The distribution, abundance, and size of tuatua (*Paphies donacina*) on New Brighton Beach, Christchurch, in 2001

H. J. Cranfield
K. P. Michael
A. Dunn

NIWA
PO Box 14 901
Wellington

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EXECUTIVE SUMMARY

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The tuatua population of New Brighton Beach was surveyed in 2001 because of management concerns that recently increased recreational harvesting might compromise the sustainability of this important resource. The number, biomass, distribution, and length frequency of tuatua in the intertidal and subtidal beach were therefore investigated in a two-phase stratified random survey in March and April 2001. Tuatua were sieved from sand excavated from 0.5 m^2 quadrats intertidally by hand and subtidally by divers using a suction dredge.

The length of all tuatua captured was measured and the weight of each sample determined and these data were used to estimate biomass and the weighted length frequency of the tuatua population. The length-weight relationship of 126 tuatua spanning the size range of the population and the cumulative length frequency were used to generate the cumulative biomass with length. The relationship can be used to estimate the biomass of the population at any length limit.

No tuatua longer than 25 mm (the size group 2–25 mm is hereafter termed juveniles) occurred on the intertidal beach. The population of juveniles was estimated to be 22.53 million (95% C.I., 19.0–26.0 million). Mean density of juveniles was 36 m^{-2} (95% C.I., 30–42), and their biomass was 3.5 t (95% C.I., 2.8–4.2 t). These juveniles were largely concentrated along the upper boundary of the beach at mean high water. The highest densities were in the northern and a southern geographic stratum of the beach. The tuatua population on the subtidal beach was estimated to be 16.9 million (95% C.I., 15.1–18.7 million). Mean density of tuatua in the subtidal beach was 5.5 m^{-2} (95% C.I., 4.9–6.1), and their biomass was 855 t (95% C.I., 729–981 t). Although most of the subtidal tuatua were longer than 25 mm, 3.8 million juveniles (17% of the subtidal population) occurred in the subtidal beach, mainly in depths of 1–2 m. Large tuatua were mainly found in depths of 2–3 m and they were densest on the two southernmost geographic strata of the beach.

We used 60 mm as an arbitrary estimate of the minimum size of the tuatua harvested by recreational fishers. Tuatua above this size have a biomass of 835 t (95% C.I., 555–1128) and a population of 11.4 million. Assuming the tuatua population has been exploited over a long period (pre-European settlement), this could represent an estimate of average biomass. Making this assumption, we estimated the Maximum Constant Yield (MCY) at 150 t y^{-1}. This catch (if it had the same size frequency as the population in 2001) would consist of 2.01 million tuatua. With the bag limit of 150 tuatua this represents about 13 000 person days of fishing. With a bag limit of 50 tuatua this represents 40 000 person days of fishing. We estimated the Current Annual Yield (CAY) at 225 t y^{-1} in 2001. With the same assumptions, this catch would consist of 3.0 million tuatua and represent 20 000 person days of fishing with the bag limit of 150 tuatua, and 60 000 person days of fishing with a bag limit of 50 tuatua.

Scientific records suggest that the size of the tuatua population and its distribution with depth on New Brighton Beach have changed considerably over the last 50 years probably due to weather-driven habitat changes. The present mainly offshore distribution of tuatua at New Brighton results in only a small proportion of the population above harvestable size being accessible now to recreational fishers. Fishers would have had difficulty in harvesting the sustainable yield estimated in 2001. The large offshore population would suggest that any local depletion of accessible stocks would pose no threat to the sustainability of the total stock.

1. INTRODUCTION

1.1 Overview

The tuatua population of New Brighton Beach is the closest major shellfish population to Christchurch and has been fished by recreational and customary fishers for years. Fishing of this resource appears to have increased in recent years and local concern on how this might affect sustainability of the population led to this investigation. There is no information on the size of the current tuatua population or of the current recreational harvest on New Brighton Beach, nor the effect the present bag limit has on this take, nor the sustainability of the present take, nor what effect any reduction in bag limit would have on the recreational take.

This report reviews the fishery and describes the results of a two-phase stratified random survey in March and April 2001 that estimates the biomass, length frequency, and the distribution of tuatua on New Brighton Beach between high water and 5 m Chart Datum. The report discusses the physical and biological factors that appear to have affected tuatua density on the beach over the years. The survey results are used to estimate the sustainable yield for this population. We briefly discuss how this yield relates to the probable present harvest level and present distribution of stocks.

The objectives of this project were:

1. To estimate the population size (numbers) of *Paphies donacina* between New Brighton Pier and the Heathcote estuary channel in both subtidal and intertidal areas in 2000–2001, with a target c.v. of 20%.
2. To estimate the weighted length-frequency of the population
3. To describe variation in density of *P. donacina* over the survey area.

1.2 Description of the fishery

In the 1950s and 1960s large tuatua were accessible in the lower levels of the intertidal of South Brighton Beach (Dawson 1954, Fenwick & Ogilvie 2001) and were dense along the entire beach. Recreational fishers hand-gathered tuatua along the entire length of the beach (Fenwick & Ogilvie 2001). Today, large tuatua are accessible only to shore pickers in the upper levels of the subtidal beach and fishing effort is largely confined to the southern end of the beach at Heathcote Estuary (Fenwick & Ogilvie 2001, Canterbury Coast Care staff, pers. comm.). The 1996 national marine recreational fishing survey estimated 87 000 tuatua were landed in QMA 3 and this catch probably came mainly from Pegasus Bay (Bradford 1998). A local commercial crab fisher estimated that "there are people harvesting tuatua most days, particularly at the tip of the spit" (Fenwick & Ogilvie 2001). Assuming "people" means three to five fishers and "most days" equates to about 300 days a year and all fishers take the limit bag, then annual recreational catch could lie between 135 000 and 225 000 tuatua. This is slightly more than indicated by the recreational survey in 1996, but the same order of magnitude (but all these estimates are very uncertain).

Maori ceased fishing tuatua between the Waimakariri River in the north and Godley Head in the south in 1956 for food because of their cultural sensitivity to the proximity of the beach to the sewage output (albeit treated) from metropolitan Christchurch. Some tuatua are still caught for bait. Maori customary take of tuatua north of the closed area has been estimated at about 60 000 each year (local iwi sources).

1.3 Biology of tuatua

Two species of tuatua, *Paphies donacina* and *P. subtriangulata*, occur on New Zealand surf beaches but only *P. donacina* is found on New Brighton Beach and around Pegasus Bay. Both species of tuatua have been found on intertidal and subtidal parts of many these beaches and in central New Zealand the two species frequently occur on the same beaches (Cranfield et al. 1994a). Although both species settle as spat intertidally, on these beaches larger *P. donacina* occur only subtidally whereas larger *P. subtriangulata* occur on the lower intertidal and overlap with *P. donacina* in the upper subtidal (Cranfield et al. 1994a).

The sexes of *P. donacina* are separate, they are broadcast spawners, and larvae are probably planktonic for between 18 and 21 days before settlement. Larvae of the closely related *P. subtriangulata* are planktonic for 18–20 days at laboratory temperatures (Redfearn 1982) and larvae of the toheroa, *P. ventricosa*, for 21 days (Redfearn 1987). Recruitment of spat occurs across the entire intertidal zone according to McLachlan et al. (1996), but Fenwick (1999) found some spat subtidally within the depth distribution of adults. Recruitment of spat is highly variable between years and between beaches (McLachlan et al. 1996) and missing year classes in subtidal populations suggests that little or no recruitment may occur for several years on some beaches (Cranfield et al. 1994b, Haddon et al. 1996). Dawson (1954) analysed the age structure of intertidal tuatua populations around Pegasus Bay and concluded that missing year classes indicated that there were large interannual differences in recruitment between different sectors within this bay as well.

Growth is moderately rapid and length frequency data from Cloudy Bay (Cranfield et al. 1994a) suggest that tuatua tend to move offshore as they get larger. The maximum size *P. donacina* attains varies around New Zealand, with North Island populations reaching a smaller maximum (73–88 mm) than South Island populations (95–109 mm) (Cranfield et al. 1993). Growth of tuatua in Cloudy Bay, northeastern South Island has been estimated from an analysis of sequential length-frequency samples. The von Bertalanffy growth parameters k and L_∞, have been estimate as 0.33 y^{-1} and 94.1 mm respectively (Cranfield et al. 1996). Using estimates of maximum age of tuatua in this population, mortality (M) was estimated to lie between 0.35 and 0.45. These data and the growth rate were used in a yield per recruit analysis to estimate the reference fishing mortality $F_{0.1}$ (Cranfield et al. 1993). The estimate of $F_{0.1}$ has been used to estimate sustainable yields for subtidal populations of tuatua whose biomass had been estimated in dredge surveys (Cranfield et al. 1994b; 1994a)

1.4 Habitat of tuatua

Paphies donacina occurs on the east coast surf beaches of the South Island, the west coast surf beaches of North Island as far north as Wanganui, and the east coast beaches of the North Island as far north as Nuhaka, Hawke Bay (Cranfield et al. 1994b, McLachlan et al. 1996). On these beaches, most of the adult population is subtidal. The species is most abundant at depths of between 1 and 4 m, although it also can extend from the shallow subtidal to the lower intertidal of beaches (Cranfield et al. 1994b). Spat are most abundant on the intertidal beach along the high-water line (McLachlan et al. 1996).

