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An updated stock assessment for Foveaux Strait dredge oysters (*Ostrea chilensis*) for the 2008–09 fishing year

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EXECUTIVE SUMMARY

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This report summarises an update of the stock assessment for Foveaux Strait dredge oysters with the inclusion of fishery data from the 2007 and 2008 years and abundance indices from the February 2009 survey. The report describes the available data, model structure, and model output. Model estimates, including current and projected stock status, are also presented. The stock assessment is implemented using Bayesian estimation in the general-purpose stock assessment program CASAL v2.20.

The basic model and the revised model from the 2007 assessment are updated with new data but with no change to the model structure. The data available since last assessment include the revised catch history and unstandardised CPUE up to the 2008 fishing year, commercial catch sampling in 2007 and 2008, and abundance indices from the February 2009 survey. The catch of 7.5 million oysters is assumed for the 2009 fishing year.

The model estimates of the state of the Foveaux Strait oyster stock suggest that the exploitation rates have been low, and the stock continues to recover following a dramatic reduction in the vulnerable abundance since the outbreak of the recent *Bonamia* epizootic. Current estimates suggest that spawning stock population in 2009 was about 25% (23–28%) B_0, and recruit-sized stock abundance (rB_{2009}) was about 20% (17–23%) of initial state (rB_{1907}). The revised model runs suggest a similar stock status.

While uncertainty exists in levels of future recruitment and continued *B. exitiosa* related mortality, projections indicate that current catch levels between 7.5 and 15 million oysters are unlikely to have any significant impact on future stock levels. Instead, future disease mortality will determine future stock status. Depending on the level of assumed disease mortality, projected status in 2012 ranged from about 34% more than current levels (assuming no disease mortality) to a level about 23% less than the current level (assuming disease mortality of 0.2 y^{-1}).

As with earlier models, 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. However, model estimates of recent and current status agree closely with recent CPUE trends and survey abundance indices.

1. INTRODUCTION

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

Before 2004 the Foveaux Strait oyster fishery was managed by current annual yield (CAY, Method 1, see Ministry of Fisheries Science Group (2006)) based on survey estimates of the population in designated commercial fishery areas. Since 2004, the TACC has been based on estimates of recruit size stock abundance from the Foveaux Strait oyster stock assessment model (Dunn 2005a, 2005b, 2007) and projections of future recruit size stock abundance under different catch limits and heightened mortality from *B. exitiosa*. A spatially explicit epidemiological model of *B. exitiosa* (Gilbert & Michael 2006) may incorporate the stock assessment model in the future to provide stock assessment of subareas of the fishery.

Dunn (2005a, 2005b) presented a Bayesian, length-based, single-sex, stock assessment model for Foveaux Strait dredge oysters. That model was updated in 2007 (Dunn 2007) to account for new data available in 2007, and a more complex variant of that model was also investigated with similar data input. This report updates the 2007 assessment with the inclusion of fishery data from the 2007 and 2008 years and abundance indices from the February 2009 survey.

The stock assessment was implemented using Bayesian estimation with the general-purpose stock assessment program CASAL v2.20 (Bull et al. 2008). The report describes the available data, model structure, and model output. Model estimates, including current and projected stock status, are also presented.

This report fulfils Objective 1 “to update model projections of recruit-sized stock abundance under different catch limits and bonamia mortality levels from the OYU5 stock assessment model” of Project OYS2008/01.

2. 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 450–530 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 fully caught some time before the end of August.

Boundaries of statistical areas for recording catch and effort were first established in 1960 (and have been revised periodically since) with the outer boundary of the licensed oyster fishery 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 2004, a total of 11 vessels fished.

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 7.5 million oysters since 2003.

