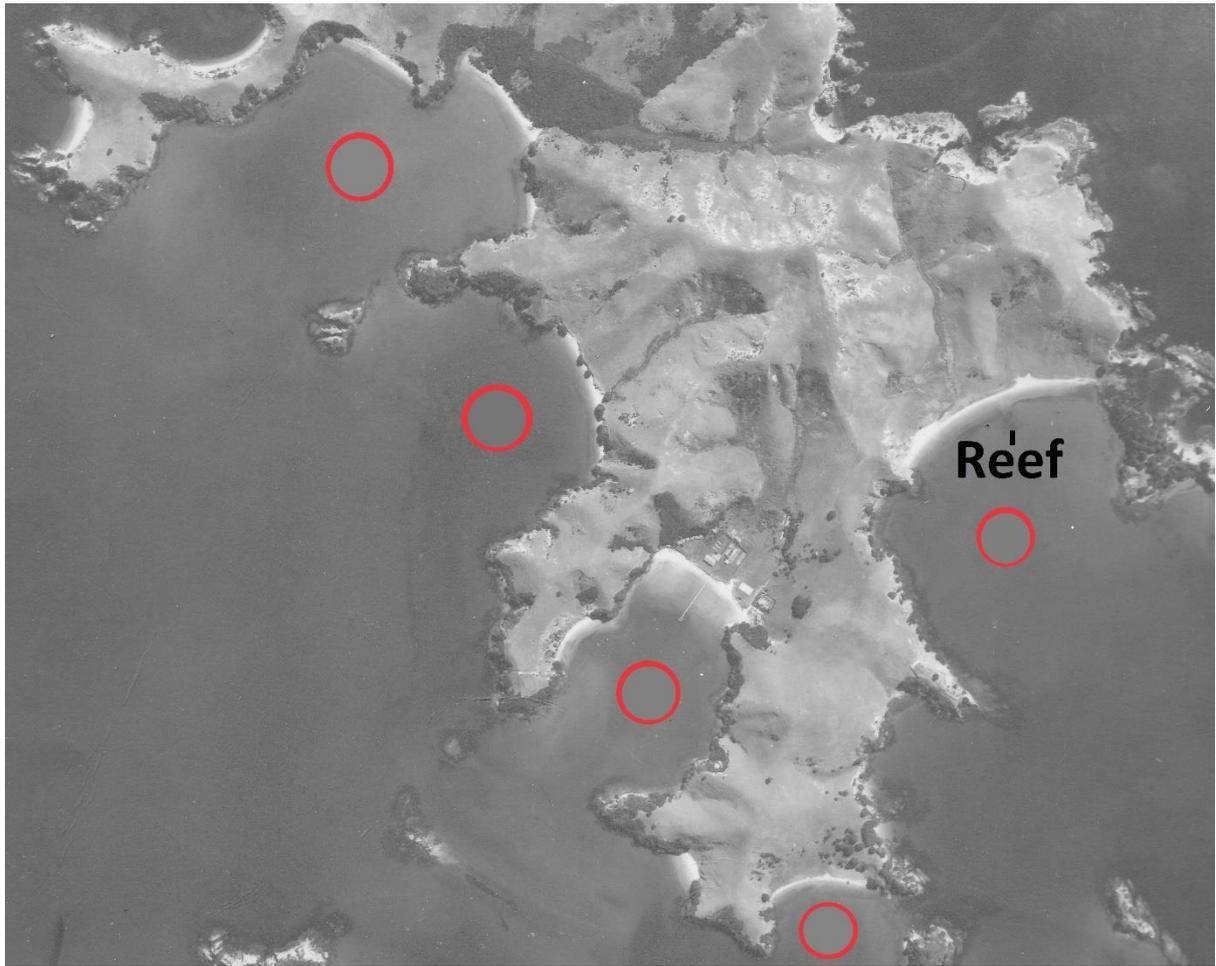
Mainland Little seagrass was indicated in the early-1950s, except in Kaimarama (NZAM Survey No. 209, 542-21) (upper), yet by spring 1959 it was widespread (NZAM Survey No. 1223, 2791-2) (lower).
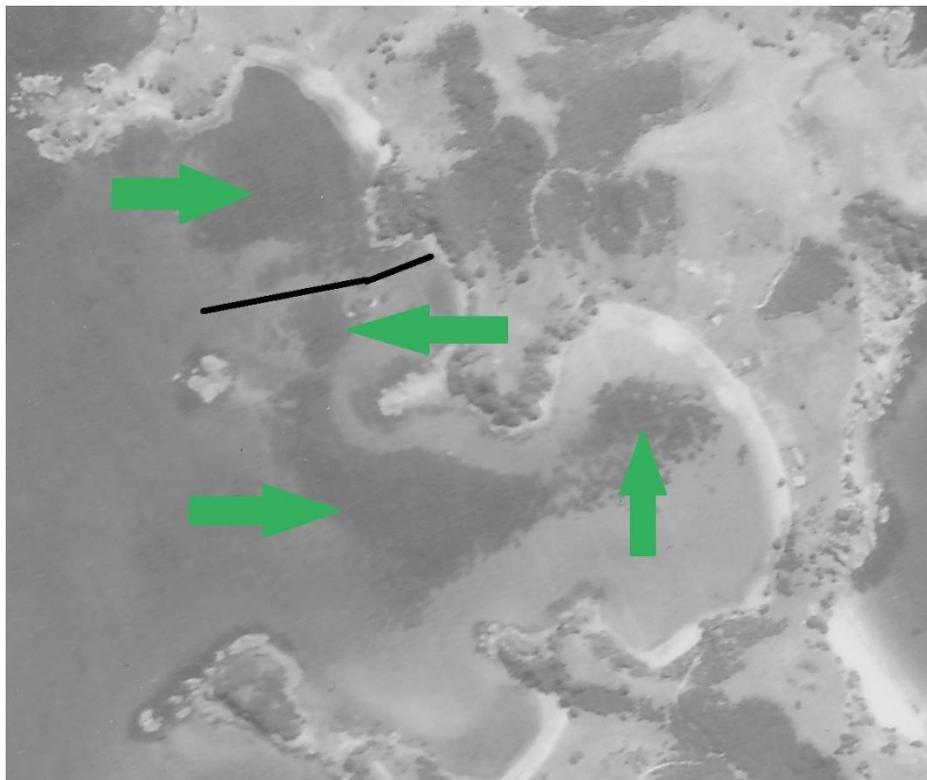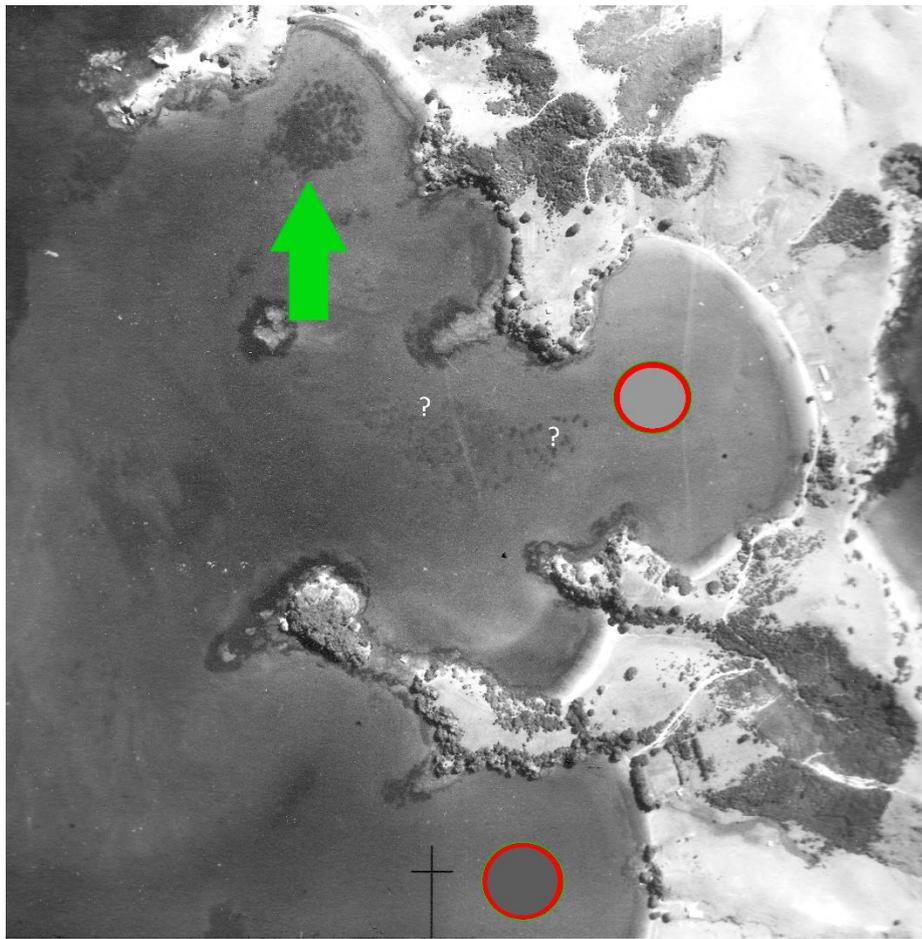
Appendix 18: Correlations in seagrass cover over time. *rho* values for Spearman Rank Correlation Coefficient comparisons of Area*% seagrass cover of beds according to direction faced, with level of