



Reviewing the far-reaching ecological impacts of human-induced terrigenous sedimentation on shallow marine ecosystems in a northern-New Zealand embayment

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REVIEW ARTICLE



Reviewing the far-reaching ecological impacts of human-induced terrigenous sedimentation on shallow marine ecosystems in a northern-New Zealand embayment

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ABSTRACT

Human settlement in Bay of Islands, New Zealand, beginning ~1300 AD, wrought immense, conspicuous and enduring change to local shallow-water marine ecologies, this review addressing those transformations attributable to increased rates of anthropogenically induced, land-derived sedimentation. Elevated silt inflow, particularly after the late-1800s, in course led to ~130% expansion in mangrove (*Avicennia marina*) cover, with concomitant loss of saltmarsh, uppershore coarse-shell beaches/cheniers, and (probably) intertidal seagrass (*Zostera muelleri*). Sedimentation also led to widespread loss of estuarine shellfish habitat, and, although not necessarily categorically causal, seems, at the same time to have contributed to such degradation among cockle (*Austrovenus stutchburyi*) populations that few individuals attain their potential size. Most changes, many seemingly irreversible, can be described as ecologically catastrophic, with ecosystems altered and destroyed, and uncommon habitats threatened. Sedimentation appears 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. Outstanding issues concern establishing the extent of relationship between levels of terrigenous sedimentation and cockles seldom attaining their previous maximum sizes, and origins of the possibly new, widespread phenomenon of living cockles accumulating and dying atop beach surfaces.

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Introduction

Sediment derived from the land inundating nearshore marine substrates is of wide ecological concern in New Zealand (e.g. Morrison et al. 2009), as well as globally (e.g. Gray 1997), with numerous coastal ecosystems being profoundly altered or lost altogether. The sand and mud habitats dominating estuaries and coastal embayments are typically biologically diverse and are 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

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ecosystems, particularly as sediment-transfer rates rise (e.g. Gray 1997; Thrush et al. 2004), with even small amounts of typically fine terrigenous sediment altering community structure and causing loss of critical species. The consequences of such sedimentation include depressed condition among filter feeders such as cockles, the silt particles abrading, clogging and smothering, reducing interstitial spaces, and reducing 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 (e.g. Swales et al. 2012). Moreover, with climate warming 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 be even more impacting (Lohrer et al. 2004; Norkko et al. 2006). Critical thresholds for benthic species can be exceeded more frequently, with less time to recover between events and with greater chance for gradual degradation in benthic community structure and function.

Progressing our understanding of ecosystem functioning just before humans arrived, and early in settlement, can assist coastal managers in developing 'marine environmental histories' and in acquiring critical insight into baseline states-of-nature before human modification (e.g. Maney et al. 2014; Klein and Thurstan 2016; MacDiarmid et al. 2016) from which change over time can be gauged.

Using both mainstream (e.g. aerial imagery) and less-widely utilised data (e.g. contents of Māori middens), this ecological study enquires into the pervasive impact of anthropogenically induced terrigenous sedimentation on shallow marine ecosystems of a northern-New Zealand embayment, the Bay of Islands (35° 12' S, 174° 10' E). After providing brief physical and social settings, I use changes in a suite of key indicator communities to demonstrate catastrophic ecological change resulting from sedimentation: (1) expansion in the mangrove (*Avicennia marina*) footprint; (2) concomitant contraction in the extent of saltmarsh; (3) loss of naturally rare and now critically endangered uppershore sand/coarse-shell beaches, and the chenier-like spits (Wiser et al. 2013; landcareresearch.co.nz/publications/factsheets/rare-ecosystems/coastal/shell-barrier-beaches-chenier-plains) that form elongate barriers at freshwater outflows; (4) extirpation of intertidal seagrass *Zostera muelleri*; and (5) loss and/or degradation of harvestable beds of shellfish (particularly cockles or tuangi/pipi, *Austrovenus stutchburyi*).

Physical and social setting

Bay of Islands (Figure 1) is a series of drowned river valleys; with about 180 km² in surface area at high-water, many of its numerous islands mark summits of what were once hills. The underlying geology is predominantly greywacke, resultant soils and clays being prone to erosion and aquatic leaching, although there are also extensive basaltic zones in the west.

Bay of Islands lies in a warm-temperate zone with strong subtropical and tropical influences, particularly during summer. Surface waters reach 20–22°C in late-summer and drop to 13–16°C in late-winter (MacDiarmid et al. 2009). However, there has been

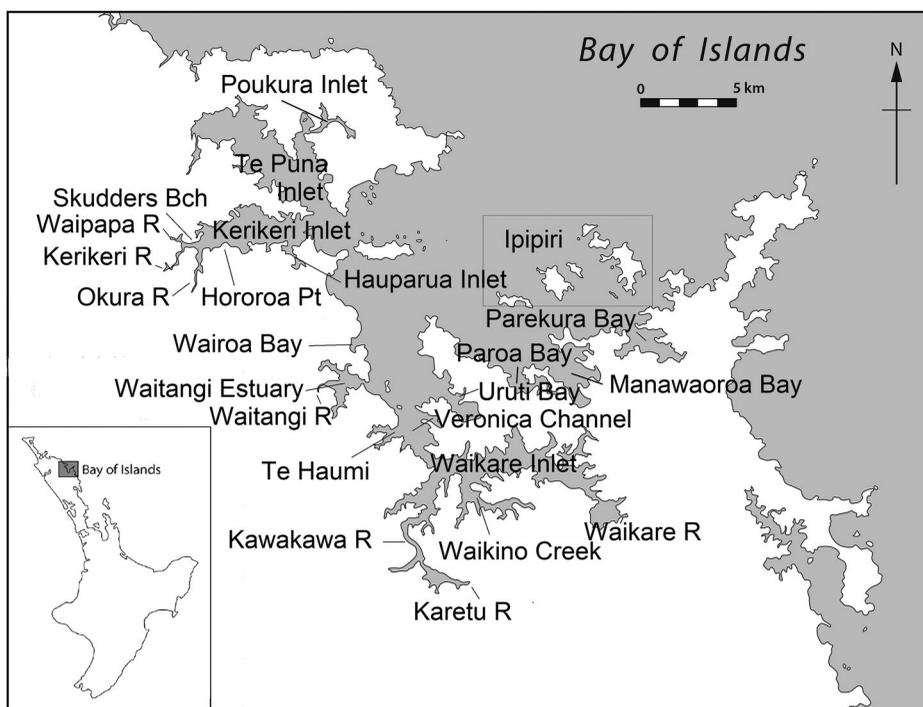


Figure 1. Bay of Islands, showing places mentioned in text and location on the North Island of New Zealand.

considerable variation in South Pacific temperatures over the past millennium, in line with global changes in climate. Briefly, 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°C–0.5°C above today’s; and during the eighteenth century about 0.8°C lower (Anderson et al. 2014).

