Fisheries New Zealand

Tini a Tangaroa

Bivalve abundance in relation to sediment properties across northern North Island

New Zealand Fisheries Assessment Report 2021/49

P. Neubauer,
D. Damodaran,
K. Berkenbusch

ISSN 1179-5352 (online)
ISBN 978-1-99-100989-0 (online)

September 2021

New Zealand Government

Requests for further copies should be directed to:

Publications Logistics Officer
Ministry for Primary Industries
PO Box 2526
WELLINGTON 6140

Email: brand@mpi.govt.nz
Telephone: 0800 00 83 33
Facsimile: 04-894 0300

This publication is also available on the Ministry for Primary Industries websites at:
http://www.mpi.govt.nz/news-and-resources/publications
http://fs.fish.govt.nz go to Document library/Research reports

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Neubauer, P.[1]; Damodaran, D.[1]; Berkenbusch, K.[1] (2021). Bivalve abundance in relation to sediment properties across northern North Island.

***New Zealand Fisheries Assessment Report 2021/49*. 17 p.**

Intertidal cockles (tuangi, or littleneck clam, *Austrovenus stutchburyi*) are an important target species for customary and recreational fisheries throughout New Zealand. Their presence in coastal habitats, including sheltered bays and estuaries, makes these intertidal populations vulnerable to human impacts, including overexploitation and habitat degradation. The latter include runoff of terrigenous sediment and increased concentrations of suspended sediment, which have been linked to decreases in cockle abundance.

Across northern North Island, regular population surveys have focused on the spatial distribution, abundance and size structure of cockle populations targeted by non-commercial fishing. In view of the importance of sediment properties and their value as potential indicators of habitat quality, a sediment sampling component was added to the northern surveys in 2013–14; subsequent improvements to the sampling design have allowed formal analyses of cockle populations in relation to sediment characteristics.

The present study provides an investigation of the relationship between cockles and sediment grain size across northern North Island survey sites, based on data from five years of monitoring. The initial exploration of data was a principal component analysis, followed by the modelling of cockle population abundances as a function of different grain size fractions; a quantile regression was used to examine sediment-mediated effects on higher quantiles (>0.5) of observed abundances. To investigate which part of the cockle distribution responds to sediment grain size distributions, quantiles between 0.50 and 0.95 were modelled. The modelling was conducted for total cockle abundance and also for individuals in the large size class (i.e., individuals >30 mm shell length). The sediment grain size fractions included in the analysis were sediment fines (>63 µm grain size), very fine sand (>125 µm), fine sand (>250 µm), medium sand (>500 µm) and gravel (>2000 µm).

The findings from the analysis documented relatively small changes in sediment properties across sites over time: there was a small reduction in samples containing gravel, and there was also a small increase in medium to fine sands. Neither of these changes were sufficient to notably affect cockle abundance; the latter was highest in fine to medium sands. With most of the sediment consistently dominated by sand fractions, observed declines in cockle populations at some sites are likely related to factors other than sediment grain size characteristics. In general, the sediment habitat in the cockle strata appeared stable throughout the study period, and there were no marked increases in fines or gravel.

Overall, the proportion of sediment fines was generally below the threshold of about 10% that has been identified to limit cockle populations. Nevertheless, there was considerable variability in this grain size fraction at some sites, evident in individual samples where fines exceeded 20% of the sediment. In addition, some sites exhibited recent changes in sediment composition, with discernible increases in fine sand and sediment fines, even though these increases did not markedly affect cockle abundances; however, the abundance of the large individuals was low when the proportion of sediment fines exceeded 20%.

With multiple pressures potentially impacting intertidal cockle populations, information of sediment properties allowed the elucidation of this potential stressor in relation to population changes. With the current analysis indicating relatively few changes in sediment grain size composition over the study period, the findings indicate that changes in cockle populations are determined by other factors at the survey sites.

[1]Dragonfly Data Science, New Zealand.

1. INTRODUCTION

Intertidal marine invertebrates such as infaunal bivalves frequently include species that are important resources for recreational, customary and commercial fisheries (Caddy & Defeo 2003). Their presence in coastal waters, including sheltered bays and estuaries, makes these intertidal populations vulnerable to human impacts, including overexploitation and habitat degradation. Adverse impacts can result in direct population declines, and also affect longer-term processes such as recruitment, growth rates and overall mortality, leading to a reduction in productivity. In addition, these impacts may generate spatial gradients in the structure of populations that are already characterised by naturally patchy distributions and highly variable population dynamics.

New Zealand's coastal, sedimentary habitats support a number of infaunal bivalve species, including cockles (tuangi, or littleneck clam, *Austrovenus stutchburyi*) that are a valued resource for recreational and customary fisheries. Cockles are found in sheltered and semi-enclosed marine habitats such as embayments, estuaries and harbours throughout New Zealand (Morton & Miller 1973). In northern North Island, cockles are one of the principal target species in sheltered coastal environments open to recreational and customary fishing (Grant & Hay 2003). Close proximity to urban and metropolitan areas (e.g., Auckland) and their prevalence in the intertidal zone make many northern cockle populations easily accessible and, therefore, vulnerable to overexploitation.

Concerns about potential population declines in the northern region have led to the implementation of a bivalve monitoring programme in the early 1990s; these surveys have been commissioned by Fisheries New Zealand (and its predecessors), and include a number of northern sites in the Auckland metropolitan area, wider Auckland, Northland, Coromandel, west coast Waikato and Bay of Plenty (see recent surveys by Pawley & Smith 2014, Berkenbusch et al. 2015, Berkenbusch & Neubauer 2015, 2016). Since the late 1990s, the survey design has remained consistent, with a sampling focus on cockles and pipi (*Paphies australis*). Population information from the surveys supports Fisheries New Zealand's management strategies to ensure sustainable recreational and customary fisheries in the northern region.

In addition to fishing pressure, human activities such as coastal development and land use have also been shown to adversely affect cockle (and other bivalve) populations. Negative population impacts have been associated with the runoff of terrigenous sediment, increased suspended sediment concentrations, and the transfer of contaminants and disease vectors to coastal habitats (Grant & Hay 2003). Increased sedimentation and terrestrial runoff have been linked to decreases in cockle abundance. Although cockles generally exhibit a relatively wide tolerance to sediment mud content (silt and clay, <63 micron grain size), they show highest abundances in sediments that contain less than about 11% mud (Thrush et al. 2003, Anderson 2008).

In view of the importance of sediment properties, the monitoring of sediment organic content and grain size was added to the northern bivalve population surveys in 2013–14 (Berkenbusch et al. 2015). The initial sampling provided general information and a baseline for future assessments of changes in sediment properties. It also led to improvements in the sampling design in the 2015–16 survey. The improvements in this survey included a greater number of samples and their random allocation across the sampling areas. Furthermore, the sediment sampling was restricted to cockle populations, because pipi beds frequently extend into subtidal areas that are inaccessible to the intertidal sampling, so that only a proportion of the population is surveyed.

The improved sediment sampling allowed formal assessments of spatial patterns and gradients in cockle abundance in relation to sediment properties (Berkenbusch & Neubauer 2016). These analyses revealed decreases in cockle abundance with increases in sediment organic content and in the proportions of fines and gravel, but the relationships were tentative only. Because the amount of sediment data has increased with subsequent surveys, the present report presents an update of the analyses of the relationship between cockles and sediment grain size properties.

2. METHODS

2.1 Field sampling of cockles

The field sampling of cockles and sediment was part of the northern North Island bivalve monitoring surveys (in Fisheries Management Areas 1 and 9), conducted between 2015–16 and 2019–20 (see details in Berkenbusch & Neubauer 2016, 2017, 2018, 2019, 2020).