significance (*, $P<0.1$; **, $P<0.05$; ***, $P<0.01$) (Booth 2019). Kaing, Kaingahoa; Kaima, Kaimarama; Haha, Hahangarua; Kapura, Kapurarahurahu; Urupuk, Urupukapuka

W-facing				S-facing						E-facing	
	Mainland		Islands		Mainland	Islands				Islands	
	18 Kaing	16 Hauai	10 Oneura		15 Kaima	1 Otarepo	2 Lagoon	3 Waipao	14 Urupuk		4 Opunga
16 Hauai	0.733***			**1 Otarepo**	-0.096					**5 Haha**	0.578**
10 Oneura	0.201	-0.091		**2 Lagoon**	-0.123	0.716***					
9 Otiao	0.450**	0.309	0.229	**3 Waipao**	-0.213	0.801***	0.613***				
				14 Urupuk	-0.036	0.390**	0.076	0.049			
				13 Kapuha	0.328*	0.622***	0.466**	0.571**	0.420**		

Appendix 19: Graphs illustrating associations between subtidal-seagrass cover and certain biotic and abiotic factors (listed in Table 4) (Booth 2019).
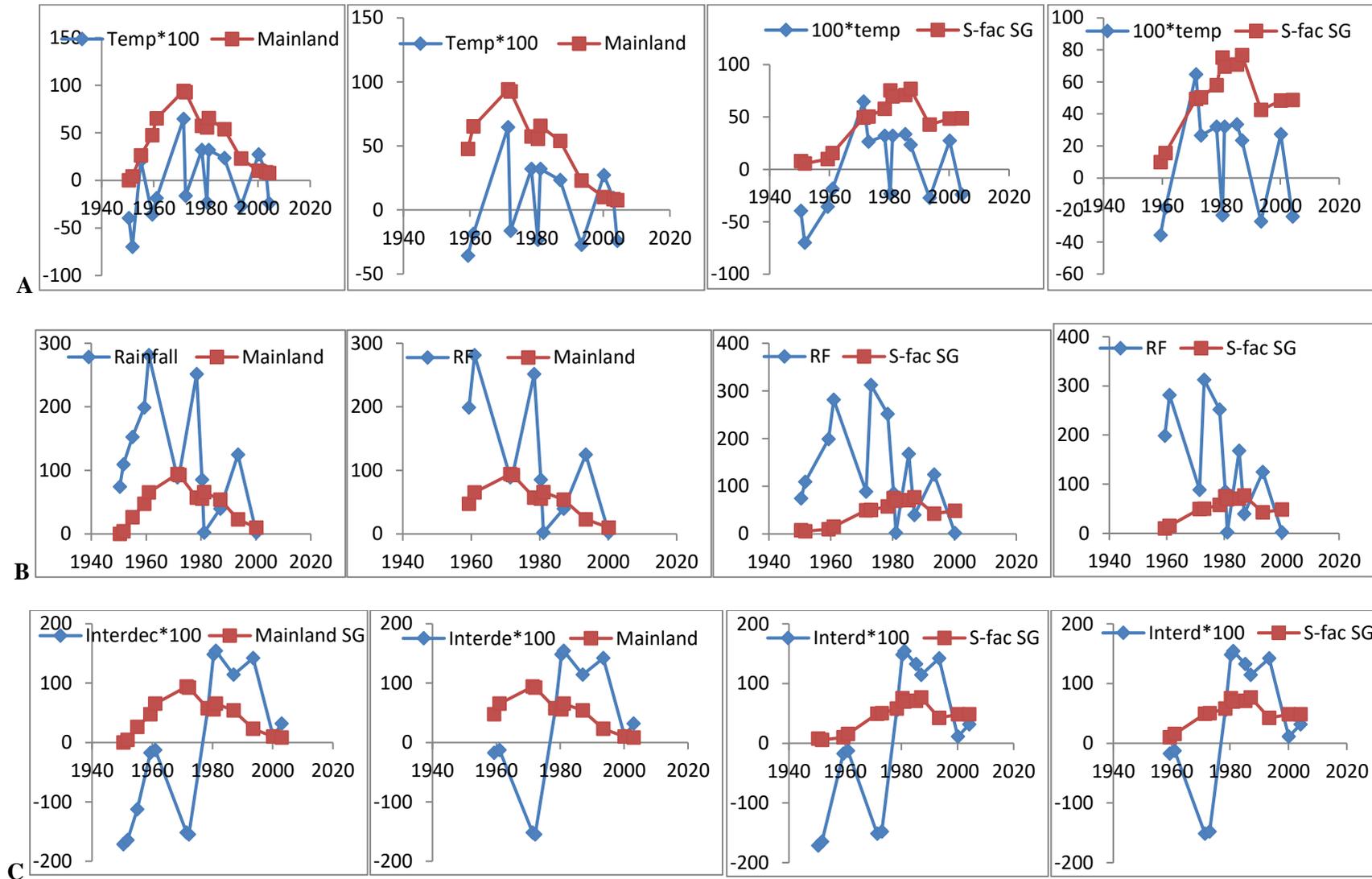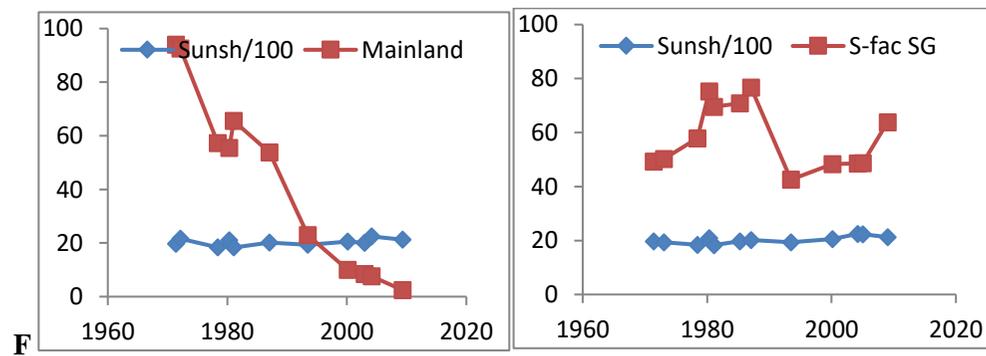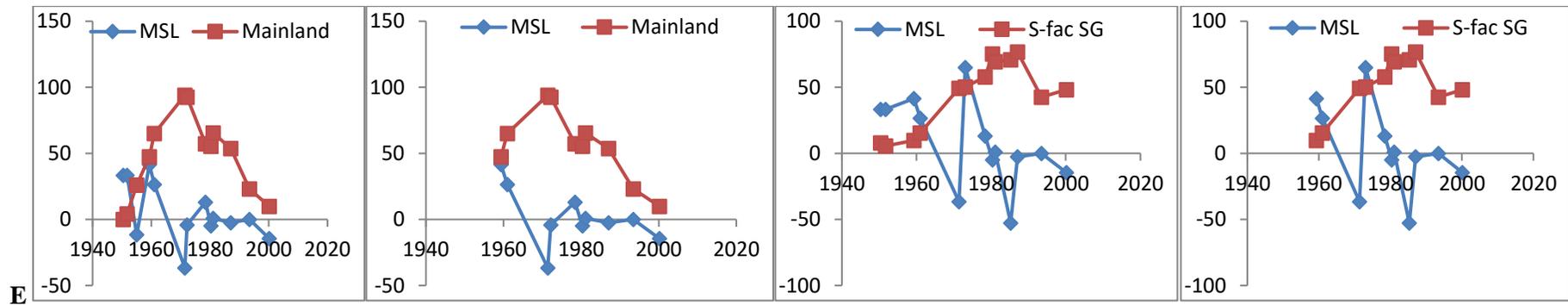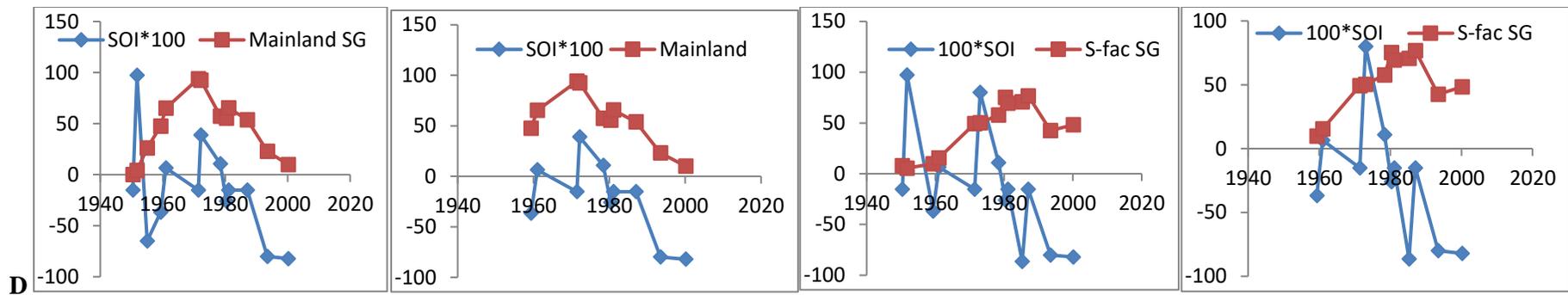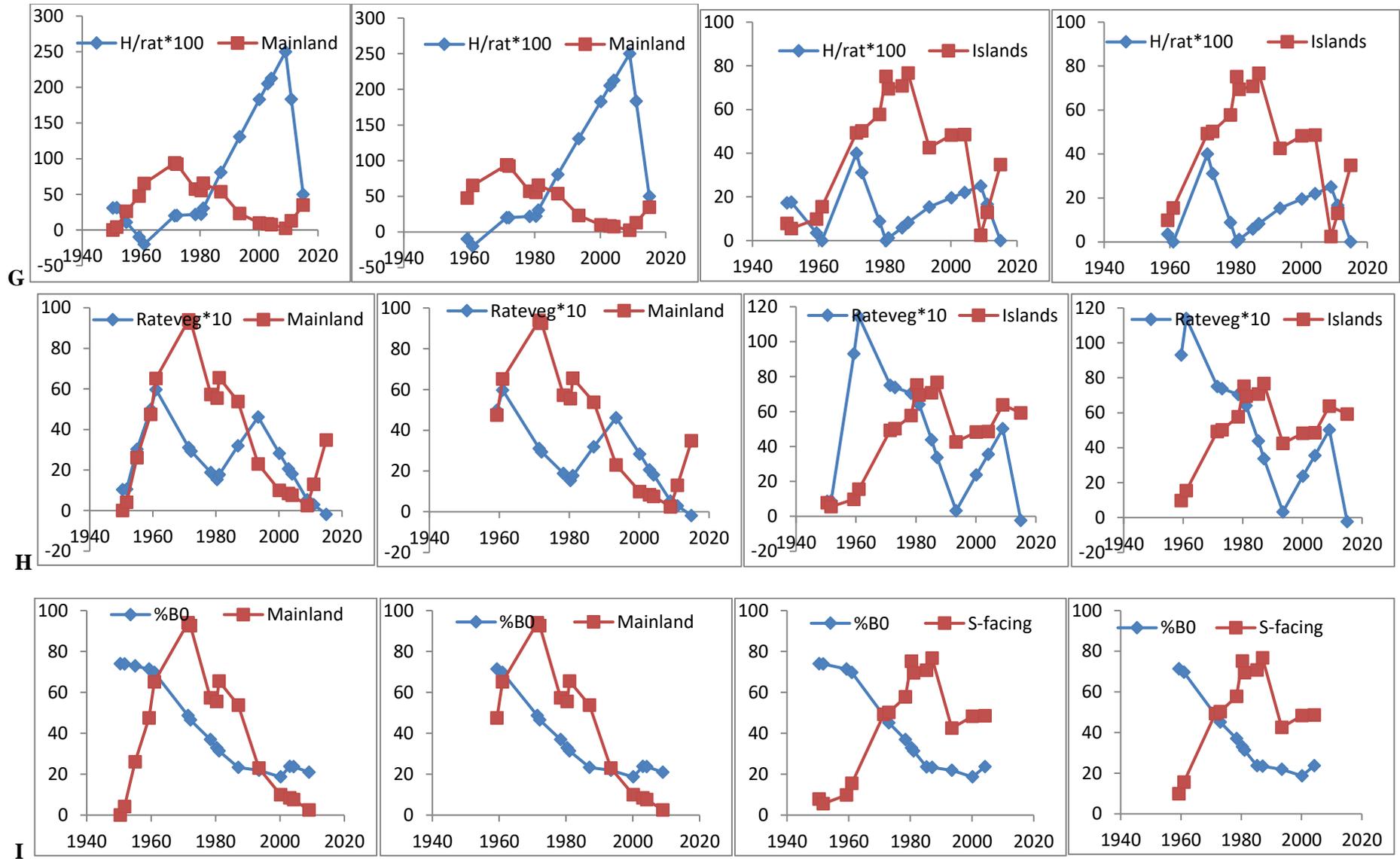
J
