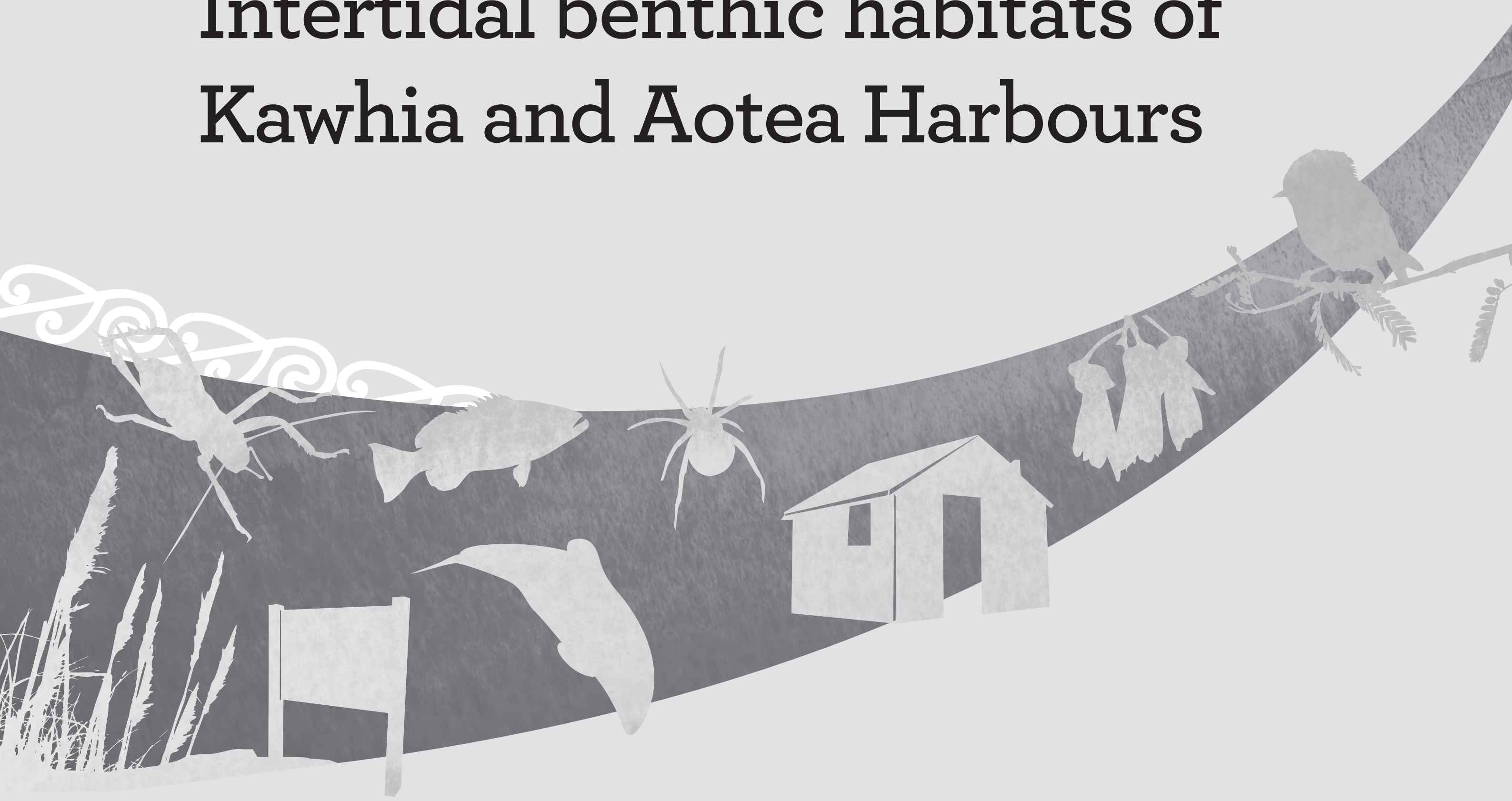
Intertidal benthic habitats of Kawhia and Aotea Harbours



DOC RESEARCH AND DEVELOPMENT SERIES 327

Kristina A. Hillock and Maheswaran Rohan

newzealand.govt.nz

Department of
Conservation
Te Papa Atawhai

DOC Research & Development Series is a published record of scientific research carried out, or advice given, by Department of Conservation staff or external contractors funded by DOC. It comprises reports and short communications that are peer-reviewed.

This report is available from the departmental website in pdf form. Titles are listed in our catalogue on the website, refer www.doc.govt.nz under *Publications*, then *Science & technical*.

ISSN 1177–9306 (web PDF)
ISBN 978–0–478–14916–6 (web PDF)

This report was prepared for publication by the Publishing Team; editing by Sue Hallas and layout by Lynette Clelland. Publication was approved by the General Manager, Research and Development Group, Department of Conservation, Wellington, New Zealand.

Published by Publishing Team, Department of Conservation, PO Box 10420, The Terrace, Wellington 6143, New Zealand.

In the interest of forest conservation, we support paperless electronic publishing.

CONTENTS

Intertidal benthic habitats of Kawhia and Aotea Harbours

Kristina A. Hillock[1] and Maheswaran Rohan[2]

[1] Department of Conservation, PO Box 516, Hamilton 3240, New Zealand.
Email: khillock@doc.govt.nz

[2] Department of Conservation, PO Box 10420, Wellington 6143, New Zealand.

Abstract

Kawhia and Aotea Harbours, on the west coast of New Zealand's North Island, are of high ecological and cultural importance. Their vast intertidal areas are known to be important for shorebirds, and also support an array of estuarine species and habitats, such as seagrass (*Zostera* sp.). This project aimed to map the distribution and abundance of the bivalves *Austrovenus stutchburyi* and *Macomona liliana*, and to record the presence and abundance of other macrofauna and habitat types. *Zostera* sp. was present in large areas of the intertidal area of both harbours. Muddy sand was the predominant habitat type towards the middle of both harbours. Areas exposed to greater wave action consisted of sandy sediment, while less-exposed areas tended to be muddier. The upper reaches of both harbours consisted of sandy-mud to mud habitats. In both harbours, *A. stutchburyi* was the most abundant species recorded, followed by *M. liliana*, and *Zostera* sp. was the most abundant plant. Density of *A. stutchburyi* and *M. liliana* was highest in sand, muddy sand and sandy mud rather than mud. In Kawhia Harbour, *A. stutchburyi* and *M. liliana* abundance was affected by an interaction between the presence of seagrass and sediment type. This was also the case for *A. stutchburyi* in Aotea Harbour, but for *M. liliana*, the presence of seagrass appeared to have no effect on abundance. This information on the abundance and distribution of *A. stutchburyi* and *M. liliana* within the two harbours is a good baseline with which future observations can be compared. Sediment characteristics have also been described, allowing future assessments to gauge the extent of increase (or decrease) in muddy sediments entering the harbour.

Keywords: *Austrovenus stutchburyi*, *Macomona liliana*, *Zostera* sp., intertidal habitats, Kawhia Harbour, Aotea Harbour, New Zealand

Hillock, K.A.; Rohan, M. 2011: Intertidal benthic habitats of Kawhia and Aotea Harbours. *DOC Research and Development Series 327*. Department of Conservation, Wellington. 44 p.

1. Introduction

Estuaries are among the world's most productive ecosystems and are important ecological assets (Perkins 1974; Costanza et al. 1997). They are complex systems that provide a transition zone between the marine and terrestrial environments (Levin et al. 2001). Estuaries provide essential ecosystem services, and the species living therein contribute to critical ecological processes influencing ecosystem health and water quality (e.g. clarity, nutrient cycling and sediment stability). Estuaries provide critical habitat for species that are important food resources not only for humans, but also for fish, birds and a range of other species.

Kawhia and Aotea Harbours are adjacent estuarine systems located on the west coast of the Waikato region of the North Island of New Zealand (Fig. 1). They were created by the partial blocking by sand barriers of drowned river valleys as sea levels rose (between 18 000 and 7000 years ago) (McLintock 1966). Kawhia is the largest of three harbours on the North Island West Coast (the third being Raglan Harbour) and comprises an area of 67.7 km^2 to Mean High Water Spring (MHWS), of which 74% is intertidal (Lundquist et al. 2004). Aotea Harbour is 31.9 km^2 to MHWS, of which 74% is also intertidal (Lundquist et al. 2004). These extensive intertidal sandflats and mudflats provide suitable habitat for diverse and abundant benthic communities and attract many different bird species, for which they form an important food resource.

Freshwater flows into both harbours from streams draining catchments comprising a mixture of grazed farmland and regenerating native forest. Although the human population around the two harbours and associated anthropogenic pollution is small (Shore Futures 2009), anecdotal evidence from the local community suggests that the infill rate of sediment in the harbours has been extensive and is continuing.

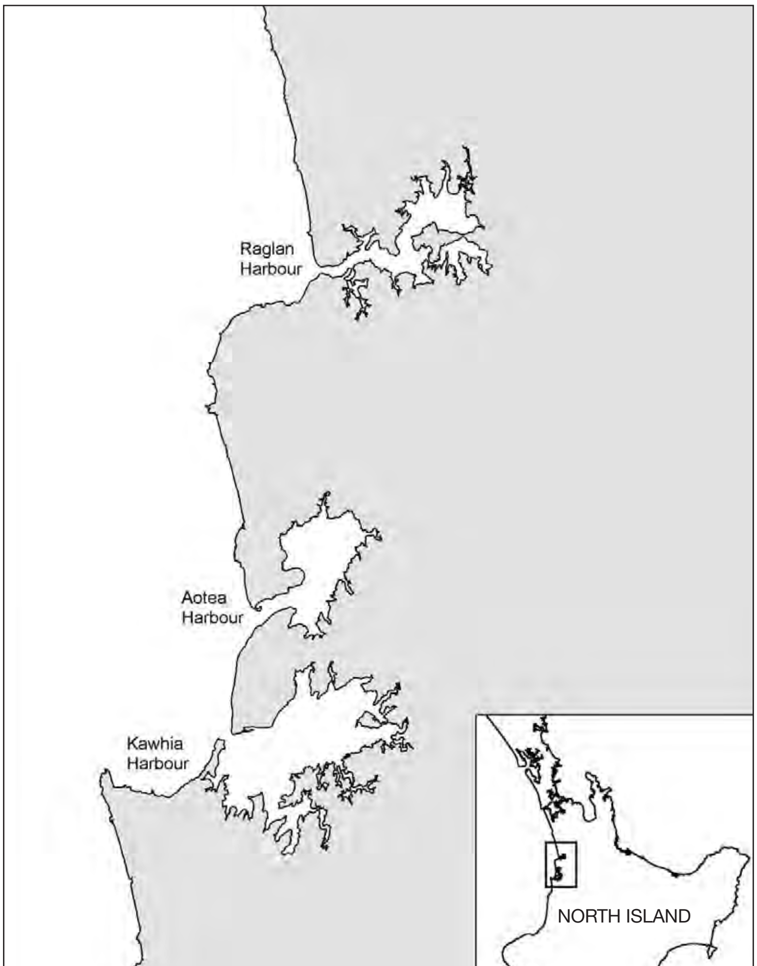


Figure 1. Map showing Aotea and Kawhia Harbours on the west coast of the North Island of New Zealand.

Both harbours have been identified as nationally important sites (1% of national population or higher) for wintering indigenous and international shorebirds (Dowding & Moore 2006). Kawhia Harbour ranks eighth as a nationally important winter site for New Zealand pied oystercatchers (*Haematopus finschi*), second for black stilts (*Himantopus novaezelandiae*), tenth for banded dotterels (*Charadrius bicinctus bicinctus*) and is also a nationally important site for pied stilts (*Himantopus himantopus leucocephalus*) (Dowding & Moore 2006). Ornithological Society counts in recent years show that about 10 000 birds use Kawhia Harbour annually (Southey 2009). Aotea Harbour ranks number 10 of nationally important winter sites for New Zealand pied oystercatchers, and is a nationally important site for pied stilts and banded dotterels (Dowding & Moore 2006).

Both Kawhia and Aotea Harbours have been identified as Areas of Significant Conservation Value by Environment Waikato in the Regional Coastal Plan (Environment Waikato 2005), and in an independent study by NIWA (Lundquist et al. 2004). Kawhia Harbour has been described as the 'seafood basket' of Tainui, because of the richness of the 'kaimoana' (Ritchie 1990). Aotea Harbour is also an important source of food for local communities.

To help protect the rich kaimoana found at Kawhia and Aotea, a taiāpure was established in 2000. This taiāpure covers Aotea and Kawhia Harbours to 2 nautical miles (n.m.) around the entrances, and includes a 1-n.m. coastal strip from Taranaki Point to Albatross Point, and 1 n.m. around Gannet Island. In 2006, the Ministry of Fisheries received an application for a mātaitai reserve within the Kawhia–Aotea–Gannet Island taiāpure. The proposed mātaitai includes all the waters of Aotea Harbour and adjacent coastline from Matawha Point to Kahua Point. A mātaitai reserve recognises a traditional fishing ground and has special status under the Fisheries Act 1996 to protect customary fishing values. Kaitiaki can be empowered to make by-laws over the reserve, and have control over food gathering. A taiāpure is similar in that it gives special status (under the Fisheries Act 1996) to a coastal/estuarine area of customary significance, where management, but not control, is vested in the local hapū or iwi.

One of the more important benthic resources in Kawhia and Aotea Harbours is the New Zealand cockle, *Austrovenus stutchburyi*. Cockles are an edible estuarine bivalve found throughout New Zealand, including Stewart Island/Rakiura and the Chatham Islands. They live on sand/mud flats from below the lowest High Water Neap tide line down to a maximum of 6–8 m below the low tide line (Grant & Hay 2003). Cockles can be found buried just below the substrate surface, and are suspension-feeders. Their two short siphon tubes, which protrude just above the surface, are used to filter phytoplankton out of the water column (Stace 1997; Grant & Hay 2003). Cockles reach sexual maturity at an 18-mm shell length, with spawning occurring from summer to autumn. Larvae are free-swimming for 2–3 weeks before settling. During this time, their dispersal is more or less determined by water movements caused by currents and wind, although the larvae are able to swim up and down the water column (Grant & Hay 2003). After a metamorphosis into juveniles that resemble small adult cockles, they settle onto the substrate. Once settled, cockles are subject to surface sediment movement and dispersal, but it has also been demonstrated that juveniles are able to passively drift in the water column via a mucous thread (Grant & Hay 2003). Adult cockles are also able to actively move for distances up to 30 cm over a single tide by crawling across the sediment surface (Hewitt et al. 1996).

Macomona liliana, or wedge shell, is another common bivalve species found on intertidal sand/mud flats of estuaries and sheltered coastal waters throughout New Zealand. Wedge shells are not commonly collected by humans for food, but do form a component of shorebird and fish diets (Francis 2001; Battley et al. 2005). They are generally found from the mid- to low-tide zone, and are usually buried in the sediment at a depth of 5–10 cm. These deposit feeders extend their siphons out of the sediment and use them to suck in loose detritus and benthic microphytes from the sediment surface (Grant & Hay 2003). Wedge shells reach sexual maturity at shell lengths greater than 22 mm, and spawning extends from spring to autumn (Grant & Hay 2003). Like cockles, their larval stage lasts 2–3 weeks, during which they are passively dispersed by water movement until settlement (Grant & Hay 2003).

Several studies have been undertaken in Aotea Harbour. In 2006, a Ministry of Fisheries survey estimated the population of cockles to be around 30.4 million (Walshe et al. 2005). The same survey found no significant pipi (*Paphies australis*) beds. A Department of Conservation (DOC) survey in 1999 found an average of 560 cockles per m^2 at a well-known cockle bed (DOC 1999). However, no study (either in Aotea or Kawhia Harbours) has attempted to map shellfish resources. The aim of our project was to map the distribution and abundance of New Zealand cockles and wedge shells in Kawhia and Aotea Harbours, as well as to record presence and abundance of other macrofauna and habitat types, and determine the relationship between these.

2. Methods

2.1 Survey design

The study area comprised the intertidal areas of Kawhia and Aotea Harbours. For each harbour, most of the intertidal area is mid- to low-intertidal, with few areas exposed for more than 7 hours in a tidal cycle. The bulk of the sampling was undertaken between 11 December 2007 and 1 February 2008, with an additional sampling day on 18 February 2008, and a second sampling period between 25 April 2008 and 5 May 2008.

Using aerial photographs of the two harbours at low tide, a systematic process was employed to select sampling locations. In ArcGIS™, a 100-m grid was laid over the intertidal areas (as determined from the aerial photographs). A GPS point was positioned at the centre of each grid square and saved as a shape file. These shape files were loaded onto Garmin 60 CSx hand-held GPS units that were then used to locate each sampling point in the field.

Originally, 5259 sampling grid points were identified in Kawhia Harbour, and 2470 in Aotea. However, only 2133 grid points (41% of total sampling points) were sampled in Kawhia Harbour, and 392 grid points (16% of total sampling points) in Aotea Harbour. This equated to a grid area of 21.33 km^2 and 3.92 km^2 in Kawhia and Aotea Harbours, respectively. This was mainly due to time constraints and accessibility issues. During the sampling, it became apparent that the benefit (in terms of data collected) of sampling some areas was low, as access was extremely difficult. At some locations, mud was so thick that it took up to 20 minutes to walk 100 m between sampling points, while not finding any of the target organisms in the muddy sediment. After several days of sampling, it was possible to distinguish areas of thick mud from areas of sand or sand-mud mix from the aerial photographs. Previous studies have suggested that cockles and wedge shells are less likely to be found in muddy areas (Cummings et al. 2002; Thrush et al. 2003; Gibbs & Hewitt 2004; Hewitt et al. 2005), thus sampling effort was focused on less muddy areas. This also became important as the time spent collecting data at each sampling location was greater than originally anticipated, and there was not time to sample all points. Therefore, areas that were easily accessible were sampled first, and some areas that were difficult to access were not sampled.

2.2 Data collection

The GPS units were used to navigate to each sampling point (within an accuracy of 4–6 m). A 25 cm × 25 cm quadrat (area = 0.0625 m^2) was placed on the located point. Where surface vegetation was present, e.g. sea lettuce (*Ulva lactuca*), percentage cover of each species was recorded by visual estimation, and grouped into the following cover classes: 0% (absence of vegetation), 1–5%, 6–25%, 26–50%, 51–75%, 76–95%, 95–100%.

Sediment type was recorded (judged by rubbing the sediment between the fingers and by noting obvious visual characteristics) and grouped into the following categories:

- Mud (no grains of sand)
- Sandy mud (more mud than sand present)
- Muddy sand (more sand than mud present)
- Sand (no mud present)
- Gravel/cobbles (this included gravel, stones and cobbles)
- Rock platform (hard continuous rock substrate)

Additionally, the presence and number of surface-dwelling mollusc species inside the quadrat were recorded (e.g. *Cominella glandiformis* (mud whelk)). Cockles are commonly found at the sediment surface, whereas wedge shells are usually found around a depth of 5–10 cm

(Hewitt et al. 1996). Consequently, the area inside the quadrat was excavated to a depth of 10 cm using an ordinary garden trowel with a 10-cm depth marked on the blade. Excavated material was sorted by hand to remove and count molluscs. Species, number and size class (cockles, wedge shells and pipi only) of these molluscs were recorded. In high-density quadrats, counting of individual molluscs stopped when the number reached 30, and total number for that quadrat (sampling unit) was recorded as '>30'.

For cockles and wedge shells, size classes based on shell length were recorded as:

- Small (<15 mm) (minimum detectable size = 5 mm)
- Medium (15–25 mm)
- Large (>25 mm)

For each quadrat, a size range was recorded, rather than the sizes of each individual (e.g. small–medium, or small–large). Where the number of cockles and wedge shells was >30, the size range of all individuals was recorded, not just a subsample of 30 individuals.

For pipi, the smallest and largest (shell length) individuals per sample point were measured to get a size range. Later, these sizes were grouped into juvenile (<40 mm) and adult (>40 mm) groups.

2.3 Analysis of sediment grain size

Sediment samples were collected from 23 sites in Kawhia Harbour and 21 in Aotea Harbour for the analysis of sediment grain size. Sites were chosen using aerial maps and covered a range of locations across the harbours. Samples were collected by scooping the top 3–4 cm of sediment into a plastic jar. This depth of sediment was chosen as it represents a period of 0.2–7 years of sedimentary deposits (Thrush et al. 2003). It is also this top layer of sediment that may influence settling by juvenile shellfish (Thrush et al. 2003).

Prior to grain size analysis, samples were pre-treated with 10% hydrogen peroxide to remove organic material and 1 M HCl to remove carbonate material. Calgon was added as a dispersant and samples were placed in an ultrasonic bath for 10 minutes to aid disaggregation. Samples were then analysed using a Galai laser sediment analyser.

2.4 Geographic Information System (GIS) analysis

2.4.1 Mapping

The distribution and abundance of cockles, wedge shells, pipi and seagrass (*Zostera* sp.) were converted into a continuous data model (i.e. raster grid) using natural neighbour interpolation, and mapped in ArcGIS based on a 2-m cell size extending to the intertidal area of each harbour.

Specifically, a GIS was used to create maps of the benthic survey data for both harbours. The attribute information (from the original data spreadsheets) and spatial location information (from the GPS shape files) were joined to form the base GIS layer for each harbour. The base GIS layer was in the form of a point dataset. The background imagery used for the maps was from aerial photographs taken at low tide.

