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Intertidal shellfish population surveys in the Auckland region, 1998–99, and associated yield estimates

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This series documents the scientific basis for stock assessments and fisheries management advice in New Zealand. Its addresses the issues of the day in the current legislative context and in the time frames required. The documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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1. Executive Summary

Eight intertidal beaches in the greater Auckland area were surveyed in the 1998–99 fishing year to estimate population size structure and abundance of cockles (*Chione stutchburyi*) and pipi (*Paphies australis*). Cockle populations were sampled with higher precision than pipi populations, consistent with previous surveys. Population size structures varied, although recruitment events appeared to have occurred over most beaches. A notable exception was the Cheltenham Beach cockle population, which had zero recruitment, and contains a population of old large animals that are gradually declining in abundance in spite of a harvest closure since 1992. However, a recruitment of pipi, albeit a modest one, was present on Cheltenham Beach, the first detectable in at least five years.

For cockles, the historical time series (3–6 years) of surveys for three of the beachs (two exploited, Mill Bay and Okoromai Bay; and one closed, Eastern Beach) were analysed to estimate population parameters. Growth rates were variable across beaches (ranges k, 0.15–0.30; L_{∞}, 33.3–54.2). Mortality estimates were made where data of sufficient quality were available, resulting in estimates of Z for the exploited beaches and M for the closed beach.

Yield per recruit and current annual yield (CAY) were estimated for cockles for the three beaches. The 1997–98 recreational harvesting research programme found few pipi to be taken from the two open beaches (probably as a result of animals being too small) and potential yields were not estimated. $F_{0.1}$ was estimated as 0.43, 0.29, and 0.53, and F_{max} as 0.61, 0.42, and 0.74 for Eastern Beach, Mill Bay, and Okoromai Bay. However, these values were sensitive to the assumed value of M (base case 0.3, range 0.2–0.4).

CAY of cockles was estimated using the Baranov equation (assuming that catch is taken through the year) for $F_{0.1}$ and F_{max}, with the following respective yields: Eastern Beach, 0.11 t, 0.15 t: Mill Bay, 1.5 t, 2.0 t; Okoramai Bay, 31.2 t, 39.9 t.

2. Introduction

2.1 Overview

The intertidal shellfish resources of the greater Auckland area are percieved to be under heavy pressure from exploitation and other impacts, such as environmental degradation.

This report documents the latest in a series of surveys designed to monitor the abundance and population structure of recreationally harvested shellfish on intertidal shores. The focus is currently on two bivalve species, the cockle (*Austrovenus stutchburyi*) and the pipi (*Paphies australis*), in contrast to previous years, when a wider range of shellfish has been examined. Recent work on three of the beaches (Cornwallis Beach, Mill Bay, and Okoromai Bay) has shown that cockles dominate the intertidal shellfish catch taken by recreational pickers, with pipi being of little or no interest (Hartill & Cryer 1999). This may be a result of the generally small pipi on these beaches, in contrast to the larger sizes that pipi may reach in subtidal habitats.

For most of the eight beaches surveyed in the current programme there is a historical survey time series of 3–6 years, and it is possible to estimate growth, mortality, and recruitment variability for cockles and pipi. From these estimated population parameters within a yield-per-recruit model (YPR), reference values of $F_{0.1}$ and F_{max} can be calculated, incorporating recreational fisher selectivity values.

Estimates of yield for the various beach and species combinations may then be calculated under a CAY approach, using the Baranov equation.

2.2 Literature Review

Information on New Zealand and overseas cockle research was summarised by Cryer (1997).

Work on New Zealand pipi is limited and confined mainly to passing mention in general resource surveys. The species occurs throughout New Zealand, including the Chatham Islands and the Auckland Islands (Powell 1979), but is restricted in the habitats that it occupies to estuarine and harbour environments (Morton & Miller 1973). The most detailed work on pipi has been by Hooker (1995a), who studied population demography in Whangateau Harbour, a small estuary in northeastern New Zealand. He found a distinct segregation of animal sizes and ages with respect to habitat, with juvenile animals occurring high on intertidal shores and fully mature adult animals (over 40 mm shell length) occurring at high densities in subtidal beds in the main channel of the harbour. Intermediate sizes occurred between these habitats. Drifting behaviour of a range of animal sizes was documented, through mechanisms such as mucus bubble strings and attachment to passing objects (Hooker 1995b). Large scale movements prevented the separation of movement and mortality effects, so mortality was not estimated. Growth was not estimated, although examination of the graphs provided indicate that growth was fairly rapid. However, this system represented a subtidal, high current environment, and is not representative of all habitats of pipi populations, especially those on low energy, sheltered intertidal beaches (the intertidal being defined as all soft habitat areas above mean low water springs – MLWS).

3. Review of the fishery

3.1 Commercial fisheries

There are several commercial fisheries for cockles and pipi, but not on the beaches covered by the surveys described here. Information on commercial cockle fisheries was reviewed by Cryer (1997).

3.2 Non-commercial fisheries

Of the eight beaches surveyed in the 1998–99 fishing year (Figure 1), six are currently open to recreational harvesting (Beachlands, Cornwallis Beach, Howick Beach, Mill Bay, Okoromai Bay, and Umupuia Beach): Cheltenham Beach and Eastern Beach are closed through fishery regulations.

Fishing pressure is reported to be high on a number of Auckland's beaches. Total recreational take of cockles was estimated to be 2.21 million in QMA 1 in 1993–94: assuming a mean weight of 25 g (green weight), this implies a harvest of 55 t (O'Brien & Annala 1998).

Eastern and Cheltenham Beaches have been closed to all harvesting since 1994 and 1993 respectively.