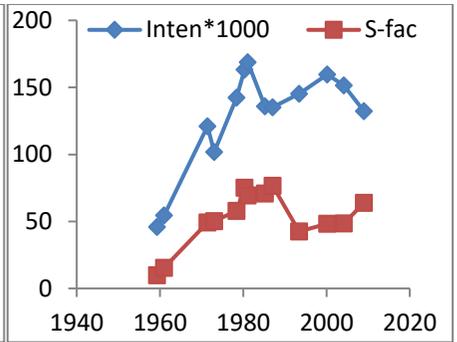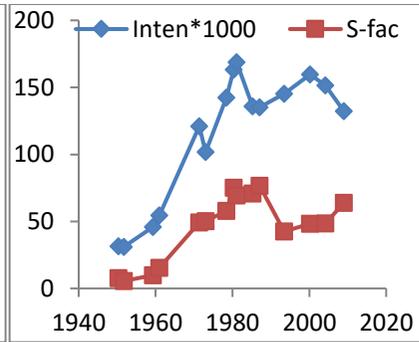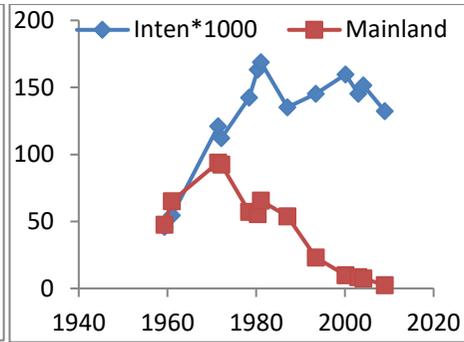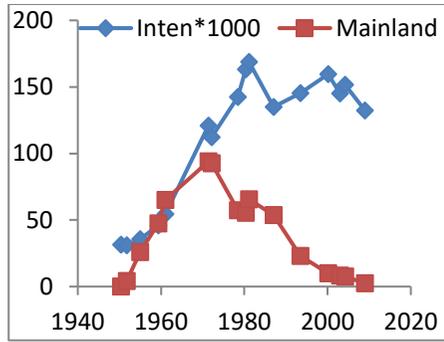
Appendix 20: Distribution of particular taxa in the 1990s. Morley & Hayward (1999) dredged at 330 points, and snorkel-surveyed numerous-other intertidal and shallow-tidal stations, around the Bay of Islands. Shown are stations where rhodoliths (live and dead) and scallops (live, and additional to those of Hayward et al. 1981) were found by Morley & Hayward (1999) (Bruce Hayward, pers. comm.).
