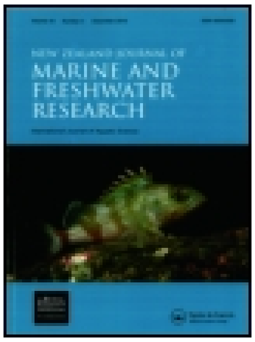

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Effects of beach erosion on abundance and distribution of toheroa (*Paphies ventricosa*) at Bluecliffs Beach, Southland, New Zealand

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Abstract Data on abundance, distribution, and size structure of toheroa (*Paphies ventricosa*) on Bluecliffs Beach, Southland, New Zealand from 42 surveys (1966 to 2005) are presented. Toheroa abundance declined from over 2 million adults in the mid 1960s to c. 80 000 by 1990 and since then has remained low but relatively stable. The decline mirrors that of other toheroa populations throughout New Zealand. Recent recruitment was highly variable but low compared with historical levels in the 1960s. Length frequency distributions are characteristically bimodal with a strong adult mode and a juvenile mode of variable strength, with relatively few toheroa of intermediate size. The distribution is related to mortality and growth characteristics of Bluecliffs Beach toheroa. Spatial distribution of adult toheroa has progressively changed over the last 40 years—historical distribution included the entire beach and toheroa were most dense just east of the Rowallan Burn. Since 1997, they have been aggregated into one large bed just west of the Rowallan Burn. Toheroa showed intertidal size zonation with small juveniles near high water and larger toheroa near mid to low water. Beach profile surveys were carried out in 1997, 2001, and 2005 to assess the dynamics of beach geomorphology and erosion. The surveys indicated a net loss of sand from the beach between 1997 and 2005, exposing underlying gravel and cobble substrates, and a general erosion of the vegetated dunes. Aerial photos from 1947 reveal that Bluecliffs Beach was homogeneous sand substrate—significant erosion and loss of sand began in the mid 1980s and only c. 54% of the beach surface is now fine/coarse sand. Our results indicate that distribution and abundance of toheroa on Bluecliffs Beach is related to the amount and distribution of sand on the beach. If the erosion continues with loss of sand habitat, the toheroa population may be at risk of collapsing.

Keywords toheroa; *Paphies ventricosa*; bivalve; Bluecliffs Beach; Te Waewae Bay; abundance; spatial distribution; size distribution; survey; substrate; erosion

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INTRODUCTION

Intertidal shellfish that occupy high wave-energy exposed sandy beaches must be adapted to an extremely dynamic and unstable environment. Survival depends on the ability to withstand shifts in substrate, intermittent submergence, and the constant pounding from surf, particularly during storm events. Survival of species from these types of beaches are thought to be more related to the physical nature of the environment than the biological interaction with other species (McLachlan 1990; McLachlan et al. 1995).

Toheroa (*Paphies ventricosa* Gray) is a mesodesmatid bivalve endemic to New Zealand and found intertidally on fine sand dissipative beaches fully exposed to surf (Rapson 1952; Cassie 1955). The largest beds are generally found midway between low and high water (Rapson 1952, 1954; Cassie 1955; Redfearn 1974; Morrison & Parkinson 2001; Beentjes et al. 2003). Toheroa are active burrowers, living from 10 to 20 cm beneath the sand where they extend siphons to the surface to filter feed and excrete waste during submergence (Redfearn 1974; Kondo & Stace 1995). The main toheroa

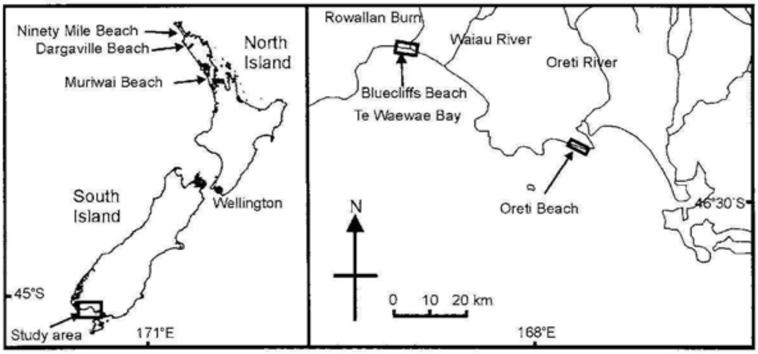

Fig. 1 Location of Bluecliffs Beach within Te Waewae Bay, and Oreti Beach, Southland, New Zealand. Other locations around New Zealand where toheroa are found are also shown.

populations are found in Northland, North Island (Ninety Mile Beach, Dargaville Beach, and Muriwai Beach), with smaller populations on the Wellington west coast, and in Southland on Oreti Beach and Bluecliffs Beach (Redfearn 1974) (Fig. 1). Toheroa have been subjected to intensive exploitation both as a commercial and amateur fishery (Cassie 1955; Stace 1991; McKinnon & Olsen 1994; Morrison & Parkinson 2001). The main commercial fishery was based around Northland and continued until 1964 when it became uneconomic as the population declined (Redfearn 1974; Stace 1991). Toheroa populations also declined markedly throughout the country and by 1980 all fishing was prohibited (Stace 1991; McKinnon & Olsen 1994) except for Maori customary take and occasional one-day recreational seasons, the last of which was in 1980 at Bluecliffs Beach and 1993 at Oreti Beach (McKinnon & Olsen 1994).

The current toheroa population at Bluecliffs Beach, Southland is only a small fraction of that in the 1960s and there are concerns for the long-term viability of this population (Beentjes & Gilbert 2006a). Anecdotal information also suggests that the beach is eroding, resulting in replacement of sand and vegetated sand dunes by gravel and cobble substrates. Forty-two surveys have been carried out at Bluecliffs Beach between 1966 and 2005 providing estimates of toheroa abundance, size composition, and distribution.

In this paper we first examine the historical abundance, distribution, and size structure of toheroa on Bluecliffs Beach from the time series of surveys. Second, we present results from beach profile surveys in 1997, 2001, and 2005 carried out to assess the dynamics of beach geomorphology. Finally, we use these findings and other information to consider the relationship between toheroa population status and physical beach structure.

MATERIALS AND METHODS

Bluecliffs Beach faces south to southwest in an embayment in the coastal cliffs at the western end of Te Waewae Bay, Southland (Fig. 1 and 2). The Waiau River flows into the middle of Te Waewae Bay. The intertidal zone of Bluecliffs Beach is flat and wide but progressively narrows and steepens toward the west. A narrow vegetated (mostly marram grass) sand dune extends c. 4 km west from the Rowallan Burn, before it ends in a steep cobble bank. The cobble bank begins c. 2 km west of the Rowallan Burn between the sand dunes and intertidal zone and becomes wider and steeper toward the west. The beach substrate at low tide is mainly fine or coarse sand but further up the beach, gravel and cobbles are common. The beach conforms to the definition of dissipative since it is generally flat with a wide surf zone (c. 150 m), high wave-energy, and the substrate is mainly fine sand (Defeo & McLachlan 2005).

Toheroa surveys

We examined data from 42 toheroa surveys of Bluecliffs Beach from 1966 to 2005 (Appendix 1). Apart from 10 Meridian Energy Ltd funded surveys between 1997 and 2001, all surveys were carried out by the New Zealand Ministry of Fisheries (MFish). Of the latter surveys, only those from 1966–70 (Street 1970, 1972), 1990 (McKinnon & Olsen 1994), and 1998 are documented (Carbines & Breen 1999). The 10 Meridian Energy surveys are unpublished but are documented in a series of client reports by National Institute of Water and Atmospheric Research Limited (NIWA) (see Beentjes & Carbines 2001). Raw data were available for all surveys except those from 1966 to 1970. Before 1997 the quality of information on the survey designs and methods used are highly variable, and many of these surveys have shortcomings and anomalies in the data.