4. Research

4.1 Estimates of growth and mortality rates, recruitment variability, and length weight

4.1.1. Estimates of growth and mortality

Beaches nominated for analysis this year were Beachlands, Eastern Beach, Mill Bay, and Okoramai Beach (as per the tender document).

All data from previous surveys were converted into scaled length frequencies for each beach/species combination. However, the historical data were poorly archived, and although all obvious errors were removed, it is likely that a number of errors remain undetected. In addition, data were missing from some year, species, and beach combinations, and despite extensive searching, appear to be lost. Time series extended from 3 to 6 years, depending on the beach.

MULTIFAN (Otter Research 1992) was used to derive estimates of K and L_∞ from the size frequency time series available. Because surveys were carried out at the same time each year (summer), seasonal growth effects were not included in the growth models. MULTIFAN uses raw length frequency data to generate population parameters, and assumes interannual stability in the timing of recruitment, growth rates, and mortality.

Data were binned into 2 mm size intervals for the Eastern Beach cockle analysis (before 1996 all shellfish were measured down to the nearest 2 mm even number).

For the 1997–98 and 1998–99 surveys, data were collected in a stratified random design, and there was potential bias as a result of more animals being measured from higher density strata (if density-dependent growth effects, or spatial gradients in size, were present). To correct for this, raw data were reweighted to represent what would have been measured had animals been taken randomly from across the beach. This was achieved by multiplying the total number of animals sampled (*n*) by the proportion-at-size taken from the scaled length frequency, for each 1 mm size increment, i.e.

$$n_{wi} = n_{tot} * prop\ (N_{toti})$$

where n_{wi} is the re-weighted number of animals measured per *i*th size class (2 mm increments), n_{tot} is the orginal number of animals measured, and $prop(N_{toti})$ is the proportion at size for the *i*th size class within the population scaled length frequency.

The significance procedure MULTIFAN (Sigtest) was used to select the most parsimonous fit to the data, given a systematic varying of the number of age classes present, and *k*.

Pipi growth and mortality rates could not be estimated for Okoramai Bay as few animals were found. For Beachlands cockle and pipi data, MULTIFAN could not find a realistic fit to the data. This may have been due to a general lack of good contrast in the data as animals appeared to be extremely slow growing. Previous work on harvesting pressure has shown Beachlands attracts virtually no recreational effort (Hartill & Cryer 1999). Eastern Beach pipi data also did not provide realistic growth estimates from the MULTIFAN approach.

Estimated growth rates of cockles were in general lower than those reported for other populations by Cryer (1997) (Table 1), but the populations examined in the current work are all on open sloping beaches, whereas Cryer's inhabited estuarine intertidal flats. No estimates of growth rates for pipi are available, though Hooker (1995a) gave raw data for a subtidal estuarine population.

The estimated mortality rate (M) for Eastern Beach cockles was 0.69, lower than last year's estimate of 1.9 (Morrison *et al.* 1999), though that estimate had a very large associated error. Few animals over 25 mm have been found on this beach (in a times series extending back to 1994, when the beach was closed to harvesting), although anetocodatally it has been reported that large cockles were once abundant.

For Mill Bay and Okoramai Bay, a large difference in estimated total mortality rate (Z) was apparent (*see* Table 1). A natural mortality value of M = 0.3 has been assumed for cockle yield calculations to date (Cryer 1997).

Estimates of M and Z should be interpreted cautiously for cockles, as they incorporate potentially substantial errors in population size and age structure estimation. For example, Eastern Beach cockle population size has displayed *c.v.*s on total population size ranging from 27 to 34 %. This error is not accounted for in MULTIFAN analyses, which are weighted according to the number of animals measured per survey, not the actual uncertainty present in each survey estimate. This error may affect growth, mortality, and recruitment indice estimates.

Similar caution should also be exercised with pipi estimates, as Hooker (1995a) showed that distinctly different components of the overall population may occupy different habitats in estuarine environments (juveniles on intertidal areas, larger adults in subtidal channels). It is not known if such patterns hold for more gently sloping coastal beaches, but if they do, then mortality and migration rates may be strongly confounded.

4.1.2 Estimates of recruitment variability

An estimate of recruitment variability, σ_R, was calculated as the standard deviation of the logarithms of available recruitment indices (1+ animals), based on the assumption that recruitment was likely to be log-normally distributed. It was assumed that growth and timing of recruitment were similar between years.

The recruitment index for Eastern Beach (closed to harvesting) was high compared to the three open beaches (Table 2). Recruitment variability for Mill Bay and Okoromai Bay was in line with that estimated for the Snake Bank cockle fishery (0.31–0.41).

Pipi showed relatively high recruitment variability in Mill Bay.

4.1.3 Estimates of length-weight relationships

A combined length-weight relationship has been estimated for cockles and pipi for the three exploited beaches (Hartill & Cryer 1999) (Table 3). A length-weight relationship is available for a subtidal estuarine population of pipi (Hooker 1995a).

4.2. Estimation of population size, distribution, and size structure in 1998–99

4.2.1. Survey methods

A two-phase stratified random design (Francis 1984) was adopted. Individual beaches were divided into rectangular strata based on results from the 1997–98 survey. Stratification incorporated both upshore and alongshore variation, and was optimised on absolute population size across both target shellfish species. A target *c.v.* of 20% was specificied for all species and beach combinations.

A baseline was run out along each beach from which all transects were run. The start of each transect within a stratum was predetermined using a random number generator for both the x coordinate (distance along the strata boundary) and y coordinate (0–10 m from the stratum boundary). Transects were run from these starting locations down or up the beach, depending on where the baseline was relative to the stratum. Quadrats were sampled at 10 m intervals along each transect, and ran until either the boundary of another stratum was encountered, or until no more habitat was available (MLWS mark or top of the beach). The basic sampling unit for analysis was the density of shellfish per quadrat averaged across an individual transect, rather than that for each individual quadrat proper.