The surf beach habitat is unique. On shallow-sloping sandy surf beaches, wave energy is typically dissipated within the seabed. Wave action pumps seawater through the fine well-sorted sand of the seabed (McLachlan & Turner 1994), where the algae and detritus are filtered out and converted to microbial, meiofaunal, and macrofaunal biomass within the sand (Brown & McLachlan 1990). Regenerated nutrients return to the sea from the interstitial water and support major blooms of surf diatoms in the surf zone. Tuatua are one of the species of surf clam that are adapted to life in the surf zone. These adaptations allow them to exploit the locally high production of algae, yet maintain themselves in this highly unstable environment (Brown & McLachlan 1990).

The intertidal and subtidal profile of surf beaches can be rapidly changed by storms. During calm conditions, wave action mobilises littoral sand, moving it inshore and building up the aerial and intertidal beach resulting in the profile of the beach becoming steeper. During storms, waves erode sand from the aerial and intertidal beach and transport it out to sea resulting in the profile of the intertidal and subtidal beach becoming flatter (Short & Wright 1983).

1.5 Pegasus Bay and New Brighton Beach

New Brighton Beach is the southern part of the continuous sandy shore that extends around the shoreline of the broadly crescent shaped Pegasus Bay. The coast of Pegasus Bay is in a state of long-term equilibrium (neither steadily growing nor steadily eroding (Kirk 1979)). As riverine sediment supply has dwindled over the last 150 years, littoral processes have become more important in supplying sediment to beaches (Allan et al. 1999). The shore at New Brighton Beach is presently advancing seaward at 2.4 m y^{-1} (Allan et al. 1999); most of the advance (an advance that has been occurring for only the last few years (Allan et al. 1999)) is the result of sand that has been mobilised from the immediate offshore zone being transported ashore (where it builds up on the upper shore) by the littoral processes driven by low wave regime of the present day lighter winds. The continuing mobilisation of offshore sand and its build up onshore from the offshore source, results in the gradient of the beach becoming steeper. Hydrographic surveys in 1998 and 1999 have shown the beach at New Brighton slopes moderately steeply (3°) to 2 m below Chart Datum (CD)[1] and the gradient lessens to 0.5° at 8 m (CD) (Allan et al. 1999), although in the past (during the more erosional regime of the stormier 1950s, 1960s, and 1970s) the profile of the beach has been much flatter (see Devine 1966, Kirk 1979).

Tuatua form a continuous band around Pegasus Bay from mid-tide to below 4 m. The more accessible intertidal stocks were surveyed in the 1950s (Dawson 1954) and in 1998 (Marsden (2000)) and both these surveys included New Brighton Beach. The stocks of subtidal tuatua in Pegasus Bay were surveyed in 1991 (Cranfield et al. 1994b); this survey did not sample New Brighton Beach. Fenwick (1999) sampled subtidal benthos along a transect extending from 3-18 m off New Brighton Beach in 1999.

Wind waves are predominantly from the northeast in summer and southeast in the winter (Brown 1976). These give rise to circulation cells that dominate water movement in the near-shore close to the beach and retain water within the surf zone (Blake 1964, Willyams 1980). However, when storm waves approached the shore obliquely (in both northerly and southerly directions) sustained long-shore drift occurred in the near-shore (Willyams 1980). Near-shore circulation cells are stable entities that retain inshore water within the surf zone (Winter 1983). This circulation is important in algal production and in retaining and concentrating pelagic tuatua larvae close to the beach before settlement, and plays an important role in maintaining regular recruitment.

During storms waves can mobilise sand of the seabed. At New Brighton, sand level has fluctuated by as much as 2.2 m along the beach profile out to a depth of 7 m during 6 months of observation. Six years of observation at Spencer Park found the profile fluctuated by 4.7 m (Allan et al. 1999). Such changes generally occur rapidly at the height of storms (Short & Wright 1983). Mobilisation of the seabed can result in localised high mortality among tuatua that have

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[1] In this report we follow the practice of Cranfield et al. (1994a) and use Chart Datum (CD) (the lowest low water spring tide depth as the reference zero depth). The geological reports quoted here use mean sea level (MSL), 1.5 m higher up the shore.

been eroded from the substrate and, through predisposing factors (low temperature, low salinity, or toxic algal poisoning), may be unable to re-bury before being swept ashore (e.g., Fenwick & Ogilvie 2001).

2. RESEARCH

2.1 Stock structure

Tuatua are unlikely to recruit to Pegasus Bay from larvae carried north in the Southland Current from populations north of Dunedin. Within Pegasus Bay, a counter-clockwise eddy of the Southland Current flows south along the shore and back out to sea (Dawson 1954, Brodie 1960). Most tuatua larvae in the bay will be retained in the stable circulation cells close inshore, but any swept from these will become entrained in this offshore eddy and probably retained within Pegasus Bay. Thus there is unlikely to be much genetic interchange with tuatua populations to the north. Tuatua are distributed continuously around Pegasus Bay and larval mixing within the bay should result in sufficient genetic interchange for these tuatua to be a single stock.

2.2 Surveys of tuatua on New Brighton Beach before 2001

Dawson (1954) sampled by sieving tuatua from sand in 0.04 m^2 quadrats excavated to a depth of 150 mm. Quadrats were sampled at 18 m intervals on transects between mean high water springs (MHWS) and mean low water springs (MLWS) (generally transects were 110–130 m long). Dawson established 54 transects 914 m apart along the entire length of Pegasus Bay from Sumner in the south to Double Corner in the north. He sampled 19 of these transects intensively at least once the 11 transects along New Brighton Beach at regular intervals throughout the study. He found the greatest densities of tuatua within the lower 37–55 m of transects, but found small tuatua were more common much higher up the beach. He estimated the mean length of all tuatua sampled and found a systematic trend from 25 mm at Amberley in the north to 52 mm in the south at New Brighton. From his intertidal sampling, He estimated the adult tuatua population in Pegasus Bay in 1954 was about 1770 million. Dawson reported density and mean size of tuatua in his quadrat samples along a transect just south of the New Brighton Pier in 1952 and 1953. Tuatua of a mean length of about 50 mm occurred at densities of between 1850 and 3500 m^{-2} in stations on the lower part of the beach, within the 50 m band of beach above MLWS (Dawson 1954).

Marsden (2000) used a stratified block design to investigate spatial variation of the tuatua population and recently settled juveniles at 11 sites between Waikuku and Taylors Mistake. She found that random sampling led to her excavating most quadrats without finding any tuatua at all, and therefore adopted an adaptive sampling method that focussed on sampling areas of uniform beach profile where the presence of tuatua was shown by tufts of hydroids growing on their shell (the anterior portion of tuatua shells can project above the substratum and so can become fouled by hydroids). At each site within a block, she estimated density indirectly from numbers of tufts of hydroids in 10 random 5 m sections of shoreline located at least 10 m apart. She then corrected for tuatua without hydroids by hand searching a 0.0625 m^2 area around the tuatua revealed by tufts of hydroids. Marsden sampled spat in six randomly selected stations at the same site. She took 105 mm diameter core samples (sample area, 0.0087 m^2) to a depth of 100 mm and separated the tuatua spat from the sand on a 0.5 mm sieve in the laboratory.

Marsden effectively sampled only the lower 10 to 15 m of the intertidal so her results are not comparable with Dawson's. Her sampling did cover most of the high-density area of tuatua in the intertidal, but if areally expanded, would underestimate the biomass of intertidal tuatua. She found the same pattern as Dawson of increasing mean size of tuatua from north to south in Pegasus Bay. She established that density of tuatua increased to the south of Pegasus Bay, but could not estimate population size from her data. She was able to estimate the density and biomass of tuatua in the area of beach that she sampled, but gave no estimate of variance. At New Brighton mean tuatua density was 1.1 m^{-2} and mean biomass was 53.9 g m^{-2}. Density per linear metre of beach here was 12.3 m^{-1} and biomass per linear metre of beach was 663.6 g m^{-1}. At South New Brighton, the same measures were lower. Density was 0.32 m^{-2} and biomass was 21.5 g m^{-2} at South New Brighton. Density per linear metre of beach here was 3.15 m^{-1} and biomass per linear metre of beach was 215.2 g m^{-1}. Mean sizes of spat sampled in Pegasus Bay between January and March 1998 ranged from 2.2 to 3.1 mm and density of spat at New Brighton ranged from 81 to 1200 m^{-2}.

