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EXECUTIVE SUMMARY

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This report describes a Bayesian, length-based, single-sex, stock assessment model for Foveaux Strait dredge oysters including data up to the end of the 2002–03 fishing year, and unstandardised and standardised CPUE indices for Foveaux Strait dredge oysters. The stock assessment is implemented using Bayesian estimation, in the general-purpose stock assessment program CASAL v2.01. The report describes the available data, structural assumptions, parameterisation of the models (including incorporating processes related to the *Bonamia exitiosa* disease epidemics), and model output. Model estimates, including projections, are also presented.

The Foveaux Strait dredge oyster fishery presents a number of unique problems in the development of a stock population model. There is a lack of good information on recruitment, growth, natural mortality, and quantitative information of the impact and mechanism of disease mortality from *B. exitiosa*. But there is good information on the size structure of the oyster population in recent years, and a time series of absolute abundance estimates (assuming the survey series are correctly calibrated) over a reasonably long period.

The model presented here, whilst fairly representing some of the data, also shows some indications of lack of fit. It is unlikely the estimates of historical stock size are reliable, given assumptions about annual recruitment and the use of the historical catch-effort indices of abundance. In particular, the selectivity and epidemiology of *B. exitiosa* is not well understood, with little available data on the size and maturity status of oysters that have been infected with and have died from *B. exitiosa*. However, model estimates of recent and current status agree closely with recent CPUE and survey abundance indices.

The model estimates of the state of the Foveaux Strait oyster stock suggest that there has been a dramatic reduction in the vulnerable abundance since the outbreak of the recent *B. exitiosa* epizootic, and that historical exploitation rates have been low. Current estimates suggest that the current spawning stock size was about 20% (19–22%) B_0, and recruit-sized stock abundance (rB_{2003}) was about 9% (8–11%) of initial state (rB_{1907}).

While uncertainty exists in levels of future recruitment and continued *B. exitiosa* related mortality, projections indicate that current catch levels are unlikely to have any significant effect on future stock levels. Instead, future disease mortality will determine future stock status. Depending on the level of assumed disease mortality, projected status in 2006 ranged from almost twice current levels (with no disease mortality) to about a third of current levels (assuming disease mortality of $0.6\ y^{-1}$).

1. INTRODUCTION

This report describes a Bayesian, length-based, single-sex, stock assessment model for Foveaux Strait dredge oysters including data up to the end of the 2002–03 fishing year, and unstandardised and standardised CPUE indices for Foveaux Strait dredge oysters. The report describes the available data, structural assumptions, parameterisation of the models (including incorporating processes related to the *Bonamia exitiosa* (Berthe & Hine 2003) disease epidemics), and model output. The stock assessment is implemented using Bayesian estimation, in the general-purpose stock assessment program CASAL v2.01 (Bull et al. 2003).This report updates and improves upon an initial stock model presented by Dunn (2004).

Foveaux Strait dredge oysters have been commercially exploited for almost 140 years (Sorensen 1968, Cranfield et al. 1999a), with historical records suggesting that commercial landings have totalled about 5000 million oysters since 1907.

Investigations of the extent and abundance of oysters in Foveaux Strait have been conducted since the mid 1870s (Sorensen 1968). Early studies included a report by the Commissioner of Crown Lands, W.H. Pearson, who reported on the state of the Foveaux Strait oyster beds. The first described survey was by R.E. Hunter in 1906 (Hunter 1906), following "complaints from retailers ... that badly culched oysters from Bluff had been received" (Sorensen 1968). A second survey was commissioned in 1926, and led by M.W. Young (Sorensen 1968). In 1945, E.F. Watson surveyed oyster beds following a request from the industry (Sorensen 1968). However, records from this survey were not analysed, and may have been lost in a fire in the Marine Department in the 1950s (Vivienne Cuff, National Archives New Zealand, pers. comm.). These surveys appear to have concentrated efforts on the oyster beds known at the time, but details of the survey region, methods, and calibration are not recorded. Hence, abundance estimates from these surveys cannot be determined.

D.H. Stead surveyed the Foveaux Strait oyster fishery area between 1960 and 1964, using a systematic survey design, as well as conducting dredge calibration experiments. Abundance and distribution surveys continued in 1973, 1974–75, 1975–76, and then more consistently between 1990 and 2002. Inter-dispersed with the abundance surveys were smaller, targeted *Bonamia exitiosa* samplings of the recruited population. The surveys since 1990 covered most of the present Foveaux Strait fishery area and used standardised dredge designs and survey methods. The more recent abundance surveys can be used to provide a consistent time series of observations of the fishery.

Allen (1979) developed a yield model for the Foveaux Strait oyster population, based on the region of Foveaux Strait fished at that time. However, he found that insufficient data were available for estimation of the population parameters. Since then, stock assessment has been restricted to estimates of CAY (see Annala et al. 2003), based on the results of the absolute abundance surveys and arbitrary biological reference point ($F_{0.1}$).

This stock assessment model has been developed as a Bayesian, length-based model, implemented using the general-purpose stock assessment program CASAL v2.01 (Bull et al. 2003). The report discusses aspects of the model implementation, model inadequacies, and provide estimates of current stock status as well as indicative projections for Foveaux Strait dredge oysters.

This report fulfils Objective 1 "To develop a length-based stock assessment model for Foveaux Strait oysters, including estimating abundance and sustainable yields" and Objective 2 "To analyse the Foveaux Strait oyster catch and effort data to provide a standardised CPUE index for inclusion into a length-based stock assessment model" of Project OYS2003/01.

1.1 Description of the fishery

Oysters have been commercially harvested from around Stewart Island by hand gathering since the 1860s and from Foveaux Strait by dredging since the 1870s. Since then, fishing methods, vessels, and dredges have changed considerably. In the 1870s, small sailing cutters, that each towed one small hand-hauled dredge, were used. Oil-powered engines were introduced in 1890 to haul the dredges. By 1913, sailing cutters were replaced with steam-powered vessels that towed two 3.35 m wide dredges weighing about 150 kg. With time, oyster vessels became more powerful and dredges heavier.

Currently oyster vessels tow two steel double-bit dredges, each 3.3–3.35 m wide and weighing 550 kg, on steel warps. The dredges are towed simultaneously on the vessel's port side, with each dredge towed off its own derrick. The dredges are usually towed along an elliptical track. Once the dredges are shot the vessel drifts down tide under minimal power turning into the tide to haul. The dredge contents are emptied on to culching benches and the oysters sorted and sized by hand.

Legal sized oysters (those that cannot pass through a 58 mm internal diameter ring) are sorted from the catch and small oysters and bycatch returned to sea through chutes. Legal sized oysters are packed live into sacks and are landed daily. Oysters are trucked from the docks to opening facilities, mainly in Bluff and Invercargill, on the day of landing. Oysters are shucked by hand the following day and marketed fresh chilled in New Zealand.

Oysters are harvested during a six-month season, defined by regulation (Southland Commercial Fisheries Regulations) as 1 March to 31 August, but oyster fishers determine the season start date between March and early June to avoid disturbing oysters after spawning, meet market demands and, more recently, to avoid increased risk of exacerbating *B. exitiosa*. The quota is usually caught some time before the end of August.

Boundaries of statistical areas for recording catch and effort were established in 1960 (but have been revised periodically since) and the outer boundary of the licensed oyster fishery was promulgated in 1979. The western fishery boundary in Foveaux Strait is a line from Oraka Point to Centre Island to Black Rock Point (Codfish Island) to North Head (Stewart Island). The eastern boundary is from Slope Point, south to East Cape (Stewart Island). Foveaux Strait and the current statistical reporting areas are shown in Figure 1.

From the late 1880s to 1962, the fishery was managed by limiting the number of vessels licensed to fish (typically between 5 and 12). The fishery was de-licensed in 1962 and boat numbers had increased to 30 by 1969. Catch limits were introduced between 1963 and 1969. From 1970 onwards vessel numbers were regulated at 23, restricting vessel numbers as well as restricting catch. In 1979 the oyster fishery was declared a licensed fishery for the 23 vessels, closing a loophole that allowed vessels to fish outside the designated fishery area. The number of vessels in the fishery then dropped from 23 in 1996 to 15 in 1997 and 12 in 2002.

In 1993 the fishery was closed after a *B. exitiosa* epizootic caused catastrophic mortality of oysters from 1986 to 1992. The fishery was reopened in 1996 with a reduced catch limit. In 1998, individual quotas were granted (Fisheries (Foveaux Strait Dredge Oyster Fishery) Amendment Act 1998) and quota holders permitted to fish their entire quota on one vessel. A second *B. exitiosa* epidemic in 2000 reduced oyster catch rates, and resulted in a reduction in catch from about 15 million oysters in 2002 to about 7 million oysters in 2003.

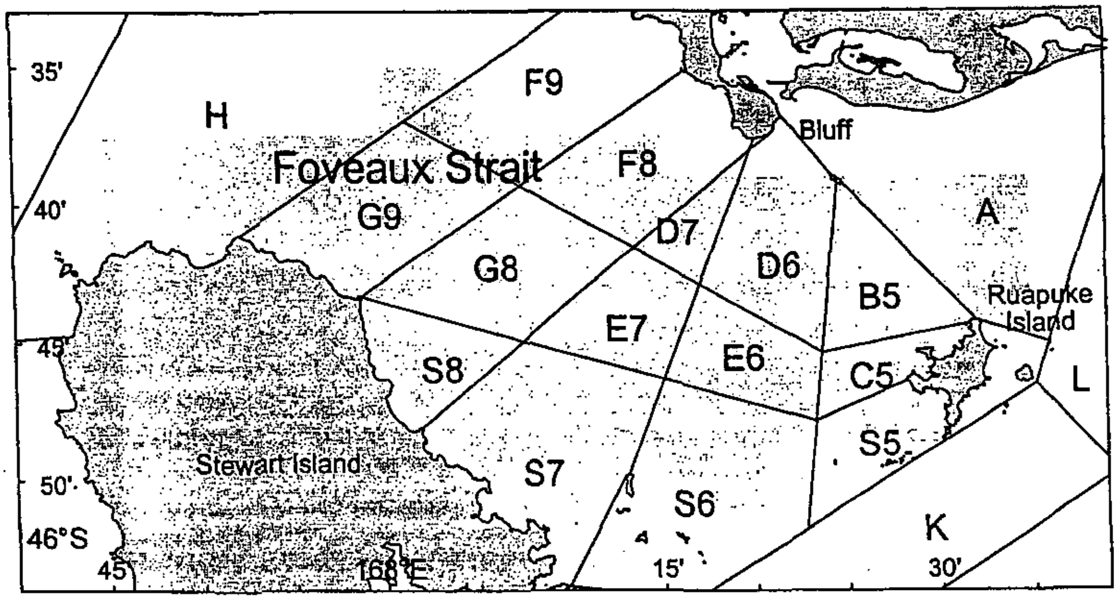

Figure 1: Foveaux Strait (OYU 5) statistical areas, with the shaded region showing the outer boundary of the October 2002 dredge survey and the region of Foveaux Strait considered by the population model.

2. MODEL STRUCTURE, INPUTS, AND ESTIMATION

2.1 Model structure

The population model partitioned Foveaux Strait oysters into a single sex population, with length (i.e., the anterior-posterior axis) classes 2 mm to 100 mm, in groups of 2 mm (i.e., from 2 to less than 4 mm, 4 mm to less than 6 mm, etc.), with the last group defined as oysters $\geq$ 100 mm. The stock was assumed to reside in a single, homogeneous area. The partition accounted for numbers of oyster by length class within an annual cycle, where movement between length classes was determined by the growth parameters. Oysters entered the partition following recruitment and were removed by natural mortality, disease mortality, and fishing mortality.

The model's annual cycle was based on the fishing year, divided into two time steps (Table 1). Note that model references to "year" within this paper refer to the fishing year, and are labelled as the most recent calendar year, i.e., the fishing year 1998–99 is referred to as "1999" throughout. References to calendar years are denoted specifically.

Catch data were available for 1907–2003, and these were used to define the years available to the model. Catches occurred in both time steps — with special permit and some customary catch assigned to the first time step (summer fishing mortality), and commercial, recreational, remaining customary, and illegal catch assigned to the second time step (winter fishing mortality).

Oysters were assumed to recruit to the model at age 1+ (see later), with a Beverton-Holt stock recruitment relationship (with an arbitrary steepness of 0.9, see Section 2.2.1) and length at recruitment defined by a normal distribution with mean 15.5 mm and c.v. 0.4. Recruitment was assumed to take place at the beginning of the second time step (i.e., the time step immediately following summer spawning).

Relative year class strengths were assumed known and equal to initial recruitment for the years up to 1984 — nine years before the first available length and abundance data on small (oysters less then 50 mm minimum diameter) and pre-recruits (oysters greater than or equal to 50 mm and less than 58 mm minimum diameter) were available; otherwise relative year class strengths were assumed to average 1.0.

Table 1: Annual cycle of the population model, showing the processes taking place at each time step, their sequence within each time step, and the available observations. Fishing and natural mortality that occur together within a time step occur after all other processes, with 50% of the natural mortality for that time step occurring before and 50% after the fishing mortality.

Step	Period	Process	Proportion in time step
1	Oct–Feb	Maturation	1.0
		Growth	1.0
		Natural mortality	0.5
		Fishing (summer) mortality	1.0
		B. exitiosa mortality	1.0
2	Mar–Sep	Recruitment	1.0
		Natural mortality	0.5
		Fishing (winter) mortality	1.0

Growth and natural mortality were assumed known (see Section 2.2.2). Disease mortality is assumed to be zero in the years where there were no reports of unusual mortality, and otherwise estimated (see Section 2.2.5)

The model used seven selectivity ogives: the commercial fishing selectivity (assumed constant over all years and time steps of the fishery, aside from changes in the definition of legal size); a survey selectivity, which was then partitioned into three selectivities (one for each for each of the size-groups) — small (greater than 50 mm minimum diameter), pre-recruit (greater than 50 mm and less than 58 mm minimum diameter), and recruit (greater than 58 mm minimum diameter); maturity ogive; and disease selectivity — assumed to follow a logistic curve equal to the maturity ogive (see Section 2.2.5 for detail).

The selectivity ogives for fishing selectivity, maturity, and disease mortality were all assumed to be logistic, where the parameterisation for each length class x was;

$$f(x)=1/\left[1+19^{(a_{50}-x)/a_{to95}}\right]$$

where x is the centre of the length class and estimable parameters are a_{50} and a_{to95}.

The overall survey selectivity ogive was assumed to be logistic with an additional parameter, a_{min}, that describes the minimum possible value of the logistic curve. The overall survey selectivity ogive was then split into three size categories using a compound selectivity (see Figure 2 for a graphical example of the compound logistic ogive parameterisation). Here, the selectivity of recruit sized oysters was assumed to be the product of the overall selectivity and a standard logistic ogive; the selectivity of pre-recruit sized oysters was assumed to be the product of the overall selectivity and a double logistic ogive; and the selectivity of small sized oysters was assumed to be the product of the overall selectivity and an inverse logistic ogive. Further, values for parameters of the respective selectivities for recruits, pre-recruits, and smalls were constrained so that they shared common values, i.e.,

$$f_{Overall}(x)=(1-a_{min})/\left[1+19^{(a_{50}-x)/a_{to95}}\right]+a_{min}$$

$$f_{Small}(x)=f_{Overall}(x)\times\left(1-1/\left[1+19^{(b_{50}-x)/b_{to95}}\right]\right)$$

$$f_{Pre\text{-}recruit}(x)=f_{Overall}(x)\times 1/\left[1+19^{(b_{50}-x)/b_{to95}}\right]\times\left(1-1/\left[1+19^{(b_{50}+b_{to50}-x)/b_{to95}}\right]\right)$$

$$f_{Recruit}(x)=f_{Overall}(x)\times 1/\left[1+19^{(b_{50}+b_{to50}-x)/b_{to95}}\right]$$

where a_{50} is the value of the 50% selectivity of the overall logistic curve, a_{to95} describes its slope, and a_{min} is the minimum value of the curve; b_{50} is the 50% selectivity of the left (inverse) logistic curve and b_{to95} describes its slope; $b_{50}+ b_{to50}$ is the 50% selectivity of the right logistic curve and b_{to95} describes its slope; and the middle double logistic is the product of the inverse of the left and right logistics.

Selectivity functions were fitted to length data from the survey proportions-at-length (survey selectivities), and to the commercial catch proportions-at-length (fishing selectivity). The data are described in Section 2.6.

The maximum exploitation rate (i.e., the ratio of the maximum catch to vulnerable numbers of oysters in any year) was assumed to be relatively high, and was set at 0.5. No data are available on the maximum exploitation rate, but the choice of this value can have the effect of determining the minimum possible virgin stock size (B_0) allowed by the model.

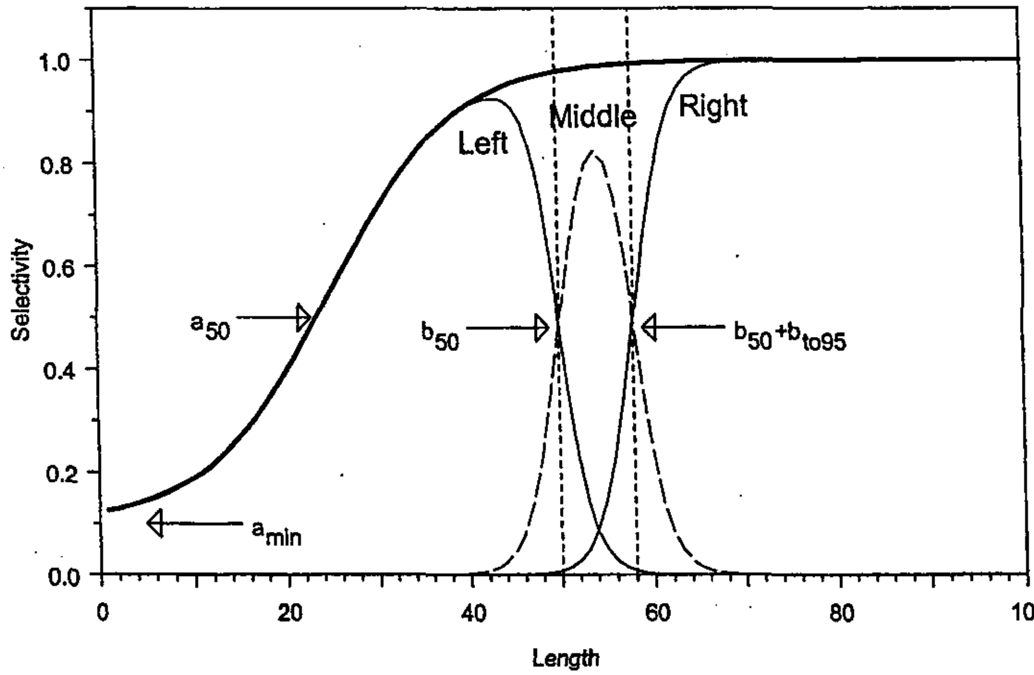

Figure 2: An example of the compound survey selectivity showing the overall selectivity (bold line, where a_{50}=25, a_{to95}=20, and a_{min}=0.1) and compound selectivity (where b_{50}=50, b_{to50}=8, b_{to95}=5) for (left) small (solid line), (middle) pre-recruit (dashed line), and (right) recruit sized (solid line) oysters. Vertical dotted lines show the nominal lengths of pre-recruit (≥ 50 mm and <58 mm) and recruit (≥ 58 mm) size groups.

2.2 Biological inputs, priors, and assumptions

2.2.1 Recruitment

Few data are available on recruitment. Relative year class strengths area were assumed to average 1.0 over all years of the model, and further, relative year class strengths in the period before 1985 were assumed constant, and defined to be equal to the initial recruitment. Lognormal priors on relative year class strengths were assumed, with mean 1.0 and c.v. 0.2.

Stock recruitment relationships for the Foveaux Strait dredge oyster are unknown. Typically, recruitment for sessile organisms is highly variable and often environmentally driven (see Jamieson & Campbell 1998). A strong recruitment pulse was observed in the fishery between 1993 and 2000, suggesting that high levels of recruitment are plausible during periods of low abundance. A Beverton-Holt stock-recruit relationship was assumed, with steepness of 0.9 — a slightly more conservative assumption than the assumption of no stock recruitment relationship by Dunn (2004). Note that this assumption has little effect on the estimates of current status, but will affect the estimates of the projected stock status from the model.

Oysters entered the partition at age 1+, before to growth as 2 year olds. The distribution was assumed to be normally distributed with mean 15.5 mm and c.v. 0.4, truncated at 2 mm (Figure 3). These values were based on the spat settlement and growth data from Cranfield et al. (unpublished results).

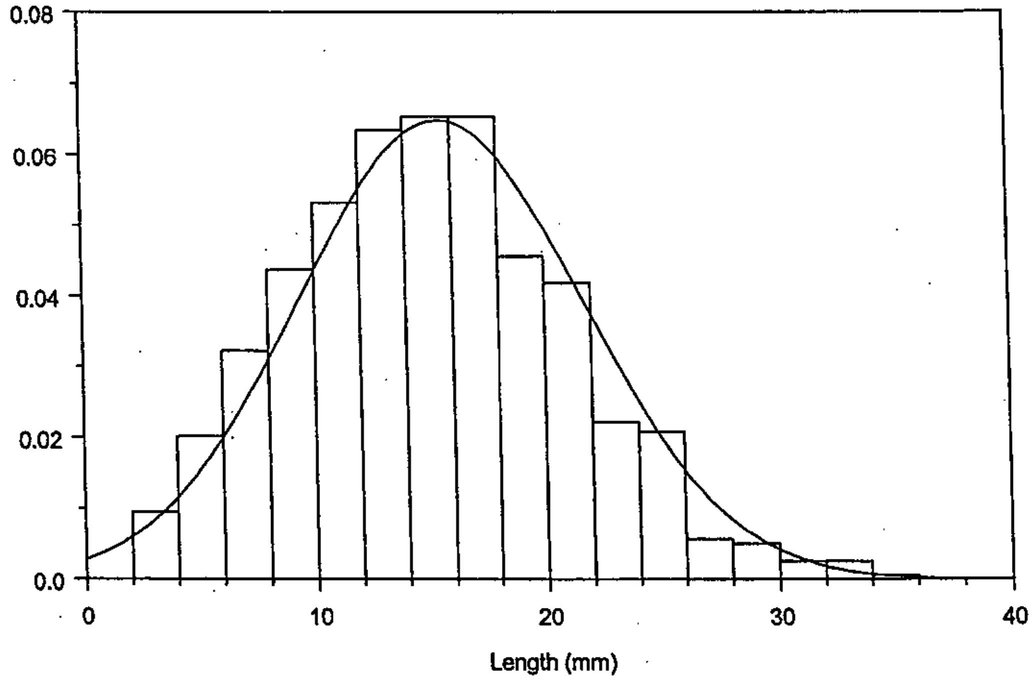

Figure 3: Size at recruitment for 1+ spat (Cranfield et al., unpublished results), overlaid with the assumed distribution for recruiting oysters — normal with mean 15.5 mm and c.v. 0.4.

2.2.2 Growth

Dunn et al. (1998b) estimated growth from tagged, caged oysters that were sampled from four areas and monitored at a single site. The oysters were re-measured at six-monthly intervals for three years. The growth models were based on a modified, length-increment von Bertalanffy growth model, estimated using maximum likelihood mixed effects models. However their growth estimates were seasonal, and allowed for areal, yearly, and breakage effects. The complexity of these estimates cannot easily be reproduced within the population model, and hence the data were re-fitted using maximum likelihood von Bertalanffy growth model, based on the parameterisation of Francis (1988), i.e.,

$$\Delta L = \left(\frac{\beta g_\alpha - \alpha g_\beta}{g_\alpha - g_\beta} - L_1 \right) \left(1 - \left[1 + \frac{g_\alpha - g_\beta}{\alpha - \beta} \right]^{\Delta t} \right)$$

where ΔL is the expected increment for an oyster of initial size L_1; g_α and g_β are the mean annual growth increments for oysters with arbitrary lengths α and β. Variation in growth was normally distributed with $\sigma = \max(c\mu_i, \sigma_{min})$ (where c is the coefficient of variation, σ_{min} is the minimum standard deviation, and μ_l is the expected growth at length L) truncated at zero.
The likelihood was then defined as (M.H. Smith, NIWA, pers. comm.);

$$L_i(\mu_i,\sigma_i,\sigma_E)=\frac{1}{\sigma_E}\phi\left(\frac{y_i}{\sigma_E}\right)\Phi\left(-\frac{\mu_i}{\sigma_i}\right)$$

$$+\frac{1}{\sqrt{\sigma_i^2+\sigma_E^2}}\phi\left(\frac{y_i-\mu_i}{\sqrt{\sigma_i^2+\sigma_E^2}}\right)\Phi\left(\frac{\sigma_i^2 y_i+\sigma_E^2\mu_i}{\sqrt{\sigma_i^2\sigma_E^2\left(\sigma_i^2+\sigma_E^2\right)}}\right)$$

where y_i is the measured growth increment for the i[th] oyster; μ_i and σ_i are the expected growth (truncated at zero to exclude the possibility of negative growth) and standard deviation respectively; σ_E is the standard deviation of measurement error (assumed to be normally distributed with mean zero); and ϕ and Φ are the standard normal probability density function and cumulative density function respectively

Winter length measurements were ignored, and hence the annual growth increment measurements were considered. The growth parameters at $\alpha=30$ and $\beta=55$ were estimated outside the population model, as $g_\alpha=11.91$ mm and $g_\beta=3.61$ mm; variation in growth had an estimated c.v. of $c=0.31$ and $\sigma_{min}=4.45$ mm; and estimated measurement error σ_E was 2.12 mm. The (annualised) growth data are shown as Figure 4, overlaid with the growth model (and 95% confidence intervals) used in the population model.

Stead (1971a) also carried out tagged growth measurements between 1960 and 1964. The raw data for that study are not available and have not been used in this analysis.

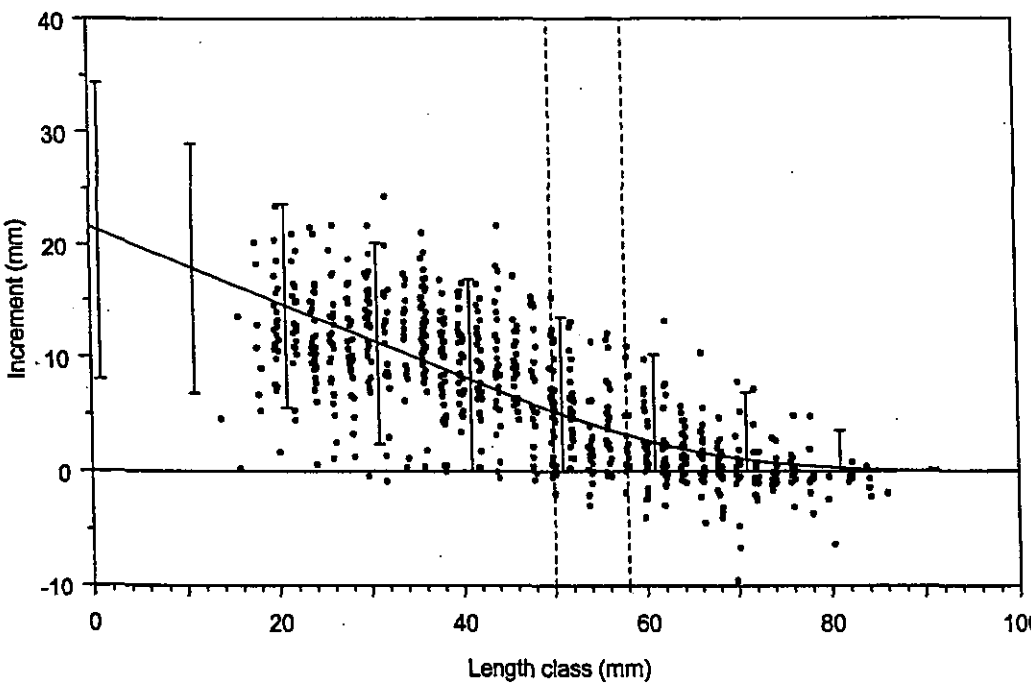

Figure 4: Initial size and mean annual increment data from Dunn et al. (1998b). Lines (and 95% confidence intervals) indicate the growth model assumed in the population model, and dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

2.2.3 Maturity

Foveaux Strait dredge oysters are protandrous hermaphrodites that breed during the late spring and summer. Most (70–90%) develop male gonads and only a small proportion breed as females (10–12%) (Jeffs & Creese 1996). Jeffs & Hickman (2000) estimated measures of maturity from the re-analysis of sectioned oyster gonads. The data for the proportion of oysters with female ova, during October–March, were used to determine the maturity ogive within the model. The estimated proportions mature (i.e., proportions of oysters with presence of female ova) by length class, along with exact 95% confidence intervals, are shown in Figure 5.

Maturity was not considered to be a part of the model partition, and proportions mature were fitted within the population model with a logistic ogive (see earlier) using a binomial likelihood (Bull et al. 2003).