A sampling intensity of 400 quadrats per beach (3200 quadrats overall) was derived from analyses of previous surveys and the *c.v.*s achieved relative to the historical sampling effort deployed. Three hundred of these were assigned to phase 1 sampling, and were allocated across strata to achieve the smallest *c.v.* possible. The number of transects varied depending on beach size and the stratification adopted.

The remaining pool of about 800 phase 2 quadrats was deployed across the eight beaches to maximise *c.v.* reductions. This meant that some beaches received a much greater phase 2 sampling effort than others. Within beaches, additional sampling effort was allocated by adding an additional transect iteratively to each of the strata, and using the existing density and variance information to predict the likely improvement in the overall *c.v.* for each possible stratum allocation. The transect was then assigned to the stratum giving the greatest improvement, and the process repeated until little gain was achieved through adding an additional transect (less than 0.3%).

Sometimes, the species with the highest *c.v.* was present in very low numbers compared with other target species, and then sampling effort was preferentially assigned to reduce the population size *c.v.* of the species which occured on the beach in meaningful numbers. Cockles were favoured over pipi for phase 2 allocations, as previous harvest estimates for three of the beaches surveyed have shown pipi to be of little or no interest to recreational pickers (Hartill & Cryer 1999).

At each sampling point a single core of 0.1 m^2 cross section and 0.15 m depth was pushed into the sediment until flush with the surface. The contents of this core were dug out and passed through a 5 mm aperture sieve

Both target species were counted and measured down to the nearest millimetre total shell length.

The total survey area for each beach was estimated from previous grid surveys, using the maximum x and y sample coordinates recorded. This estimate is likely to be conservative. Stratum boundaries (and hence areas) were modified during data analysis where the 1999 sampling extended further up or down the beach than predicted in simulations.

Areas of unsuitable habitat were removed from strata area estimates if present (e.g., at Eastern Beach, total available habitat area appeared to fluctuate slightly from year to year depending on sand movement). Total population sizes were calculated by combining scaled estimates of population size from each stratum,

$$N = \sum_{h=1}^{L} A_h * \overline{y_h}$$

where N is the total population size, A_h is the area in square metres of stratum h, and y_h is the density of animals per square metre in stratum h.

The variance estimator for this is expressed as

$$\text{var}(N) = \sum_{h=1}^{L} A_h^2 \frac{s_h^2}{n_h}\left(\frac{N_h - n_h}{n_h}\right)$$

Summed length frequencies were generated from each stratum, and strata estimates of length frequency combined using their relative area as a weighting factor. This was done for each beach/species combination, expressed as

$$N_i = \sum_{h=1}^{L} A_{hi} * \overline{y_{hi}}$$

where N_i is the ith 2 mm size increment for a beach/species combination.

4.2.2 Survey results and discussion

The target *c.v.* of 20% on absolute animal abundance was met for cockles, except for Cheltenham Beach and Eastern Beach (Table 4). As in previous surveys, the Eastern Beach population was present in very small, localised, high density patches below the scale of the inter-quadrat distance (10 m), making it difficult to achieve precise abundance estimates. Although Eastern Beach had a population of 3.2 million cockles, the population was spread over a large area and densities were very low. The largest populations of cockles were found at Okoromai Bay, Umupuia Beach, and Beachlands.

Absolute pipi population sizes were more poorly estimated, and high *c.v.*s were obtained for Cornwallis Beach, Okoromai Bay, Umupuia Beach, Beachlands, and Eastern Beach, although for the last three beaches population sizes were modest. Population sizes differed less between beaches than for cockles, with most beaches holding 1–6 million animals.

Precise estimates of abundance continue to be difficult to achieve for some of the beaches, especially for pipi. This may be due to shifts in recruitment spatial dynamics from year to year, movement of larger and older animals, and/or selective harvesting by recreational fishers.

There are large differences in the size frequency of target shellfish populations between beaches. For cockles, Beachlands, Cornwallis Beach, Eastern Beach, and Mill Bay all showed evidence of recent recruitment (Figure 2; animals less than 15 mm). Cornwallis Beach, Mill Bay, Okoromai Bay, and Umupuia Beach also contained populations of larger animals. Very little or no recruitment was found for Cheltenham Beach or Umupuia Beach from the 1998 recruitment, which for Cheltenham Beach represents nil recruitment for at least the last 6 years, and for Umupuia Beach at least the last 2 years. The cockle population at Cheltenham Beach has gone into a substantial decline in the last year, with numbers falling about 75% between the last two surveys (although the margin for error is substantial).

Pipi recruitment occurred at Beachlands, Cheltenham Beach, Cornwallis Beach, and Mill Bay (Figure 3). Overall densities at Okomorai Bay and Umupuia Beach were low. The recruitment at Cheltenham Beach is the first recorded in the last five years, but is modest compared with that in 1993. The adult component of the population is now in substantial decline, matching the trend for cockles at this beach.

4.3. Fisher size selectivity

Hartill & Cryer (1999) generated selectivity ogives using data from the 1998 intertidal beach survey combined with recreational harvest data. Critical sizes for cockles were estimated as 25 and 31 mm for Mill Bay and Okoromai Beach, respectively. No estimates are available for Eastern Beach, which has been closed to harvesting since 1994. For this beach, a nominal value of 25 mm was selected for use in analysis.

4.4 Yield per recruit analysis and estimation of reference fishing mortality

Sufficient biological information was available to estimate reference fishing mortalities for cockles at Eastern Beach, Mill Bay, and Okoromai Bay. Pipi are not an important harvest species at the two open beaches (Hartill & Cryer 1999). A quarterly yield per recruit analysis, using vulnerability to the fishery based on critical sizes rather than ages (Cryer 1997), was adapted for the current analysis.