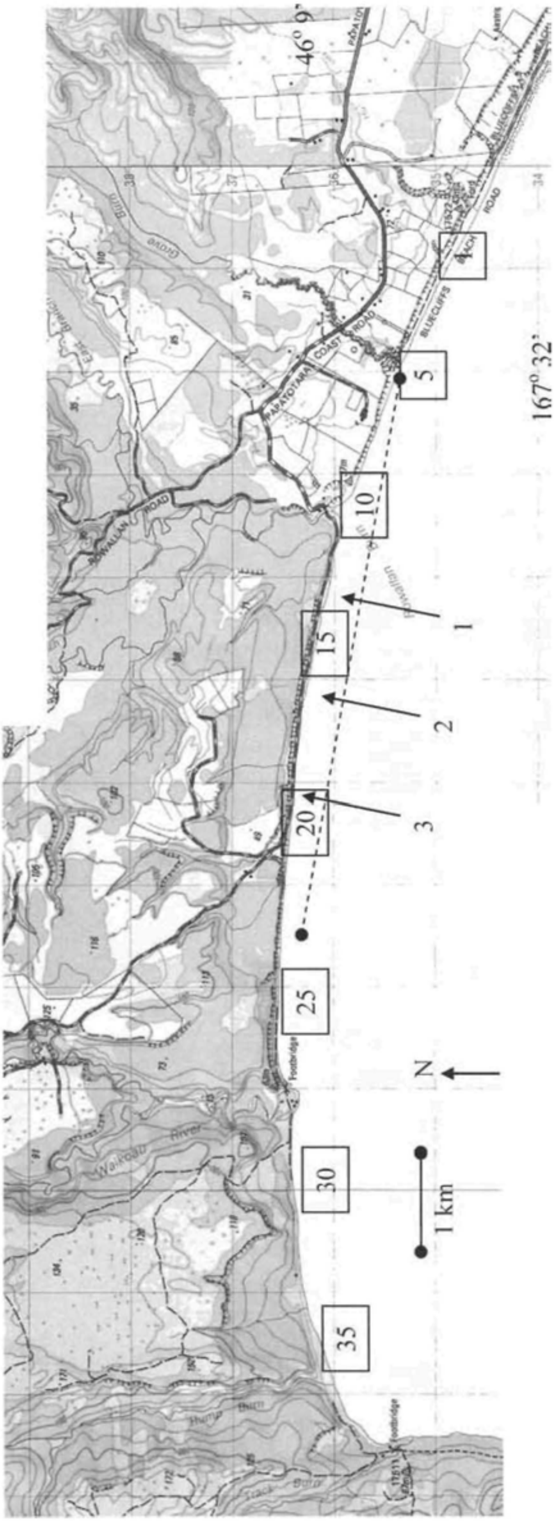

Fig. 2 Survey transect locations on Bluecliffs Beach, New Zealand, for toheroa (*Paphies ventricosa*) surveys between 1966 and 2005 (bordered) as well as three cross-sections (1, 2, and 3) where beach profile was surveyed. The survey areas for surveys from 1990 to 2005 are shown by the dashed line (see Appendix 1 for transects used for each survey). Map reproduced by permission of Land Information New Zealand.

Following a 7-year absence of surveys after 1990, 12 surveys were carried out between 1997 and 2005 and these form the basis of our analyses on the current status of the toheroa population on Bluecliffs Beach (Appendix 1).

From 1966 to 1984 the surveys covered a distance of c. 11 km and 35 transects (1.6 km east of the Grove Burn west to the Hump Burn) (Fig. 2). Erosion of the beach and loss of sand around 1985 prevented access to the beach west of transect 24. Further erosion in 1987 resulted in loss of sand substrate from the east end of Bluecliffs Beach and the survey area was further truncated. Thus, for the 1990 survey and those thereafter, the most eastern transects started at transect 5 (Grove Burn) running west to about transect 23. Hence, from 1985 onward the length of the beach covered by surveys ranged from c. 4.5 to 6.1 km. We assume that there were few toheroa on Bluecliffs Beach outside the survey areas.

For all surveys, transects were marked out along the beach between high water (edge of sand dunes) and low water. The surveys from 1997 onward were timed to coincide with several days of low tides allowing the maxiumum possible extent of the intertidal beach to be surveyed. No details of tide heights are available during the earlier surveys, although McKinnon & Olsen (1994) stated that the 1990 survey covered the area from mean low water to mean high water. For each transect, quadrats of 0.5 m^2 (1.0 × 0.5 m) spaced at 5 m intervals were excavated to a depth of 30 cm with a spade or fork. From 1966 to 1990 and the five Meridian Energy summer surveys (1997–2001) the sand was spread out near the hole and searched for toheroa. Maximum shell length (to the nearest 1 mm or 5 mm—surveys 1966–70) was measured for all toheroa found in each quadrat, and the toheroa returned to the substrate. These surveys were termed adult surveys because not all juveniles were likely to be sampled by this method. For the five Meridian Energy winter surveys (1997–2001) and the 1998 and

2005 MFish surveys, samples were sieved from every second systematic transect, or two transects from each strata for random stratified transects to estimate the distribution, size structure, and abundance of juvenile toheroa (<40 mm for MFish surveys and <45 mm for Meridian Energy surveys). For sieved transects, sand was either fed into nylon mesh bags and dragged to the water, or shovelled into a trolley lined with fine steel mesh and then wheeled down to the water where the action of the surf washed out the sand, leaving behind only debris and toheroa.

From 1997 onward, substrate type (= coarseness) was qualitatively assessed and recorded for each quadrat as one of seven categories: fine sand, coarse sand, sand and some gravel, sand and moderate gravel, sand and mainly gravel, sand and mainly cobble, and cobble.

All surveys except the MFish 1998 and 2005 surveys used a systematic sampling design with transects spaced every 321 m (1966–87), 330 m (1990), or 250 m (Meridian Energy surveys 1997–2001) along the beach (Appendix 1). For surveys before 1997 the precise locations of transects are unknown, but it is likely that they varied among surveys in the absence of documented benchmarks and without the aid of GPS.

MFish surveys in 1998 and 2005 used a two phase, stratified random transect design (Francis 1984). Eight strata of various lengths were marked out using hand-held GPS. Within each stratum, transects were marked using randomly generated distances from the east end of each stratum, with a requirement that there be at least 20 m between transects. About 75% of transects were allocated to phase 1, and the remaining 25% to phase 2. A minimum of three transects was initially assigned to each stratum with additional transects allocated to those strata where toheroa density was known to be historically high. Phase 2 transects were allocated from the survey mean catch of legal-sized toheroa per transect in each strata, and optimised using the "area mean squared" method of Francis (1984). In this way, transects were assigned iteratively to the stratum in which the expected gain was greatest, where $expected\ gain_i = A_i^2\ mean_i^2 / (n_i(n_i+1))$ where for the ith stratum, $mean_i$ is the mean number of toheroa encountered per transect, A_i is the area of the stratum, and n_i is the number of transects.

Population estimates

Population estimates for toheroa of minimum legal size (≥75 mm until 1978, and ≥100 mm from 1979) before 1997 were derived from survey reports and were calculated using the simple scaling method (Street 1972; McKinnon & Olsen 1994). The method scales the number of toheroa from the area sampled (i.e., total quadrat area sampled) to the total survey area. No variance estimates were available.