Cranfield et al. (1994b) surveyed the biomass and distribution of subtidal surf clams in the surf zone of Pegasus Bay. They divided the bay at the major rivers (Waimakariri and Ashley) into three sections in each of which the beach profile was uniform and randomly chose a 450 m wide strip of each of the three sections to sample surf clams. They estimated the biomass of each species of surf clam in this strip from 1 m to 10 m in a stratified random survey using a hydraulic dredge. The bathymetry of each strip was mapped from 10 depth-corrected bathymetric profiles made normal to the beach. Vessel position was determined by Differential GPS, depth below CD was determined from integrated echo-soundings, and depth strata mapped and areas determined in the survey software, HYDRO. Three randomly determined 50 m tows were made with a 0.80 m-wide hydraulic dredge (see Cranfield et al. 1994a) in the depth strata: 1–2, 2–3, 3–4, 4–5, 5–6 and 6–10 m. Because the beach along the southern section of Pegasus Bay was uniform, the biomass and distribution of tuatua at the randomly chosen section sampled at Spencer Park was unlikely to have been different from that at New Brighton. The mean biomass of tuatua over the whole area of the subtidal beach sampled at Spencer Park in 1991 was 157 g m^{-2} and biomass of tuatua per linear metre of beach was 48 kg m^{-1} (c.v. for the total surf clam biomass estimated here was 18%, Cranfield et al. 1994b). Marsden sampled the biomass of tuatua along the intertidal beach at the same site in 1998 and found the mean biomass was 2.30 g m^{-2} and mean biomass per linear metre of beach was 0.011 kg m^{-1}.

3. AREA AND METHODS

3.1 New Brighton Beach

New Brighton Beach extends from the New Brighton Pier to the Heathcote Estuary channel 6.4 km to the south (Figure 1). In this report we term the smallest tuatua we caught (2–25 mm long) juveniles.

The subtidal population of larger *P. donacina* at Spencer Park, 8.8 km north of New Brighton Pier, was estimated in 1991 (the dredge did not retain juveniles less than 20 mm long (Cranfield et al. 1994a). Biomass of tuatua per linear metre of the beach was estimated to be 48 kg. The intertidal beach with adult tuatua surveyed in 1998 was narrow (5 m) and had very low densities and biomass of adult tuatua: 0.66 tuatua per linear metre of the beach and a biomass of 0.012 kg per linear metre of beach (Marsden 2000). Spatfall was low on the intertidal beach here in 1998 (about 23 juveniles m^{-2}). However, Marsden (2000) sampled only the lower portion of the intertidal beach whereas most tuatua spat settle along the high water line (McLachlan et al. 1996) so spatfall was likely to have been much higher. The biomass of tuatua in the intertidal was less than 1% of that found subtidally on this beach seven years earlier. The survey of New Brighton Beach in 2001 therefore sampled the tuatua population on the subtidal beach as well as intertidal beach.

Tuatua recruit sporadically and mainly intertidally on New Zealand beaches (McLachlan et al. 1996). Comprehensive sampling of tuatua, particularly the smaller sizes, throughout the entire depth range of tuatua distribution is important in developing an understanding of the recruitment process in this species. The distribution of tuatua differed in the intertidal and subtidal beach and the habitats required use of different sampling techniques. We therefore decided to estimate the population numbers for the intertidal and subtidal separately. This approach had the additional benefit of allowing us to estimate the distribution of juveniles better, as well as enabling us to spread sample locations along and down the beach more regularly, which was advantageous in estimating the spatial variation of tuatua density.

We followed a stratified random sampling design to estimate the population with a variance of 20% c.v. Individual species of surf clams (including tuatua) are distributed in distinct depth zones, reaching the highest density in the centre of the zone (Cranfield et al. 1994a, 1994b). As depth was the greatest source of variation in tuatua density we stratified primarily by depth. Depth contours along surf beaches parallel the shoreline closely, so we stratified the subtidal beach out to the limit of tuatua distribution (5 m) in five equal-width strips parallel to the shoreline. We stratified the intertidal beach in four equal-width strips also parallel to the shoreline.

The next greatest source of variation in surf clam numbers is caused by changes of topography, sediment grain size change, and riverine input of freshwater, nutrients, or sediment along the shore Cranfield et al. 1994b). We therefore subdivided the beach into four strata normal to the shoreline to encompass such variations. We term these geographic strata. The intertidal beach was stratified into a total of 16 strata made up of a rectangular grid of four by four, and the subtidal beach was stratified into a total of 20 strata made up of a rectangular grid of five by four.

Fenwick (1999) recorded juvenile tuatua subtidally off New Brighton Beach, an area that we thought was likely to be dominated by adults (Cranfield et al. 1994b). Both Marsden (2000) and Dawson (1954) reported numerous adult tuatua in the intertidal which we also knew was dominated by juveniles (McLachlan et al. 1996). Because both regions of the beach could potentially have both juvenile and adult animals, they required sampling and sieving methods that would capture both adults and the smallest juvenile tuatua. We determined that a sample size of 0.5 m^2 would capture sufficient adult tuatua to estimate length-frequency distributions without requiring us to sub-sample spat where they occurred in high densities.

3.2 Estimating abundance of tuatua

For the stratified random sampling design, we estimate abundance and variance of tuatua for the subtidal and intertidal areas from standard theory (Raj 1968, Jolly & Hampton 1990). The sample mean $\overline{x}_s$ from a stratified random sampling design is calculated as

$$\overline{x}_s = \sum_{i=1}^{L} \frac{A_i \overline{x}_i}{A}, \text{ where } \overline{x}_i \text{ is the mean density in area } A_i \text{ for strata } i = 1,..,L$$

which has variance

$$\mathrm{Var}[\overline{x}_s] = \frac{\sum_{i=1}^{L} A_i^2 \mathrm{Var}[\overline{x}_i]}{A^2}, \text{ where}$$

$$\mathrm{Var}[\overline{x}_i] = \frac{\sum_{j=1}^{n_i} (x_{ij} - \overline{x}_i)^2}{n_i^2 (n_i - 1)} \text{ for the } j^{th} \text{ sample in stratum } i.$$

Intertidal survey

The intertidal survey area was defined using satellite-derived DGPS navigation (OMNISTAR Dodici receiver) and HYDRO navigation software on a PC. The upper and lower boundaries of the intertidal beach were determined at high and low water springs carrying this system in a 4-wheel drive vehicle. The remaining soft substrate area around the estuary was surveyed on foot with the equipment on a backpack. The intertidal beach was 6.4 km long and about 90 m wide over most of the beach, but about 150 m at the southern end. The beach was divided in to four narrow strata parallel to the shoreline and four geographic strata normal to the shoreline. sectors with boundaries at the New Brighton pier, Bridge, Caspian, and Turn Streets, and the Heathcote Estuary (Figure 1). We obtained too little information on the distribution of tuatua from recreational and customary fishers to enable us to stratify the intertidal area based on tuatua density (see Fenwick & Ogilvie 2001). We designated the boundaries of the geographic strata on habitat criteria. Strata 1 and 2 (Figure 1) divided the long homogeneous length of beach to the north from New Brighton Pier to Caspian Street at Bridge Street. The beach between Caspian Street and Turn Street is stratum 3 and is separated from the Heathcote Estuary by a narrow spit through which estuarine water can readily percolate, so the beach sand contains more interstitial water. The soft estuary channel area where the beach was much wider is stratum 4. Stratum 4 was characterised by sand bars that dried at low water leaving isolated pools of water in the troughs.

Because the depth strata were so narrow, we established a centre line along each one and determined sample stations at random distances along the stratum, and at random distances on either side of the stratum centre line. Random distances were derived from a table of random numbers. Both first- and second-phase stations were allocated in this manner. Sixty-four stations were sampled in the first phase of the survey and 26 in the second phase. The number of second phase stations allocated to each stratum was determined using the method of Francis (1984).

The intertidal survey was completed between 19 and 24 March 2001. Stations were located by distance from the stratum boundary and centre line using DGPS and marked with labelled stakes. A 0.5 m^2 galvanised steel quadrat was excavated with spades and hand trowels to a depth of 200 mm. The contents of the quadrats were put in to high-sided box sieves with 11 x 16 mm and 2.5 x 2.5 mm stainless steel mesh screens, and the sand washed through with seawater. These sieves retained tuatua spat 2 mm and longer and the visually controlled sampling resulted in all sizes of tuatua being sampled without bias.

Despite the calm surf throughout the survey, we experienced difficulty in sampling stations closest to the low water boundary (stratum 4). Swash from the surf inundated some quadrats during sampling, but in spite of this quadrat design and usage ensured that no tuatua were lost. The sides of the sampling quadrats penetrated the substrate below the 200 mm depth of sampling and projected above the water line; sediments could not cave-in, nor could tuatua wash out.