Catchment land-use is mainly agricultural, the low levels of industry (including quarrying) around the Bay meaning generally low chemical contamination of aquatic systems (Griffiths 2011, 2013, 2014, 2015). Waters are reasonably well mixed, with a residence time of ~19 tidal periods (MacDiarmid et al. 2009).

Human settlement in the Bay of Islands apparently began around 1300 AD (Robinson et al. 2019), early accounts indicating a large Māori population ($\geq 10,000$) in the Bay at first-European arrivals (1769, then 1772) (Booth 2017). European settlement escalated following the Christian missions that began in 1814. The ‘usually resident’ population of the Bay of Islands today is ~40,000, about half living within 5 km of the shore.

Land cores show how Polynesians had devastating impact on the vegetation of the Bay of Islands and its surrounds, initially through fire (e.g. Elliot et al. 1997), forest being cleared to promote growth of starch-rich bracken *Pteridium esculentum* in particular. But erosion from these catchments was minimal, soil structure being maintained by networks of 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 of Islands showed these early firings resulted in only modest increases in SAR (Swales et al. 2012).

With European settlement, soil erosion increased markedly, key land-use changes including widespread land clearance for pastoral farming, beginning in the late-1800s, and, later, plantation-pine planting and citrus orcharding (Swales et al. 2012). Replacement of soil-stabilising vegetation with pasture left soft-rock hill-country soils vulnerable to erosion and landslides (Wilmshurst 1997).

Average annual sediment deposition in the Bay of Islands 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 4,300 t; Kerikeri 12,100 t; Waitangi 62,700 t; and Waikare 9,100 t. Most terrestrial material enters the sea after heavy rainfall on steep and erosion-prone terrain, resulting in increasing suspended sediments in the water column and fine sediments deposited within channels and on their margins, some subsequently being resuspended and transported seaward. Bay of Islands SARs are now 10–20 times higher than before European settlement (Swales et al. 2012), with values typically several times greater in upper estuaries (Oldman et al. 2009), leading to higher rates there of, for example, mangrove expansion.

Methods

Mangrove cover: Information on changes in mangrove distribution throughout the Bay of Islands was derived from (1) nineteenth and early-twentieth-century maps, plans and commentaries and (2) synoptic aerial imagery, beginning in the early 1950s, which additionally allowed estimates concerning changes in individual tree size and density.

Photographed from above, mangroves present dark shadows that contrast with the lighter-coloured surrounding substrate, although the boundary between mangrove and saltmarsh was sometimes tricky to determine. Areal cover of mangroves was estimated from the images listed in Tables S1 and S2 after they had been uploaded into QGIS and orthorectified; crowns of individual trees had to have been at least 2 m across in order to be unequivocally mangrove. The areal cover of groups or lines of *individual* mangroves was more difficult to evaluate than for dense groves of trees, this probably leading to some overestimation. In order to minimise error associated with what was inevitably a certain amount of subjective interpretation, the author alone analysed all images in one session.

Uppershore sand/coarse-shell beaches and spits: These beaches and spits were most readily distinguished in the earliest (mainly early 1950s) synoptic aerial imagery (although the minor streams that once also had small spits at their freshwater/seawater confluence were not necessarily visible) – but many such shores were already overrun by mangroves by then. Nevertheless, these images formed the baseline from which to estimate the extent of subsequent loss of this biome, shoreline lengths being derived from orthorectified images uploaded into QGIS, with Kerikeri Inlet being considered representative of the entire Bay of Islands.

Intertidal seagrass: Orthorectified aerial images examined in a standard manner (Booth 2019), merged with memories of long-term locals, were the basis for developing understanding around intertidal/shallow-subtidal seagrass cover for the entire Bay of Islands. Images were systematically examined for evidence of shadows in shallow areas of soft substrate that appeared similar to known seagrass beds visible in the same or associated images. But because intertidal beds tend to show less-well than those subtidal, the full extent of intertidal seagrass may not have been captured.

Cockle size and density: Mid-Kerikeri Inlet was the main focus for detailed assessment of changes over the past two centuries in the characteristics of cockle populations, the main data sources being historical accounts, midden records and field sampling; for the broader Bay of Islands, the approach taken was to compare and contrast the features of the cockles present in middens with the living cockles found nearby today.

The historical information around cockle beds was gleaned from early missionary and explorer accounts, with midden-cockle size data derived from Site Record Forms (SRFs) on ArchSite, New Zealand Archaeological Association's Site Recording Scheme website and from examination of surface cockles on specific middens. Although proportions of pure shell to organic material vary a lot, standardised estimates of midden volumes were derived from the SRFs by assuming 1-m width and 0.2-m depth for each reported metre-length of midden.

Recent cockle sizes and densities were derived from published accounts and from dedicated field sampling (Table S3). For consideration, cockle beds in the field sampling extended over $\geq 100 \text{ m}^2$, and were near low-tide level and close to open water, with sampling taking place only where cockles appeared plentiful ($\geq 200 \text{ m}^{-2}$). Usually, three replicates (each 0.03 m^2 of surface substrate to a depth of 5 cm, the middle replicate GPS-ed) perpendicular to the shore and separated by 20–30 m were obtained, sieved to 2 mm, and the counts combined. For certain samples, the second and third full-years' growths were estimated based on winter depressions on the external shells; the first full-year's growth was not estimated because of frequent difficulty in determining the first winter depression shortly after settlement, it lying close to the umbo and often faint.

