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Assessment of cockles on Snake Bank, Whangarei Harbour, for 1996

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1. Executive Summary

Biomass surveys using identical methods have been conducted on Snake Bank, Whangarei Harbour, since the inception of the commercial fishery there in 1982. While commercial landings increased dramatically between this time and 1991, recruited biomass fell to about one-third of its virgin level and the proportion of very large cockles to less than 10% of virgin. Growth rates and recruitment appear to have increased during this time. Estimates of growth rate and mortality allowed the estimation of the reference fishing mortalities of $F_{0.1}$ and F_{max} for the first time in 1995. These estimates have been refined using a more appropriate model in 1996. Productivity and recruited biomass estimates are also updated for this assessment, giving yield estimates (depending on the choice of reference fishing mortality) of MCY = 200–300 t and CAY = 235–325 t compared with recent average landings of about 500 t and theoretically available landings of 584 t in 1996–97.

2. Introduction

2.1 Overview

This document summarises the history of the Snake Bank, Whangarei Harbour, fishery for cockles and available research information. New estimates of recruited biomass for August 1996 are described. A yield per recruit (YPR) model is developed using quarterly (rather than annual) increments and critical sizes (rather than ages) for recruitment and maturity. Reference fishing mortality rates are estimated using the YPR model, and yield estimates for 1996–97 are derived.

2.2 Description of the Fishery

Commercial picking of cockles, *Austrovenus (Chione) stutchburyi*, is carried out on Snake Bank (Whangarei Harbour, FMA 1), Tapu Bay (Tasman Bay, FMA 7), Pakawau Beach (Golden Bay, FMA 7), and Papanui and Waitati Inlets (FMA 3). Picking is by hand or, within FMA 7 only, mechanical harvester.

Commercial picking on Snake Bank in Whangarei Harbour began in the early 1980s and is undertaken year round, with no particular seasonality. Catch statistics are unreliable before 1986, although 165 t of Snake Bank cockles were exported to the United States in 1982 (Martin 1984). There was probably some under-reporting of landings before 1986, and this may have continued since. There are eight permit holders, each allowed a maximum of 200 kg (greenweight) per day by hand-gathering. If all permit holders took their quota every day a maximum of 584 t could be taken in a 365 day year. Landings increased rapidly from less than 200 t before the 1988–89 fishing year to exceed 90% of the theoretical maximum in all years since 1991–92, other than 1992–93 when the fishery was closed during the summer because of high levels of biotoxins.

2.3 Literature Review

There are no previous FARDs summarising the assessment and biology of cockles in New Zealand. Previous assessments were briefly summarised by Annala & Sullivan (1996), and notes on early assessments and estimates of productivity were given by Holdsworth & Cryer (1991) and Cryer & Holdsworth (1993). This is the first detailed summary of available information and modelling.

The New Zealand cockle, *A. stutchburyi*, is a shallow-burrowing suspension feeder of the family Veneridae and is one of the most abundant bivalves in the New Zealand intertidal zone (Morton & Miller 1968). In mature specimens, the shell is heavy, rounded, and marked with radial ribs. Sexes are separate and of approximately equal abundance. Maturity appears to be primarily a function of size rather than age, with sexual maturity occurring at a maximum shell dimension of about 18 mm (Larcombe 1971). Spawning extends over spring and summer (e.g. Stephenson 1981, Booth 1983), and fertilisation is followed by a planktonic larval stage lasting about 3 weeks prior to metamorphosis and settlement to a benthic surface (Stephenson & Chanley 1979).

Quite extensive movements of juveniles and smaller animals have been documented (Martin 1984; *see* also byssus drifting in *Cerastoderma edule,* Montaudouin *et al.* 1996), but individuals over 25 mm in length remain largely sessile, apparently moving only in response to disturbance. The growth rate is greatest during spring and summer (Larcombe 1971, Cryer & Holdsworth 1993) and is greatest for the smaller size classes. Growth is somewhat slower in the higher tidal ranges and in high density beds (Larcombe 1971). Significant increases in the growth rate have been observed for individuals remaining in areas "thinned out" by simulated harvesting (Martin 1984) and growth rates have apparently increased on Snake Bank following the development of the fishery (Cryer & Holdsworth 1993). It is not thought possible to age cockles using external shell "rings" as their deposition rate has been found to be variable, at least in northern populations.

Recruitment in *A. stutchburyi,* as in many other bivalves, varies considerably from year to year. It is frequently observed that recruitment of juveniles is depressed at high adult biomass through intraspecific competition (e.g., Hamner 1978, Moeller & Rosenberg 1983, Peterson & Black 1993). However, Martin (1984) showed that recruitment of juveniles to small scale experimental plots was significantly lower (by an average 65%) in those plots from which all live cockles had been removed. Similar responses of lower recruitment at low adult density have been observed for the European cockle *Cerastoderma (Cardium) edule* (Kreger 1940 cited in Brock 1980, Andre & Rosenberg 1991), and for an Australian species *Katelysia scalarina* (Peterson & Black 1989, 1993). Poor recruitment apparently stems mostly from poor settlement (spatfall), but in *K. scalarina* it appeared to be due to heavy predation of juveniles. Abiotic factors such as temperature are recognised as being important determinants of recruitment success in European species (Moeller & Rosenberg 1983, Beukema et al. 1992, Dijkema 1992, Guillou *et al.* 1992). Low availability of eggs or larvae stemming from low temperatures and poor adult condition has been identified as one cause of poor recruitment in European cockles (e.g., Guillou *et al.* 1991).

3. Review of the Fishery

3.1 Catch limits and landings

Reported landings for Snake Bank, from Licensed Fish Receiver Returns (LFRRs) are shown in Table 1. Reported landings before 1986–87 were less than 50 t (J. Holdsworth, pers. comm.), but the fishery (anecdotally) supported up to six full-time pickers in some years, suggesting that there was probably some under-reporting of landings. Effort and catch information for this fishery has not been adequately reported in the past, and there are problems interpreting the information that is available. Landed weights reported on Catch Effort and Landing Returns (CELR) summed to only 50–90% of weights reported on LFRRs during 1989–90 to 1992–93, although more recent data match more closely. In addition, reported landing weights are based on an assumed sack weight of 28 kg whereas actual measured weights are closer to 30 kg. Landings are therefore estimated using LFRRs where these are available.

Table 1: Reported landings (t, greenweight) from Licensed Fish Receiver Returns for the Snake Bank cockle fishery. The Snake Bank fishery has, since its inception, been limited by a daily limit of 200 kg per permit which equates to an annual aggregate catch of 584 t in a 365 day year (586 t in a leap year). *, landings in 1992–93 constrained by an extended closure due to biotoxin contamination, **, the estimated landings of 566 t in 1993–94 may be unreliable

Fishing year	Landings (t)	Sum of daily limits (t)
1986–87	114	584
1987–88	128	586
1988–89	255	584
1989–90	426	584
1990–91	396	584
1991–92	537	586
1992–93	*316	584
1993–94	**566	584
1994–95	501	584
1995–96	495	584

For several years, landings in the Snake Bank fishery were not apparently limited by the daily catch limit of 200 kg per permit. However, since the 1991–92 fishing year, reported landings have been close to the theoretical maximum imposed by the daily limit. The aggregate limit of 584–586 t was not based on research information or yield estimates.

3.2 Non-commercial Fisheries

Cockles, in common with many other intertidal shellfish, are important to Maori as a traditional food source. They are also taken by amateurs. Non-commercial harvesters of cockles prefer relatively large individuals, a length of about 30 mm or greater being acceptable. Accurate estimates of cockle harvest for amateur fishers are not available for areas as small as Snake Bank, but about 50–60 t was taken by amateurs throughout the Auckland Fishery Management Area during the 1994 regional telephone and diary survey (T. Sylvester, MFish, pers. comm.). The proportion of these cockles taken from Whangarei Harbour (probably Snake Bank) was only about 2% of the whole, indicating that amateur harvest was insignificant (about 1 t) compared with commercial landings (about 500 t).

4. Research

4.1 Historical estimates of recruited biomass on Snake Bank

The term *recruited* will be taken in this document to mean cockles of 30 mm or greater maximum shell dimension. This maximum dimension is parallel to the direction of movement in cockles, approximately along the axis through anterior and posterior adductor muscles, and perpendicular to any axis passing through the hinge. This dimension is here defined as shell *length*. Before about 1985, a recruited length of 35 mm was used as this was the preferred size of cockles for the export market and few smaller cockles were taken.

Biomass estimates for the Snake Bank cockle population were made from orthogonal grid sampling carried out six times between 1982 and 1995 (full sampling methods are given in section 4.3). The size and shape of the bank varied slightly each year, as did the amount of sampling time dedicated to each survey. This means that not all surveys completely covered the area of the cockle bed and some underestimation of cockle biomass was likely in 1985 and 1991. During these surveys, sampling was not sufficiently extensive to achieve zero counts all round the sampled area, and may not have covered the entire area inhabited by cockles. For calculation of total biomass, therefore, it was assumed that, in 1985 and 1991, the sampled area of bank was equal to that area sampled in 1982, being the most extensive survey. This is likely to lead to slight overestimates of biomass in these years, as the peripheral areas not sampled would, from historical data, probably have contained lower densities of cockles than the mean density over the rest of the bank. Estimates of precision (i.e., the standard error of mean density and the resultant *c.v.*) further assumed that the samples were taken at random from this area.

Between 1982 and 1992, there was a consistent decline in the biomass of cockles of 35 mm or greater shell length on Snake Bank (Table 2, Figure 1). This trend is also apparent in length frequency distributions which showed a population dominated (in biomass terms) by cockles of 34–39 mm shell length in the early 1980s, whereas samples taken since 1991 have been dominated by cockles smaller than 34 mm (Figure 2).