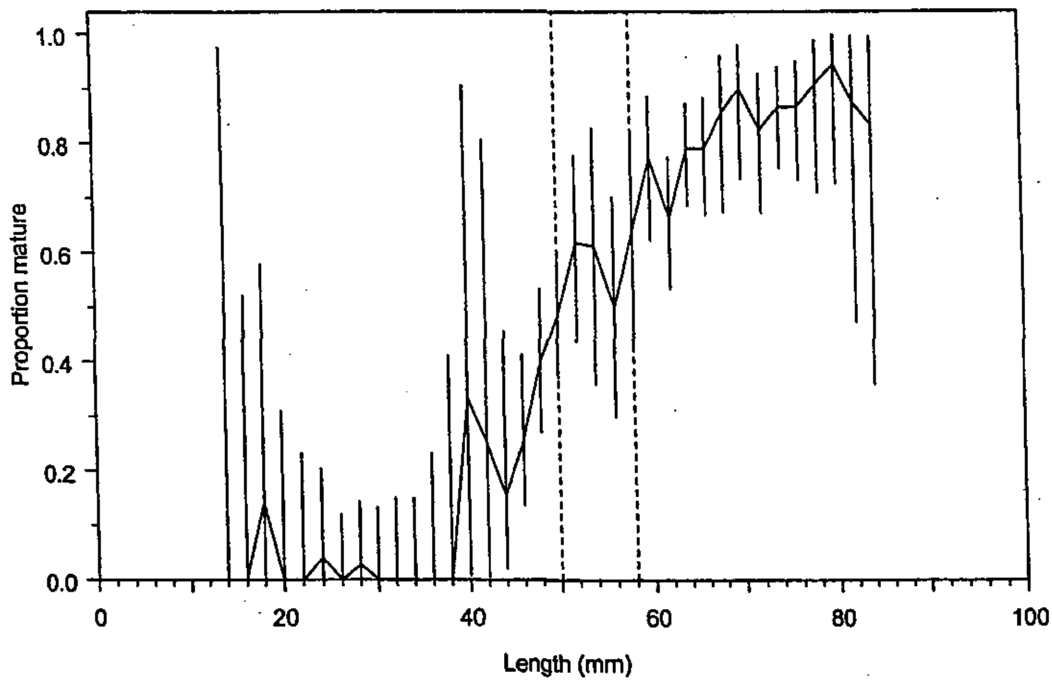

Figure 5: Proportions of mature oysters (defined as the proportion of oysters with female ova) by length (Jeffs & Hickman 2000). Vertical bars give exact 95% confidence intervals, and dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

2.2.4 Natural mortality

Dunn et al. (1998a) estimated natural mortality (*M*) for 1974 to 1986 by re-analysing data from Cranfield & Allen (1979). Estimated natural mortality was found to increase from 0.017 y^{-1} to 0.188 y^{-1} from 1974 to 1986 for oysters released in 1974, and from 0.009 y^{-1} to 0.199 y^{-1} for oysters released in 1973. Dunn et al. (1998a) concluded that they were unable to determine how good these estimates of natural mortality were, and suggested that the observed increase in rates of *M* with time may be related to senescence.

A constant value for natural mortality of 0.1 y^{-1} was assumed, implying a maximum age (at which 1% survive) of 46 years. However, there were few data available, other than from Dunn et al. (1998b), on which to base this assumption — except that two oysters tagged at recruit size (one from 1973 and one from 1976 or 1977 — see Cranfield & Allen 1979) were recaptured (live) in early 2003 (K.P. Michael, NIWA, pers. comm.), suggesting that the value of *M* and F was not high, as at least two oysters lived to recruit size and survived a further 26–29 years.

2.2.5 Disease mortality

Data on disease mortality events are limited. Anecdotal reports exist of a mortality event during the late 1940's (H.J. Cranfield, NIWA, pers. comm.). Stead (1971b) noted that "during a parasite outbreak in 1960–63 many oysters died; this caused a sharp decline in dredging catch rates". In addition, Stead (1971b) reported the height frequencies of 11 576 live oysters and 8612 clocks (i.e., articulated shells of recently dead oysters with the ligament attaching the two valves intact) from

Foveaux Strait, suggesting that clocks made up about 43% of the catch — a rate similar to that found in abundance surveys during the *B. exitiosa* epidemics in the early 1990s and early 2000s. Hine (1996) later noted that the most likely cause of the mortality during the 1960s was *B. exitiosa*.

No other reports exist of unusual mortality events in the Foveaux Strait fishery until the late 1980s. The *B. exitiosa* outbreak in the late 1980s was thought to have started in 1985–86, with evidence of continued *B. exitiosa* mortality up until March 1995. No further evidence of unusual mortality was found in the fishery until the summer of 2000. Disease mortality is set to zero for 1907–1948 (the period before any abundance estimates); 1952–1959 (to allow for disease mortality in the late 1940s); 1967–1984 (to allow for disease mortality in the early 1960s); and 1996–1999 (to allow for the epizootic in the late 1980s and the subsequent epizootic in 2000). Where disease mortality was estimated, a normal prior with mean -0.2 (sic), standard deviation 0.2, and bounds [0.0, 0.8] was used (see Figure 6).

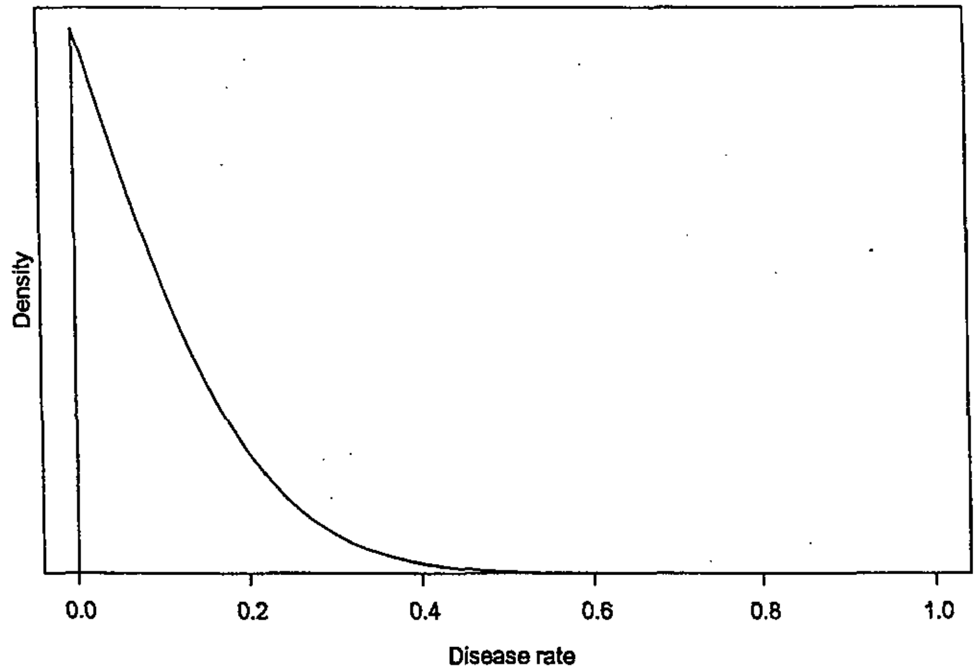

Figure 6: Prior assumed for the rate of disease mortality (normal with mean –0.2, standard deviation 0.2, and bounds [0.0–0.8]).

There are a number of options in applying disease mortality to the population, but no studies have attempted to quantify the relationship between disease mortality, oyster length, or oyster maturity. An indicative relationship can be inferred from the proportion, by length, of oysters infected with *B. exitiosa* (stage 1 or greater) from the October 2001, January 2002, March 2002, October 2002, and February 2003 surveys (Figure 7). The relationship for oysters up to a length of about 80 mm appears to be increasing in a manner similar to that for the maturity ogive (see Figure 5), although there may be a decrease in proportions infected over 80 mm in length. However, these data should be interpreted with caution as the *B. exitiosa* samples were not a representative sample of the length frequency of the oyster population.

Stead (1971b) presented a graph of the height frequency of live oysters and clocks measured during the 1960–64 survey. The proportion of clocks in the catch from that survey by length derived from that graph are shown in Figure 8. Length was estimated from the height using a length–height relationship determined from a linear regression of the length (*l*) and height (*h*) data collected during the October 2001, January 2002, March 2002, October 2002, February 2003, and January 2004 surveys (see Section 2.6.2 for details). Assuming that the observed mortality was related to *B. exitiosa* infection, this suggests a strong monotonic relationship of increased mortality with length, similar to that for the maturity data of Jeffs & Hickman (2000).

The disease selectivity ogive was therefore assumed to be the same as the maturity ogive, i.e., that disease causes oyster mortality, for each length class, at a rate equal to the maturity selectivity multiplied by the estimated yearly rate. However, other relationships may have considerable effect on model estimates.

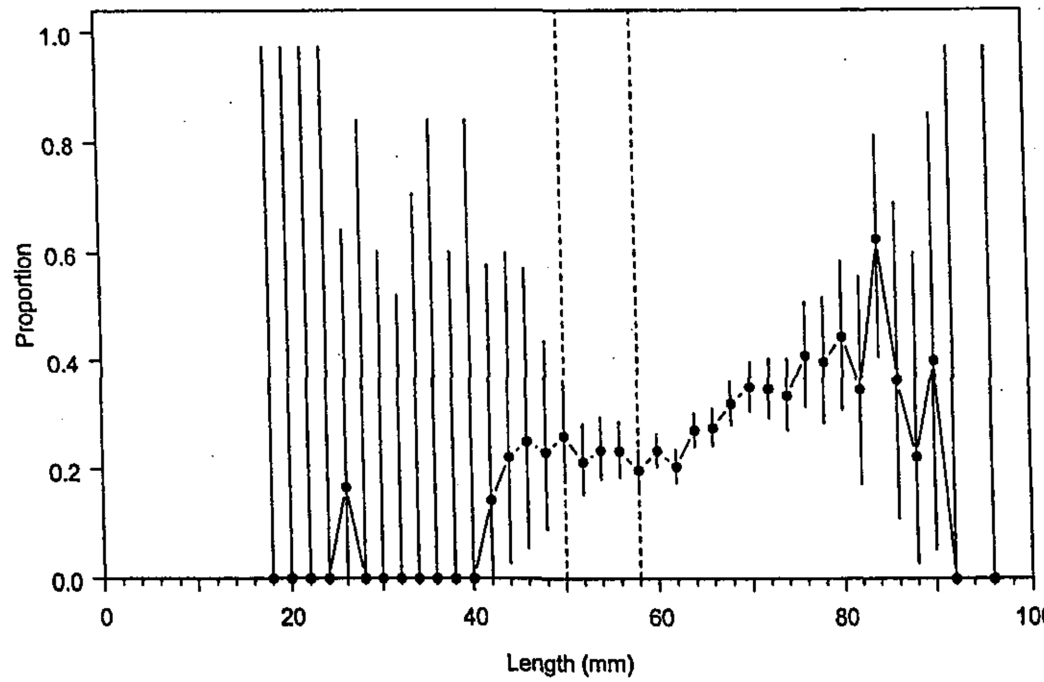

Figure 7: Proportions of oysters (and 95% confidence intervals) with a *B. exitiosa* infection of level 1+ from *B. exitiosa* sampling in the October 2001, January 2002, March 2002, and October 2002 surveys by length. Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

2.3 Commercial catch data

2.3.1 Winter season commercial catch

The total commercial catch of oysters in Foveaux Strait has been recorded since at least 1907, initially in annual reports of the Marine Department, and later by MAF (Fisheries) and the Ministry of Fisheries. The recorded catch was in "sacks" of oysters up to 1997, and total numbers of oysters since. The catch history (converted to millions of oysters) is given in Figure 9.

The conversion rate of 774 oysters per sack was reported by Cranfield et al. (1999b). Data from early Marine Department Annual Reports (where measures of dozens of oysters and sacks of oysters were occasionally referred to together) suggest that this figure is broadly correct. The Annual Report of the Marine Department (1910) suggested a figure of 1103 oysters per sack, but the Report of the Sea Fisheries Investigation Committee (1937–38) suggested a figure of 720 oysters per sack. The Marine Department Report on Fisheries (1944) reported that the mean number of oysters in a sack in 1943 "had increased from 62–65 dozen (744–780) to 70–80 dozen (840–960)" as a result of the declining quality (size) of oysters at that time.

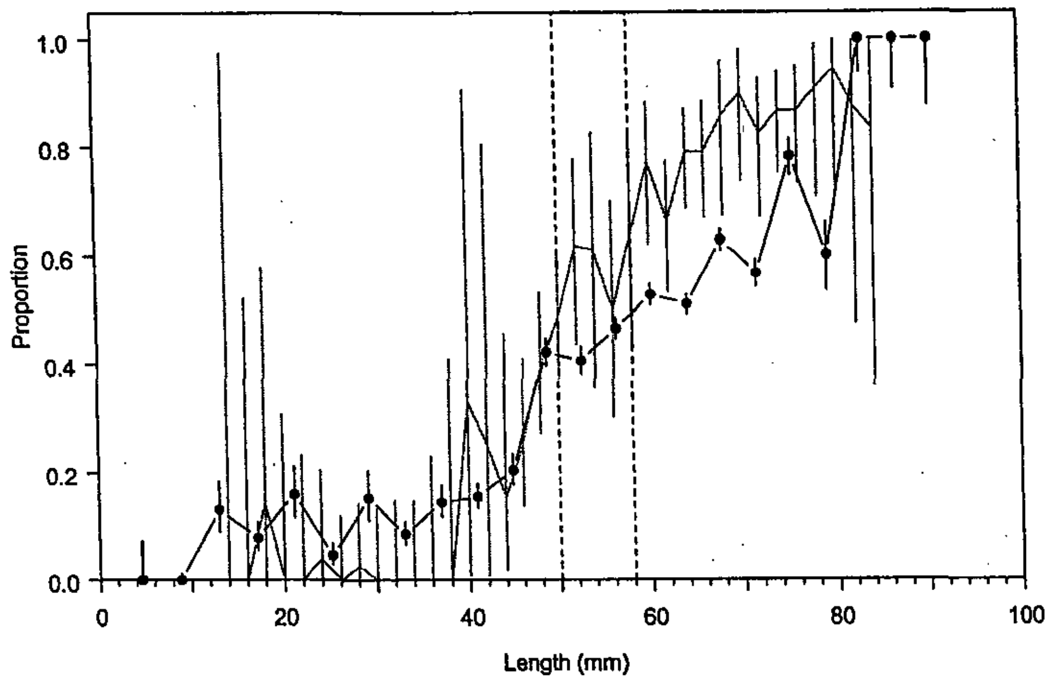

Figure 8: Proportions of clocks (and 95% confidence intervals) in the catch from the 1960–64 survey by length (solid circles and lines, data reproduced from a figure in Stead (1971b)), overlaid with the proportion of mature oysters (and 95% confidence intervals) by length derived from Jeffs & Hickman (2000). Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

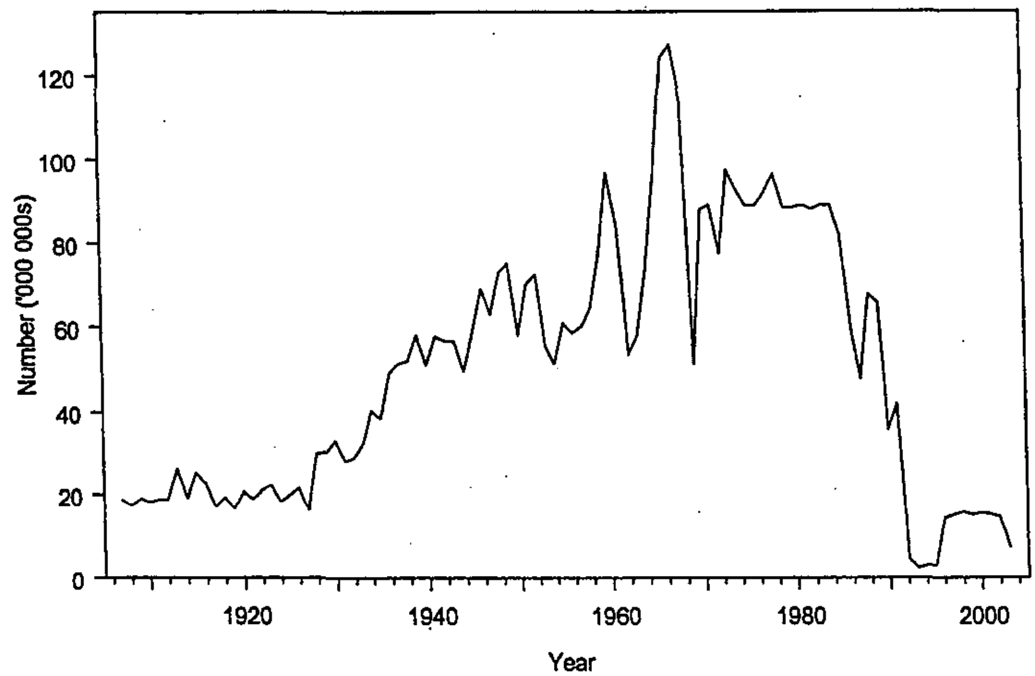

Figure 9: Total commercial catch (winter and summer) by year (millions of oysters), 1907–2003.

Before 1929 the minimum takeable size limit was defined as 1.75 inches (minimum diameter, 44.45 mm), increased to 2.0 inches (50.80 mm) in 1929, then increased again to 2.125 inches (53.98 mm) in 1941. In 1969, a takeable size limit of 2.25 inches (57.15 mm) minimum diameter was introduced, where it has remained since. The shape of the fishing selectivity ogive was assumed to have remained constant, and was defined by the size selectivity determined by model fits to the commercial catch sampling in 2002 and 2003. But the changes in the legal size were allowed for by shifting the selectivity curve to the left by 12.700 mm (0.5 inches) for years before 1929, 6.350 mm

(0.25 inches) for years from 1929 to 1940, and 3.175 mm (0.125 inches) for years from 1941 to 1968.

2.3.2 Summer season catches made under special permits

Between 1992 and 2000, the Bluff Oyster Management Company Ltd. was granted a special permit to catch oysters during the breeding season as part of their study of the viability of enhancing the oyster population using spat settled on oyster shell. These were issued for the summer (November–February), and were in addition to the usual commercial catch (Table 2).

Table 2: Reported oyster catch of vessels fishing under special permits for Bluff Oyster Management Company Ltd. 1992–93 to 1999–2000 fishing years. Fishing took place over the summer season (November–February). No special permit was issued for the 1998–99 fishing year.

Year	1993	1994	1995	1996	1997	1998	1999	2000
Number (millions)	2.43	3.09	3.03	0.93	0.20	0.72	0.00	1.00

2.3.3 Length frequency of the winter season commercial catch

Length samples from the commercial catch were taken during the 2002 (Michael et al. 2004a) and 2003 fishing seasons. In 2002, 15 580 oysters were measured (15 269 recruited and 311 pre-recruits); and in 2003, 18 940 oysters were measured (18 189 recruited and 751 pre-recruits).

Estimates of the catch-at-length frequencies (with associated c.v.s) of the commercial catch were derived using catch-at-age software (Bull & Dunn 2002), using 2 mm length classes. The software scaled up the length frequency from each stratum up to the total catch, to yield length frequencies by stratum and overall (Figure 10). The c.v.s are calculated by bootstrapping. Strata were defined from the sampling regime, where each vessel's catch was sampled at approximately two week intervals.

Proportions at length were included in the model with a multinomial likelihood. The effective sample sizes for the length frequency data with a multinomial likelihood were estimated by calculating a sample size that represented the best least squares fit of $\log(cv_i) \sim \log(P_i)$, where cv_i was the bootstrap c.v. for the ith proportion, P_i. Estimated and actual sample sizes are given in Table 3. (See also Appendix A, Figure 41 for a plot of the relationship).

Table 3: Actual samples sizes and effective sample sizes determined for the multinomial likelihood for the commercial catch proportions at length data.

Year	Actual sample size	Effective sample size
2002	15 580	10 932
2003	18 940	15 254

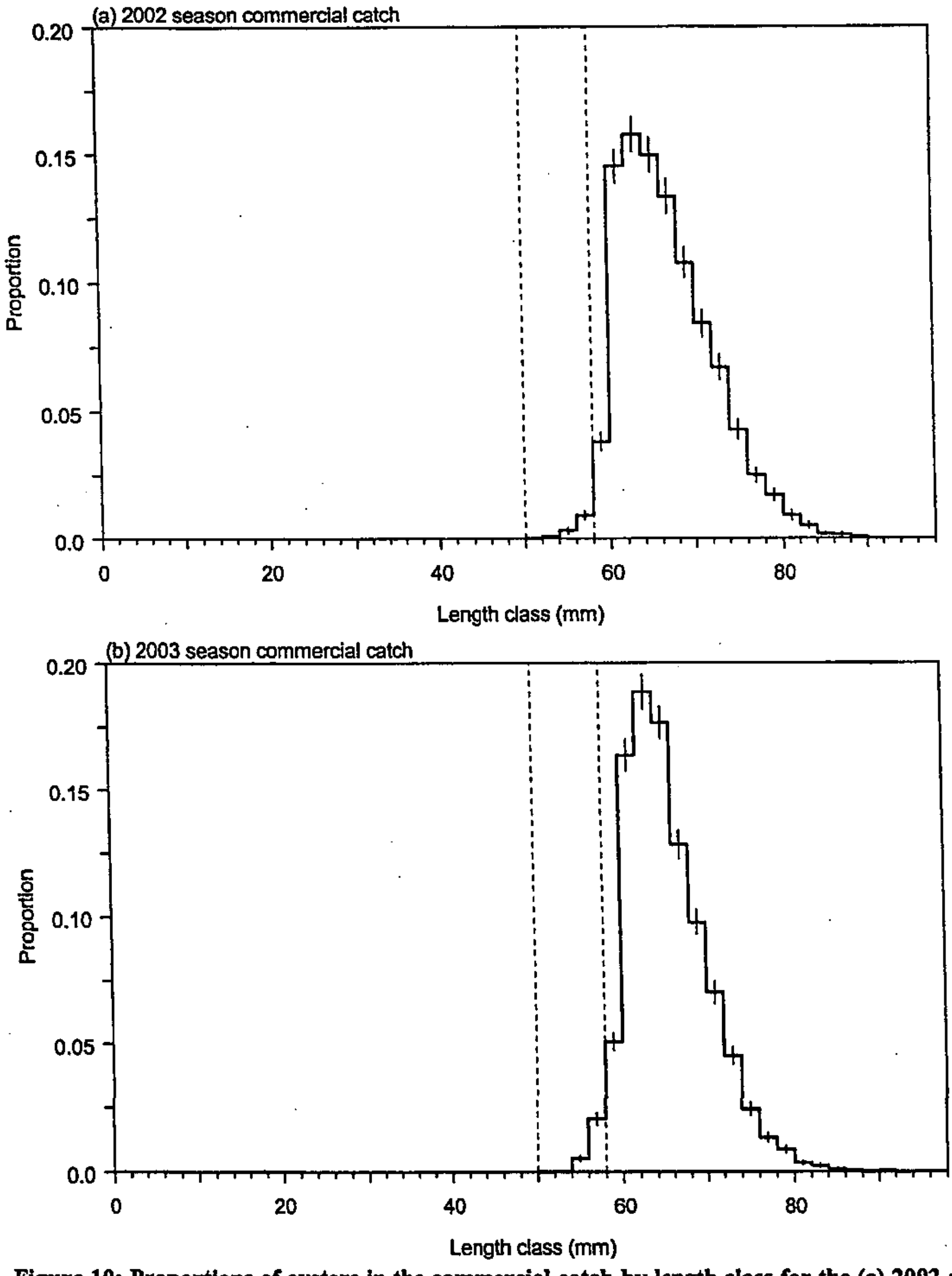

Figure 10: Proportions of oysters in the commercial catch by length class for the (a) 2002 and (b) 2003 fishing seasons. Vertical bars give approximate 95% confidence intervals. Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

2.4 Non-commercial catch

The non-commercial catch is made up of recreational, customary, and illegal catch (described below). Estimates for the amount of non-commercial catch are poor, but suggest that it may be as high as 8% of the commercial catch in recent years (Figure 11).

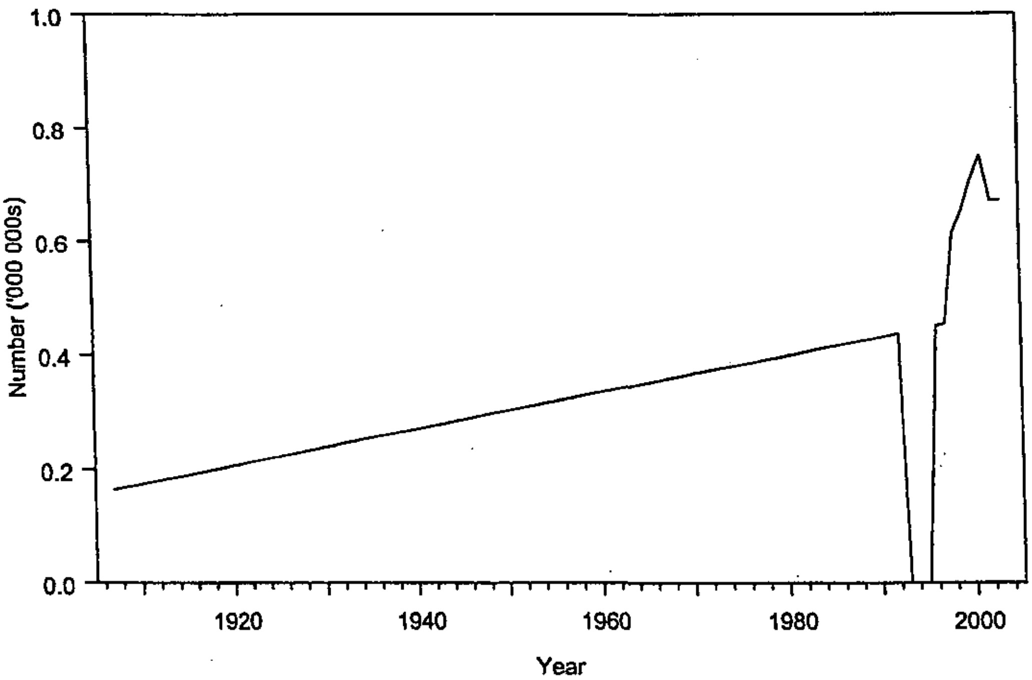

Figure 11: Total non-commercial catch (winter and summer) by year (millions of oysters), 1907–2003.

2.4.1 Recreational catch

The Ministry of Fisheries commissioned two surveys of recreational fishing in recent years, the South region 1991–92 survey (Teirney et al. 1997) and the 1996 national survey (Bradford 1998). However, the catch of oysters cannot be reliably estimated from these surveys because of the small number of local respondents who reported catches of oysters in their diaries. The Southland Recreational Marine Fishers Association estimated the annual recreational catch of oysters in Foveaux Strait in 1995 to be about 390 sacks (equivalent to 387 000 oysters) (Annala et al. 2003). Since then, the Ministry of Fisheries believe the catch has increased significantly (Annala et al. 2003).

The Ministry of Fisheries estimates commercial oyster fishers land an additional 140 000 oysters as an amateur catch during the fishing season (as commercial fishers are entitled to a take a recreational catch of 50 oysters per fisher per day). Hence, the best estimate of the total recreational catch is about 430 000 (500 sacks) (Annala et al. 2003). The reliability of these estimates of recreational catch is not known.

The recreational catch in each year was assumed to have increased linearly from 150 000 in 1907 to 430 000 in 2003, except that the recreational catch in 1993–1995 (when the fishery was closed) was zero. Further, the recreational harvest was assumed to take place over the winter season with a selectivity equal to the commercial fishing selectivity.

2.4.2 Customary catch

Reporting of Maori customary harvest is specified in the Fisheries (South Island Customary Fisheries) Regulations 1999. Customary catch of Foveaux Strait oysters, reported by Ngai Tahu to the Ministry of Fisheries, is given in Table 4. Annala et al. (2003) reported that "no customary fishing takes place between 31 August and mid-November while oysters are spawning".

The customary catch in each year was assumed equal to the reported catch, but with all catch allocated to the winter season (i.e., the dominant season for customary harvest, see Table 4). Further these catches are assumed to take place with a selectivity equal to the commercial fishing selectivity.

Table 4: Reported customary catch (number) between 1 July 1998 and 30 September 2002 by year and quarter from *Kaitiaki* data collected by *Ngai Tahu*. '–' denotes *not available*.

Year	1 Jan–31 Mar	1 Apr–30 Jun	1 Jul–30 Sep	1 Oct–31 Dec	Total
1998	–	–	106 380	37 560	143 940
1999	0	107 520	69 840	0	177 360
2000	63 582	113 634	34 356	11 760	223 332
2001	25 514	136 973	72 996	23 760	259 243
2002	0	117 219	67 116	–	184 335

2.4.3 Illegal catch

The Ministry of Fisheries estimated the illegal catch of oysters for the 1998 and 1999 fishing years to be about 10% of the total non-commercial catch — 66 436 oysters. However, this estimate cannot be verified (Annala et al. 2003).