Subtidal survey

The subtidal survey began 3 weeks after the intertidal survey. No storms occurred between the intertidal and subtidal surveys so the beach profile remained the same for both surveys. The sea conditions throughout the subtidal survey were calm or moderately calm and thus the density estimates in both surveys are comparable and provide a continuous estimate of density from 5 m below CD to mean high water springs.

The NIWA research vessel *Rangatahi*, a 10 m catamaran, was used for the survey. The survey area was defined using DGPS navigation and HYDRO. Five transects were surveyed at high water from close inshore out to 5 m CD at the sector boundaries of the intertidal survey (New Brighton Pier, Bridge, Caspian and Turn Streets, and the Heathcote Estuary channel, Figure 1). Tidal height data were obtained from a NIWA tide model CASHCANZ. Depth data from these transects were corrected for tidal height to give depths below CD, and the 5-m depth contour charted between transects. Using these data the area was divided into five equally spaced strata from mean low water to 5 m CD with the same four geographic strata used in the intertidal survey also dividing the beach subtidally. The subtidal beach profile became shallower and the beach became wider to the south. This was especially marked in geographic stratum 4 where sand bars and channels extended well offshore. The sand here was softer and coarser and alongshore water movement was much higher with the water ebbing from the estuary.

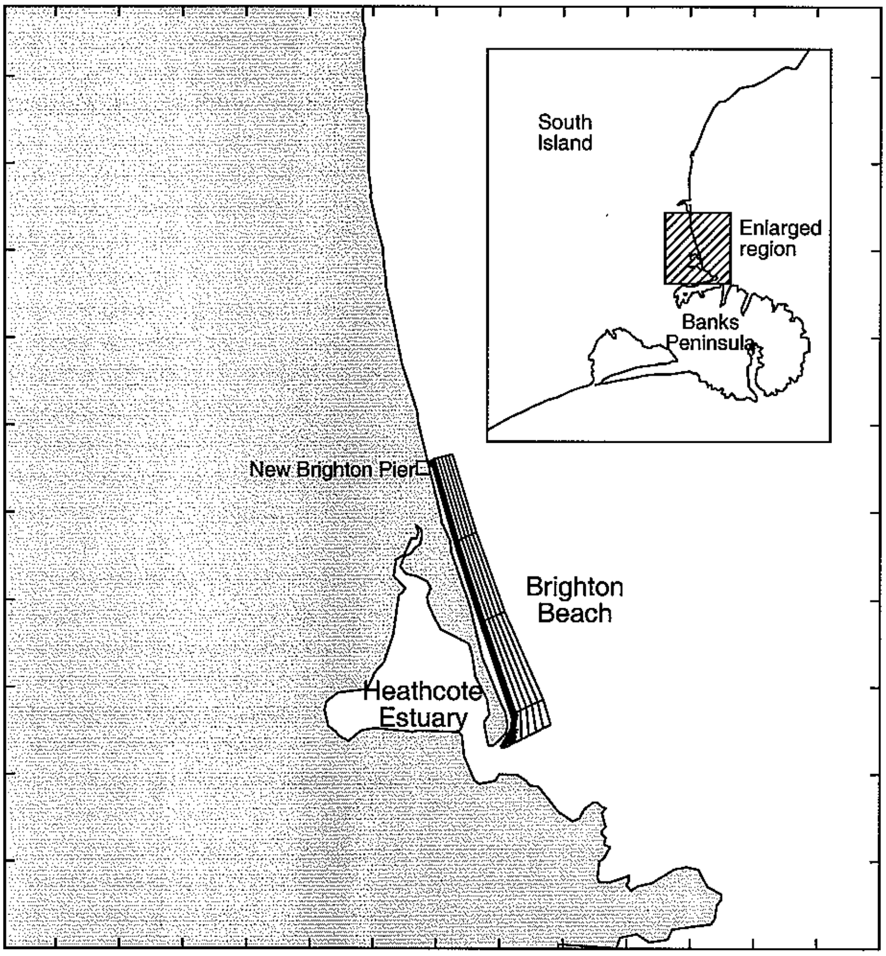

Figure 1: New Brighton beach showing stratum boundaries parallel to the shore reducing the effects of variation in tuatua density with depth on the population estimate and stratum boundaries normal to the shore reducing the effects of variation of tuatua density with changing habitat.

Survey stations were generated using PC based software RAND_STN and plotted on screen. Because the station positions were rounded to 0.1 of a minute of latitude and longitude, but plotted to 0.001, we used the plots to determine sample positions. We calculated the distance from stratum and sector boundaries, and positioned the vessel above each sample station using DGPS and HYDRO. We sampled 80 first-phase stations and 40 second-phase stations. The number of second phase stations allocated to each stratum was determined using the method of Francis (1984).

The survey of the subtidal beach was completed between 21 and 30 April. Sampling was carried out using an airlift sampler (see Michael et al. 1990) from the anchored vessel. Air was pumped down to an air induction chamber mounted above a heavily weighted 0.5 m^2 quadrat. Divers vacuumed out the substrate within the quadrat to a depth of 200 mm. The visibility was adequate for them to ensure that all the sand in the entire quadrat was vacuumed and that no tuatua were left behind in the quadrat. The sample was sucked up a hose by the rising air and delivered to a sealed box sieve on the surface. We used the same box sieves with the 11 x 16 mm and 2.5 x 2.5 mm mesh used to sieve intertidal samples. These sieves retained tuatua spat as small as 2 mm in length and the subtidal sampling being visually controlled by the divers resulted in all sizes of tuatua being sampled without bias. The sieve was retrieved when sampling was completed and the sample removed. The airlift sampler worked well as long as there was at least 0.5 m of water above the air induction chamber.

There was some swell even on calm days and we could not manoeuvre the vessel inshore to the stations in the shallowest stratum even at high tide. Thirty-five first-phase and second-phase stations were therefore sampled from the shore at low tide. Each station was located by measuring the distance along the shore from the sector boundary with the vehicles odometer and the distance from the low water mark paced off by divers. We were able to reach all stations using this method but still had to combat swash from the swell during sampling as in the intertidal survey. Divers placed a 0.5 m^2 sampling quadrat on the site and excavated the quadrat using plastic jugs to avoid damaging spat and prevent surf clams and sediment being washed away. The samples were filtered through a catch bag with 1.5 x 1.0 mm heavy-duty nylon mesh.

3.3 Weight and length measurements

All surf clams sieved at each station were bagged and labelled with the station number on site. Back at the laboratory all individuals were counted, and the length of all individuals measured (length is the longest shell dimension measured along the anterior/posterior axis) with vernier callipers to the nearest 1 mm (rounded downwards).

Each sample from the intertidal survey was weighed to the nearest 0.001 g (rounded downwards), and each sample from the subtidal survey was weighed to the nearest 0.1 g (rounded downwards). The mean biomass per square metre in each stratum was weighted by the stratum area and summed over all strata to estimate total biomass.

The length measurements were used to generate length frequencies for each stratum and weighted by the stratum area and summed over all strata to estimate the weighted length frequencies of intertidal and subtidal tuatua.

One hundred and twenty-six tuatua covering the size range from 2 to 98 mm in length were measured to the nearest 1 mm (rounded downwards) and weighed to the nearest 0.001 g to estimate the relationship between length and weight in this species. We estimated the length weight/relationship in the form $w = al^b$, where w = weight in grams, l = length in centimetres.

The data were fitted using a normal linear regression of log(weight) and log(length). i.e., $\log(w) \sim \log(a) + b\log(l) + \varepsilon, \varepsilon \sim N(0, \sigma^2)$. This relationship and the cumulative length frequency were used to estimate the cumulative biomass at length.

4. RESULTS

4.1 Abundance

We found only juvenile tuatua intertidally. We estimated the population of juveniles along the 6.4 km of intertidal beach to be 22.53 million with a c.v. of 8%. Mean density of juvenile tuatua was 36 m^{-2} (Table 1a).

We found both juvenile and adult tuatua subtidally. We estimated the population of subtidal tuatua along the 6.4 km of the beach to be 16.92 million tuatua with a c.v. of 5%. Mean density of tuatua was 5.5 m^{-2} (Table 1b).

4.2 The estimated distribution of tuatua

We smoothed the surface plots using an algorithm based on a Generalised Additive Model (GAM) with degree-2 loess fits (Cleveland & Devlin 1988). The plots are estimated density of tuatua (m^{-2}, Figure 2a), and biomass of tuatua (kg m^{-2}, Figure 2b).

4.3 Estimated length-frequency of tuatua

The weighted length-frequency of *P. donacina* is shown in Figures 3a and 3b. Only juvenile tuatua were found intertidally and they were largely concentrated at the top of the beach along the mean high water mark (Figure 3a). Adult tuatua were confined to the subtidal beach, but some juveniles occurred there too (Figure 3b).