Table 2: Biomass estimates (t) by shell length size classes for cockles on Snake Bank. Approximate coefficients of variation (percentage) are given in parentheses for recent biomass estimates. n = the number of samples in each survey. Estimates for 1985 and 1991 corrected assuming measured density and sampling area as in 1982. For derivation of data for 1996, *see* section 4.3

								Biomass estimates	
Year	n	Total	*c.v.*	<30 mm	*c.v.*	≥30 mm	*c.v.*	≥35 mm	*c.v.*
1982	199	2 556		216		2 340		1 825	
1983	187	2 509		321		2 188		1 700	
1985	136	2 009	(± 8)	347		1 662	(± 8)	1 174	
1991	158	1 447	(± 9)	686	(± 10)	761	(± 10)	197	(± 12)
1992	191	1 642	(± 8)	862	(± 10)	780	(± 8)	172	(± 11)
1995	181	2 480	(± 7)	1 002	(± 9)	1 478	(± 7)	317	(± 12)
1996	193	1 755	(± 7)	959	(± 9)	796	(± 8)	157	(± 11)

4.2 Estimates of growth and mortality rates, and recruitment variability

4.2.1 Historical estimates of growth and mortality

Experimental work on Snake Bank in 1983 by Martin (1984) led to estimates of absolute natural mortality of 17–30% per annum, equating to an instantaneous rate of 0.19–0.35 with a midpoint of M = 0.28. The estimated natural mortality rate for cockles of 30 mm shell length or greater was slightly higher at 19–37% per annum (M = 0.21–0.46 with a midpoint of 0.33). This higher estimate was caused by relatively high mortality rates for cockles of 35 mm shell length or greater and, as these are now uncommon in the population, a value of M = 0.30 (range 0.20–0.40) was assumed for yield calculations.

Martin (1984) also estimated growth rates for cockles in the nearby Whangateau Harbour and found that tagging studies showed higher size-specific annual growth increments than length and age frequency analysis. The difference was particularly noticeable for large animals. He calculated parameters for the von Bertalanffy growth equation for the length frequency analysis as $L_\infty = 27.03 \pm 0.19$ mm and $K = 0.44 \pm 0.01$ y^{-1}. He considered this to underestimate growth, however, and attributed the difference in the two estimates to errors in ageing. This type of error can also be caused by high size-specific mortality in larger animals.

Studies in 1992 and 1993 to estimate growth rate by simultaneous length frequency analysis using MULTIFAN (Cryer & Holdsworth 1993) led to an estimate of K = 1.10. This indicates rapid growth (about 2 years) to the size of interest to both commercial and amateur fishers (about 30 mm), much faster than Martin's (1984) estimate, where up to 4 or 5 years could be taken to attain a shell length of 30 mm.

4.2.2 Revised estimates of growth and mortality for 1996

A revised MULTIFAN (Otter Research 1992) analysis was carried out in 1996 using data from 1991 to 1996 (Appendix 1). Estimates of $L_\infty = 31.0 \pm 0.24$ mm and $K = 1.02 \pm 0.02$ y^{-1} were generated (Table 3) which are not very different from those generated by Cryer & Holdsworth (1993), but are very different from those made by Martin (1984).

Table 3: Estimates of parameters for the von Bertalanffy growth equation for cockles on Snake Bank (or the nearby Whangateau Harbour for 1983–84) by various authors

Years	L_∞(mm)	sd	K (y^{-1})	sd	t_0	Method	Reference
1983–84	27.0	0.19	0.44	0.01	0.00	Ageing	Martin (1984)
1992–93	34.0	0.31	1.10	0.03	0.00	MULTIFAN	Cryer & Holdsworth (1993)
1991–96	31.0	0.24	1.02	0.02	0.00	MULTIFAN	This FARD

4.2.3 Recruitment variability on Snake Bank

Seven surveys of Snake Bank have been completed since 1982, permitting an examination of the variability of recruitment to this population. Analyses of length frequency distributions from 1991 to 1996 using MULTIFAN were used to estimate the size (in numbers of individuals) of the smallest cohort in August of each survey year. The smallest cohort always spanned shell lengths from the minimum detectable to 21 mm. For surveys not included in the MULTIFAN analysis, a comparable estimate of the size of the recruiting cohort was generated by estimating the number of cockles of 21 mm or less within the survey area each year (Table 4).

Table 4: Total abundance of cockles (N_{total}), the estimated abundance of the first cohort (age 1, $N_{recruit}$) and the base 10 logarithm of each such recruitment index for Snake Bank cockles between 1982 and 1996. An index of recruitment variability σ_R, can be calculated as the standard deviation of the logarithms

Year	N_{total}	$N_{recruit}$	$\log(N_{recruit})$
1982	176.1	10.7	7.029
1983	172.8	10.5	7.021
1985	155.5	17.1	7.233
1991	161.1	19.3	7.285
1992	225.8	87.2	7.941
1995	344.7	86.1	7.935
1996	237.8	60.0	7.778

The recruitment index for Snake Bank varied from about 10 million animals in the early 1980s to almost 90 million in 1992. The abundance of the recruiting cohort from earlier surveys may be overestimated if the growth rate on Snake Bank has increased as the biomass has decreased (as some small animals included in early recruitment indices would be older than those in later indices). Conversely, the relative abundance of the cohort may be underestimated if coarser sieves were used in earlier surveys (as some small animals may have passed through the sieves).

An index of recruitment variability, σ_R, can be calculated as the standard deviation of the logarithms of available recruitment indices, based on the assumption that recruitment is likely to be log-normally distributed. Using all the available information on Snake Bank, σ_R is estimated to be 0.41. Using data only from 1991 onwards (during which time the mesh size of sampling grids has remained constant), σ_R is estimated to be 0.31.

It is not possible to determine which of these estimates of recruitment variability is the more appropriate for predicting future recruitment variability. If recruitment of cockles on Snake has increased largely in response to the depression of recruited biomass (as is common in bivalve populations worldwide), then future recruitment variability might be better predicted using $\sigma_R = 0.31$. However, if historical recruitment has varied randomly, then $\sigma_R = 0.41$ would be more appropriate. In the light of this uncertainty, a range of $\sigma_R = 0.31–0.41$ will therefore be assumed. Given the recruitment variability estimated for many finfish species in New Zealand and overseas (often σ_R is greater than 1.0), a general observation that shellfish fisheries are more variable than finfish fisheries, and the shortness of this time series, it seems likely that both values of σ_R are underestimates of the true recruitment variability in this population.

4.3 Recruited biomass for 1996

4.3.1 Survey methods

Sampling for all biomass surveys on Snake Bank has been conducted using an orthogonal grid with intersections 50 m apart in both dimensions. Transect lines were fixed between surveys by reference to a semi-permanent "backbone" of stations marked using pegs. The size and shape of the bank varies slightly from year to year, so it is not possible or practical to sample exactly the same sites on all surveys, although most sites with appreciable numbers of cockles are common to all surveys.

The sampling design is systematic, as the location of all subsequent samples is determined by the location of the first sample. At each grid intersection, a square quadrat of 0.5 * 0.5 m was thrown haphazardly onto the bank, within about 3 m of the point of intersection. All sediment beneath the quadrat was excavated by hand, including those animals directly under the south- and west-facing sides. Cockles were removed from the sediment using a metal sieve of 5 mm aperture. A subsample of up to 100 cockles selected at random was measured to the next whole millimetre down, and all other cockles from the sample were counted. The aggregate weight of all cockles in each of three size classes (less than 30 mm, 30–34 mm, and 35 mm or more) were determined for each site. Number and standing biomass per square metre of substrate were estimated for each site by scaling by the fraction of cockles measured and weighed, and by the size of the quadrat (constant at 0.25 m^2).

Population length frequency distribution was estimated as the weighted average of all sample length frequency distributions, weights being proportional to the numerical density of cockles at each site. This average length frequency was then scaled to population size using the total area of the bank, estimated from the number of (possible) grid intersections occupied.

Recruited biomass and its variance were estimated by assuming that samples taken were randomly located on the bank. This will probably overestimate the real variance, perhaps seriously (Dunn & Harrison 1993), so an alternative estimator was applied in 1995 and 1996 involving overlapping 2 * 2 groups of samples as strata within the sampling frame (Millar & Olsen 1995). This is one of several techniques available to take account of spatial structure within systematic samples, although there is no generally accepted method of estimating such a variance.

4.3.2 Survey results and discussion

The estimated recruited biomass of cockles on Snake Bank as determined by weighing and scaling of subsamples was 796 t with a *c.v.* of about 8% (Table 2). This is only about half the estimated recruited biomass in 1995 (1480 t with a *c.v.* of 7%), but very similar to survey results from 1991 and 1992 (760 and 780 t respectively with *c.v.*s of 10 and 8%). It is likely that the higher value in 1995 stemmed from the full recruitment to the fished stock of the pulse of juveniles first observed in 1992. It appears that the abundance of this cohort has now been substantially reduced.

Coefficients of variation calculated using Millar & Olsen's (1995) method are slightly lower than those calculated assuming entirely random distribution of samples on the bank. This indicates that there is some spatial structure (autocorrelation) in sample counts. However, the difference between the two methods is not large, *c.v.*s being approximately 1% lower for Millar & Olsen's method compared with the previous method. Given that precision is already good (*c.v.* = 7–10% for estimates of recruited biomass), this difference is not considered important.

Length frequency distributions from all Snake Bank surveys since 1983 are shown in Figure 2. Early surveys show a unimodal length frequency distribution with modes larger than 30 mm shell length. Surveys since 1991 (including the latest 1996 survey) have bimodal length frequency distributions with the first mode at about 10 to 15 mm (assumed to be a recruiting year-class) and the second (corresponding to the accumulated biomass of older cockles) at slightly under 30 mm. The right hand tail of the length frequency distribution for cockles on Snake Bank appears to have been truncated since 1991.

The proportion of biomass in the "fishable" portion of the stock (shell length 30 mm or more) has declined from about 90% in the first two surveys when the stock was probably near virgin (1982 and 1983) to only about 35% in 1996. For large cockles of shell length 35 mm or more (the most desirable fraction of the population), the proportion of total biomass has fallen from about 70% to less than 10%.

Using the current definition of size at recruitment (30 mm), the estimated 1996 biomass ($B_{current}$) is about 34% of virgin biomass (B_0, assumed to be equal to the first survey estimate in 1982). Had the original definition of size at recruitment (35 mm) been retained, then $B_{current}$ would be only 8.6% of B_0. The (1982) estimate of B_0 may be an underestimate if anecdotal reports of heavy fishing during the years prior to 1986 are accurate.

Recruited biomass was estimated directly by determining at each site the aggregate weight of all individuals of recruited size. However, for the purposes of yield per recruit analyses or re-analyses of biomass and yield at different sizes at recruitment, length weight regressions have also been derived from Snake Bank (Table 5). In 1996, separate regressions were derived for the most popular part of the fishery ("The Lagoon") and for mid-tide locations on the rest of the bank. These regressions were statistically different, although the actual difference in predicted weight for common size classes is small (Figure 3). Previous regressions of weight on shell length for Snake Bank are also summarised in Table 5.