Results

Expansion in mangrove footprint

Two main perspectives prevail concerning biogeomorphic development of recent New-Zealand forests (Swales et al. 2015): either mangroves are opportunistic, forest development primarily driven by physical processes; or biophysical feedbacks strongly influence sedimentation and the resulting geomorphology. Most observations from the Bay of Islands appear consistent with the biophysical-feedback model.

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/>) have 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 shown little change in areal cover, most have expanded (Figure S1). The first *Bay of Islands-wide* assessment of mangrove presence/absence appears to be that of Ferrar and Cropp (1922), followed by the 1939 hydrographic chart and the 1942 inch-to-mile plans: between 1922 and 1942, mangroves had spread significantly, especially in regions beyond upper estuaries (Figure S2).

In the earliest aerial images, in the early 1950s, mangrove cover throughout most of the Bay of Islands (Table S1 and Figure S3) was characterised as follows. 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 groves). 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.

About-decadal follow-up aerial photography, culminating in the 2009 Oceans 20/20 imagery (<http://www.os2020.org.nz/>), 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 still identifiable), and most of the expansion was shoreward. Although grazing of mangroves by cattle has taken place in certain parts of the Bay of Islands (e.g. Chapman 1978), it does not adequately explain this pattern of mangrove expansion: ‘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). Greatest expansion ($\geq 100\%$) during 1950s–2009 has taken place in Te Puna/Poukoura and Kerikeri inlets, Veronica Channel, the Waikare/Waikino waterways, and especially Parekura Bay.

Case study: Parekura Bay

The predominant biophysical-feedback pattern of mangrove expansion in the Bay of Islands is well-exemplified by an embayment in southeastern Parekura Bay (Figure 2, other good examples being listed in Table S2). Mangroves were already present in the early 1920s, a distinct line having become well-established by the time of the first aerial image, in 1951, followed by rapid infilling of new recruits and consolidation during the late-1970s to the 1990s. Meagre knowledge concerning mangrove age and

Table 1. Surface area (ha) of mangroves in the Bay of Islands in 1950–53 (orthorectified images given in Table S1) compared with 2009.

Waterway	Present study					Swales et al. (2012)				
	1950–53 ha	2009 ha	Increase			1978 ha	2009 ha	Increase		
			ha	%	% y ⁻¹			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 Creek	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	1154	648	128.1	2.2	-	1169	-	-	-
<i>Kawakawa, Karetu, Waikare & Waikino</i>	282	639	357	126.6	2.1	615	666	51	8.3	0.3
<i>Paroa Manawaora & Parekura</i>	23	58	35	152.2	2.6	40	58	18	45.0	1.5

In grey are estimates of mangrove cover by Swales et al. (2012) for 1978 and 2009, with close alignment between the two independent estimates for 2009 (1154 ha [present study] and 1169 ha (which includes the two values below in the column)). Italicised entries reflect different geographical groupings. *, incomplete data; -, uncalculatable. Rounding has led to small inconsistencies.

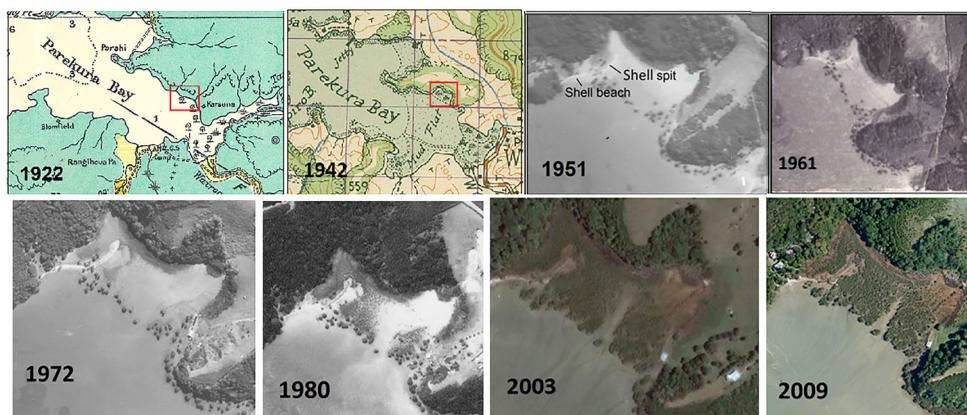


Figure 2. Changes in mangrove cover in Parekura Bay, 1922–2009, boxed-mangroves in the 1922 and 1942 maps presumably representing the tree-line visible in 1951. During rapid infilling and consolidation of new recruits, initial individual trees remained discernible.

growth means the period of propogule recruitment that had led to the line of mangroves is difficult to judge, but, 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 years), 1890–1910 may be a reasonable starting point.

Synthesis

It appears likely in pre-human times that mangroves, although widespread in the Bay of Islands, were much-more restricted to freshwater sources than they are today. 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 suggesting a reasonably discrete recruitment episode. 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 being offered in Table S4). 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 to parts of southeast Australia (Saintilan et al. 2014), but contrasts with the Firth of Thames (250 km to the south) where mangroves occupied mudflats once the shore had reached sufficient elevation in the intertidal (Lovelock et al. 2007; Swales et al. 2015). Furthermore, upper sheltered shores with soft substrates will almost certainly continue to accrue sediment in a manner similar to the Firth of Thames, inevitably leading to further *alongshore*-expansion of mangroves that can potentially fill every void.

Loss of associated habitats

Expansion in mangrove cover, from being almost exclusively near freshwater sources to take in essentially all sheltered soft-shores, has led to widespread loss of associated habitats.