The illegal catch in each year was assumed to be equal to exactly 10% of the sum of the recreational and customary catch in each year. Further, these catches are assumed to take place over the winter season with a selectivity equal to the commercial fishing selectivity.

2.4.4 Incidental mortality

Cranfield et al. (1997) investigated the incidental mortality of oysters from a single encounter with a dredge in March 1997. They found that a light dredge (320 kg) caused lower damage and resulting mortality than a heavy dredge (550 kg). Mortality resulting from both types of dredge was inversely proportional to the oysters' size. They concluded that recruited oysters appeared robust to dredge encounters (1–2% mortality from the heavy dredge), but pre-recruit were less so (6–8% mortality). Spat were very fragile and many were killed. The mortality of spat less than 10 mm in height ranged from 19 to 36%.

As these mortality estimates are low, and the estimated level of fishing mortality (see later) was also low, the effects of incidental dredge damage or mortality are ignored in this model.

2.5 Resource surveys and other abundance information

2.5.1 Absolute abundance estimates

Resource surveys of Foveaux Strait dredge oysters have been conducted since 1906 (Hunter 1906). However, different survey designs, areas of coverage, and dredge design confound the interpretation of the time series. Re-analysed estimates of abundance were made for surveys since 1990, and were based on an estimate of the population size within the 2002 survey area using the dredge calibration from the 1990 dredge/dive survey. These estimates were generated to provide a consistent time series over a constant region (Table 5). This process is described in more detail below..

In general, resource surveys counted the number of "takeable" oysters. Early surveys often used uncalibrated dredges, and/or failed to document the survey methods. Later surveys also estimated the number of pre-recruit sized oysters and small oysters, as well as estimating the number of clocks and levels of *B. exitiosa* infection.

Clocks are the articulated shells of recently dead oysters with the ligament attaching the two valves intact. New clocks are defined as those shells that have clean inner valves that have retained their lustre without fouling. The shells of oysters that are fouled or in which the inner valves have lost their lustre are termed old clocks, and can be covered in fouling organisms on both external and internal surfaces. The ligament of oysters breaks down over a three-year period, and, hence, old clocks represent oysters that died between 6 months and 3 years previously (Cranfield et al. 1991). New clocks are usually assumed to be the shells of those oysters that died since the settlement of fouling organisms in the previous summer — although this may depend on the timing of the survey — and may give an indication of levels of recent mortality.

Typically, the catch from each survey tow was sorted into live oysters, gapers, and new and old clocks. The numbers of each were counted within three size groups (recruit, pre-recruit, and small), where size was determined by the failure of the oyster to pass through a 58 mm or 50 mm diameter reference ring, respectively.

More recently, surveys counted the number of gapers. Gapers are live moribund oysters in which the two shells are parted, which when tapped, do not fully close as the adductor muscle has lost its ability to fully contract. These have been counted as "new clocks", as they are considered very close to death.

2.5.2 Dredge efficiency

Two estimates of dredge efficiency have been made. Allen & Cranfield (1979) estimated the dredge efficiency of the 1.25 m wide survey dredge (for recruit-sized oysters) from the 1975–76 surveys, as 0.16 (95% confidence intervals 0.04–0.42). Then, Doonan & Cranfield (1992) estimated dredge efficiency for a 3.35 m width dredge from a dive and dredge survey (for recruit-sized oysters) in 1990 as 0.17 (95% confidence intervals 0.11–0.24).

Dredge efficiency was assumed known after Doonan & Cranfield (1992), and this value was used to determine absolute abundance measures of recruit-sized oysters from resource surveys between 1990 and 2002. However, uncertainty in dredge efficiency was incorporated into the uncertainty of the abundance estimates (i.e., in the estimated c.v.s). Estimates of abundance for pre-recruit and small oysters were generated using the same estimate of dredge efficiency.

2.5.3 Pre-1960 surveys

No abundance data from the early surveys of Foveaux Strait (i.e., 1906, 1926, 1927, and 1945) are available. No abundance estimates from these surveys were reported, and they cannot be used as abundance estimates in the population model. However, individual length data were collected on the 1926–27 surveys by M.W. Young, and reported by Sorensen (1968). These data are described later.

2.5.4 1960–64 survey

Stead (1971b) surveyed Foveaux Strait extensively between 1960 and 1964 using a light 0.9 m wide survey dredge towed for 5 minutes in a straight line. Although the tow length and methods were similar to those used in later surveys, there was no calibrated estimate of the efficiency of the much lighter dredge. However, Stead (1971b) also conducted some experiments in which he collected data that could be used to determine the overall dredge efficiency. Fifteen samples were taken where divers estimated the number of takeable oysters (defined as ≥ 2.125 inches in size, reflecting the legal size of takeable oysters at that time) in a single quadrat (1 m^2) and where the survey dredge was towed using the standard methods (Figure 12).

Table 5: *Summary of Foveaux Strait dredge oyster survey data 1906–2002 (numbers of live, new clocks, and old clocks in millions). '–' indicates unknown.*

Date	Design[1]	Area (km²)	Stations	Type[2]	Category	Live	c.v.	New clocks	Old clocks	*B. exitiosa.*	Lengths	Reference
Jan 1906	Unknown	*ca.* 1 200	–	A		–	–	–	–	–	–	Hunter (1906)
Mar–Aug 1926[3]	CD	*ca.* 400	–	B		–	–	–	–	–	19 272	Sorensen (1968)
Jan 1927[3]	Unknown	–	–	B		–	–	–	–	–	4 135	Sorensen (1968)
1945[4]	CD	*ca.* 400		B		–	–	–	–	–	–	Sorensen (1968)
1960–64	Grid	*ca.* 1 800	542	E	*Recruit*	~1 000	–	–	–	–	11 576[5]	Stead (1971b)
		1 055	310	E*	*Recruit*	3 059	0.21	–	–	–	–	Re-analysed estimate
1962	Specific	–	36	Dive	*Recruit*	–	–	–	–	–	–	Stead (1971b)
1965–1971	Specific	374	6	C	–	–	–	–	–	–	–	Street & Crowther (1973)
1973	Grid	–	150	F	*Recruit*	–	–	–	–	–	–	Allen & Cranfield (1979)
Apr–Aug 1974	MR	374	–	C	*Recruit*	~1 800	0.20	–	–	–	–	Cranfield & Allen (1979)
Apr–Aug 1975	MR	374	–	C	*Recruit*	~1 500	0.11	–	–	–	–	Cranfield & Allen (1979)
1975–76	Grid	374	929	F	*Recruit*	1 140	0.15	–	–	–	–	Allen & Cranfield (1979)
Sep 1986	Specific	–	27	F	*Recruit*	–	–	–	–	–	–	Dinamani (1987)
Jan 1987	Specific	–	67	F	*Recruit*	–	–	–	–	–	–	Dinamani (1987)
Jul 1990	Grid	1 116	293	D*	*Recruit*	771	0.14*	–	–	Yes	–	Cranfield et al. (1991)
		1 055	293	D*	*Recruit*	707	0.11	41	574	–	–	Re-analysed estimate
Oct 1990	SR	646	83	Dive	*Recruit*	–	–	–	–	–	412[5]	Cranfield et al. (1991)
		646	83	Dive	*Pre-recruit*	–	–	–	–	–	420[5]	Cranfield et al. (1991)
		646	83	Dive	*Small*	–	–	–	–	–	1 280[5]	Cranfield et al. (1991)
Oct 1990	SR	646	116	F	*Recruit*	607	0.11	–	–	Yes	–	Cranfield et al. (1991)
		1 055	116	F*	*Recruit*	623	0.12	35	–	–	–	Re-analysed estimate
Mar 1992	Grid	1 229	370	D*	*Recruit*	319	0.18	–	–	Yes	–	Doonan & Cranfield (1992)
		1 055	293	D*	*Recruit*	285	0.12	2	285	–	–	Re-analysed estimate
Oct 1993	Grid	875	177	D*	*Recruit*	372	0.21	–	–	–	–	Cranfield et al. (1993)
		1 055	177	D*	*Recruit*	397	0.10	1	292	–	–	Re-analysed estimate
		1 055	177	D*	*Pre-recruit*	383	0.11	2	173	–	–	Re-analysed estimate
		1 055	177	D*	*Small*	1 004	0.10	–	–	–	–	Re-analysed estimate
Mar 1995	SR	680	50	D*	*Recruit*	543	0.30	–	–	Yes	–	Cranfield et al. (1995)
		680	50	D*	*Pre-recruit*	–	–	–	–	Yes	–	Cranfield et al. (1995)
		1 055	49	D*	*Recruit*	576	0.25	6	48	–	–	Re-analysed estimate
		1 055	49	D*	*Pre-recruit*	401	0.28	15	40	–	–	Re-analysed estimate
		1 055	49	D*	*Small*	402	0.25	–	–	–	–	Re-analysed estimate
Oct 1995	SR	680	154	D*	*Recruit*	639	0.19	–	–	–	–	Cranfield et al. (1996)
		1 055	154	D*	*Recruit*	782	0.11	1	44	–	–	Re-analysed estimate
		1 055	154	D*	*Pre-recruit*	380	0.10	~0	22	–	–	Re-analysed estimate
		1 055	154	D*	*Small*	718	0.21	–	–	–	–	Re-analysed estimate

Table 6 (continued): Summary of Foveaux Strait dredge oyster survey data 1906–2002.

Date	Design[1]	Area (km²)	Stations	Type[2]	Category	Live	c.v.	New clocks	Old clocks	*B. exitiosa.*	Lengths	Reference
Oct 1997	SR	693	107	D*	*Recruit*	630	0.21	–	–	–	–	Cranfield et al. (1998)
		1 055	107	D*	*Recruit*	660	0.14	~0	74	–	–	Re-analysed estimate
		1 055	107	D*	*Pre-recruit*	727	0.14	~0	111	–	–	Re-analysed estimate
		1 055	107	D*	*Small*	918	0.14	–	–	–	–	Re-analysed estimate
Jan 1998	Specific	–	–	D*	*Recruit*	–	–	–	–	Yes	–	Cranfield (1998)
		–	–	D*	*Pre-recruit*	–	–	–	–	–	–	Cranfield (1998)
Oct 1999	SR	1 055	199	D*	*Recruit*	1 461	0.16	–	–	–	–	Michael et al. (2001)
		1 055	199	D*	*Recruit*	1 453	0.16	~0	176	–	16 054	Re-analysed estimate
		1 055	199	D*	*Pre-recruit*	896	0.12	0	97	–	8 424	Re-analysed estimate
		1 055	199	D*	*Small*	1 364	0.11	–	–	–	16 085	Re-analysed estimate
Mar 2000	Specific	–	35	D*	*Recruit*	–	–	–	–	Yes	–	Dunn et al. (2000)
Oct 2001	SR	1 055	192	G*	*Recruit*	995	0.11	10	466	Yes	4 227	Michael et al. (2004b)
		1 055	192	G*	*Pre-recruit*	872	0.12	3	111	Yes	3 460	Michael et al. (2004b)
		1 055	192	G*	*Small*	1 410	0.12	–	–	Yes	7 475	Michael et al. (2004b)
Jan 2002	Specific	–	35	G*	*Recruit*	–	–	–	–	Yes	–	Dunn et al. (2002b)
Mar 2002	Specific	–	35	G*	*Recruit*	–	–	–	–	Yes	–	Dunn et al. (2002a).
Oct 2002	SR	1 055	155	G*	*Recruit*	502	0.14	68	587	Yes	–	Michael et al.(2004a)
		1 055	155	G*	*Pre-recruit*	520	0.11	11	94	Yes	–	Michael et al.(2004a)
		1 055	155	G*	*Small*	1 243	0.10	–	–	–	–	Michael et al.(2004a)
Feb 2003	Specific	–	16	G*	*Recruit*	–	–	–	–	Yes	–	Dunn et al. (2003)
Jan 2004	Specific	–	40	G*	*Recruit*	–	–	–	–	Yes	–	K.P. Michael (unpublished)

1. Survey designs either circumscribed the known oyster beds (CD), sampled specific stations non-randomly (specific), followed a grid pattern (grid), were stratified random (SR), or were mark-recapture surveys (MR).
2. * indicates a calibrated estimate. A–F indicate the type of dredge; 'Dive' indicates a dive survey. The dredges are: (A) Light, hand-hauled commercial dredge about 1 m wide, used up to 1913; (B) Commercial dredge, about 3.35 m wide with single-bit and single ring bag, weighing ~150 kg and used up to 1968; (C) Commercial dredge, about 3.35 m wide, introduced in 1968 with double-bit and double ring bag and weighing about 400 kg; (D) The 1968 commercial dredge, about 3.35 m wide, modified in 1984 increasing weight to about 530 kg; (E) 0.91 m wide light survey dredge with a rigid mesh catch bag; (F) 1.25 m wide survey dredge, designed to be a smaller version of 1968 commercial dredge with double-bit and double flexible ring bag; (G) 3.32 m wide commercial dredge similar to the 3.35 m wide dredge introduced in 1968 with double-bit and double ring bag, and weighing 400 kg.
3. The original reports detailing the Mar–Aug 1926 and Jan 1927 surveys have been lost; these summaries are reproduced from Sorensen (1968).
4. Data from the 1945 survey were never analysed and are suspected of having been destroyed in a fire in the 1950s.
5. Data recorded as height, not length. In the October 1990 dive survey, height frequencies were grouped by size class according to the height measurement, and not their ability to pass through a 50 mm or 58 mm diameter ring.

These data can be used to estimate the dredge efficiency of the 1960–64 sampling, and calculate an absolute abundance estimate. Estimates of c.v.s can also be made via bootstrapping. Survey stations that occurred outside the 1999–2002 survey boundary were ignored, and the remainder used to calculate a calibrated survey absolute abundance estimate (for recruit-sized oysters) that is consistent with later surveys. The estimated dredge efficiency was 0.11 (95% confidence intervals 0.08–0.16) resulting in an estimated mean (takeable) population from the 1960–64 survey from stations within the 2001 survey boundary of 3059 million oysters (c.v. 0.21). The estimated dredge efficiency compares reasonably well to the estimates of efficiency from Doonan & Cranfield (1992), 0.17, for the larger (3.35 m width) and heavier commercial dredge.

Although the survey was conducted over a number of years, the year of the abundance estimate from the survey was assumed to be 1962. The shape of the selectivity of the gear was assumed to be the same as for later surveys (1993–2002) using the larger, commercial dredge. The 1962 estimate thus became a part of the October survey series of recruit-sized oysters. However, to account for the change in definition of legal size (i.e., 2.125 inches in the 1960s c.f. 2.25 inches from 1969), the selectivity curve was shifted to the left by 3.175 mm (0.125 inches) for the 1962 survey.

Some individual height data were reported by Stead (1971b). These data are described in more detail later.

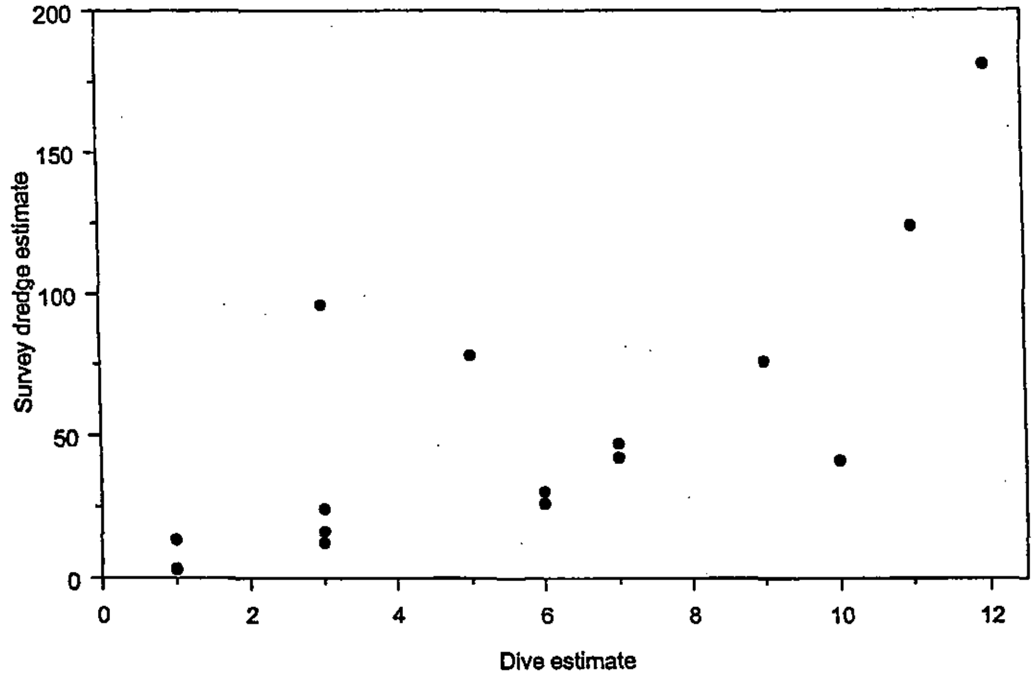

Figure 12: Data used to calibrate the 1960–64 dredge survey. Estimated number of "takeable" oysters sampled by divers on 1 m^2 quadrats (x-axis) and from 5 minute survey tows using the 0.9 m wide survey dredge (y-axis) (reproduced from data in Stead 1971b).

2.5.5 1974–75 mark-recapture surveys

Cranfield & Allen (1979) reported the results of a mark-recapture experiment, based on the recapture of tagged, recruit-sized oysters released in 1974 and 1975. Tagged oysters were released over a number of beds within the main commercial fishery (about 374 km^2, and roughly corresponding to the region surveyed in the 1975–76 dredge survey). The number of tagged oysters returned by fishers was used to estimate the size of the standing crop for 1974 and 1975 respectively.

In the model, the estimates of abundance were assumed to be relative estimates, with selectivity set equal to the dredge survey selectivity for recruit-sized oysters and the survey catchability coefficient (q) is the ratio of abundance inside the 1974–75 survey region to that inside the 2001 survey region.

2.5.6 1975–76 survey

The 1975–76 survey was carried out over two seasons (actually as three separate surveys in February 1975, June 1975, and May 1976 on adjacent areas) using a light, 1.25 m wide survey dredge. The survey region encompassed the extent of the commercial fishery region at that time (374 km^2). Survey abundance estimates were calibrated from both diving observations and the recapture rate of tagged oysters from the mark-recapture experiment in 1974 and 1975. The estimate used here is a re-analysed estimate from Cranfield et al. (1991).

The estimate of abundance is assumed to be a relative estimate, with a selectivity set equal to the dredge survey selectivity for recruit-sized oysters. However, as this is used as a single survey estimate in the model with associated catchability, the data have almost no effect on resulting model estimates (other than as a direct result of the influence of the prior on the catchability constant, q). Hence, the resulting estimates of q can be considered to be a measure of the ratio of abundance inside the 1975–76 survey region compared with that for the 2001 survey region.

2.5.7 1990 to 1997 surveys

The design of some of the abundance surveys (in particular, the 1960–64 survey and surveys between 1990 and 1997 inclusive) allow an estimate to be made that is comparable to those conducted between 1999 and 2002. Where possible, revised estimates using a consistent estimate of dredge efficiency have been made (see Table 5).

Survey data from the October series between 1990 and 1997 were re-analysed to (a) scale up (or down) the estimates to account for the part of the population outside the original survey region but within the region bounded by the 1999–2002 surveys, and (b) to account for revised estimates of dredge efficiency that have been made since the original survey estimates were published. The 1960–64 survey (Stead 1971b) covered an area larger than any survey since. These data allow an estimate of the ratio of recruit-sized oysters that occurred inside and outside the survey regions defined in the 1990–2002 abundance surveys (1055 km^2). These data were post-stratified to estimate that about 5% of oysters were outside the region surveyed in the October 1990–1997 and inside the 1999–2002 survey region. The re-analysed estimates of the 1990 to 1997 October surveys were therefore multiplied by 1.05 to account for oysters outside the survey boundaries. This makes the strong assumption that the ratio of densities of oysters within each of these regions does not change over time.

Estimates for the July 1990 and March 1992 surveys were re-stratified using the external boundary of the surveys from 1999–2002, and re-analysed with the revised dredge efficiency estimates (Table 5 and Figure 13).

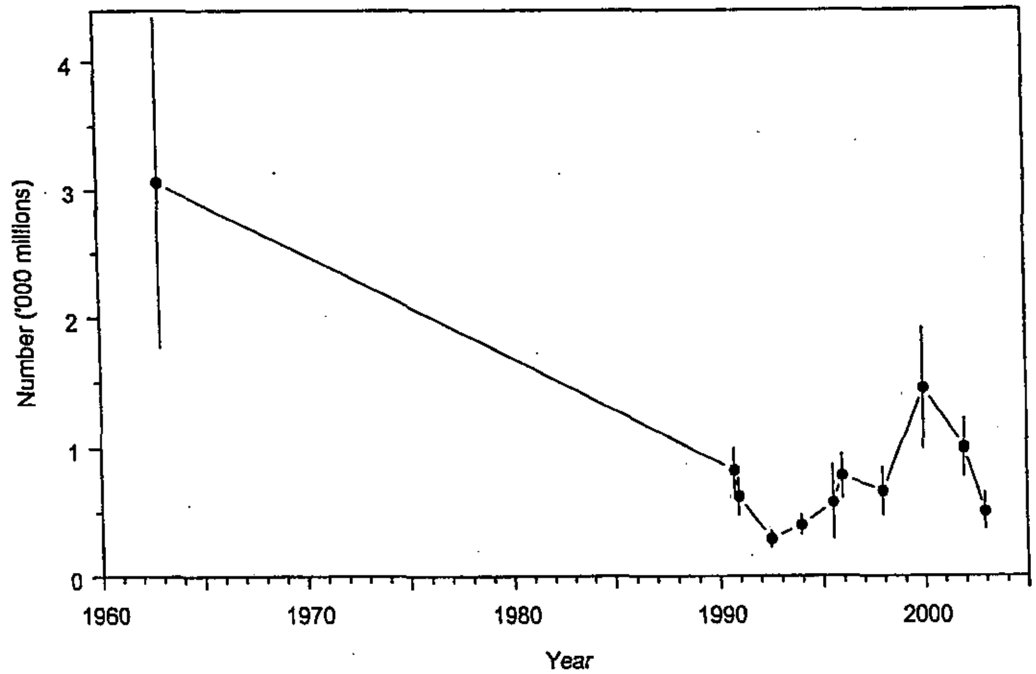

Figure 13: Revised estimates of the recruit-sized absolute abundance from surveys between 1962 and 2002. Vertical lines show approximate 95% confidence intervals.

2.5.8 1999–2002 surveys

The abundance surveys between 1999 and 2002 used the current survey boundary and current estimates of dredge efficiency (see Figure 1). However, the 1999 survey also included an additional stratum of a recreational area closed to commercial fishing on the eastern side of Stewart Island. The estimates reported here exclude that stratum.

2.5.9 Catch-effort data

Raw (unstandardised) catch and effort data have been collected in the Foveaux Strait dredge oyster fishery since about 1948. The total number of sacks landed from Foveaux Strait and the total number of hours fished from 1948 to 1971 were tabulated in Marine Department Annual Reports, from 1972–1994 by MAF (Fisheries) and since then by the Ministry of Fisheries (Annala et al. 2003).

The definition of minimum legal size (i.e., the legal takeable size) of oysters and regulations governing dredge design and size have changed over time. Hence, the CPUE indices may not be comparable over the full time series. The indices were split into three series, namely (i) Series A, from 1948 to 1968 when the legal size was defined as 2.125 inches and the typical commercial dredge was about 3.35 m wide with single-bit and single ring bag and weighing about 150 kg, (ii) Series B, from 1969 to 1984 when the legal size was 2.25 inches, and the typical commercial dredge was about 3.35 m wide with double-bit and double ring bag and weighing about 400 kg, and (iii) Series C, years after 1984 when the typical commercial dredge was modified by increasing its weight to about 530 kg (Table 6).

The Ministry of Fisheries catch-effort database system holds catch and effort data for the Foveaux Strait oyster fishery from 1972 onwards. These data were derived from collections before those collected under the Fisheries Statistics Unit (FSU) system (pre-FSU data), data collected by the

FSU system (FSU data) and under the Quota Management System (QMS) on Catch Effort Landing Returns (CELR data). No daily vessel catch and effort data are available for the period before this.

Table 6: Reported catch rate estimates and revised estimates from source records for series A, B, and C, for Foveaux Strait oysters 1901–2003 (sacks per hour). (Data from 1948–1971 Marine Department Annual Reports, 1972 MAF (Fisheries) Annual Report, 1973–2002 Annala et al. (2003).)

Year	Series	Reported	Revised	Year	Series	Reported	Revised	Year	Series	Reported	Revised
1948	A	14.7	14.7	1967	A	9.3	9.3	1986	C[3]	10.5	10.5
1949	A	14.6	14.6	1968	A	7.7	7.7	1987	C	10.9	9.1
1950	A	14.2	14.2	1969	B	6.5	6.6	1988	C	10.0	10.0
1951	A	12.6	12.6	1970	B	7.3	7.6	1989	C	10.7	–
1952	A	13.7	13.7	1971	B	6.9	7.1	1990	C	6.4	9.7
1953	A	12.6	12.6	1972	B	6.7	6.7	1991	C[4]	5.8	5.8
1954	A	11.0	11.0	1973	B[1]	10.0	10.0	1992	C[5]	3.4	3.2
1955	A	12.2	12.2	1974	B[1]	11.5	10.8	1993	[6]	–	–
1956	A	10.0	10.0	1975	B	11.9	11.9	1994	[6]	–	–
1957	A	9.0	9.0	1976	B	13.4	13.3	1995	[6]	–	–
1958	A	9.5	9.5	1977	B[2]	15.9	15.4	1996	C	5.9	5.2
1959	A	10.7	10.7	1978	B[2]	17.1	15.6	1997	C	7.0	6.4
1960	A	10.5	10.5	1979	B	16.6	14.5	1998	C	8.3	6.3
1961	A	10.5	10.5	1980	B	15.2	15.2	1999	C	7.5	6.4
1962	A	8.0	8.0	1981	B	13.4	13.4	2000	C	7.2	6.6
1963	A	6.0	6.0	1982	B	13.2	13.2	2001	C	7.0	6.5
1964	A	6.8	6.8	1983	B	12.3	12.3	2002	C	3.2	3.2
1965	A	7.9	8.0	1984	B	13.8	13.8	2003	C	–	2.3
1966	A	10.6	10.6	1985	C	12.1	12.1	2004	–	–	–

1. Landings include catch given as incentive to explore "unfished" areas.
2. Landings include catch given as an incentive to fish Area A.
3. Season closed early after diagnosis of *B. exitiosa*
4. Landings include catch given as an incentive to fish a 'firebreak' to stop the spread of *B. exitiosa*
5. Fishing permitted only in outer areas of fishery.
6. Between 1993 and 1995, the fishery was closed and therefore no catch rate data are available.

An extract of the Ministry of Fisheries catch effort data for Foveaux Strait oysters was made on 30 January 2004, where data extracted were restricted to those events where the primary method code was "D" (dredge) and the estimated catch species code was either "OYS" or "OYU", and includes all returns received by 15 January 2004. Data were provided by the Ministry of Fisheries Information Management Group (Ministry of Fisheries Catch Effort Client Report No. 5240).

A total of 39 281 records was extracted (Table 7). The date of tow was not specified for three records and these were removed before analysis. No data were available from the Ministry of Fisheries catch-effort database system for the 1989 year. The data extracted from the Ministry of Fisheries catch-effort database system were daily summaries of the total daily catch and effort for each vessel (Table 8). Total catch was recorded in either number of sacks (between 1972 and 1988), catch weight (in kilograms, between 1990 and 30 March 1998), or numbers of oysters (after 30 March 1998). Total catch was converted to a catch in sacks of oysters by assuming that the a sack of oysters weighed 79 kilograms (for catches recorded as weight) or contained 774 oysters (for catches recorded as numbers).

Table 7: Total numbers of catch effort oyster records extracted by year and month, 1972–2003.