Table 5: Length weight regressions ($W = a.L^b$) for cockles on Snake Bank. Locations relate to the area on Snake Bank from which the cockles were collected

Year	Location	a	b	Reference
1992	Random	0.00110	2.721	Cryer & Holdsworth (1993)
1995	Random	0.00015	3.285	Annala & Sullivan (1996)
1996	Mid-tide	0.00018	3.253	This FARD
1996	Lagoon	0.00037	3.060	This FARD
All data combined		0.00061	2.924	This FARD

4.4 Yield per recruit analysis and estimation of reference fishing mortality

4.4.1 Historical models

The reference fishing mortality $F_{0.1}$ was first estimated for Snake Bank (Cryer & Holdsworth 1993) using an annual yield per recruit model assuming approximate annual mean vulnerability to the fishery of 0 at age 0+, 0.2 at 1+, and 1.0 subsequently. Growth rate parameters from analysis of 1992–93 length frequencies (Cryer & Holdsworth 1993), an estimate of $M = 0.30$ (range 0.20–0.40) from Martin's (1984) tagging study in 1983, and a length-weight relationship from 1992 were also used. Values of size at maturity of 18 mm and size at recruitment of 30 mm were based on general biological knowledge of the species and the preferred minimum harvest size respectively. Under these assumptions, $F_{0.1} = 0.53$ for the base case of $M = 0.30$ and this was not very sensitive to changes in M within the range of uncertainty of the tagging estimate ($F_{0.1} = 0.51$ for both $M = 0.20$ and $M = 0.40$). This analysis, using annual increments and approximate annual mean vulnerability for a rapidly-growing animal ($K \sim 1.0$), is now considered to be a rather crude approximation.

4.4.2 Quarterly yield per recruit analysis using critical sizes

Because of the inadequacies of the previous analysis and the availability of additional length frequency information, a new quarterly yield per recruit analysis was carried out using vulnerability to the fishery based on critical sizes rather than ages.

The mean length of animals at a given age, in quarter year steps, is derived using parameters for the von Bertalanffy growth equation estimated 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 (Appendix 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 and L is the length of a given size of cockles.

Numbers surviving to each successive age class were estimated using the following equation:

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

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 are estimated using the full version of the Baranov equation (as cockles are taken throughout the year with no particular seasonality):

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

Spawning stock biomass is simply 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 (SSBPR) 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 of 30 mm, when vulnerability was assumed to be 1.0. Updated von Bertalanffy parameters, Martin's (1984) estimate of M, and a variety of length-weight regressions were used in the quarterly analysis. The input parameters for the base case and sensitivity analyses are shown in Table 6. Results and sensitivities to changes in M, length at recruitment and length-weight regression used are shown in Table 7.

Lengths at recruitment for use in sensitivity studies were selected by comparing the length frequency distributions of cockles measured in commercial packing sheds and during biomass surveys (Figures 4 to 7). Jacobs' (1974) index (originally devised for the determination of prey electivity in predators) was used for this comparison.

$$D = \frac{(r-p)}{(r+p-2rp)}$$

where D is the electivity index, r is the fraction of a given size class of cockles in landings, and p is the fraction of the same size class in the population at large. Possible values of the index, D, range from -1 to +1, positive values indicating a proportion in landings (c.f. the diet of a predator) higher (and negative values lower) than the proportion of a given species or size class in the environment.

Approximate (probably minimum) confidence intervals were estimated for each value of Jacobs' D using a non-parametric bootstrap technique. For each of 1000 bootstrap iterations, the number of animals measured in field surveys and in samples of landings were randomly re-sampled (with replacement) for each size class independently. Proportions at length were then recalculated and D estimated for each size class. Confidence intervals were estimated as the 2.5 and 97.5 percentile values of the 1000 bootstrap estimates of D for each size class.

In 1992, Jacobs' index was positive for all size classes of cockles 30 mm or greater, with some tendency for the index to decrease for sizes above about 37 mm (although confidence intervals above this size are very broad). In 1996, Jacobs' index was positive for all size classes of cockles 29 mm or greater, with a similar tendency for the index to decrease for sizes above about 35 mm (although confidence intervals are again very broad). Inspection of the indices and their confidence intervals suggest that the only substantive difference between the selectivity patterns of fishers in 1992 and 1996 was in the size range 29–30 mm, fishers accepting slightly more smaller cockles in 1996 than in 1992. This may be related to the greater availability of large cockles in 1992, or it may be an artefact of small sample size in 1996. In both years, the smallest cockles measured in packing sheds were about 25 mm in length. The lower and upper limits to size at recruitment for sensitivity analyses were therefore set at 25 and 30 mm respectively.

Table 6: Input parameters used for yield per recruit and spawning stock biomass per recruit analyses. 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 commercial fishery

Parameter	Base case	Sensitivities		
M (y^{-1})	0.30		0.20	0.40
K (y^{-1})	1.02			
L_∞ (mm)	31.00			
t_0 (y)	0.00			
a	0.00061	0.00110	0.00015	0.00018
b	2.924	2.721	3.285	3.253
$L_{maturity}$ (mm)	18.0			
$L_{recruit}$ (mm)	30.0		28.0	25.0

While the heights of yield per recruit curves vary with the assumed values of M, length at recruitment and the length-weight regression used (Figure 8), the reference fishing mortalities $F_{0.1}$ and F_{max} (the value of F at which maximum yield per recruit is obtained) are not very sensitive to these changes. The base case analysis gives $F_{0.1} = 0.41$, and the greatest sensitivity is to the assumed size at recruitment (range 25 mm > $L_{recruit}$ > 30 mm) and the assumed value for M (range 0.20 > M > 0.40). The base case analysis gives $F_{max} = 0.62$ with similar sensitivity to input parameters.

The spawning stock biomass per recruit analysis suggests that egg production is not likely to be a limiting factor for this population. The (probably conservative) reference fishing mortality $F_{50\%}$ (at which spawning stock biomass per recruit is reduced to 50% of its level without any fishing pressure) is equal to or greater than $F_{0.1}$ for all sensitivities examined. Only with a very small assumed size at recruitment to the fishery of 25 mm is $F_{50\%}$ for the sensitivity smaller than the base case $F_{0.1}$. Under none of the scenarios examined is SSBPR (spawning stock biomass per recruit, where spawning stock biomass is a surrogate for fecundity in an egg per recruit model) reduced to a level close to 25% of virgin.

Table 7: Estimates of $F_{0.1}$, F_{max}, and $F_{50\%}$ from yield per recruit and spawning stock biomass per recruit analyses carried out using input parameters specified in Table 5 (length weight regressions) and Table 6. $F_{50\%}$ is that fishing mortality at which spawning stock biomass per recruit is reduced to 50% of its level at F = 0, "M" is the assumed rate of natural mortality, "$L_{recruit}$" is the length at which cockles are first taken by the commercial fishery and "L-wt" is the length weight relationship used for weight and yield estimation

	Input parameters			Estimates		
	M	$L_{recruit}$	L-wt	$F_{0.1}$	F_{max}	$F_{50\%}$
Base case	0.30	30	all data	0.41	0.62	4.52
Sensitivity to M	0.20	30	all data	0.38	0.56	1.41
	0.40	30	all data	0.45	0.69	∞
Sensitivity to $L_{recruit}$	0.30	28	all data	0.38	0.58	0.70
	0.30	25	all data	0.34	0.52	0.39
Sensitivity to L-wt	0.30	30	1992 data	0.41	0.63	5.77
	0.30	30	1995 data	0.41	0.62	3.44
	0.30	30	1996 data	0.41	0.62	3.52

Given an assumed value for the rate of natural mortality, fishing mortality on the Snake Bank cockle population varies according to the size of the stock and the annual landings. Given the exploited nature of the stock, biomass now fluctuates largely according to recruitment success, and landings have been influenced in recent years mostly by closures due to rainfall or biotoxin events. Table 8 summarises changes in biomass and landings since 1991, during which time the fishery has been considered to be fully exploited. For each year in which an estimate of biomass is available, the current instantaneous rate of fishing mortality, $F_{current}$, was estimated by iterative solution of the Baranov catch equation assuming $M = 0.30$. The average instantaneous rate of fishing mortality for the three years in which data are available since 1991 has been 0.89 with a range of $F_{est} = 0.50$ to 1.55. This rate is fishing pressure is about double the current estimate of $F_{0.1}$.

Table 8: Estimates of biomass, landings, and estimated fishing mortality F_{est} for Snake Bank cockles assuming $M = 0.30$ and a size at recruitment of 30 mm. Projected fishing pressure is shown as F_{est} and as an index relative to $F_{0.1}$ for a range of management options for the 1996–97 fishing year (based on the 1996 biomass estimate reported here)

Survey year	Biomass (t)	Landings (t)	Source of landings information	F_{est}	F_{est} relative to $F_{0.1}$
1991	761	537	1991–92	1.548	–
1992	780	316	1992–93	0.620	–
1995	1 478	510	projected 95–96	0.502	–
Mean ‘91, ‘92, ‘95	1 006	454	calculated	0.890	–
1996	796	235	CAY ($F_{0.1}$) option	0.413	1.00
1996	796	323	CAY (F_{max}) option	0.620	1.50
1996	796	400	arbitrary option	0.843	2.04
1996	796	510	projected *status quo*	1.270	3.08
1996	796	584	maximum possible	1.693	4.10

Landings of about 510 t might be expected for the 1996–97 fishing year in the absence of further constraint on landings and assuming there is no long-term biotoxin event. This would lead to an estimated fishing pressure of $F_{est} = 1.27$ which is about three times the current estimate of $F_{0.1}$. This level of fishing pressure would probably lead to a considerable reduction in recruited biomass.

4.4.3 Predictive use of the quarterly YPR model

The yield per recruit model can be used to predict the future length frequency distribution and relative biomass of cockles on Snake Bank under conditions of steady recruitment and fishing pressure. To predict population length composition for a given season, the predicted age distribution of individuals from the YPR model was converted to an expected length distribution using estimates of mean length at age and cohort width from the best MULTIFAN fit to 1991–96 length frequency distributions (*see* Appendix 1). This is essentially the reverse process to the application of an age-length key to a length frequency distribution to estimate an age frequency distribution.