The point dataset was converted into several raster models to represent density and distribution for the following data fields:

- Wedge shell
- Seagrass
- Pipi
- Cockle

Natural neighbour interpolation was used to create these models. Both the ‘vegetation’ and ‘sediment’ data fields were also represented as raster models. However, no interpolation was undertaken on these datasets. The data were displayed in 100 m × 100 m-cell format, where each cell represented the actual value surveyed at that point.

Size class maps were produced for both wedge shells and cockles, as were maps showing occurrence of species other than wedge shells and cockles.

2.4.2 Sampling effort analysis

In order to find the optimum sampling unit for an efficient sampling programme, a grid analysis was undertaken for the Kawhia Harbour cockle dataset. Five sampling grids were established based on the original dataset:

- Original 100 m sample grid
- 200 m re-sampled grid
- 300 m re-sampled grid
- 400 m re-sampled grid
- 500 m re-sampled grid

The additional re-sampled grids all used the original survey results from actual surveyed locations.

New raster models were created for the re-sampled grids. A map of the 200-m raster was produced for direct comparison with the original 100-m raster. The difference between the two raster models was calculated by subtracting the value of each individual cell within the 100 m raster from the value of the corresponding cell within the 200 m raster. The result was a range of individual cell values from 0 to 30, i.e. no difference in cockle density between the two raster models to maximum difference, respectively.

For each new raster model, interpolated counts at each original sampling point were calculated, along with the difference between the interpolated counts and original data at each point. These difference values were converted into percentage difference between the original 100-m grid and the new re-sampled grids.

All GIS data was projected in New Zealand Map Grid (NZMG).

2.5 Statistical analysis

2.5.1 Presence/absence

Analyses of cockle and wedge shell data were undertaken separately for each harbour. Although the harbours are in close proximity to each other (approximately 5 km of coastline separates their entrances), they differ in size and shape, have separate catchments and represent separate systems. Cockles and wedge shells were analysed independently for each harbour, as the correlation coefficient in an initial analysis suggested that there was no association between the abundance of cockles and wedge shells. In total, 2104 samples were analysed for Kawhia Harbour and 386 for Aotea Harbour, as not all recorded data were complete for each field. Although the habitat type ‘rock platform’ was recorded at Kawhia Harbour, it was not used in the analysis as it was not considered suitable habitat for cockles or wedge shells. Seagrass percentage cover was treated as a factor, with the seven cover classes being designated ‘levels’, ranging from 0 (0% cover) to 6 (96–100% cover). Box plots were used to explore the relationship between cockle and wedge shell abundance v. sediment type, and abundance v. percentage cover of seagrass. Classification trees (based on the presence and absence of cockles and wedge shells) were used to investigate the possible interaction effect between sediment type and percentage cover of seagrass.

A statistical pruning criteria was applied to obtain an optimum tree. The classification tree results were used to inform the variable groupings (sediment type, seagrass percentage cover) used in the modelling below.

2.5.2 Density modelling

In order to address over-dispersion, a negative binomial generalised linear model was used to investigate the relationship between the response variable of abundance of cockles and wedge shells, and the covariates such as sediment type and vegetation percentage cover. The Information Theoretic Approach (Burnham & Anderson 2001) was used to select the model that best explained the data. For modelling purposes, sediment was divided into two levels: 'sand' (sand, sandy mud and muddy sand) and 'no sand' (mud and gravel/cobbles). This was based upon results from the classification tree and box plots. However, there was no clear distinction between sediment levels for wedge shells in Aotea Harbour. In order to maintain consistency, model selection was based on a comparison between two models (Model 1: 'sand' = sand, muddy sand, sandy mud, and 'no sand' = gravel, cobbles, mud; Model 2: 'sand' = sand, muddy sand, and 'no sand' = gravel, cobbles, mud, sandy mud) for each species at each harbour. The results showed that Model 1 was preferred for all cases except wedge shells in Aotea Harbour (see Appendix 1.1) All analyses were conducted in statistical software R (www.r-project.org). Results are expressed as number of individuals per 0.0625 m^2.

3. Results

3.1 Kawhia Harbour

All analyses for cockles and wedge shells were conducted separately, because of a low correlation between the abundance of cockles and wedge shells (r = 0.17; the value suggests that the abundance of cockles was not related to the abundance of wedge shells).

3.1.1 Cockles

Cockles were more numerous than any other animal species sampled, both in terms of the numbers of quadrats in which they were recorded (n = 1286, of 2133 sampled), and the total number of individuals recorded (n = 14 390) (Table 1). The mean number of cockles per quadrat (only from quadrats where they were recorded) was 11.19. The median number of cockles per quadrat for all quadrats sampled (including quadrats where no cockles were recorded) was 7 (Fig. 2).

Cockles were observed in most of the sites sampled, with a number of dense cockle beds identified (see Fig. 3). Cockle size ranged from small (< 15 mm) to large (> 25 mm), but the most frequent size class group was 'small–medium' (Fig. 4). Most of the large cockles observed in this study were approximately 25–30 mm long. Because of the method of collection, it is not clear from the data whether particular size classes were more clearly associated with particular sediment types. However, the dense areas of cockles contain a mix of size classes (Fig. 5). None of the sampled areas stood out as particular 'hot spots' for cockle recruitment (i.e. there were no areas with high numbers of juvenile ('small') cockles).

Cockle density was highest in muddy sand (based on the median values in Fig. 6A). While there appears to be a positive relationship between cockle density and seagrass cover, cockles were still dense in areas where seagrass was not present (Fig. 6B). The classification tree analysis indicated that the presence of cockles depends on the combination of percentage cover of seagrass and sediment type (Table 2; for tree diagram see Appendix 1, section A1.2).

In this study, no seagrass was recorded growing on sediments classed as gravel, cobbles or mud. These were the habitat types also least likely to contain cockles. There was an 85% chance of finding cockles when the sediment was a mix of sand and mud, or just sand, and seagrass cover was 6% or higher.

Table 1. List of species and sediments sampled in Kawhia Harbour.

SPECIES	COMMON NAME	MĀORI NAME	NUMBER OF QUADRATS WHERE RECORDED	TOTAL NUMBER OF INDIVIDUALS RECORDED	PROPORTION OF QUADRATS WHERE RECORDED (%)
Animals					
Austrovenus stutchburyi	Cockle	Tuangi	1286	14390	60.29
Macomona liliana	Wedge shell	Hanikura	921	3503	43.18
Diloma subrostrata	Harbour topshell	Whētiko	458	997	21.47
Zeacumantus lutulentus	Hornshell	Koeti	365	879	16.97
Amphibola crenata	Mud snail	Tītiko	150	461	7.03
Cominella glandiformis	Mud whelk		131	184	6.14
Paphies australis	Pipi	Pipi	87	222	4.08
Xenostrobus pulex	Little black mussel		25		1.17
Musculista senhousia	Asian date mussel		20		0.94
Fellaster zelandiae	Snapper biscuit	Kina papa	9	23	0.42
Saccostrea glomerata	Rock oyster	Tio, tiopara, tio repe	8		0.38
Struthiolaria papulosa	Ostrich foot	Kaikaikaroro	8	12	0.38
Perna canaliculus	Green lip mussel	Kuku	6	9	0.28
Lunella smaragdus	Cat's eye	Pūpū, ataata	4	7	0.19
Dosinia anus	Biscuit shell		3	6	0.14
Mactra sp.	Bivalve		3	8	0.14
Amalda australis	Olive shell	Pūpū pīataata	3	3	0.14
Diacanthurus spinulimanus	Hermit crab	Pāpaka moke	3	3	0.14
Patiriella regularis	Cushion star		1	1	0.05
Plants					
Zostera sp.	Seagrass		502		23.53
Gracilaria chilensis	Red alga		191		8.95
Corallina officinalis	Red alga		2		0.09
Unidentified red algae			8		0.38
Ulva sp.	Sea lettuce		20		0.94
Spartina sp.			1		0.05
Bare substrate			1409		66.06
Sediment					
Muddy sand			704		33.01
Sand			632		29.63
Sandy mud			529		24.80
Mud			234		10.97
Rock platform			25		1.17
Gravel-cobbles			7		0.33
Shell hash			2		0.09

Total number of quadrats smapled = 2133

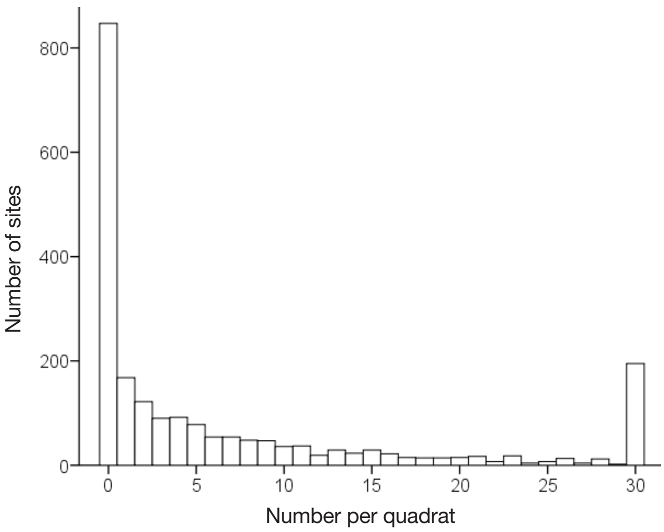


Figure 2. Frequency distribution of cockle (*Austrovenus stutchburyi*) densities (number per quadrat) at the sample sites in Kawhia Harbour (n = 2133 quadrats).

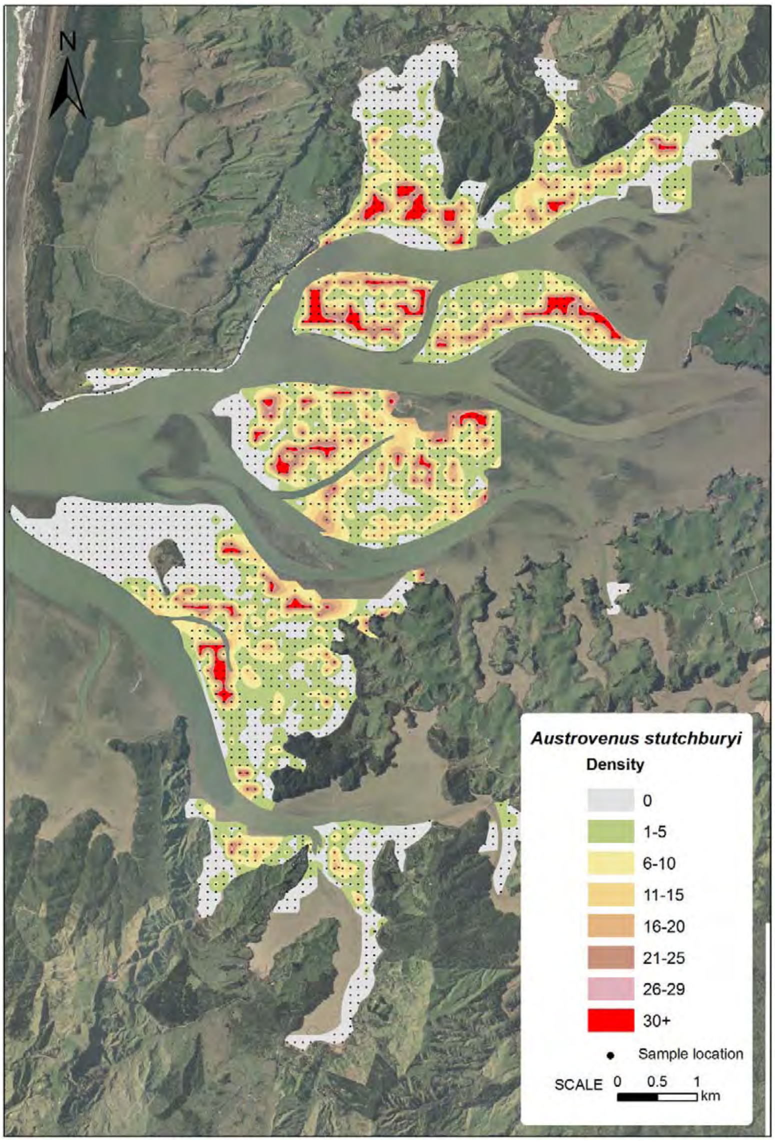


Figure 3. Density (number per quadrat) and distribution of cockles (*Austrovenus stutchburyi*) in the sampled areas of Kawhia Harbour. Displayed as a raster model based on interpolation of original point dataset.

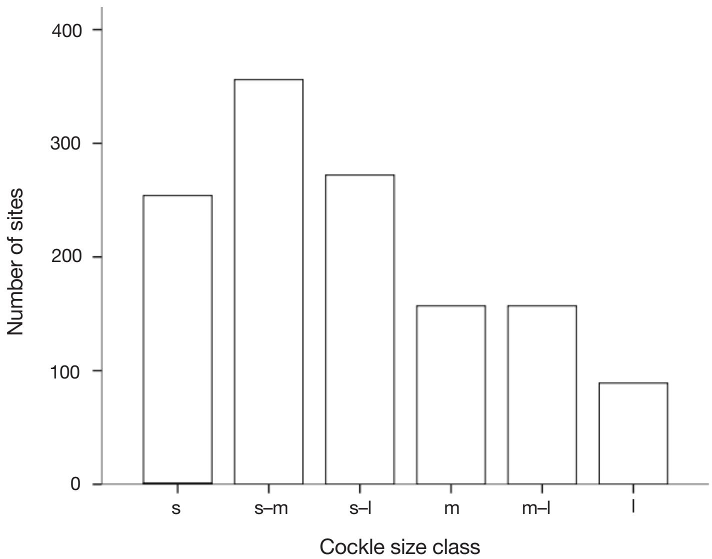


Figure 4. Frequency of size class groups of cockles (*Austrovenus stutchburyi*) sampled in Kawhia Harbour. s = small (< 15 mm), m = medium (15–25 mm), l = large (> 25 mm).

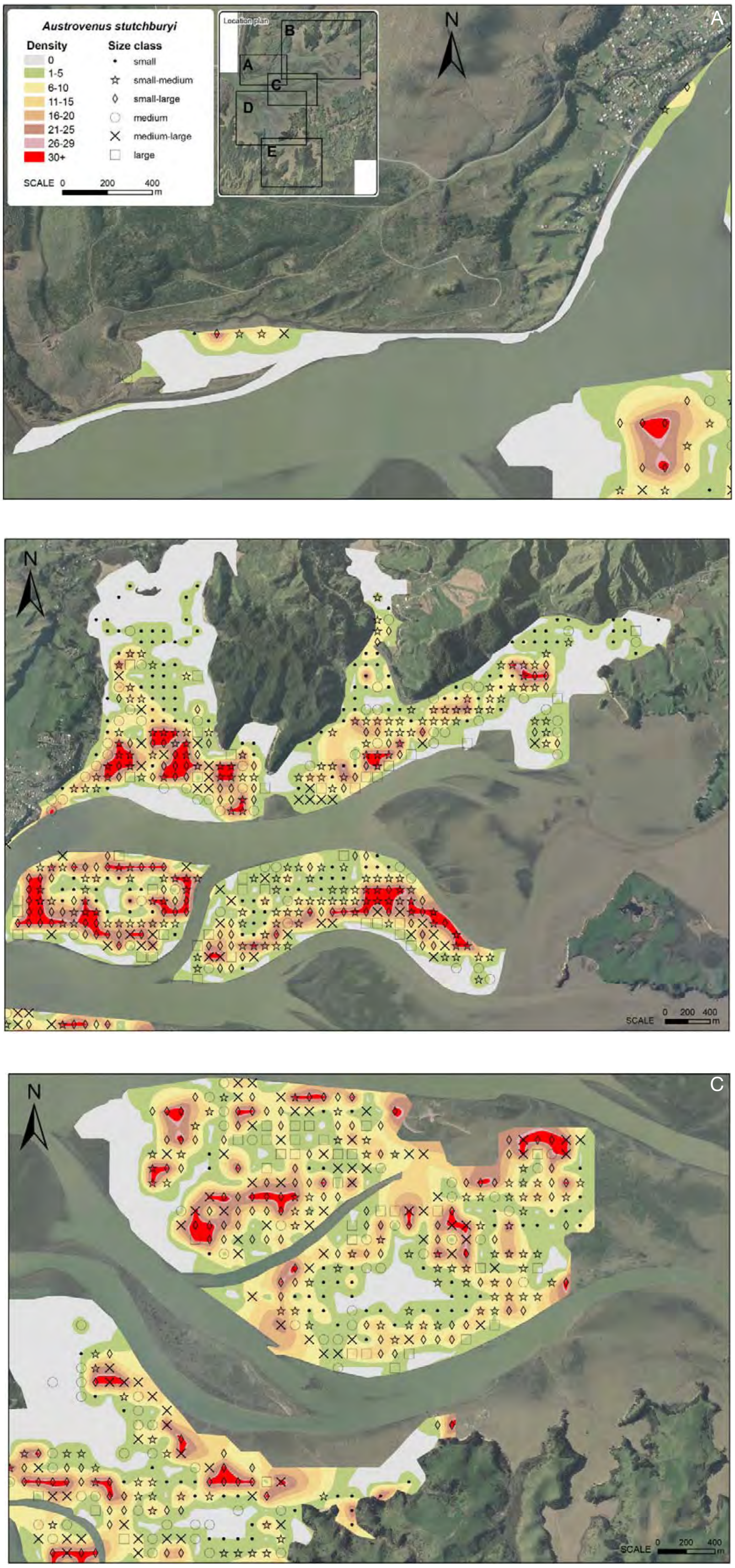
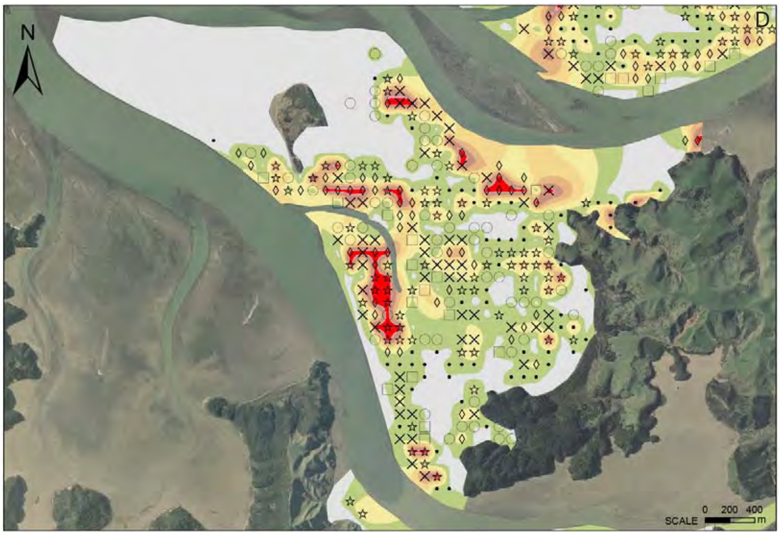
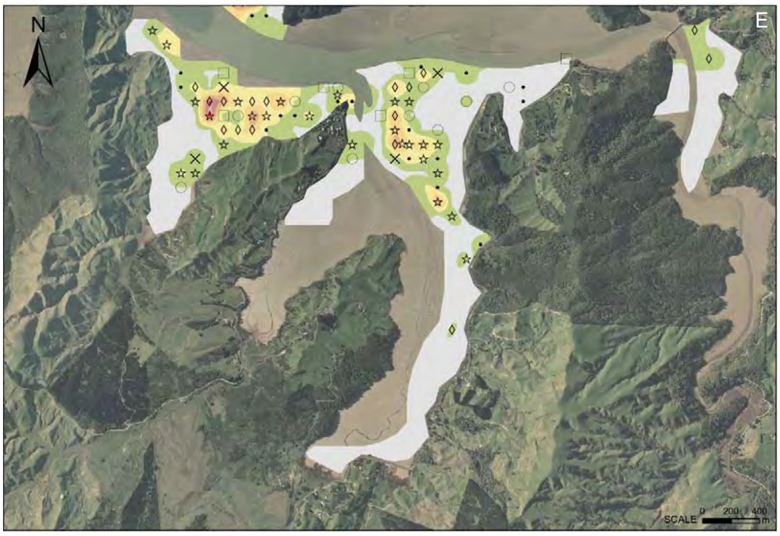


Figure 5. Cockle (*Austrovenus stutchburyi*) size classes in the sampled areas of Kawhia Harbour, over-laying density data (see Fig. 3). Small = <15 mm, medium = 15–25 mm, large = >25 mm. Displayed as a raster model based on interpolation of original point dataset. Locations of areas in maps A–E shown in insert box on A.