For the 12 surveys from 1997 to 2005, where data were of a higher standard, we estimated population number and variances. For the systematic surveys we used the sampling fraction method to estimate the population of toheroa of various size ranges. This method scales the total number of toheroa sampled by the reciprocal of the fraction of the area surveyed, calculated from the distance between transects (Millar & Olsen 1995). Variances were calculated using a systematic sampling variance estimator described by Millar & Olsen (1995). Simple random sampling variance can overestimate the sampling error in systematic surveys (Dunn & Harrison 1993), because the quadrat position is not random, but is directly related to the position of the first quadrat.

For the random stratified transect MFish surveys in 1998 and 2005, the population size of toheroa on Bluecliffs Beach was estimated from the mean density of legal-sized toheroa in each stratum and the area of each stratum. In the ith stratum, the estimated number of legal-sized toheroa $N_i = 10\ mean_i A_i$, where $mean_i$ is the mean number of toheroa encountered per transect, and A_i is the area of the stratum (= length of each stratum and equivalent to the number of transects in a stratum). The possible number of 1 m wide transects in a stratum is the length of the upper beach in the stratum. The factor of 10 scales from the area sampled (0.5 m^2 every 5 m along the transect) to the entire area of a 1 m wide transect. The population estimate on the whole beach (= survey area) is given by $N = \Sigma\ N_i$ where summation is over all strata. The estimated variance of the $mean_i$, is $VC_i = var_i/n_i$ where var_i is the variance of the observed numbers for each transect in stratum i, and the estimated variance of N estimate is $VN = 100\ \Sigma\ (A_i^2\ VC_i)$. The factor 100 is introduced in scaling up from the sampled transect area to the whole transect. The coefficient of variation is $CV = \text{sqrt}\ (VN) / N$.

Population estimates and variances for juveniles (defined as <40 mm in MFish 1998 and 2005 surveys, and <45 mm for Meridian Energy surveys) were estimated as described above for systematic or random stratified transects in the above way but using only those transects that were sieved.

Analyses of distribution and substrate

For the analyses of spatial distribution of toheroa and substrate we combined data from 12 surveys

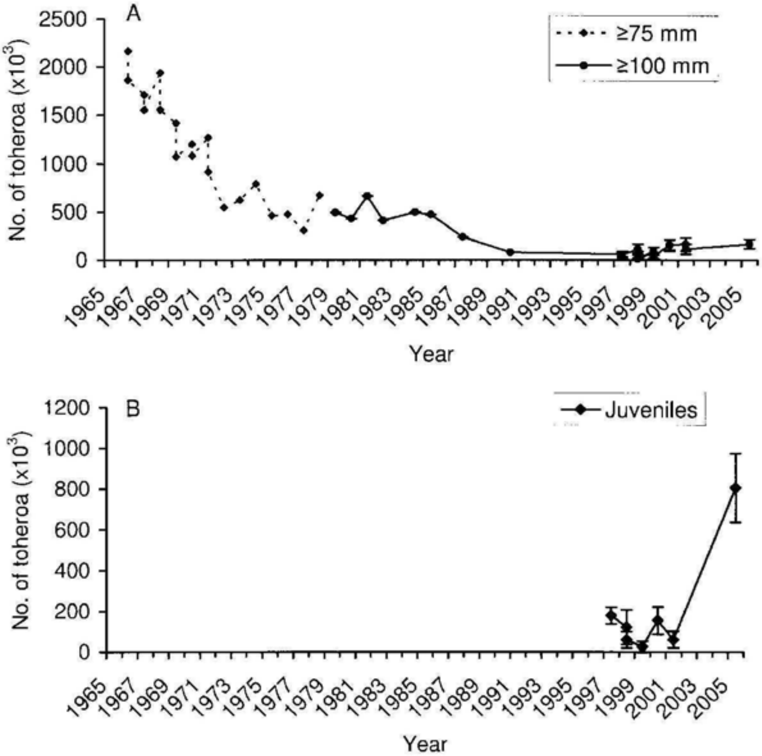

Fig. 3 Bluecliffs Beach, New Zealand, population estimates for toheroa (*Paphies ventricosa*) **A**, ≥75 mm (1966–1978) and ≥100 mm maximum shell length (1979–2005); and **B**, juveniles (1997–2005). Juveniles defined as <40 mm maximum shell length for random transect surveys in 1998 and 2005 survey, and <45 mm for others. Error bars for 95% confidence intervals are shown for surveys from 1997 onward.

between 1997 and 2005 (Appendix 1). These surveys covered a relatively short time period and sampled juveniles and substrate type. The methods are well documented and the data are of high quality. Earlier surveys were used for comparison of population abundance and distribution along the beach.

For the 1998 and 2005 random stratified surveys, transects that fell within each 250 m block (distance between systematic transects) were assigned to the nearest eastern systematic transect to allow systematic and random transects surveys to be combined, i.e., all random transects between 1 and 249 m were assigned to transect 5, between 250 and 499 m to transect 6, etc.

The relationship between toheroa distribution/abundance and substrate type was examined using a Pearson *r* correlation analysis (Statsoft 2003).

Beach profiles

To examine the dynamics of beach morphology over time, the physical structure of the beach was studied in the vicinity of the main toheroa bed. First, three beach profiles were surveyed from the vegetated sand dunes to below mean low water spring (MLWS). Profile 1 was located 1 km west of the Rowallan Burn with additional profiles 1 km and 2 km west of the first (Fig. 2). These surveys were carried out in the summer of 1997, 2001, and 2005. The survey in 1997 was carried out using Optical Total Station located on benchmarks at each profile with points measured every 5 m or at changes in slope. Boundaries where substrate changed within each cross-section were also recorded, i.e., the transition from marram grass-covered dune to sand or cobble. For the 2001 and 2005 surveys, RTK GPS was used to re-survey the profiles and also to map the interface of the vegetated sand dunes and the sand/cobble edge along the beach from the Rowallan Burn west to cross-section 3 (c. 3000 m).

RESULTS

Population estimates and size structure

Toheroa abundance declined steeply between the mid 1960s and mid 1970s when population numbers (≥75 mm) decreased from c. 2.2 million to c. 500 000 (Fig. 3). This was followed by a further decline in the late 1980s to 78 000 by 1990, although this estimate was for toheroa ≥100 mm, so the decline is likely to be slightly less severe. The most recent surveys from 1997 to 2005 indicate that the population had not recovered, but appeared to be stable with relatively small numbers of toheroa ≥100 mm (mean number = 97 000). The population abundance declined to a record low of only 10 000 toheroa in August 1998, however, the 2005 estimate of 165 000 toheroa (≥100 mm) is the highest estimate since 1987.

Juvenile toheroa were sampled in seven surveys between 1997 and 2005. Numbers ranged from 25 000 to 180 000 (mean = 100 000) for the 1997 to 2001 surveys, but in 2005 they increased more than 8–fold to 805 000 (Fig. 3).

Length frequency distributions are shown only for the 2005 survey (Fig. 4). The large number of toheroa from this survey (Table 1) generated a well-defined size distribution and was typical of those from earlier surveys (data not shown). Length frequency distributions were generally bimodal with a strong adult mode between 110 and 145 mm and a juvenile mode (<40 mm) of variable strength, with relatively few toheroa between the two modes. In 2005, the juvenile mode was pronounced, reflecting strong recruitment. A relatively higher proportion of juveniles to adults were sampled from sieved compared to non-sieved transects.