Year	Month												Total
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1972	0	0	422	308	221	281	448	492	107	0	0	0	2 279
1973	0	0	478	250	331	417	466	289	0	0	0	0	2 231
1974	0	0	228	437	295	276	313	372	0	0	0	0	1 921
1975	0	0	283	240	315	327	356	272	0	0	0	0	1 793
1976	0	0	384	333	236	284	197	310	0	0	0	0	1 744
1977	0	0	65	246	393	334	357	334	0	0	0	0	1 729
1978	0	0	251	331	359	337	345	252	0	0	0	0	1 875
1979	0	0	362	267	319	304	310	253	0	0	0	0	1 815
1980	0	0	132	266	294	352	360	251	0	0	0	0	1 655
1981	0	0	383	221	322	330	359	258	0	0	0	0	1 873
1982	0	0	404	340	247	377	319	198	0	0	0	0	1 885
1983	0	0	329	330	301	290	362	201	0	0	0	0	1 813
1984	0	0	402	213	309	232	346	179	0	0	0	0	1 681
1985	0	0	13	29	404	357	397	386	0	0	0	0	1 586
1986	0	0	325	262	291	299	332	0	0	0	0	0	1 509
1987	0	0	77	244	294	251	254	122	0	0	0	0	1 242
1988	0	0	332	295	292	324	247	286	0	0	0	0	1 776
1989	0	0	0	0	0	0	0	0	0	0	0	0	0
1990	0	0	354	176	173	277	40	0	0	0	0	0	1 020
1991	1	0	78	156	304	331	388	327	0	0	0	0	1 585
1992	0	1	63	105	67	67	35	3	21	31	58	23	474
1993	0	0	0	0	0	0	0	0	0	51	71	36	158
1994	0	1	0	0	0	0	0	0	0	0	0	0	1
1995	80	67	0	0	0	0	0	0	0	0	0	0	147
1996	15	16	0	0	0	123	261	225	0	0	0	0	640
1997	8	0	0	0	1	266	262	122	0	0	1	0	660
1998	19	5	0	18	247	207	129	47	0	0	0	0	672
1999	0	0	21	190	208	107	72	21	2	21	9	5	656
2000	12	0	201	145	169	83	32	32	0	0	0	0	674
2001	0	0	36	170	187	108	70	10	0	0	0	0	581
2002	0	0	46	266	157	155	203	155	0	0	0	0	982
2003	0	0	83	152	124	119	104	39	0	0	0	0	621
Total	135	90	5 752	5 990	6 860	7 215	7 364	5 436	130	103	139	64	39 278

Table 8: Variables and descriptions for the catch-effort data (*derived variables).

Variable	Description
Date	Date of record
*Year**	Year of record
*Month**	Month of record
*Day**	Day of month of record
Vessel	Vessel identification number
Statistical area	OYS or OYU statistical area (consistent definition from 1975 onwards)
Catch	Total catch of oysters
Units	Unit of measurement of the total catch of oysters (either sacks, weight, or numbers)
*Sacks**	Total catch of oysters in sacks
Duration	Total duration of effort in hours
Tows	Number of tows (data available from 1990 onwards)
Width	Dredge width in metres (data available from 1990 onwards)

Catch effort data typically contain many errors, mostly as invalid codes, and missing or implausible values (although the Foveaux Strait dredge oyster data were remarkably cleaner than for many other fisheries). Data were checked for errors, using simple checking algorithms.

1. Catch totals that were greater than 150 sacks were assumed to be errors, and were set to missing (0.04 %).
2. Durations of fishing that were greater than or equal to 13 hours were assumed to be errors, and set to missing (0.04 %).
3. Catch records where the catch rate exceeded 50 sacks per hour were assumed to be errors, and set to missing (0.05 %).

Further, any catch that was recorded as taken outside March to August in any year was assumed to be from special permits (i.e., outside the usual winter fishing season). In some years (e.g., 1978 and 1979), special permits were issued to allow fishers to investigate or explore regions outside the areas of their usual fishing grounds, but during the usual winter season. Some of these records were removed from the data presented by Annala et al. (2003) (see footnotes for Table 6), but all winter data are used here. The data from the Ministry of Fisheries catch-effort database system can be used to recalculate the unstandardised catch rates, without adjustment (Table 9).

The statistical reporting areas used in the Foveaux Strait fishery have been modified from time to time, with the latest revision taking place at the beginning of the 1975 fishing season. Hence, further analysis of the data was restricted to years from 1975. Further, core vessels were defined as those vessels that had fished in Foveaux Strait for at least five years.

Estimates of relative year effects for standardised indices of relative abundance were obtained from a stepwise multiple regression method in which the positive catch (i.e., non-zero, 99.975% of the data) data were modelled using a lognormal generalised linear model. A forward stepwise multiple regression fitting algorithm was employed (Chambers & Hastie 1991, Venables & Ripley 1994).

The algorithm generates a final regression model iteratively starting with the term *year* as the initial model. At each step, the reduction in residual deviance relative to the null deviance (denoted r^2) was calculated for each single term added to the base model. The term giving the greatest reduction in residual deviance was then added to the base model if this would result in an improvement in the residual deviance of more than 1%. The algorithm then repeats this process, updating the base model, until no new terms can be added.

The model indices are presented in canonical form. Model fits were investigated using standard residual diagnostics, and, for each model, plots of model residuals and fitted values were investigated for evidence of departure from model assumptions (Figure 14). The resulting model included the variables *duration*, *statistical area*, and *vessel*; and had an overall r^2 of 0.764. CPUE model fits are given in Table 9, and expected catch rate diagnostic plots in Figure 14. Residual and quantile-quantile normal diagnostic plots are shown in Figure 15. Model diagnostics plots shown considerable deviation from model assumptions, with poor fits evident in the prediction of very low or very high catch rates.

Data from voluntary fisher logbooks are available for 1999–2003. Logbook data are much more extensive that those from daily summaries on the Ministry of Fisheries catch-effort database system, but are less complete. At most, about 50% of the total annual commercial catch was recorded on logbook records (A. Dunn, NIWA, unpublished data). Table 9 shows the mean catch rate (sacks per hour) determined from all available logbook records.

Comparison of all indices, standardised to have mean equal to one over the years 1999–2002, is given in Figure 16. Clearly, all indices show similar trends, with only slight differences discernible between data sets or methods of analyses. As the unstandardised indices (i.e., unstandardised indices recalculated from source catch-effort records) showed very similar trends to the standardised indices, and, moreover, covered a longer period of the fishery, these were used as relative indices of abundance in the stock model (see also Table 6), with a lognormal likelihood and assumed c.v.s of 0.25.

Table 9: Unstandardised catch rate indices from Ministry of Fisheries reports (reported); unstandardised catch rate indices calculated from source catch-effort records (Sacks/hr); unstandardised catch rate indices calculated from core vessels catch-effort records (Core sacks/h); unstandardised catch rate indices calculated from logbook data (logbook sacks/h); standardised CPUE indices from source catch effort records (Model) for Foveaux Strait oysters 1972–2003.

Year	Series	Reported	Sacks/h	Core sacks/h	Logbook sacks/h	Model Index	Model 95% C.I.s	Model c.v.
1972	B	6.67	6.72	–	–	–	–	–
1973	B	10.00	9.95	–	–	–	–	–
1974	B	11.50	10.81	–	–	–	–	–
1975	B	11.90	11.92	11.87	–	1.33	(1.31–1.35)	0.01
1976	B	13.40	13.33	13.25	–	1.50	(1.47–1.53)	0.01
1977	B	15.90	15.43	15.38	–	1.71	(1.68–1.74)	0.01
1978	B	17.10	15.58	15.51	–	1.76	(1.73–1.79)	0.01
1979	B	16.60	14.53	15.18	–	1.70	(1.67–1.73)	0.01
1980	B	15.20	15.20	15.20	–	1.68	(1.65–1.71)	0.01
1981	B	13.40	13.42	13.43	–	1.49	(1.46–1.52)	0.01
1982	B	13.20	13.18	13.20	–	1.46	(1.43–1.48)	0.01
1983	B	12.30	12.26	12.28	–	1.38	(1.35–1.40)	0.01
1984	B	13.80	13.81	13.82	–	1.56	(1.54–1.59)	0.01
1985	C	12.10	12.13	12.12	–	1.36	(1.33–1.38)	0.01
1986	C	10.50	10.51	10.51	–	1.17	(1.14–1.19)	0.01
1987	C	10.90	9.13	9.13	–	1.02	(1.00–1.05)	0.01
1988	C	10.00	10.00	9.95	–	1.16	(1.14–1.19)	0.01
1989	C	10.70	–	–	–	–	–	–
1990	C	6.40	9.65	9.60	–	1.13	(1.10–1.15)	0.01
1991	C	5.80	5.82	5.82	–	0.73	(0.72–0.75)	0.01
1992	C	3.40	3.16	3.47	–	0.48	(0.45–0.50)	0.03
1993	1	–	–	–	–	–	–	–
1994	1	–	–	–	–	–	–	–
1995	1	–	–	–	–	–	–	–
1996	C	5.90	5.16	5.75	–	0.63	(0.61–0.65)	0.02
1997	C	7.00	6.43	6.72	–	0.72	(0.70–0.74)	0.01
1998	C	8.30	6.27	8.22	–	0.84	(0.82–0.87)	0.02
1999	C	7.50	6.37	7.37	7.32	0.75	(0.72–0.77)	0.02
2000	C	7.20	6.56	7.27	10.16	0.74	(0.72–0.76)	0.02
2001	C	7.00	6.50	6.57	7.73	0.70	(0.68–0.72)	0.02
2002	C	3.20	3.18	3.33	4.17	0.36	(0.35–0.37)	0.01
2003	C	2.30	2.32	2.42	3.06	0.31	(0.30–0.32)	0.02

1. Between 1993 and 1995 the fishery was closed and therefore no CPUE data are available.

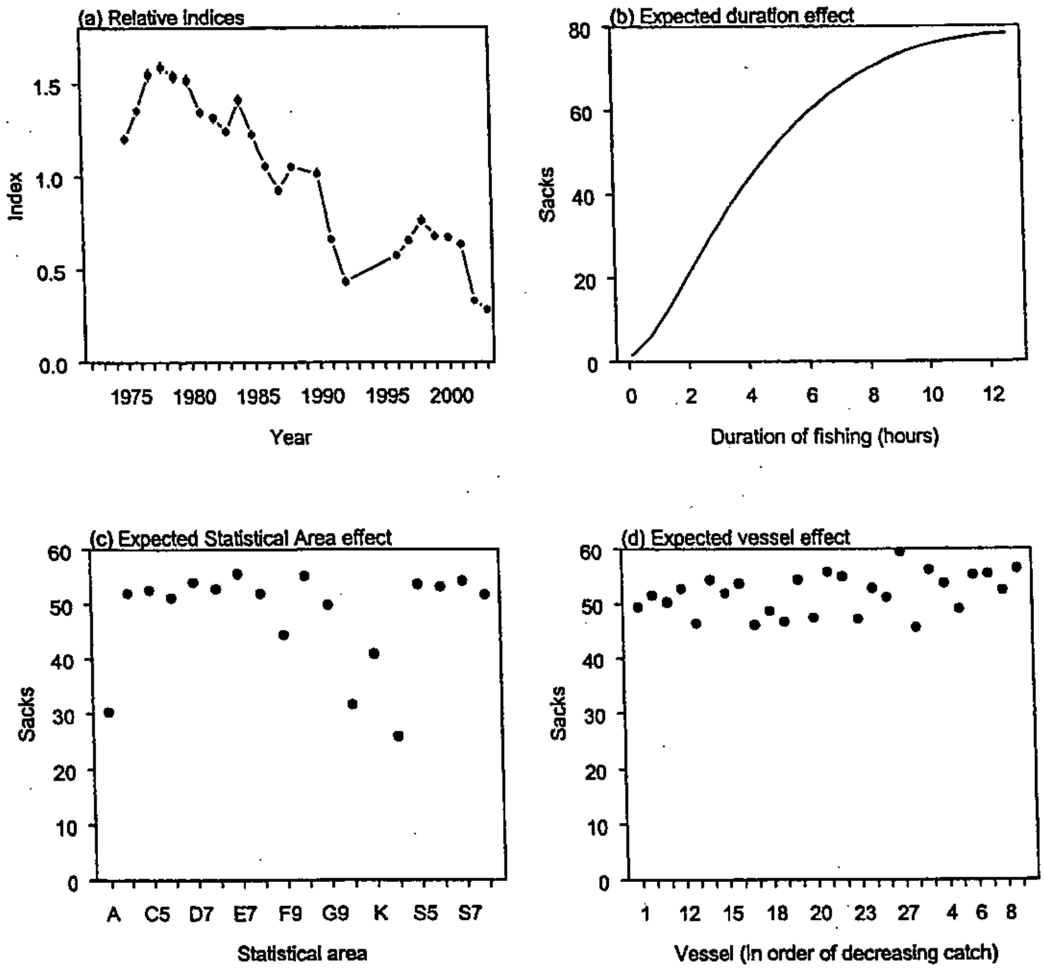

Figure 14: Relative indices (Model A), and expected catch rate (sacks) plots for median values of the fixed parameters the standardised CPUE model (*Year*=1986, *Statistical area*=F8, *vessel*=15, *and duration*=5 *hours*).

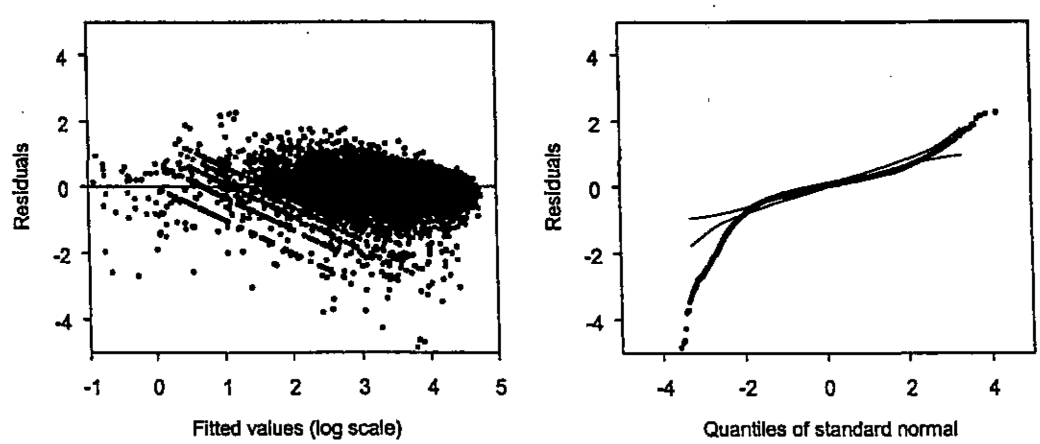

Figure 15: Residual and quantile-quantile diagnostic plots for the standardised CPUE model.

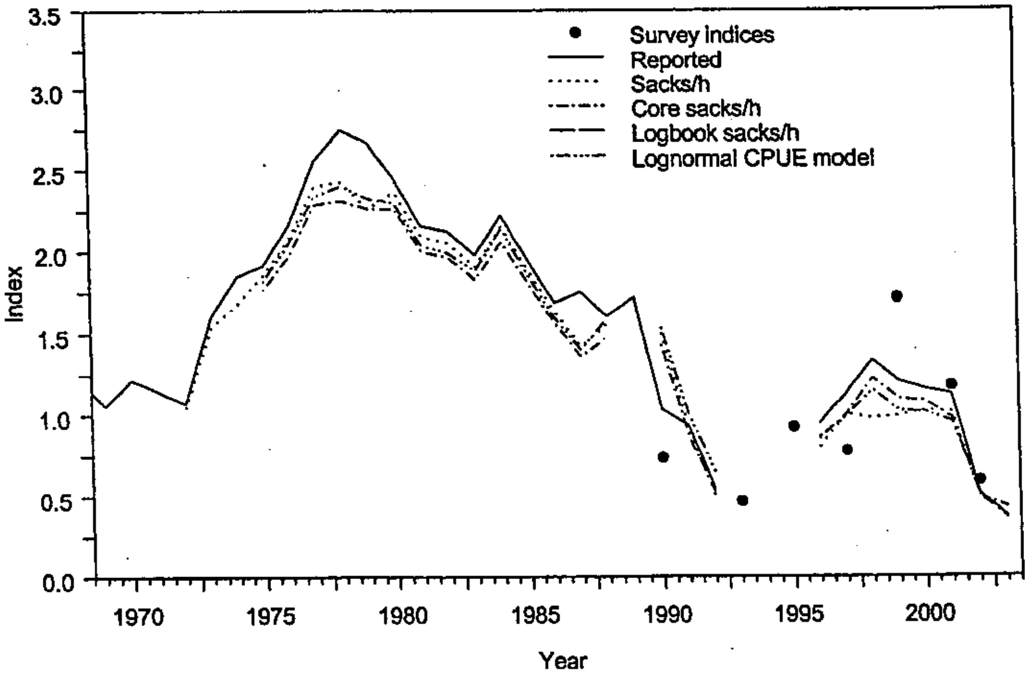

Figure 16: Comparison of the alternative CPUE indices (reported catch per hour, revised catch per hour, core vessels sacks per hour, logbook sacks per hour, and model indices) by year, 1969–2003. Indices have been standardised to have mean one over the years for which survey data were available (i.e., 1990, 1997, 1999, 2001, 2002).

2.6 Population length frequency estimates

Height data were collected on the October 1990 dive survey, and the 1960–64 dredge survey. Length data were collected from the 1926–27, 1999, and 2001 surveys. The length and height samples collected from the 1926-27 and the 1960–64 dredge surveys have not been included within the model, but are described here for completeness.

2.6.1 1926 Survey

Individual length data were collected on the 1926–27 surveys by M.W. Young, and reported in table 3 of Sorensen (1968). However, the method of sampling, dredge selectivity, and dredge calibration are unknown for that survey, and hence these data are not able to be included within the population model. The data in Sorensen (1968) are reproduced in Figure 17 below, after converting the length measurements from inches to millimetres.

2.6.2 1960–64 survey

Individual height data were collected on the 1960–64 survey and reported in a graph in Stead (1971b). Raw height frequency data from that survey are unavailable, but can be inferred from the published graph.

Height measurements of oysters are about 25% larger than length measurements, and using an appropriate conversion factor (based on the length and height of oysters collected in 2001–2003), the height frequencies can be converted to length frequencies, i.e.,

$$\log(\mathit{length}) = a \log(\mathit{height}) + \varepsilon ,$$

where $\varepsilon \sim N(0,\sigma^2)$, and hence estimate the conversion factor (in log space) as $a = 0.949$.

The data in Stead (1971b) are reproduced in Figure 18 below, after converting the height measurements to length.

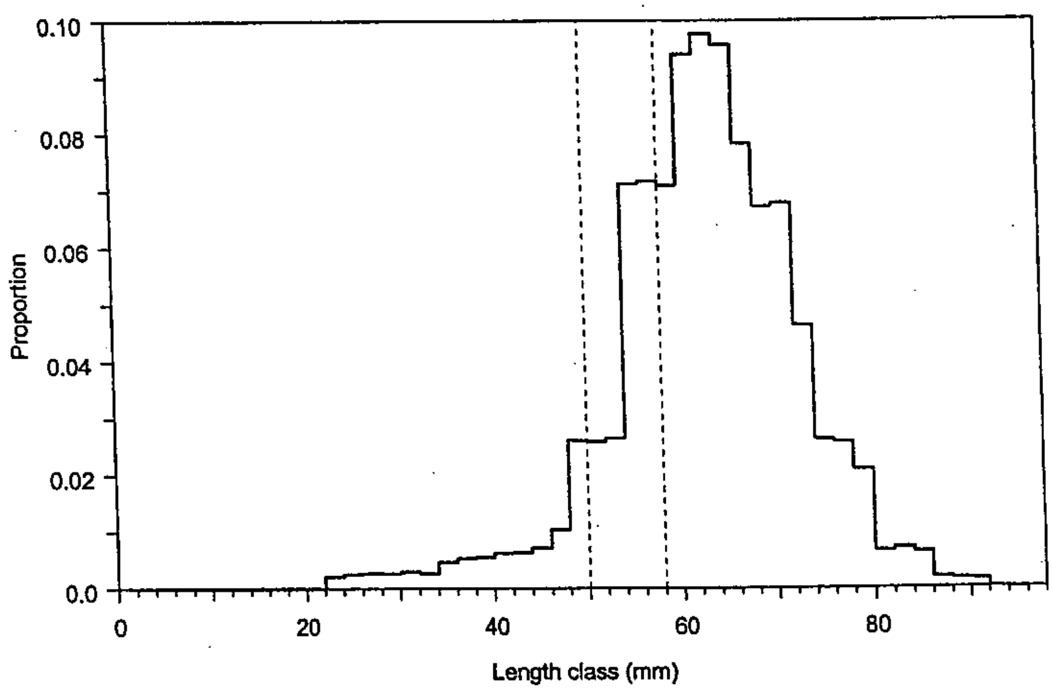

Figure 17: Proportions of oysters by length class from the 1926–27 survey, reproduced from data given in table 3 in Sorensen (1968). Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

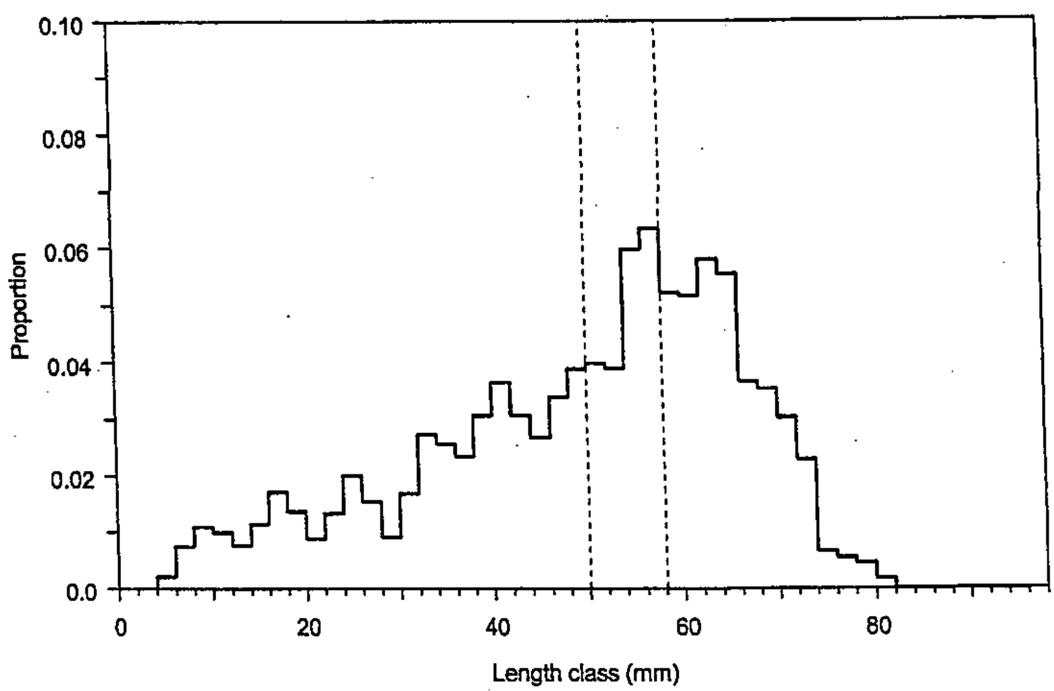

Figure 18: Proportions of oysters by length class from the 1960–64 survey, reproduced from data given in Figure 1 in Stead (1971b). Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

2.6.3 October 1990 dive survey

During the dive survey in October 1990, height measurements were collected from the oysters sampled. These were converted to length frequencies using the conversion factor described above. The dive survey length frequencies were assumed equal to the population length frequency at the time of the survey (Figure 19, after converting the height measurements to length, truncated at 10 mm). Proportions at length were included in the model using a multinomial likelihood. The effective sample sizes for the length frequency data were estimated by calculating a sample size that represented the best least squares fit of $\log(cv_i) \sim \log(P_i)$, where cv_i was the bootstrap c.v. for the ith proportion, P_i (Table 10, and Appendix A, Figure 42).

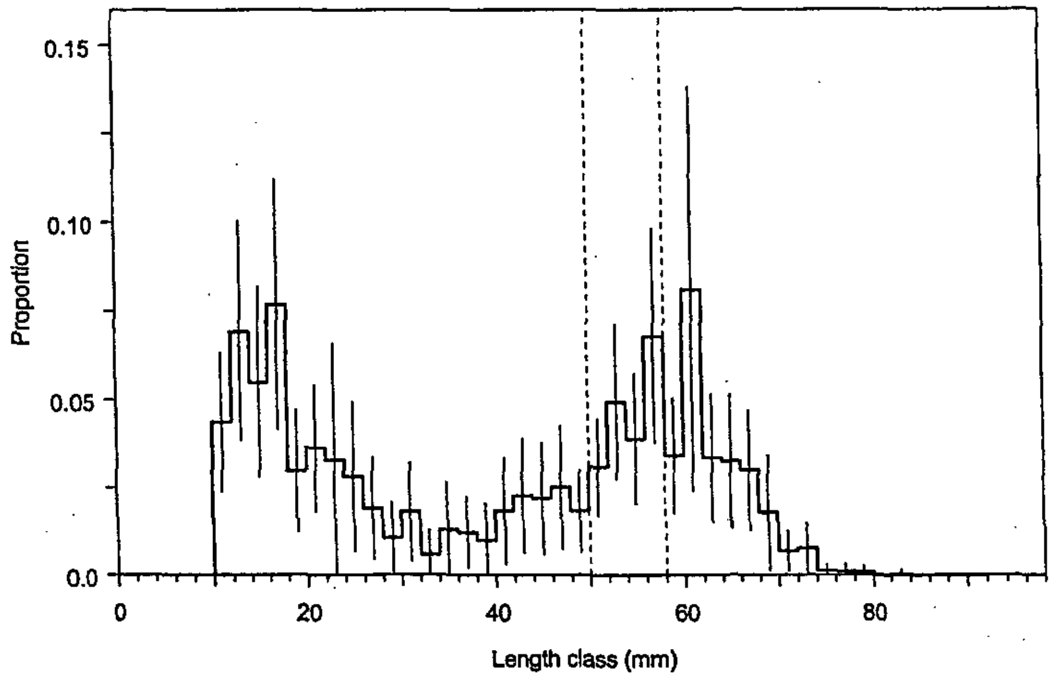

Figure 19: Proportions of oysters by length class from the 1990 dive survey. Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

Table 10: Actual sample sizes and effective sample sizes determined for the multinomial likelihood for the survey proportions at length data.

Survey	Size	Actual sample size	Effective sample size
October 1990 dive	All	2 115	461
October 1999	Small	16 085	1 273
	Pre-recruit	8 424	953
	Recruit	16 054	1 277
October 2001	Small	7 475	1 074
	Pre-recruit	3 460	544
	Recruit	4 227	887

2.6.4 1999 and 2001 survey

Length samples from the 1999 and 2001 October resource surveys were collected for oysters classified as "smalls", "pre-recruits", and "recruits". Catch-at-length estimates were produced using the catch-at-age software (Bull & Dunn 2002). This scales up the length frequency of fish from each tow up to the total tow catch, sums over tows in each stratum and scales up to the total stratum catch, to yield length frequencies by stratum and overall. The c.v.s are calculated by bootstrapping; individual oyster length measurements are resampled within each tow and tows are resampled within each stratum (Figures 20–25).

Proportions at length were included into the model with a multinomial likelihood. The effective sample sizes were estimated by calculating a sample size that represented the best least squares fit of $\log(cv_i)$~$\log(P_i)$, where cv_i was the bootstrap c.v. for the ith proportion, P_i (Table 10, and Appendix A, Figure 43).