Saltmarsh: Saltmarsh cover reduced as mangrove cover extended shoreward. Although I was unable to distinguish with confidence saltmarsh from other vegetation in the aerial images, particularly at the landward margins of saltmarsh in the black and white imagery, Swales et al. (2012) estimated around 12% loss of Bay of Islands saltmarsh between 1978 and 2009 (Table S5). However, *total* loss over the longer term will have been far greater. For example, there was 78% loss in Whangaroa Harbour (40 km north) between 1909 and 1981 (Morrison et al. 2014).

Uppershore sand/coarse-shell beaches and spits: Mangrove expansion has overwhelmed uppershore sand/coarse-shell beaches that had, at least until the early 1950s, comprised the margin of many soft, upper shores of the Bay of Islands (e.g. 1951 in Figure 2). The *intertidal* of associated shores today are feeding grounds for birds such as 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 here above high-water level; instead, birds must nest in ever-diminishing areas of intact sand/shell uppershore elsewhere, which is often where people with their pets gather.

In mid-Kerikeri Inlet, 2.04 km of the sand/coarse-shell beaches (58% of the total length of such shore still relatively intact in the 1951 images) had been overwhelmed by mangroves by 2009, and all of the nine obvious, ecologically distinctive spits overrun (Figure S4, with other smaller, unperceivable spits also invaded).

Intertidal seagrass: Today's Bay of Islands seagrass appears largely confined to ~12 significant and recovering subtidal beds (sometimes extending into the low-intertidal) around the islands of Ipipiri and on adjacent shores (Booth 2019), and, elsewhere, mainly small intertidal patches.

Based on long-term memories and aerial images (Table S6), about 30 sites of intertidal seagrass identified Bay of Islands-wide for the 1950s had declined to nine by the 1970s. In a 1987 survey (Walls 1987), the single significant intertidal seagrass bed was in Parekura Bay (14.7 ha, none of which remains today; Figure S5); and in 2009 only three small areas were identified (although they were not recorded by Hewitt et al. 2010).

Today, apart from the subtidal beds of the eastern Bay which extend upbeach into the low intertidal, intertidal seagrass appears largely confined to a few, mainly small patches among mature mangrove-groves, and on certain low shores (including Uruti and Wairoa bays, and Hauparua Inlet). It is unclear how widespread seagrass among mangroves used to be (e.g. Morton and Miller 1968 apparently did not mention it), but because mangrove cover has been expanding and consolidating, this may represent a significant prospect for seagrass areal expansion.

In summary, intertidal seagrass, both in living memory and persisting today, is insignificant on the landscape. Although there is no evidence that intertidal seagrass was ever prominent and extensive in the Bay of Islands (as it still is today in nearby places like Houhora Harbour, 100 km northwest; MacDiarmid et al. 2009), almost certainly intertidal seagrass would have been prominent in the pristine condition, mangroves having since come to occupy vast areas of the intertidal.

Extirpation and degradation of harvestable cockle beds

This section addresses likely impacts of land-sourced sediment on the nature and extent of harvestable estuarine shellfish beds of the Bay of Islands, focussing particularly on cockles in Kerikeri Inlet and Waikino Creek. Cockles are ‘harvestable’ when ≥ 30 -mm individuals are present at $\geq 25 \text{ m}^{-2}$ (Pawley and Smith 2014).

Essential cockle biology: Cockles are ubiquitous, shallow-burrowing bivalves of soft estuarine and sheltered shores (Morton and Miller 1968). Living from near high-water mark to lowest shores, most abundantly (up to 4500 m^{-2}) in sediments with $\sim 11\%$ mud (Anderson 2008; MPI 2018), cockles are ecosystem engineers, creating, modifying and maintaining habitats (Gutiérrez et al. 2003). Maturing at around 18-mm shell length (distance between the anterior and posterior ends, the only shell dimension reported without qualification), spawning is protracted over late-summer (Larcombe 1971) and interannual recruitment is typically highly variable (e.g. Adkins et al. 2014).

Cockle growth rates and condition decline with distance above low-tide level, and along salinity gradients with distance from estuary mouths (Dobbinson et al. 1989; Marsden 2004; Adkins et al. 2016). Growth in Northland over each of the first two full years is typically 5–10 mm shell height (at these sizes, essentially the same as shell length), cockles reaching ~ 30 -mm height (~ 33 -mm length) by age four (Larcombe 1971; MPI 2018). Macro-increments visible on shell surfaces are associated with annual growth (e.g. Larcombe 1971; Coutts 1974), a year’s growth being the distance between the sharp depressions of successive winters. In pristine populations, individuals ~ 12 y are not uncommon, with ~ 20 y the maximum age (~ 60 mm [Stephenson and Chanley 1979], although shells to 66 mm were recorded in the present study). Main predators include shorebirds, finfish, and drilling shellfish such as *Cominella* spp. (Larcombe 1971). Parasites can cause cockles to lose burrowing capacity and to ‘surface’, leaving them prone to predation (Babirat et al. 2004; Studer et al. 2013). Cockles and other bivalves are also afflicted by disease that can cause mass die-offs (e.g. Harvell et al. 1999; Guo and Ford 2016; Jones et al. 2017).

Historical context: Sediment-induced declines in distribution, abundance and individual-size of New Zealand cockles is frequently cited, but changes in particular beds over long periods (decades) have received little directed attention. Among our most useful early insights into the characteristics of the cockles of the Bay of Islands are within Māori middens, midden abundance and universality pointing to extensive and particularly rich cockle resources in pre-Contact (pre-1800) times. Moreover, with a documented history going back to the early 1800s, information around the early-Contact-period estuarine cockle resources of the Bay of Islands, when they had become a dietary staple in the north (Smith 2013; Booth 2016), may be among the most detailed available.

Case study 1: Kerikeri Inlet’s Hororoa Point cockle beds

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

Kerikeri Inlet (biologically and physically illustrative of most, if not all, Bay of Islands estuaries) is an 8-km-long 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),

with tidal mudflats occupying around half the surface area (Figure S6). 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 $\geq 90\%$ 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]; Table S7), 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 apparently prevents cockles establishing in many parts of Kerikeri Inlet, particularly along its mid- and upper-reach margins (e.g. Griffiths 2011), and, elsewhere, cockles may be abundant but not necessarily harvestable. Yet, at least during early-Contact times (starting in 1800), the Hororoa beds provided large quantities of medium to large cockles on an apparently enduring basis.