Continued on next page

Fig. 5 continued





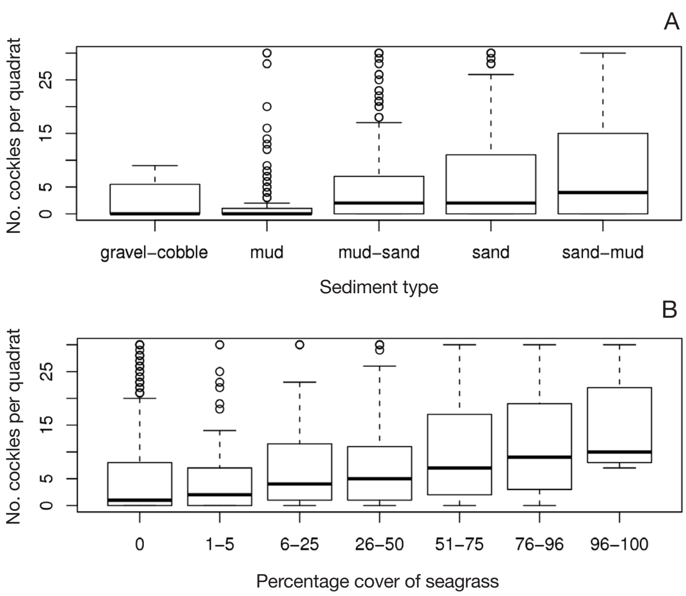


Figure 6. Box plot of density per quadrat of cockles (*Austrovenus stutchburyi*) by A. Sediment type and B. Percentage cover of seagrass (*Zostera* sp.) in Kawhia Harbour.

Table 2. Expected probability of cockle presence in a quadrat in Kawhia Harbour, based on sediment type and percentage cover of seagrass (*Zostera* sp.), as calculated by classification tree.

SEDIMENT TYPE	SEAGRASS COVER (%)	EXPECTED PROBABILITY OF PRESENCE OF COCKLES
Gravel/cobbles, mud	0	0.27
Sandy mud, sand, muddy sand	6–100	0.85
Sandy mud, muddy sand	0–5	0.65
Sand	1–5	0.66
Sand	0	0.46

Table 3. Predicted mean number of cockles (*Austrovenus stutchburyi*) present per quadrat in Kawhia Harbour, based on sediment type and seagrass (*Zostera* sp.) percentage cover.

SEDIMENT TYPE	SEAGRASS GROUP	PREDICTED MEAN NUMBER OF COCKLES PER QUADRAT
'No sand'	'No seagrass'	1.62
'Sand'	'No seagrass'	6.98
'Sand'	'Seagrass'	8.95

The results from the classification tree indicate that there is a low chance of cockle presence in gravel, cobbles and mud. Therefore, sediment type was divided into two groups: 'sand' (included sand, muddy sand and sandy mud) and 'no sand' (included gravel, cobbles and mud). Percentage cover of seagrass was also divided into two groups (levels): 'no seagrass' (seagrass absent) and 'seagrass' (seagrass present).

Simply, cockle abundance may be interpreted in terms of habitat factors (two types of sediment and two levels of seagrass percentage cover). The results suggest that the greatest number of cockles can be predicted when sediment group is 'sand' (sand, sandy mud or muddy sand) and seagrass is present, and the fewest when sediment type is 'no sand' (mud, cobbles or gravel) (Table 3; Appendix 1, section A1.3).

3.1.2 Wedge shells

Wedge shells were the second-most numerous species sampled after cockles, being recorded in 921 of 2133 quadrats, with a total number of 3503 individuals (Table 1). The mean number of wedge shells per quadrat (only from quadrats where they were recorded) was 3.80. The median number of wedge shells per quadrat for all quadrats sampled (including quadrats where no wedge shells were recorded) was 3 (Fig. 7).

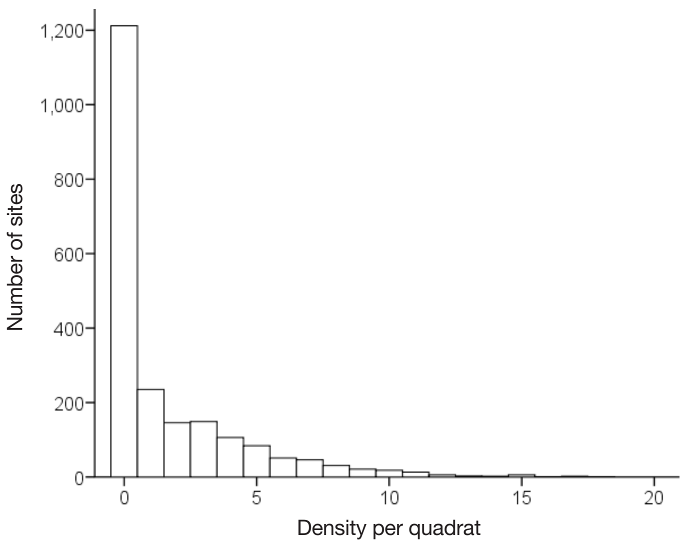


Figure 7. Frequency distribution of wedge shell (*Macomona liliana*) densities (number per quadrat) at the sample sites in Kawhia Harbour (n = 2133 quadrats).

The greatest numbers of wedge shells were recorded towards the middle of Kawhia Harbour, with fewer in the southern part of the harbour (Fig. 8). Wedge shells were not often observed in mud. Wedge shell size ranged from small (<15 mm) to large (>25 mm), and the most frequent size class was 'medium' followed by 'small' (Fig. 9). Because of the method of sample collection, it is not clear from the data whether particular size classes were more clearly associated with particular sediment types. The more dense areas of wedge shells contained a mix of classes (Fig. 10). None of the sampled areas stood out as particular 'hot spots' for wedge shell recruitment.

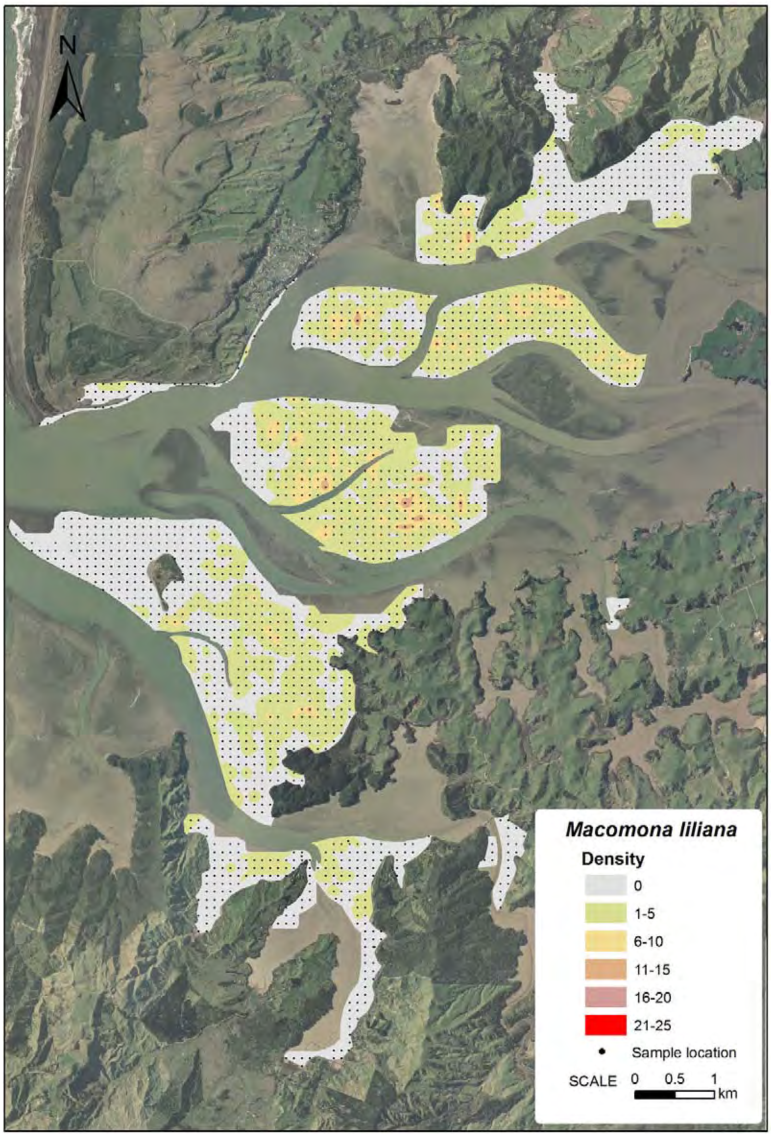


Figure 8. Density (number per quadrat) and distribution of wedge shells (*Macomona liliana*) in the sampled areas of Kawhia Harbour. Displayed as a raster model based on interpolation of original point dataset.

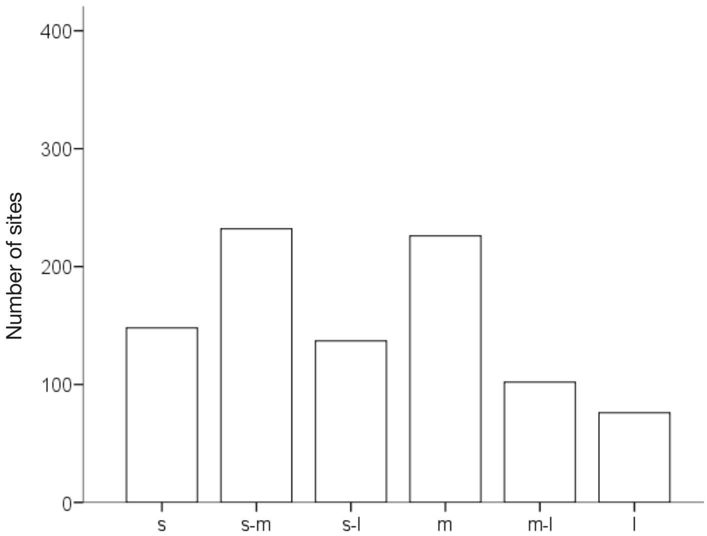


Figure 9. Frequency of size class groups of wedge shells (*Macomona liliana*) sampled in Kawhia Harbour. s = small (<15 mm), m = medium (15–25 mm), l = large (>25 mm).

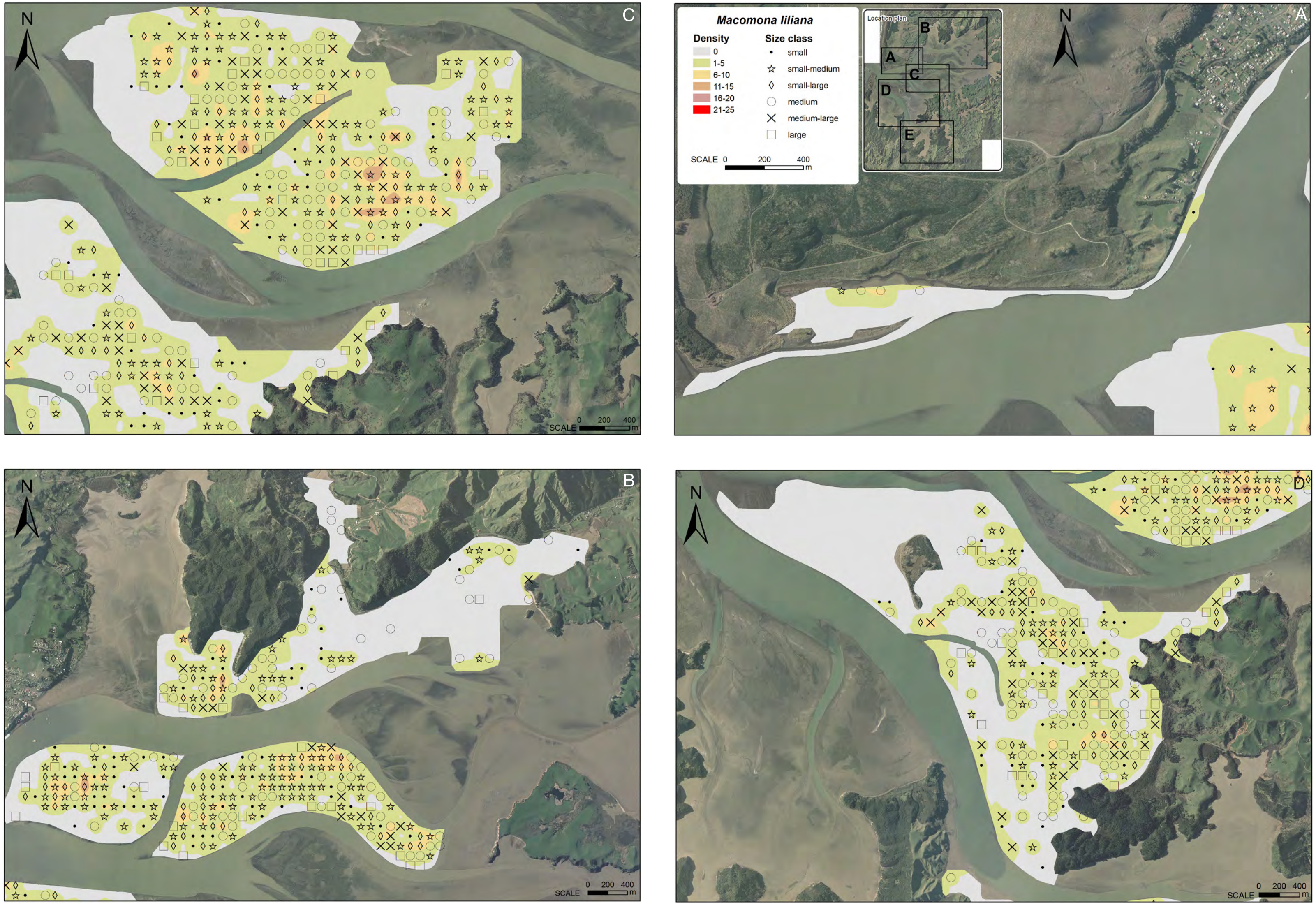
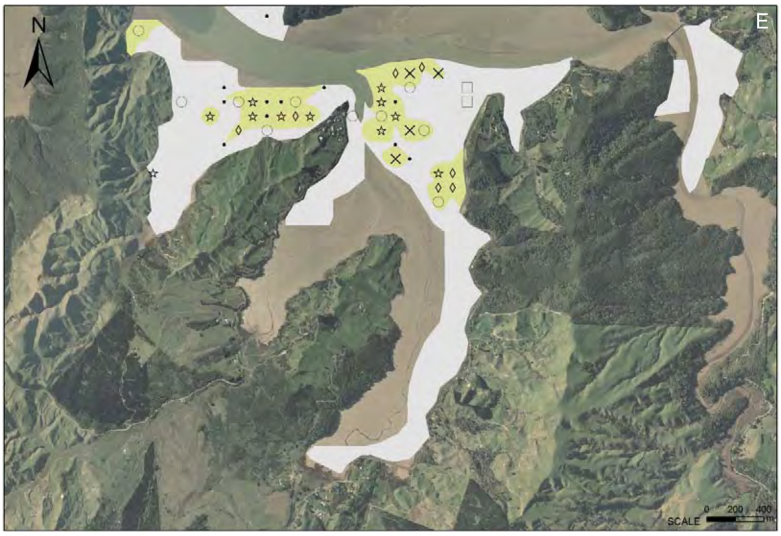


Figure 10. Wedge shell (*Macomona liliana*) size classes in the sampled areas of KawhiaHarbour, over-laying density data (see Fig. 9). small = <15 mm, medium = 15–25 mm, large = >25 mm. Displayed as a raster model based on interpolation of original point dataset. Locations of areas in maps A–E shown in inset map on A.

Continued on next page

Fig. 10 continued



Wedge shell abundance was observed to be highest when sediment type was sand or muddy sand (based on the median values in Fig. 11A), showing a similar pattern to that of cockles. However, wedge shells were not often observed in sandy mud, contrary to cockles.

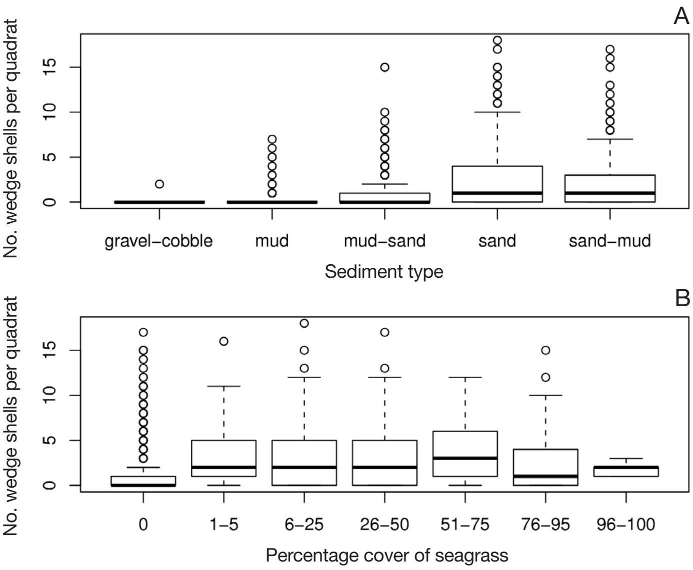


Figure 11. Box plot of density per quadrat of wedge shells (*Macomona liliana*) by A. Sediment type and B. Percentage cover of seagrass (*Zostera* sp.) in Kawhia Harbour.

Table 4. Expected probability of wedge shell (*Macomona liliana*) presence in a quadrat in Kawhia Harbour, based on percentage cover of seagrass (*Zostera* sp.), as calculated by classification tree.

SEAGRASS COVER (%)	EXPECTED PROBABILITY OF PRESENCE OF WEDGE SHELLS
0	0.35
1–100	0.73

There was no clear association between the abundance of wedge shells and percentage cover or absence of seagrass—wedge shells were occasionally abundant when seagrass was absent, as indicated by the outliers in the graph (Fig. 11B). This may have been due to the influence of sediment type. The classification tree analysis indicated that seagrass presence and absence was more important for explaining the presence and absence of wedge shells than sediment type (Table 4; for tree diagram see Appendix 1, section A1.4). There was a 73% chance of finding at least 1 wedge shell per quadrat when there was ≥1% cover seagrass, while only a 35% chance in the absence of any seagrass.

Sediment type and seagrass percentage cover were divided into two groups, similar to that for cockles above. The greatest number of wedge shells can be expected when the sediment type contains 'sand' (sand, muddy sand or sandy mud) and there is at least 1% or greater cover of seagrass present, and the fewest when the sediment type is 'no sand' (mud, gravel or cobbles) and seagrass is absent (Table 5; Appendix 1, section A1.5).

Table 5. Predicted mean number of wedge shells (*Macomona liliana*) present per quadrat in Kawhia Harbour, based on sediment type and seagrass (*Zostera* sp.) percentage cover.

SEDIMENT TYPE	SEAGRASS GROUP	PREDICTED MEAN NUMBER OF WEDGE SHELLS PER QUADRAT
'No sand'	'No seagrass'	0.22
'Sand'	'No seagrass'	1.35
'Sand'	'Seagrass'	3.25

3.1.3 Pipi

Fewer pipi were recorded in comparison with cockles and wedge shells (Fig. 12 and Table 1). Pipi were recorded in 87 of 2133 quadrats, with a total of 222 individuals. Most were smaller than 25 mm (shell length) and only 1 was larger than 40 mm.

3.1.4 Other species

A number of other surface-dwelling species were recorded inside the quadrats (Table 1). *Diloma subrostrata* (harbour topshell) and *Zeacumantus lutulentus* (hornshell) were abundant and most often recorded lower on the shore in more exposed areas, usually in association with sand or muddy sand (Fig. 13). Conversely, *Amphibola crenata* (mud snail) occurred most frequently in more sheltered areas, often close to shore and were associated with sandy mud and mud.

3.1.5 Invasive species

Musculista senhousia, an invasive bivalve commonly called the Asian date mussel was recorded at 20 sampling points around the harbour (Fig. 13). At 13 sites *M. senhousia* formed a 100% cover of the substrate, in predominantly muddy substrate. It was always observed at the edge of large channels, often in sheltered locations. In most cases, *M. senhousia* formed dense raised beds that excluded all other bivalve species. No vegetation was recorded in association with *M. senhousia*.

3.1.6 Vegetation

Seagrass was the most abundant vegetation cover in the areas sampled, with large beds extending over most of the sand bars in the middle of the harbour (Fig. 14). Seagrass was often absent from the upper reaches of the harbour where the sediment was muddier. The red alga *Gracilaria chilensis* was also present at several locations at the fringes of seagrass beds, and in some muddier places (Fig. 15).

3.1.7 Sediment

Muddy sand was the sediment type represented most in the areas sampled. This was followed by sand, sandy mud and mud (Table 1; Fig. 16). Intertidal areas that were more exposed were generally sandier, and the upper reaches of the harbour were very muddy, with soft mud and silt present closer to shore. It was also often observed that small ephemeral channels accumulated muddier sediments on their banks, sometimes forming hummocks usually only 1 m wide.
Few areas of gravel, cobbles or rock platform were sampled, and most of these occurred at the landward edges of the intertidal area.

3.1.8 GIS mapping

Raster modelling indicated an asymptotic relationship between information loss and sampling resolution (Fig. 17). The smaller, less-dense cockle beds were not represented on the re-sampled 200 m grid, whereas the larger dense beds were still identifiable (Fig. 18). A comparison of the 100 m, 200 m and 500 m re-sampled grids is shown in Fig. 19. Most of the information lost in the 200-m grid was towards the outside of the re-sampled areas (Fig. 19B, C).