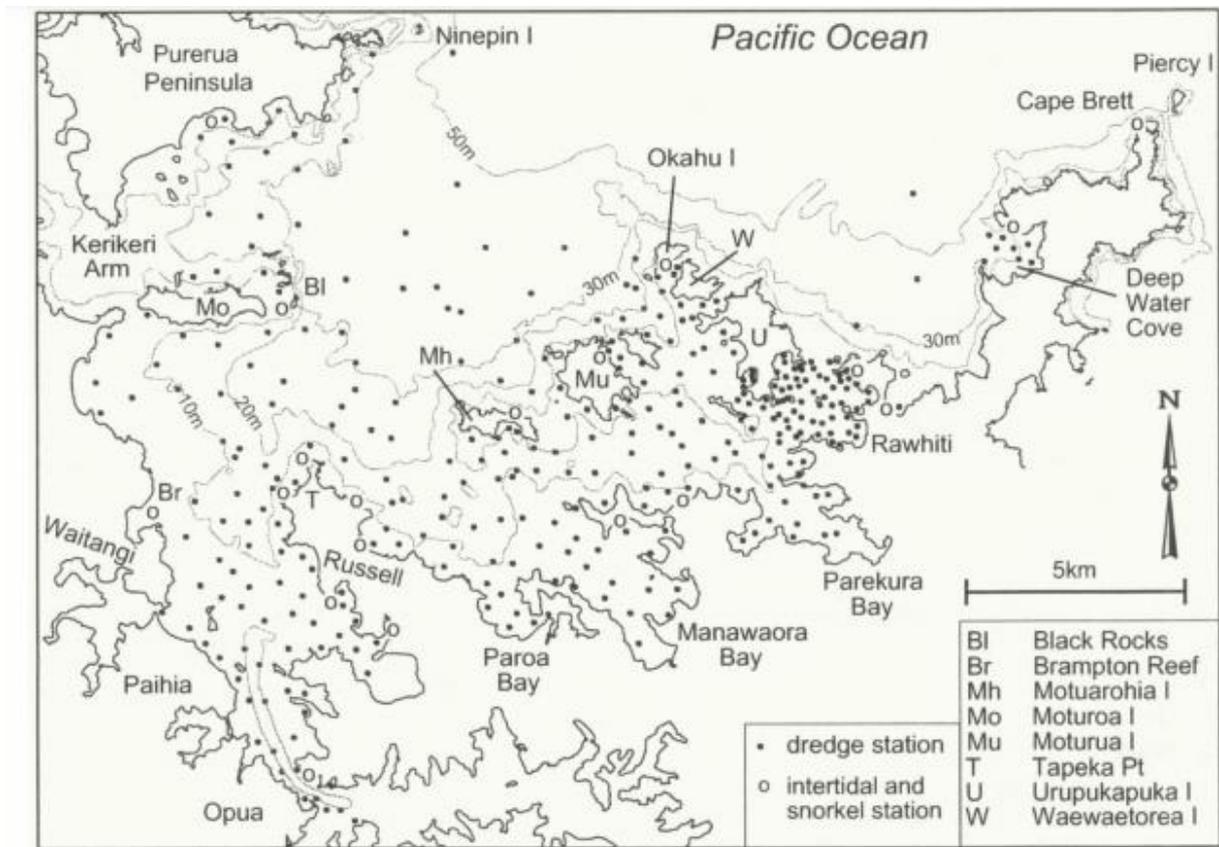
Appendix 21: Hayward's et al. (1981) benthic communities in eastern Bay of Islands. Dominant benthic species (upper left) and benthic habitats (upper right) off the south end of Urupukapuka Island (Hayward et al. 1981) in January 1980 superimposed on the aerial imagery for that date (Crown_5651_J_6). Indicative seafloor communities in 2009 (Ocean Survey 20/20) (lower left). Location of study site (lower right). For species: C, *Corbula zelandica*; M, *Mesodesma australe* (= *Paphies australis*); Z, *Zeacolpus pagoda-Zegalerus* (= *Sigapatella*) *tenuis*; Zm, *Zostera muelleri-Nucula hartvigiana*. For substrates: FS, fine sand; MS, medium sand; MuS, muddy sand; VCS, very coarse sand; SG, shell gravel. For 2009 image: AT, algal turf; MS, muddy sand; R, reef; S, sand; SG, seagrass.
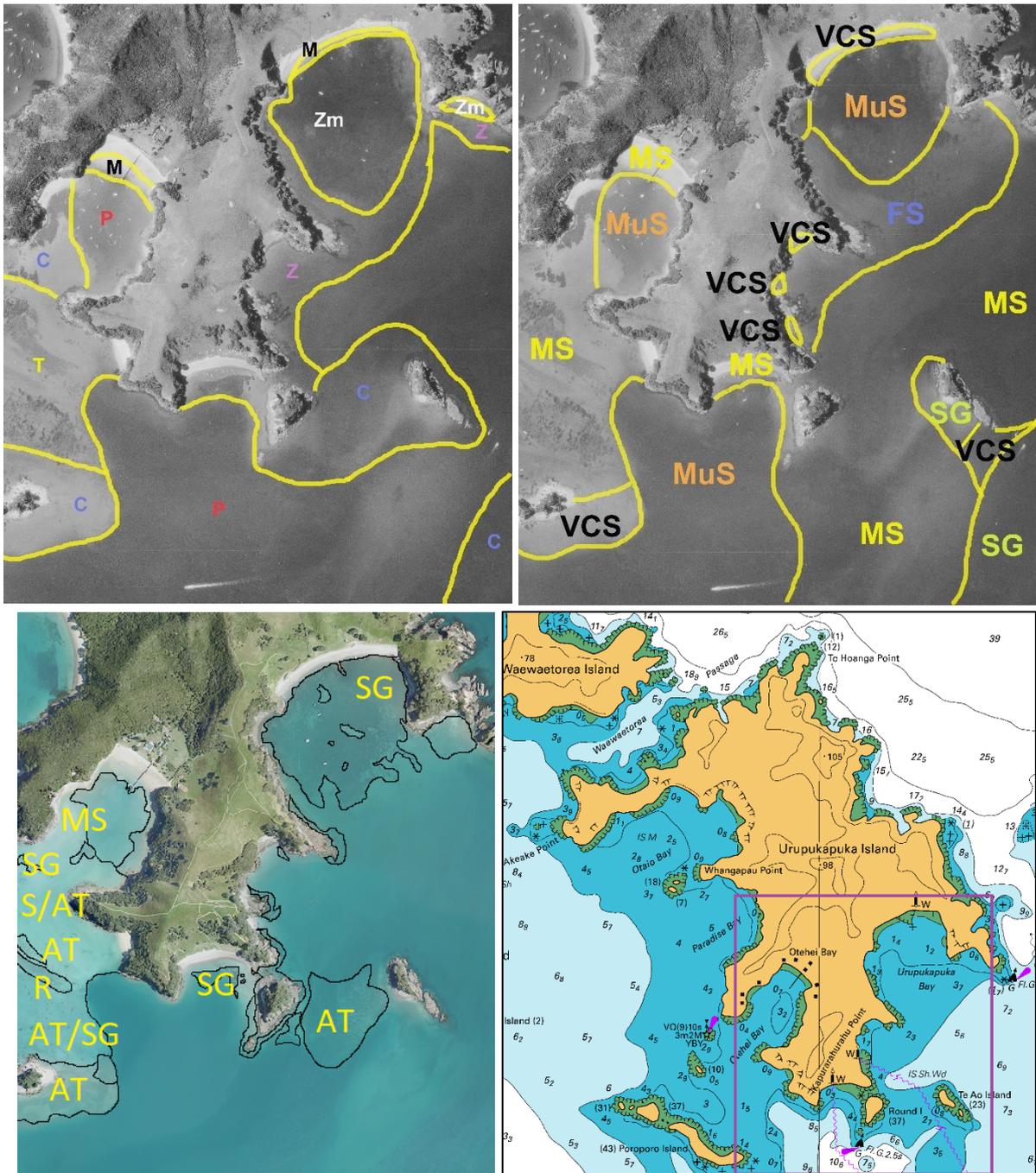
Appendix 22: Rhodolith beds near Kahuwera Point and Te Miko (Nelson et al. 2012). These beds broadly cover southwest parts of Ipipiri at depths mainly ≥8 m.