Archaeological and early-Contact cockles: Mid-Kerikeri Inlet presents an archaeologically rich landscape, its density of recorded shoreline middens approaching 4 km^{-1} of coast being among the highest in the Bay of Islands (Figure S7). Cockles dominate almost all middens, essentially all shells recorded on the archaeological Site Record Forms (SRFs) being 30–55-mm, opened individuals (Table S8).

Cockle middens associated with Hororoa Point were still conspicuous in the early 1900s, when Ferrar and Cropp (1922) pointed out two ‘Huge pipi [= cockle]-shell middens’ (Figure S8); and, later, at least two kilns produced burnt-lime from them (Challis 1994; NAR 2004). The main kiln derived shell for this agricultural dressing not only from immediately adjacent middens, but apparently also from huge (now covered/excavated) middens on the banks of Ōkura River. Many tonnes of both whole cockles and machine-crushed cockles were trucked from here to nearby properties in the mid-1900s, most shells having been whole (or nearly so) and identifiable when mined. Moreover, relics of these middens remain.

Part of one of the middens referred to by Ferrar and Cropp (1922), a component of midden complex P05/464 that in 1984 had an estimable volume of 1660 m^3 (SRF), persists unmined. The eroding midden face is around 6-m high, without evidence of layering and comprised almost solely of ‘clean’, tightly packed, disarticulated but whole and unburnt cockle valves (Figure S9); virtually no other shellfish were present apart from an occasional pipi *Paphies australis*. Similarly, parts of nearby P05/465 ($\sim 330 \text{ m}^3$), up to 3-m high with densely packed cockles, also remain. Scarcity of stones discoloured by heat that are normally associated with day to day cooking points to visible parts of both middens being essentially shell refuse only, the cockles presumably having been steamed open in great quantities nearby.

Cockle valves haphazardly located on the surfaces of both these middens in December 2018, in approximate proportion by size to the shells present, were medium to large (essentially all 30–50 mm [see Figure 4], each cubic metre containing $\sim 134,000$ valves). Because it is most unlikely small cockles were absent from the beds when harvesting occurred, it appears the larger ones were being targeted.

Given the magnitude of the Hororoa middens, most cockles were probably harvested nearby. And, from at least early-Historical times the only extensive tidal flats in Kerikeri

Inlet have been those near Hororoa Point, they appearing geomorphologically similar today as they did in the mid-nineteenth century (Figure S10). First written records concerning a significant cockle fishery near Hororoa (and extending upstream to at least Skudders Beach) also emerge from this time. In the early nineteenth century, the south side of Kerikeri Inlet, and particularly near the entrance to Ōkura River, was where people of (or closely allied to) Taiaimai (near Ōhaeawai, 18 km inland) had land, access and fishing rights (e.g. Sissons et al. 2001), summer months being spent (among other fishing) harvesting and preparing cockles for transport inland. At such shellfishing camps, cockles were steamed open, threaded on string, then hung to harden for transport/storage (e.g. Best 1929). And, for 1819–26, there are at least four independent accounts of significant cockle stocks being fished there (Table S9).

Cockles more recently: Small cockles are numerous today away from the immediate shores of Hororoa Point, yet residents with expansive views over the tidal flats report no significant harvesting of cockles here for decades (e.g. Adrian Walker, Department of Conservation, Kerikeri, pers. comm., 2019). But it has not always been like this: long-time local resident Richard Civil (21 Rangitane Rd, Kerikeri, pers. comm., 2018) recalled high proportions of plentiful, large cockles here in the 1940s–1950s; Booth (1972) reported living bivalves significant on the nearshore intertidal and shallow-subtidal flats at Shelly Beach (and Skudders) in 1971–72 to include plentiful cockles and pipi, as well as wedge shells *Macomona liliانا* (with essentially none now present); and long-term locals report harvestable cockles being present at Skudders Beach until the early 1970s.

Although in 2009 Hewitt (NIWA Hamilton, pers. comm., 2019) found few cockles nearshore near Hororoa (Station 9 in Figure S11), substantial numbers ≤ 30 mm have been present since at least 2008 on the intertidal flats a little further upstream but offshore (Pickmere Channel [PIC] in Figure 3 [Richie Griffiths, Northland Regional Council 2011; pers. comm., 2019]). Moreover, it appears that, although SARs have averaged $1.8\text{--}2.4$ mm yr⁻¹ since $\sim 1880/1900$, and mud predominates surface sediments in much of Kerikeri Inlet today (Swales et al. 2012; Figures 3 and S11), anecdotal evidence suggests there had been significant increases in SARs leading up to the close of the twentieth century (although there are no confirmatory cores). 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. Significantly, the boat-launching ramp at Skudders Beach, a concrete slab extending seaward across the upper 15 m of the 70-m wide intertidal, is now useable only at the top of the tide because today it terminates in deep mud. SARs may, however, have very recently declined, with those near Hororoa since 2009 being ~ 1.4 mm yr⁻¹ (Griffiths, pers. comm., 2019).

Near Hororoa today, there are essentially no cockles in the deep nearshore mud, but further offshore, they are widespread and abundant (up to ≥ 2400 m⁻², at and near the surface) at Middle Bank (MB) and South Shore (SS) and PIC – but are barely ‘harvestable’ (Figure 3; Table S3). Moreover, the recently dead cockles present are no larger than the living ones.