The cumulative length-frequencies of the intertidal and subtidal populations of tuatua are shown in Figure 4. About 17% of the juvenile population occurred in the subtidal and both confirms the findings of McLachlan et al. (1996) who found spat of *P. donacina* predominated in the upper levels of the intertidal beach and Fenwick (1999) who found spat also occurred subtidally at New Brighton.

As recreational fishers were not able to give any guidance on the lowest size at which they harvested tuatua, we have estimated total biomass at length using the cumulative length frequency relationship (Figure 6), so the total biomass above any length selected for recreational harvest can be estimated.

4.4 Estimation of sustainable yield

The biomass of tuatua over 60 mm long (selected by the authors as a likely size of harvest by recreational fishers) on New Brighton Beach from Figure 8 was 835 t. The size of the tuatua population above 60 mm in the subtidal beach from Figure 6 was 11.44 million.

The estimates of recreational harvest of tuatua from New Brighton Beach have not been validated. Furthermore, we have no historical information on how long tuatua have been harvested from this beach by customary or recreational fishers. Customary fishing has probably been pursued on this beach for some centuries, so the present biomass could be assumed to represent the average biomass (B_{av}) of a developed fishery. Using method 2 of Annala et al. (2001), the Maximum Constant Yield (*MCY*) can be estimated:

$$MCY = 0.5F_{0.1}B_{av}$$

As the maximum size of *P. donacina* at New Brighton Beach is similar to that at Cloudy Bay, we use the estimate of $F_{0.1}$ from there (Cranfield et al. 1993) to estimate *MCY* at New Brighton Beach:

$$\begin{aligned} MCY &= 0.5*0.36*835 \text{ t} \\ &= 150 \text{ t} \end{aligned}$$

Using the proportion of total biomass to numbers of tuatua longer than 60 mm, this equates to 2.01 million tuatua. With a daily bag limit of 150 tuatua this represents about 13 000 person days of recreational fishing. With a daily bag limit of 50 tuatua this represent about 40 000 person days of recreational fishing.

The risk to the stock of harvesting at the estimated *MCY* cannot be determined.

Where estimates of current biomass are available, a Current Annual Yield (*CAY*) strategy may be more appropriate for managing tuatua populations.

We estimate *CAY* using the estimate of current biomass and the estimate of $F_{0.1}$ from Cloudy Bay. With fishing mortality spread throughout the year, method 1 of Annala et al. (2001) has been followed:

$$\begin{aligned} CAY &= \frac{F_{ref}}{F_{ref}+M}\left(1-e^{-(F_{ref}+M)}\right)B_{beg} \\ &= \frac{0.36}{0.36+0.25}\left(1-e^{-(0.36+0.25)}\right)835 \\ &= 225.0 \text{ t} \end{aligned}$$

Using the proportion of total biomass to numbers of tuatua longer than 60 mm, this equates to 3.01 million tuatua. With a daily bag limit of 150 tuatua this represents about 20 000 person days of recreational fishing. With a daily bag limit of 50 tuatua this represents about 60 000 person days of recreational fishing.

The risk to the stock of harvesting at the estimated *CAY* cannot be determined.

4.5 Estimated length/weight relationship of tuatua

The length/weight relationship shown in Figure 5 was estimated as $a = 0.129$, and $b = 2.967$:

Table 1a: Estimated numbers (thousands), biomass (kg) , mean density (numbers m^{-2}), and estimated c.v. of intertidal tuatua, New Brighton Beach, March 2001.

Stratum	N	Estimated number (95% C.I.s)		Estimated biomass (95% C.I.s)		Mean density	c.v.
11	4	1 676	(621–2 731)	91.9	(24.7–159.0)	41.0	0.32
12	4	2 271	(1 433–3 109)	177	(95.9–258.0)	59.0	0.19
13	4	608	(478–738)	9.6	(7.5–11.7)	16.5	0.11
14	4	219	(133–306)	19.4	(5.2–33.5)	5.5	0.20
21	4	1 218	(873–1562)	76.9	(46.6–107.2)	27.5	0.14
22	4	357	(198–515)	7.2	(4.1–10.2)	8.5	0.23
23	4	434	(284–584)	30.7	(5.0–56.4)	11.0	0.18
24	4	255	(165–344)	32.1	(6.9–57.3)	6.0	0.18
31	20	5 689	(4 598–6 780)	892.9	(731.7–1 054.2)	112.0	0.10
32	4	3 506	(2 061–4 951)	1124.1	(580.9–1 667.2)	66.0	0.21
33	4	545	(372–718)	46.4	(13.0–79.8)	10.5	0.16
34	4	320	(274–366)	113.3	(10.3–216.3)	6.5	0.07
41	4	4 736	(2 126–7 346)	683.2	(338.2–1 028.1)	238.5	0.28
42	4	391	(217–565)	46.2	(31.8–60.5)	16.0	0.23
43	4	69	(55–82)	1.9	(1.4–2.5)	2.5	0.10
44	4	244	(132–357)	145.1	(75.1–215.1)	10.0	0.23
Total	80	22 537	(19 047-26 027)	3497.8	(2 812.0–4 183.6)	36.0	0.08

Table 1b: Estimated numbers (thousands), biomass (kg) , mean density (numbers m^{-2}), and estimated c.v. of subtidal tuatua, New Brighton Beach, April 2001.

Strata	n	Estimated number (95% C.I.s)		Estimated biomass (95% C.I.s)		Mean density	c.v.
11	4	201	(4–399)	114	(2–225)	1.5	0.50
12	10	862	(737–986)	9 740	(6 889–12 590)	6.0	0.07
13	4	212	(4–419)	13 786	(275–27 297)	1.5	0.50
14	4	0	–	0	–	0	–
15	4	0	–	0	–	0	–
21	6	1 422	(667–2 176)	6 469	(2 821—10 117)	9.3	0.27
22	4	401	(203–599)	9 687	(3 871–15 503)	2.5	0.25
23	4	160	(70–251)	11 625	(4 980–18 270)	1.0	0.29
24	4	0	–	0	–	0	–
25	4	0	–	0	–	0	–
31	22	3 450	(3 133–3 768)	163 321	(140 351–186 292)	15.5	0.05
32	10	3 665	(2 637–4 693)	250 627	(181 295–319 960)	15.8	0.14
33	4	115	(2–229)	6 523	(130–12 916)	0.5	0.50
34	4	118	(2–233)	10 853	(217.1–21 490.8)	0.5	0.50
35	4	115	(2–227)	12 316	(246–24 386)	0.5	0.50
41	5	2 169	(1 373–2 965)	121 506	(45 279–197 733)	26.8	0.19
42	4	1 161	(415–1 906)	78 858	(19 460–138 256)	13.5	0.33
43	11	2 356	(2 031–2 682)	124 875	(108 641–141 110)	27.6	0.07
44	4	510	(265–755)	34 859	(14 800–54 918)	6.0	0.25
45	4	0	–	0	–	0	–
Total	120	16 917	(15 110–18 724)	855 166	(728 988–981 344)	5.5	0.05