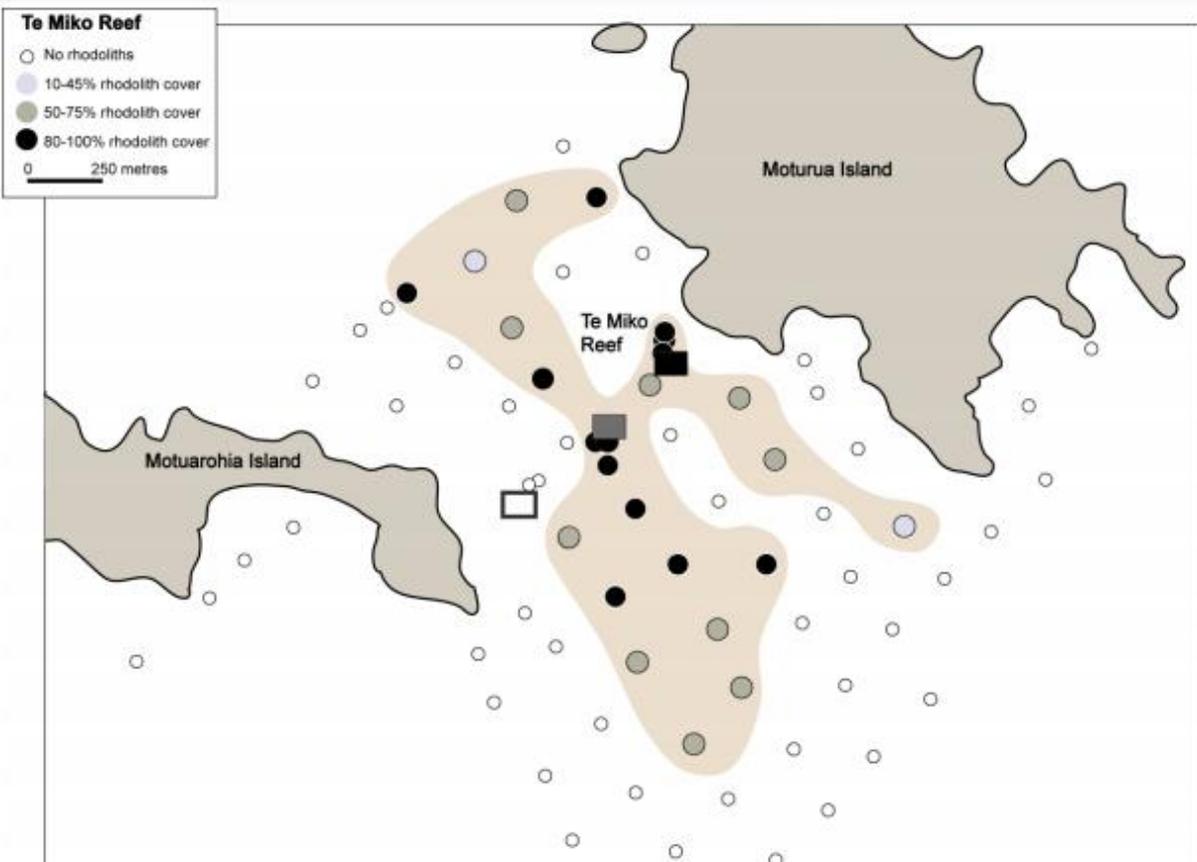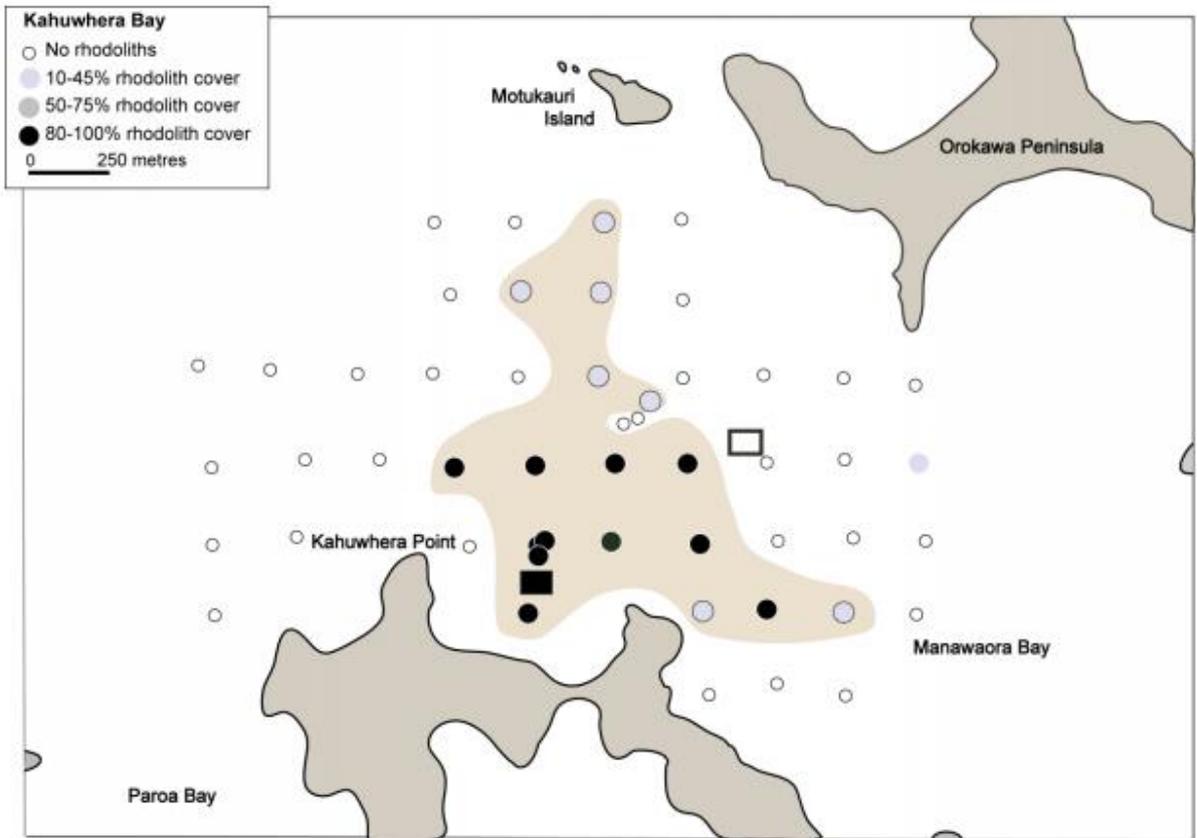
Appendix 23: Biogenic habitats of Poroporo Channel. Shown below are representative images taken in February 2020 at depths of 3-5 m within the soft-bottom red-algal turf biome shown in Figure 45.