Expected length frequency distributions for Snake Bank cockles under equilibrium fishing pressures of $F_{ref} = F_{0.1}$, $2*F_{0.1}$, and $3*F_{0.1}$ (approximately equivalent to a CAY($F_{0.1}$) strategy and catch limits of 400 and 500 t, respectively) and under assumed sizes at recruitment to the fishery of 25, 28, and 30 mm are shown in Figures 9 to 11. Predicted equilibrium recruited biomass is roughly proportional to the heights of the second (recruited) modal length classes.

The expected length frequency distribution is always bimodal, reflecting the implicit assumption of continued successful (and steady) recruitment. Under conditions of variable recruitment, the relative heights of the recruiting and "adult" peaks in the length frequency distributions would vary according to recent historical recruitment. On the average, however, length frequency distributions should approximate those generated through simulation. The simulated length frequency distribution for $F_{ref} = F_{0.1}$ and $L_{recruit} = 30$ mm is very similar to the 1996 population length frequency distribution (although the latter cannot be considered to be in equilibrium). The height of the second length mode relative to the first mode decreases for all simulations with increasing fishing pressure, and with decreasing size at recruitment. The extreme case of $F_{ref} = 3*F_{0.1}$ and $L_{recruit} = 25$ mm (a continuation of recent average landings applied to current biomass and a smaller minimum size) leads to the so few cockles surviving to 30 mm that the second length mode is almost flattened to a shoulder. Very few cockles survive under these conditions to the size of interest to commercial and amateur fishers.

4.5 Yield Estimates

4.5.1 Estimation of Maximum Constant Yield

MCY was calculated using the equation

$$MCY = 0.50 * F_{ref} * B_{av}$$

where F_{ref} is a reference fishing mortality, and B_{av} is the average recruited biomass during a time when the fishery is thought to have been fully exploited (Method 2, Annala & Sullivan 1996). Average recruited biomass was estimated as the mean of all survey estimates from 1991 to 1996 (during which time the fishery is thought to have been fully exploited) being 954 t with a standard error of 175 t (*c.v.* = 18%). $F_{0.1} = 0.41$ and $F_{max} = 0.62$ were selected as alternative reference fishing mortality rates. This calculation using $F_{0.1} = 0.41$ is directly analogous to that carried out for the May 1996 assessment (Annala & Sullivan 1996), but incorporates the new survey and reference fishing mortality information.

For $F_{0.1}$, $MCY = 0.50 * 0.41 * 954 = 196$ t (rounded to 200 t), or

For F_{max}, $MCY = 0.50 * 0.62 * 954 = 296$ t (rounded to 300 t)

The level of risk to the stock by harvesting the population at either of the estimated MCY values cannot be determined, but would be greater for the F_{max} option. Both estimates of MCY would have an associated *c.v.* of at least 18% (that associated with the estimate of average biomass).

4.5.2 Estimation of Current Annual Yield

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

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

where F_{ref} is a reference fishing mortality, M is natural mortality, and B_{beg} is the start of season recruited biomass. Using the new estimates of $F_{0.1} = 0.41$ and $F_{max} = 0.62$ as alternatives for F_{ref}, the estimate of M = 0.30 from Cryer & Holdsworth (1993) and the latest estimate of recruited (30 mm or greater) biomass, therefore:

For $F_{0.1}$, CAY = 0.5775 * 0.5084 * 796 t = 234 t (rounded to 235 t), or

For F_{max}, CAY = 0.6739 * 0.6015 * 796 t = 323 t (rounded to 325 t)

The level of risk to the stock by harvesting the population at either of the estimated CAY values cannot be determined. Both estimates of CAY would have an associated *c.v.* of 8% (that associated with the estimate of current absolute biomass).

4.5.3 Factors modifying yield estimates

As amateur, Maori, and commercial interest relates mainly to cockles of 30 mm shell length or greater, 30 mm has been assumed as the size at recruitment. Biomass and yield estimates for different sizes at recruitment are different (Table 9). The assumed size at recruitment in 1983 was 35 mm and few cockles smaller than this were taken from the bank. However, over the years the commercial fishery has taken progressively smaller cockles and a new assumed size at recruitment of 30 mm was introduced in about 1990 to take account of this shift. Some cockles as small as 27–28 mm shell length have been taken by the commercial fishery in recent years, although an electivity index calculated for commercial pickers does not indicate positive selection until 29–30 mm shell length.

The estimated value for recruitment variability for Snake Bank cockles of $\sigma_R = 0.31–0.41$ is probably an underestimate and, even if correct, does not give strong guidance on the choice between $F_{0.1}$ and F_{max} as a reference fishing mortality as part of a CAY strategy. If recruitment is particularly variable (as it is for orange roughy at $\sigma_R = 1.10$), then the more conservative $F_{0.1}$ should probably be the target mortality of choice, whereas under conditions of steady recruitment, F_{max} might be appropriate to achieve higher yield with little apparent risk. The estimated value of recruitment variability for Snake Bank cockles is low, suggesting that other factors should be taken into consideration in choosing a reference fishing mortality.

Factors which might be considered in the choice of a reference fishing mortality, especially in a mixed commercial / non-commercial fishery are the expected size and standing biomass of individuals predicted to become available for harvest under different regimes. Predictions of equilibrium conditions from the yield per recruit model (Table 9) suggest that the choice of reference fishing mortality and size at recruitment will have little effect on the average length and weight of available cockles, but that equilibrium standing biomass is quite sensitive to these choices. If it is assumed that the current biomass (about 33% of B_0) is close to B_{msy}, and that a CAY policy using $F_{ref} = F_{0.1}$ is likely to maintain this situation, then strategies using F_{max} are predicted to reduce long-term recruited biomass to as low as 50% of B_{msy}. Further, while CAY_{1996} is considerably greater for F_{max} strategies than for $F_{0.1}$ strategies, the predicted long term CAY (= MAY, *sensu* Annala & Sullivan 1996) is quite similar for all strategies. Thus, while considerable additional yield can probably be extracted from the fishery in the short term, the long term yield is likely not to be much greater, and the cost (risk) in terms of reductions in recruited biomass below B_{msy} could be considerable.

Table 9: Variation in estimated 1996 recruited biomass (B_{1996} estimated from length frequency distributions and a length weight regression), the reference fishing mortality $F_{0.1}$ or F_{max} (from a yield per recruit analysis), and estimated yield (CAY_{1996}) with changes in the assumed length at recruitment ($L_{recruit}$) to the Snake Bank cockle fishery. Predicted equilibrium values for mean length (L_{av}), mean weight (W_{av}), and standing biomass (relative to the base case: B/B_{msy}) of cockles 28 mm in length or greater, and for average recruited biomass (B_{av}) and long term average CAY (CAY_{av}) assuming given values of $L_{recruit}$ were generated using a quarterly yield per recruit model assuming that B_{1996} is close to B_{msy} and that a CAY($F_{0.1}$) policy is likely to maintain this situation

								Equilibrium values
	Assumed values					Cockles >28 mm		Cockles $>L_{recruit}$
$L_{recruit}$ (mm)	B_{1996} (t)	F_{ref}	CAY_{1996} (t)	L_{av} (mm)	W_{av} (g)	B/B_{msy}	B_{av} (t)	CAY_{av} (t)
		At $F_{0.1}$ =						
30	796	0.41	234	31.00	14.23	1.000	796	234
28	1 027	0.38	283	30.90	14.10	0.801	823	227
25	1 314	0.34	330	30.88	14.07	0.678	891	224
		At F_{max} =						
30	796	0.62	324	30.91	14.11	0.887	712	289
28	1 027	0.58	396	30.75	13.89	0.647	664	256
25	1 314	0.52	466	30.71	13.83	0.500	657	233

Given that cockles recruit to the spawning biomass at about 18 mm shell length, but do not recruit to commercial or non-commercial fisheries until closer to 30 mm shell length, there is probably considerable protection for the stock against egg overfishing. As the Snake Bank cockle population may receive spat from other parts of Whangarei Harbour, it may not be realistic to assume that the Snake Bank stock is discrete and self-recruiting, and that reduced egg production (as a result of heavy fishing mortality on medium and large sized individuals) would necessarily lead to egg overfishing. Spawning stock biomass per recruit analysis suggests that $F_{50\%}$ is usually much greater than F_{max} except where a very small size at recruitment (25 mm shell length) is considered as a sensitivity test. Serious depression of egg production is therefore unlikely if fishing mortality is restrained to within F_{max}, and the size of interest to the fishery does not fall below about 26 mm.

However, recruitment in *A. stutchburyi* can be depressed by the removal of a large proportion of adult cockles from a given area of substrate (Martin 1984). Conversely, there did not seem to be heavy recruitment to Snake Bank during the years when adult biomass was close to virgin (1982 to 1985), and there appears to have been relatively consistent recruitment since 1992. This would be consistent with observations on several bivalve populations overseas that recruitment can be depressed by high densities of adults (through intraspecific competition) and by low densities of adults (through, for example, sediment conditioning or suppression of predators). This suggests that there may be some optimal range of adult biomass within which recruitment of juveniles is more likely to be successful, although the limits of this range are not known.

It would appear prudent, therefore, to exercise some caution in depressing the biomass of adult cockles. If adult biomass is driven too low, then recruitment overfishing of this population could still occur through the inhibition of spatfall or early juvenile survival, despite high levels of egg production. In addition, sporadic recruitment of juveniles (perhaps in response to environmental variables such as temperature and precipitation) will probably lead to a fluctuating biomass, suggesting that a CAY approach may be more appropriate than a constant catch approach.

5. Management Implications

Catch limits for the Snake Bank cockle fishery have not been modified since their inception as rather arbitrary daily limits not intended to define an annual total quota. Increased commercial fishing activity in the late 1980s and 1990s towards the theoretical upper limit imposed by the daily limit has significantly reduced recruited biomass and curtailed the right hand limb of the length frequency distribution. Recruitment and growth rates may have increased (as might be expected from overseas studies of similar species and from ecological theory), but the fishery is now essentially recruitment-driven and dependent on continued of pulses of recruitment.

Since 1989–90, reported landings have exceeded all estimates of MCY and CAY, other than in 1995 when CAY was close to the theoretical upper limit imposed by daily limits, following excellent recruitment. Recent average fishing mortalities, F_{est}, are much greater than the reference fishing mortalities F_{max} or $F_{0.1}$, although not as great as $F_{50\%}$. Biomass has fallen considerably during these years, despite good recruitment (the three most recent recruitment indices being the highest in the history of the fishery). Current biomass, $B_{current}$, is about one-third of virgin biomass, B_0, and is probably close to B_{msy}.