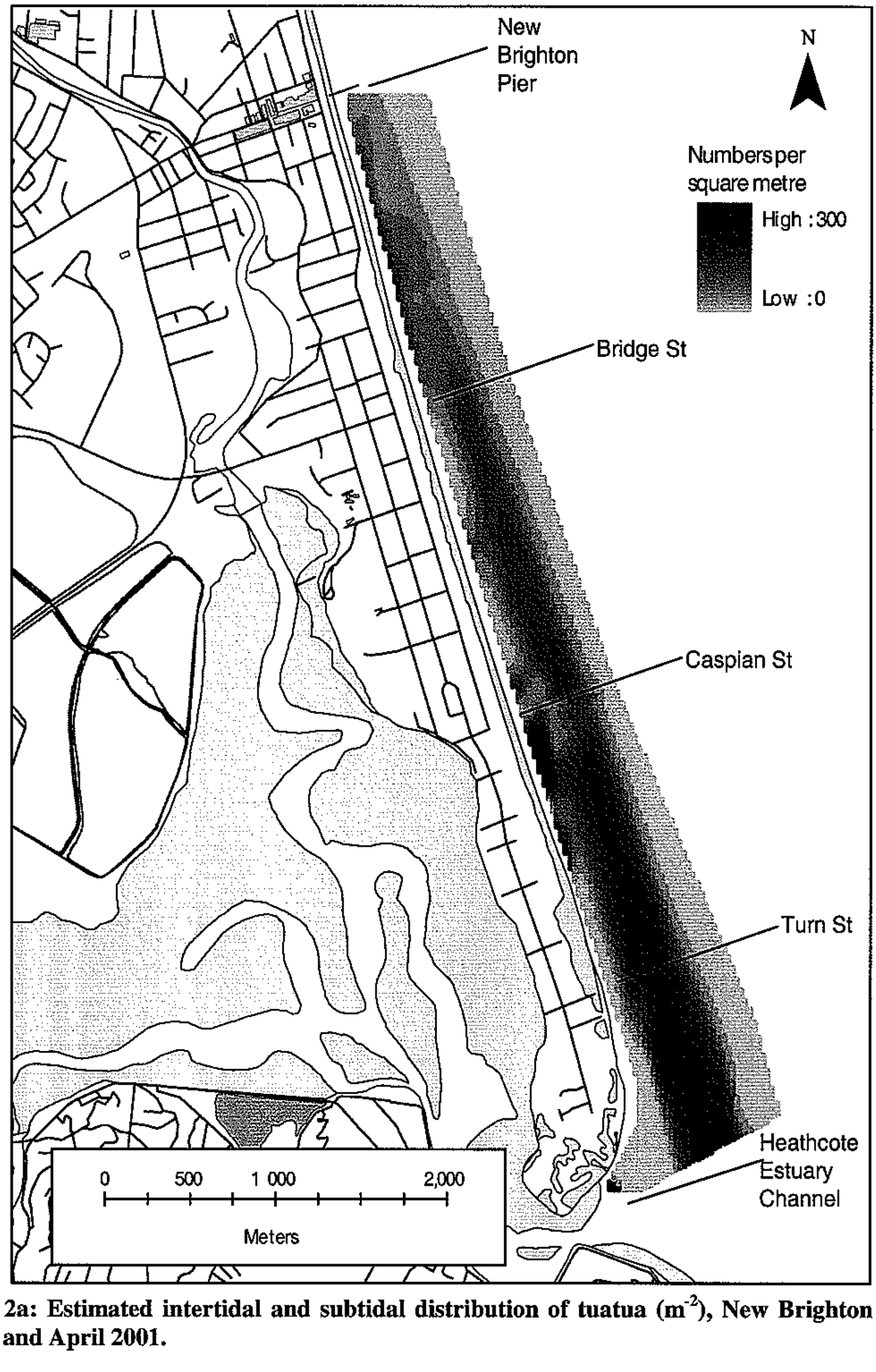

Figure 2a: Estimated intertidal and subtidal distribution of tuatua (m^{-2}), New Brighton Beach, March and April 2001.

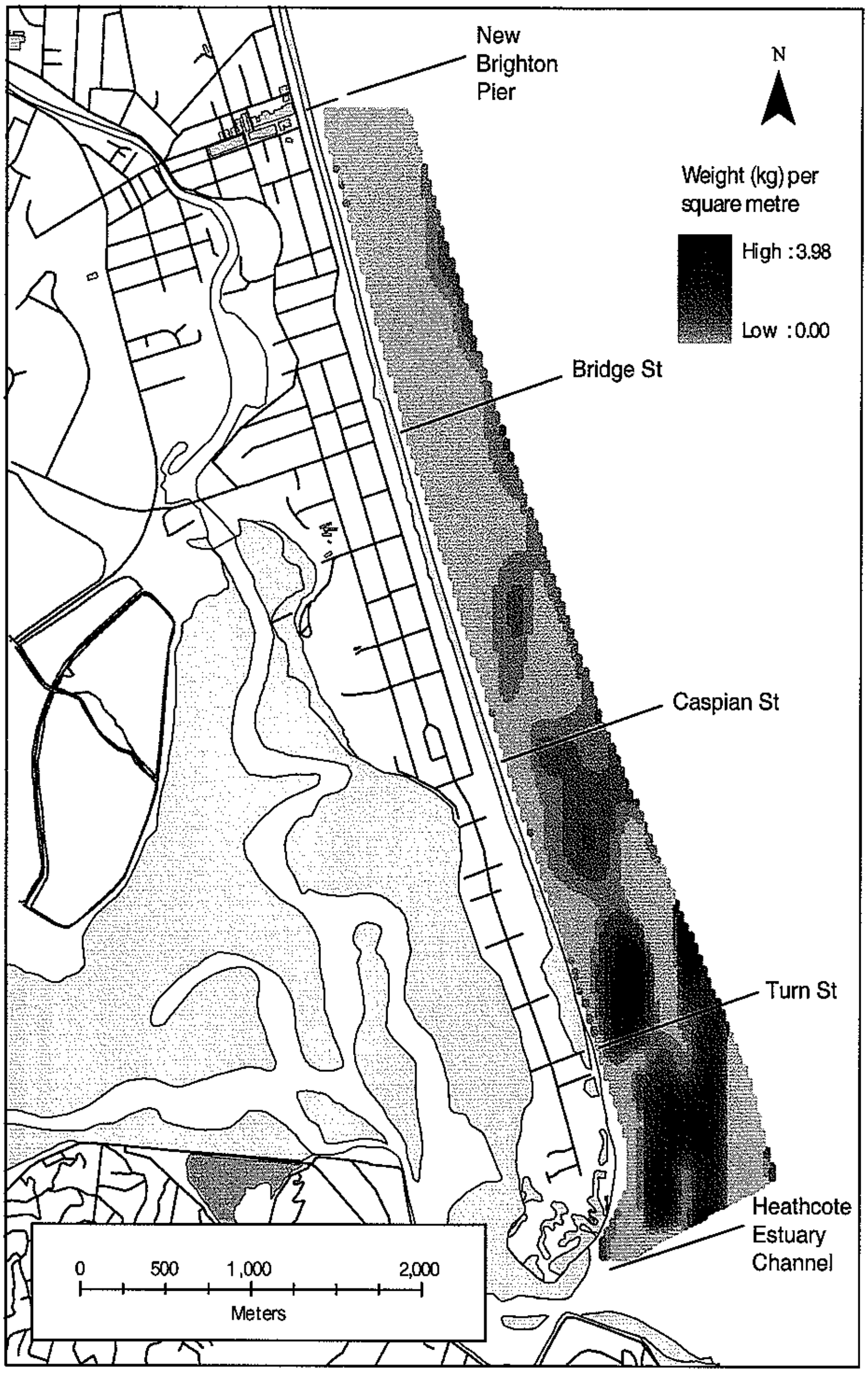

Figure 2b: Estimated intertidal and subtidal distribution of tuatua biomass (kg m^{-2}), New Brighton Beach, March and April 2001.

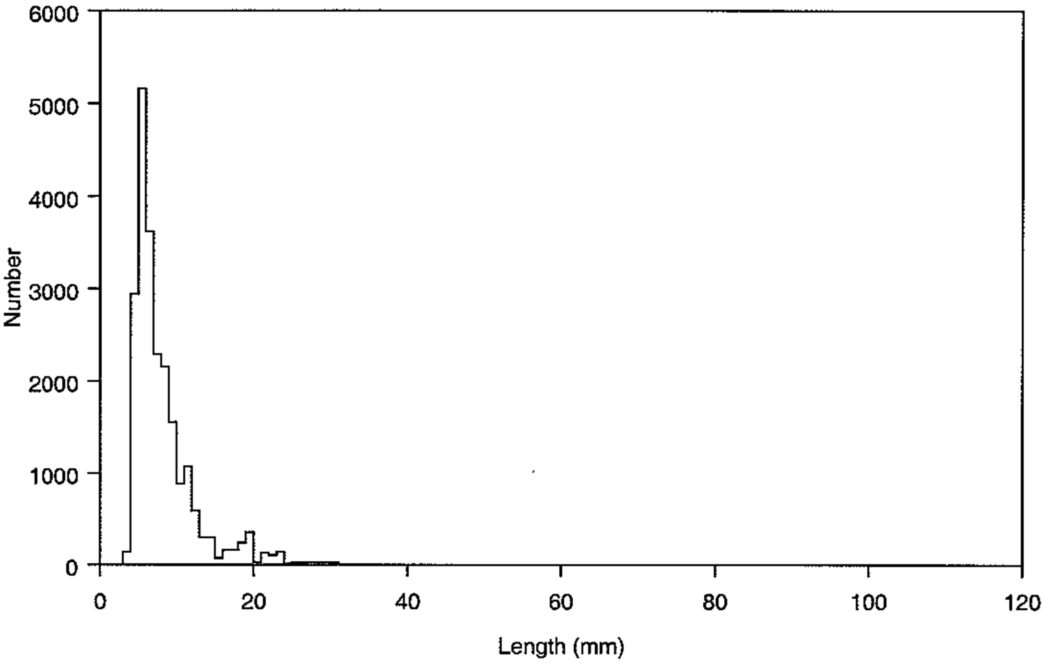

Figure 3a: Length-frequency of intertidal tuatua, New Brighton Beach, March 2001.