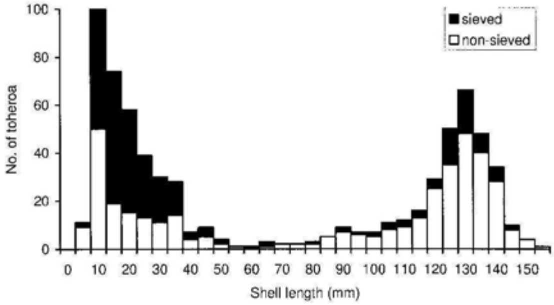

Fig. 4 Length frequency distribution of toheroa (*Paphies ventricosa*) from Bluecliffs Beach, New Zealand, in 2005 from sieved transects (n = 289 toheroa and 16 transects) and non-sieved transects (n = 392 toheroa and 31 transects).

Spatial distribution of toheroa

For the 12 surveys between 1997 and 2005, 1728 toheroa were sampled from 6183 quadrats and 277 transects (Table 1). Toheroa numbers ranged from 31 to 123 for the 10 systematic surveys and 330 to 681 for the random stratified surveys. Numbers of toheroa per quadrat ranged from 0 to 23 but most (86%) had zero toheroa, with 1 the most frequent number encountered (7%). The mean number of toheroa per quadrat was 0.28 overall, and 2.05 when excluding quadrats where no toheroa were found.

Plots of the vertical distribution (high to low water) of toheroa of all sizes combined indicate a strong preference for the zone between c. 65 and 120 m from the sand dunes (= high water), with the highest density at c. 95 m (mean distance = 89 m) (Fig. 5). Further, vertical distribution differed by size, with juveniles (<40 mm), subadults (40–99 mm) and adults (≥100 mm) occupying different zones between high and low water (Fig. 5). Adults were most abundant within a well-defined and narrow zone from c. 65 to 125 m (mean distance = 94 m)

Table 1 Sampling details from 12 surveys between 1997 and 2005 (see Appendix 1). All surveys were systematic transect surveys except those marked with an asterisk which were random stratified transect surveys. The standard error of the mean number of toheroa (*Paphies ventricosa*) per quadrat is shown in parenthesis.

Survey	Transects (n)	Quadrats (n)	Toheroa (n)	Mean no. toheroa per quadrat	Quadrats with fine sand and/or coarse sand (%)
Mar 1997	19	413	50	0.12 (0.07)	57
Jul 1997	19	357	67	0.19 (0.09)	40
Jan 1998	19	380	87	0.23 (0.09)	53
Jan 1998*	40	862	330	0.38 (0.05)	70
Aug 1998	19	370	31	0.08 (0.06)	28
Feb 1999	19	399	123	0.31 (0.13)	66
Aug 1999	19	392	34	0.09 (0.06)	53
Jan 2000	19	466	74	0.16 (0.08)	66
Jul 2000	19	486	107	0.22 (0.07)	45
Feb 2001	19	528	73	0.14 (0.09)	54
Aug 2001	19	460	71	0.15 (0.08)	59
Feb 2005*	47	1070	681	0.63 (0.05)	55
Overall	277	6183	1728	0.28 (0.02)	55

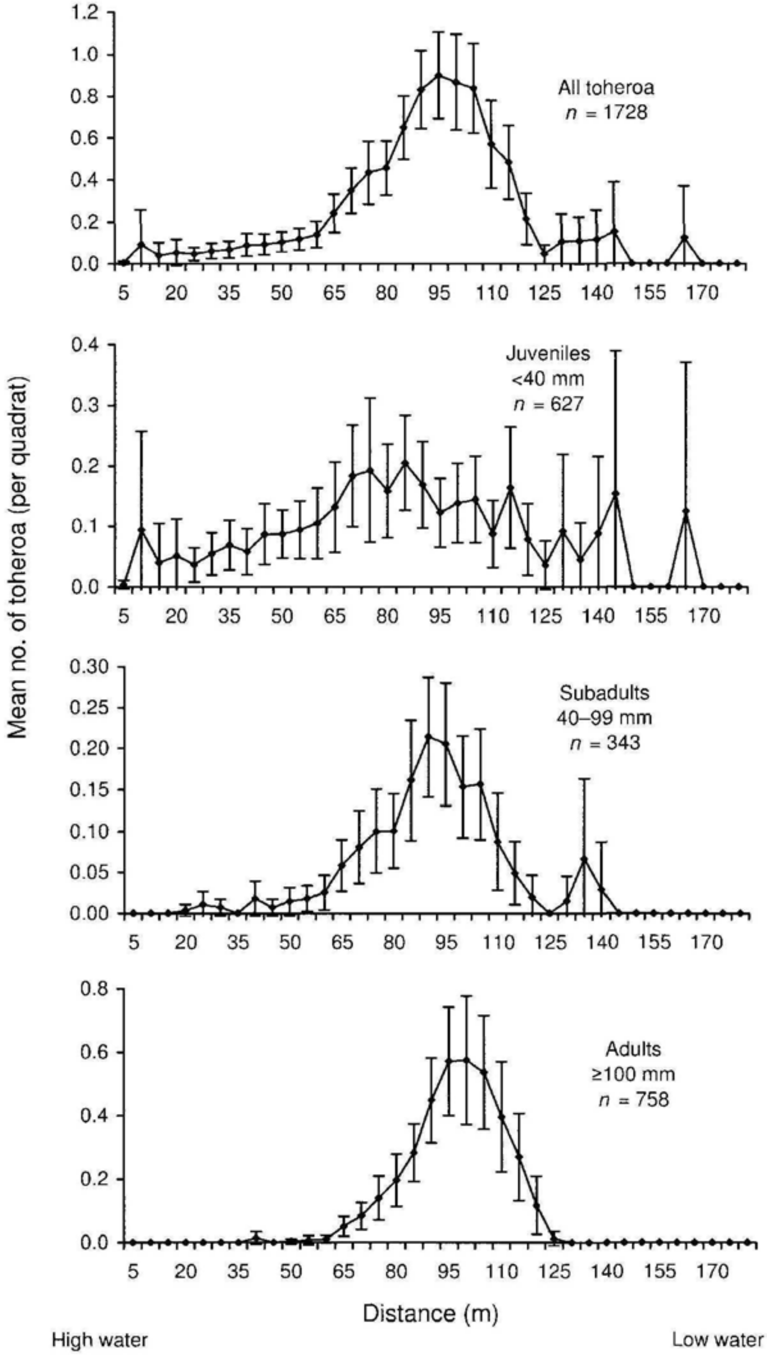

Fig. 5 Vertical distribution of toheroa (*Paphies ventricosa*) across (high to low water) Bluecliffs Beach, New Zealand, expressed as mean number of toheroa per quadrat by distance from high water. The distributions are shown for all toheroa and by three size ranges. Error bars represent 95% confidence intervals. Data are from 12 surveys between 1997 and 2005.

from the dunes, and subadults within a similar zone, but over a wider range (mean = 88 m). Juveniles had the widest vertical distribution and were found across almost the entire beach, but were most abundant higher on the beach from c. 45 to 120 m (mean distance = 83 m).