The field surveys were based on a combination of a systematic design and two-phase random-stratified sampling. Strata were chosen based on cockle densities ascertained in preceding surveys, with a focus on retaining the overall sampling extent throughout the survey series (i.e., since 1999–2000).

For each stratum, a regular grid was generated, with the size and shape of the grid cells reflecting the desired sampling density and the orientation of the stratum. This step included ascertaining the intersection of the grid with the boundary of the stratum. For strata with odd shapes, the number of grid cells did not necessarily reflect the number of desired cockle samples; if there were more grid cells than sampling points, not all cells had sampling points allocated to them. Instead, cockle sampling points were allocated across all cells with a probability proportional to the area of the cells.

The position of the point within a cell was randomly allocated. All sampling points were pre-calculated for two phases before the sampling began. All phase-1 points were sampled, whereas sampling of phase-2 points was only carried out when the coefficient of variation (CV) of the total cockle abundance estimate after first-phase sampling exceeded the target value of 20%. The number of required phase-2 samples was calculated using the method of Francis (1984).

At each site, sampling points within each stratum were located using Global Positioning System (GPS) units. Bivalves were sampled using a pair of benthic cores that were 15-cm diameter each; the combined cores sampled a surface area of 0.035 m^2. The cores were sampled to a sediment depth of 15 cm, and all sediment within the cores was subsequently sieved on 5-mm mesh. All cockles retained on the mesh were counted and measured (length of the maximum dimension, to the nearest millimetre), before returning them to the benthos. When the number of individuals in both cores exceeded 70 (equating to 2000 individuals per m^2) and there were at least 50 individuals in the first core, the recording of shell length measurements was based on subsampling. The subsampling consisted of recording shell length measurements for all individuals in the first core, whereas bivalves in the second core were not measured. When there were fewer than 50 individuals in the first core, all bivalves were measured in both cores. Length measurements were used to determine the number of individuals in different size classes, with cut-off lengths defined as $\leq$15 mm for recruits, $\geq$30 mm for large individuals, and medium-sized individuals at sizes between these two size classes.

2.2 Sediment sampling

Since 2013–14, the surveys have also collected information on sediment properties, i.e., organic content and sediment grain size data (Berkenbusch et al. 2015, Berkenbusch & Neubauer 2015). Following the initial two years of baseline information, the sampling design was refined in 2015–16 to allow the formal analysis of sediment properties; the latter was focused on spatial patterns in sediment variables, and on assessing gradients in cockle abundance in relation to sediment properties (Neubauer et al. 2015, Berkenbusch & Neubauer 2016).

The sediment sampling was based on the collection of a subset of 24 sediment cores (5-cm diameter, sampled to a depth of 10 cm) that were collected within existing cockle strata at each site. Subsequent sample analyses determined the organic content and grain size distribution of the sediment.

The grain size analysis was based on wet sieving to ascertain the proportion of six different size classes: sediment fines (silt and clay; $<$63-µm grain size), very fine sand (VFS; $>$63-µm grain size), fine sand (FS; $>$125-µm grain size), medium sand (MS; $<$250-µm grain size), coarse sand (CS; $>$500-µm grain size), and gravel ($>$2000 µm grain size) (Eleftheriou & McIntyre 2005). Each sample was homogenised before processing through a stack of sieves to determine the proportion in each sediment grain size fraction (i.e., <63, >63, >125, >250, >500, and >2000 µm). Sediment retained on each sieve was subsequently dried to constant weight at 60 °C before weighing it (accuracy ± 0.0001 g).

Descriptive sediment data from these analyses include the proportions of sediment in the different grain size fractions for each sample.

For the current study, sediment grain size data were included from 24 northern survey sites where sediment had been sampled in at least two surveys (Table 1).

Table 1: Number of sediment samples taken at northern North Island bivalve survey sites by year.

Survey site	Survey year				
	2016	2017	2018	2019	2020
Aotea Harbour		24		24	
Bowentown Beach	24		24		24
Cockle Bay	24		23		24
Eastern Beach		24			24
Grahams Beach		24			24
Kawakawa Bay		24		24	
Little Waihi Estuary	24		24		24
Mangawhai Harbour		22		24	
Mill Bay			24	24	
Ngunguru Estuary		23		24	
Ōhiwa Harbour	22			24	
Okoromai Bay	24		24		
Otūmoetai		24		23	
Pataua Estuary	23		24		24
Raglan Harbour			24		24
Ruakaka Estuary		24		24	
Tairua Harbour	24		24		24
Te Haumi Beach		24		24	
Umupuia Beach	24		24		24
Waiotahe Estuary		24			24
Whangamatā Harbour		24		24	
Whangapoua Harbour		24		24	
Whangateau Harbour	24		24		24
Whitianga Harbour	24		24		24
Total	237	285	263	263	288

2.3 Exploratory data analysis

The initial exploration of data applied a principal component analysis (PCA) to data on the sediment composition (proportions of fines, very fine sand, fine sand, medium sand, coarse sand, and gravel) across sites and years. Zero values for sediment composition were replaced with minimum values contained within the data and re-normalised to sum to 1; subsequently, compositions were central-log-ratio (CLR) transformed, where $CLR(p_i) = log(p_i)/\log(\bar{p})$, placing the composition on the axis of real numbers. All analyses were carried out in R statistical software (R Core Team 2019).

2.4 Modelling cockle density in relation to sediment characteristics

To gain an understanding of cockle density in relation to sediment grain size composition across sites, the current modelling distinguished between the total number of individuals and abundance of individuals in the different size classes. Cockle population abundances were modelled as a function of the principal component axes (i.e., as a function of the relative proportion of fines, and coarse sand relative to fine sand). Because a number of factors are likely to influence cockle abundance (e.g., fishing, habitat degradation), a quantile regression was used to gain insights into sediment-mediated effects on higher quantiles (>0.5) of observed abundances. This approach was also chosen, because mean abundance may be influenced by other factors, such as fishing and recruitment (Thrush et al. 2003, Anderson 2008). To investigate which part of the cockle distribution responds to sediment grain size distributions, quantiles between 0.50 and 0.95 were modelled here.

3. RESULTS

The sediment composition across sites remained relatively stable over time (Figure 1). Nevertheless, there was an increase in samples that did not contain gravel in recent years, and there was a slight increase in samples with medium to fine sediment. Samples with high total cockle abundance (i.e., across all size classes) were mostly in medium to very fine sands. At the same time, high individual cockle counts were rare in samples with a high proportion of sediment fines or coarse sand and gravel (Figure 2). A similar pattern was evident for cockles in the large size class (Figure 3). Nevertheless, for both population measures, most of the samples were characterised by relatively low cockle abundance.