Robust dog cockle valves and worm mounds are scattered throughout the algal turf.
(Image: Tim Booth, with permission)

Widespread tawera shell hash often contains rhodoliths. (Images: Tim Booth, with permission)

**Worms are in places abundant among the shell hash. (Image: Tim Booth, with permission)**

Hydroclathrus **formed large accumulations in places, with scattered** *Codium fragile* **(background).**
(Image: Tim Booth, with permission)

Appendix 24: Changes over time in the seafloor biodiversity of Poroporo Channel. Five historical images are examined, the first from 1951, and compared with that for 2020. The pre-2000 images are the only useful ones known to exist; later, there may be others (eg, Google historical).

The resolution of the earliest images (1951 and 1971) is such that seafloor biological and physical features cannot be determined with confidence, but the impression is that the nature and orientation of contrasting light/darker features suggest concurrence with those seen in the later, and in today's, imagery. From 1980, seagrass, algal turf and reef are generally distinguishable in the aerial imagery. The images over time suggest stability in the distribution of the algal turf, but with changes in the extent of the surface expression of seagrass, in particular. For seagrass, although not readily distinguished in the 1951 and 1971 images, but it was widespread in 1980, had become greatly diminished in extent in 2009, and then became increasingly obvious from 2015 onwards.
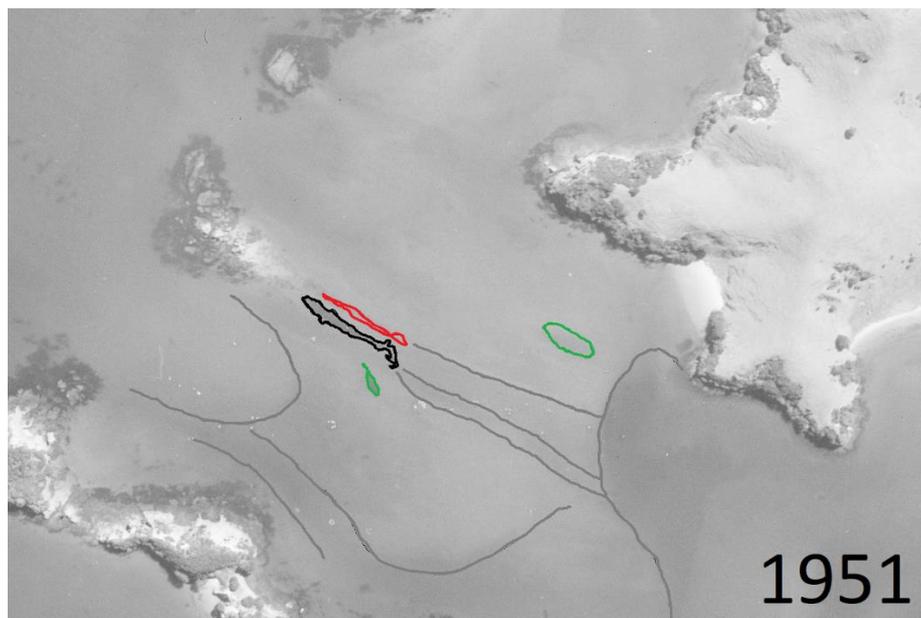
Poroporo Channel aerial imagery indicating the distribution of biomes in 1951. Green, putative seagrass; red, putative algal turf; black, reef.
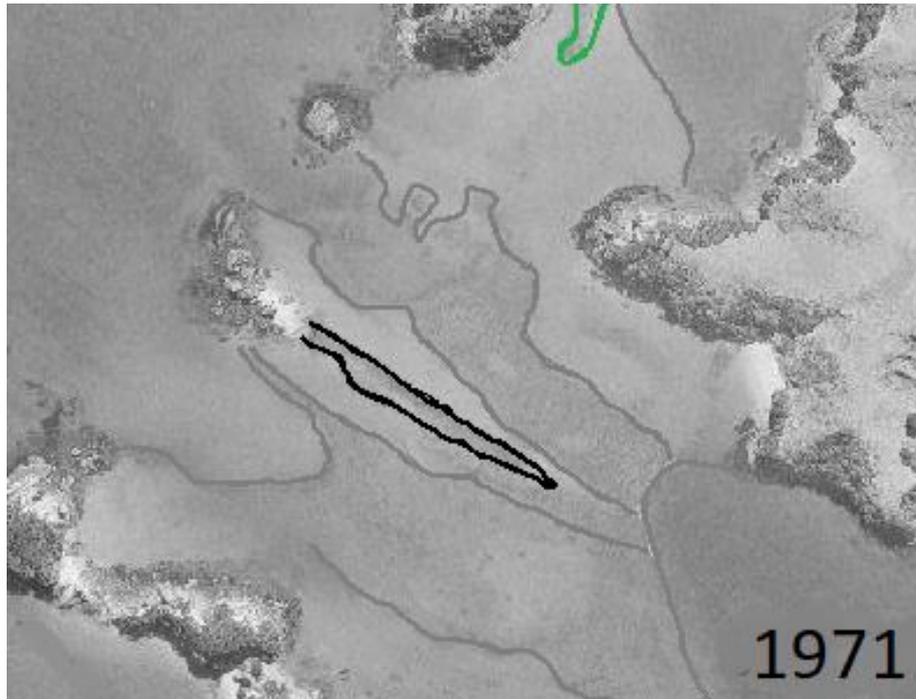
Poroporo Channel aerial imagery indicating the distribution of biomes in 1971. Green, putative seagrass; red, putative algal turf; black, reef.