The mean length of cockles at a given age, in quarter year steps, was derived for each beach from the von Bertalanffy growth equation parameters using MULTIFAN

$$L_t = L_\infty\left[1 - e^{(-K(t-t_0))}\right]$$

where L_t is the shell length at time t and L_∞, K, and t_0 are the parameters for the von Bertalanffy growth equation (*see* Table 1). The mean weight of individuals of this length was then predicted from length weight regressions of the form $W = aL^b$, where W is the weight (g) and L is the length (mm) (*see* Table 3).

Numbers surviving to each successive age class were estimated from

$$N_{t+1} = N_t(e^{-(F+M)})$$

where M is the assumed instantaneous rate of natural mortality and F is the instantaneous rate of fishing mortality, equal to zero as long as the predicted mean length of the age class is less than the critical length at recruitment to the fishery, $L_{recruit}$.

Landings, C, from the fishery at each age class were estimated using the full version of the Baranov equation (assuming cockles are taken throughout the year with no seasonality):

$$C = \frac{F}{F+M} * \left(1 - e^{-(F+M)}\right) * W.N_t$$

Spawning stock biomass is the value of $W.N_t$ at each age class, as long as the predicted mean length of the age class is more than the critical size at recruitment to the spawning stock.

Yield per recruit (YPR) is estimated as the sum of all age specific values of C, and spawning stock biomass per recruit is estimated as the sum of all age specific values of $W.N_t$.

In the base model, vulnerability of a given age class of individuals was assumed to be zero, unless the predicted mean length of that age class exceeded the critical size (determined from examination of recreational survey size data versus animal abundance survey data).

M was set at 0.3, based on the estimates of Martin (1984), since most of the mortality estimates in this study are for Z. Input parameters for the base case and sensitivity analyses are shown in Table 5 for each beach. Results and sensitivities to changes in M, and length at recruitment, are shown in Table 6.

For the three beaches for which YPR models were constructed (Figure 4), the heights of the model curves were found to be quite sensitive to the assumed values of M (which are not known for the harvested beaches). However, the reference fishing mortalities $F_{0.1}$ and F_{max} were not very sensitive to these changes.

Length at recruitment was found to have only a minor effect on curve height. The reference fishing mortalities $F_{0.1}$ and F_{max} were less sensitive to these changes than to changes in M.

The base case analyses for the three beaches gave estimates of $F_{0.1}$ of 0.29–0.53, and F_{max} of 0.42–0.74.

Spawning stock biomass per recruit, where spawning stock biomass is a surrogate for fecundity in an egg per recruit model, was never reduced to a level close to 25% of virgin for any of the reference fishing mortalities estimated.

4.5 Yield Estimates

4.5.1 Estimation of Maximum Constant Yield

No estimate of MCY can be calculated as the recreational catch history for the various beaches is unknown.

4.5.2 Estimation of Current Annual Yield

CAY can be estimated using the full version of the Baranov catch equation assuming that fishing is carried out year round and natural and fishing mortality act simultaneously (Annala & Sullivan 1996).

$$\mathrm{CAY} = \frac{F_{ref}}{F_{ref} + M}\left(1 - e^{-\left(F_{ref} + M\right)}\right)B_{beg}$$

where F_{ref} is a reference fishing mortality, M is natural mortality, and B_{beg} is the start of season recruited biomass. Using the base case estimates of Table 5, and B_{beg} estimates derived from multiplying the scaled size frequency by the length-weight parameters of Table 3, the current annual yields for cockles at the three beaches are;

Eastern Beach

For $F_{0.1}$ CAY = 0.5890 * 0.5181 * 0.37 t = 0.11 t

For F_{max} CAY = 0.6703 * 0.5975 * 0.37 t = 0.15 t

Mill Bay

For $F_{0.1}$ CAY = 0.4915 * 0.4457 * 6.65 t = 1.5 t

For F_{max} CAY = 0.5833 * 0.5132 * 6.65 t = 2.0 t

Okoromai Bay

For $F_{0.1}$ CAY = 0.6386 * 0.5640 * 86.7 t = 31.2 t

For F_{max} CAY = 0.7115 * 0.6465 * 86.7 t = 39.9 t

The level of risk to the stock by harvesting the population at either of the estimated CAY values cannot be determined.

4.5.3. Empirical estimates of yield

Estimated cockle harvest figures for 1998 were 4.98 t for Mill Bay, and 17.19 t for Okoromai Bay (Hartill & Cryer 1999).

4.5.4 Factors influencing yield estimates

The lack of recovery of bivalve populations on the two closed beaches (Cheltenham and Eastern) indicates that unknown factors other than harvesting pressure may be influencing some populations. One of the obvious possibilities is some change to the physical environment of the beach. Such changes are not allowed for in standard YPR models, which implicitly assume the holding capacity of the environment to be in equilibrium. The possible existence of such effects has implications for management options of intertidal shellfish resources such as minimum sizes, bag limits, and, in certain situations, full beach closures.

5. Management implications

The CAY estimates represent an attempt to determine optimal harvesting rates for some of Auckland's intertidal shellfish resources. Cockles appear to be the main focus of harvesters. Pipi attracted little or no harvesting effort, perhaps due to the generally small fish available in intertidal habitats.