Plots of alongshore (east to west) distribution of toheroa of all sizes combined show that toheroa were

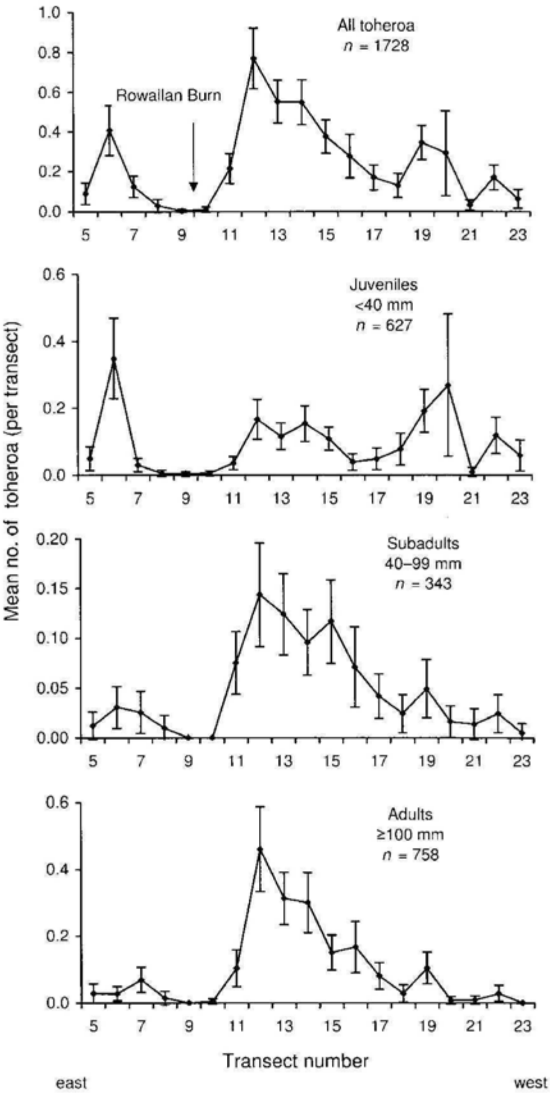

Fig. 6 Alongshore (east to west) distribution of toheroa (*Paphies ventricosa*) on Bluecliffs Beach, New Zealand, expressed as mean number of toheroa per quadrat by transect. Distributions are shown for all toheroa and by three size ranges. Error bars represent 95% confidence intervals. Data are from 12 surveys between 1997 and 2005.

distributed along the entire 5.07 km of beach, but with highest numbers in the middle between transects 12 and 15, and at either end (Fig. 6). Transects in proximity to the mouth of the Rowallan Burn had few toheroa. Juveniles, subadults, and adults had different spatial distributions. Most adults were concentrated within a 1 km wide band in the middle of the beach, just west of the Rowallan Burn, with few adults at either end (Fig. 6). The distribution of subadults was similar, but less concentrated in the middle of the beach. In contrast, juveniles were found along the entire beach but were most abundant at either end.

Because of changes to the survey area over time, comparison of the spatial distributions of toheroa along Bluecliffs Beach over the 40-year time series may not be valid. However, comparison of the proportion of adult toheroa within transect groups from surveys in 1966, 1978, and 1984, before the survey area was reduced, indicates a general shift in the distribution of toheroa (Fig. 7). During the 1960s through to the mid 1980s, toheroa were found along the entire 11 km beach but were most abundant within c. 1300 m either side of the Rowallan Burn (transects 6 to 15). Distribution of the main population progressively changed from the 1960s through to the 1980s with an eastward shift in abundance—by 1984 the area adjacent to and east of the Rowallan Burn contained by far the densest beds. The present distribution (1997 to 2005 surveys) is plotted for comparison, despite the truncated survey area, and indicates a major departure from the historical pattern as the bulk of the adult population was found west of the Rowallan Burn within a narrow stretch of beach (Fig. 7).

Toheroa distribution in relation to substrate

For the combined 12 surveys between 1997 and 2005, fine sand was the predominant substrate type on Bluecliffs Beach (44% of quadrats), with the other six categories ranging from 6% to 17% of quadrats (Fig. 8A). Toheroa (all sizes) were most abundant in fine sand and numbers decreased as substrate coarseness increased (Fig. 8B). 94% of toheroa were found in fine and coarse sand and toheroa number was negatively correlated with substrate coarseness ($r = -0.22$, $n = 6163$, $P < 0.05$). Substrate became progressively finer from high water to low water (Fig. 8B) and correspondingly, toheroa number was positively correlated with distance from high water ($r = 0.19$, $n = 6183$, $P < 0.05$). The relatively low correlations reflect the high numbers of zeros in the data, i.e., quadrats with no toheroa.

The percentage of fine and coarse sand for each of the 19 transects was strongly positively correlated with toheroa numbers ($r = 0.81$, $n = 19$, $P < 0.05$), indicating that toheroa distribution along the beach is, in part, dependent on substrate availability.

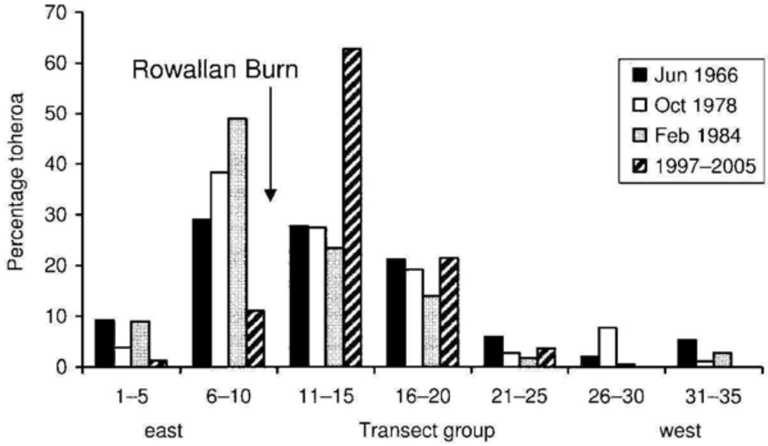

Fig. 7 Distribution of toheroa (*Paphies ventricosa*) along Bluecliffs Beach, New Zealand, expressed as percentage of the total number of toheroa by transect group for each of three surveys in June 1966, October 1978, and February 1984 (see Appendix 1). (n = 760, 183, and 180 toheroa, respectively.) Each survey covered the full 35 transects (see Fig. 2 for transect locations). Distribution is also shown for the 12 surveys between 1997 and 2005 where surveys spanned from transect 5 to 23 (n = 1728 toheroa).

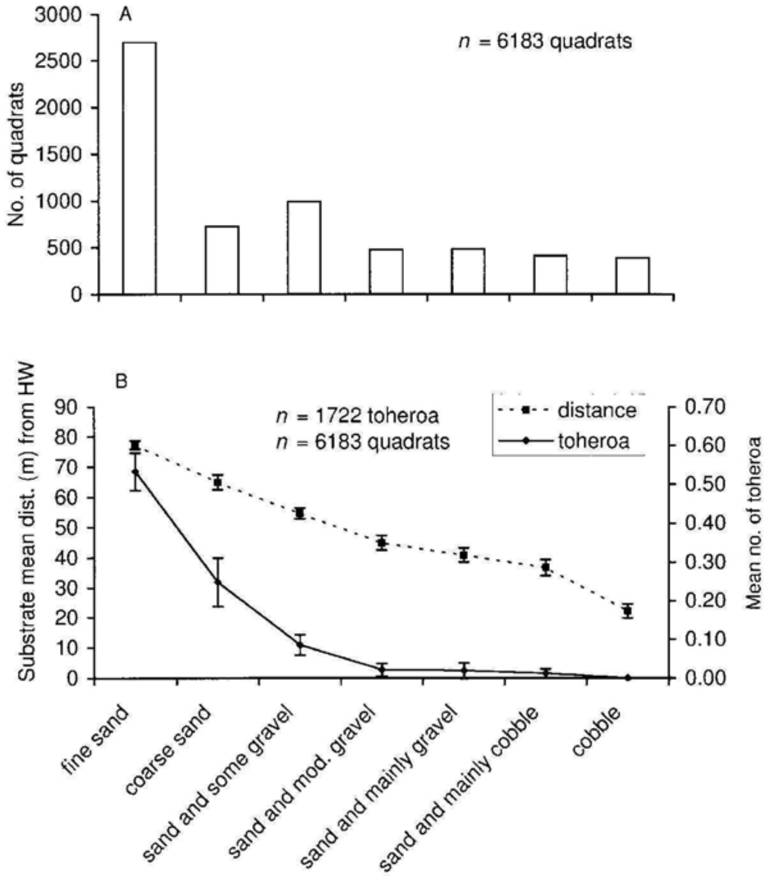

Fig. 8 **A**, substrate frequency, and **B**, mean number of toheroa (*Paphies ventricosa*) by substrate type, and mean distance from high water (HW = sand dunes) for each substrate type. Substrate is ordered by increasing coarseness. Error bars represent 95% confidence intervals. Data are from 12 surveys of Bluecliffs Beach, New Zealand, between 1997 and 2005.