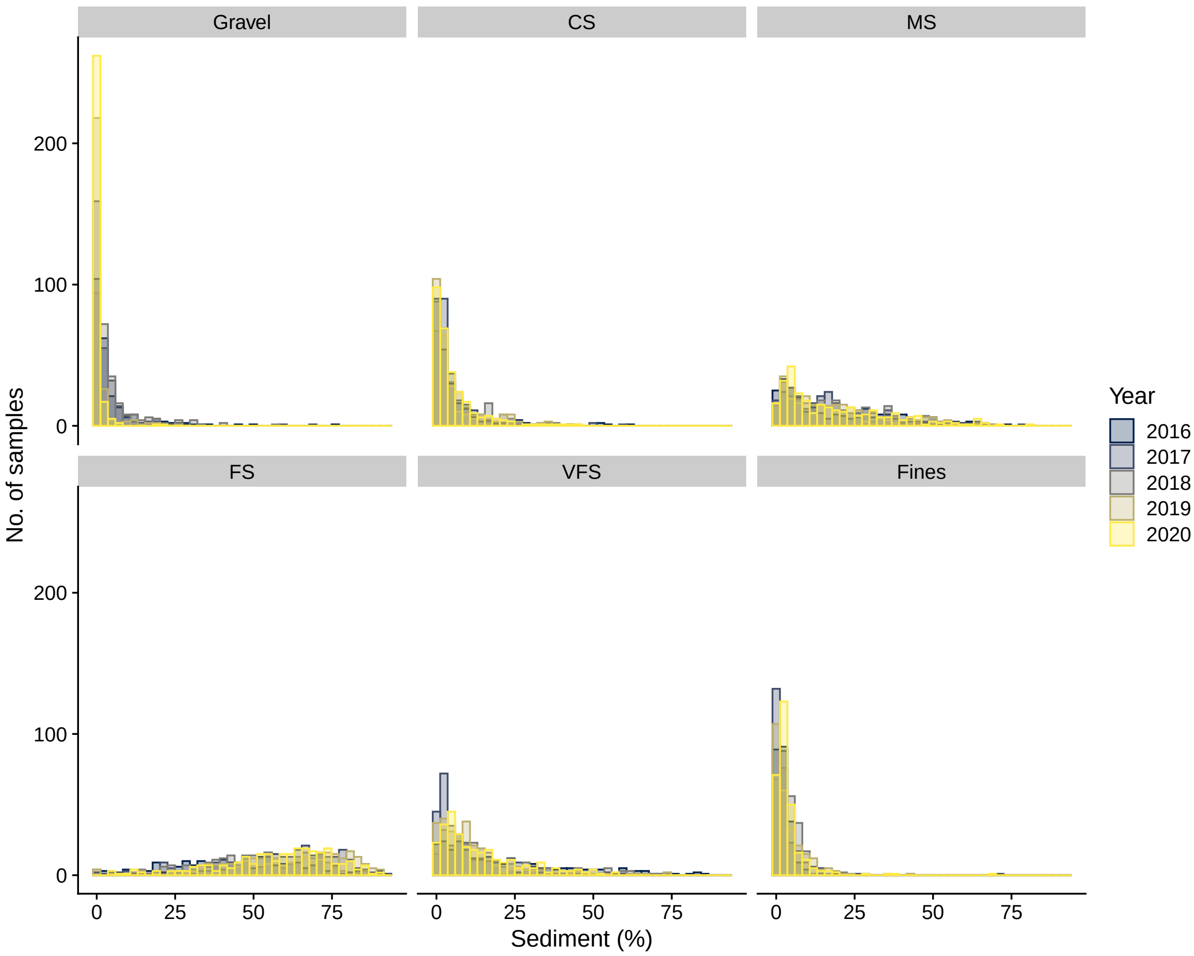

Figure 1: Proportion of sediment (%) in different grain size fractions in samples collected across 24 northern North Island survey sites between 2015–16 and 2019–20. Sediment grain size fractions were fines (silt and clay, <63 µm), very fine sand (VFS, >63 µm), fine sand (FS, >125 µm), medium sand (MS, >250 µm); coarse sand (CS, >500 µm), and gravel (>2000 µm).

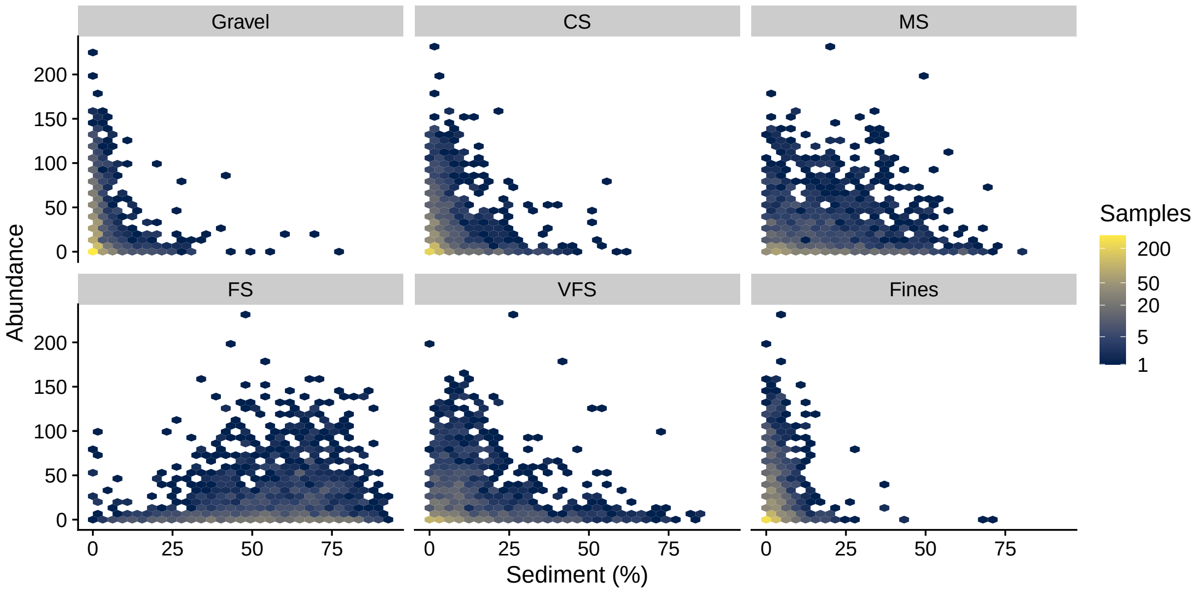

Figure 2: Abundance of cockles (total number of individuals per sample, all sizes) as a function of sediment composition for samples collected across 24 northern North Island survey sites between 2015–16 and 2019–20. Sediment grain size fractions were fines (silt and clay, <63 µm), very fine sand (VFS, >63 µm), fine sand (FS, >125 µm), medium sand (MS, >250 µm), coarse sand (CS, >500 µm), and gravel (>2000 µm).

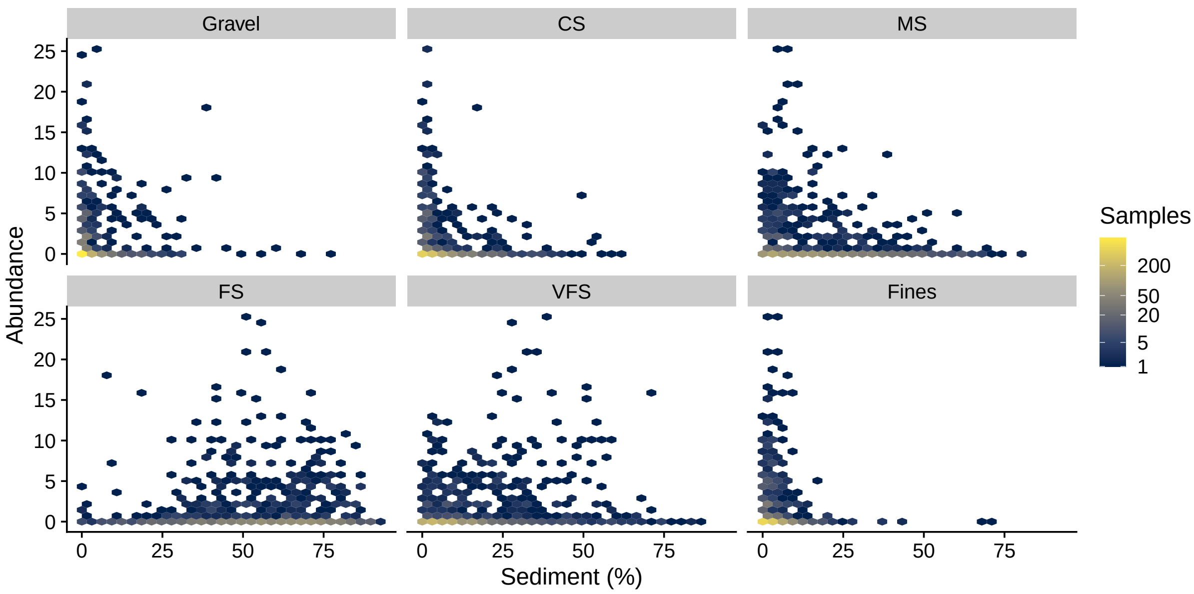

Figure 3: Abundance of large cockles (number of individuals per sample, ≥30 mm shell length) as a function of sediment composition for samples collected across 24 northern North Island survey sites between 2015–16 and 2019–20. Sediment grain size fractions were fines (silt and clay, <63 µm), very fine sand (VFS, >63 µm), fine sand (FS, >125 µm), medium sand (MS, >250 µm), coarse sand (CS, >500 µm), and gravel (>2000 µm).