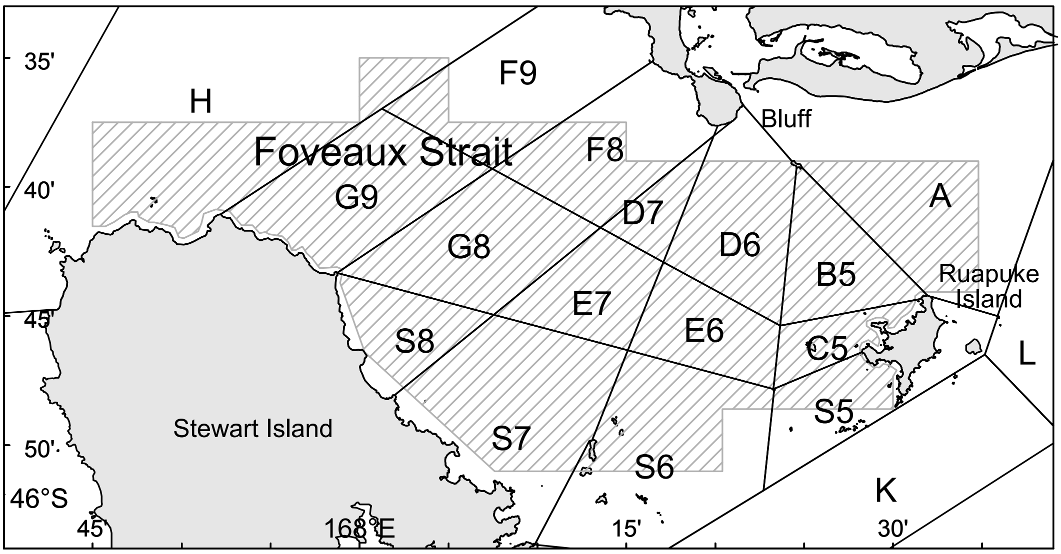

Figure 1: Foveaux Strait (OYU5) statistical areas, with the shaded region showing the outer boundary of the October 2002 dredge survey and the region of Foveaux Strait considered by the population model.

3. MODEL STRUCTURE, INPUT, AND ESTIMATION

3.1 Model structure

Dunn (2005a, 2005b) presented a model for Foveaux Strait dredge oysters for the 2004–05 fishing year, updated in 2007 (Dunn 2007) with inclusion of catch data up to the end of the 2006–07 fishing year and the February 2007 abundance survey. A more complex variant of that model was also investigated with similar data input in that assessment. We update both the basic model and the revised model of the 2007 assessment with the inclusion of commercial fishery data for 2007 and 2008 (catch, CPUE, and commercial catch frequencies for 2007 and 2008), revised recreational and customary catches, and the inclusion of the February 2009 abundance survey.

The population models 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 4 mm, 4 mm to 6 mm, etc.), with the last group defined as oysters equal to or greater than 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 models 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.

The models were run for the years 1907–2009 (see Section 3.2). Catch data were available for 1907–2008, and we assumed a catch for 2009 similar to that taken in 2008 (see Section 3.2). 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 at age 1+ (see Section 3.3.1), with a Beverton-Holt stock recruitment relationship (with an arbitrary steepness of 0.9) 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 up to 1984 — nine years before the first available length and abundance data on small (oysters less than 50 mm minimum diameter) and pre-recruits (oysters between 50 and 58 mm minimum diameter) were available; otherwise relative year class strengths were assumed to average 1.0.

Growth and natural mortality were assumed known, except in one run where growth was estimated from tag-recapture data. Disease mortality is assumed to be zero in the years when there were no reports of unusual mortality, and otherwise estimated (see Section 3.3.5)

The models used six 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 of the size-groups) — small (less than 50 mm minimum diameter), pre-recruit (greater than or equal to 50 mm and less than 58 mm minimum diameter), and recruit (greater than or equal to 58 mm minimum diameter); maturity ogive; and disease selectivity — assumed to follow a logistic curve equal to the maturity ogive (see Section 3.3.5 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

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

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.,

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

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 3.7.

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 this value can determine the minimum possible virgin stock size (B_0) allowed by the model.

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

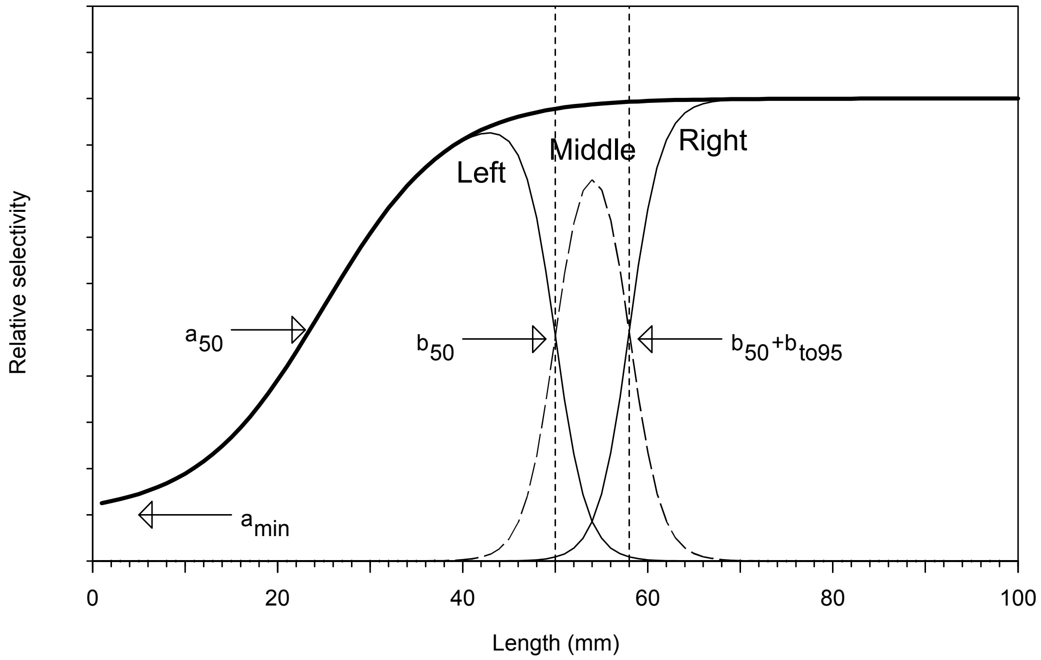

Figure 2: An example of the compound survey selectivity showing the overall selectivity (bold line, where a_{50}=25, a_{to95}=20, and a_{min}=0.1) and compound selectivity (where b_{50}=50, b_{to50}=8, b_{to95}=5) for (Left) small (solid line), (Middle) pre-recruit (dashed line), and (Right) recruit 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.