The proportion of quadrats with fine and coarse sand varied among the 10 systematic surveys from 28% to 66% and generally followed the pattern of increasing in summer and decreasing in winter, but overall was 55% (Table 1).

Beach structure

In each of the three cross-sections (see Fig. 2) the vertical height of the beach from 1997 to 2005 was reduced by c. 0.5m on the lower section below the normal high tide level (Fig. 9). Cross-section

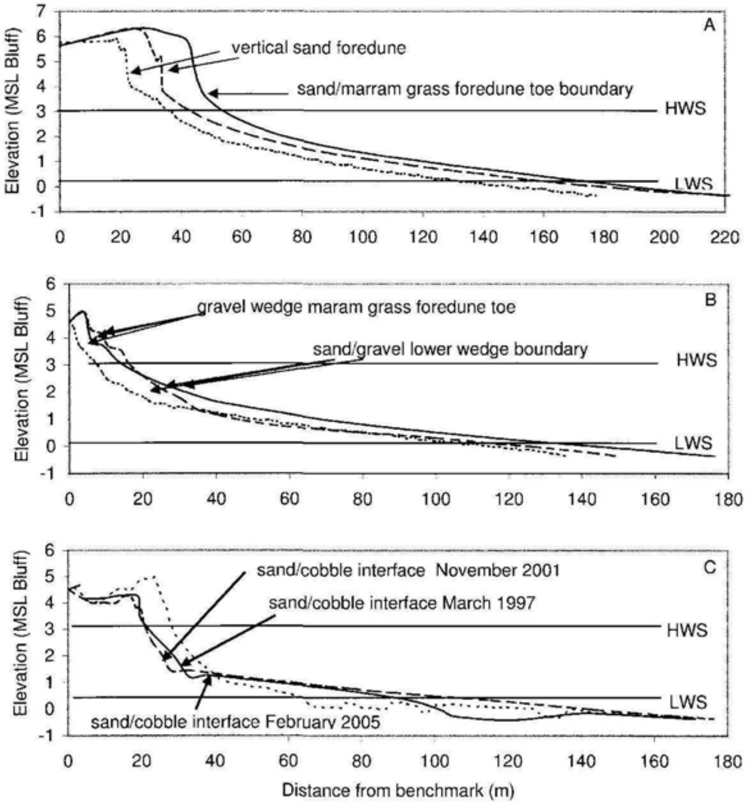

Fig. 9 Beach profiles of Bluecliffs Beach, New Zealand, in February of 1997, 2001, and 2005. Profiles 1 (A), 2 (B), and 3 (C) are 1 km, 2 km, and 3 km, respectively, west of the Rowallan Burn (see Fig. 2). (1997 survey, solid line; 2001 survey, long dashed line; 2005 survey, short dashed line. HWS, high water spring; LWS, low water spring; MSL, mean sea level.)

3, although showing an overall net loss of sand, displays a higher degree of variation among years with indications of local scouring events creating an undulating profile. In cross-section 1 the dunes eroded steadily and the transition between sandy beach and vegetated sand dunes moved landward by 11 m (Fig. 9). Similarly, in cross-section 2 the boundary between the gravel and dunes moved landward between 1997 and 2005, with a loss of 2.7 m of dunes. Cross-section 3 had a steep cobble substrate on the upper part of the beach between the dunes and sandy beach. There was no change in the dune-cobble interface in cross-section 3, but the sand-cobble interface lowered as sand was lost, and the cobble bank grew in height and volume.

The GPS mapped interface of the vegetated sand dunes and the sand/cobble edge along the beach indicates an average overall loss in sand dunes of 3 m from 2001 to 2005 (Fig. 10). The maximum erosion of 15.8 m occurred near cross-section 1, where the beach substrate was predominantly sand and also where adult toheroa were most abundant. A slight seaward movement of the vegetated edge occurred at the west end where the cobble wedge on the beach was largest.

DISCUSSION

Population status

The Bluecliffs Beach toheroa population has experienced a major decline from the mid 1960s when there were in excess of 2 million adult toheroa present. One-day open harvesting seasons at Bluecliffs Beach were in 1972, 1974, 1978, 1979, and 1980 (McKinnon & Olsen 1994), and before 1972 there were more extensive seasons with larger bag limits. Management measures were taken to address declining numbers of toheroa throughout New Zealand as early as 1932 (McKinnon & Olsen 1994) and therefore it is likely the Bluecliffs Beach population was considerably larger before 1966 (see Fig. 3). Since 1990, when there were only an estimated 78 000 adult toheroa, the population appears to have largely stablised and the 2005 estimate of adults (160 000) is the highest since 1987.

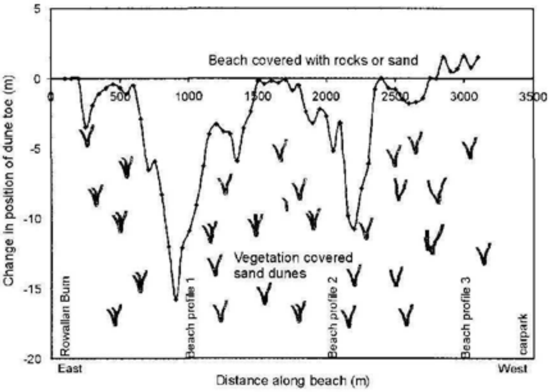

Fig. 10 Change in position of vegetation-covered dune and sand/gravel interface (foredune toe) between February 2001 and February 2005 on Bluecliffs Beach, New Zealand. Profiles 1, 2, and 3 are 1 km, 2 km, and 3 km, respectively, west of the Rowallan Burn (see Fig. 2).

Further, although recruitment has been variable, the relatively high numbers of juveniles recorded in 2005 is encouraging for the survival of this population. However, given that recruitment and mortality are highly variable in toheroa, and that good recruitment often does not translate into large numbers of adults (Greenway 1969; Street 1970; Redfearn 1974; Morrison & Parkinson 2001; Beentjes et al. 2003; Beentjes & Gilbert 2006a,b), future surveys are needed to determine if the strong 2005 recruitment results in an increase in the population size. Overall, recruitment is still low compared to the late 1960s when 3 to 5 million toheroa juveniles were estimated (Street 1970) (multiplied by 5 to adjust for lack of sieving, using Street's (1970) estimate of sampling efficiency).