The first three principal components explained 86.6% of the variance in sediment composition (Figure 4). The first PC axis distinguished between samples characterised by large grain size fractions and fine grain sizes, whereas the second axis distinguished samples with a high proportion of gravel from samples dominated by fine to coarse sands (Figure 5). The third axis distinguished samples characterised by fines from other sediment types (although samples with fines co-varied with coarse sand). PC axes four and five did not show a clear pattern by sediment grain size fraction.

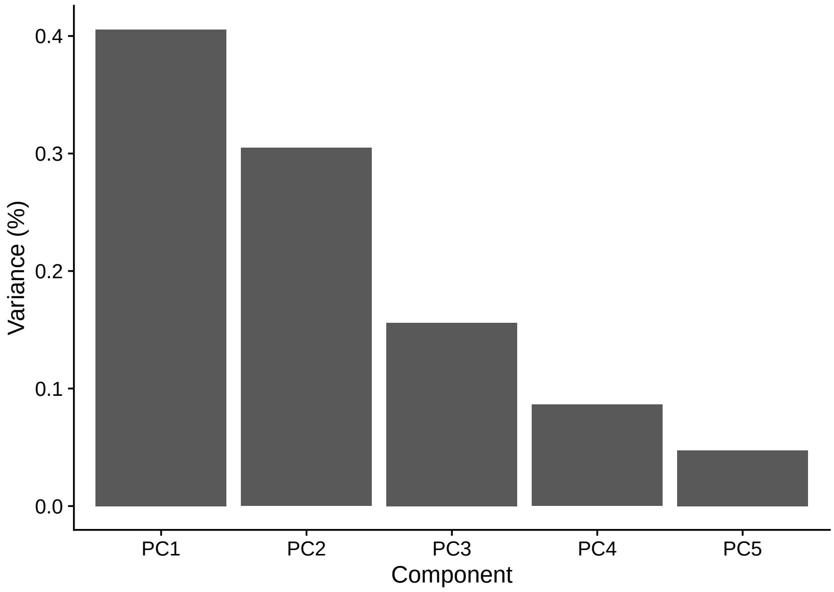

Figure 4: Scree plot of the proportion of variance in sediment composition explained by principal component.

For each size class, overlaying cockle abundance by year onto principal components did not reveal a clear pattern of abundance in relation to fine compared with coarse sediment fractions (PC1) or sediment fines (PC3; Figure 6). Nevertheless, changes in sediment composition across years were evident for a number of sites (e.g., Cockle Bay, Bowentown Beach, Raglan and Whitianga harbours), which showed a shift towards higher fractions of fine sand and fines in recent surveys (Figures 7 and 8). The recent shift in sediment grain size did not seem to be associated with a change in total cockle abundance or in the abundance of large cockles.

Using principal components one and three as predictors for quantile regressions, there were distinct patterns between effects of sediment for quantiles of total cockle abundance and also of the abundance of large cockles (Figure 9). For all size classes, the effect of fine sand fractions and of sediment fines declined towards higher quantiles. This finding suggested a higher median cockle abundance in finer-sized sediment, but little effect on abundance peaks. For large cockles, however, there was an opposing effect for sediment fines (PC3) and fine versus coarse sediments (PC1), with higher peaks of large individuals in finer sand, but an increasingly negative effect of fines on higher quantiles of large cockle abundance. The latter negative effect suggested that the peak abundance of large cockles is lower when the proportion of sediment fines exceeded 20% (Figure 10).

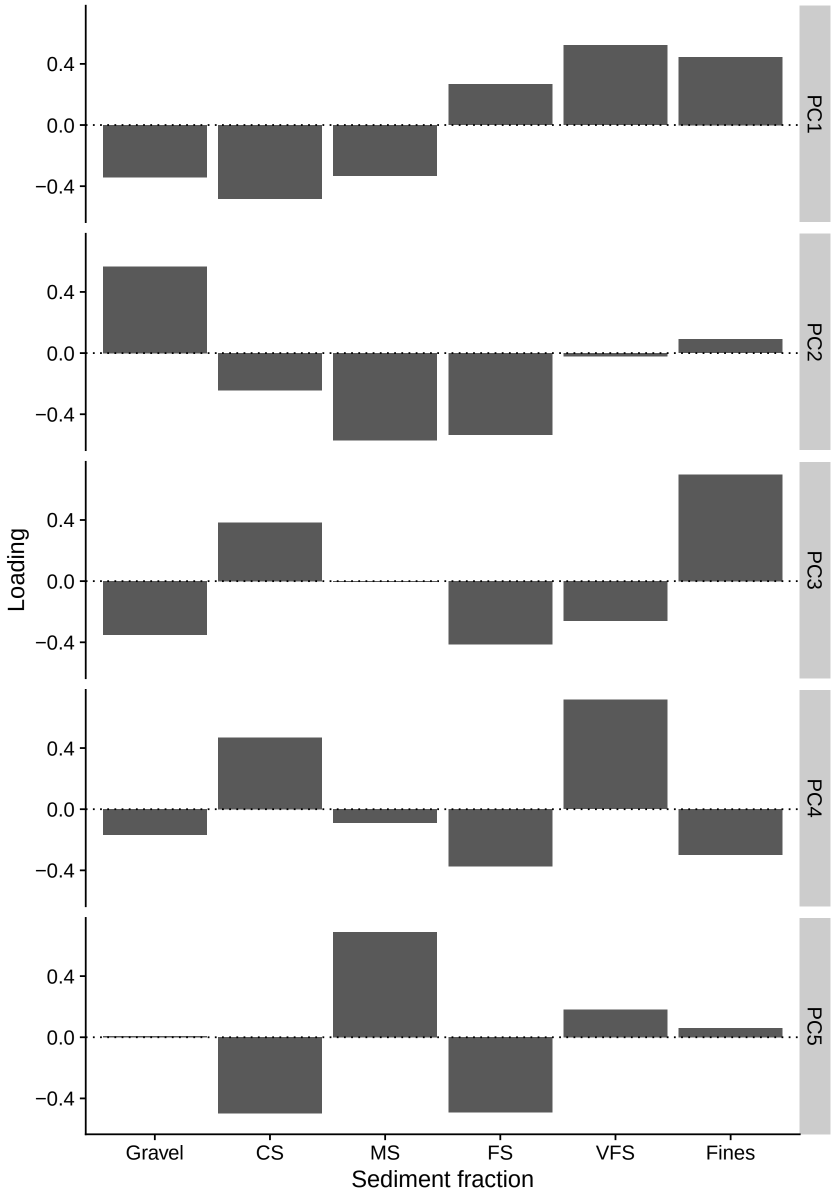

Figure 5: Correlation (loading) of principal components (PCs) with sediment granulometry. Sediment grain size fractions were fines (silt and clay, <63 µm), very fine sand (VFS, >63 µm), fine sand (FS, >125 µm), medium sand (MS, >250 µm), coarse sand (CS, >500 µm), and gravel (>2000 µm).