Alternative estimates of yield are given here based on strategies using $F_{0.1}$ and F_{max}. For a constant catch regime based on MCY, an F_{max} strategy would entail higher (though unquantified) risk for the stock than a strategy based on $F_{0.1}$. For a constant mortality regime based on CAY, either reference mortality could be adopted. Predictions of equilibrium conditions derived from yield per recruit modelling suggest that long term yield using F_{max} and $L_{recruit}$ = 30 mm should be about 25% greater than that using $F_{0.1}$. However, an F_{max}

strategy is likely to lead to further reductions in recruited biomass (probably to levels below B_{msy}), especially if the assumed or actual size at recruitment to the fishery declines much below 30 mm.

Acknowledgments

I am grateful to those hardy souls who trudged Snake Bank, invariably in August during screaming sou' westerlies, to pick and measure cockles for these assessments. Thanks also to John Holdsworth of MFish for his continued interest, patience, and support during all stages of the work. Paul Taylor, John Cranfield, and John Annala and many members of the Shellfish Stock Assessment Working Group made perceptive comments on several earlier drafts which have considerably improved the work.

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Appendix 1: Output files from Multifan 32(d) analyses

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#  penalty contribution to the objective function 8.482500E-0002
#  L infinity    31.0
#  Brody rho  0.36
#  von Bertalanffy K  1.02
#  maximum magnitude gradient component = 4.0000E-0004
#  number of active parameters    15
#  standard deviations at age in month 1 are
#
#       3.38 3.38 3.38 3.38
#
#  the number of non-empty length intervals is   369
#  the approximate number of degrees of freedom is   354
#  the estimated age of the first age class  0.20
#
#   number of age classes
              4
#
#     first length      minimum first      maximum first
 5.614716053E+0000           0.000              8.965
#      last length      minimum last       maximum last
 2.983645439E+0001          26.836             42.000
#           K             minimum  K         maximum  K
 1.019677997E+0000         0.68000            1.32000
#
#  First month mean length sampling bias for first age class
 0.000000000E+0000
#
#    ------- seasonal growth -------
#       amplitude             phase
 9.507139921E-0001 -4.05419990E-0002
#  average std dev   min avg std dev   max avg std dev
 3.378536940E+0000           1.308              3.488
#    ------- ratio of the last/first std dev -------
#          ratio      minimum ratio     maximum ratio
 1.000000000E+0000           0.500              2.000
#  bounds on the standard deviation of the first age class
#      lower bound        upper bound
          1.3080             3.4881
#  bounds on the standard deviation of the last age class
#      lower bound        upper bound
          1.3080             3.4881
```

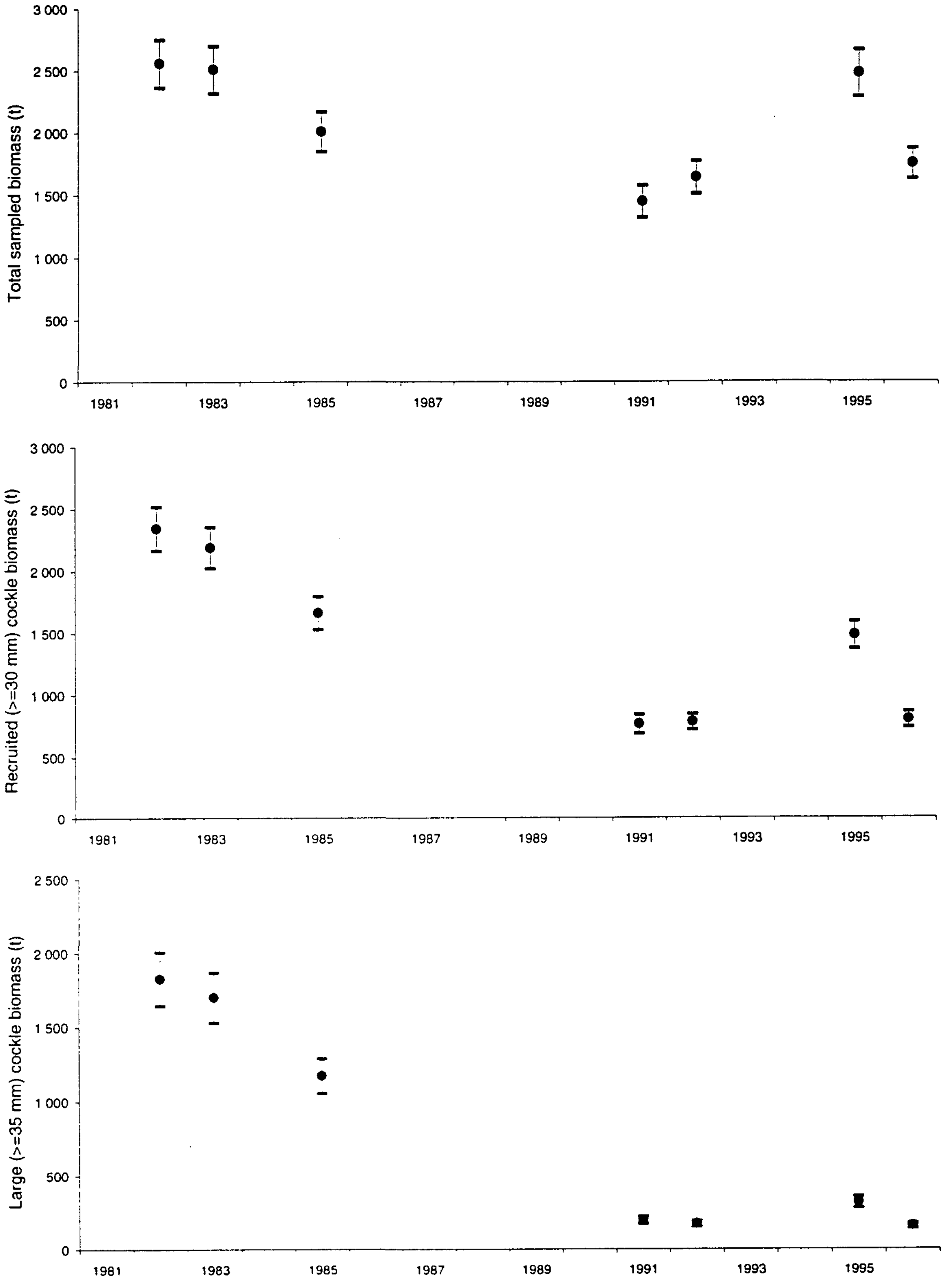