Historically, toheroa populations throughout New Zealand have shown significant fluctuations and as early as the 19th century populations suffered marked declines in numbers (Rapson 1952) followed by a major decline in the 1930s (Redfearn 1974). There appears to be no documented explanation for the current decline in toheroa populations throughout New Zealand. There has been no significant harvest of any population (except for Oreti Beach, Southland in 1993) for over 25 years, exceeding the lifespan of toheroa which is thought to be c. 20 years (Cassie 1955), and the current low abundance estimates are unlikely to be related to fishing pressure. Toheroa populations are characterised by mass mortality events and erratic recruitment pulses, both of which contribute to the high annual variability in biomass and spatial distribution (Redfearn 1974; Morrison & Parkinson 2001). The cause of mass mortalities is speculative but suggested factors have included heat stress, storm events, suffocation from wind-blown sand, crushing and/or liquifaction of sand from vehicle traffic, toxic algal blooms, and substrate changes (Rapson 1954; Redfearn 1974; McKinnon & Olsen 1994; Carbines 1997; Carbines & Breen 1999). Mass mortalities or strandings of toheroa and other bivalves occurred on Bluecliffs Beach in 1970, and were ascribed to a prolonged period of low temperatures, heavy rainfall, and gale-force winds (Eggleston & Hickman 1972). However, these events tend to be sporadic and could not explain the general low abundance of toheroa throughout New Zealand. It has also been suggested that toheroa migrate between the littoral and sub-littoral zone, where they would fall outside the survey area, thus explaining large fluctuations in toheroa populations (Cassie 1951, 1955; Waugh & Greenway 1967; Greenway 1969). However, extensive underwater observations by divers, 250 m from low water on Bluecliffs Beach, found no signs of toheroa (Street 1970).

Fluctuations in abundance, recruitment, and mass mortalities are characteristic of many bivalve species found on exposed ocean beaches throughout the world (McLachlan et al. 1996). We suggest that the low abundance of toheroa throughout New Zealand is likely related to wide-scale environmental and climatic conditions that have prevailed in recent years acting on spawning, recruitment, growth, and mortality. The decline in the toheroa populations of Bluecliffs and neighbouring Oreti Beach have probably been affected by these conditions, however, the population on Bluecliffs Beach was also affected by erosion of the beach. This is discussed in detail below.

Size structure

The consistency in length frequency distributions over nearly 40 years of surveys is notable (see Beentjes & Gilbert 2006a for a detailed analysis of length frequency distributions over the entire time series). In general, the distributions are characterised by one juvenile and one adult mode, with relatively few subadults of intermediate size (see Fig. 4). The juvenile modes vary, depending on the strength of annual recruitment, as well as the shortcomings of surveys before 1997 when sand was not sieved. The low number of subadults is probably a result of high mortality of juveniles with relatively few surviving through to the subadult size range. Based on growth determined from mark-recapture data, those that do survive grow rapidly through the subadult size range and reach adult size at c. 3 years of age (Beentjes

& Gilbert 2006a). The strong adult mode between 110 and 145 mm represents the accumulation of multiple cohorts (3–20 years) within which growth slowed substantially compared with the subadults, and where mortality was relatively low.

Toheroa at Bluecliffs Beach have similar size distributions to those at Oreti Beach (Beentjes et al. 2003; Beentjes & Gilbert 2006b) with the notable difference that Bluecliffs Beach juveniles are less abundant, reflecting low annual recruitment, and toheroa reach a greater maximum size at Bluecliffs Beach. In contrast, size structure of populations of toheroa in Northland, North Island is different. Both historically and as recently as 2000, subadult toheroa were well represented, but large adult toheroa (100 mm or over) were largely absent (Greenway 1969; Morrison & Parkinson 2001; Akroyd et al. 2002). The smaller maximum size and lower numbers of large toheroa in Northland suggest that factors affecting growth and mortality are very different from those at Southland beaches. Toheroa from Bluecliffs Beach attain the largest maximum size of any New Zealand population and maximum size appears to have increased in recent years compared to the 1960s (Street 1970; Beentjes & Gilbert 2006a). The increase in maximum size of Bluecliffs Beach toheroa may be explained by the theory that growth and mortality of populations with low abundance from harsh environments are physically controlled by density-independent environmental factors and not by intraspecific interactions (Defeo & McLachlan 2005).

Spatial distribution

Alongshore distribution of toheroa on Bluecliffs Beach had the same characteristic of other populations from the beaches throughout New Zealand, i.e., it was heterogeneous and dynamic (Redfearn 1974; Beentjes et al. 2003; Beentjes & Gilbert 2006b). The distribution of adult toheroa on Bluecliffs Beach progressively changed over the last 40 years. Historically toheroa were distributed along the entire 11 km of the beach and were most dense on the east side of the Rowallan Burn (see Fig. 7). In contrast, since 1997, adult toheroa have aggregated into a large bed just west of the Rowallan Burn. The length of beach surveyed after 1985 is almost half that of the previous surveys dating back to 1966. We assume that toheroa were not present in any number outside the survey areas and that the erosion of the beach, preventing access to the west of the bay, was accompanied by a concomitant loss of toheroa. Regardless, even within the overlapping survey areas, toheroa distribution changed markedly and adult toheroa are now scarce to the east of the Rowallan Burn where historically they were most dense.

The more widespread distribution of subadults and particularly juveniles on Bluecliffs Beach since 1997 indicates that settlement of spat and recruitment occurs along the entire beach. This is consistent with observations of spat settlement on Dargaville Beach, North Island which was found to be a passive process dependent on characteristics of wave action and alongshore currents (Redfearn 1974). Given that settlement is a passive process, we might expect the distribution of large toheroa to reflect that of juveniles and be more evenly distributed along Bluecliffs Beach. Therefore, it appears that either toheroa physically migrate along the beach as they grow, or toheroa from discrete areas experience enhanced growth and survivorship resulting from a more favourable position on the beach. Movement between the east and west of the Rowallan Burn is not possible unless toheroa migrate along the sub-littoral zone. The densest beds of adult toheroa have always been close to the Rowallan Burn and probably receive considerable nutrients from the freshwater outfall which will enhance phytoplankton productivity and thus food available to toheroa. Similarly, the densest adult beds on Oreti Beach are close to the mouth of the Oreti River (Beentjes & Gilbert 2006b). The importance of phytoplankton as a food source for toheroa and also as a key factor controlling distribution has been documented in previous studies (Rapson 1954; Cassie 1955; Redfearn 1974).

The three size groups of toheroa on Bluecliffs Beach, to some extent, occupied distinct height zones, with juveniles more abundant near high water and adults near mid to low water (see Fig. 5). This intertidal size zonation was also described for toheroa from Bluecliffs Beach in the 1960s (Street 1970), and recently from Oreti Beach (Beentjes et al. 2003; Beentjes & Gilbert 2006b), but the separation is more defined on Oreti Beach, probably because the beach is considerably wider than Bluecliffs Beach. Intertidal size zonation was also described for toheroa from Northland beaches (Redfearn 1974). The zonation occurs during settlement, when spat washed onto the beach experience a protracted period of alternating settlement and dislodgement by wave action (Redfearn 1974). Eventually, most of the spat are washed up just above high water where they are able to settle and successfully burrow into the sand without being displaced. As juveniles grow in size, they burrow deeper, become more physically able to withstand the pounding of waves, and migrate down the beach at c. 15 m per month (Redfearn 1974). The largest toheroa on Bluecliffs Beach and elsewhere are probably less vulnerable to dislodgement and the narrow vertical band (30–40 m) occupied by the adults at mid- to low-tide level suggests that the degree of submergence experienced at this level provides the optimal feeding regime. Small recruited toheroa high up the beach, however, have significantly less time to feed, and are more susceptible to damage from storms, crushing by vehicle/foot traffic, predation by birds, and desiccation.