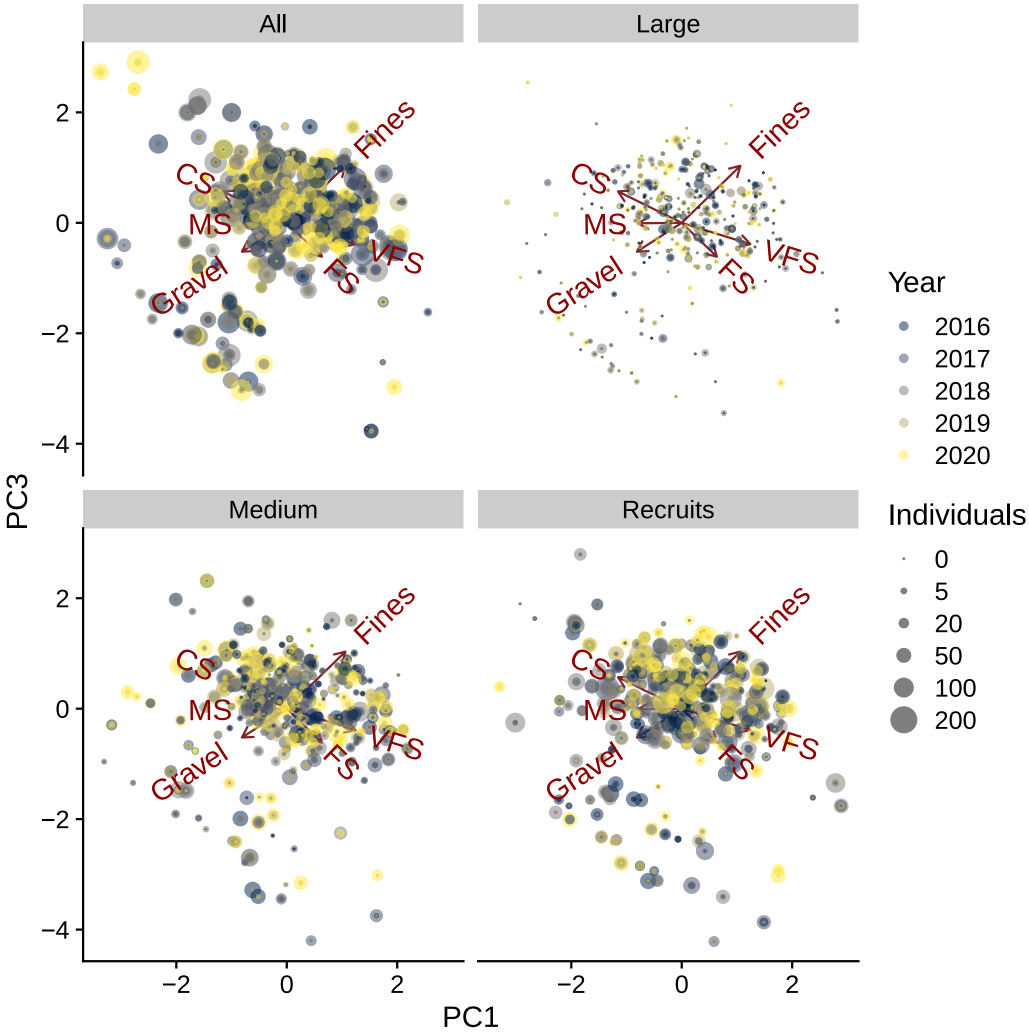

Figure 6: Cockle abundance along two principal components (standardised PCs) of sediment granulometry for all cockle size classes (all), large (≥30 mm shell length) and medium-sized (≥10 mm and <30 mm) individuals, and recruits (<10 mm). PC1 explained 40.5% of the variance and distinguished fine (≤250 µm) and coarse (>250 µm) sediment sand fractions; PC3 explained 15.6.% of the variance and was mainly associated with sediment fines (silt and clay, <63 µm).

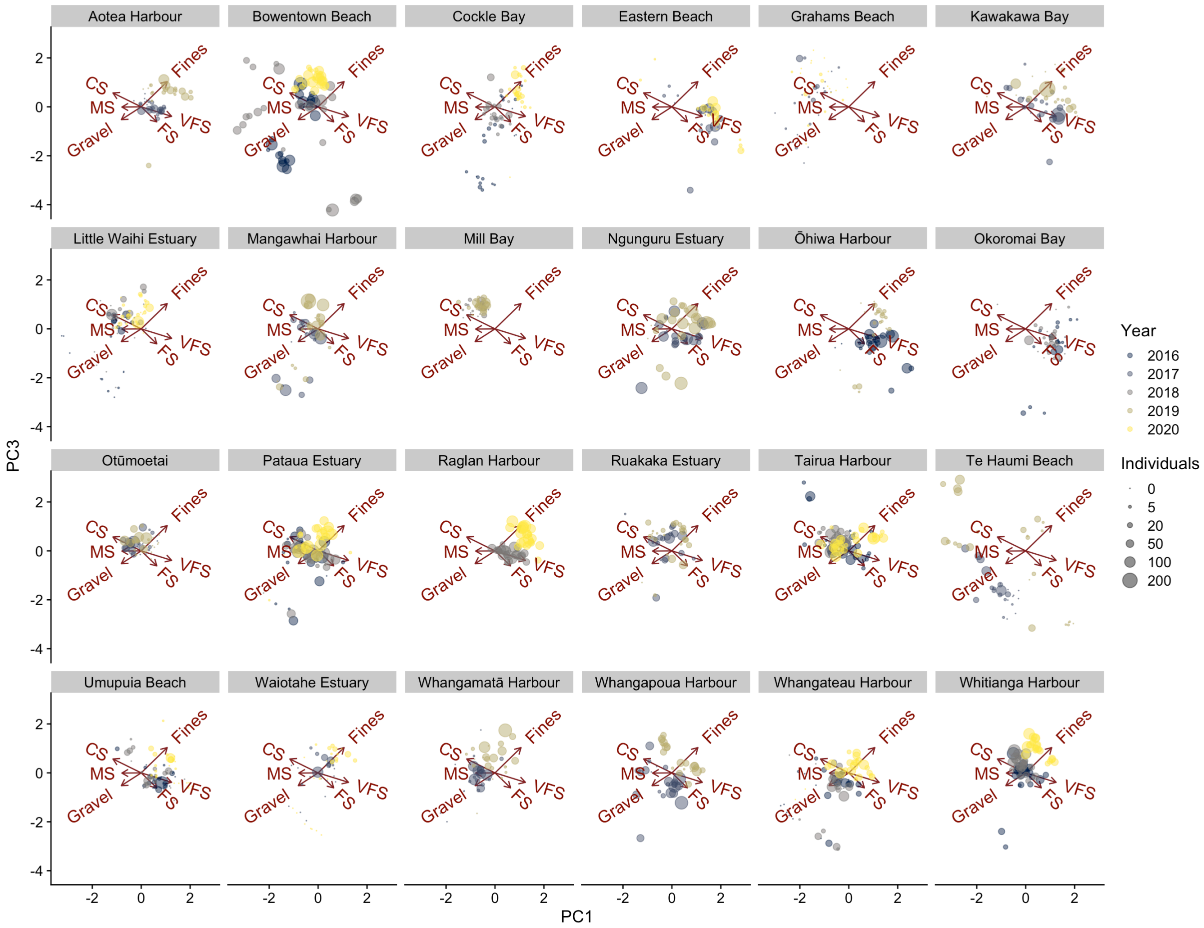

Figure 7: Total cockle abundance by site along two principal components (standardised PCs) of sediment granulometry. PC1 explained 40.5% of the variance and distinguished fine (≤250 µm) and coarse (>250 µm) sediment sand fractions; PC3 explained 15.6.% of the variance and was mainly associated with sediment fines (silt and clay; <63 µm).