Figure 1: Trajectories (± one standard error) of total, recruited (>30 mm), and large (>35 mm) cockle biomass on Snake Bank since the inception of the fishery in 1982.

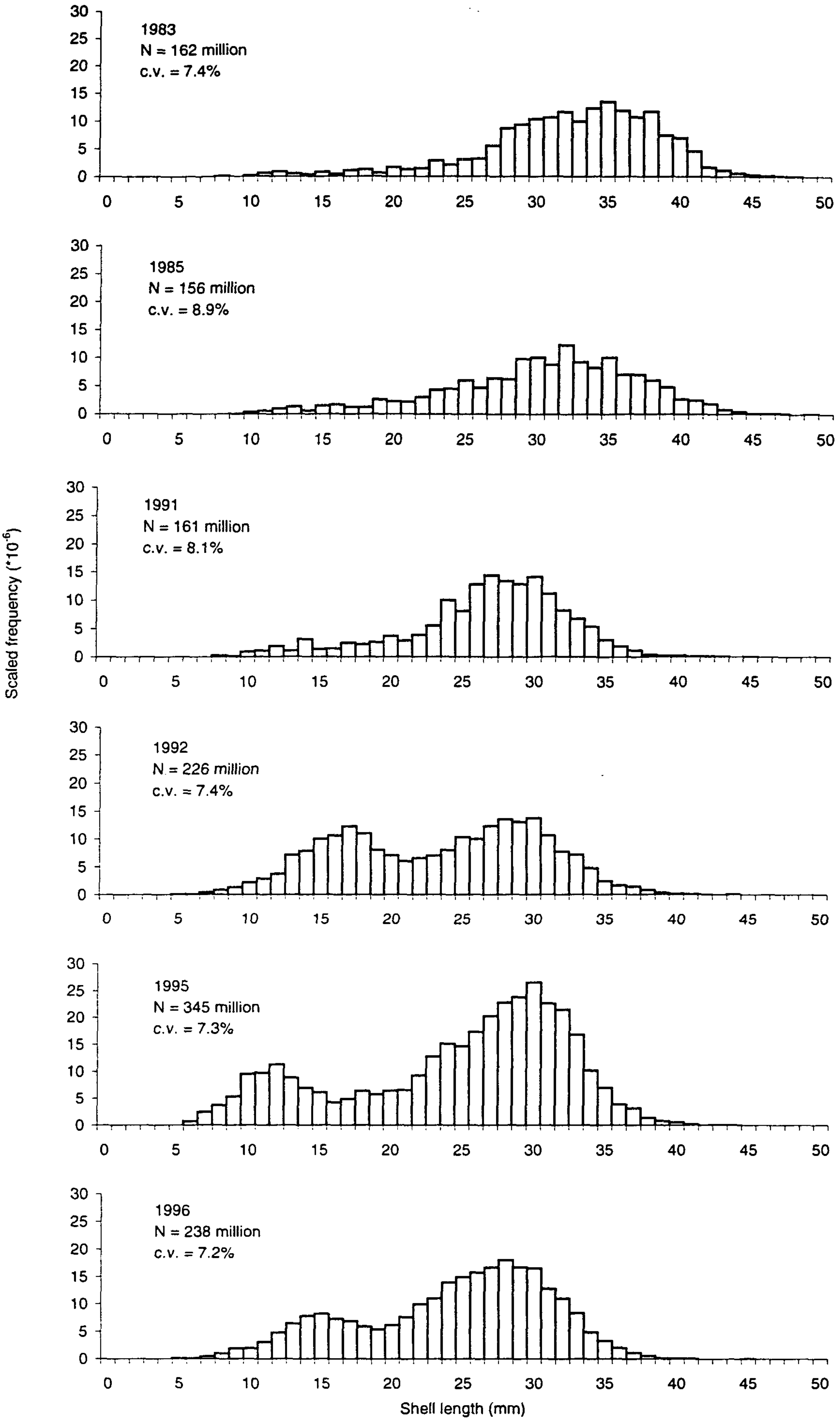

Figure 2: Length frequency distributions, scaled to total population size, for cockles on Snake Bank, Whangarei Harbour, during full biomass surveys, 1983–96.

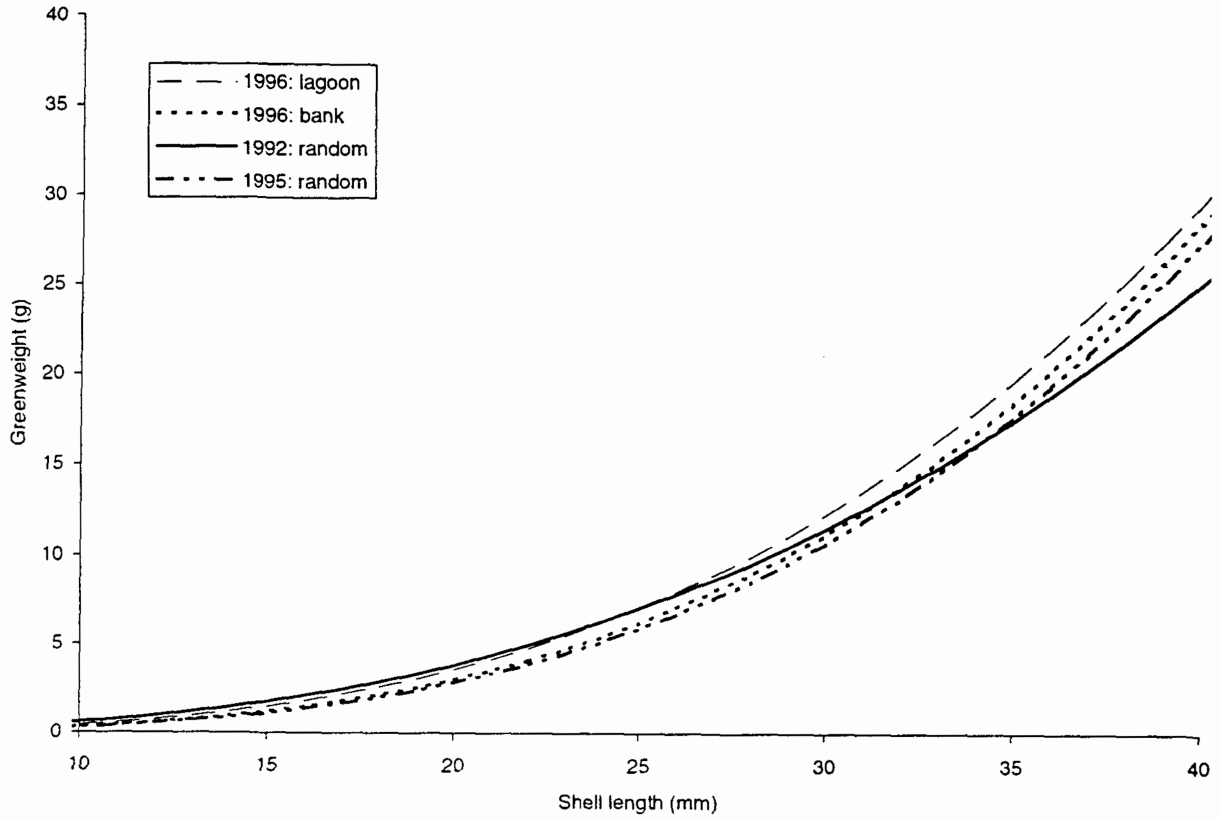

Figure 3: Length weight regressions for Snake Bank cockles in 1992, 1995, and 1996. 1996 data separated into the low-lying lagoon area and elsewhere on the bank, data for other years collected at random.

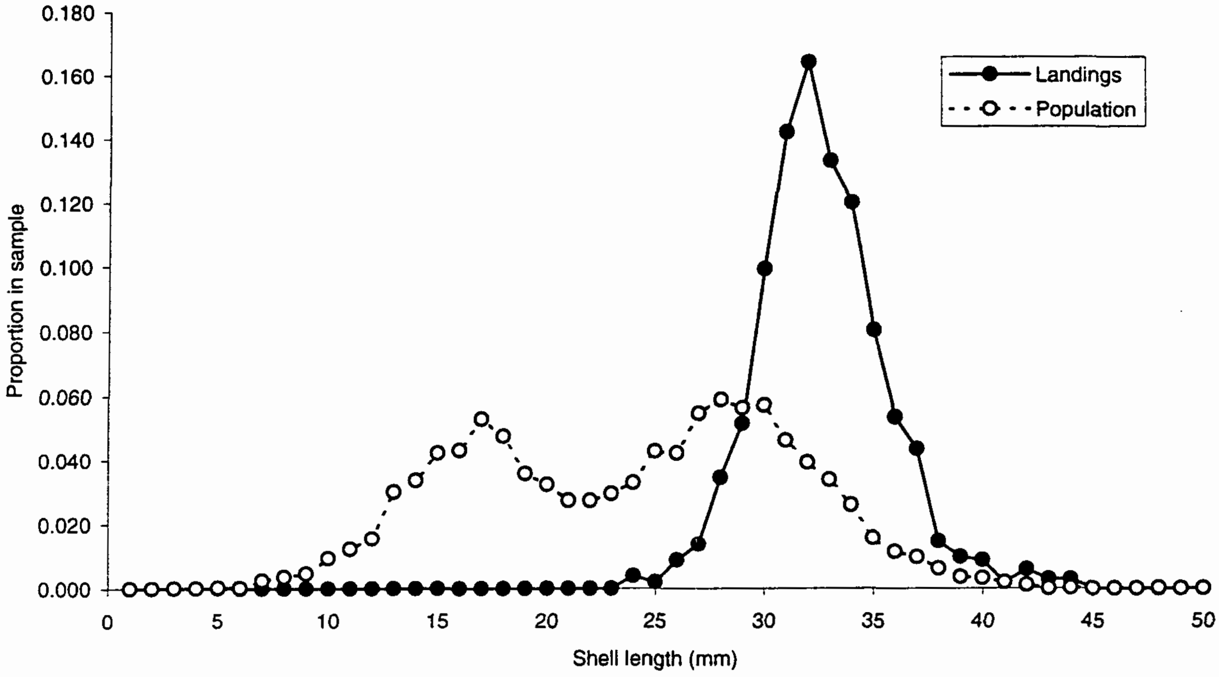

Figure 4: Proportional length fequency distribution of cockles on Snake Bank and measured from landings in commercial packing sheds in 1992.

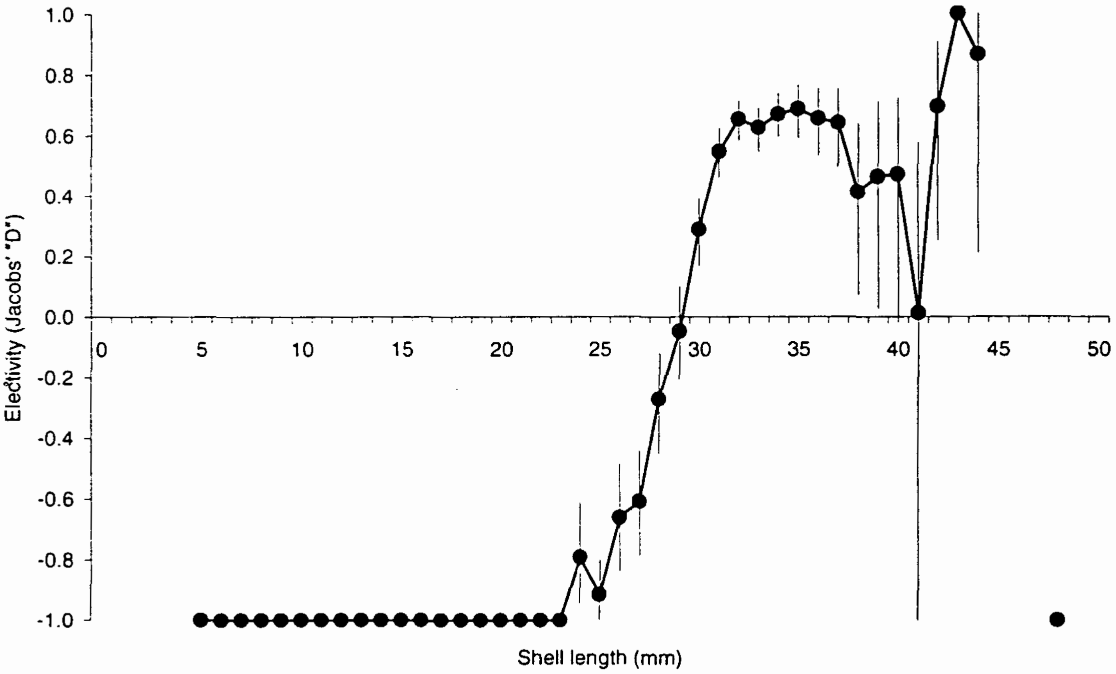

Figure 5: Electivity (as Jacobs' "D") of commecial pickers for cockles on Snake Bank in 1992. Possible values of D range from +1 to -1, positive values indicating a proportion in landings higher than in the environment and vice versa. Vertical bars represent approximate 95% confidence interval calculated using a bootstrap technique.

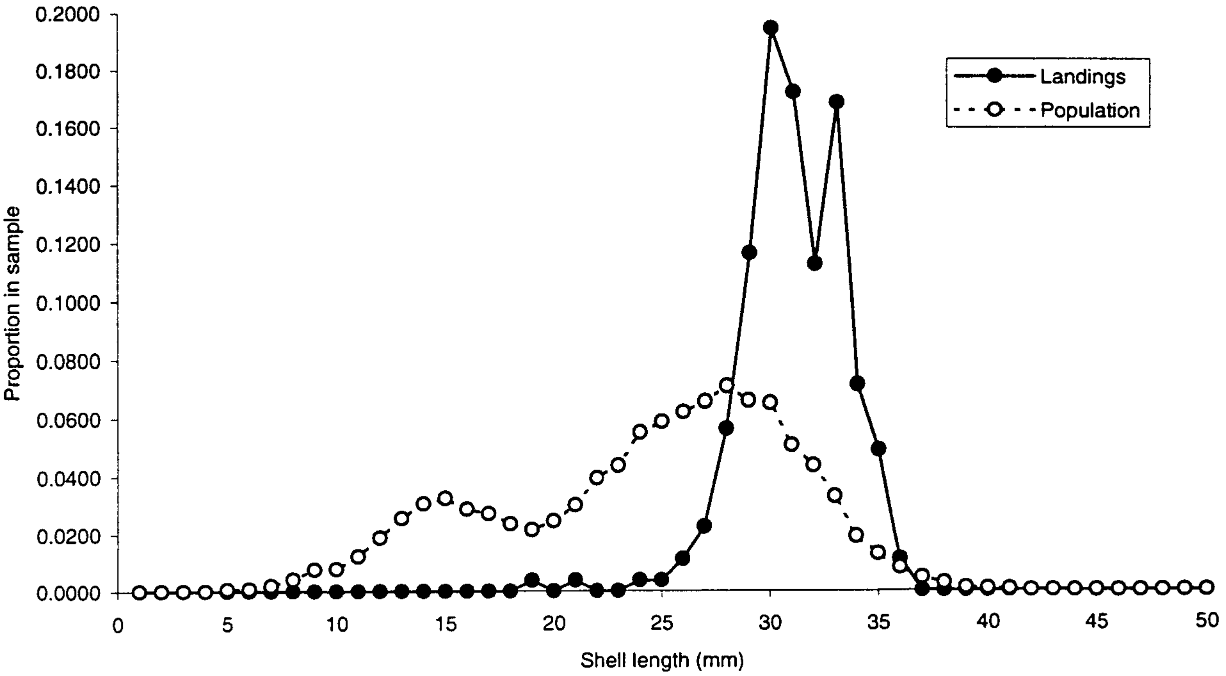

Figure 6: Proportional length fequency distribution of cockles on Snake Bank and measured from landings in commercial packing sheds in November 1996.

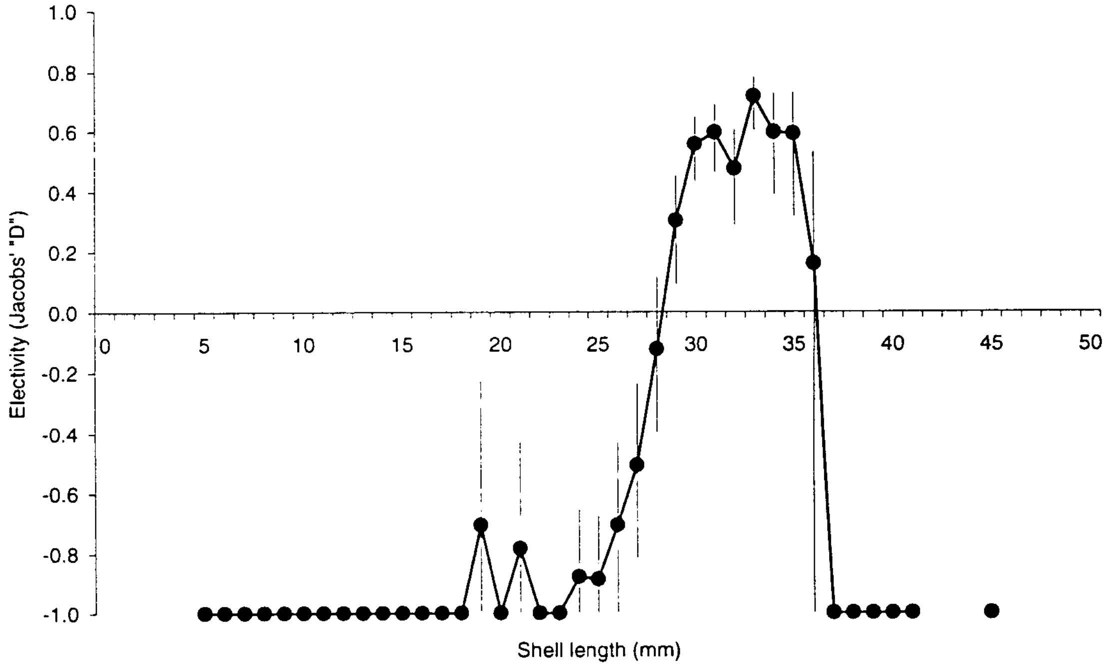

Figure 7: Electivity (as Jacobs' "D") of commecial pickers for cockles on Snake Bank in 1996. Possible values of D range from +1 to -1, positive values indicating a proportion in landings higher than in the environment and vice versa. Vertical bars represent approximate 95% confidence intervals calculated using a bootstrap technique.