Changes in distribution, size and growth rate over time: The early 1800s accounts indicate significant quantities of large cockles present at least as far up the Kerikeri as Skudders Beach, but, based on shore examinations early in 2019 (Figure 3), it appears $\sim 50\%$ of their

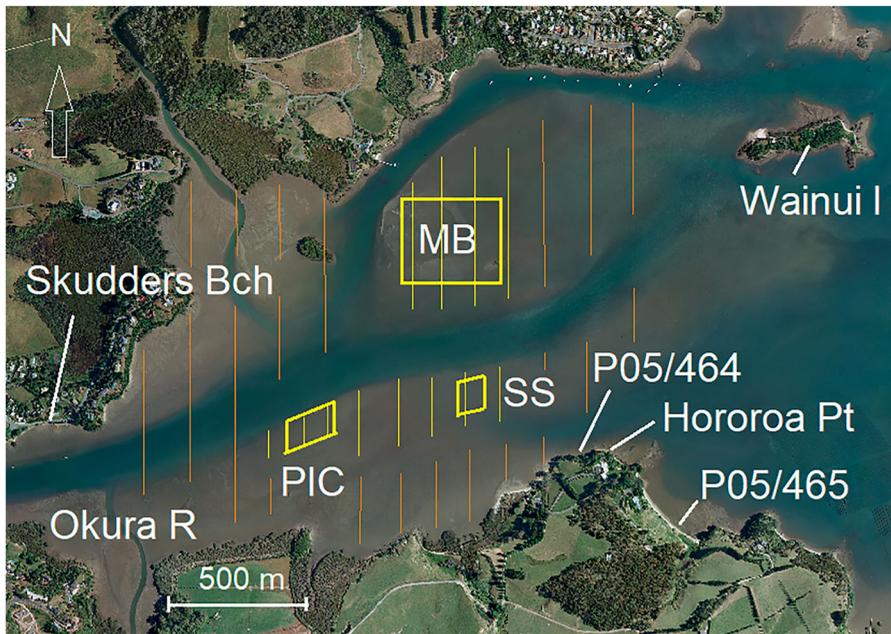


Figure 3. Mid-Kerikeri Inlet in 2009, the geomorphology apparently having changed little over the previous 170 y, but for shoaling (Figure S10). The main extent of the cockle beds in 2018–19 are indicated by yellow vertical lines; orange vertical lines denote areas of deep mud essentially devoid of cockles. MB, Middle Bank; PIC, Pickmere Channel; SS, South Shore.

habitat – much of it nearshore – is now deep (≥ 15 cm), fine mud bereft of cockles. Furthermore, it seems that cockles today seldom survive to reach large sizes, despite early annual growth increments being indistinguishable from those of similar size among the midden cockles (Figure 4 [overlapping SDs]). MB, SS and PIC all contain reasonably high or high densities of cockles, but the largest individuals – live or dead – are smaller than the average of those in the adjacent middens.

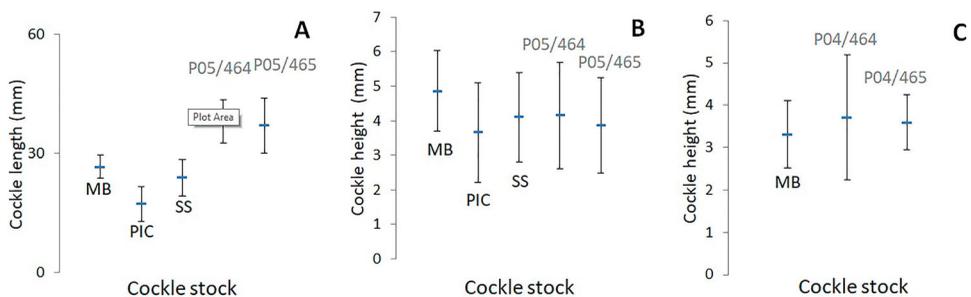


Figure 4. For Hororoa Point cockles, mean size (mm length ± 1 SD) (left), mean second full-year's growth (mm height ± 1 SD) (middle), and mean third full-year's growth (mm height ± 1 SD) (right). MB, Middle Bank (December 2018); PIC, Pickmere Channel (April 2019); SS, South Shore (January 2019); middens P05/464 and P04/465 (December 2018, using cockles 25–35 mm long), the length ranges given on the archaeological Site Record Forms being 35–51 mm and 34–54 mm respectively (Table S8).

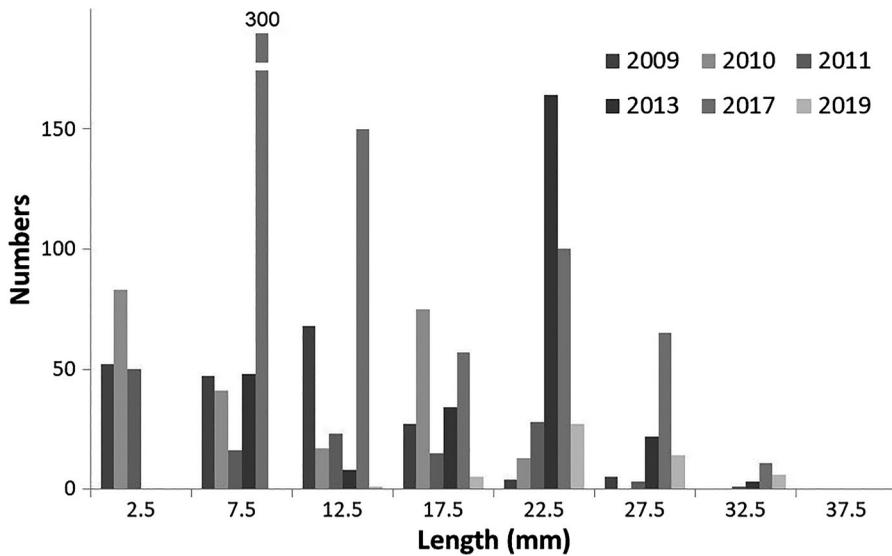


Figure 5. Length frequencies by year (2009-19) for cockles sampled during April at Pickmere Channel, Kerikeri Inlet (Griffiths, pers. comm. 2019; author's unpubl. data).

Moreover, a decade now of sampling of PIC cockles suggests successful (albeit annually variable) recruitment, but with essentially none surviving to exceed 30 mm (Figure 5), their die-off apparently more age/size-related than episodic.