The closure of beaches to harvesting pressure would appear to be a good management technique for allowing depleted shellfish beds to recover, but data from the two closed beaches do not support this method as always ensuring recovery. Cheltenham Beach continues to hold ageing populations of cockles and pipi, with only a very modest recruitment of pipi in the last year (at a level insufficient to maintain historical population abundance). This suggests that either some environmental aspect/s of the beach important to juvenile bivalve recruitment has changed from that historically present, and/or that the level of adult spawning stock has been depressed below some critical level of the stock-recruitment relationship. For Eastern Beach, closed since 1994, some cockle recruitment has occurred each year, but subsequent mortality rates are high, and few cockles appear to reach sizes of 25 mm or greater. Given the anecdotally once abundant adult cockles on this beach, it is suggested that some environmental variable/s on this beach may also have changed, to the detriment of the survival of cockles.

The yield per recruit estimates suggest that natural mortality rate as an important parameter for beaches open to harvest would be the most beneficial variable to examine in future work. Current CAY estimates indicate that Mill Bay harvest rates are currently in excess of CAY. However, given the poor knowledge of M for these beaches, these results should be viewed with caution.

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Table 1: Estimated growth and mortality parameters for selected beaches, based on MULTIFAN analyses. – denotes insufficient individuals measured for parameter estimation, or unrealistic fits generated. Bracketed values are standard error estimates

Beach	Harvest status	Cockles			Pipi		
		K	L_∞	Z	K	L_∞	Z
Mill Bay	Fished	0.28 (0.02)	54.2 (2.34)	1.48 (0.08)	0.094 (0.01)	84.6 (8.06)	1.00 N/A
Okoromai	Fished	0.15 (0.02)	53.3 (4.27)	0.20 (0.03)	–	–	–
Eastern	Unfished	0.30 (0.024)	33.3 (1.35)	0.69 (0.06)	–	–	–
Previous estimates (Cryer 1997)							
Whangateau	Fished	0.44	27				
Snake Bank	Fished	1.10	34				
Snake Bank	Fished	1.02	31				
(Morrison *et al.* 1999)							
Cornwallis	Fished	0.26	48.1				

Table 2: Recruitment indices for the various beach and species combinations

Beach	Survey years	Recruits (000)	Index
Cockles			
Mill Bay	1996	2 767	0.44
	1997	1 071	
	1998	2 216	
	1999	1 336	
Okoromai	1996	8 968	0.27
	1997	1 709	
	1998	2 651	
	1999	1 449	
Eastern	1994	1 727	1.31
	1995	1 643	
	1996	330	
	1997	103	
	1998	781	
	1999	90	
Pipi			
Mill Bay	1996	2 340	0.85
	1997	662	
	1998	3 990	
	1999	3 998	

Table 3: Length-weight regression for cockles and pipi ($W = aL^b$, weight in grams, length in mm)

Species	Year	Location	a	b	Reference
Cockles	1998	Cornwallis / Mill Bay / Okoromai	0.00037	3.026	Hartill & Cryer (1999)
Pipi	1993	Whangateau Harbour	0.00003	3.315	Hooker (1995a)

Table 4: Summary statistics by beach for the two shellfish species, 1998 survey. N, total population size (000s) and coefficients of variation (*c.v.*)

Beach	Area (m^2)	Cockles		Pipi	
		N	*c.v.*(%)	N	*c.v.* (%)
Cheltenham	112 000	115.1	21.3	1 729.6	19.3
Cornwallis	135 625	5 575.1	17.6	6 378.3	27.3
Okomorai	195 050	36 220.7	8.2	151.4	45.3
Howick	39 500	402.3	13.7	962.5	10.8
Umupuia	300 000	96 009.1	5.6	710.1	50.1
Beachlands	260 000	57 502.3	12.4	2 297.3	22.6
Eastern	480 000	3 183.8	27.3	976.6	43.8
Mill Bay	48 000	2 927.6	14.5	5 694.6	19.3

Table 5: Input parameters used for yield per recruit and spawning stock biomass per recruit analyses, for cockles. M is the rate of natural mortality, K, L_∞, and t_0 are the parameters of the von Bertalanffy equation, a and b are the parameters of length weight regressions, $L_{maturity}$ is the size at first spawning, and $L_{recruit}$ is the size at recruitment to the recreational fishery

Parameter	Base case	Sensitivities	
Eastern			
M (y^{-1})	0.30	0.20	0.40
K (y^{-1})	0.263		
L_∞ (mm)	48.1		
t_0 (y)	0.00		
A	0.00037		
B	3.02582		
$L_{maturity}$ (mm)	18.0		
$L_{recruit}$ (mm)	25.0	20	
Mill Bay			
M (y^{-1})	0.30	0.20	0.40
K (y^{-1})	0.28		
L_∞ (mm)	54.2		
t_0 (y)	0.00		
A	0.00037		
B	3.02582		
$L_{maturity}$ (mm)	18.0		
$L_{recruit}$ (mm)	25.0	25	30
Okoromai			
M (y^{-1})	0.30	0.20	0.40
K (y^{-1})	0.231		
L_∞ (mm)	54.2		
t_0 (y)	0.00		
A	0.00037		
B	3.02582		
$L_{maturity}$ (mm)	18.0		
$L_{recruit}$ (mm)	31.0	25	35

Table 6: Estimates of $F_{0.1}$, and F_{max} from yield per recruit analyses for cockles using input parameters specified in Table 3 (length weight regressions) and Table 5. M is the assumed rate of natural mortality, and $L_{recruit}$ is the length at which cockles are first taken by the recreational fishery

	Input parameters		Estimates	
	M	$L_{recruit}$	$F_{0.1}$	F_{max}
Eastern				
Base case	0.30	25	0.43	0.61
Sensitivity to M	0.20	25	0.40	0.57
	0.40	25	0.46	0.66
Sensitivity to $L_{recruit}$	0.30	20	0.33	0.47
Mill Bay				
Base case	0.30	25	0.29	0.42
Sensitivity to M	0.20	25	0.26	0.37
	0.40	25	0.32	0.47
Sensitivity to $L_{recruit}$	0.30	22	0.25	0.35
	0.30	30	0.31	0.44
Okoromai				
Base case	0.30	31	0.53	0.74
Sensitivity to M	0.20	31	0.51	0.71
	0.40	31	0.55	0.77
Sensitivity to $L_{recruit}$	0.30	25	0.36	0.51
	0.30	35	0.80	1.08