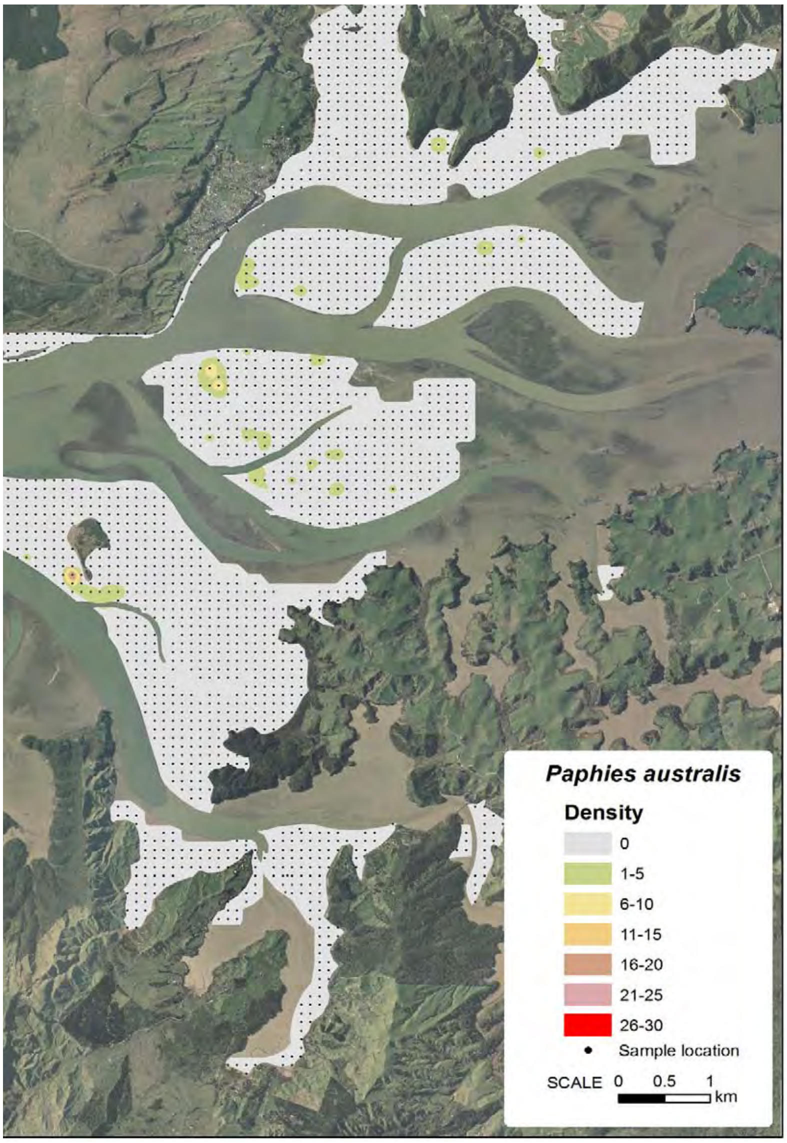


Figure 12. Density (number per quadrat) and distribution of pipi (*Paphies australis*) in the sampled areas of Kawhia Harbour. Displayed as a raster model based on interpolation of original point dataset.

3.2 Aotea Harbour

Two areas of Aotea Harbour were sampled during this study—the southernmost area (close to the harbour entrance), and a section to the northeast (furthest away from the harbour entrance). This was solely due to accessibility within the sampling timeframe available. The northeast section was noticeably muddier than the southern section.

In the areas that were sampled, wedge shells were slightly more widespread, being found in 233 quadrats (of 392 sampled) v. 214 for cockles, but cockles were dominant in terms of total number of individuals recorded (2425, v. 1206 wedge shells). Pipi were recorded in only 13 quadrats, with a total of 23 individuals (Table 6).

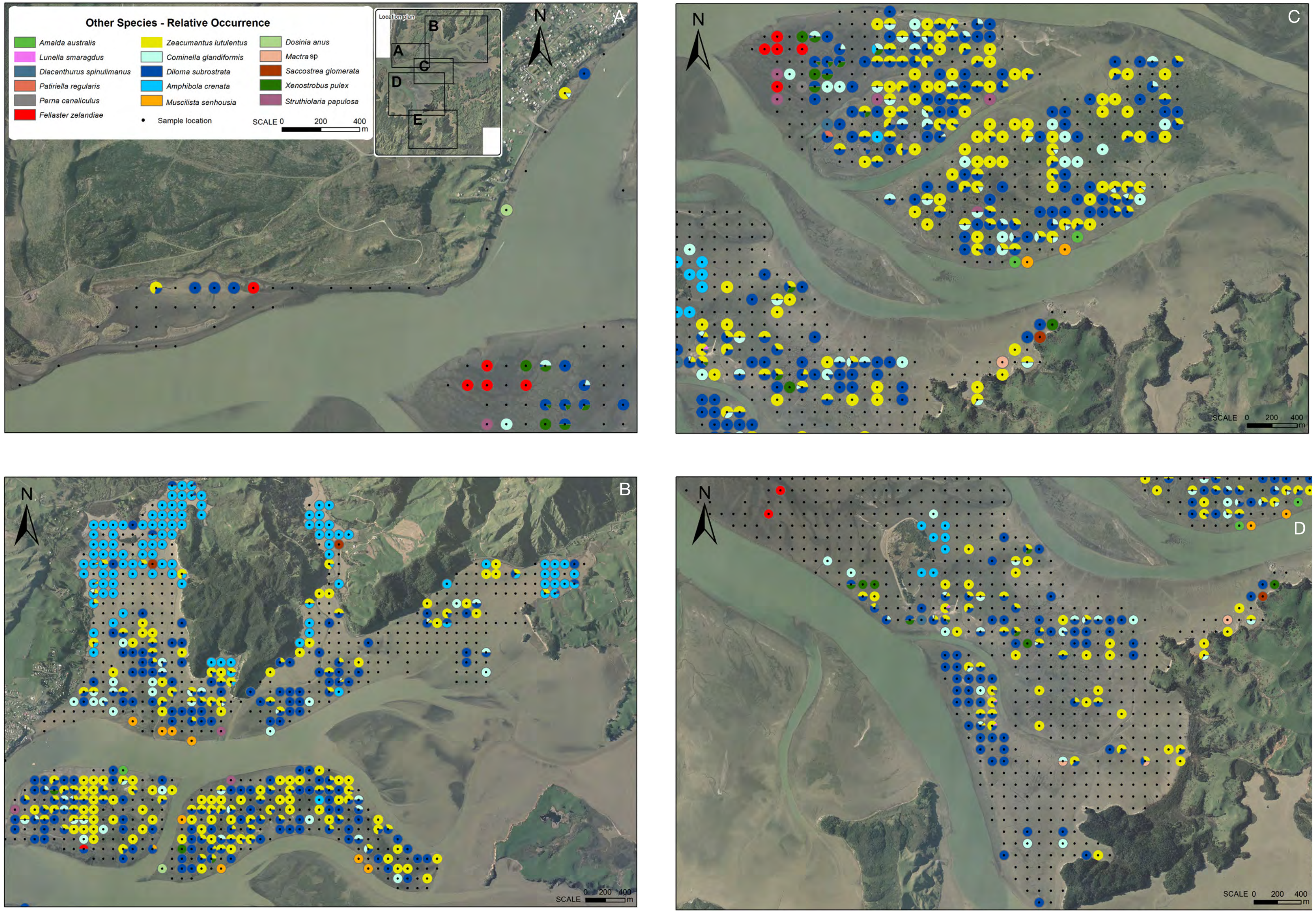
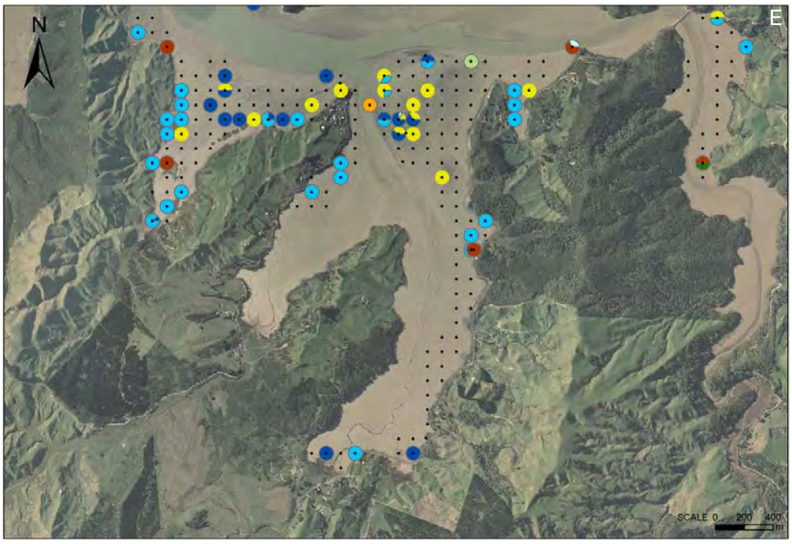


Figure 13. Relative occurrence of other species in the areas sampled in Kawhia Harbour. Pie symbols represent the proportion of each species at each site in relation to other species present (not including cockles (*Austrovenus stutchburyi*), wedge shells (*Macomona liliana*) or pipi (*Paphies australis*)). The absence of a pie indicates no other species were recorded. Locations of areas in maps A–E shown in inset map on A.

Continued on next page

Fig. 13 continued



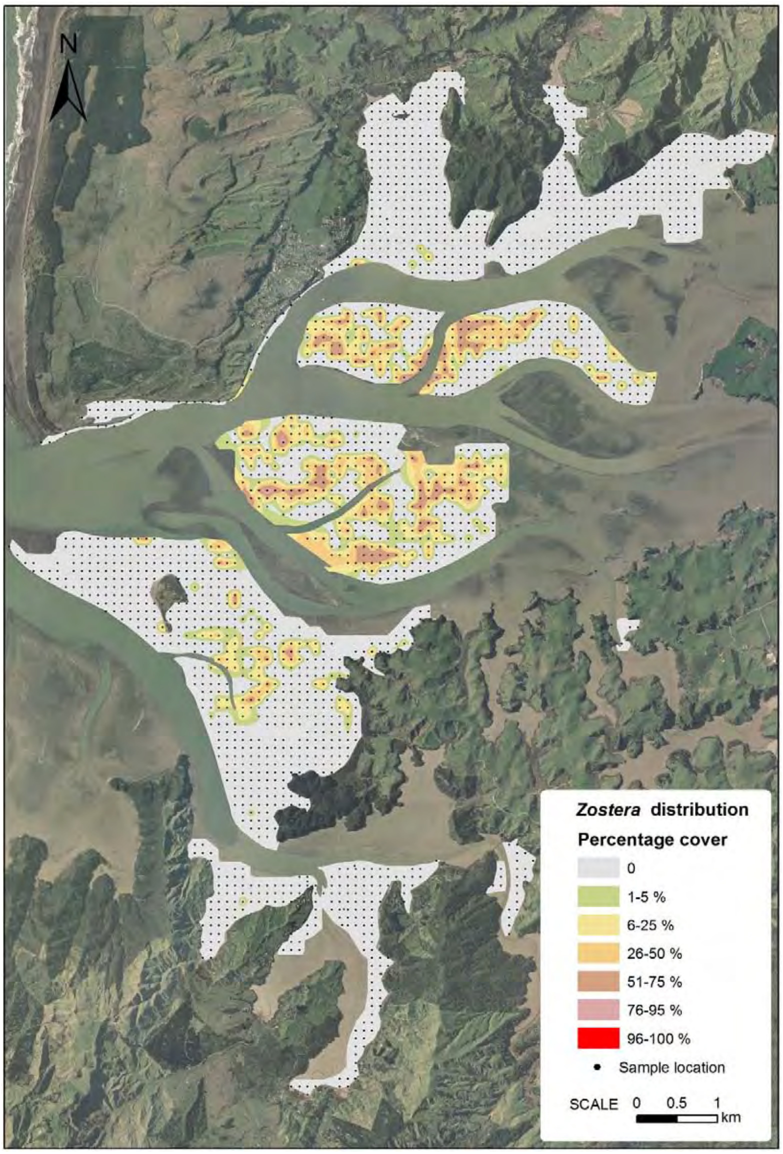


Figure 14. Density (percentage cover per quadrat) and distribution of seagrass (*Zostera* sp.) in the sampled areas of Kawhia Harbour. Displayed as a raster model based on interpolation of original point dataset.

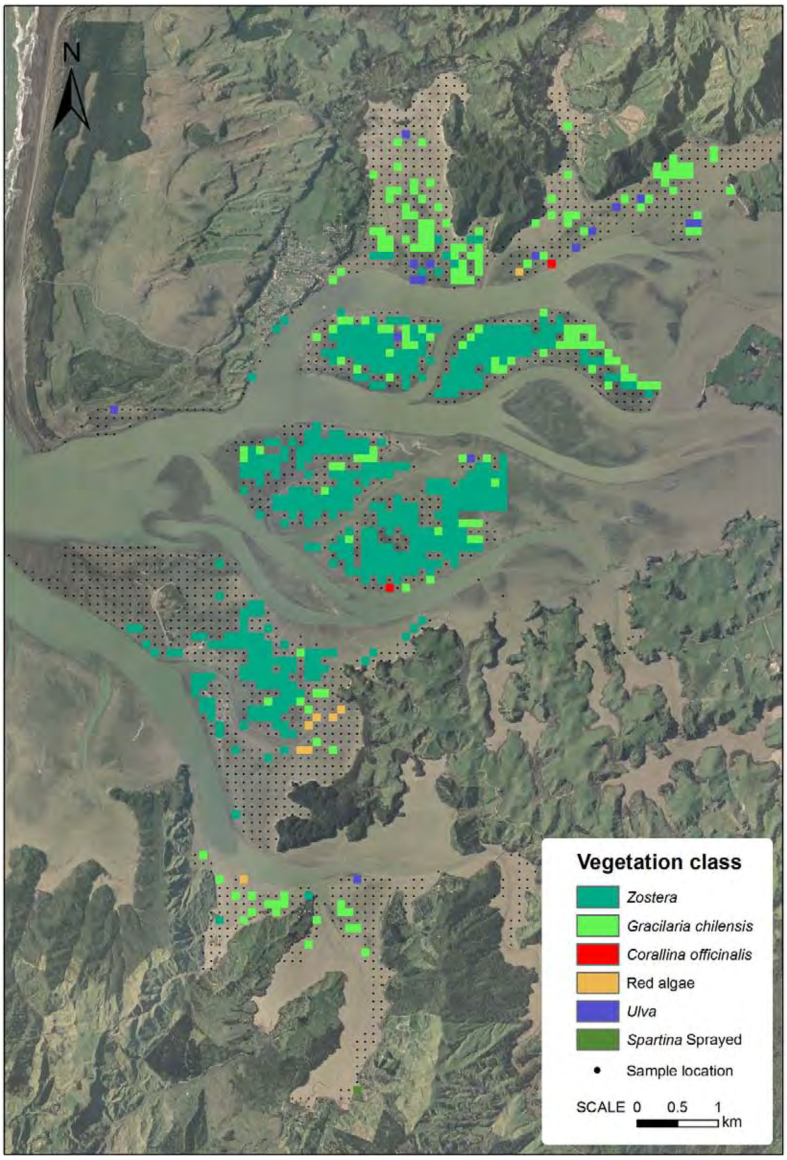


Figure 15. Vegetation distribution in the areas sampled in Kawhia Harbour.

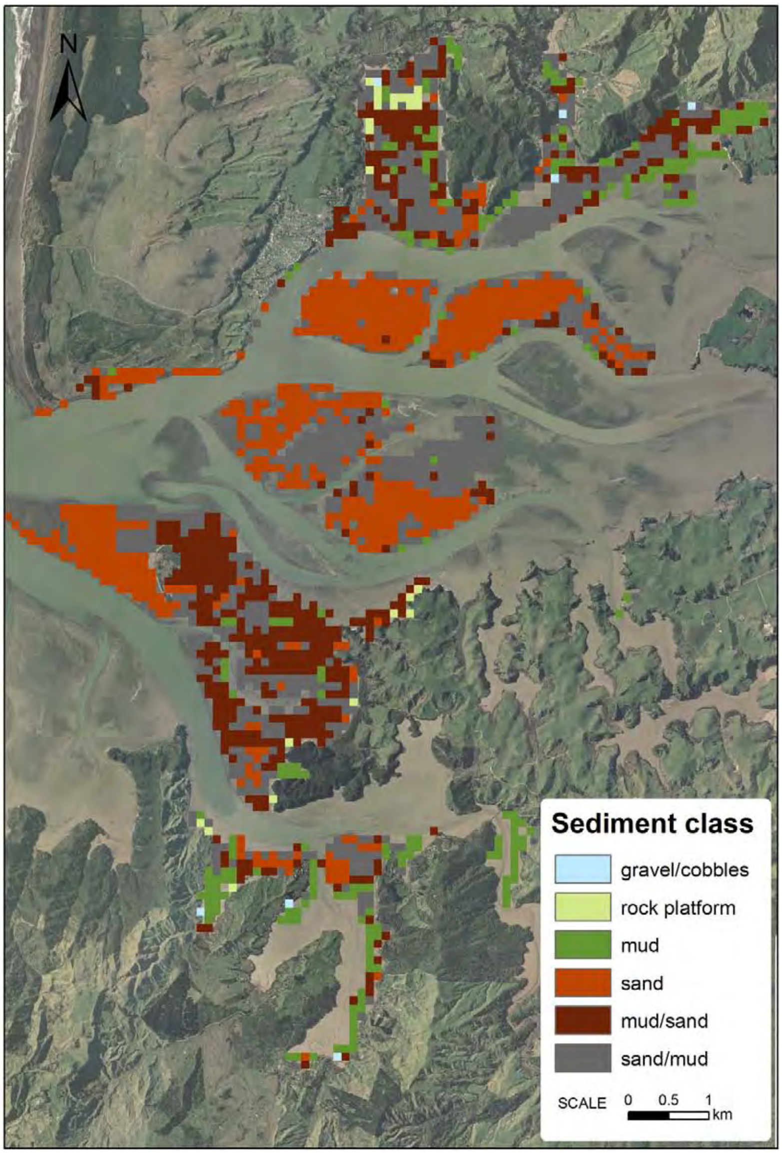


Figure 16. Sediment class distribution in the areas sampled in Kawhia Harbour.

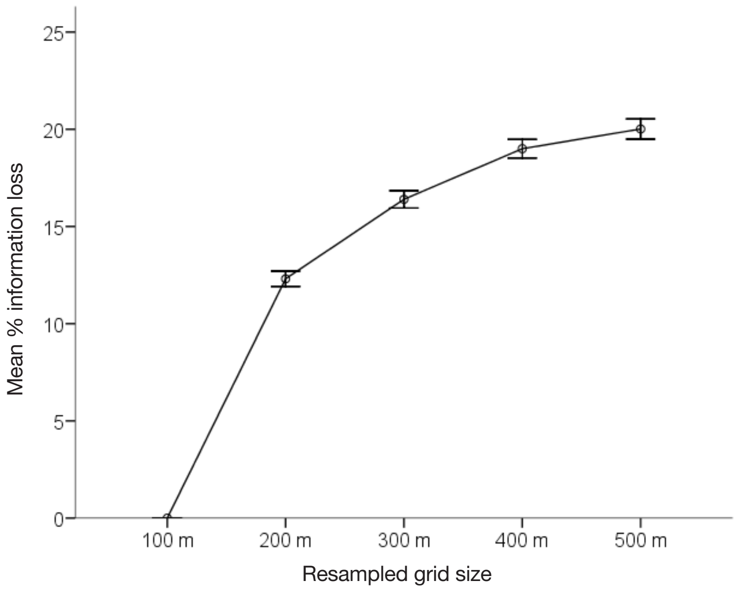


Figure 17. Mean percentage loss of information for re-sampled grids compared with the original 100 m sampled grid (± 1 standard error).