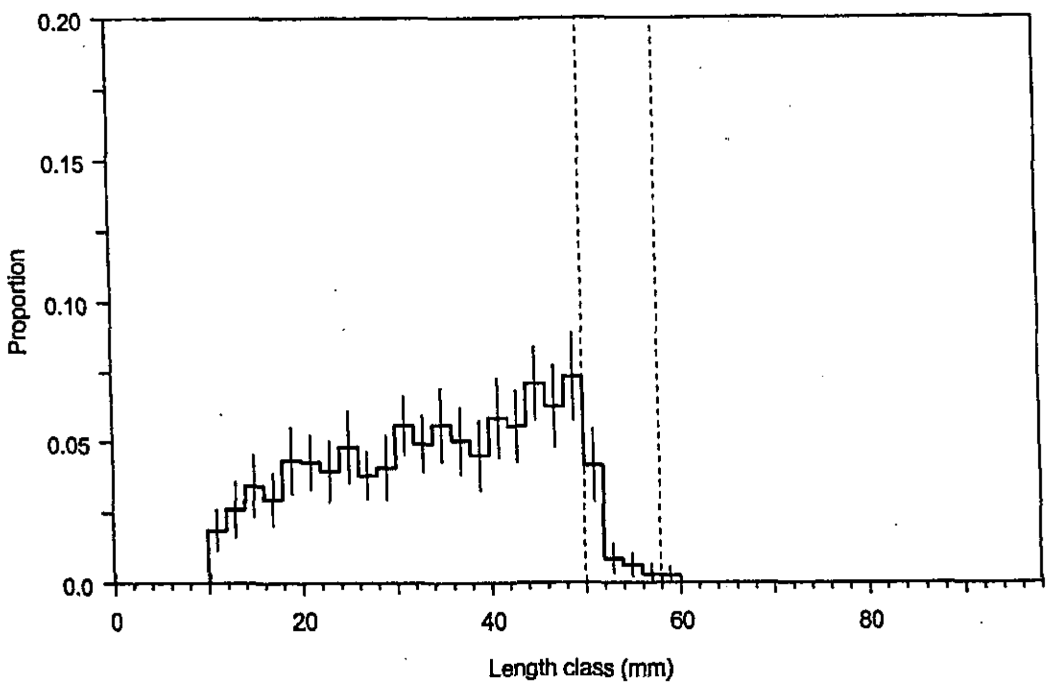

Figure 20: Proportions of oysters classified as "smalls" by length class from the 1999 October resource survey. Vertical bars give approximate 95% confidence intervals. Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

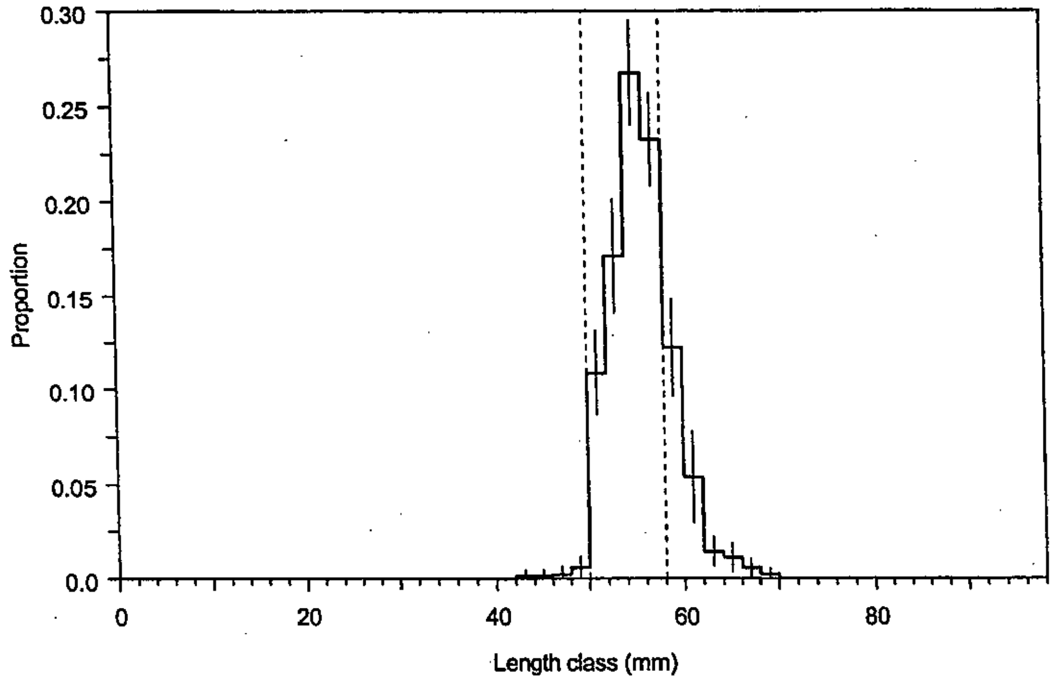

Figure 21: Proportions of oysters classified as "pre-recruits" by length class from the 1999 October resource survey. Vertical bars give approximate 95% confidence intervals. Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

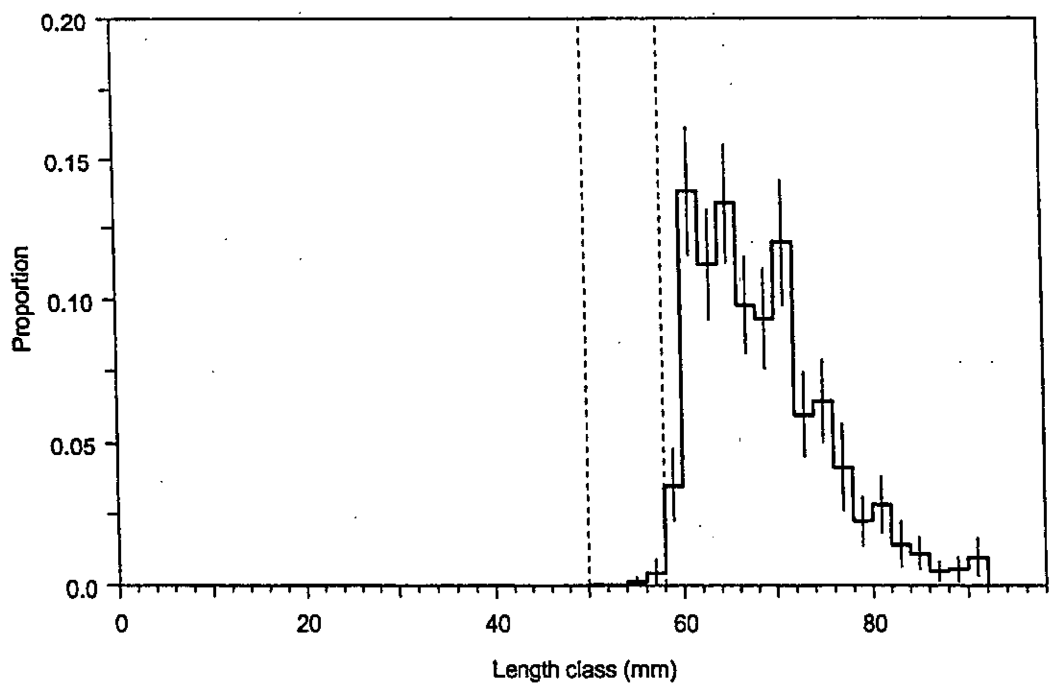

Figure 22: Proportions of oysters classified as "recruits" by length class from the 1999 October resource survey. Vertical bars give approximate 95% confidence intervals. Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

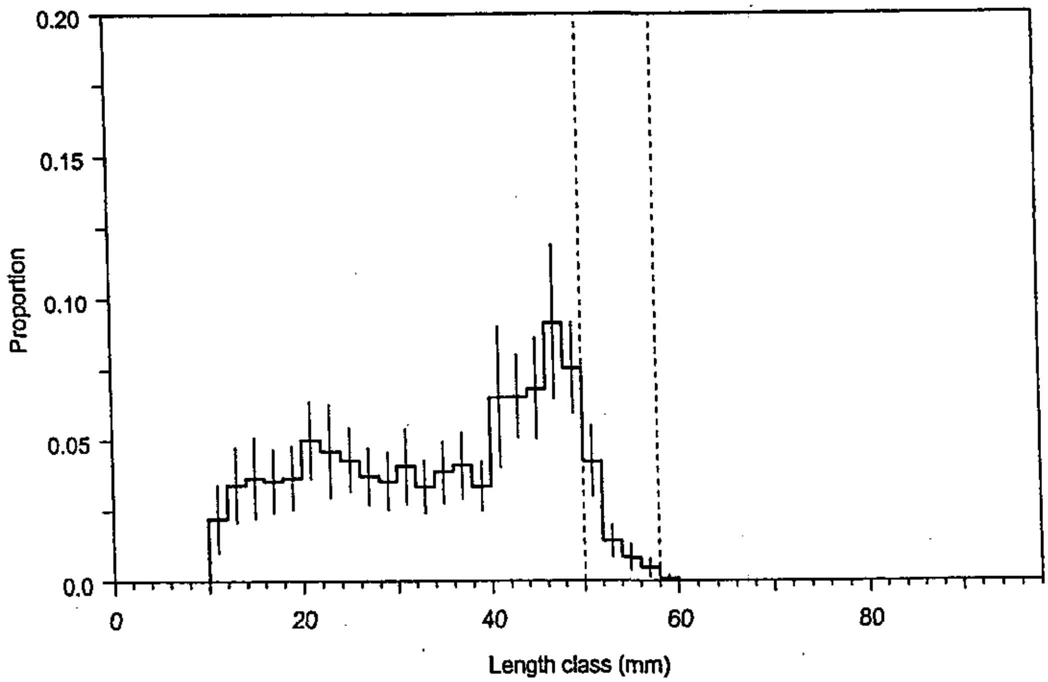

Figure 23: Proportions of oysters classified as "smalls" by length class from the 2001 October resource survey. Vertical bars give approximate 95% confidence intervals. Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

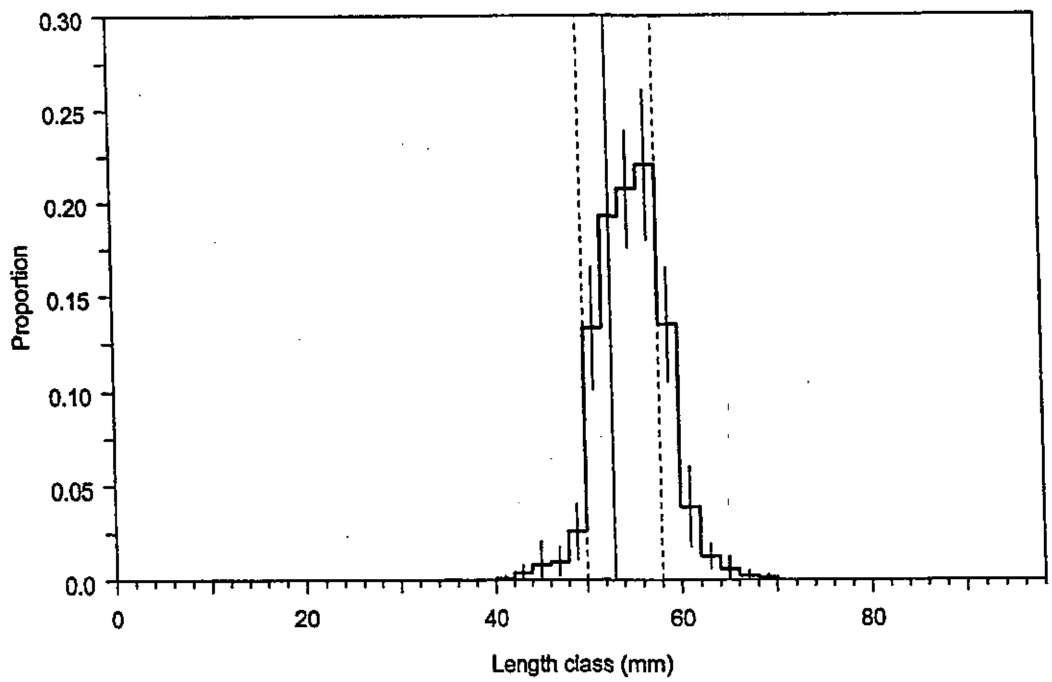

Figure 24: Proportions of oysters classified as "pre-recruits" by length class from the 2001 October resource survey. Vertical bars give approximate 95% confidence intervals. Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

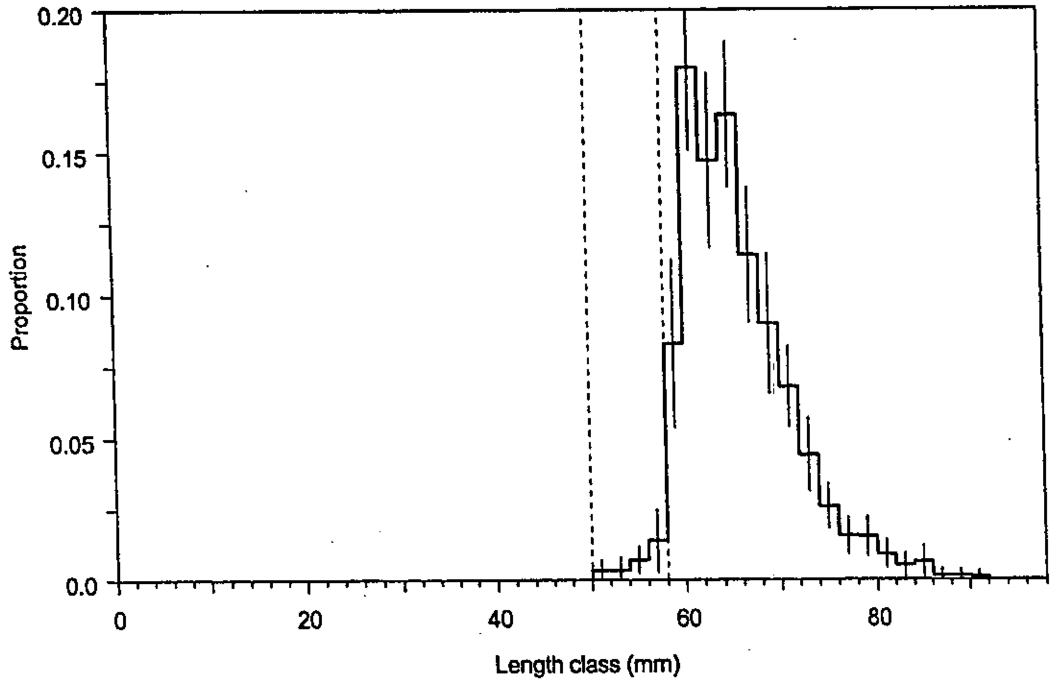

Figure 25: Proportions of oysters classified as "recruits" by length class from the 2001 October resource survey. Vertical bars give approximate 95% confidence intervals. Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

3. MODEL ESTIMATES

3.1 Model set-up and priors

Model estimates of numbers of oysters were made using the biological parameters and model input parameters described in Section 2.2. Objective function values (negative log-likelihood) are shown in Table 11. MPD (Mode of the Posterior Distribution) trajectories of the base case and sensitivity case MPD for the recruit-sized stock abundance are shown in Figure 26. Additional summary plots of the base case MPD model fits are given as Appendix A. Assumed priors for parameters are summarised in Table 12. Priors for selectivity ogives (not shown) were chosen to be non-informative, and were uniform across wide bounds. Sensitivity runs were limited to a few scenarios where strong assumptions may have influenced model fits. The sensitivity runs are given in Table 11 and were,

1. CPUE q — the same as the base case, except that the catchability coefficient for the three CPUE series was constant, i.e., the CPUE catchability coefficient q was set equal for all three CPUE series.
2. Survey q — the same as the base case, except that the absolute abundance time series from the dredge surveys were assumed to be a relative series, with a log-uniform prior on the catchability coefficient,
3. Short — the same as the base case, except that the model only included catch and research data from 1985 onwards and assumed equilibrium initial abundance in 1984,
4. Low M — the same as the base case, except that the rate of natural mortality (M) was assumed to be 0.05 y^{-1}, rather than 0.1 y^{-1}.
5. Constant YCS — the same as the base case, except that the relative year class strength for all years were set equal to one.

A single Monte-Carlo Markov Chain (MCMC) was run on each model, with length 1.5×10^6 iterations including a burn-in of 0.5×10^6 iterations. Final posterior distributions were derived from systematic subsampling ("thinning") of the chain, excluding the burn-in, to 1000 samples.

Convergence diagnostics for all parameters in the model were not formally investigated, but the trace for B_0 suggests little change during the last million iterations (Figure 27).

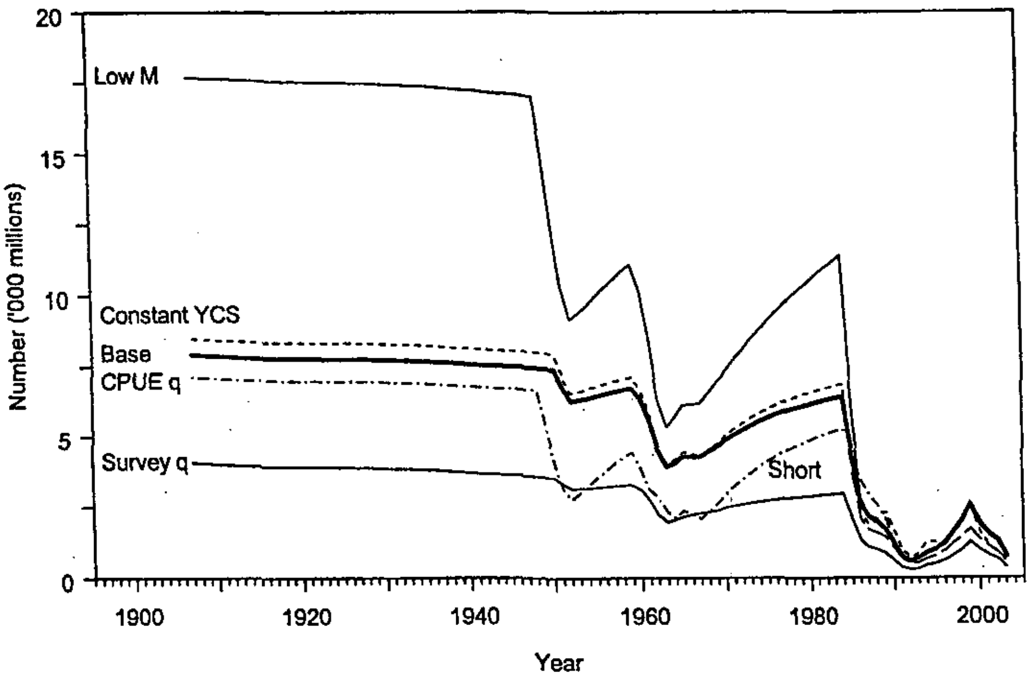

Figure 26: MPD trajectories of recruit-sized stock abundance for the base case and sensitivity cases.

Table 11: Objective function values (negative log-likelihood) for MPD fits to data (data), priors, penalties resulting from penalties to catch (penalties), and the total objective function (negative log-likelihood) value for the base case and sensitivity cases.

Model	Data	Priors	Penalties	Total
Base case	490.5	82.3	0.0	572.8
CPUE *q*	522.1	98.5	0.0	620.6
Survey *q*	489.0	78.5	0.0	567.5
Short series	403.5	49.4	0.0	452.9
Low *M*	500.8	103.0	0.0	603.8
Constant YCS	723.2	100.3	0.0	823.5

Table 12: The priors assumed for key parameters. The parameters are mean and c.v. for lognormal (in natural space); and mean and s.d. for normal.

Parameter	Distribution	Parameters		Bounds	
CPUE *q*	Uniform-log	–	–	1×10^{-8}	0.1
Survey *q*	Uniform-log[1]	–	–	0.10	10.0
1976 survey *q*	Lognormal	0.5	0.3	0.15	0.95
Mark-recapture survey *q*	Lognormal	0.5	0.3	0.10	0.90
YCS	Lognormal	1.0	1.0	0.01	100.0
Disease mortality	Normal	-0.2	0.2	0.00	0.80

1. Used in the Survey *q* model run only.

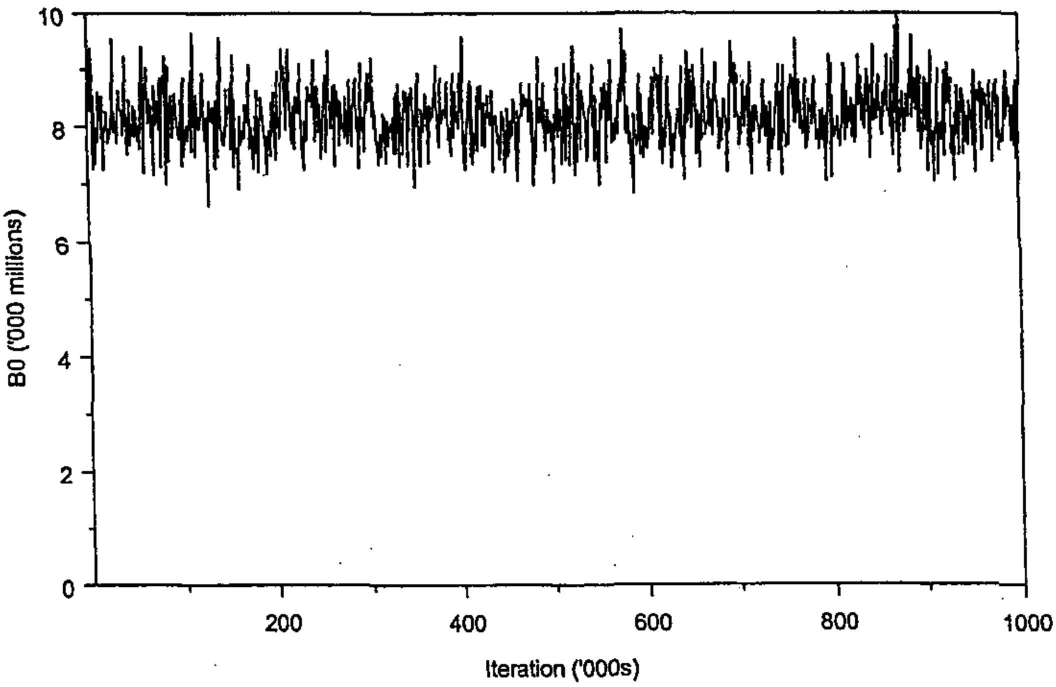

Figure 27: Trace diagnostic plot for MCMC chain for estimates of B_0.

3.2 Current status

The MCMC posterior distributions for estimated relative selectivities for dredge survey recruits, pre-recruits, and smalls; fishing selectivity; and proportions mature (but note that the maturity ogive is also applied as the disease selectivity ogive) are shown in Figure 28. Model fits to recruit-sized and pre-recruit-sized dredge survey length frequencies, maturity data, and fishing length frequencies were adequate, although there was some evidence of over-fitting to the recruit-sized length frequencies (Appendix A, Figures 49–53). Diagnostic plots of the combined fits to recruit, pre-recruit, and small dredge survey selectivities (see, for example, Figure 28d) suggested that the parameterisation of selectivities for the three size groups (recruit, pre-recruit, and small) was adequate, but additional length frequency data would improve the estimates. Estimated CPUE *q*s showed an increase in relative catchability from series A and B to series C, possibly corresponding with improved technology and dredge size (Figure 29). The 1975–76 and mark-recapture abundance data contribute little to the model fits, as these series are short and are unrelated to other abundance data in the model. The *q*s for these data are probably more a reflection of how the model interprets the estimates to be consistent with other abundance information from longer time series, i.e., about 30% of the total abundance available at that time (both of these survey data represent abundance within a smaller survey region than that was covered in subsequent surveys). However, posterior distributions for all the catchability constants were relatively narrow

MPD model fits to abundance indices showed no evidence of poor fit to the data. However, most of the historical data provided to the model were derived from the catch-effort indices, and it is not known how well these index abundance (although comparisons with survey data suggest that these are broadly informative). It has been suggested (I.J. Doonan, NIWA, pers. comm.) that the CPUE can remain high for oysters in years of rapidly declining abundance, as fishers can easily target any remaining high density patches.

Estimates of the disease mortality rate ranged from 0.0 up to a maximum of 0.80 y^{-1} (the upper bound) in the mid 1980s and early 2000s, and accounted for the dramatic declines in the abundance of oysters during periods of epidemic (Figures 30 and 31).

Estimates of relative year class strength were uncertain and variable (Figure 32), but suggest that there may have been a pulse of strong recruitment during the mid to late 1990s. Without other, better, data on historical levels of recruitment, however, these estimates cannot be validated.

Stock number trajectories are plotted in Figures 33 and 34; the first shows the estimated spawning stock size trajectory (SSB), and the second the recruit-sized (i.e., ≥ 58 mm in length) stock abundance.

Model estimates suggested that the initial recruit-sized population abundance was about 6000 million oysters, and the current size is about 600 million (Table 13). Current spawning stock size in 2003 was about 20% (19–22%) of B_0. However, when considering the recruit-sized stock abundance, the current stock size (labelled rB_{2003}) was only about 9% (8–11%) of initial state (rB_{1907}).

Table 13: Bayesian median and 95% credible intervals of B_0 (millions), recruit-sized stock abundance rB_{2003} (millions) and rB_{2003} as a percentage of rB_{1992}.

Model	B_0	rB_{1992}	rB_{2003}	rB_{2003} (% rB_{1907})
Base case	8 139 (7 207–9 255)	635 (557–731)	769 (646–922)	9 (8–11)
CPUE q	6 891 (6 179–7 610)	649 (568–741)	769 (668–879)	11 (10–13)
Survey q	5 115 (3 805–7 466)	398 (284–589)	475 (341–716)	9 (8–11)
Short series	5 963 (5 190–6 981)	524 (458–612)	604 (494–741)	–
Low M	17 329 (15 250–19 754)	623 (538–720)	763 (652–914)	4 (4–5)
Constant YCS	8 334 (7 546–9 245)	749 (656–864)	575 (510–643)	7 (6–8)

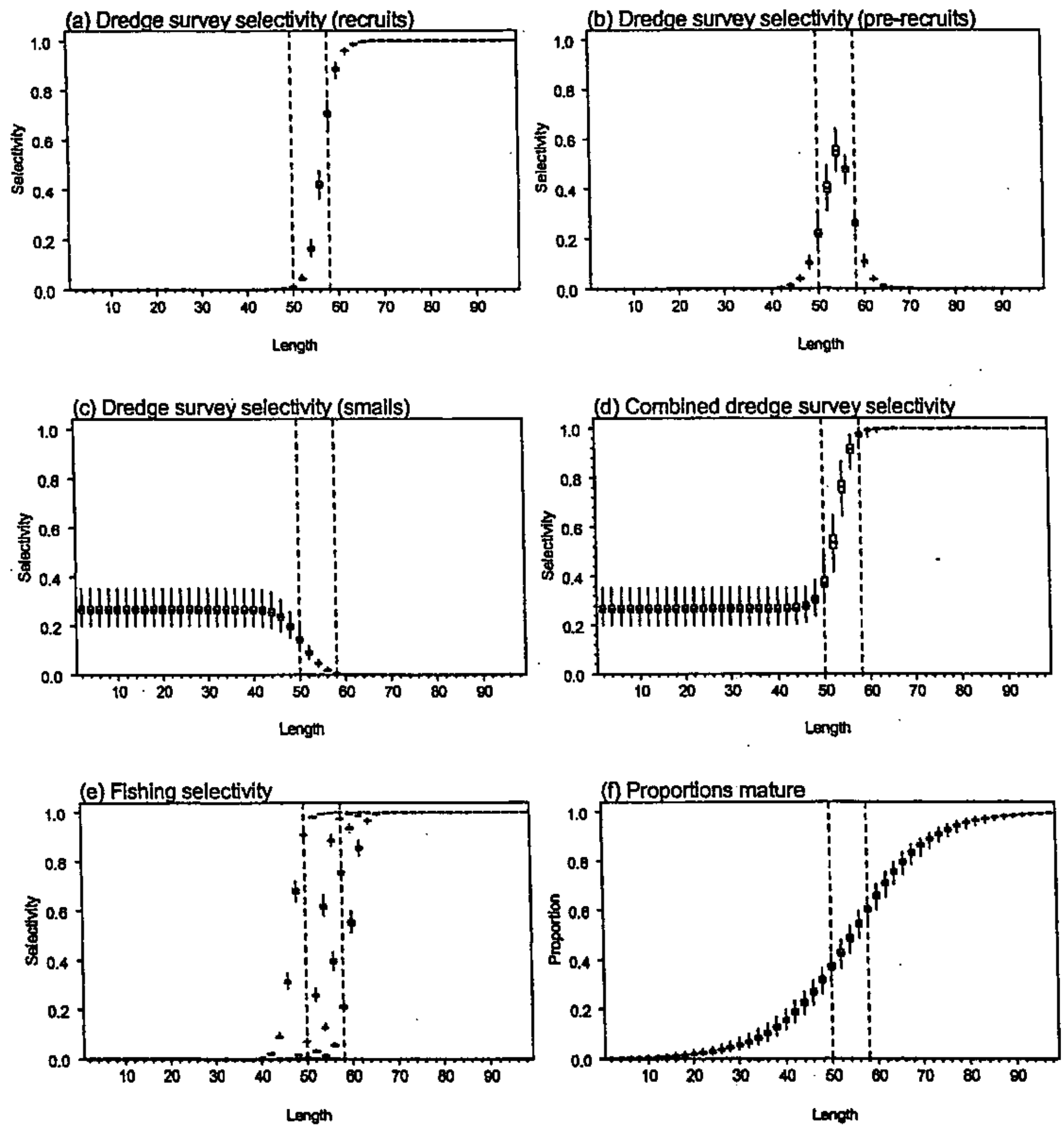

Figure 28: Estimated posterior distributions of selectivity by length for (a) dredge survey recruits; (b) dredge survey pre-recruits; (c) dredge survey smalls; (d) total recruit, pre-recruit, and small dredge survey selectivities combined; (e) fishing selectivities (greys show shifted selectivities); and (f) proportions mature (equivalent to disease selectivity). Individual distributions show the marginal posterior distribution, with horizontal lines indicating the median. Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

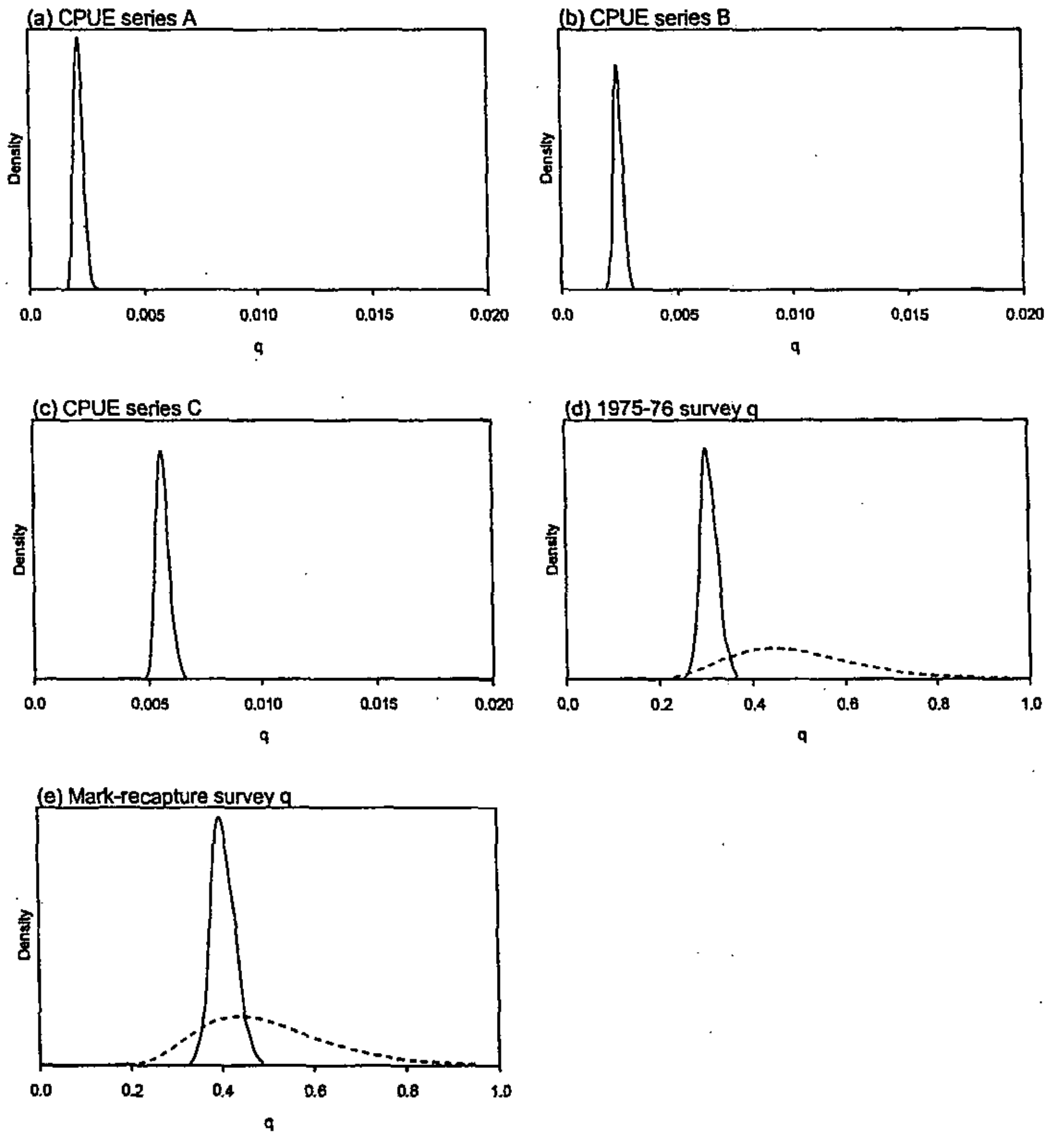

Figure 29: Estimated posterior distributions (solid lines) and priors (dashed lines) of the (figures a–c) CPUE series A, B, and C (log-uniform priors not shown); (d) 1975–76 survey, and (e) mark-recapture survey relativity constants.