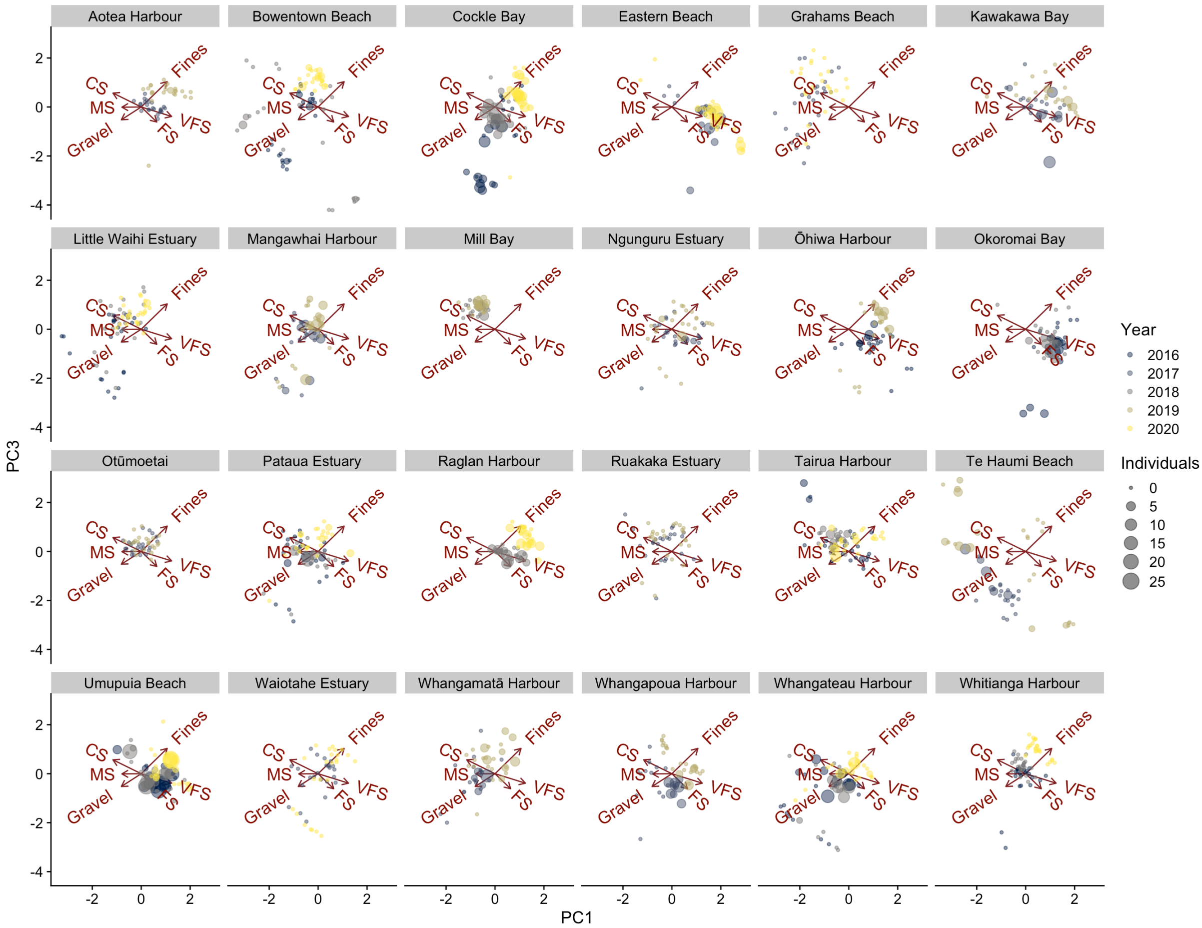

Figure 8: Abundance of large cockles (≥30 mm shell length) by site along two principal components (standardised PCs) of sediment granulometry. PC1 explained 40.5% of the variance and distinguished fine (≤250 µm) and coarse (>250 µm) sediment sand fractions; PC3 explained 15.6.% of the variance and was mainly associated with sediment fines (silt and clay; <63 µm).

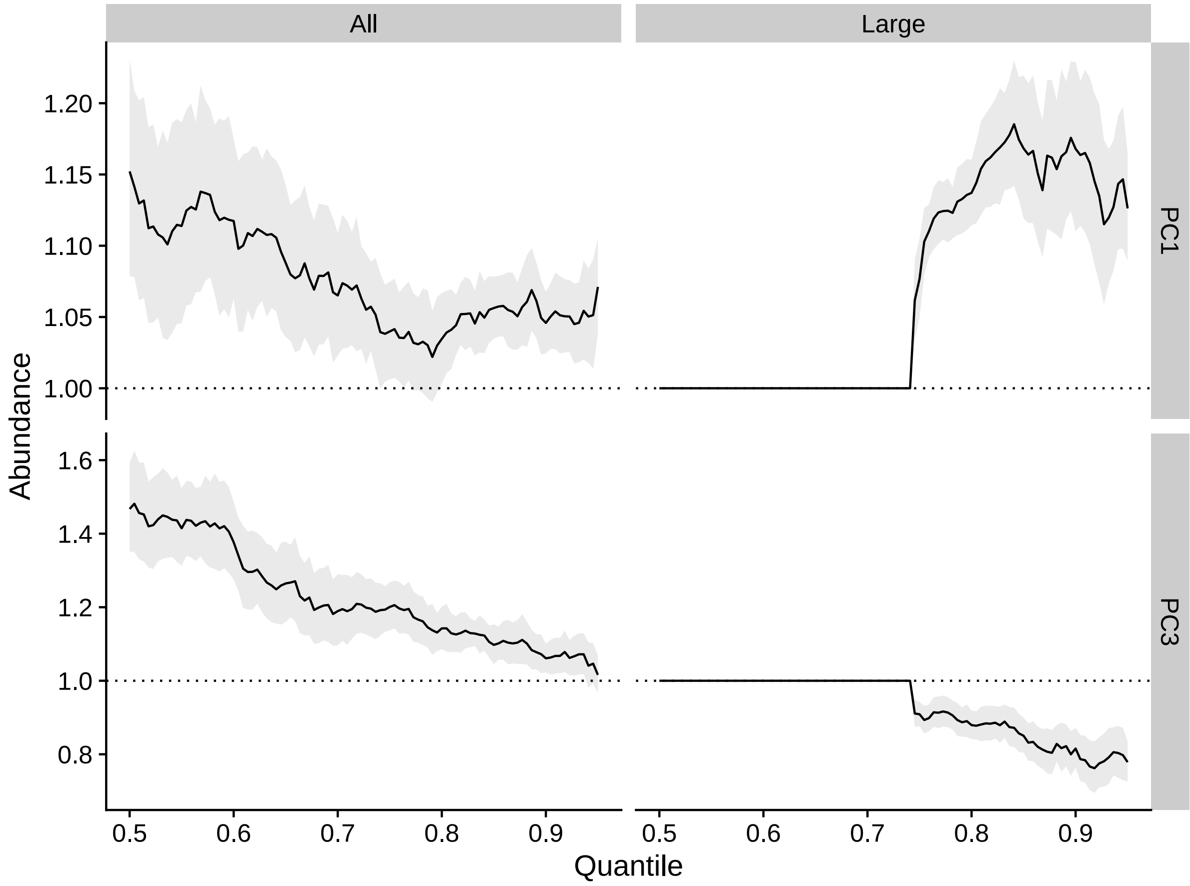

Figure 9: Quantile process plot (coefficients and associated standard error for quantiles from 0.50 to 0.95), showing multiplicative effects per standardised principal component (PC), for all cockle size classes and large (≥30 mm) cockles. PC1 distinguished fine (≤250 µm) and coarse (>250 µm) sediment fractions, whereas PC3 was mainly associated with sediment fines (silt and clay; <63 µm).