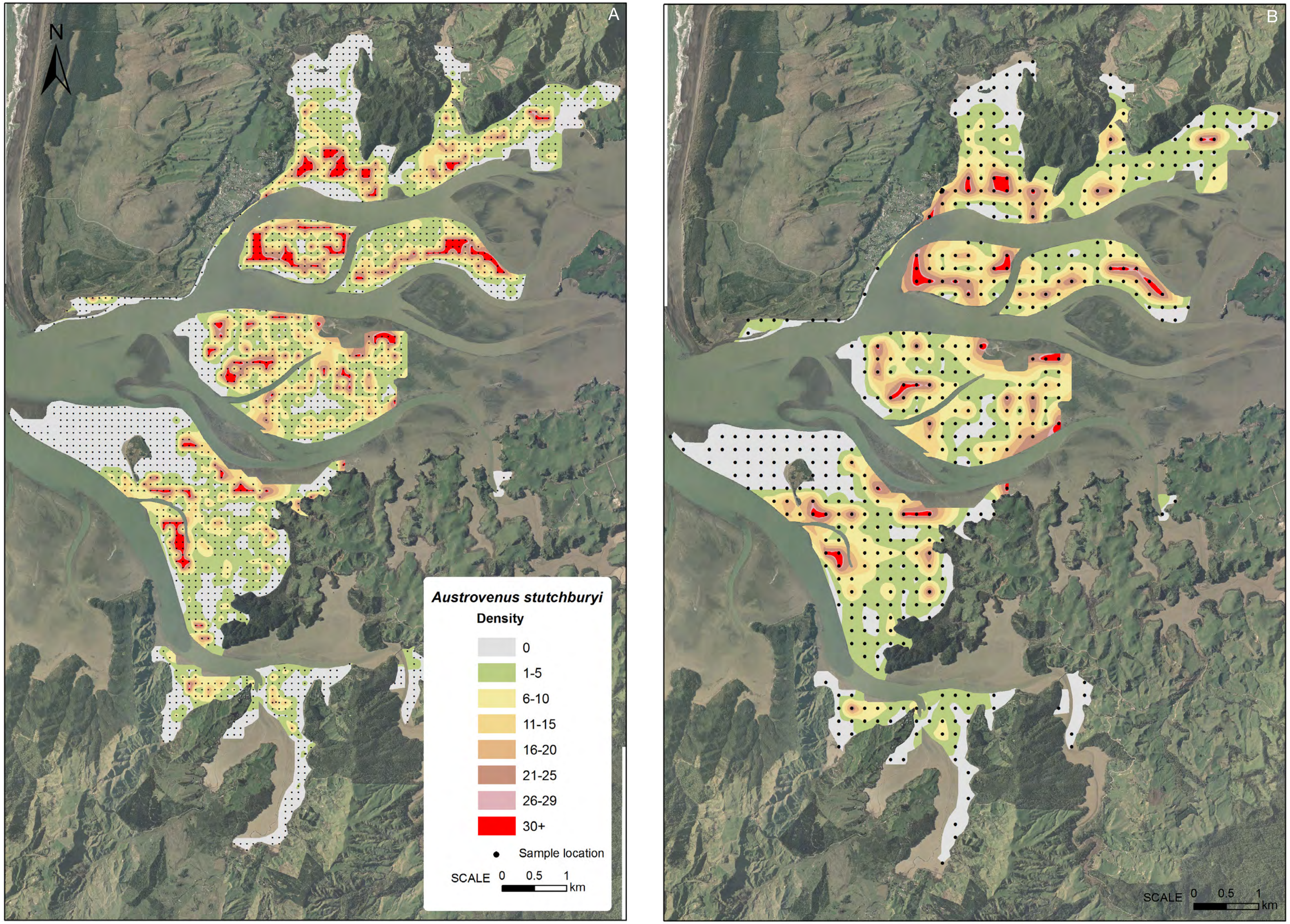


Figure 18. A. Original 100 m sample grid showing cockle (*Austrovenus stutchburyi*) distribution and abundance sampled in Kawhia Harbour. B. Re-sampled 200 m grid showing cockle (*Austrovenus stutchburyi*) distribution and abundance sampled in Kawhia Harbour. Displayed as a raster model based on interpolation of original point dataset.

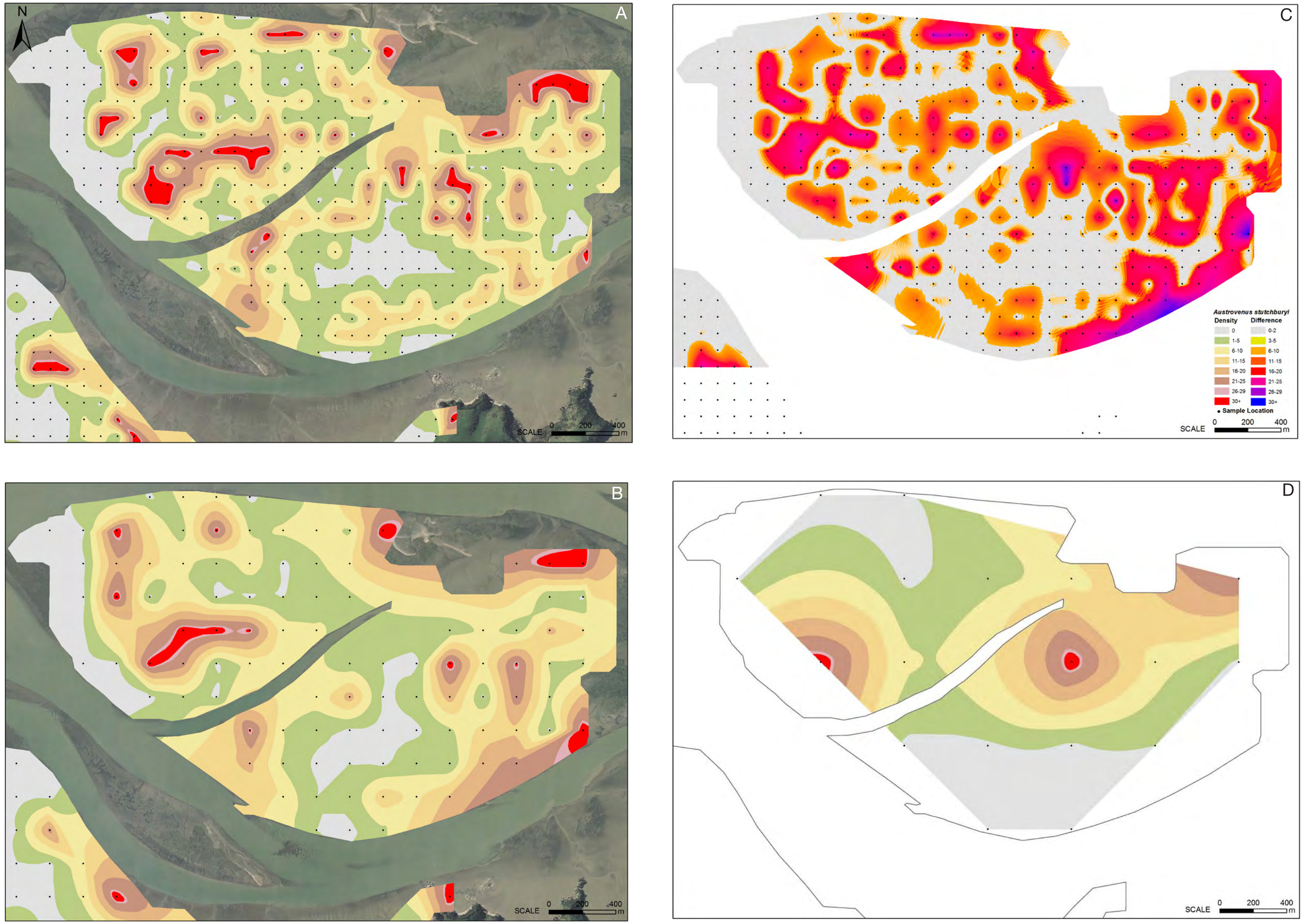


Figure 19. A section of cockle (*Austrovenus stutchburyi*) distribution in the sampled area of Kawhia Harbour. A = the original 100 m grid analysis. B = the 200 m re-sampled grid analysis. C = the difference between A and B. D = the 500 m re-sampled grid analysis. Displayed as a raster model based on interpolation of original point dataset.

Table 6. List of species and sediments sampled in Aotea Harbour.

SPECIES	COMMON NAME	MĀORI NAME	NUMBER OF QUADRATS WHERE RECORDED	TOTAL NUMBER OF INDIVIDUALS RECORDED	PROPORTION OF QUADRATS WHERE RECORDED (%)
Animals					
Austrovenus stutchburyi	Cockle	Tuangi	214	2425	54.59
Macomona liliana	Wedge shell	Hanikura	233	1206	59.44
Diloma subrostrata	Harbour topshell	Whētiko	97	196	24.74
Zeacumantus lutulentus	Hornshell	Koeti	141	449	35.97
Amphibola crenata	Mud snail	Tītiko	36	129	9.18
Cominella glandiformis	Mud whelk		29	35	7.40
Paphies australis	Pipi	Pipi	13	23	3.32
Musculista senhousia	Asian date mussel		2		0.51
Fellaster zelandiae	Snapper biscuit	Kina papa	3	23	0.77
Amalda australis	Olive shell	Pūpū pīataata	1	1	0.26
Diacanthurus spinulimanus	Hermit crab	Pāpaka moke	1	1	0.26
Plants					
Zostera sp.	Seagrass		54		13.78
Gracilaria chilensis	Red alga		75		19.13
Ulva sp.	Sea lettuce		16		4.08
Bare substrate			247		63.01
Sediment					
Muddy sand			92		23.47
Sand			238		60.71
Sandy mud			43		10.97
Mud			16		4.08
Gravel-cobbles			3		0.77
Total number of quadrats sampled = 392					

3.2.1 Cockles

Cockles were the most numerous species recorded in Aotea Harbour (n = 2425). The mean number of cockles (only from quadrats where they were recorded) was 11.33. The median number of cockles recorded in all quadrats sampled (including quadrats where no cockles were recorded) was 1 (Fig. 20). Cockles were recorded in most places in the southern area of the harbour, but were far less frequent in the northeast area (Fig. 21). A number of dense cockle beds were identified in the southern part of the harbour, most of which were close to the main channels. Proportionately more large cockles were recorded in Aotea Harbour than in Kawhia Harbour, although the most frequent size class was 'small', followed by 'small–medium' and 'small–large' (Fig. 22). The dense areas of cockles comprised a mix of size classes (Fig. 23). In the southern area of Aotea Harbour, there were a few high-density areas of only 'small' cockles, which may indicate areas of high recruitment.

Cockles were almost completely absent from areas of gravel and cobbles, and where mud was dominant (mud and sandy mud), but density was highest in sand and muddy sand habitats (Fig. 24A). There was no clear pattern for the relationship between cockle density and percentage cover of seagrass (Fig. 24B).

The classification tree analysis indicated an interaction effect between seagrass percentage cover and sediment type when defining the presence of cockles (Table 7; for tree diagram see Appendix 1, section A1.6). When seagrass was absent, there was a 53% chance of recording at least one cockle when sediment type was sand or muddy sand, but only a 24% chance when sediment type was gravel, cobbles, mud or sandy mud. When seagrass was present, irrespective of sediment type, there was a 94% chance of recording at least 1 cockle.

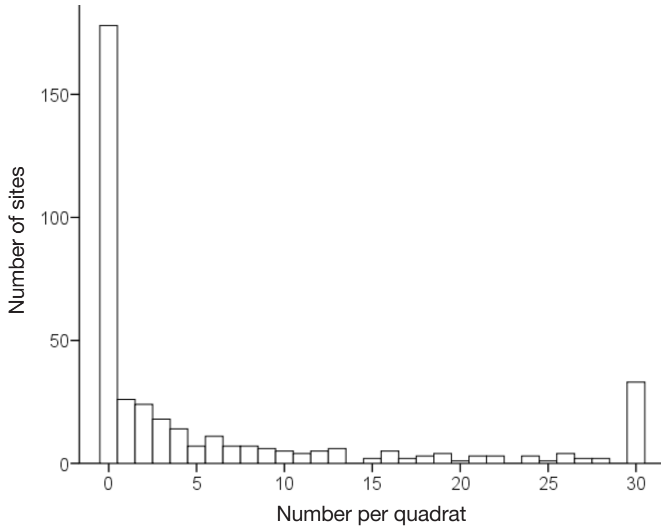


Figure 20. Frequency distribution of cockle (*Austrovenus stutchburyi*) densities (number per quadrat) at sample sites in Aotea Harbour (n = 392 quadrats).

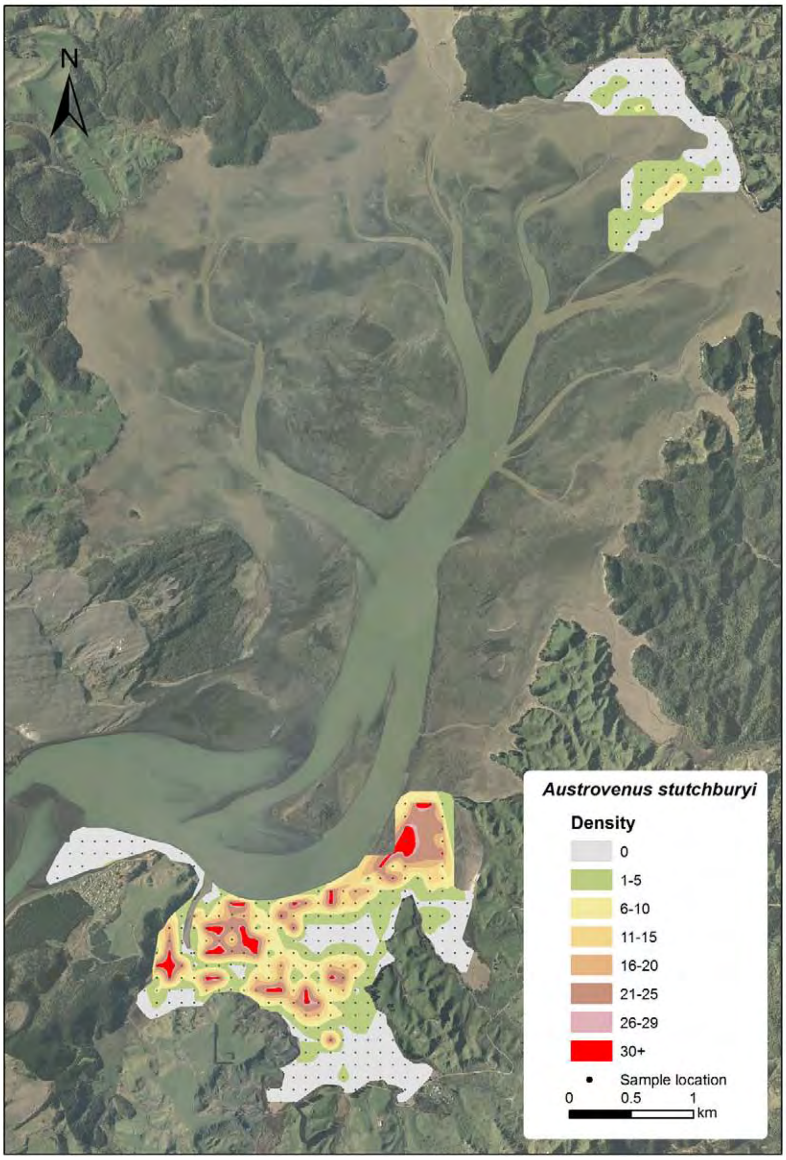


Figure 21. Density (number per quadrat) and distribution of cockles (*Austrovenus stutchburyi*) in the sampled areas of Aotea Harbour. Displayed as a raster model based on interpolation of original point dataset.

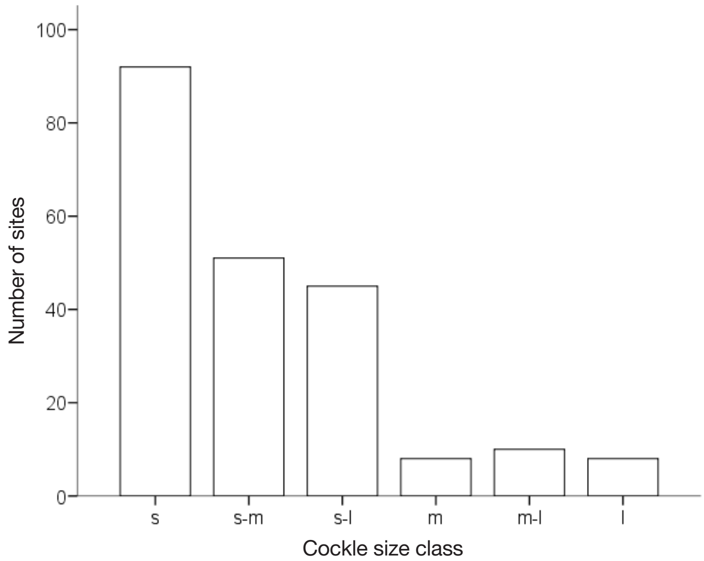


Figure 22. Frequency of size class groups of cockles (*Austrovenus stutchburyi*) sampled in Aotea Harbour. s = small (<15 mm), m = medium (15–25 mm), l = large (>25 mm).

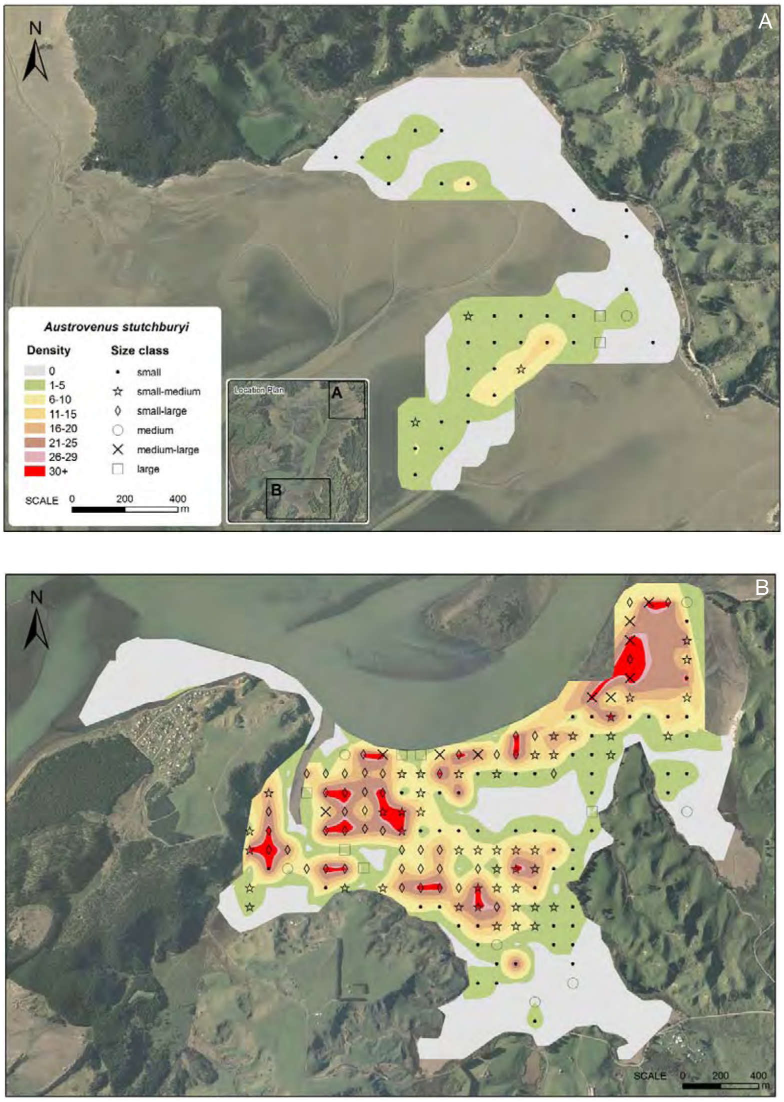


Figure 23. Cockle (*Austrovenus stutchburyi*) size classes in the sampled areas of Aotea Harbour, over-laying density data (see Fig. 22). Small = <15 mm, medium = 15–25 mm, large = >25 mm. Displayed as a raster model based on interpolation of original point dataset. Locations of areas in maps A and B shown in inset map on A.

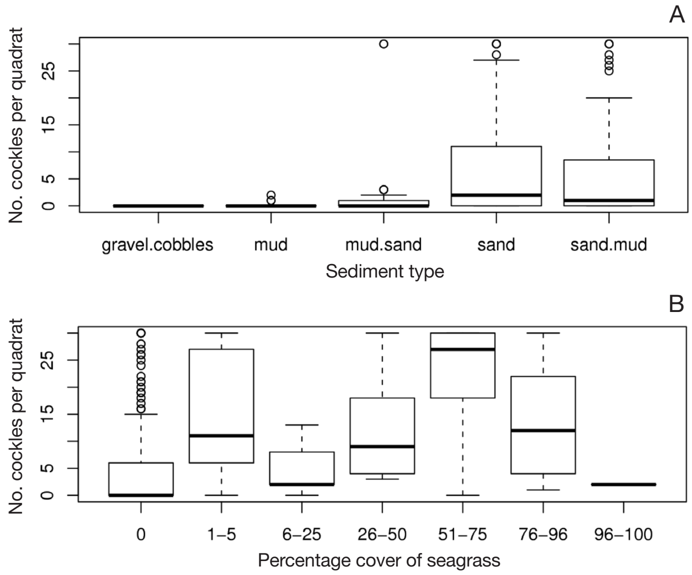


Figure 24. Box plots of density per quadrat of cockles (*Austrovenus stutchburyi*) by A. sediment types and B. percentage cover of seagrass (*Zostera* sp.) in Aotea Harbour.

Table 7. Expected probability of cockle (*Austrovenus stutchburyi*) presence in a quadrat in Aotea Harbour, based on sediment type and percentage cover of seagrass (*Zostera* sp.), as calculated by classification tree.

SEDIMENT TYPE	SEAGRASS COVER (%)	EXPECTED PROBABILITY OF PRESENCE OF COCKLES
Gravel/cobble, mud, sandy mud	0	0.24
Sand, muddy sand	0	0.53
Any sediment type	1–100	0.94

Consistent with the approach taken with the Kawhia data, sediment type and percentage cover of seagrass were divided into two groups: 'sand' (sand, muddy sand and sandy mud), and 'no sand' (gravel/cobble and mud); 'no seagrass' (no seagrass) and 'seagrass' (seagrass present). The results predicted that the greatest number of cockles was likely to be recorded in 'sand' (sand, sandy mud or muddy sand) when there is also seagrass present, and the fewest when the sediment type is 'no sand' (gravel, cobbles or mud) (Table 8; Appendix 1, section A1.7).