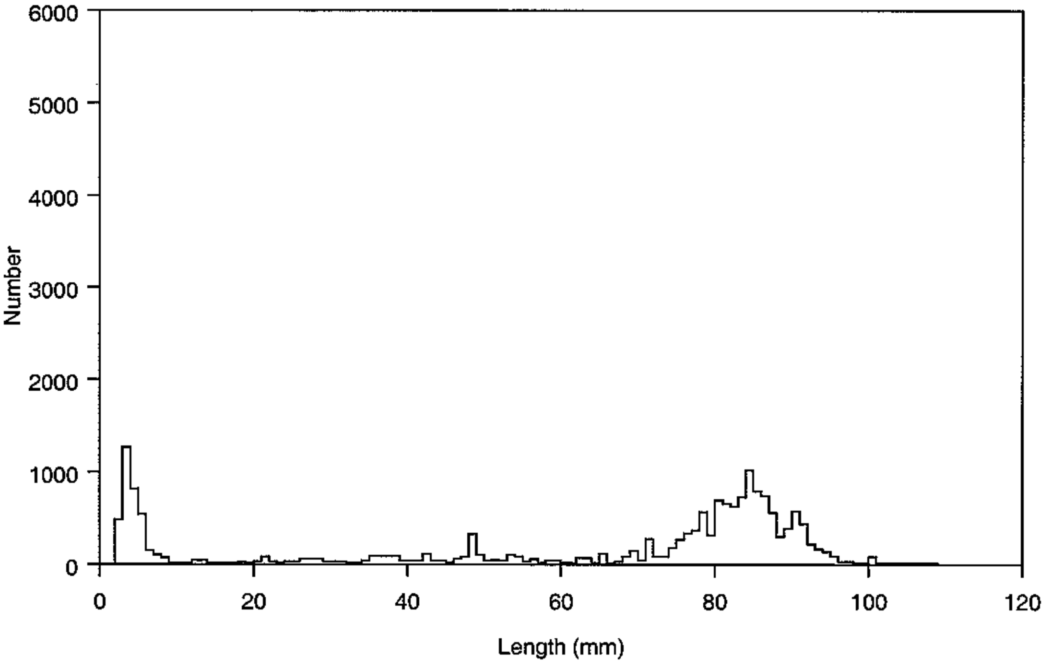

Figure 3b: Length-frequency of subtidal tuatua, New Brighton Beach, April 2001.

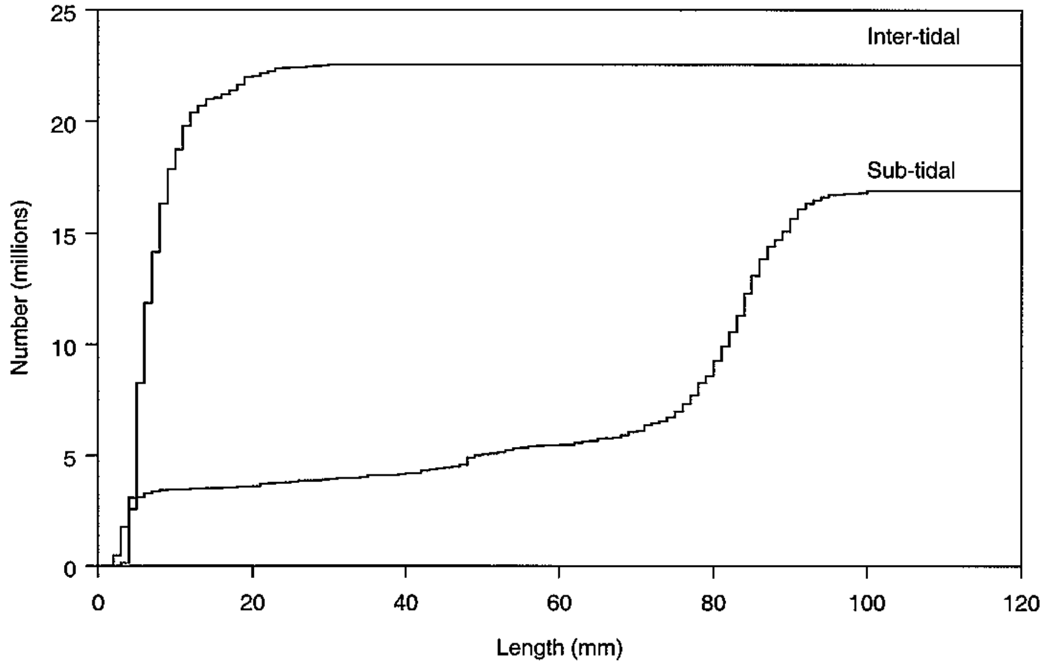

Figure 4: Cumulative length-frequency of populations of intertidal and subtidal tuatua, New Brighton Beach, March and April 2001.

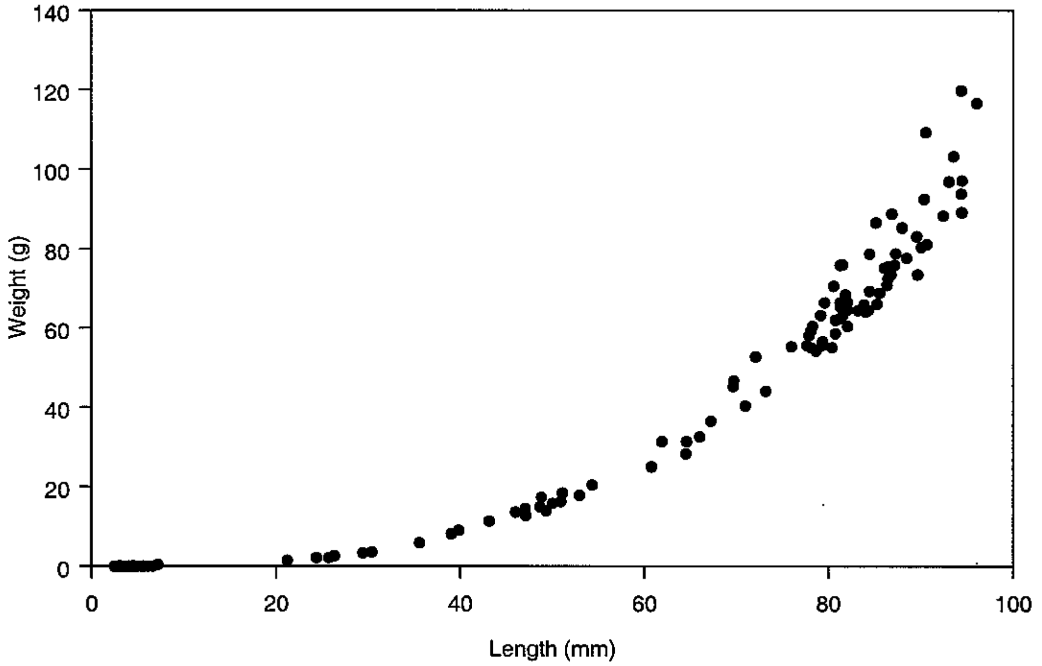

Figure 5: Length and weight of 126 *Paphies donacina* sampled intertidally and subtidally, New Brighton Beach, March and April 2001.

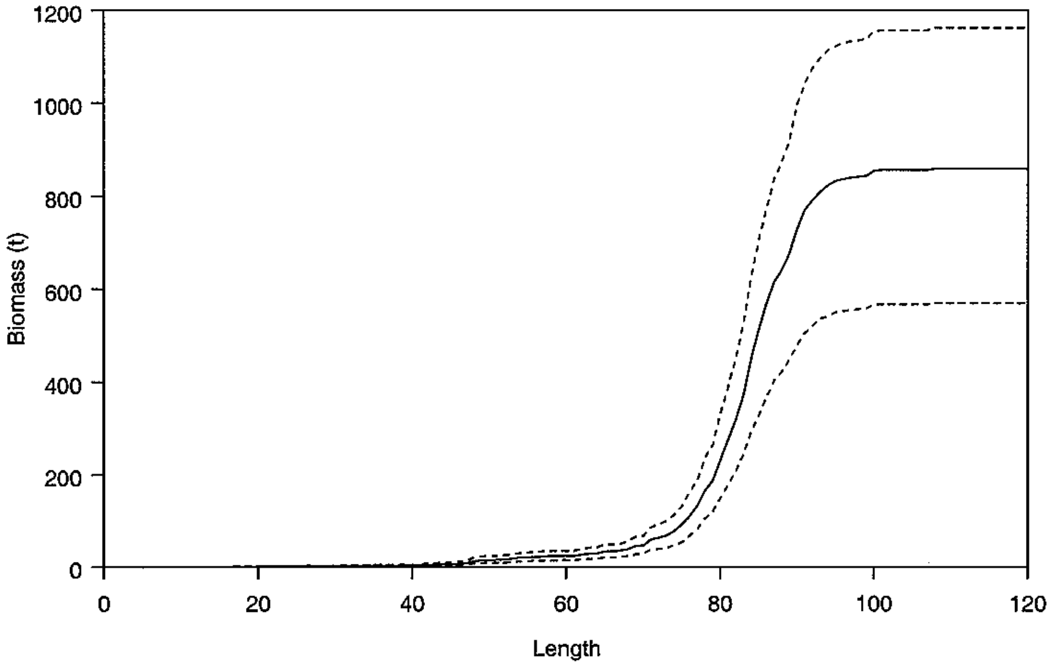

Figure 6: Cumulative biomass plotted against length of size groups of intertidal and subtidal *Paphies donacina*, New Brighton Beach, March and April, 2001. 95% coefficient interval (CI) shown by dotted lines.