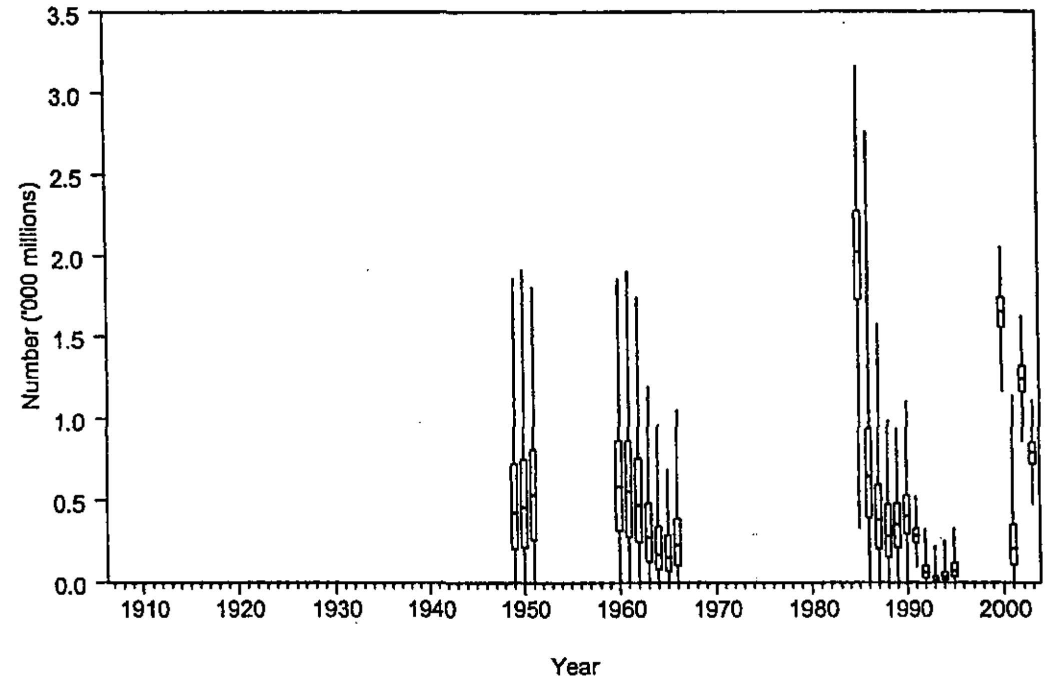

Figure 30: Estimated posterior distributions of disease mortality (number, '000 millions). Individual distributions show the marginal posterior distribution, with horizontal lines indicating the median.

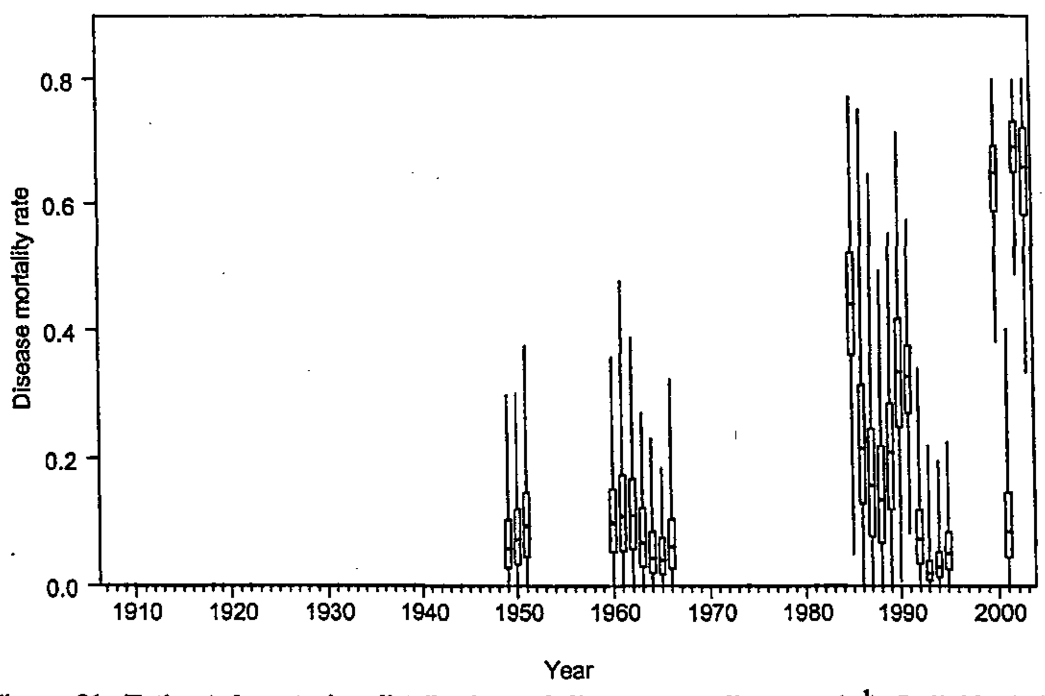

Figure 31: Estimated posterior distributions of disease mortality rate (y^{-1}). Individual distributions show the marginal posterior distribution, with horizontal lines indicating the median.

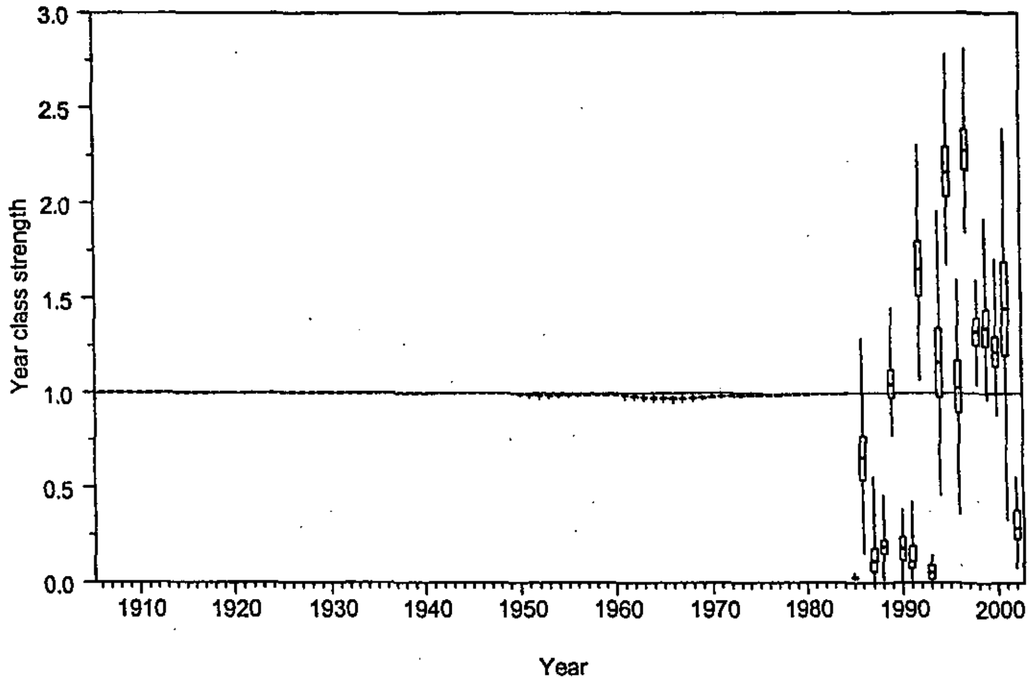

Figure 32: Estimated posterior distributions of year class strengths. The file horizontal line indicates the year class strength of one. Individual distributions show the marginal posterior distribution, with horizontal lines indicating the median.

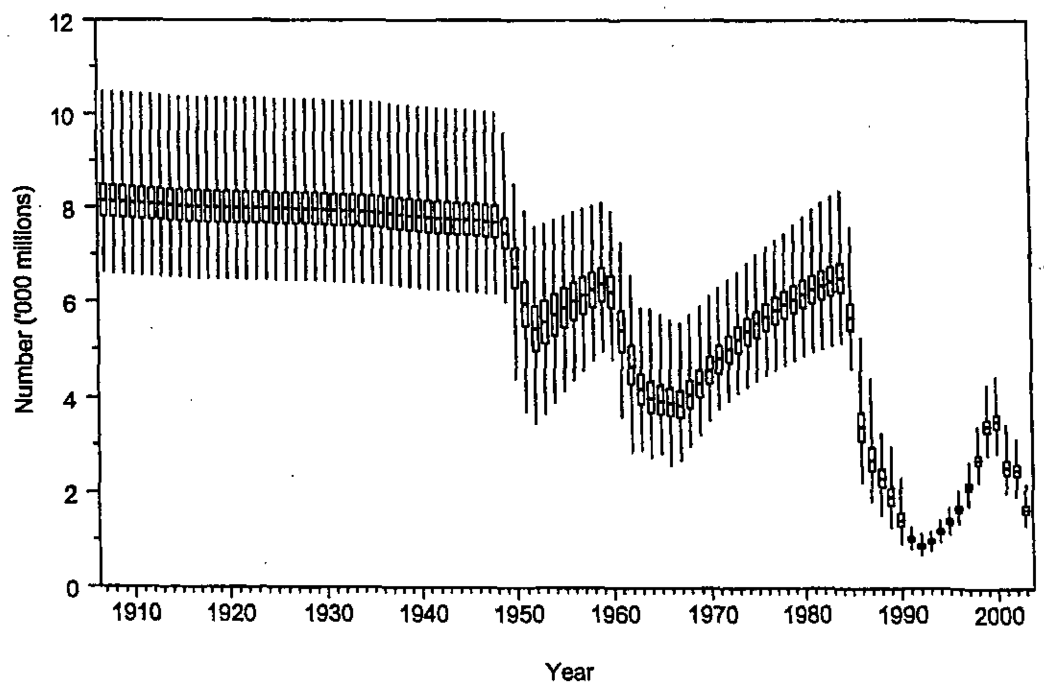

Figure 33: Estimated posterior distributions of SSBs. Individual distributions show the marginal posterior distribution, with horizontal lines indicating the median.

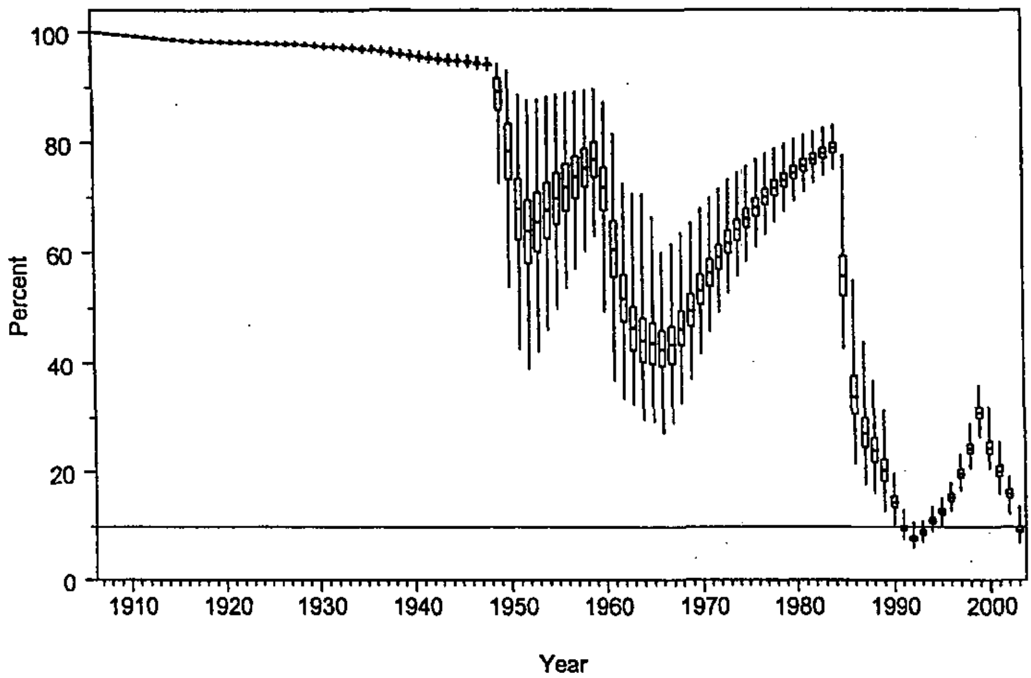

Figure 34: Estimated posterior distributions of recruit-sized stock abundance. Individual distributions show the marginal posterior distribution, with horizontal lines indicating the median. The solid horizontal line indicates the level equal to 10% of the 1907 stock abundance.

3.3 Sensitivity results

Model runs for the sensitivity cases all suggested a similar stock status as for the base case. The relative estimates of B_0 from the base and sensitivity cases suggested some variability in the estimates of the initial population size (Figure 35), but estimates of the current status and recent change in the current status were very similar (Figures 36–37).

However, sensitivity runs for the "survey q" were more pessimistic than that for the base case, reflecting the more conservative assumption of a greater catchability than was assumed for the base case (Figure 38). Posterior distributions for the survey catchability had median 1.6, and ranged from 0.8 to 2.5 (95 % C.I.s 1.1–2.3). These estimates suggest that this model run estimated the dredge efficiency as about 0.28 (0.13–0.50) rather than the assumed efficiency of 0.17 (0.11–0.24) in the base case.

3.4 Projected stock status

Projected stock estimates were made assuming that future recruitment will be log-normally distributed with mean 1.0 and standard deviation equal to the standard deviation of log of recruitment between 1985 and 2000 (1.6 with 95% range 1.3–2.1). Projections were made assuming no future disease mortality and with future disease mortality assumed to be 0.20 y^{-1}, 0.40 y^{-1}, and 0.6 y^{-1}. Two catch levels were considered, nil annual commercial catch in 2004–06 and an annual commercial catch of 15 million oysters. Future customary, recreational, and illegal catch were assumed equal to levels assumed for 2003. Projected output quantities are summarised in Tables 14–15.

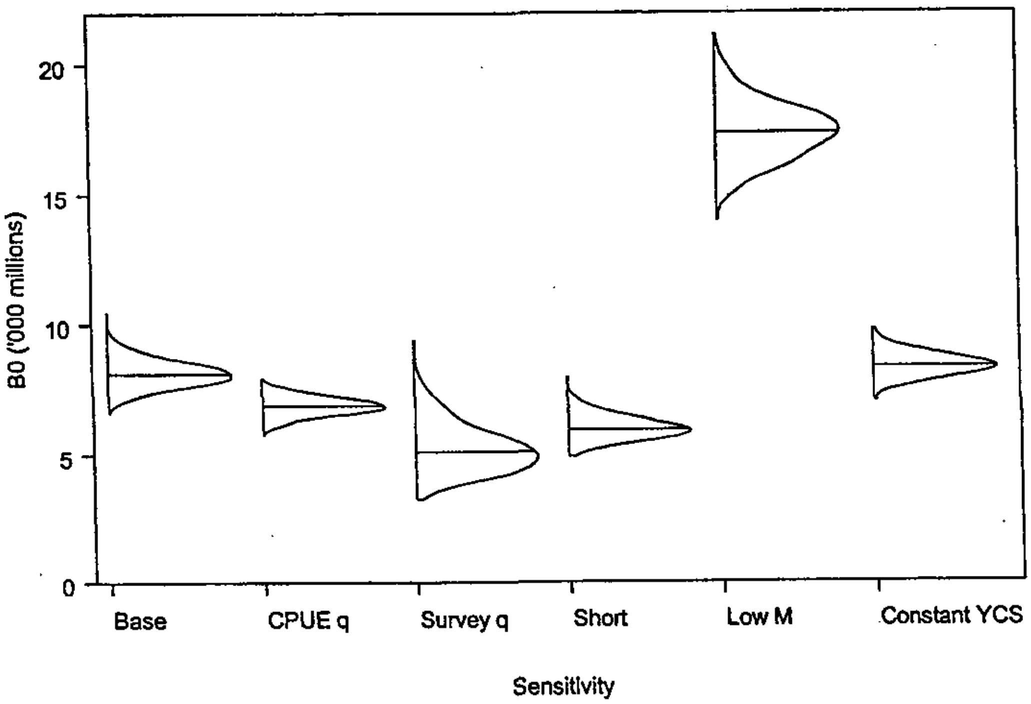

Figure 35: Posterior distributions of B_0 for the initial and sensitivity cases.

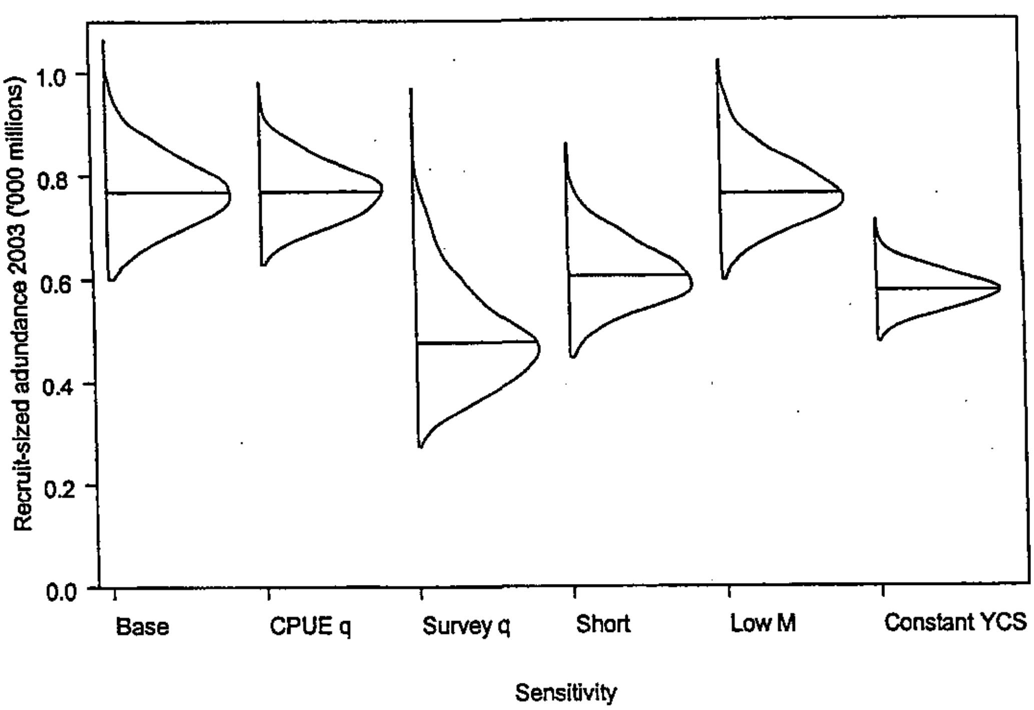

Figure 36: Posterior distributions of recruit-sized abundance (rB_{2003}) for the initial and sensitivity cases.

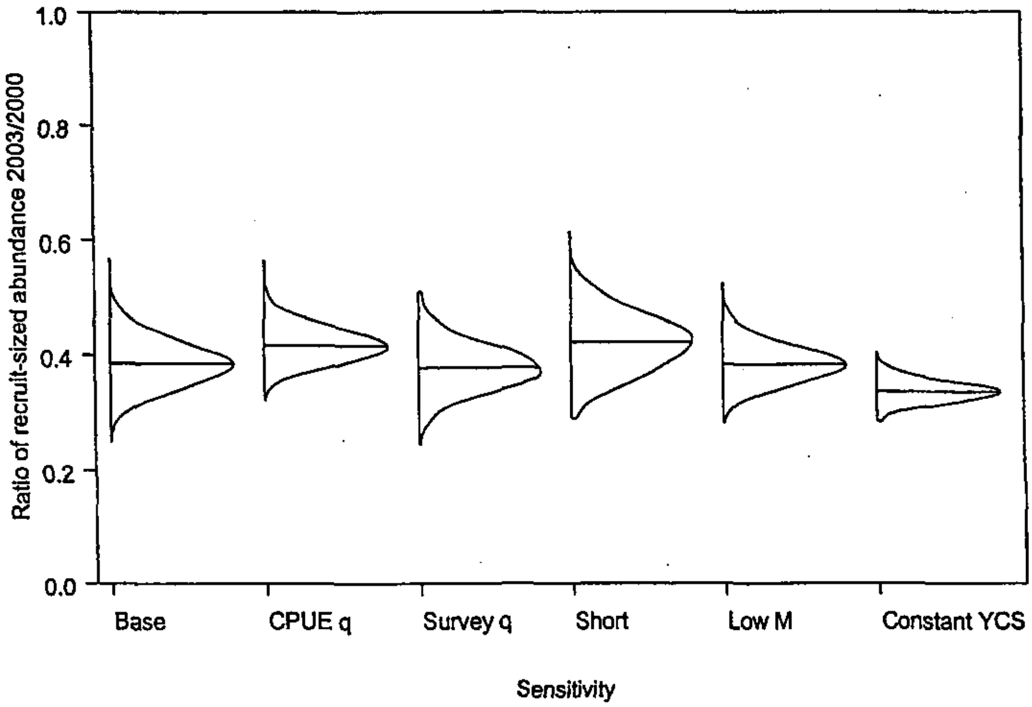

Figure 37: Posterior distributions of the ratio of recruit-sized stock abundance in 2003 over 2000 (rB_{2003}/rB_{2000}) for the initial and sensitivity cases.

Table 14: Bayesian median and 95% credible intervals of current spawning stock biomass 2003 (B_{2003}), and projected spawning stock biomass for 2004 (B_{2004}), 2005 (B_{2005}) and 2006 (B_{2006}) as a percentage of B_0 with an assumption of future disease mortality rate of 0.0, 0.2, 0.4, and 0.6 y^{-1} and future catch levels of 0 and 15 million oysters.

Disease mortality	Catch (millions)	B_{2003} (% B_0)	B_{2004} (% B_0)	B_{2005} (% B_0)	B_{2006} (% B_0)
0.00	0.0	0.09 (0.08–0.11)	0.09 (0.07–0.14)	0.13 (0.10–0.30)	0.17 (0.11–0.57)
	15.0	0.09 (0.08–0.11)	0.09 (0.07–0.14)	0.13 (0.10–0.30)	0.17 (0.11–0.56)
0.20	0.0	0.09 (0.08–0.11)	0.08 (0.06–0.12)	0.09 (0.06–0.21)	0.09 (0.06–0.34)
	15.0	0.09 (0.08–0.11)	0.08 (0.06–0.12)	0.09 (0.06–0.21)	0.09 (0.06–0.34)
0.40	0.0	0.09 (0.08–0.11)	0.07 (0.05–0.11)	0.06 (0.04–0.15)	0.05 (0.03–0.21)
	15.0	0.09 (0.08–0.11)	0.07 (0.05–0.11)	0.06 (0.04–0.15)	0.05 (0.03–0.20)
0.60	0.0	0.09 (0.08–0.11)	0.06 (0.05–0.09)	0.04 (0.03–0.11)	0.03 (0.02–0.13)
	15.0	0.09 (0.08–0.11)	0.06 (0.05–0.09)	0.04 (0.03–0.11)	0.03 (0.02–0.13)

Under each assumption of disease mortality, model projections either with or without a catch of 15 million oysters showed little difference in expected population size (e.g., the projected recruit-sized stock abundance in 2006, assuming no disease mortality, was 1397 (919–4623) million oysters with nil future annual commercial catch, and 1371 (893–4599) million oysters with a future annual commercial catch of 15 million oysters). Depending on the level of assumed disease mortality, projected status in 2006 ranged from almost twice current levels (with no disease mortality) to about one-third of current levels (assuming disease mortality of 0.6 y^{-1}) (Figure 39).

Table 15: Bayesian median and 95% credible intervals of expected recruit-sized stock abundance for 2004 ($E(rB_{2004}/rB_{2003})$), 2005 ($E(rB_{2005}/rB_{2003})$) and 2006 ($E(rB_{2006}/rB_{2003})$) with an assumption of future disease mortality rate of 0.0, 0.2, 0.4, and 0.6 y^{-1} and future catch levels of 0 and 15 million oysters.

Disease mortality	Catch (millions)	$E(rB_{2004}/rB_{2003})$	$E(rB_{2005}/rB_{2003})$	$E(rB_{2006}/rB_{2003})$
0.00	0.0	1.01 (0.89–1.40)	1.41 (1.14–3.16)	1.81 (1.29–5.98)
	15.0	1.01 (0.89–1.40)	1.39 (1.12–3.14)	1.77 (1.26–5.95)
0.20	0.0	0.87 (0.77–1.22)	0.95 (0.76–2.26)	0.99 (0.67–3.46)
	15.0	0.87 (0.77–1.22)	0.93 (0.75–2.25)	0.97 (0.65–3.44)
0.40	0.0	0.76 (0.67–1.06)	0.64 (0.51–1.61)	0.56 (0.36–2.11)
	15.0	0.76 (0.67–1.06)	0.63 (0.50–1.60)	0.54 (0.34–2.10)
0.60	0.0	0.66 (0.58–0.93)	0.44 (0.35–1.16)	0.32 (0.19–1.32)
	15.0	0.66 (0.58–0.93)	0.43 (0.34–1.16)	0.31 (0.18–1.31)

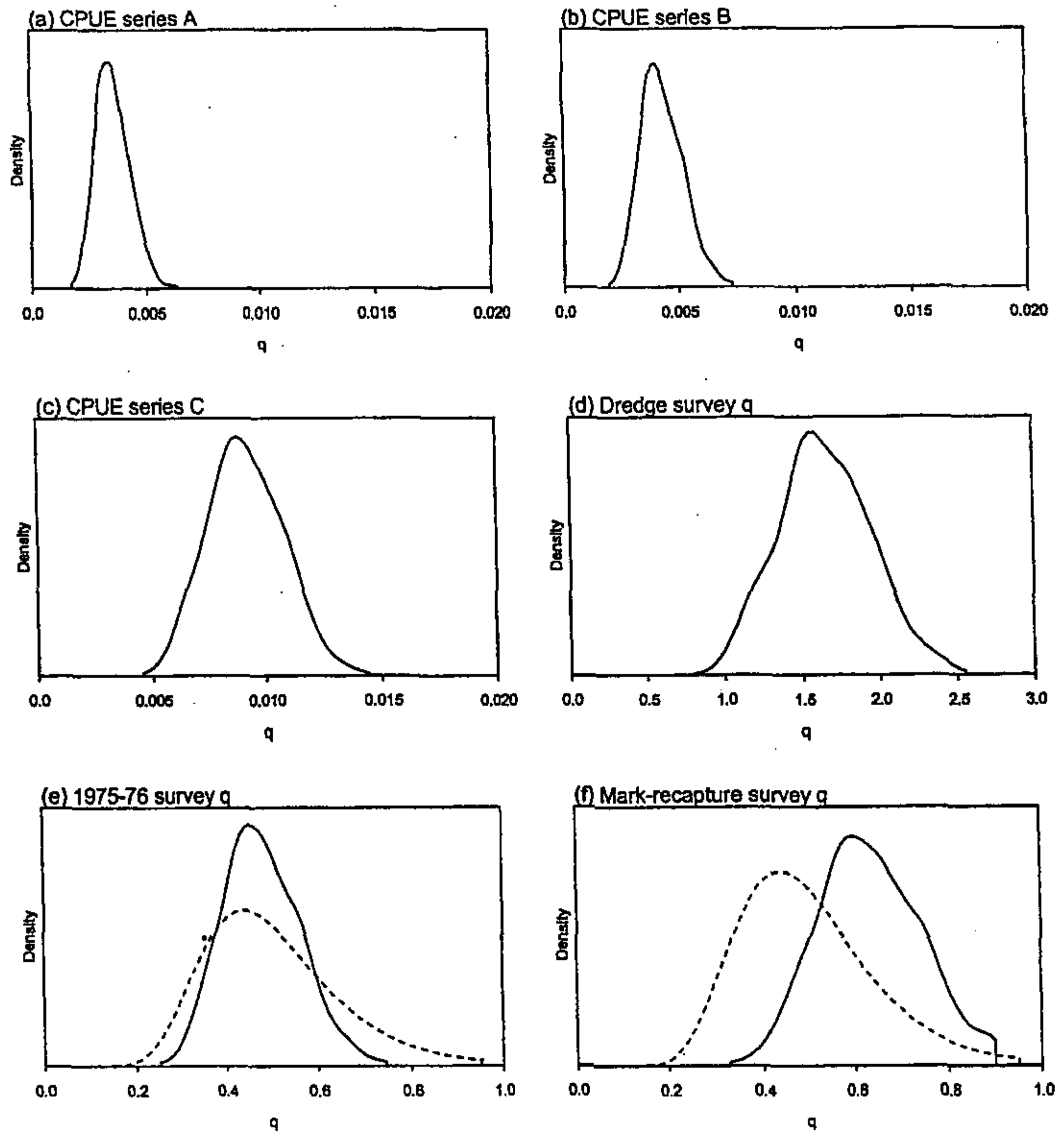

Figure 38: Estimated posterior distributions (solid lines) and priors (dashed lines) of the (figures a–c) CPUE series A, B, and C (priors not shown); (d) dredge survey; (e) 1975–76 survey, and (f) mark-recapture survey relativity constants.