3.2.2 Wedge shells

Wedge shells were present at most of the sample sites (Fig. 25). While not recorded in as large numbers as cockles, they were present at more sample sites (n = 233 of 392 quadrats, n = 1206 individuals) (Table 6). The mean number of wedge shells (only from quadrats where they were recorded) was 5.18.

The median number of wedge shells recorded in all quadrats sampled (including quadrats where no wedge shells were recorded) was 2 (Fig. 26). The most common size class of wedge shells was medium (Fig. 27). The dense areas of wedge shells comprised a mix of size classes (Fig. 28), with no areas that stood out as densely populated with 'small' wedge shells, indicating that there were particular areas for recruitment.

Wedge shells were almost completely absent from areas of gravel, cobbles and mud, and were few in sandy mud, but were dense in sand and muddy sand (Fig. 29A). There was no apparent pattern between percentage cover of seagrass and wedge shell abundance (Fig. 29B). The classification tree analysis indicated that sediment type was a more important variable for predicting wedge

Table 8. Predicted mean number of cockles (*Austrovenus stutchburyi*) present per quadrat in Aotea Harbour, based on sediment type and seagrass (*Zostera* sp.) percentage cover.

SEDIMENT TYPE	SEAGRASS GROUP	PREDICTED MEAN NUMBER OF COCKLES PER QUADRAT
'No sand'	'No seagrass'	0.25
'Sand'	'No seagrass'	5.27
'Sand'	'Seagrass'	13.56

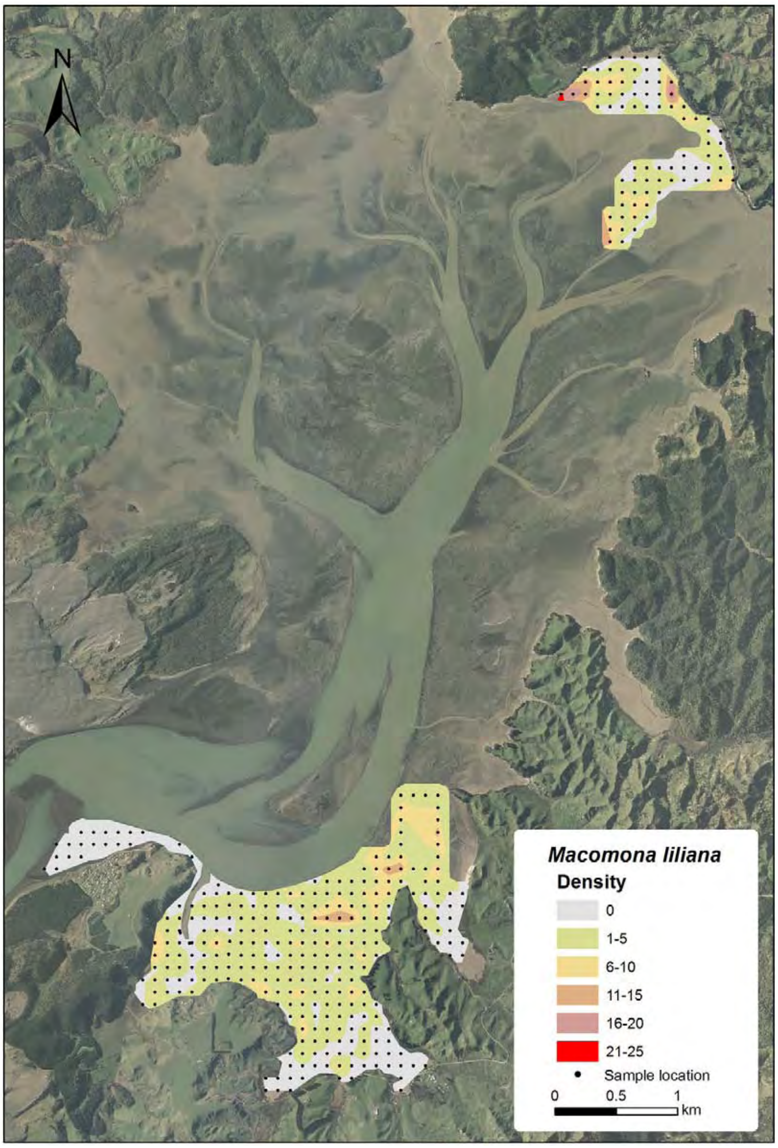


Figure 25. Density (number per quadrat) and distribution of wedge shells (*Macomona liliana*) in the sampled areas of Aotea Harbour. Displayed as a raster model based on interpolation of original point dataset.

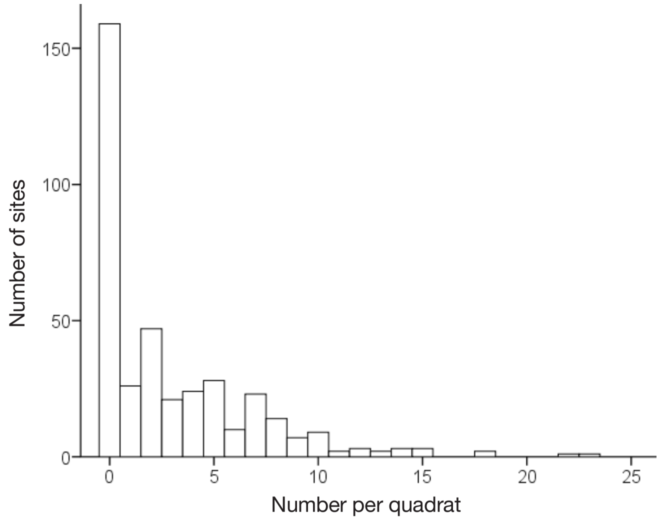


Figure 26. Frequency distribution of wedge shell (*Macomona liliana*) densities (number per quadrat) at the sites where they were recorded in Aotea Harbour (n = 392 quadrats).

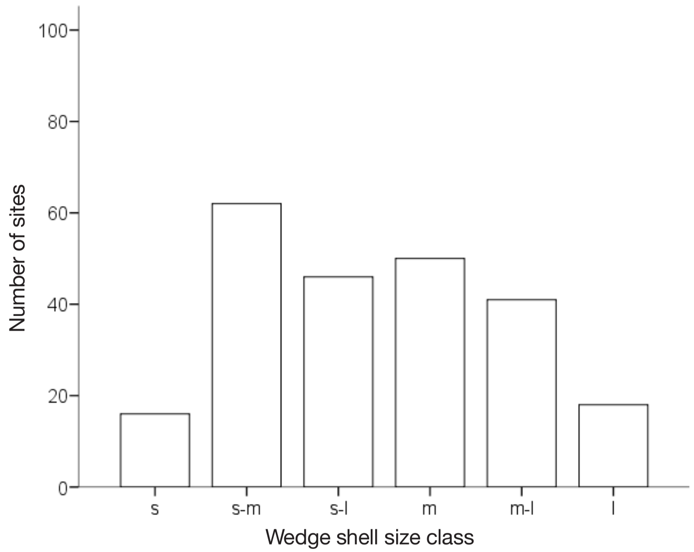


Figure 27. Frequency of size class groups of wedge shells (*Macomona liliana*) sampled in Aotea Harbour. s = small (<15 mm), m = medium (15–25 mm), l = large (>25 mm).

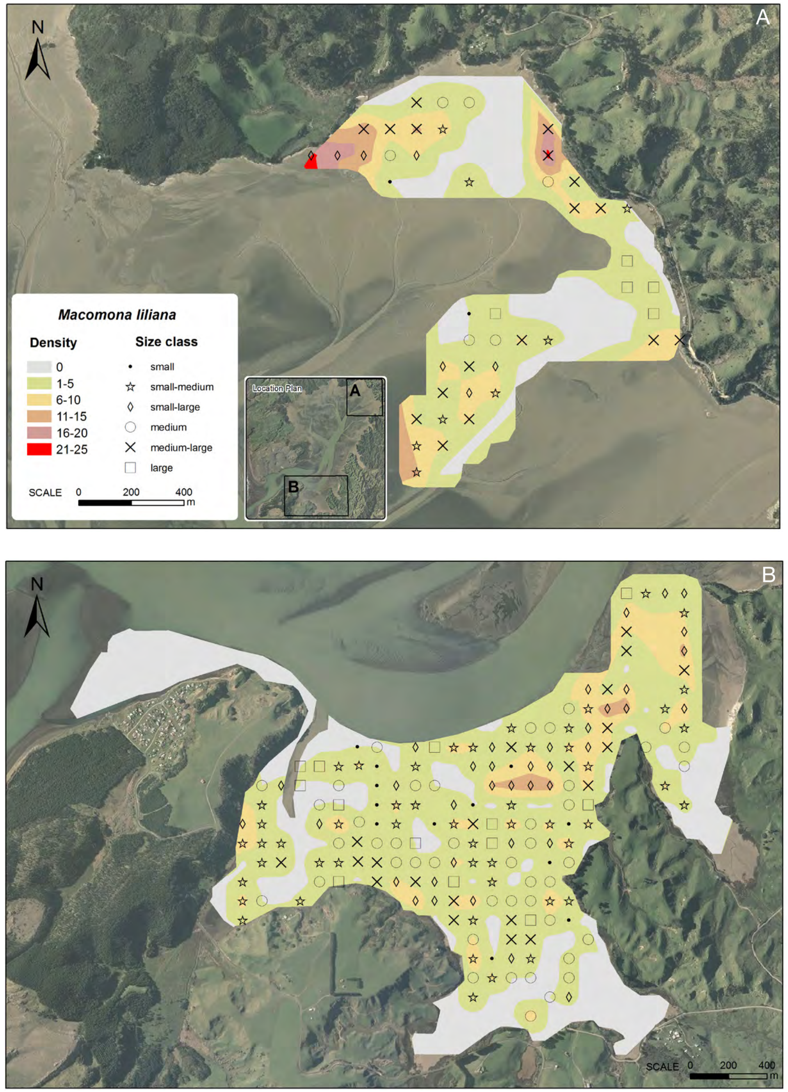


Figure 28. Wedge shell (*Macomona liliana*) size classes in two sampled areas of Aotea Harbour, over-laying density data (see Fig. 27). Small = <15 mm, medium = 15–25 mm, large = >25 mm. Displayed as a raster model based on interpolation of original point dataset. Locations of areas in maps A & B shown in inset map on A.

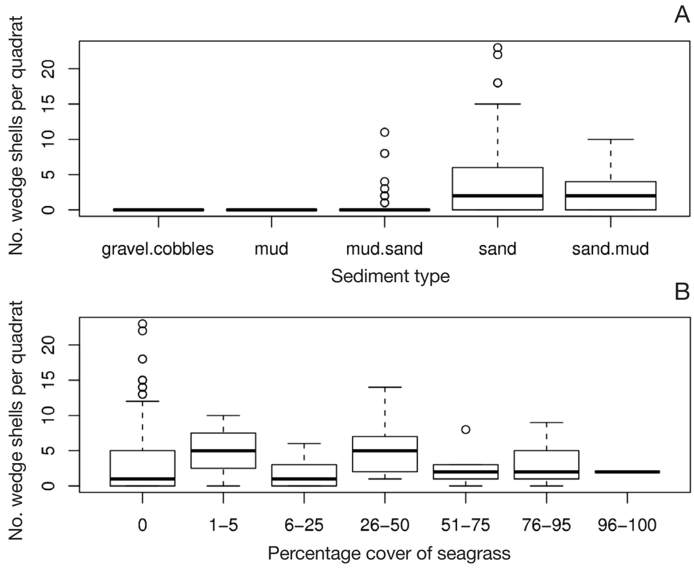


Figure 29. Box plots of density per quadrat of wedge shells (*Macomona liliana*) by A. Sediment type and B. Percentage cover of seagrass (*Zostera* sp.) in Aotea Harbour.

shell presence or absence than seagrass percentage cover (Table 9; for tree diagram see Appendix 1, section A1.8). When sediment type was sand or muddy sand, there was a 67% chance of finding wedge shells, but only a 16% chance when sediment type was gravel, cobbles, mud or sandy mud.

The classification tree result suggested that sediment be grouped as follows: 'sand' = sand, muddy sand; 'no sand' = gravel, cobbles, mud, sandy mud. However, this grouping is inconsistent with previous analyses (in Kawhia Harbour and Aotea Harbour cockles), so the two models were tested (see section 2.5.2). The AIC values indicated that Model 2 was the better fit for the data (AIC = 1670.285 for Model 1 v. AIC = 1666.937 for Model 2), and was consistent with the classification tree, so the Model 2 groupings were used. Seagrass was divided into two groups, similar to that for cockles above. The model indicated that seagrass was not a significant variable for predicting wedge shell density, so was removed and the model run again. When sediment type was 'no-sand' (gravel, cobble, mud or sandy mud), the expected number of wedge shells per quadrat was less than 1, and when sediment was 'sand' (sand or muddy sand) the expected number was 3 (Table 10; Appendix 1, section A1.9).

Table 9. Expected probability of wedge shell (*Macomona liliana*) presence per quadrat in Aotea Harbour, based on sediment type, as calculated by classification tree.

SEDIMENT TYPE	EXPECTED PROBABILITY OF PRESENCE OF WEDGE SHELLS
Gravel/cobble, mud, sandy mud	0.16
Sand, muddy sand	0.67

Table 10. Predicted mean number of wedge shells (*Macomona liliana*) present per quadrat in Aotea Harbour based on sediment type.

SEDIMENT TYPE	PREDICTED MEAN NUMBER OF WEDGE SHELLS PER QUADRAT
'no sand'	0.71
'sand'	3.42

3.2.3 Pipi

Pipi were recorded at 13 sampling locations, with a total of 23 individuals, only one of which was greater in size than 40 mm (41 mm) (Fig. 30).

3.2.4 Other species

Fewer surface dwelling species were recorded inside the quadrats at Aotea Harbour than Kawhia. Once again, *D. subrostrata* and *Z. lutulentus* were abundant in areas associated with sand and muddy sand. *Amphibola crenata* occurred mostly in sheltered areas close to the shore and associated with sandy mud and mud (Fig. 31).

3.2.5 Invasive species

Musculista senhousia were recorded in two locations in the southern area of Aotea Harbour (Fig. 31). Both locations were adjacent to a mostly sheltered, large channel. The two beds were dense and raised, and appeared to exclude all other bivalves.

3.2.6 Vegetation

Seagrass was recorded in the southern area of Aotea Harbour but not in the areas sampled in the northeast (Fig. 32), but was present in large areas immediately south of the northeast area. Seagrass was the densest form of vegetation in the areas that were sampled in terms of percentage cover (average 51–75%). However, *Gracilaria chilensis* (a red alga) occurred at a greater number of sampling sites, but only at low densities (usually 1–5% cover) (Fig. 33). *Gracilaria chilensis* and *Ulva* sp. were both present in the northeast area of the harbour.

3.2.7 Sediment

Sand and muddy sand were the sediment types represented most in the southern area of the harbour that was sampled. In the northeast area, there were fewer areas of sand, with mud being the most represented sediment type (Fig. 34). As was observed in Kawhia Harbour, small ephemeral channels accumulated muddier sediments on their banks. Few areas of gravel or cobbles and no rock platforms were sampled.

3.3 Sediment characteristics for Kawhia and Aotea

In Kawhia Harbour, sites located in the eastern half of the harbour had higher fractions of clay and silt (Fig. 35). These locations are at a greater distance from the entrance, in the sheltered arms of the harbour. A similar pattern was recorded in Aotea Harbour although distance from the harbour entrance was not so evident (Fig. 36).

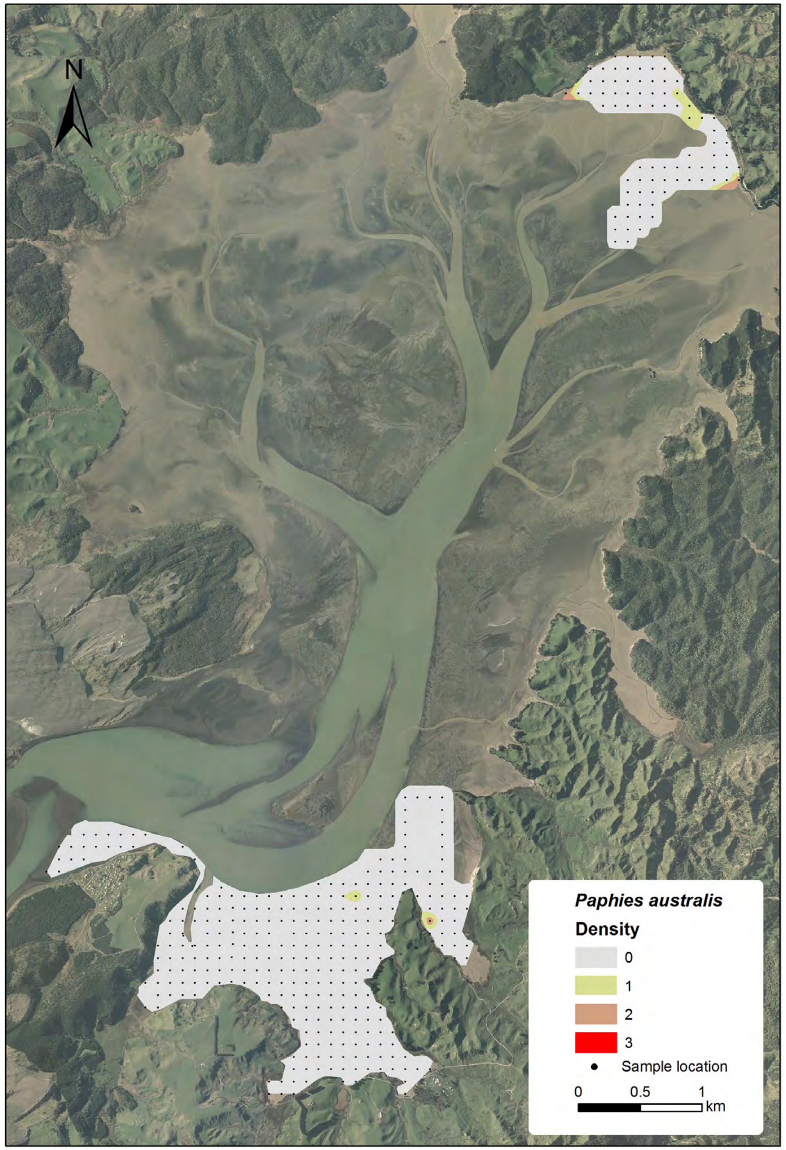
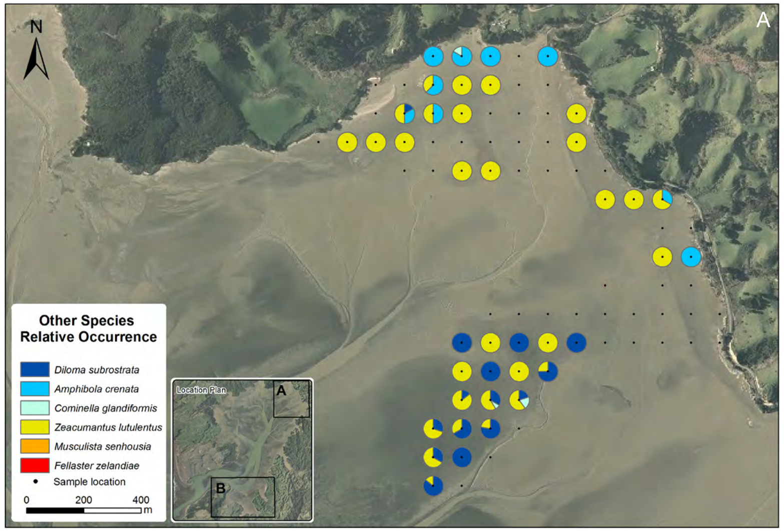
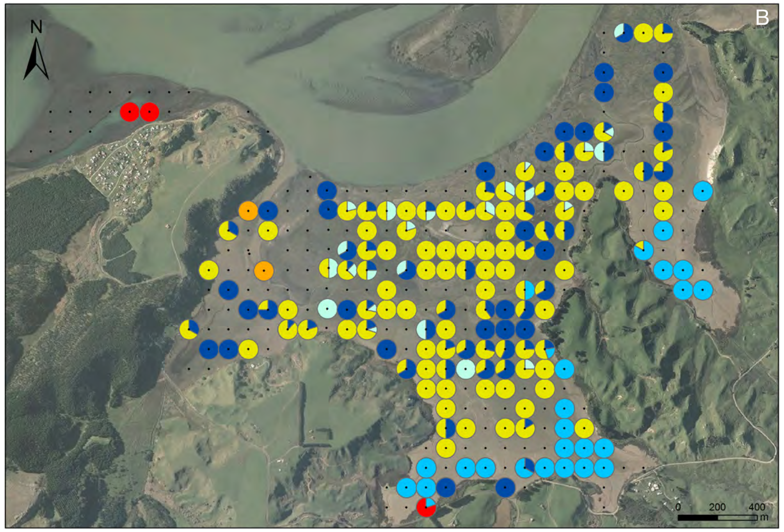


Figure 30. Density (number per quadrat) and distribution of pipi (*Paphies australis*) in the sampled areas of Aotea Harbour. Displayed as a raster model based on interpolation of original point dataset.