Synthesis: 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 near Hororoa today represent the current, more or less steady state (a depressed stock, with barely harvestable cockles, despite little gathering), then there has been massive status-change in 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).

Case study 2: Waikino Creek and Waikare Inlet cockles

Although densities are lower in the Waikino/Waikare waterways ($\sim 1.3 \text{ km}^{-1}$; Booth 2016) than in Kerikeri Inlet, there are many recorded shoreline middens (102), several 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, with further kilns nearby, in the Waikare [Peter Clark, Waikino Creek, pers. comm., 2019]), remnants of this enormous midden in 2005 forming a terrace 30-m long and up to 3.5-m thick (Turner 2006), and containing mainly large opened cockles (Figure S12). The surface cockles of this midden today are mainly 30–45 mm (author's unpubl. obs.).

Long-time local resident Peter Clark stressed the importance of cockles (and pipi) as food for families here during the 1950s–60s in particular, high proportions of large individuals being widely available. In early 2019, however, it was difficult to locate any significant cockle beds to sample: deep fine mud means beds are essentially absent from the

upper Waikare Inlet, and in the Waikino/mid- to outer-Waikare, the extent and depth of the mud also precluding cockle establishment on most shores. Undoubtedly the numerous oyster farms contribute significantly to these high levels of shoreline siltation, but, more importantly, large quantities of terrigenous silt derived from the Kawakawa River are transported and deposited into these waterways (Swales et al. 2012, pp. 51–52). Where cockles were present, they were frequently as numerous dead valves (up to ~35 mm) on the surface with sparse living individuals beneath (Table S3).

Cockles in the broader Bay of Islands

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

Cockles dominate middens throughout the Bay of Islands, most middens almost certainly being the result of many years of harvesting during late pre-Contact/early post-Contact times (some dated; Booth 2016, p. 80), rather than being ancient and derived entirely from pristine stocks. Despite large local human populations capable of intense fishing pressure (Booth 2017), and strong dependence by Māori on estuarine shellfish by late-pre-Contact times (Smith 2013), most middens with associated size data contain large to very large cockles (≥ 40 mm) (Figure 6A).

Maximum cockle sizes throughout the Bay of Islands today are typically much lower (usually ≤ 33 mm; Figure 6B–C), even though the beds are essentially unfished, this being a common refrain among long-term locals. (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; Berkenbusch and Neubauer 2015.) Moreover, valves located among the living cockles do not suggest significant proportions of larger cockles having been recently present. Dearth of cockle-size data from the twentieth century means it is unknown when precisely mean cockle size dropped, the one length frequency located (Larcombe's 1971: Figure 4.32) showing that large cockles (>40 mm) were still present in 'Parekura Bay' in the mid-1900s.

Scatterings of living, surfaced individuals were both common and widespread on Bay of Islands cockle beds during the recent sampling on which Figure 6B–C is largely based, their shells proud of the substrate surface, or lying on their sides atop the sediment; in certain places most of the cockles lay partly exposed (e.g. Figure S13; author's unpubl. obs.). Large numbers of surfaced cockles may be recent because neither Larcombe (1971) nor Hewitt et al. (2010; pers. comm., 2019) appear to have encountered them in their observations of Bay of Islands cockles, and, because surfacing is disadvantageous, it appears significant proportions of the cockles are compromised. Large-scale surfacing events may account for recent mass mortalities in the Bay of Islands, each mortality evidenced by waves of almost entirely uniformly fresh and articulated 20–35 mm cockles;

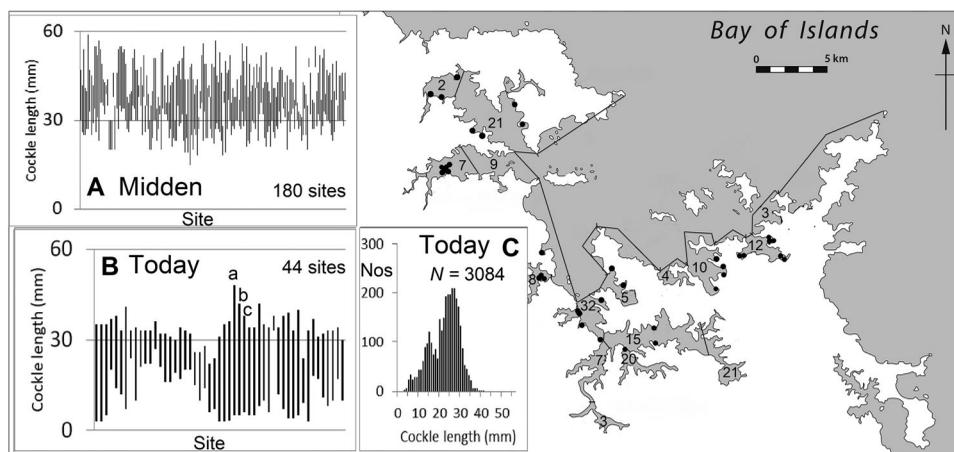


Figure 6. Length ranges of midden cockles reported on archaeological site record forms (**A**, with numbers of middens shown on the map according to Booth's [2016] archaeological compartments), and recent (since 2009) living cockles (**B** and **C**, with sampling sites indicated by dots; Table S3, with the author sieving to 2 mm, but others' mesh sizes varying) for the Bay of Islands; each vertical line denotes maximum and minimum cockle lengths for a particular locality. In **B**, designations a, b and c are *beach-wide* maximum and minimum values (Berkenbusch and Neubauer 2015).

sites have included Crowles and Wharengaere bays (Te Puna Inlet), Waitangi, Whiorau Bay (Parekura Bay) and outer Waikino Creek (author's unpubl. obs.; Figure S14).

Synthesis

In pre-human times, cockles – with pipi – would have been the prominent estuarine shellfish of the Bay of Islands. Significant proportions and quantities of large cockles (40–55 mm) continued to be available for harvest during late pre-Contact (and into early post-Contact) times in the Bay on an apparently enduring basis, yet today, even under low fishing pressure, they are barely harvestable on most shores.