Substrate changes and implications for toheroa on Bluecliffs Beach

The beach profile study on Bluecliffs Beach showed that over 8 years from 1997 to 2005 there was a net loss of sand, exposing gravel and cobble substrates, as well as a general erosion of the sand dunes. The proportions of fine and coarse sand combined tended to increase in summer and decrease in winter, presumably a result of winter storm events scouring and shifting sand offshore (see Table 1). This seasonal pattern was also observed during more intensive beach profile studies of Bluecliffs Beach (NIWA unpubl. data). Further, the sand substrate in places is a thin sheet overlying a basement of gravel and cobble sediment which is exposed periodically at varying locations on the beach. This exposure is most severe on either side of the Rowallan Burn where there is virtually no sand substrate from high to low water and accordingly toheroa are absent. As the sand dunes recede they tend to expose underlying cobble and gravel.

A series of aerial photos of Bluecliffs Beach taken in 1947 (New Zealand Aerial Mapping Ltd, Hastings. Photos references 1247/43, 44, and 45) show that there was no exposed gravel or cobble banks on Bluecliffs Beach at that time and the entire beach appeared to be homogeneous sand substrate. Anecdotal reports (Bob Street pers. comm.) indicate that significant loss of sand from Bluecliffs Beach occurred in the mid 1980s and this observation is supported by the reduction in survey area in 1985 as access to the western end of the beach became limited because of exposed rocks. The erosion of the beach over the last 20 years has reduced the habitat available to toheroa to the extent that now only c. 54% of the beach surface is fine/coarse sand. Historically, it appears to have been close to 100%, as it is on Oreti Beach (Beentjes et al. 2003; Beentjes & Gilbert 2006b).

Accretion of sediments at the west end of Te Waewae Bay occurred for at least 75 years until 1963, whereas over the same period the eastern end of the bay underwent erosion (Gibb 1978). The sediment load deposited by the Waiau River into Te Waewae Bay together with alongshore drift to the west contributed to maintaining the beach structure at the western end of Te Waewae Bay (Kirk & Shulmeister 1994). The outflow of the Waiau River into Te Waewae Bay was significantly reduced in 1972 when water was diverted through Manapouri Power Station into Deep Cove and the sediment load declined to c. 25% of the previous level (Kirk & Shulmeister 1994). Cranfield (1996) reviewed the impacts of the reduced flow from the Waiau on bivalve populations in Te Waewae Bay and suggested that a number of factors may have affected bivalve abundance and distribution. These factors included possible changes in nutrients, water circulation, salinity, surf zone, as well as loss of beach habitat from erosion, although Cranfield (1996) concluded that there was no evidence that the reduction in flow from the Waiau River had altered bivalve populations.

Toheroa are only found on wide dissipative beaches that have fine sand, essential to virtually all aspects of their ecology, and our analyses showed that toheroa on Bluecliffs Beach were more abundant on parts of the beach where fine sand dominates. As the upper beach becomes increasingly dominated by gravel and cobbles, juvenile toheroa are most adversely affected because they tend to occupy this zone at settlement. The distribution and abundance of toheroa on Bluecliffs Beach appear to be related to the ongoing erosion of the beach. Thus, the current low abundance of toheroa on Bluecliffs Beach is probably a result of the same environmental factors that are impacting populations throughout New Zealand, with the added problem of progressive habitat loss. We consider that this population is at risk of collapsing if the erosion continues.

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Appendix 1 Toheroa surveys of Bluecliffs Beach, New Zealand, from 1966 to 2005. Transect 1 begins at east end of the beach. All surveys funded by New Zealand Ministry of Fisheries except those marked. Adult and juvenile surveys included sieved transects, and adult surveys had no sieved transects.

Survey no.	Survey date	Survey design	Transects	Distance between transects (m)	Total distance (km)	Target size	Reference
1	May 1966	Systematic	1–35	321	11	adult	Street 1970
2	Dec 1966	Systematic	1–35	321	11	adult	Street 1970
3	Apr 1967	Systematic	1–35	321	11	adult	Street 1970
4	Nov 1967	Systematic	1–35	321	11	adult	Street 1970
5	Mar 1968	Systematic	1–35	321	11	adult	Street 1970
6	Dec 1968	Systematic	1–35	321	11	adult	Street 1970
7	Mar 1969	Systematic	1–35	321	11	adult	Street 1970
8	Nov 1969	Systematic	1–35	321	11	adult	Street 1970
9	Mar 1970	Systematic	1–35	321	11	adult	Street 1970
10	Oct 1970	Systematic	1–35	321	11	adult	Street 1972
11	Feb 1971	Systematic	1–35	321	11	adult	Street 1972
12	Dec 1971	Systematic	1–34	321	11	adult	undocumented
13	May 1972	Systematic	1–35	321	11	adult	undocumented
14	Jun 1973	Systematic	1–35	321	11	adult	undocumented
15	Mar 1974	Systematic	5–35	321	11	adult	undocumented
16	Oct 1974	Systematic	1–35	321	11	adult	undocumented
17	May 1975	Systematic	1–35	321	11	adult	undocumented
18	Jul 1976	Systematic	4–35	321	11	adult	undocumented
19	Jun 1977	Systematic	1–26	321	11	adult	undocumented
20	May 1978	Systematic	1–35	321	11	adult	undocumented
21	Oct 1978	Systematic	1–35	321	11	adult	undocumented
22	Apr 1979	Systematic	1–36	321	11	adult	undocumented
23	Mar 1980	Systematic	1–35	321	11	adult	undocumented
24	Nov 1980	Systematic	10–13	321	11	adult	undocumented
25	May 1981	Systematic	1–36	321	11	adult	undocumented
26	Jun 1982	Systematic	1–36	321	11	adult	undocumented
27	Feb 1984	Systematic	1–36	321	11	adult	undocumented
28	Jun 1985	Systematic	*1–19	321	6.1	adult	undocumented
29	Sep 1987	Systematic	5–19	321	6.1	adult	undocumented
30	Mar 1990	Systematic	5–19	330	5.3	adult	McKinnon & Olsen 1994
31‡	Mar 1997	Systematic	5–23	250	4.5	adult	undocumented
32‡	Jul 1997	Systematic	5–23	250	4.5	adult and juvenile	undocumented
33‡	Jan 1998	Systematic	5–23	250	4.5	adult	undocumented
34	Jan 1998	†Random stratified	40	variable	5.07	adult and juvenile	Carbines & Breen 1999
35‡	Aug 1998	Systematic	5–23	250	4.5	adult and juvenile	Beentjes & Carbines 2001
36‡	Feb 1999	Systematic	5–23	250	4.5	adult	Beentjes & Carbines 2001
37‡	Aug 1999	Systematic	5–23	250	4.5	adult and juvenile	Beentjes & Carbines 2001
38‡	Jan 2000	Systematic	5–23	250	4.5	adult	Beentjes & Carbines 2001
39‡	Jul 2000	Systematic	5–23	250	4.5	adult and juvenile	Beentjes & Carbines 2001
40‡	Feb 2001	Systematic	5–23	250	4.5	adult	Beentjes & Carbines 2001
41‡	Aug 2001	Systematic	5–23	250	4.5	adult and juvenile	Beentjes & Carbines 2001
42	Feb 2005	†Random stratified	47	variable	5.07	adult and juvenile	Beentjes & Gilbert 2006a

*West of transect 19 stones after this time, and western transects could no longer be surveyed.
†Transects were randomly allocated within strata and fell within systematic transects 5 to 23.
‡Meridian Energy surveys.