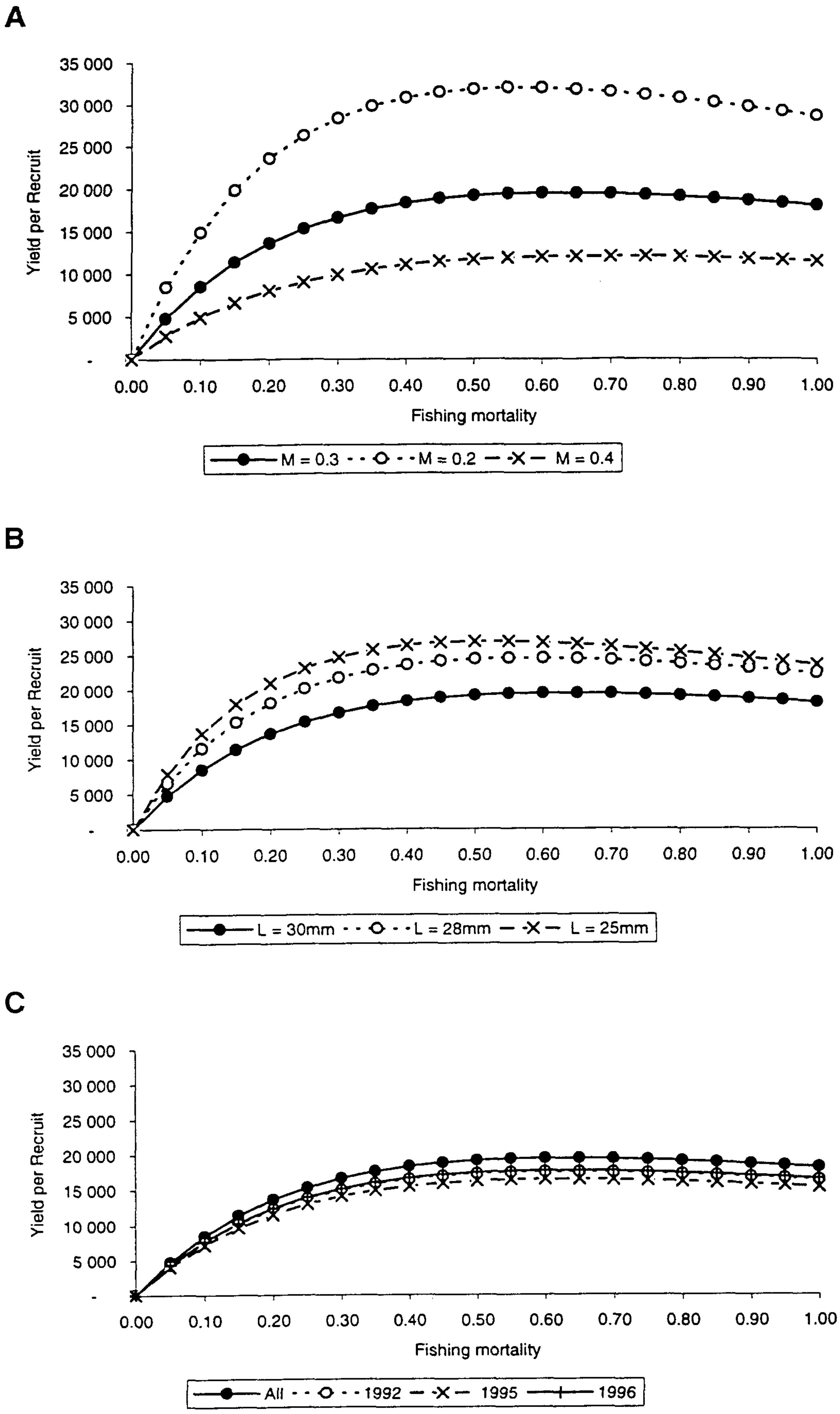

Figure 8: Yield per recruit curves for Snake Bank cockles. In all cases, the base case analysis is shown as a solid line with closed circles, and sensitivity tests otherwise. Plots show sensitivity to A, assumed rate of natural mortality; B, assumed length at recruitment to the fishery; C, assumed length weight regression for estimating mean weight.

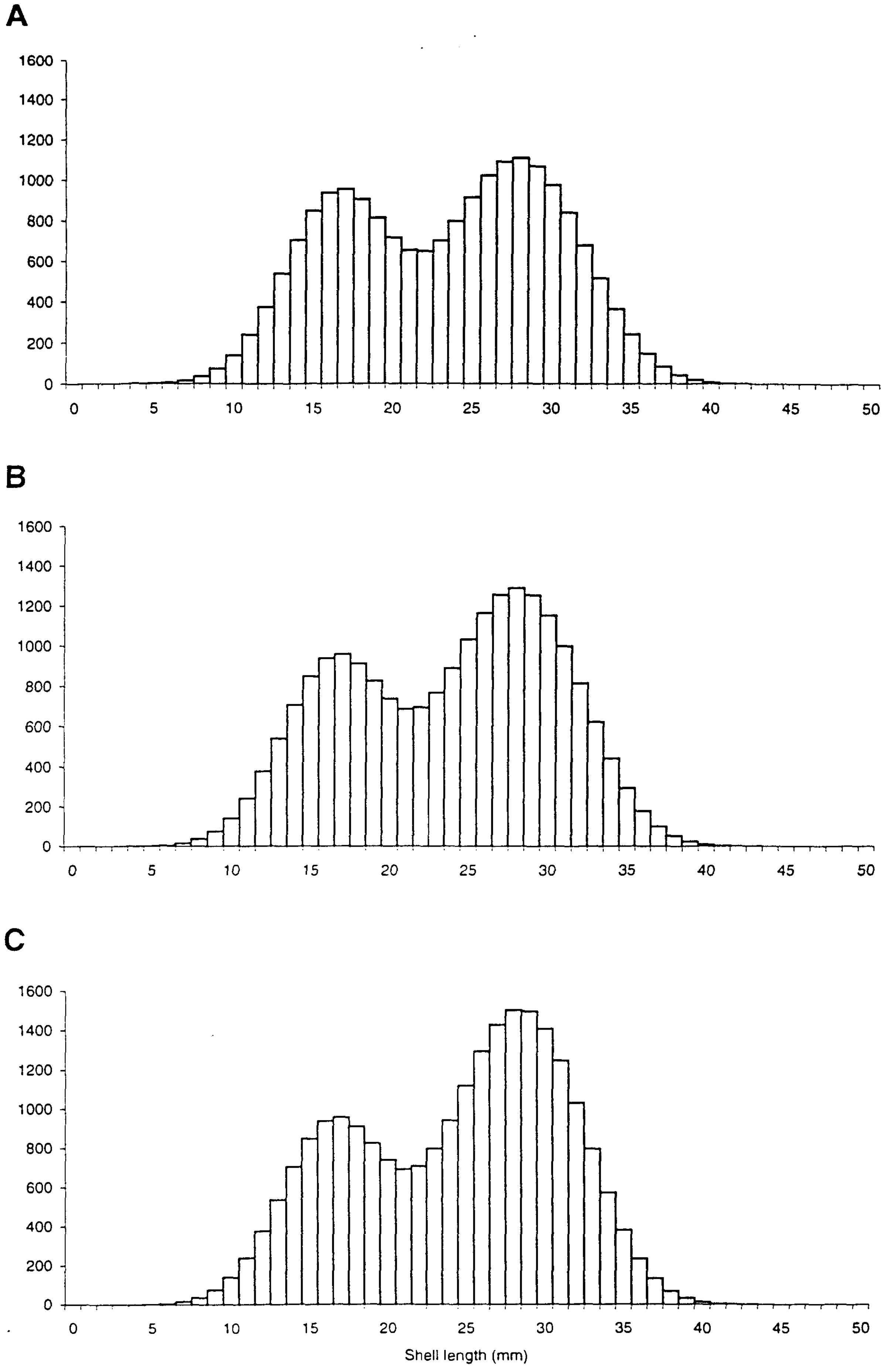

Figure 9: Simulated length frequency distributions for Snake Bank cockles in July given constant recruitment and a constant rate of fishing mortality of $F = F_{0.1}$. Length at recruitment to the fishery is assumed to be A, 25 mm; B, 28 mm; and C, 30 mm). Frequency distributions from 10 000 recruits at age 0.

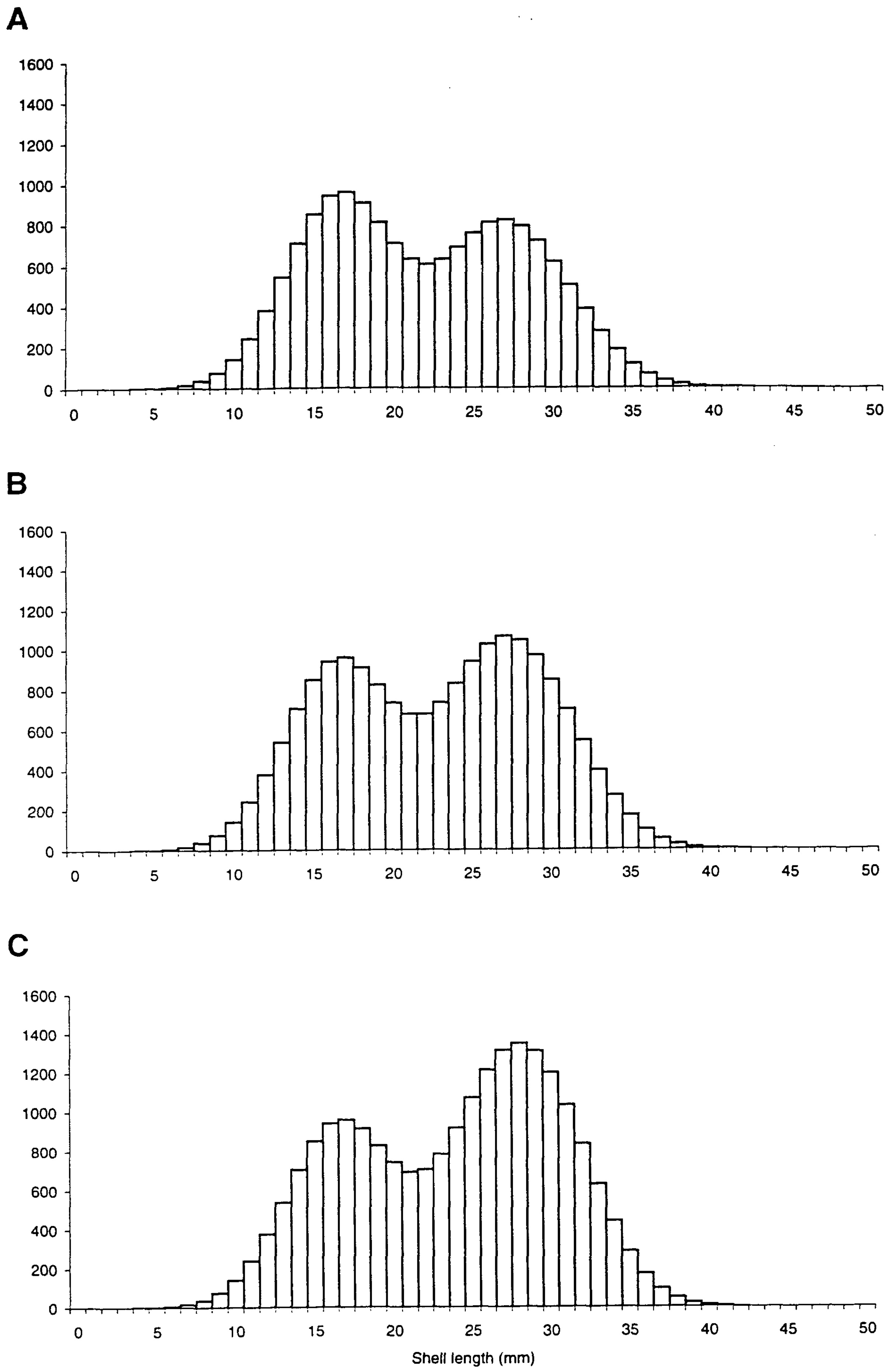

Figure 10: Simulated length frequency distributions for Snake Bank cockles in July given constant recruitment and a constant rate of fishing mortality of $F = 2*F_{0.1}$. Length at recruitment to the fishery is assumed to be A, 25 mm; B, 28 mm; and C, 30 mm). Frequency distributions from 10 000 recruits at age 0.

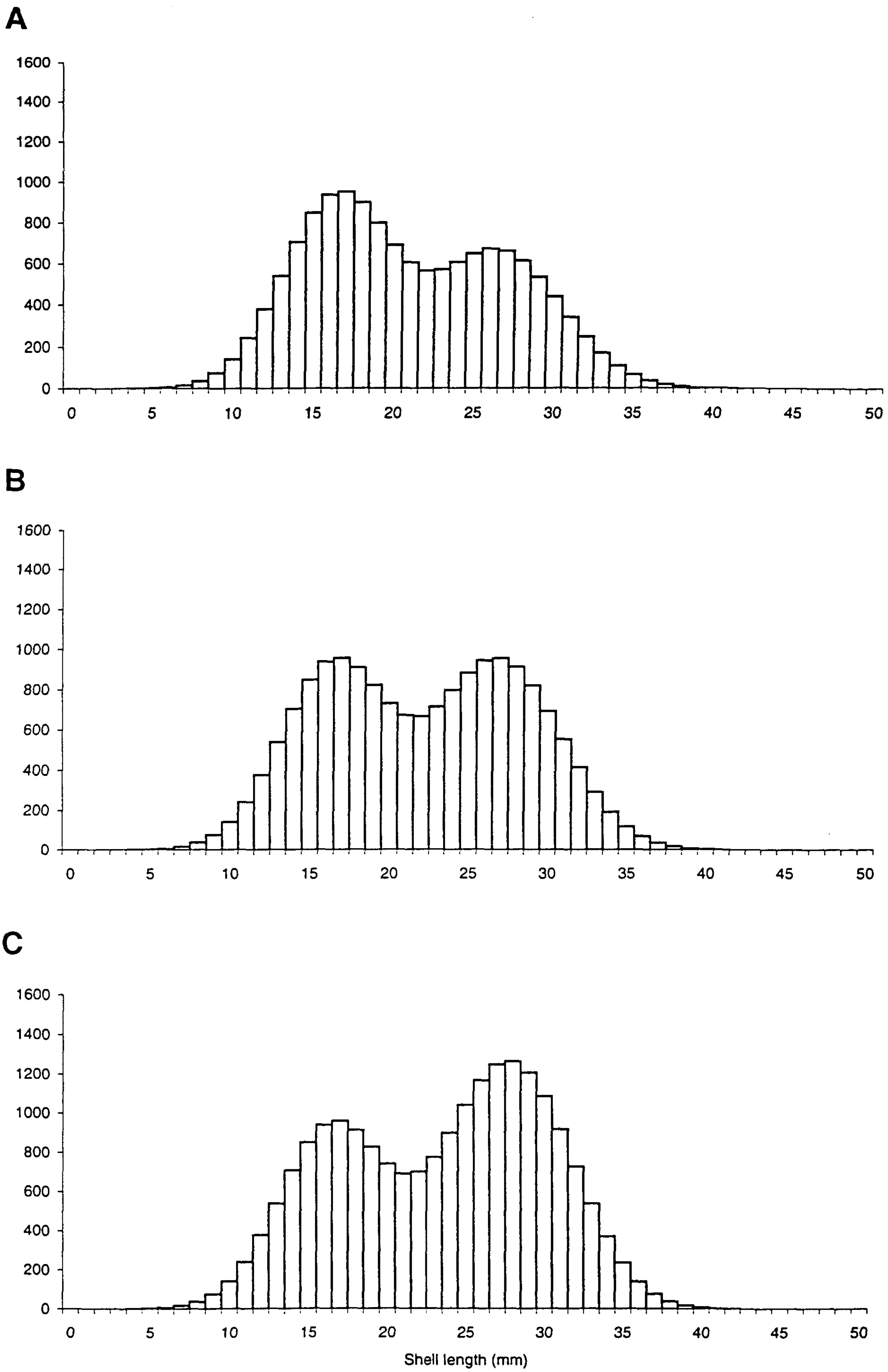

Figure 11: Simulated length frequency distributions for Snake Bank cockles in July given constant recruitment and a constant rate of fishing mortality of $F = 3^*F_{0.1}$. Length at recruitment to the fishery is assumed to be A, 25 mm; B, 28 mm; and C, 30 mm). Frequency distributions from 10 000 recruits at age 0.