Size-range is an extremely coarse metric, and although the archaeologists' observations (Figure 6A) necessarily stand, sizes of the living cockles of the Bay of Islands in recent times (Figure 6B–C) can be examined more perceptively. Although the recent sampling was necessarily limited, it was nevertheless widespread, and the length-frequency distributions and other data (Table S3) support the notion that cockles are much smaller on average today than in late pre-Contact/early post-Contact times, precisely in accord with the intensive sampling at Hororoa.

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 *abundant* (except in the Waikare and Waikino waterways), but seldom reach large sizes. Terrigenous sedimentation certainly restricts the current cockle distribution, nearshore areas being most affected, but the presence of fine silt is also invoked as fundamental in compromising cockle vigour elsewhere such that few now reach 40 mm, survival beyond a few years seemingly being more affected than early growth rates. Although there are many potential explanations for low proportions of large individuals in the cockle beds today, from climate change to direct anthropogenic impact (e.g.

Table S10), generally low densities of harvestable cockles in the Bay of Islands today probably result from multiple stressors underpinned by chronic levels of fine terrigenous-silt accumulation – a well-known inhibitor of cockle vigour (e.g. Lohrer et al. 2004).

At many localities, significant *scatters* of 20–35-mm long surfaced cockles were present, possibly suggesting – combined with the high levels of fine silt – high parasite infestation, or the effects of some other contagion or debilitating contaminant. Surfacing can be characteristic of trematodes: 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, the parasites infecting (albeit at low individual densities) all cockles in parts of the Bay of Islands (Studer et al. 2013). But surfacing sometimes involved large numbers of individuals: a ‘surfacing event’ now plays out on a beach 1 km south of Te Haumi, where thousands of live cockles forming low ridges on the beach’s mid- and low-intertidal were first observed in early December 2019 (although it is unknown when the cockles became surfaced) and were still present alive (albeit at much lower densities) in early-March 2020 (Figure S13, although I cannot be sure they had been the same individuals throughout). (A similar event appears to have recently taken place among the pipi at Te Haumi; Berkenbusch and Neubauer 2015, p. 111.) Given the waves of uniformly fresh recent mortalities seen on many beaches in the Bay, *mass surfacing* may be a major source of mortality.

Chronic and intolerably high levels of organic or inorganic contaminants are an *unlikely* primary reason for surfacing and eventual mortality, enrichment in the water column and surficial sediments, at least since 2008, having been at most low to moderate in much of the Bay of Islands, with no lethal levels of bivalve toxins (Cornelisen et al. 2011; Griffiths 2011, 2014; Bamford 2016). Accordingly, new parasites and/or novel disease-causing organisms, or greater prevalence of existing ones, with impacts positively age/size-related, may 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. Either way, 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.

Moreover, significant proportions of large individuals now appear rare in cockle beds throughout much of the northeast of the North Island, including within unfished situations, with some size declines recent and rapid (e.g. Cummings and Hatton 2003; Marsden and Adkins 2010; Berkenbusch and Neubauer 2015, 2016; 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 (SRFs).

Discussion

This review has explored the ecological impacts of elevated levels of terrigenous sedimentation resulting from human activity on the shallow communities of a northern New Zealand embayment since its first colonisation in about 1300 AD, and particularly since

European arrivals from 1800. Drawing on data little-used in ecological studies, such as the contents of middens, together with more-mainstream approaches such as analysis of aerial imagery, I have characterised the effects of sedimentation on the nature and extent of key indicator shallow-water communities of the Bay of Islands: mangrove forests and associated habitats, and the cockle beds. Even though seafood overharvesting in the Bay has led to massive negative ecological consequences, few of them are seen as being essentially irreversible, as is the case with many of the changes wrought by sedimentation. High and chronic levels of sedimentation are therefore probably the most important and enduring contributors to ecological degradation here, a situation apparently replicated widely throughout northeast New Zealand.

Impacts of fluxes of terrigenous sediment have been catastrophic (far-reaching, persistent, and seemingly irreversible), 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. Froude 2016; Booth 2017), 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-shell beaches and spits, and (probably) intertidal seagrass. Simultaneously, previously productive shellfish beds have been eliminated by deposition of fine silt.

Furthermore, although in late pre-Contact times through (apparently) into the mid-1900s, large cockles (40–55 mm) abounded, it appears beds are not – or are barely – harvestable today in much of the Bay of Islands, even in places where there has been little or no shellfish gathering for decades. Despite potential remedies (e.g. reducing fishing pressure, thinning, transplanting; Marsden and Adkins 2010), no reference was found for a recovered (e.g. $\geq 20\%$ 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. Some crucial tipping point has possibly been breached – or some level of prevalence and persistence of disease/parasite reached (Harvell et al. 1999) – whereby re-attainment of a full size range, with substantial proportions of older cockles, even in the context of reducing sedimentation rates, is presently not possible.

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-shell upper beaches and cheniers will be lost altogether. Arguably, it is 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 native birds and invertebrates.

Most changes in the Bay of Islands brought about by sedimentation are ecologically adverse, having destroyed ecosystems, reduced biodiversity, and threatened uncommon habitats. Nevertheless, rates of terrigenous sediment runoff may have recently slowed, or even reversed, in certain parts of the Bay after the highs suggested for the late-1900s, as seen recently in lower SARs on sedimentation plates in Kerikeri Inlet, and in the recovery of the subtidal seagrass beds. Also, although much of the previous cockle habitat is now deep mud (e.g. around 50% areally in mid-Kerikeri Inlet, and essentially the entire Waikare/Waikino waterways), cockle densities in many other parts of the Bay of Islands remain high ($>500 \text{ m}^{-2}$), and recovery of significant proportions of *harvestable* cockles may be achievable if siltation and other key restraints to growth and survival are rectified. Additional, aspirational, indicators of reducing SARs in the Bay of Islands would include re-establishment of the extensive Parekura Bay intertidal seagrass beds last reported in the 1980s, and return of essentially mud-free intertidal shores with abundant and large cockles in at least outer parts of the Waikino/Waikare waterways.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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