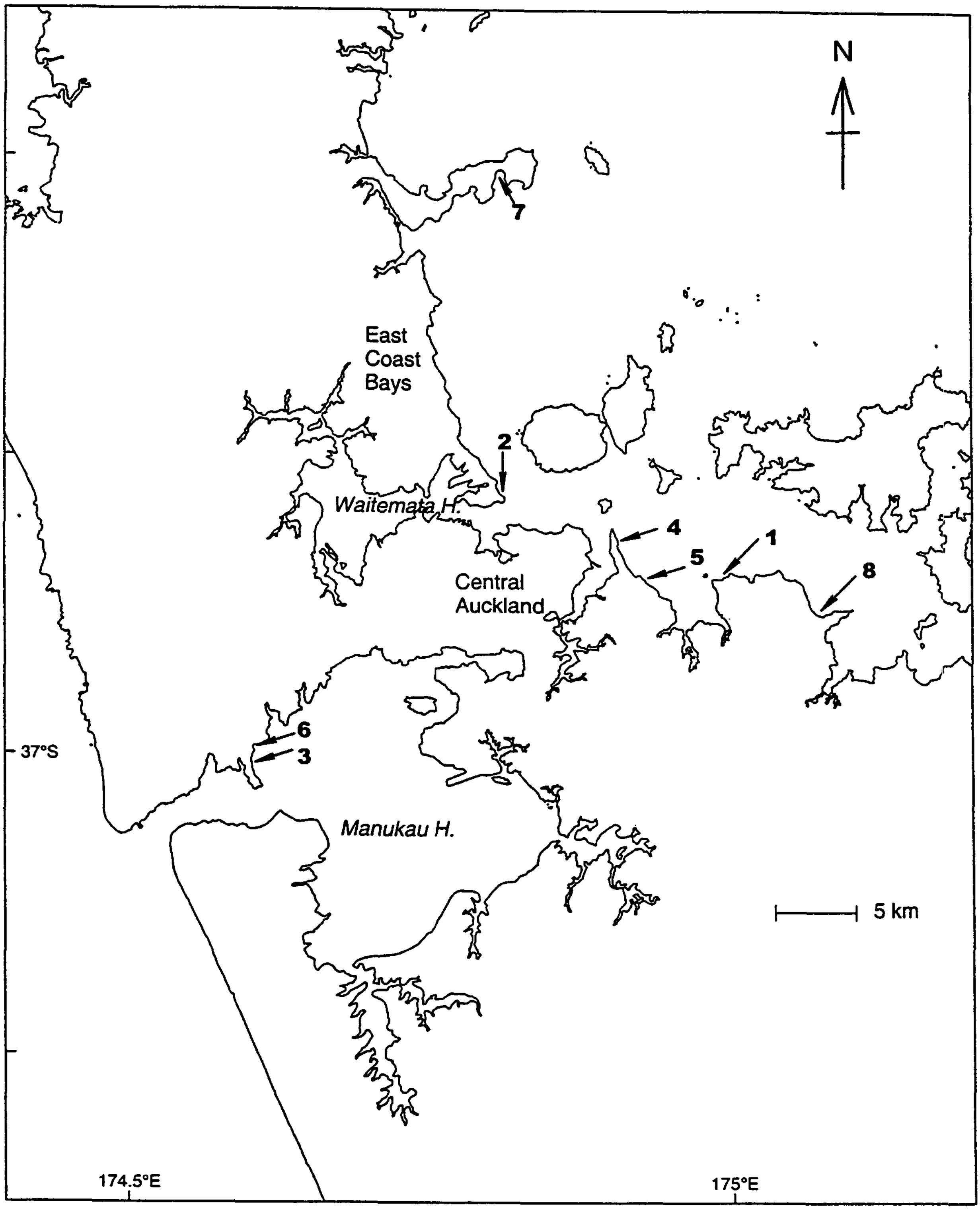

Figure 1: **Beach locations in the greater Auckland metropolitan area.**

1 Beachlands
2 Cheltenham Beach
3 Cornwallis Beach
4 Eastern Beach
5 Howick Beach
6 Mill Bay
7 Okomorai Bay
8 Umupuia Beach