Figures 31. Relative occurrence of other species in two areas sampled in Aotea Harbour. Pie symbols represent the proportion of each species at each site in relation to other species present (not including cockles (*Austrovenus stutchburyi*), wedge shells (*Macomona liliana*) or pipi (*Paphies australis*)). The absence of a pie indicates no other species were recorded. Locations of areas in maps A & B are shown in inset map on A.

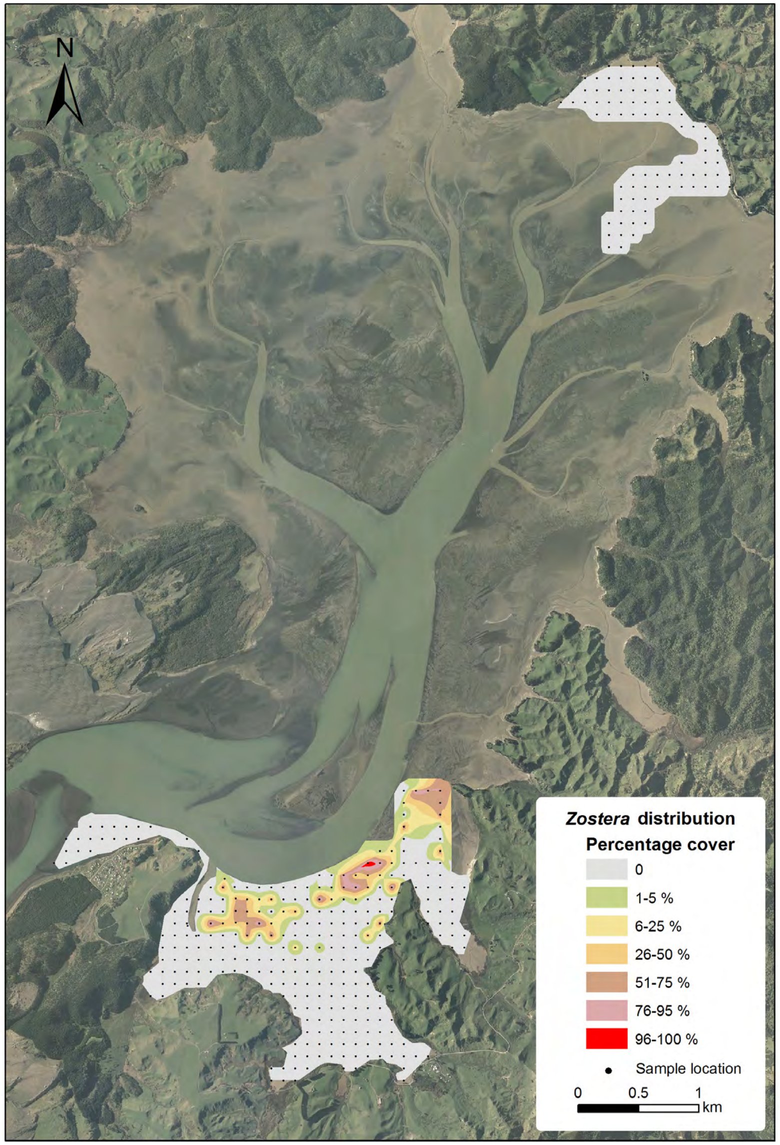


Figure 32. Density (percentage cover per quadrat) and distribution of seagrass (*Zostera* sp.) in the sampled areas of Aotea Harbour. Displayed as a raster model based on interpolation of original point dataset.

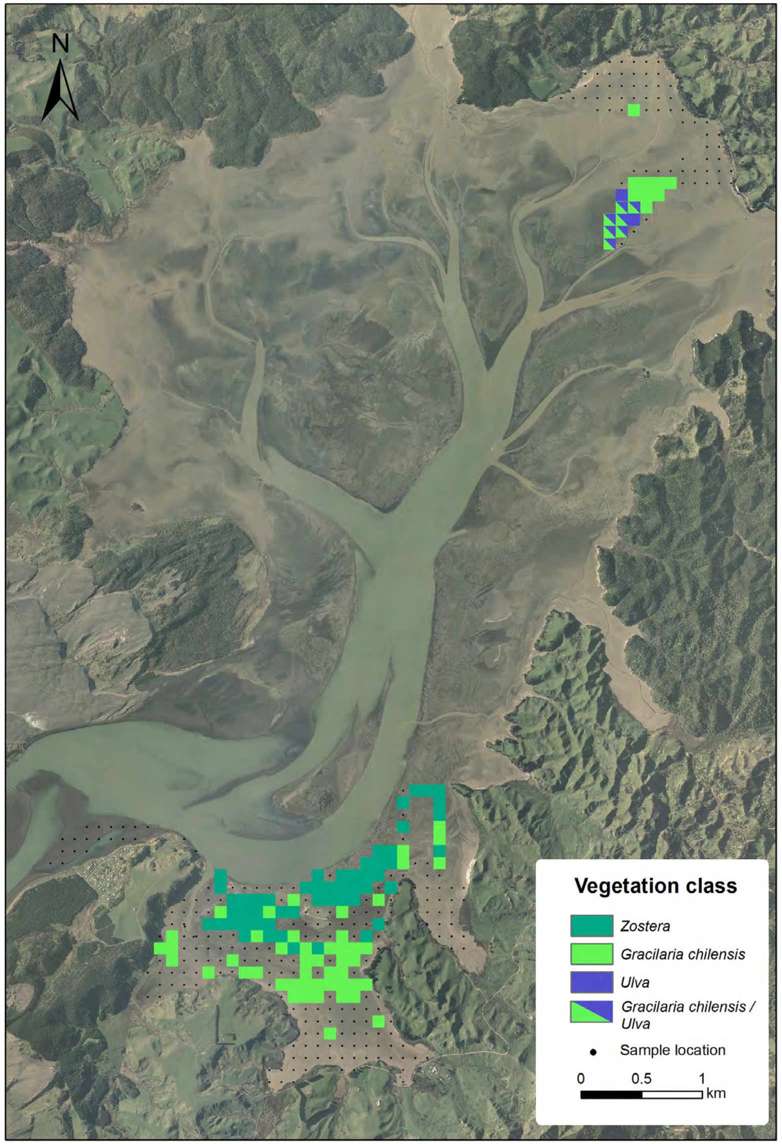


Figure 33. Vegetation distribution in the areas sampled in Aotea Harbour.

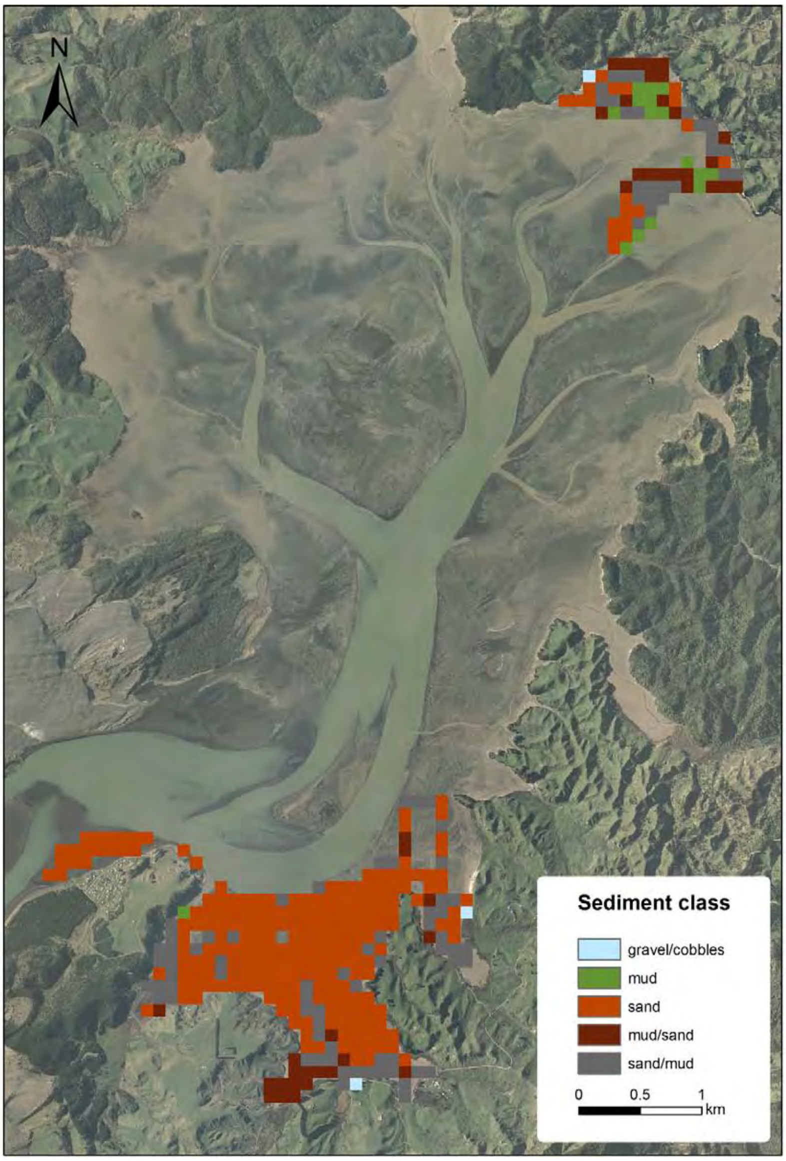


Figure 34. Sediment class distribution in the areas sampled in Aotea Harbour.

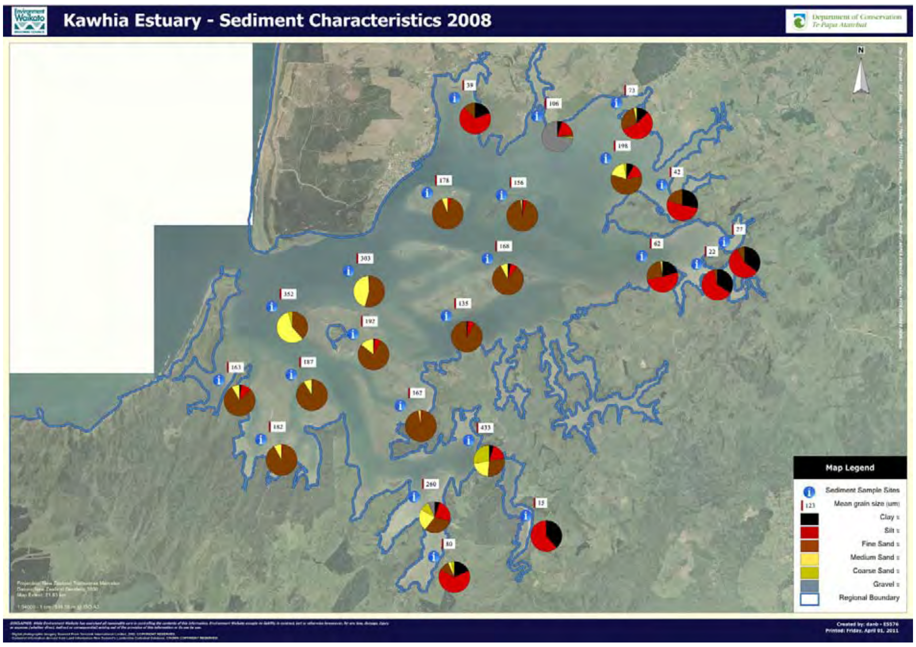


Figure 35. Sediment grain size analysis data from the sites in Kawhia Harbour, showing grain size fractions.

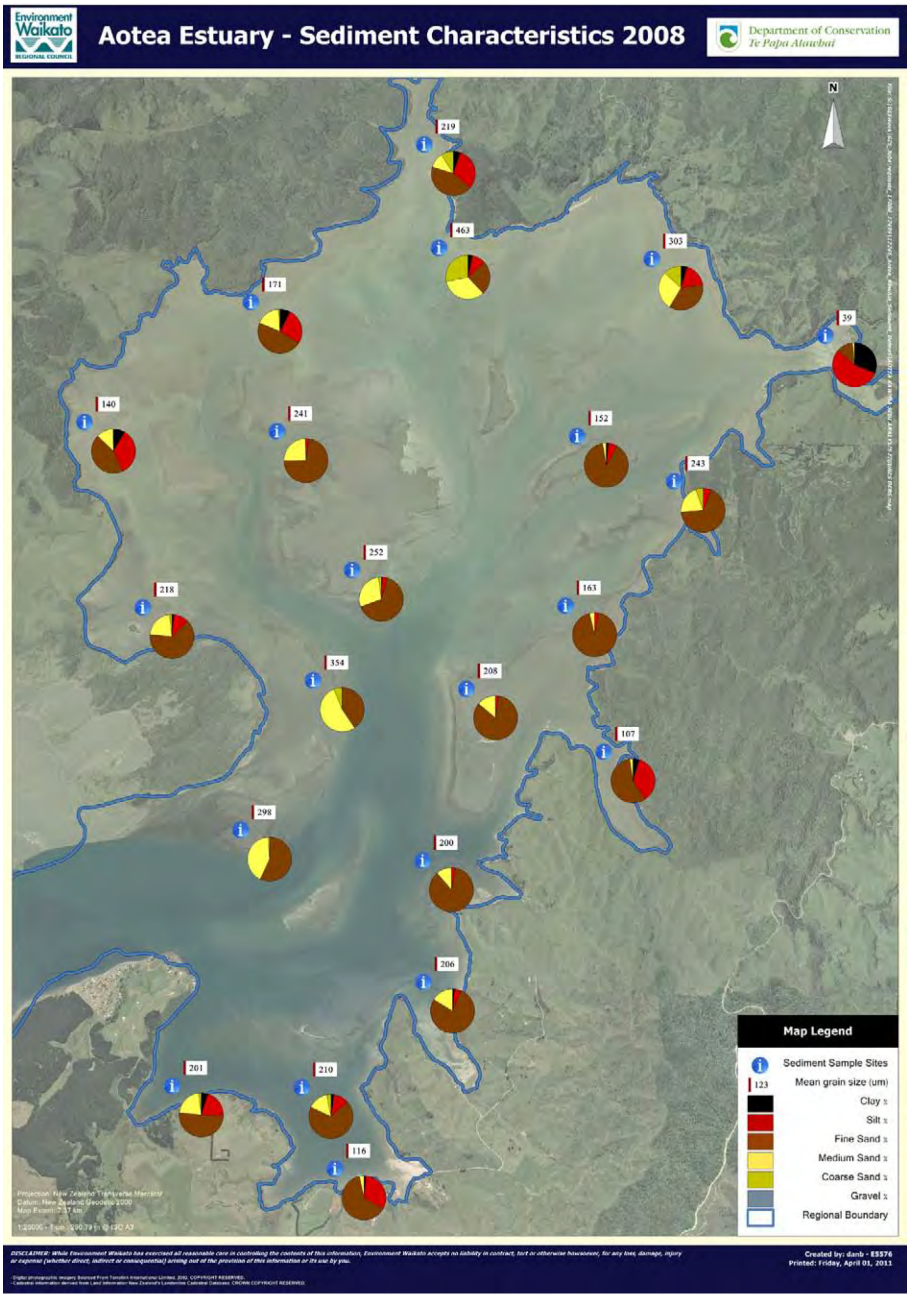


Figure 36. Sediment grain size analysis data from the sites in Aotea Harbour, showing grain size fractions.

4. Discussion

The aim of this study was to map the distribution and abundance of the intertidal shellfish resources in Kawhia and Aotea Harbours, specifically, cockles and wedge shells, which are two common estuarine bivalve species. Both species form a component of shorebird and fish diets, and cockles are an important recreational and cultural food source.

Cockles and wedge shells were recorded as abundant in both harbours. The mean number of cockles per quadrat in quadrats in which they were recorded was similar for both harbours (11.19 and 11.33 for Kawhia and Aotea Harbours, respectively). However, the mean number of wedge shells was less in Kawhia Harbour than in Aotea Harbour (3.80 and 5.18, respectively).

The results show that both cockles and wedge shells were more abundant in sandy habitats, followed closely by muddy sand. The only exception to this was cockles in Kawhia Harbour, which were more abundant in muddy sand, closely followed by sand. This finding is consistent with other studies that have reported that cockles and wedge shells exhibit a preference for less-muddy habitats (Cummings et al. 2002; Thrush et al. 2003; Gibbs & Hewitt 2004; Hewitt et al. 2005). For example, Thrush et al. (2003) showed that the probability of occurrence and maximum density of cockles and wedge shells is negatively affected by increasing mud content, an effect more pronounced in wedge shells than cockles. Norkko et al. (2001) reported that cockles and wedge shells exhibit a sand preference, and have optimum ranges of 5–10% and 0–5% mud content, respectively, at which they are most abundant.

No clear pattern emerged with respect to cockle and wedge shell abundance in the absence or presence of seagrass in either harbour. However, vegetation, in conjunction with sediment type, may be important for both species, as suggested by a positive interaction between seagrass presence and sediment type with respect to cockle presence in both harbours. There was a similar relationship for wedge shells in Kawhia, but the results indicated that seagrass was not important for wedge shells in Aotea.

Effect of seagrass

It has been well documented that seagrass may greatly influence the composition and function of associated macroinvertebrate communities (Turner et al. 1999; van Houte-Howes et al. 2004; Alfaro 2006). Seagrass alters local physical, chemical and biological habitat conditions by providing structural complexity and heterogeneity in marine ecosystems (Turner et al. 1999). A number of studies have reported that seagrass supports higher macroinvertebrate species diversity, abundance, biomass and productivity compared with adjacent unvegetated habitat (in van Houte-Howes et al. 2004). Turner et al. (1999) reported higher macroinvertebrate species richness and diversity within seagrass patches compared to adjacent unvegetated soft sediment habitats. Alfaro (2006) also reported higher densities of cockles in seagrass habitats compared with other associated adjacent habitats (e.g. mangrove, channels, sand flats). This pattern was further investigated by van Houte-Howes et al. (2004), who reported up to three times greater abundance of wedge shells and cockles near the edge of seagrass beds, i.e. at sites 1 m inside seagrass beds and adjacent unvegetated areas compared with sites 50 m inside seagrass beds. At estuaries with high seagrass biomass (dense beds), they also reported a significantly higher biomass, diversity and abundance of macroinvertebrates at sites 1 m inside a seagrass patch than at sites 50 m inside. This is likely due to the dense root structure of the seagrass inhibiting the burrowing and growth of macrofauna.

These results are consistent with the studies of Alfaro (2006) and van Houte-Howes et al. (2004) in suggesting that although seagrass habitat influences macroinvertebrate community composition, it is not the only factor driving the demographic patterns of cockles and wedge shells in Kawhia and Aotea Harbours. Although tidal currents, wave dynamics and water depth indirectly influence macroinvertebrate community dynamics through their effects on the spatial configuration of seagrass beds (Turner et al. 1999), they also influence macroinvertebrate communities directly through their role in shaping habitat. In the present study, the lack of a common pattern in cockle and wedge shell abundance within seagrass habitat and unvegetated habitat may be due to the influence of environmental factors not measured. In addition to those factors mentioned above, period of inundation, sediment transport, foraging of predators and recruitment will all interact to influence the presence or absence and demographics of cockles and wedge shells, both within seagrass habitat and in unvegetated areas.

Cockle size

The majority of the cockles sampled in this study were in the size classes small to medium (i.e. were all < 25 mm), but cockles can grow as large as 50 mm (Gunson 1993). Most populations of cockles from around New Zealand consist of adults with a mean size of 40 mm (Grant & Hay 2003). There are a number of possible reasons for the small size of cockles sampled in these harbours. Selective harvesting by humans can have an influence on the size of cockles because large cockles are more desirable, easier to find and more likely to be removed from the population, leaving smaller cockles disproportionately represented. Growth in cockles generally slows once they reach a shell length of 40 mm (about 8–10 years) (Grant & Hay 2003). Long-term harvesting of large cockles may result in removal of this size class from the population. Consequential increases in harvesting pressure on smaller cockles may then further drive down the average size within populations.

Another possible contributing factor to smaller cockles in the two harbours may be increases in sedimentation. Sediment usually first enters an estuary as suspended particles from the surrounding catchment, causing a corresponding increase in turbidity. The associated backscattering of light in the water column reduces the primary production of phytoplankton and benthic microphytes on which cockles (and other benthic suspension feeders, deposit feeders and grazers) feed. Reduction in the amount and/or quality of food can affect growth rate and condition (Grant & Hay 2003; Morrison et al. 2009).

As mentioned above, cockles and wedge shells are more abundant in less-muddy habitat. The input of terrestrial (originating from land) sediment into an estuary over time increases the amount of muddy habitat, resulting in a reduction of suitable habitat for cockles, wedge shells, and other macroinvertebrates. Terrestrial sediment settling in the intertidal area can result in smothering of benthic organisms, from which they may or may not recover, depending on the frequency and magnitude of the deposition (Gibbs & Hewitt 2004). Laboratory and field experiments have demonstrated that a burial depth of 2–3 cm can result in the death of nearly all intertidal macrofauna within 10 days (Gibbs & Hewitt 2004). Deposits of 1–2 cm thickness lasting more than 7 days have also been shown to adversely affect macrofauna (Gibbs & Hewitt 2004). The same studies have shown that recovery from a catastrophic deposition event (up to 2–3 cm) can take as long as 2 years (Gibbs & Hewitt 2004).