5. DISCUSSION

Because the weight of all tuatua captured at each station was measured, we were able to extend the original objectives of the survey and estimate biomass and yield as well as population size. Because we estimated the length-weight relationship of tuatua on New Brighton Beach, biomass (and yield) can be estimated for the population fraction above any size designated as harvestable by fishers.

The surveys of the intertidal and subtidal population of tuatua estimated the population size with a much greater precision than the target c.v. of 20%. Earlier biomass surveys of subtidal beaches stratified in a similar manner to that used here, have sampled surf clams with a hydraulic dredge. The variability of dredge efficiency resulted in much less precise estimates of biomass and population size (Cranfield et al. 1994a, 1994b). The direct sampling employed here did not suffer this source of variation and sampling precision was visually verified by sampling personnel in both the subtidal and intertidal beach. The data indicate that the distribution of larger tuatua in the subtidal is more uniform than that of the juveniles in the intertidal. The greater variability in the fine scale distribution of juveniles reflected in the higher c.v. may be a reflection of the greater movement of these juveniles up and down and along the beach as waves cover their habitat at high water (McLachlan et al. 1996; c.f. also toheroa (Redfearn 1974)).

The changes in density and distribution of tuatua across the intertidal beach indicated by surveys in 1954, 1998 and 2001, suggest caution in placing too much reliance on the long-term stability the size of this population or the distribution of tuatua found in this first "snapshot" of the entire beach. For example, if we areally expand the mean density of adult tuatua that Dawson (1954) found in 1952–53 on the lower 60 m of the intertidal beach to the whole length of New Brighton Beach, the adult population then could have been 812 million. If density of tuatua increased to the south in 1953 as it did in 2001, then this extrapolation, based on a mean density close to New Brighton Pier in the north, will be very conservative. Furthermore, this estimate takes no account of subtidal tuatua. The evidence from around

New Zealand (Cranfield et al. 1994a) suggests that there may have been an equally large population of tuatua further offshore in 1953. Hence the total population of harvestable size on New Brighton Beach may have declined from between 800 and 1600 million in 1953 to the 11.44 million estimated in 2001.

Changes as substantial as this may reflect some significant change in the environment over this period. The nature of the intertidal beach differs between surveys and may indicate wave climate and/or current change. In 1953 the lower 60 m of the intertidal beach was very flat (less than 0° 30′. Dawson, pers comm.), remained wet at low water, and contained high densities of large tuatua. In 1962 the beach still had a similar profile with the lower 80 m of the intertidal beach being flat (0° 36′) and always remained wet at low water, but the upper intertidal was steeper (2° 18′) (Devine 1966). In 1998 Marsden found the beach was steeper and large tuatua occurred only in the lower 10 m of the intertidal beach. When surveyed in 2001, the intertidal beach was mostly narrow (90 m in the north and 150 at the estuary channel) and steep, possibly similar to the 3° found by Allan et al. (1999). These are the changes that Short & Wright (1983) predicted would happen during prolonged calm periods with the sublittoral sand being progressively moved inshore resulting in an increasingly steep beach and a prograding shoreline. Devine (1966) recorded such changes after a winter storm in 1992 removed almost half a metre of sand along a beach profile he was monitoring. The sand had rebuilt to almost the same level again by the middle of the following summer in the lower wave climate of summer.

A series of storms in the late 1970s resulted in considerable erosion of the beach (Kirk 1979) (and presumably resulted in flatter beach profiles), but the beach has aggraded in the following years. For the last 8 years the shoreline has been prograding on average 2.4 m y^{-1} (Allan et al. 1999), resulting in the whole intertidal beach becoming steeper and narrower. We do not know how such changes affect productivity of the beach, the stability of the beach, or how they interact with growth, mortality, and recruitment of tuatua to result in changes in population density and distribution. When Dawson (1954) surveyed New Brighton Beach he found very high densities close to New Brighton Pier where densities were very low in the present survey. A time series of abundance surveys including beach changes would enable better predictive modelling of tuatua populations.

Major storms are irregular events and can produce significant changes as they mobilise and transport large quantities of sand and change the profile of beaches. Evidence from Traditional Ecological Knowledge (TEK) and middens may help us understand how such changes influence tuatua density. Dawson (1997) referred to a Scarborough midden investigated by Haast in 1872 that indicated changes in tuatua densities over 600 years of occupation. These changes may reflect changes in tuatua density on the nearby Sumner Beach. Evidence from middens and TEK may nevertheless indicate broader changes in tuatua stocks around Pegasus Bay from the reduction in sediment supply to Pegasus Bay beaches that started 150 years ago (Allan et al. 1999).

Such environmental changes appear likely to have resulted in an almost 50-fold reduction in the size of the population. The life histories of tuatua and other surf clams are adapted to rapid resurgence of the population after storm driven changes in habitat (Cranfield et al. 1994a, McLachlan et al. 1996). The decrease in the population could be readily matched by a similar scale increase should the beach environment improve again. The present biomass could be considered to be an estimate of average biomass in a fluctuating environment. Recruitment can be great enough to allow resurgence of such populations regardless of the sources of mortality.

Recruitment of tuatua (and all surf clams) is highly variable both between beaches and even within beaches, and may account for different population structure and species composition over the years. A series of surveys over a period of years would show the effect of changes in recruitment on population structure and species composition. Inter-regional variation could be assessed if another local beach area were included in the survey. Future surveys could perhaps include Waikuku or Kairaki Beach populations as well (in consultation with Ngai Tahu). Some caution should be exercised in managing this fishery using the results of a model (that is used here) that assumes recruitment is regular and constant.

The spat of *P. donacina* in the high intertidal are especially vulnerable. This may contribute to variability of recruitment in this species. The high tide mark on New Brighton Beach (and other sandy beaches of New Zealand) is the area most favoured by vehicles driven along the beach. The weight of a vehicle alters the physical packing of the sand causing it to become dilatant instead of thixotropic (see Chapman 1949, Webb, 1969, McLachlan & Turner 1994). Tuatua spat are no longer able to dig in this physically altered sand can become desiccated and may die. The importance of such mortality could be assessed in studies of changes in spat density in the parts of the intertidal beach at New Brighton treated to different levels of vehicle compaction.

If the estimate of recreational harvest of 87 000 tuatua in QMA 3 by the 1996 log book scheme relates to landings from New Brighton Beach alone, then this recreational harvest is very small compared with the sustainable yields estimated here. If the slightly larger landings estimated from observations by Fenwick & Ogilvie (2001) are valid, it still represents a small proportion of the estimated yield. Beach cameras (beachcams) can provide a useful tool for monitoring both the amount and distribution of recreational harvesting of shellfish on beaches. Present recreational fishing is concentrated on the southern end of New Brighton Beach (outside the range of the beachcam on Brighton Pier) and would require a new camera to cover this southern area.

The present distribution of large tuatua, confined to the subtidal of New Brighton Beach, results in only a very small percentage of the population being vulnerable to harvesting. The present distribution is likely to be a response of tuatua to the slope of the beach and beach slope is the result of sand transport in the prevailing weather conditions. If moderate weather patterns prevail in the future (as they have done for the last 8 years), then the present tuatua distribution will probably remain stable. If New Brighton Beach is impacted by a series of southerly storms (as it was in the late 1970s (Kirk 1979, Allan et al. 1999)) tuatua distribution could change and a much greater proportion become vulnerable to recreational harvest intertidally.

If fishing is concentrated on a narrow strip of beach in the upper subtidal beach, tuatua could become depleted locally. However, there is some evidence that tuatua are quite mobile and individuals from the deeper water could therefore re-colonise harvested areas. For example, a commercial surf clam fisher has observed changes in the distribution of *P. donacina* both along and up and down the subtidal beach in Cloudy Bay. This indicates this species can emerge from the substrate to be transported up or down the beach by waves or along the beach in alongshore currents before digging in again. Alongshore currents occur in Pegasus Bay when storm swell approaches the shoreline obliquely (Willyams 1980). The closely related *Paphies ventricosa* have been observed elevating themselves from the substrate as the tide rises and allowing themselves to be carried up or down the beach in waves or across the beach in alongshore currents in the intertidal before reburying again.

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