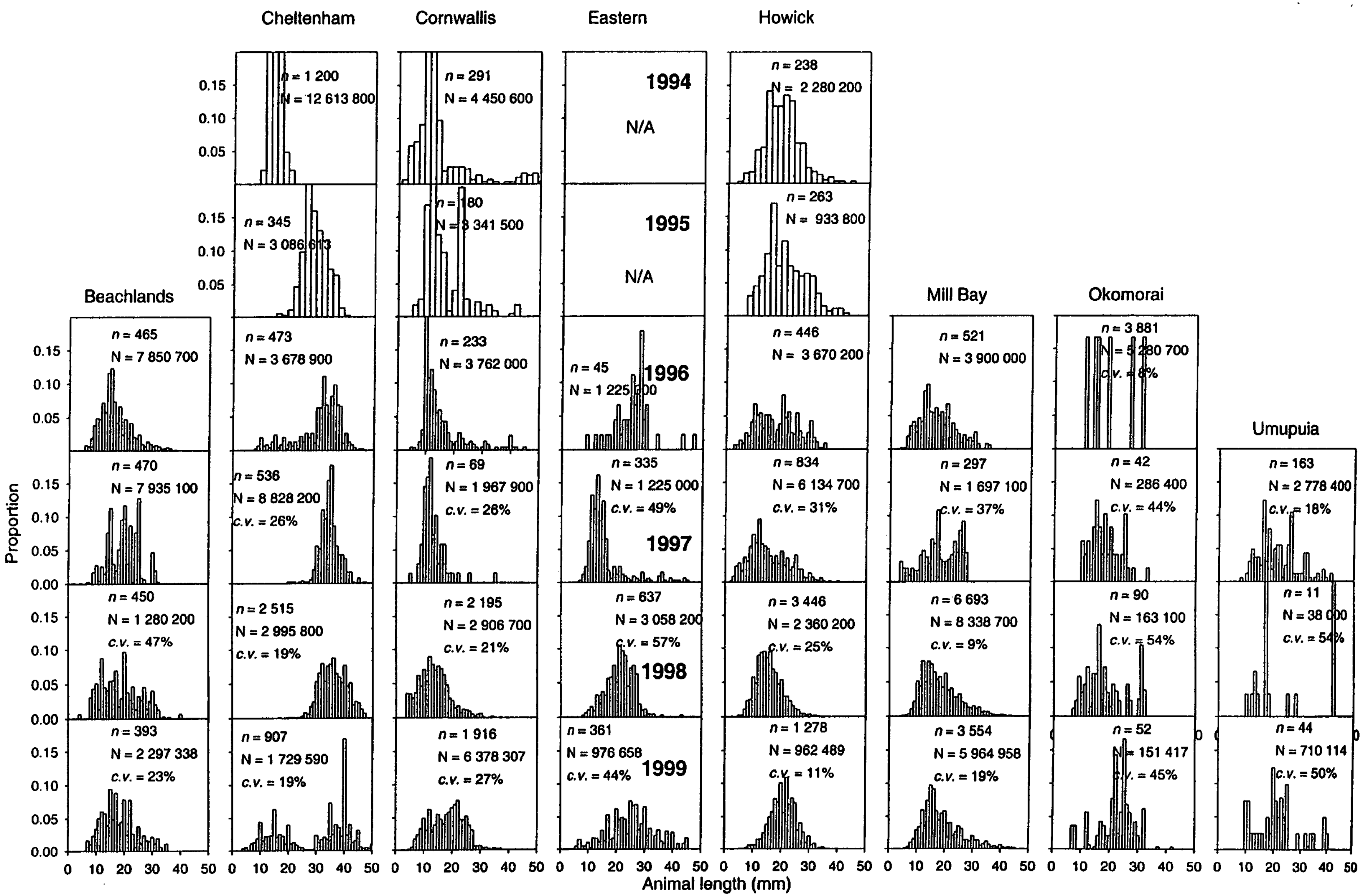

***Figure 3*: Pipi population size frequencies for the eight surveyed beaches. n, number of animals measured; N, estimated number of animals within the stratum; *c.v.*, coefficient of variation. N/A, length frequency data not available.**