Anecdotal evidence suggests that there has been a significant increase in mud in Kawhia and Aotea Harbours over the past decades resulting from clearance of land for farming in the catchments. A number of studies undertaken in the North Island have found that the greatest amount of erosion occurs on pasture during storm events, particularly on rolling (17–20°) to steep (> 30°) slopes, such as those found around Kawhia and Aotea Harbours (cited in Morrison et al. 2009). The presence of extensive areas of deep mud rendered some areas of the harbours logistically inaccessible during this survey. Further increases of muddy sediments in the harbours are likely to result in a reduction of suitable habitat for cockles, wedge shells and, possibly, other species that are a dietary component of birds and fish, and would likely negatively affect the overall productivity of the harbours.

Significant loss of filter feeding organisms can have a profound impact on water quality. Cockles feed by pumping water across their gills and filtering out food particles at per-animal rates of up to 3 L per hour for 2 hours each side of high tide (Grant & Hay 2003). In large estuaries, with hundreds of thousands of cockles, potentially millions of litres of water are filtered each tidal cycle. An estimated 9 million cockles in the sampled area of Kawhia Harbour (based on the average density of cockles per quadrat and using the equation in Walshe et al. 2005) potentially filter up to 108 million litres during each tidal cycle. The removal of organic particles from the water column is likely to result in increased water clarity and quality. The flow-on benefits from increased water clarity include an increase in primary production by plant species through increased levels of light required for photosynthesis.

Other species

Pipi are a valuable food resource for humans and other organisms (fish, birds and other invertebrates). Almost all pipi that were recorded in this study were smaller than 40 mm. However, the methods used here were not aimed at accurately sampling other species, so while distribution maps have been included for pipi and other species, they should be treated as indicative only for them.

The invasive mussel *M. senhousia* was present at a number of locations in both harbours. During sampling, several shorebird species such as oystercatchers, terns and godwits were observed feeding in the *M. senhousia* beds. However, it is unknown whether the birds were feeding directly on the mussels or on small invertebrates that may have been living in the beds. It is thought that this mussel was introduced to New Zealand via ship fouling, in ship seawater systems or in ballast water (Cohen 2005). The mussels settle on both hard and soft substrates (but with a preference for soft), and form dense mats over the sediment surface by secreting fibrous threads that attach to their neighbours (Cohen 2005). At almost every location where *M. senhousia* was recorded in Kawhia and Aotea Harbours, they formed dense mats, and no other species were recorded in the sediment. However, Crooks (1998) reported that while *M. senhousia* excluded other large bivalves from beds in Mission Bay, San Diego, it seemed to facilitate other organisms—in particular, a tanaid (small crustacean) and a micro-gastropod. It appears from the literature that only small and mobile organisms are able to live in the dense habitat created by *M. senhousia*, and that larger organisms, especially suspension-feeding bivalves, are not compatible with them. This is most likely related to competition for space and food, and that the anoxic sediment trapped in and under the mussel mat is not a suitable habitat for other organisms (Creese et al. 1997; Crooks 1998; Reusch 1998). Creese et al. (1997) reported that beds of *M. senhousia* in the Tamaki Estuary, Auckland, were relatively short-lived and ephemeral, a finding consistent with other literature. They concluded that, while the mussel is likely to persist in the Tamaki Estuary where it is firmly established, it is not likely to have any long-term effect on the environment. They also concluded that where the mussel occurs intertidally, it does have a detrimental effect on the sediment, but that this effect is localised. Once the mussels die and are eventually washed away by the currents, the sediment is likely to recover over time. While further research would be needed to draw the same conclusions for the populations at Kawhia and Aotea Harbours, literature from other countries also supports this view (Crooks 1998; Reusch 1998).

Study limitations

The sampling methods used in this study were primarily aimed at mapping cockle and wedge shell distribution in the two harbours. As such, there is some limitation in their use and interpretation of the results. For example, there was no replication at each sampling site—instead, a single sample was taken. This was judged adequate to detect most of the cockle and wedge shell beds, but also allowed a greater area to be sampled given the resources available. This means that each sample was a snapshot of the benthos at that point only, and does not account for any spatial variation that can occur at very small scales in estuaries. The method used for sorting through the excavated sediment for shellfish precluded detection of very small or soft-bodied individuals.

Another key limitation of the methods used, and that should be considered when interpreting the results, is the classification of sediment type. This was done in the field by sight and touch and, as such, was subjective. This was further confounded by the fact that a number of people were involved in the sampling, each with their own subjectivity. However, subjectivity was minimised by comparing the assessment of sediment type between samplers at the beginning of the sampling period.

Logistical difficulties also contributed to the limitations of this study. Areas that were easily accessible were sampled in preference to areas that were either remote, or consisted of thick mud, which was difficult to move through. This will have introduced a bias towards less-muddy habitats. However, the results are still useful and show the distribution of cockles and wedge shells in relation to broad sediment types and vegetation type and density.

Survey designs

The sample sites in this study formed a 100-m grid. GIS analysis compared the samples taken at every 100 m with a re-sampled data set at every 200 m and 500 m. The results indicated that although it was expected that some information would be lost by sampling at scales coarser than 100 m, sampling at 200 m still identified most of the high-density cockle beds. However, sampling at the coarser scale of 500 m resulted in a loss of most of the information about the cockle beds in Kawhia Harbour, and would not have been useful in this type of survey. Although this result is not surprising, it is valuable information to have when planning future surveys and subsequent analyses of this type. While it is not often practical to sample at a scale of 100 m in large estuaries such as Kawhia and Aotea, it may be practical in much smaller estuaries. The impracticality of intensively sampling such large estuaries was highlighted during this study with timing and accessibility issues.

5. Conclusions

Kawhia and Aotea Harbours have been identified as areas of significant conservation value. One reason for this is their importance as wintering sites for a number of endangered shorebird species. Any changes in shorebird abundance may relate to changes in the availability of food supply. Also, anecdotal evidence suggests that abundance of cultural food resources has decreased over the past decades. However, without baseline surveys such as the present study, it is difficult to quantify any changes, assign causes to those changes, and implement management tools to prevent or mitigate further changes. The results of this study show the distribution and approximate abundance of cockles, wedge shells and some other benthic species. Further increases of terrestrial sediments in the harbours could reduce the distribution and abundance of these valuable food resources, and result in further changes in water quality, sediment stabilisation, hydrodynamics and overall health of the estuarine ecosystem.

This study provides a baseline against which anthropogenic effects or natural impacts (e.g. storm events) can be assessed. It is recommended that future research focus on changes in habitat within the harbours, such as increases in sedimentation, and changes in vegetation.

6. Acknowledgements

The authors would like to thank Haley Mankelow, Kate Scarlett and Minghao Hu for their dedication and work in collecting the majority of the field data; Keith Greggor and the Bay of Plenty Polytechnic team, Andrew Hansford (DOC), Carolyn Lundquist (NIWA), Luca Chiaroni (NIWA), William Gumbley, Chris Hillock, Laurence Barea (DOC), Doug Taucher (DOC) and Adrienne Grant (DOC) for help in the field; Andrew Hansford for GIS support; Mark Ivamy (Tonkin & Taylor Ltd) and Rick Liefting (Tonkin & Taylor Ltd) for GIS analyses; Environment Waikato for sediment grain size analysis; and Laurence Barea and Debbie Freeman (DOC) for valuable comments and feedback on the report. This research was funded by the Department of Conservation (Investigation No. 3123)

7. References

Alfaro, A.C. 2006: Benthic macro-invertebrate community composition within a mangrove/seagrass estuary in northern New Zealand. *Estuarine, Coastal and Shelf Science 66*: 97–110.

Battley, P.F.; Melville, D.S.; Schuckard, R.; Ballance, P.F. 2005: Quantitative survey of the intertidal benthos of Farewell Spit, Golden Bay. *Marine Biodiversity Biosecurity Report No. 7*. Ministry of Fisheries, Wellington. 119 p.

Burnham, K.P.; Anderson, D.R. 2001: Kullback-leibler information as a basis for strong inference in ecological studies. *Wildlife Research 28*: 111–119.

Cohen, A.N. 2005: Guide to the exotic species of San Francisco Bay. www.exoticsguide.org (viewed 3 February 2011).

Costanza, R.; d'Arge, R.; de Groot, R.; Farber, S.; Grasso, M.; Hannon, B.; Limburg, K.; Naeem, S.; O'Neill, R.V.; Paruelo, J.; Raskin, R.G.; Sutton, P.; van den Belt, M. 1997: The value of the world's ecosystem services and natural capital. *Nature 387*: 253–260.

Creese, R.; Hooker, S.; De Luca, S.; Wharton, Y. 1997: Ecology and environmental impact of *Musculista senhousia* (Mollusca: Bivalvia: Mytilidae) in Tamaki estuary, Auckland, New Zealand. *New Zealand Journal of Marine and Freshwater Research 31*: 225–236.

Crooks, J.A. 1998: Habitat alteration and community-level effects of an exotic mussel, *Musculista senhousia*. *Marine Ecology Progress Series 162*: 137–152.

Cummings, V.; Hatton, S.; Nicholls, P. 2002: Upper Waitemata Harbour benthic habitat survey. *Auckland Regional Council Technical Publication 219*. Auckland Regional Council, Auckland. 65 p.

DOC (Department of Conservation) 1999: Aotea Harbour shellfish study. Waikato Conservancy (Unpublished report). 8 p.

Dowding, J.E.; Moore, S.J. 2006: Habitat networks of indigenous shorebirds in New Zealand. *Science for Conservation 261*. Department of Conservation, Wellington. 99 p.

Environment Waikato 2005: Regional Coastal Plan. *Environment Waikato Policy Series 2005/06*. Environment Waikato, Hamilton East. 286 p. www.ew.govt.nz/Policy-and-plans/Regional-Coastal-Plan/ (viewed 2 February 2011).

Francis, M. 2001: Coastal Fishes of New Zealand. An identification guide. Reed Publishing (NZ) Ltd, Auckland. 103 p.

Gibbs, M.; Hewitt, J.E. 2004: Effects of sedimentation on macrofaunal communities: a synthesis of research studies for ARC. *Auckland Regional Council Technical Publication 264*. Auckland Regional Council, Auckland. 48 p.

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. Unpublished report prepared for the Hauraki Gulf Forum. AquaBio Consultants Ltd. 99 p.

Gunson, D. 1993: A guide to the New Zealand seashore. Penguin Books (NZ) Ltd, Auckland. 152 p.

Hewitt, C.L.; Campbell, M.L.; McEnnulty, F.; Moore, K.M.; Murfet, N.B.; Robertson, B.; Schaffelke, B. 2005: Efficacy of physical removal of a marine pest: the introduced kelp *Undaria pinnatifida* in a Tasmanian marine reserve. *Biological Invasions 7*: 251–263.

Hewitt, J.E.; Thrush, S.F.; Cummings, V.J.; Pridmore, R.D. 1996: Matching patterns with processes: predicting the effect of size and mobility on the spatial distributions of the bivalves *Macomona liliana* and *Austrovenus stutchburyi*. *Marine Ecology Progress Series 135*: 57–67.

Levin, L.A.; Boesch, D.F.; Covich, A.; Dahm, C.; Erseus, C.; Ewel, K.C.; Kneib, R.T.; Moldenke, A.; Palmer, M.A.; Snelgrove, P.; Strayer, D.; Weslawski, J.M. 2001: The function of marine critical transition zones and the importance of sediment biodiversity. *Ecosystems 4*: 430–451.

Lundquist, C.J.; Chiaroni, L.; Halliday, J.; Williston, T. 2004: Identifying areas of conservation value in the Waikato coastal marine environment. Unpublished NIWA client report prepared for Department of Conservation. 98 p.

McLintock, A.H. (Ed.) 1966: An encyclopaedia of New Zealand. New Zealand Government, Wellington.

Morrison, M.A.; Lowe, M.L.; Parsons, D.M.; Usmar, N.R.; McLeod, I.M. 2009: A review of land-based effects on coastal fisheries and supporting biodiversity in New Zealand. *New Zealand Aquatic Environment and Biodiversity Report No. 37*. Ministry of Fisheries, Wellington. 102 p.

Norkko, A.; Talman, S.G.; Ellis, J.; Nicholls, P.; Thrush, S.F. 2001: Macrofaunal sensitivity to fine sediments in the Whitford embayment. *Auckland Regional Council Technical Publication 158*. Auckland Regional Council, Auckland. 38 p.

Perkins, E. 1974: The biology of estuaries and coastal waters. Academic Press, London. 678 p.

Reusch, T.B.H. 1998: Native predators contribute to invasion resistance to the non-indigenous bivalve *Musculista senhousia* in southern California, USA. *Marine Ecology Progress Series 170*: 159–168.

Ritchie, S. 1990: Marine protection for the Kawhia coastal area. Unpublished Bachelor of Regional Planning (Honours) thesis, Massey University, Palmerston North. 172 p.

Shore Futures 2009: Shore Futures: a collective vision for healthy harbours and communities in the Kawhia and Aotea catchments. Preferred futures report. Environment Waikato, Waitomo District Council, Otorohanga District Council, Waikato District Council and Department of Conservation. 58 p. www.ew.govt.nz/PageFiles/1188/Shore%20Futures%20Report%20FINAL%20WEB09.pdf (viewed 28 February 2011).

Southey, I. 2009: Numbers of waders in New Zealand 1994–2003. *DOC Research & Development Series 308*. Department of Conservation, Wellington. 70 p.

Stace, G. 1997: What's on the beach. Penguin Books, Auckland. 67 p.

Thrush, S.F.; Hewitt, J.E.; Norkko, A.; Nicholls, P.; 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.

Turner, S.J.; Hewitt, J.E.; Wilkinson, M.R.; Morrisey, D.; Thrush, S.F.; Cummings, V.; Funnell, G. 1999: Seagrass patches and landscapes: the influence of wind-wave dynamics and hierarchical arrangements of spatial structure on macrofaunal seagrass communities. *Estuaries 22(4)*: 1016–1032.

van Houte-Howes, K.S.S.; Turner, S.J.; Pilditch, C.A. 2004: Spatial differences in macroinvertebrate communities in intertidal seagrass habitats and unvegetated sediment in three New Zealand estuaries. *Estuaries 27(6)*: 945–957.

Walshe, K.A.R.; Akroyd, J.M.; Manly, B.F.J. 2005: Intertidal shellfish monitoring in the Auckland Fisheries Management Area AKI 2005. Report prepared for the Ministry of Fisheries. Akroyd Walshe Limited. 47 p.

Appendix 1

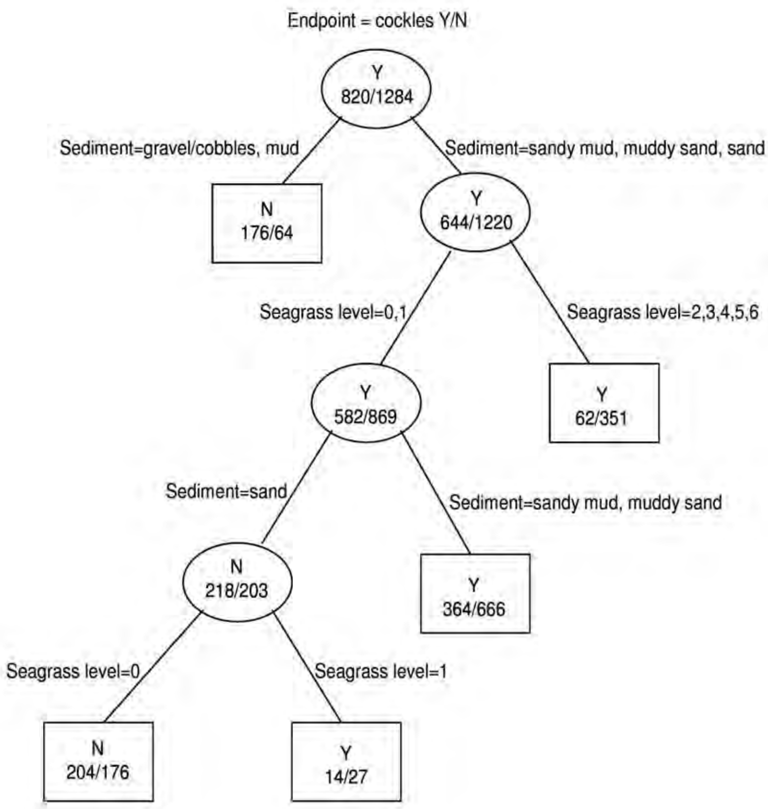
Additional statistical results

A1.1 R script used in general linear model

Call: glm.nb(formula = CockleCount ~ sediment.level + seagrass.level,
data = co, init.theta = 0.350007255726174, link = log)

A1.2 Classification tree to explain the presence and absence of cockles in Kawhia Harbour

Oval indicates a further split is possible. Box indicates no further split is possible. ‘Y’ indicates presence of cockles is greater than absence. ‘N’ indicates absence is greater than presence.



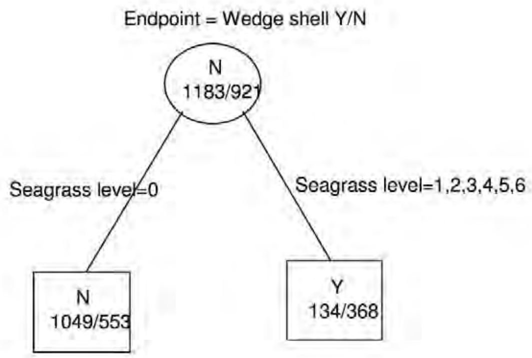
A1.3 Output from Kawhia cockle negative binomial general linear model

Coefficients:

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	0.48520	0.12033	4.032	5.52e–05***
Sand	1.45769	0.12866	11.330	< 2e–16***
Seagrass Present	0.24848	0.08986	2.765	0.00569**

A1.4 Classification tree to explain the presence and absence of wedge shells in Kawhia Harbour

Oval indicates a further split is possible. Box indicates no further split is possible. 'Y' indicates presence of wedge shells is greater than absence. 'N' indicates absence is greater than presence.



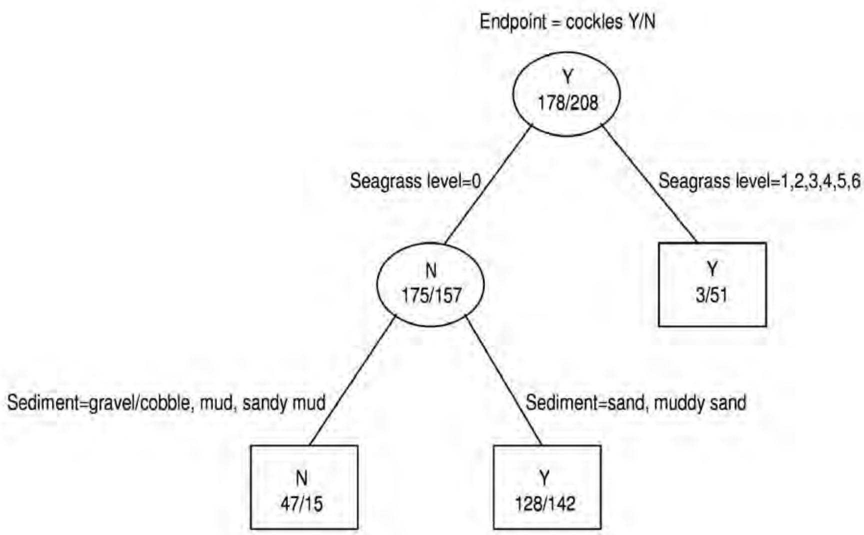
A1.5 Output from Kawhia wedge shell negative binomial general linear model

Coefficients:

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	–1.50421	0.16722	–8.995	< 2e–16***
Sand	1.80776	0.17323	10.436	< 2e–16***
Seagrass Present	0.87635	0.08623	10.163	< 2e–16***

A1.6 Classification tree to explain the presence and absence of cockles in Aotea Harbour

Oval indicates a further split is possible. Box indicates no further split is possible. 'Y' indicates presence of cockles is greater than absence. 'N' indicates absence is greater than presence.



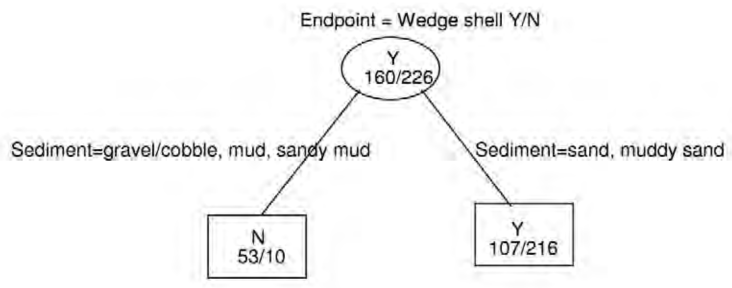
A1.7 Output from Aotea cockle negative binomial general linear model

Coefficients:

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	−1.3863	0.6872	−2.017	0.043672*
Sand	3.0475	0.6958	4.380	1.19e−05***
Seagrass Present	0.9456	0.2812	3.362	0.000773***

A1.8 Classification tree to explain the presence and absence of wedge shells in Aotea Harbour

Oval indicates a further split is possible. Box indicates no further split is possible. 'Y' indicates presence of wedge shells is greater than absence. 'N' indicates absence is greater than presence.



A1.9 Output from Aotea wedge shell negative binomial general linear model

Coefficients:

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	−0.3399	0.2280	−1.491	0.136
Sand	1.5692	0.2407	6.518	7.11e−11***