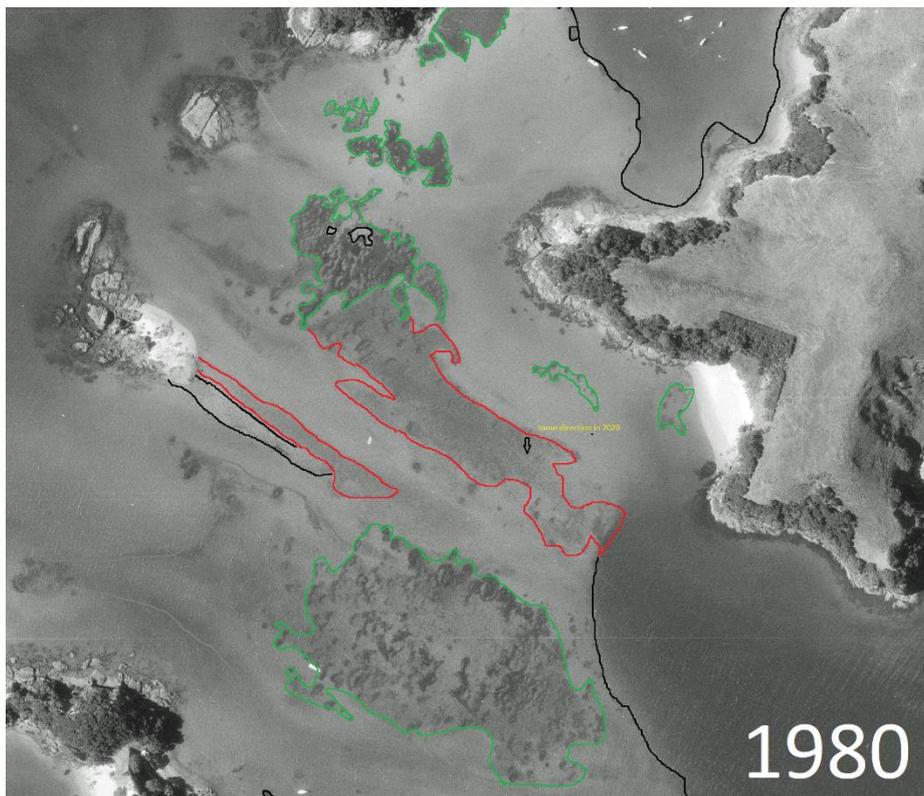

Poroporo Channel aerial imagery indicating the distribution of biomes in 1980. Green, putative seagrass; red, putative algal turf; black, reef.

Poroporo Channel aerial imagery indicating the distribution of biomes in 2009 (Oceans 20/20). Green, putative seagrass; red, putative algal turf; black, reef.
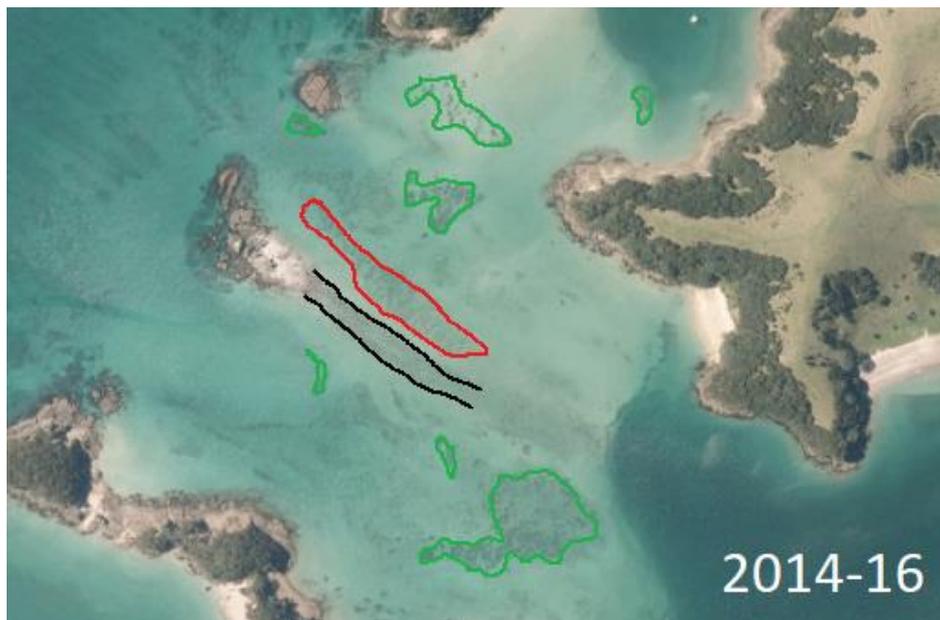
Poroporo Channel aerial imagery indicating the distribution of biomes in 2014-16 (NRC). Green, putative seagrass; red, putative algal turf; black, reef.
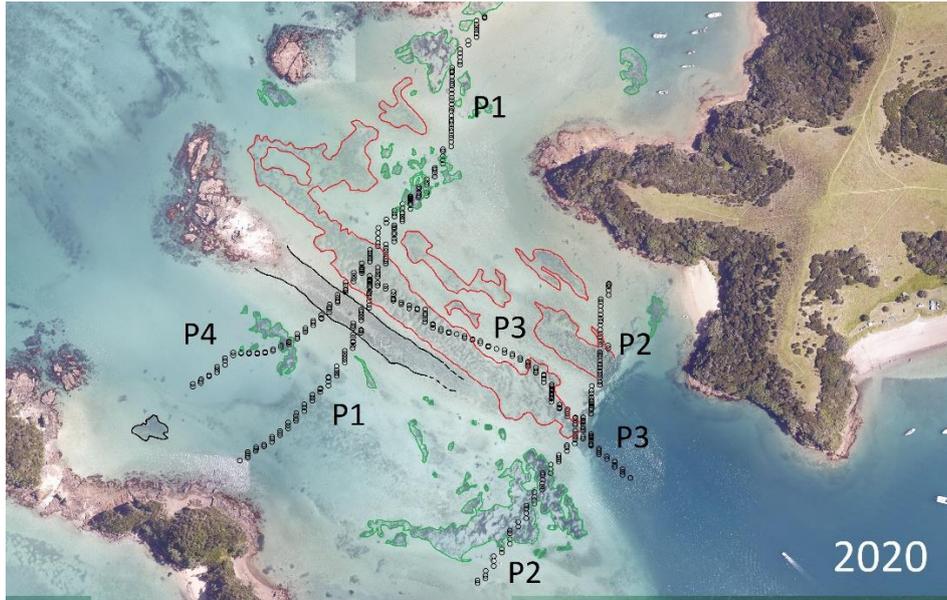
Poroporo Channel aerial imagery indicating the distribution of biomes in 2020 (NRC). Green, putative seagrass; red, putative algal turf; black, reef.