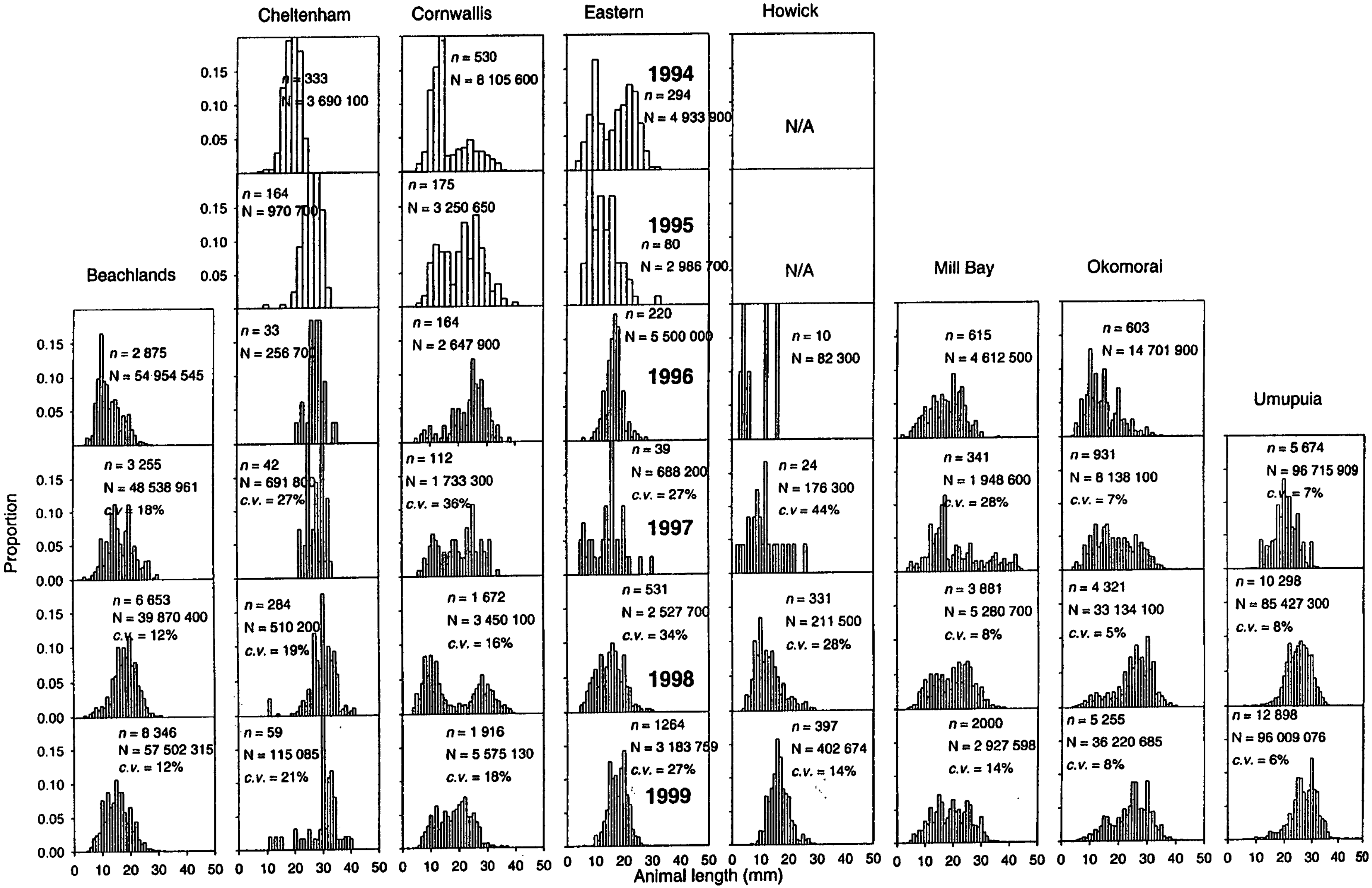

Figure 2: **Cockle population size frequencies for the eight surveyed beaches. n, number of animals measured; N, estimated number of animals within the stratum; *c.v.*, coefficient of variation. N/A, length frequency data not available.**

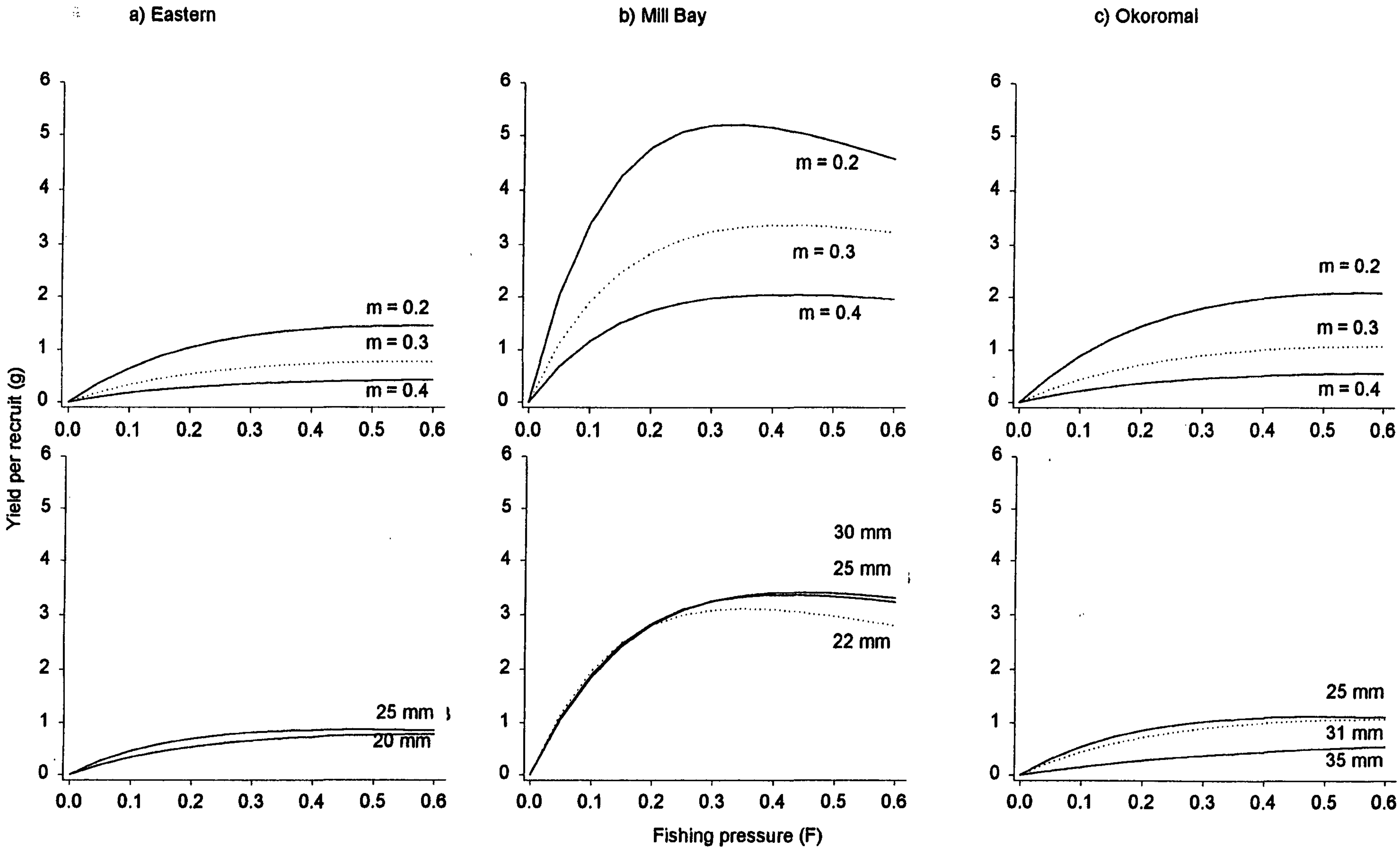

Figure 4: **Yield per recruit curves for cockles at a) Eastern, b) Mill Bay, and c) Okoromai. von Bertalanffy growth curve parameters are from Table 1 and are based on MULTIFAN analyses of length frequencies measured over the time series available. Sizes of 18 mm at biological maturity and 25, 25, and 31 mm respectively as critical recruitment lengths are assumed for the top three graphs, with M allowed to vary from 0.2 to 0.4. For the bottom three graphs, critical recruitment size to the recreational fishery is allowed to vary, as per Table 8.**