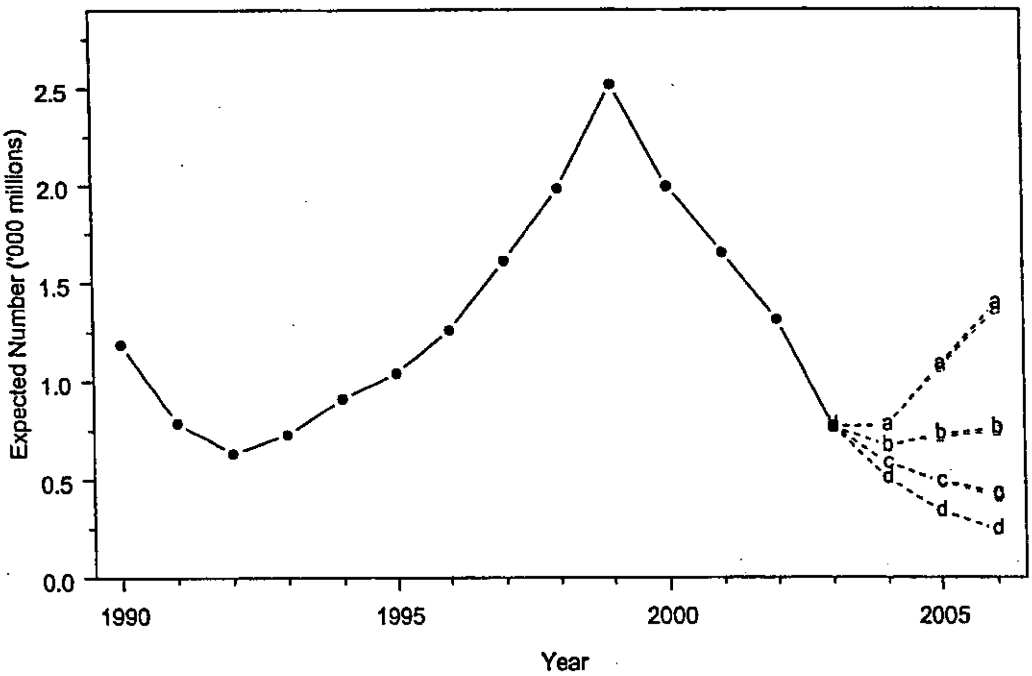

Figure 39: Model estimates of recent recruit-sized stock abundance and projected recruit-sized stock abundance for 2004–06 with a projected catch of nil (grey dashed lines) and 15 million oysters (black dashed lines), under assumptions of (a) no disease mortality, (b) disease mortality of 0.20 y^{-1}, (c) disease mortality of 0.40 y^{-1}, and (d) disease mortality of 0.60 y^{-1}.

4. DISCUSSION

The Foveaux Strait dredge oyster fishery presents a number of unique problems in the development of a stock population model. There is a lack of good information on recruitment, growth, natural mortality, and quantitative information of the impact of disease mortality from *B. exitiosa*. But there is good information on the size structure of the oyster population in recent years, and a time series of absolute abundance estimates (assuming the survey series are correctly calibrated) over a reasonably long period.

The model presented here, whilst fairly representing some of the data (e.g., the biomass indices), also shows some signs of poor fit. It is unlikely that the estimates of historical stock size are reliable, given assumptions about annual recruitment and the reliance on the historical catch-effort indices of abundance. Current stock status as estimated by the model closely agrees with recent stock abundance surveys, although this may be a consequence of the assumptions used to fit these data.

Few data were available to the model on historical recruitment. In addition, the model assumptions of the stock-recruitment relationship have not been validated. Hence, model estimates of recent recruitment and short-term projections may be unreliable.

The rate of natural mortality is also unknown, and possibly may vary with age, size, and between years. Preliminary MPD runs that attempted to estimate natural mortality failed to produce reasonable estimates of *M*, possibly because of confounding with mortality from *B. exitiosa*. If natural mortality is not constant (and Dunn et al. (1998a) found some evidence for senescence in their analyses of natural mortality from tagging data), then appropriate parameterisations of this process would also require further investigation.

Estimates of disease mortality appeared reasonable however, the yearly variation, in particular in 1987, suggested further investigation is required. In general, model estimates were consistent with estimates calculated directly from the ratio of clocks to live oysters. The life of clocks in Foveaux Strait is not known, but they are often assumed to persist for at least 18 months and may be present for up to 3 years (Cranfield et al. 1991). Estimates of mortality, assuming that all clocks observed in a single survey represent the total (natural plus disease) mortality over the preceding year, are given in Figure 40. Also shown are the estimates of total (natural plus disease) annual mortality estimated within the model. This suggests that the relative size of disease effects estimated between 1985 and 2003 were of a similar order of magnitude to that suggested by the counts of clocks — although the model allocated most of the disease mortality at the start of the epidemic. Estimates of disease mortality in earlier years (e.g., 1948–50 and 1960–64) correspond to suspected disease mortality events, although model constraints leave little alternative choice to explain changes in relative abundance signals. More informed priors on the levels of annual disease mortality and inclusion of clock data within the model may provide better estimates

The selectivity and epidemiology of *B. exitiosa* are not well understood, and few data have been collected on the size and maturity status of oysters (particularly pre-recruit and small oysters) that have been infected with or have died from *B. exitiosa*. Future work on the relationship between oyster sex, maturity, and *B. exitiosa* infection may provide additional insight.

Model projections require assumptions about future disease mortality. While this paper presents projections based on arbitrary levels of disease mortality, better estimates may be possible by modelling the epidemic process directly. However, the projections here show that the size of the recruit-sized stock abundance in future years is primarily dependent on levels of disease mortality, or conversely, that catch at recent levels has little influence on future stock size. Estimates of future stock size, under assumptions of nil and high future disease mortality, ranged from twice down to about a third of the current level.

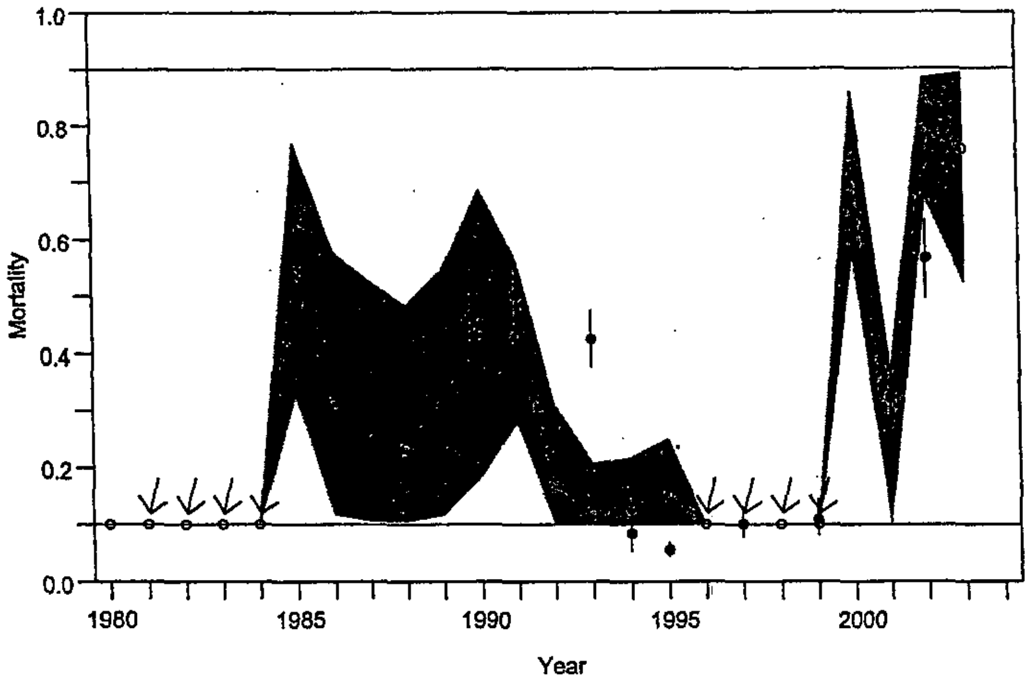

Figure 40: Estimated median MCMC mortality (natural plus disease) rate (dashed line with open circles) and 95% credible intervals (shaded region) for the base case, and estimated mortality (and 95% confidence intervals) from the ratio of new and old clocks from survey sampling (closed circles). Arrows indicate values that were constrained within the model.

5. ACKNOWLEDGMENTS

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Appendix A: Summary MPD model fits

Table 16: Objective function values (negative log-likelihood) for MPD fits to data, priors, penalties resulting from penalties to catch, the total objective function (negative log-likelihood), and number of free parameters for the base case and sensitivity cases.

Observation, penalties, and priors	Base	CPUE *q*	Survey *q*	Short	Low *M*	Constant YCS
CPUE-A	-25.7	-16.3	-26.1	–	-23.2	-25.4
CPUE-B	-16.5	-17.2	-14.9	–	-18.2	-17.0
CPUE-C	-6.5	6.4	-6.6	-9.6	-3.5	-10.4
July survey (recruit)	-2.1	-2.2	-2.1	-1.9	-2.0	-1.3
March survey (recruit)	5.3	7.9	5.5	3.6	5.3	8.5
October survey (recruit)	-6.2	-6.0	-5.8	-5.5	-2.1	11.0
March survey (pre-recruit)	-0.7	-0.7	-0.8	-1.3	-0.6	-0.7
October survey (pre-recruit)	0.9	3.8	-0.3	-10.7	4.3	20.0
March survey (smalls)	2.7	3.3	2.3	0.0	2.9	7.3
October survey (smalls)	-4.1	-2.6	-4.2	-4.1	-2.6	-5.1
1975/76 survey (recruit)	-1.4	-1.8	-1.9	–	-0.3	-1.3
Mark recapture survey (recruit)	-2.6	-2.6	-2.7	–	-2.0	-2.6
Proportions mature data	23.8	28.4	22.7	21.2	26.4	37.9
Commercial catch LFs	126.4	127.9	126.7	129.7	125.5	139.2
1990 October dive survey LFs	47.0	48.7	43.9	43.6	49.6	89.3
October survey (recruit) LFs	168.4	165.3	171.9	101.6	162.7	264.3
October survey (pre-recruit) LFs	69.3	71.4	68.8	68.9	70.5	64.7
October survey (smalls) LFs	112.4	108.4	112.6	68.2	108.3	144.7
Data objective function	490.5	522.1	489.0	403.5	500.8	723.2
Customary catch penalty	0.0	0.0	0.0	0.0	0.0	0.0
Illegal catch (penalty)	0.0	0.0	0.0	0.0	0.0	0.0
Recreational catch penalty	0.0	0.0	0.0	0.0	0.0	0.0
Summer commercial catch penalty	0.0	0.0	0.0	0.0	0.0	0.0
Winter commercial catch penalty	0.0	0.0	0.0	0.0	0.0	0.0
Penalties objective function	0.0	0.0	0.0	0.0	0.0	0.0
Prior on disease mortality	98.4	104.8	93.9	54.3	113.2	115.8
Prior on B_0	0.0	0.0	0.0	0.0	0.0	0.0
Prior on proportions mature	0.0	0.0	0.0	0.0	0.0	0.0
Prior on CPUE-A *q*	-6.3	-5.6	-5.6	–	-6.7	-6.3
Prior on CPUE-B *q*	-6.1	–	-5.3	–	-6.6	-6.1
Prior on CPUE-C *q*	-5.2	–	-4.5	-4.9	-5.2	-5.1
Prior on dredge survey *q*	–	–	0.7	–	–	–
Prior on mark recapture survey *q*	0.0	-0.6	-0.1	–	2.7	0.2
Prior on 1975/76 survey *q*	1.4	0.0	-0.6	–	5.6	1.8
Prior on year class strengths	0.0	0.0	0.0	0.0	0.0	–
Prior on dredge survey selectivity	0.0	0.0	0.0	0.0	0.0	0.0
Prior on fishing selectivity	0.0	0.0	0.0	0.0	0.0	0.0
Prior objective function	82.3	98.5	78.5	49.4	103.0	100.3
Total objective function	572.8	620.6	567.5	452.9	603.8	823.5
Number of free parameters	54	54	54	48	54	36
Catchability (*q*) parameters	5	3	6	1	5	5
Total parameters	59	57	60	49	59	41

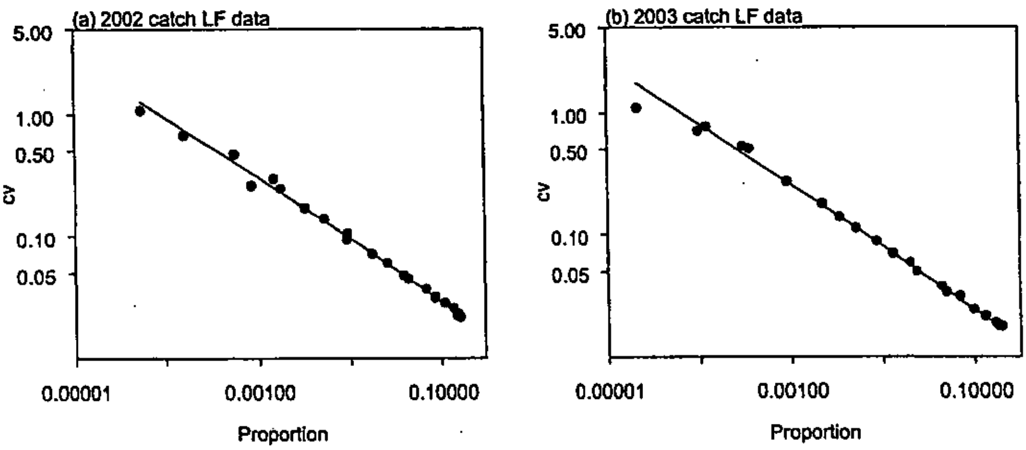

Figure 41: Estimated proportions versus c.v.s for the commercial catch length frequencies for (a) 2002 and (b) 2003. Lines indicate the best least squares fit for the effective sample size of the multinomial distribution.

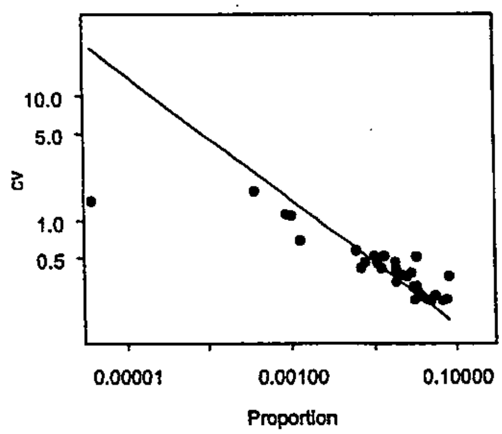

Figure 42: Estimated proportions versus c.v.s for the October 1990 dive survey length frequencies. Lines indicate the best least squares fit for the effective sample size of the multinomial distribution.

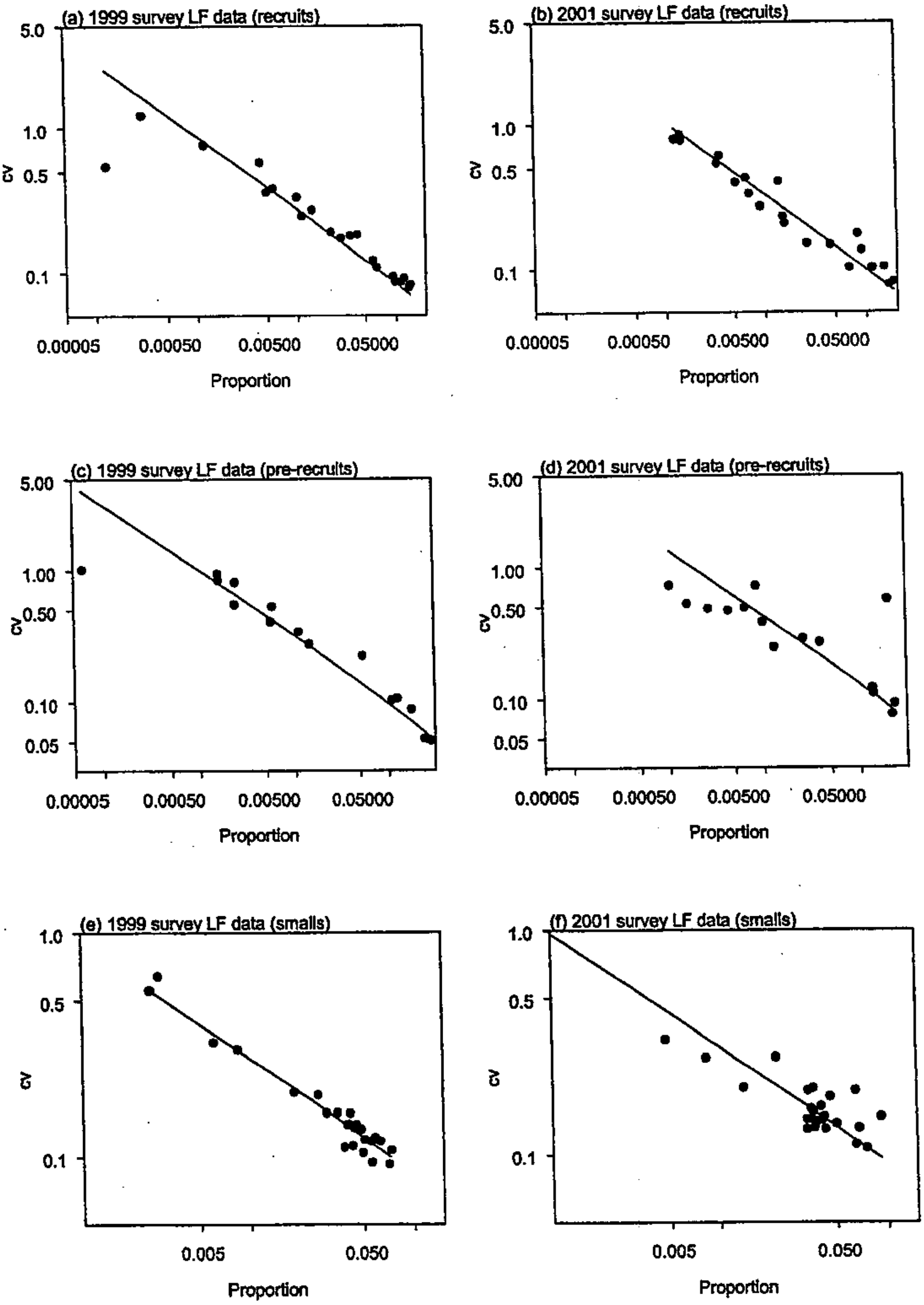

Figure 43: Estimated proportions versus c.v.s for the 1999 and 2001 October survey length frequencies for (a–b) recruits, (c–d) pre-recruits, and (e–f) smalls. Lines indicate the best least squares fit for the effective sample size of the multinomial distribution.

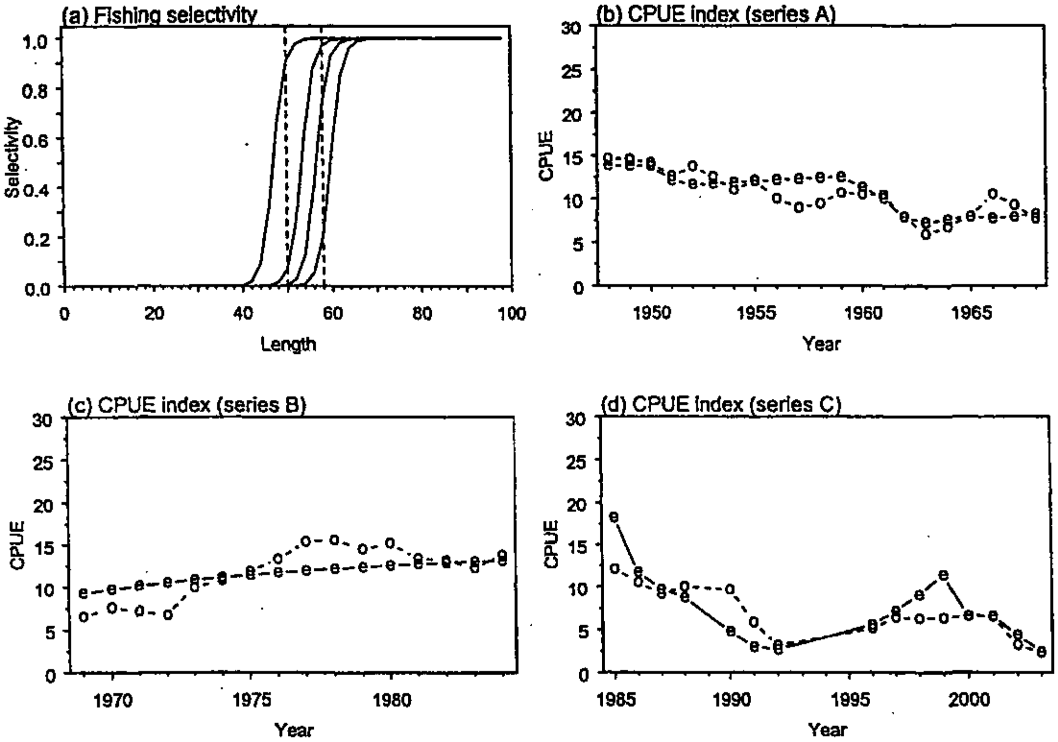

Figure 44: MPD estimates of (a) fishing selectivity and model fits to (b) series A, (c) series B, and (d) series C CPUE indices ("e"=expected and "o"=observed). Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

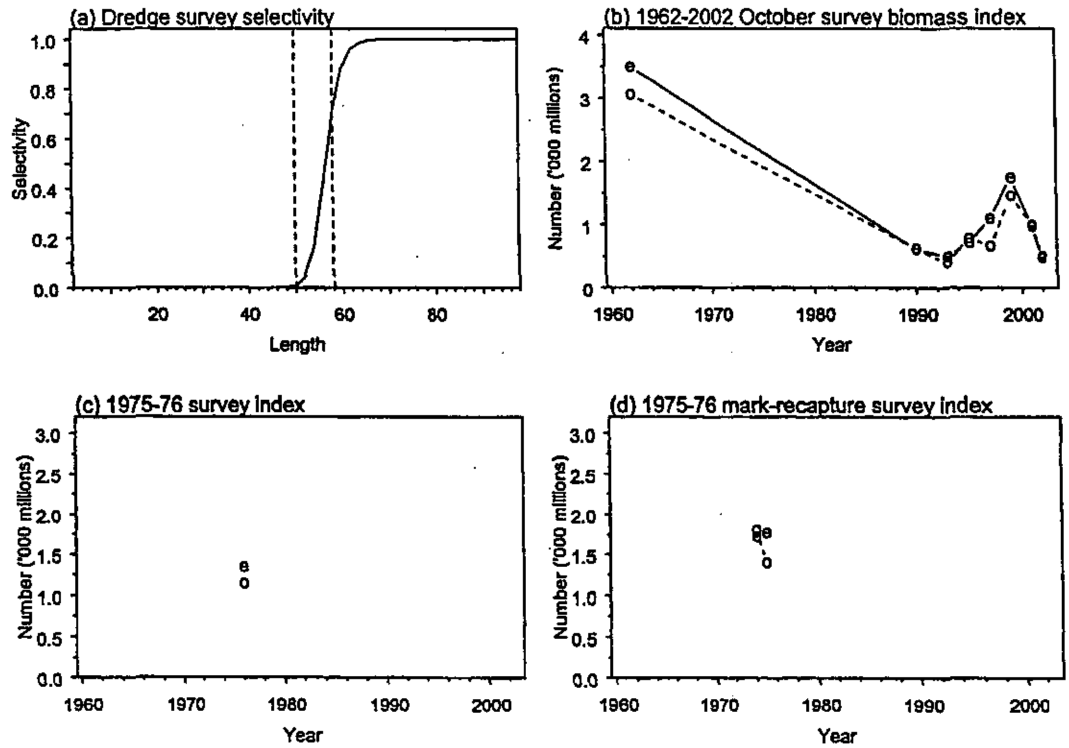

Figure 45: MPD estimates of (a) recruit-sized dredge survey selectivity and model fits to recruit-sized abundance indices for the (b) October surveys 1964–2002, (c) 1975–76 survey, and (d) 1975–76 mark-recapture survey ("e"=expected and "o"=observed). Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

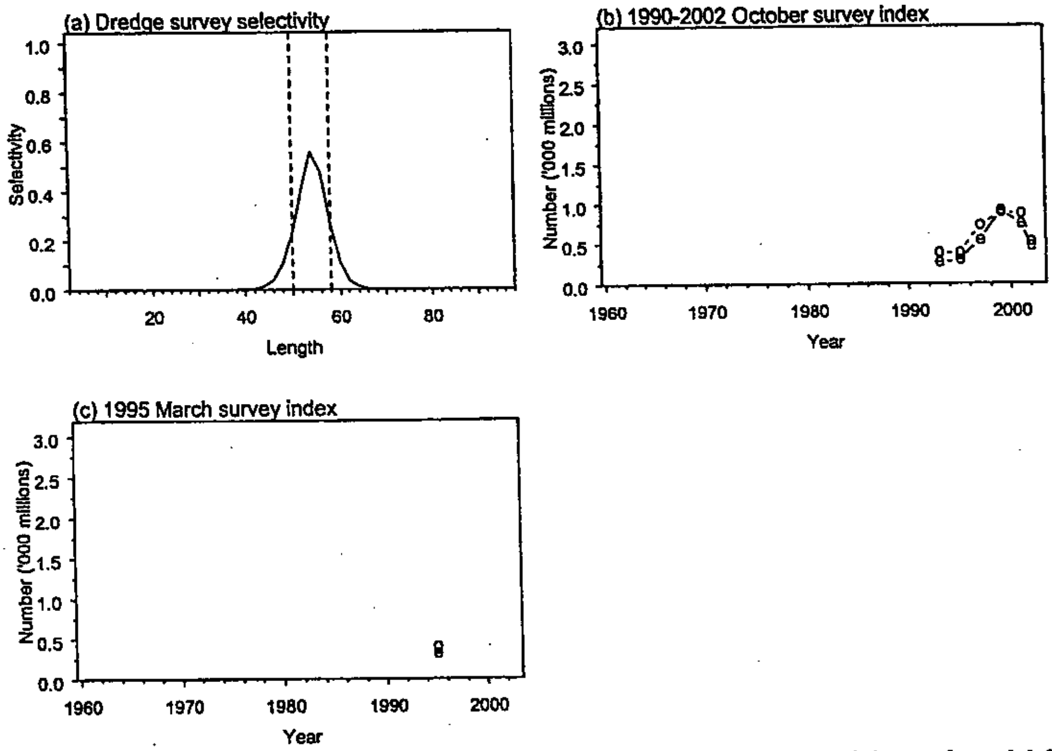

Figure 46: MPD estimates of the (a) pre-recruit-sized dredge survey selectivity and model fits to pre-recruit-sized abundance indices for the (b) October surveys 1990–2002, and (c) March 1995 survey ("e"=expected and "o"=observed). Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