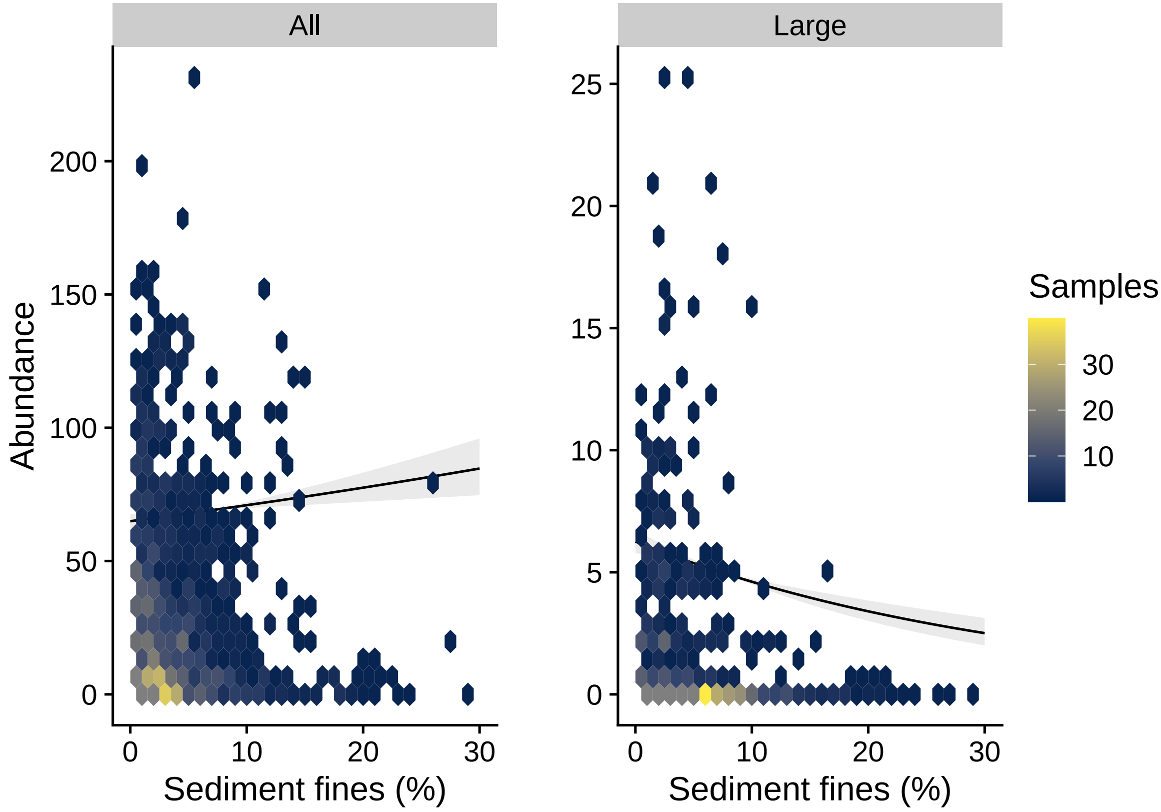

Figure 10: Fitted quantile regression line at $q = 0.9$ and associated standard error, for all cockle size classes and large ($\geq$30 mm) cockles as a function of the proportion of sediment fines (%) along principal component 3 (PC3), which was mainly associated with sediment fines (silt and clay; $<$63 µm).

4. DISCUSSION

Intertidal cockle populations in northern New Zealand are vulnerable to human-induced stressors, such as overfishing, increased sediment loading, pollution and nutrient enrichment (Grant & Hay 2003). The magnitude and repercussions of these factors are often difficult to assess. For example, the general lack of information pertaining to recreational and customary take of intertidal bivalves precludes a direct assessment of fishing impacts on cockle populations. Similarly, data pertaining to changes in coastal environments are often scarce, particularly when these changes are not associated with an acute event or point source and occur over time.

In the context of habitat quality, recognition of the importance of sediment characteristics, particularly increased concentrations of sediment fines (silt and clay, <63 μm) and organic content, has led to the inclusion of sediment in State of the Environment and coastal monitoring programmes throughout New Zealand (Robertson et al. 2002). As sediment data provide information about the condition of coastal environments, including the habitat suitability for resident species, regular surveys by regional councils collect sediment data that are aimed at quantifying sediment properties and potential changes over time (e.g., Robertson & Robertson 2018, Hunt & Jones 2019). In northern North Island, sediment characteristics have also been included in specific management objectives for the Hauraki Gulf Marine Park: the recently-completed spatial plan for the marine park specifies that muddy areas (i.e., mud content $>25\%$) within all estuaries should not expand, and that the sediment mud content should not exceed 10% in 95% of exposed intertidal areas within the marine park by 2050 (Sea Change – Tai Timu Tai Pari 2017).

In the wider Auckland region, several experimental studies have focused on assessing the direct impact of sediment runoff on benthic communities, including cockles (Hewitt et al. 2001, Norkko et al. 2002a, Anderson et al. 2004, Lohrer et al. 2004). In addition, two separate modelling studies examined the habitat preference of cockles and other macrofaunal species in relation to sediment grain size (i.e., mud content) across northern North Island estuaries, based on data from a number of monitoring sites (Thrush et al. 2003, Anderson 2008). Their findings revealed that the optimum proportion of fines (<63 μm) for cockles is less than 10 to 11%, with higher proportions in this grain size fraction limiting maximum cockle abundance.

Based on the habitat preference of cockles, and the ability to monitor sediment properties as one of the factors that influence their distribution and abundance, sediment sampling was included in the northern North Island survey series in 2013–14 (Berkenbusch et al. 2015). The initial two years of the sediment sampling provided baseline information, with subsequent improvements to the sampling design in 2015–16 intended to support formal analyses of cockle population data in relation to sediment characteristics (Berkenbusch & Neubauer 2016).

The formal assessment of the 2015–16 stratum-level survey data revealed a decrease in total cockle abundance with increases in three sediment variables: organic content, the proportion of fines and the proportion of gravel (Berkenbusch & Neubauer 2016). At the same time, there was an increase in large cockle abundance with increases in sediment fines. Nevertheless, these relationships were tentative only, and the analysis was limited by the amount of data, which were based on one-off sediment samples from the 2015–16 survey sites.

The current study presents an updated analysis, based on the five years of sediment monitoring as part of the northern bivalve surveys (i.e., providing up to three years of sediment data for the 2019–20 sites). Throughout the survey period, the monitoring documented relatively small changes in sediment properties across sites over time: there was a small reduction in samples containing gravel, and there was also a small increase in medium to fine sands. Assessing the cockle-sediment relationships across the northern sites showed that neither of these changes in sediment composition were sufficient to notably affect cockle abundance; the latter was highest in fine to medium sands. With most of the sediment consistently dominated by sand fractions, it is likely that any observed declines in cockle populations are related to factors other than sediment grain size characteristics.

In general, the sediment habitat in the cockle strata appeared stable throughout the study period, i.e., without marked increases in fines or gravel. Part of this outcome may be related to the sampling depth of the sediment cores: both sediment grain size and organic content were determined for the top 10 cm of the sediment, instead of surficial sediment only. For this reason, the current sediment data reflect the overall characteristics of the habitat which may influence cockle abundance (e.g., through burrowing ability, and other physical and biogeochemical characteristics that affect cockles); however, this sampling depth also means that changes at only the sediment surface are less likely to be detected because they are less pronounced in relation to the entire sampling depth. Although changes at the sediment surface may be more pronounced, they are likely to be short-term, unless the impacts are significant, such as through catastrophic sediment runoff events (Norkko et al. 2002b).

Overall, the proportion of sediment fines was generally below the threshold of about 10% that may limit cockle populations. Nevertheless, there was considerable variability in this grain size fraction at some sites, evident in individual samples where fines exceeded 20% of the sediment. Examples included Umpuia Beach in 2019–20 (individual samples with 35 and 69% of fines; Berkenbusch & Neubauer 2020) and Kawakawa Bay (West) in 2018–19 (43%; Berkenbusch & Neubauer 2019).