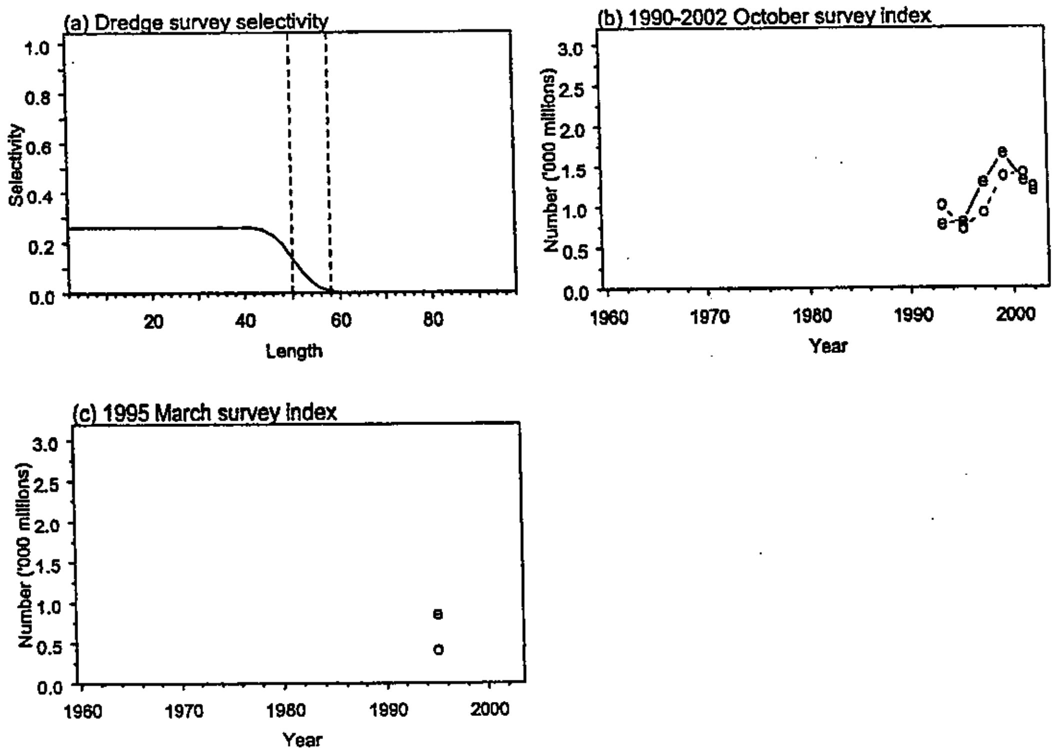

Figure 47: MPD estimates of small-sized dredge survey selectivity and model fits to small-sized abundance indices for the (b) October surveys 1990–2002, and (c) March 1995 survey ("e"=expected and "o"=observed). Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

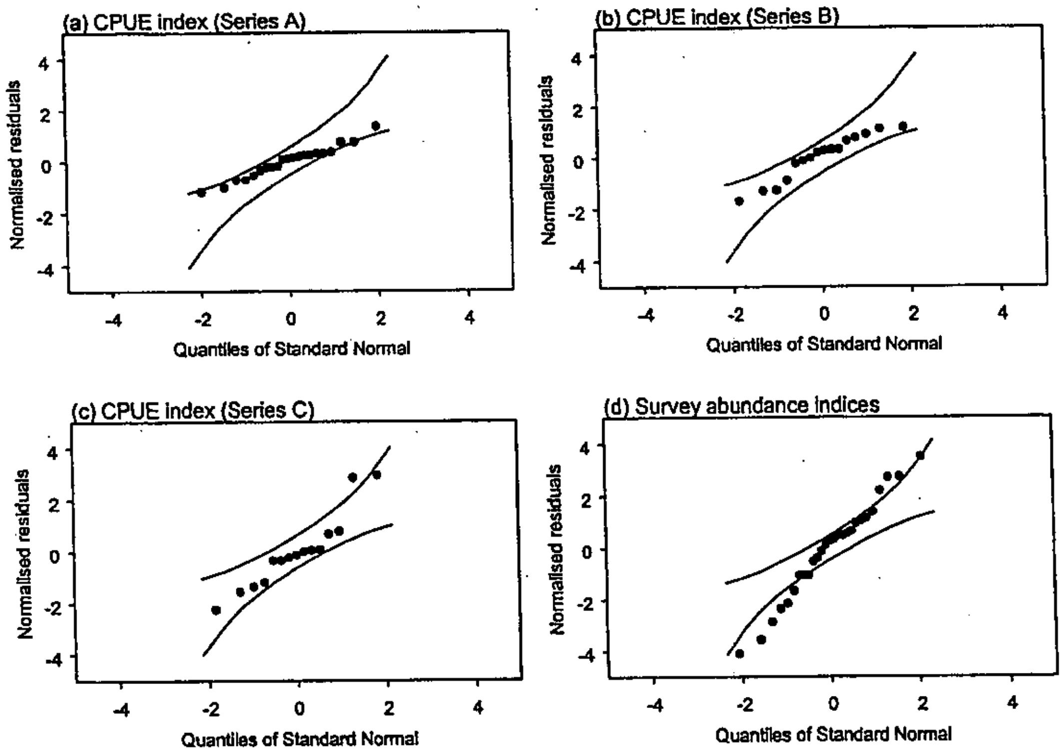

Figure 48: MPD estimates of fits (normal quantile-quantile plots) to the (a) series A, (b) series B, (c) series C CPUE indices, and (d) 1964–2002 survey abundance indices combined. Curved lines show 95% confidence envelopes for a true normal distribution.

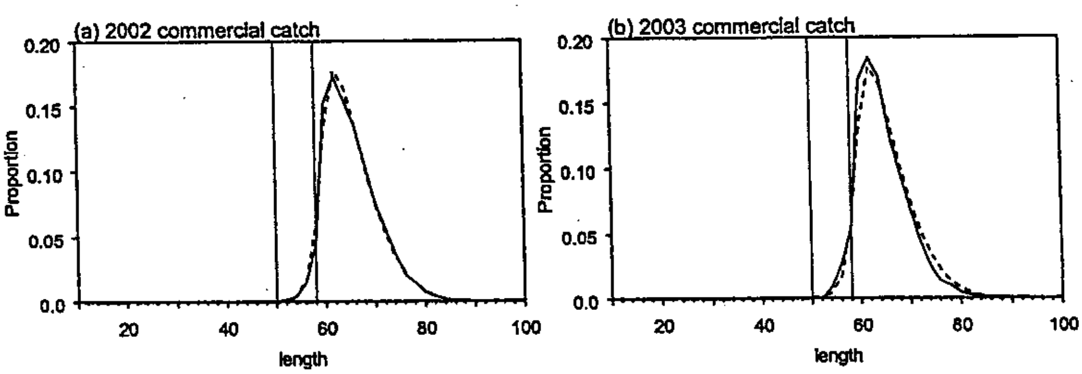

Figure 49: MPD estimates of fits to the (a) 2002 and (b) 2003 commercial catch length frequencies. Vertical lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

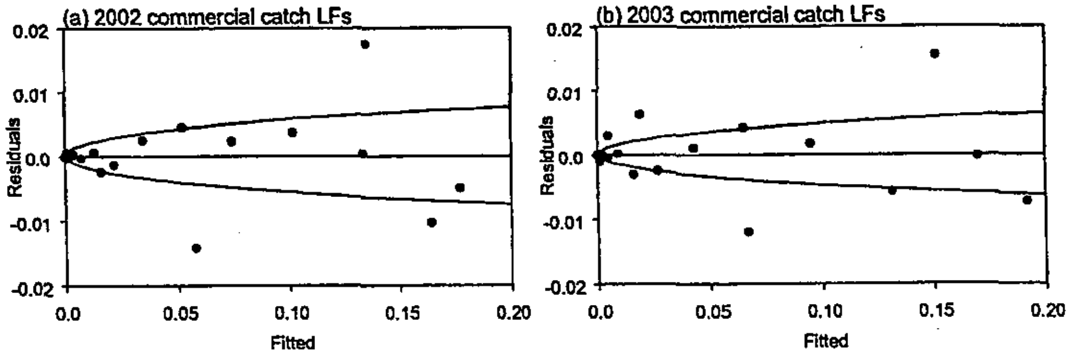

Figure 50: MPD estimates of residuals versus fitted values for the (a) 2002 and (b) 2003 commercial catch data (*curved lines show 95% confidence intervals for the multinomial distribution*).

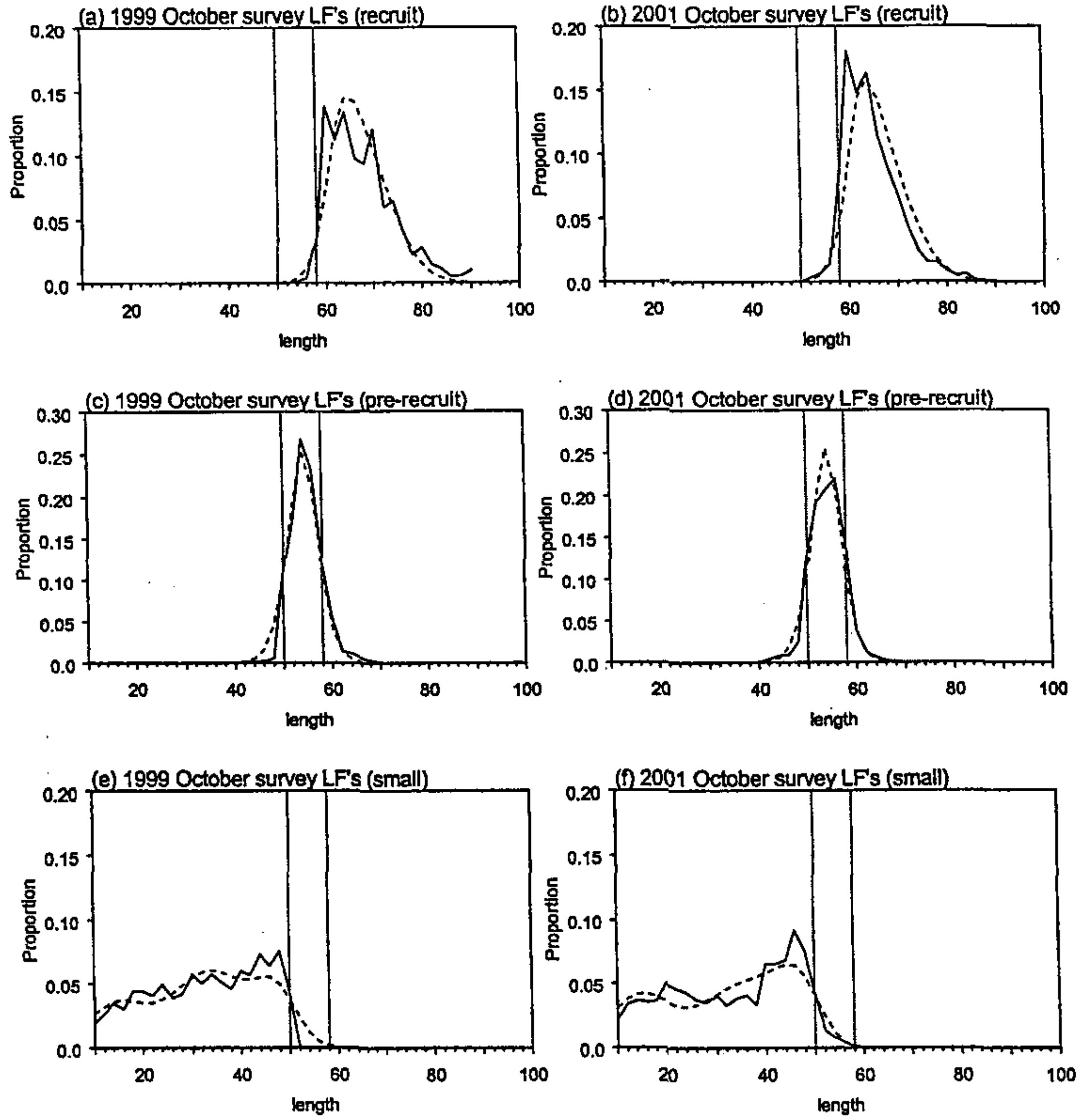

Figure 51: MPD estimates of fits to the survey data length frequencies for (a–b) recruit-sized, (c–d) pre-recruit size, and (e–f) smalls from the 1999 and 2001 abundance surveys respectively. Vertical lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

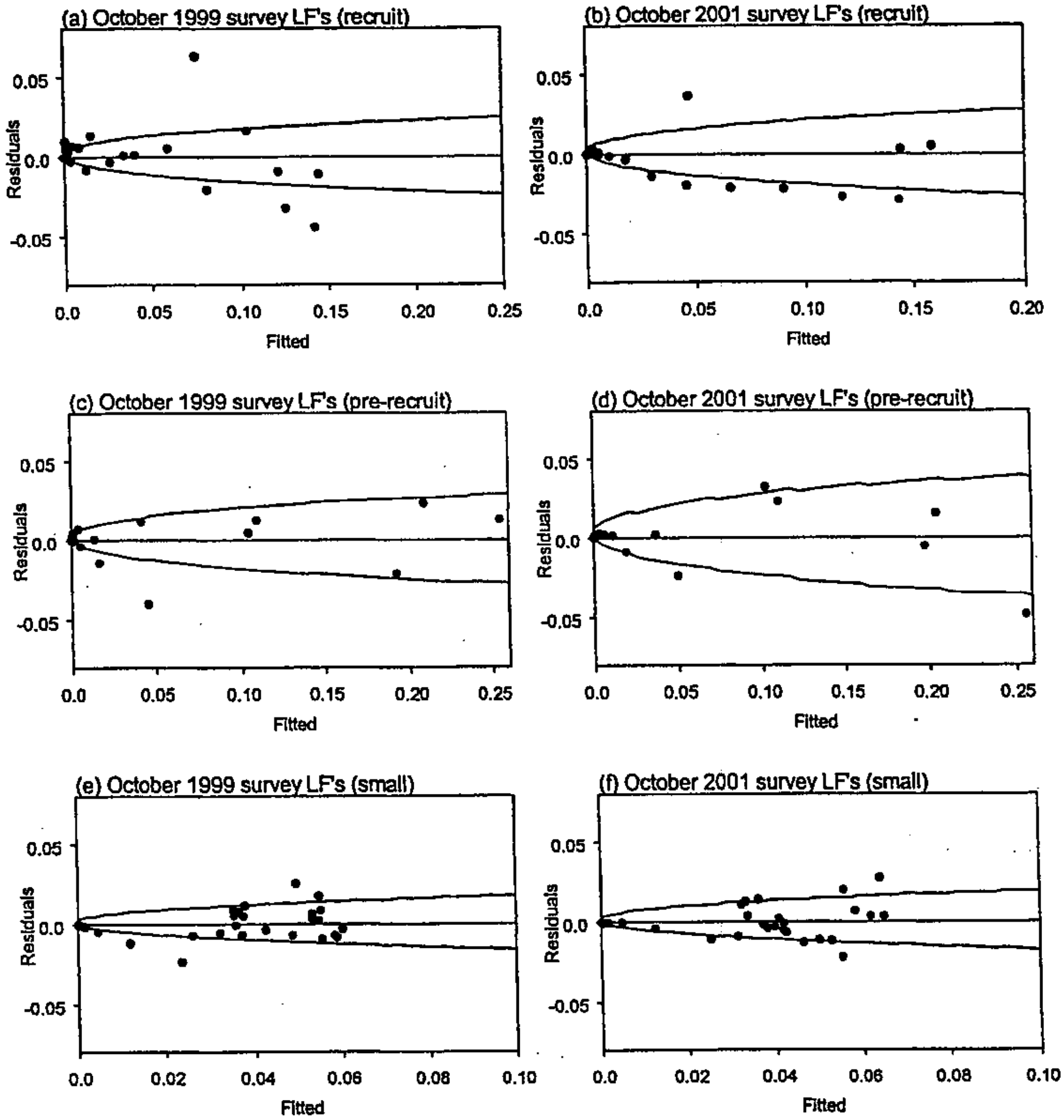

Figure 52: MPD estimates of residuals versus fitted values for the survey data length frequencies for (a–b) recruit-sized, (c–d) pre-recruit size, and (e–f) smalls from the 1999 and 2001 abundance surveys respectively (curved lines show 95% confidence intervals for the multinomial distribution).

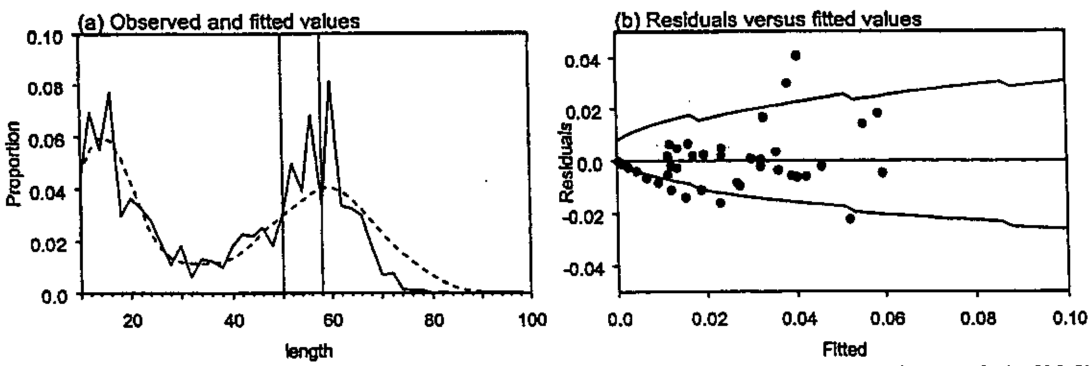

Figure 53: MPD estimates for the 1990 dive survey length frequencies (a) observed (solid line) and MPD estimates of fits (dashed line), and (b) residuals versus fitted values (curved lines show 95% confidence intervals for the multinomial distribution). Vertical lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

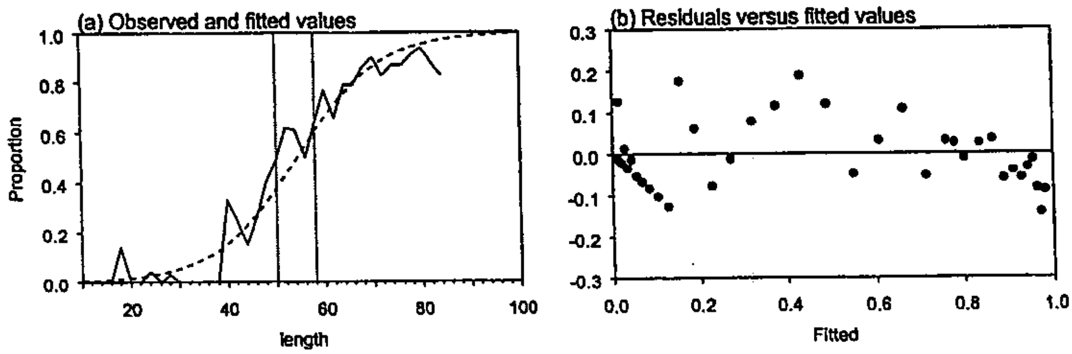

Figure 54: MPD estimates for the Jeffs and Hickman (2000) maturity data (a) observed (solid line) and MPD estimates of fits (dashed line), and (b) residuals versus fitted values. Vertical lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

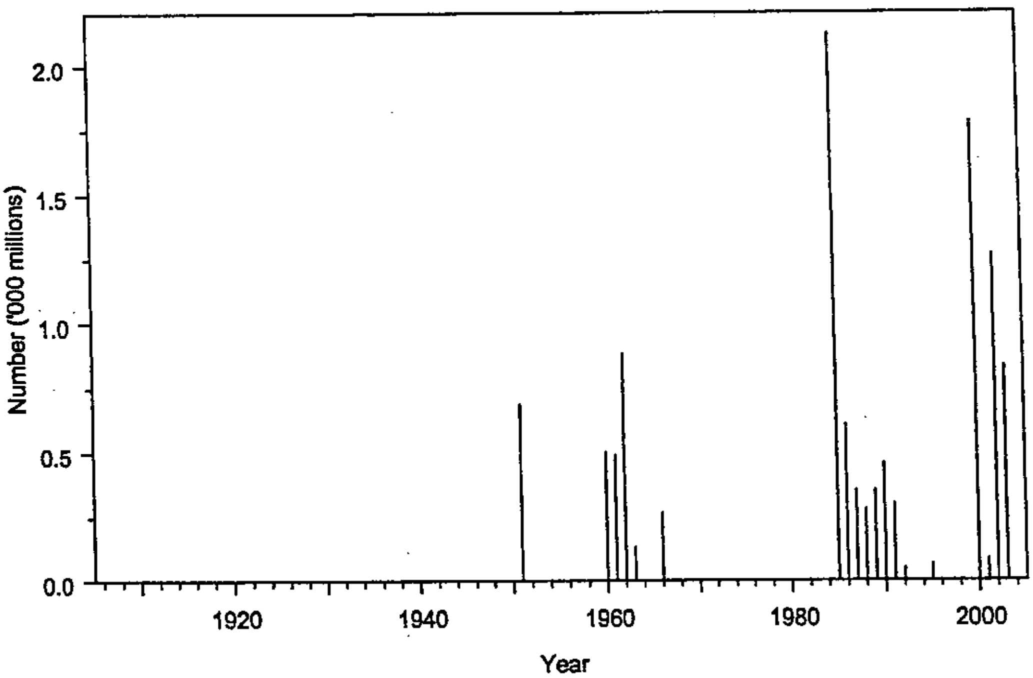

Figure 55: MPD estimates of disease mortality, converted to numbers of oysters.

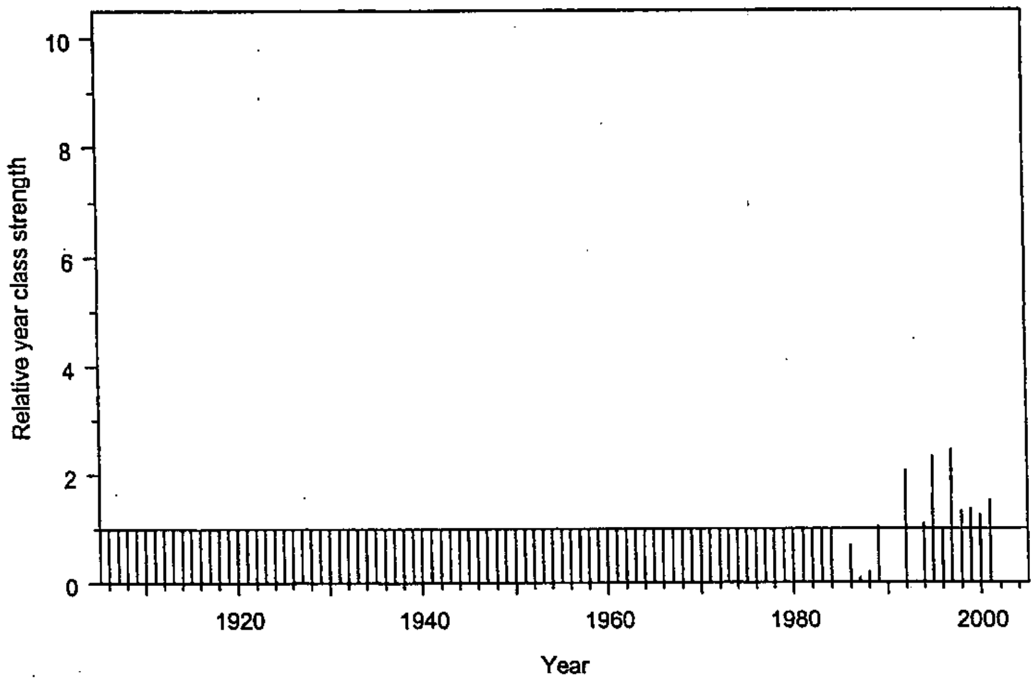

Figure 56: MPD estimates of relative year class strengths.

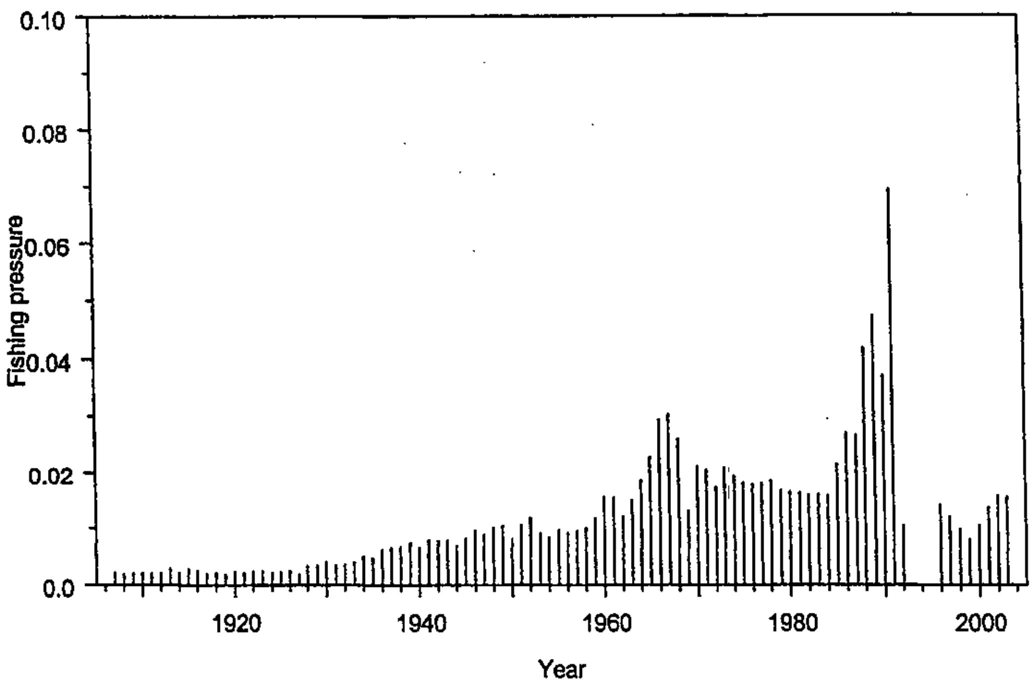

Figure 57: MPD estimates of fishing pressure (U_{max}), i.e., catch divided by fishing vulnerable stock size.

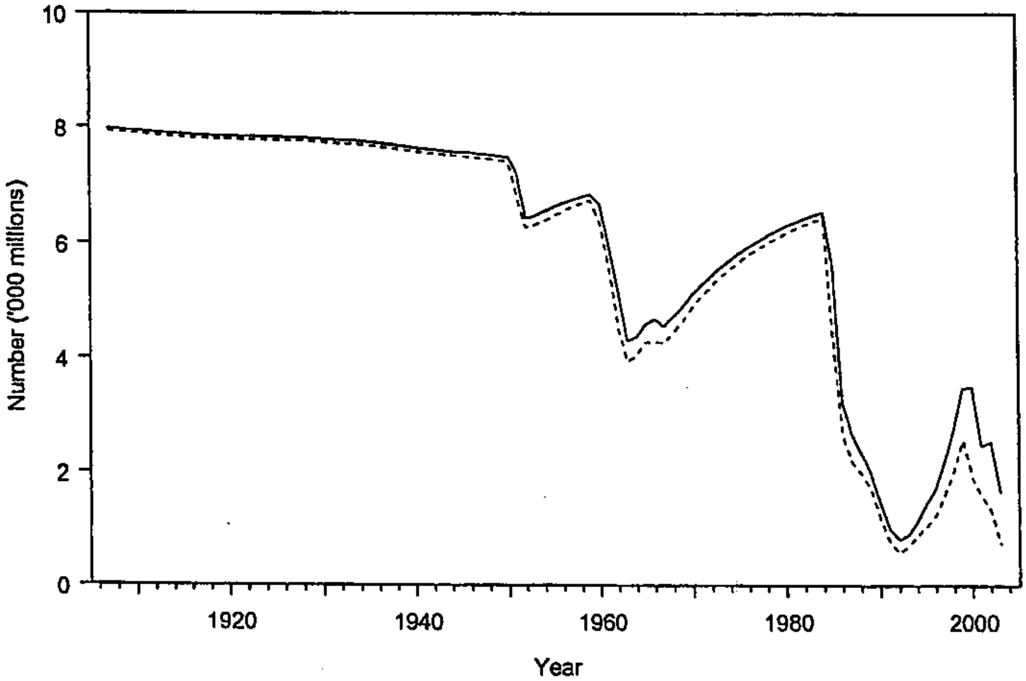

Figure 58: MPD estimates of spawning stock size (SSB, solid line) and recruit-sized stock abundance (dashed line).