In addition, some sites exhibited recent changes in sediment composition, with discernible increases in fine sand and sediment fines, even though these increases did not affect abundance of all cockles or of individuals in the large size class. Nevertheless, the abundance of large-sized individuals was low when the proportion of sediment fines exceeded 20%.

With sediment properties playing an significant role in determining intertidal cockle populations, the sampling of the northern bivalve populations allows the monitoring of these habitat characteristics across different survey sites and over time. With multiple pressures potentially impacting resident cockles, information of sediment properties allows the elucidation of this potential stressor in relation to changes in cockle populations. The current analysis indicated relatively few changes in sediment over the study period, highlighting the role of other factors in relation to cockle populations at the survey sites.

5. ACKNOWLEDGMENTS

Funding for this study was provided by Fisheries New Zealand project AKI2018-01.

6. REFERENCES

Anderson, M.J. (2008). Animal-sediment relationships re-visited: Characterising species' distributions along an environmental gradient using canonical analysis and quantile regression splines. *Journal of Experimental Marine Biology and Ecology 366 (1)*: 16–27.

Anderson, M.J.; Ford, R.B.; Feary, D.A.; Honeywill, C. (2004). Quantitative measures of sedimentation in an estuarine system and its relationship with intertidal soft-sediment infauna. *Marine Ecology Progress Series 272*: 33–48.

Berkenbusch, K.; Abraham, E.; Neubauer, P. (2015). Intertidal shellfish monitoring in the northern North Island region, 2013–14. *New Zealand Fisheries Assessment Report 2015/15*. 83 p. Retrieved from https://fs.fish.govt.nz/Page.aspx?pk=113&dk=23774.

Berkenbusch, K.; Neubauer, P. (2015). Intertidal shellfish monitoring in the northern North Island region, 2014–15. *New Zealand Fisheries Assessment Report 2015/59*. 110 p. Retrieved from https://fs.fish.govt.nz/Doc/23960/FAR_2015_59_2933_AKI%202014-01.pdf.ashx.

Berkenbusch, K.; Neubauer, P. (2016). Intertidal shellfish monitoring in the northern North Island region, 2015–16. *New Zealand Fisheries Assessment Report 2016/49*. 108 p. Retrieved from https://fs.fish.govt.nz/Page.aspx?pk=113&dk=24186.

Berkenbusch, K.; Neubauer, P. (2017). Intertidal shellfish monitoring in the northern North Island region, 2016–17. *New Zealand Fisheries Assessment Report 2017/51*. 103 p. Retrieved from https://fs.fish.govt.nz/Page.aspx?pk=113&dk=24505.

Berkenbusch, K.; Neubauer, P. (2018). Intertidal shellfish monitoring in the northern North Island region, 2017–18. *New Zealand Fisheries Assessment Report 2018/28*. 99 p. Retrieved from https://fs.fish.govt.nz/Page.aspx?pk=113&dk=24620.

Berkenbusch, K.; Neubauer, P. (2019). Intertidal shellfish monitoring in the northern North Island region, 2018–19. *New Zealand Fisheries Assessment Report 2019/32*. 106 p. Retrieved from https://fs.fish.govt.nz/Page.aspx?pk=113&dk=24738.

Berkenbusch, K.; Neubauer, P. (2020). Intertidal shellfish monitoring in the northern North Island region, 2019–20. *New Zealand Fisheries Assessment Report 2020/38*. 103 p. Retrieved from https://fs.fish.govt.nz/Page.aspx?pk=113&dk=24836.

Caddy, J.F.; Defeo, O. (2003). Enhancing or restoring the productivity of natural populations of shellfish and other marine invertebrate resources. *Food and Agriculture Organization of the United Nations, FAO Fisheries and Aquaculture Technical Paper No. 448*. 159 p.

Eleftheriou, A.; McIntyre, A. (2005). Methods for the study of marine benthos. 418 p. Blackwell Science, Oxford, United Kingdom.

Francis, R.I.C.C. (1984). An adaptive strategy for stratified random trawl surveys. *New Zealand Journal of Marine and Freshwater Research 18*: 59–71.

Grant, C.M.; Hay, B.E. (2003). A review of issues related to depletion of populations of selected infaunal bivalve species in the Hauraki Gulf Marine Park. A report prepared for the Hauraki Gulf Marine Park Forum by AquaBio Consultants Limited. (Unpublished report held by Auckland Regional Council, Auckland.)

Hewitt, J.; Hatton, S.; Safi, K.; Craggs, R. (2001). Effects of suspended sediment levels on suspension-feeding shellfish in the whitford embayment. *Auckland Regional Council, Technical Publication No. 159*.

Hunt, S.; Jones, H.F. (2019). Sediment grain size measurements are affected by site-specific sediment characteristics and analysis methods: Implications for environmental monitoring. *New Zealand Journal of Marine and Freshwater Research 53 (2)*: 244–257.

Lohrer, A.M.; Thrush, S.F.; Hewitt, J.E.; Berkenbusch, K.; Ahrens, M.; Cummings, V.J. (2004). Terrestrially derived sediment: response of marine macrobenthic communities to thin terrigenous deposits. *Marine Ecology Progress Series 273*: 121–138. doi:10.3354/meps273121.

Morton, J.E.; Miller, M.C. (1973). The New Zealand sea shore. 653 p. Collins, London.

Neubauer, P.; Abraham, E.R.; Berkenbusch, K. (2015). Predictability of cockle (*Austrovenus stutchburyi*) population trends in New Zealand's northern North Island. *PeerJ PrePrints 3*: e1772. doi:10.7287/peerj.preprints.1422v1.

Norkko, A.; Talman, S.; Ellis, J.; Nicholls, P.; Thrush, S. (2002a). Macrofaunal sensitivity to fine sediments in the Whitford embayment. *Auckland Regional Council. Technical Publication No. 158*.

Norkko, A.; Thrush, S.F.; Hewitt, J.; Cummings, V.; Norkko, J.; Ellis, J.I.; Funnell, G.; Schultz, D.; MacDonald, I. (2002b). Smothering of estuarine sandflats by terrigenous clay: the role of wind-wave disturbance and bioturbation in site-dependent macrofaunal recovery. *Marine Ecology Progress Series 234*: 23–42.

Pawley, M.D.M.; Smith, A.N.H. (2014). The distribution and abundance of pipis and cockles in the Northland, Auckland and Bay of Plenty regions, 2013. *New Zealand Fisheries Assessment Report 2014/29*. 75 p.

R Core Team (2019). R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria.

Robertson, B.; Gillespie, P.; Asher, R.; Frisk, S.; Keely, N.; Hopkins, G.; Thompson, S.; Tuckey, B. (2002). Estuarine environmental assessment and monitoring: A national protocol. Part C: application of the estuarine monitoring protocol. (Unpublished report prepared by Cawthron Institute for supporting councils and the Ministry for the Environment.)

Robertson, B.; Robertson, B. (2018). Fortrose Estuary fine scale monitoring 2017/18. (Wriggle Ltd. Unpublished report prepared for Environment Southland.)

Sea Change – Tai Timu Tai Pari (2017). Hauraki Gulf Marine Spatial Plan. https://www.seachange.org.nz/read-the-plan. Sea Change – Tai Timu Tai Pari, Hauraki Gulf.

Thrush, S.F.; Hewitt, J.E.; Norkko, A.; Nicholls, P.E.; Funnell, G.A.; Ellis, J.I. (2003). Habitat change in estuaries: Predicting broad-scale responses of intertidal macrofauna to sediment mud content. *Marine Ecology Progress Series 263*: 101–112.