3.2 2009 model runs

The 2007 assessment model (Dunn 2007) ran for the years 1907–2007 with the inclusion of data up to the end of the 2006 fishing year and the February 2007 abundance survey (labelled ‘2007 basic model’). We revised that model with the inclusion of observations of CPUE, commercial catch proportions-at-length, and catch up to the end of 2008 (‘2009 model’), and similarly the February 2009 (summer) survey was included as a part of the March survey series (i.e., as a pre-fishing season survey, occurring after all summer natural mortality, growth, and *B. exitiosa* disease mortality has occurred) for 2009. Hence, the model ran from 1907 to 2009, with the commercial catch in 2009 assumed to be 7.5 million oysters, and the recreational, customary, and illegal catch assumed equal to 2008 levels.

The 2007 assessment also investigated a more complex model structure, based on the 2007 basic model (‘revised 2007 model’), which included (i) estimation of growth by the inclusion of the growth increment estimates from the tag-recapture data (Section 3.3.2), (ii) a penalty function on the disease that encouraged annual estimates of the rate of disease mortality to be smooth, (iii) decoupling of the maturity and disease selectivity ogive, (iv) removal of the 1976 survey data, and (v) estimation of the relative catchability for the abundance surveys. We also revised that model with the new data available to 2009 ('revised 2009 model').

This model assumed, as with the 2009 model, that growth occurred in a single episode at the start of the first time step, but we estimate the growth parameters with the inclusion of the mark recapture data. Growth data were included in the model as a separate 'stock' of fixed size and with growth equal to that of the main population, but no recruitment and no natural, disease, or fishing mortality. Data on the proportions of oysters at length, with a 3+ level *B. exitiosa* infection were from B.K. Diggles (NIWA, unpublished data). Here, the disease selectivity was fitted to these proportions, and decoupled from the maturity ogive.

3.3 Biological inputs, priors, and assumptions

3.3.1 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. More recently, even at low stock levels, the numbers of small oysters found in population surveys have remained relatively high. Here, we assumed a Beverton-Holt stock-recruit relationship, with steepness of 0.9.

Oysters entered the partition at age 1+, prior 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 experiments that collected spat settlement and growth data (H.J. Cranfield, NIWA, pers. comm.).

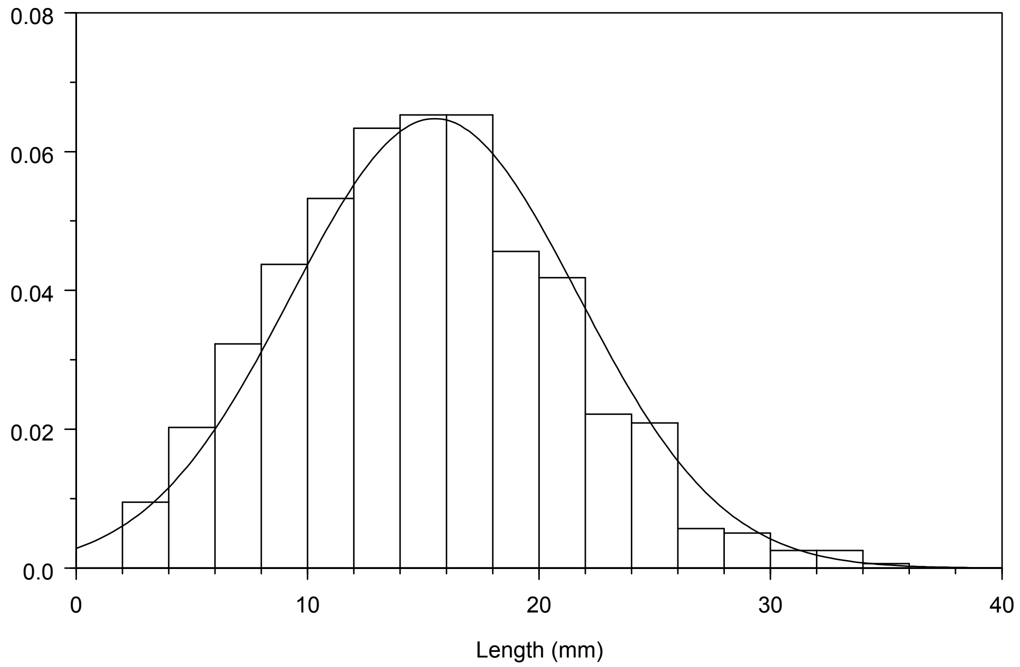

Figure 3: Size at recruitment for 1+ spat (H.J. Cranfield, NIWA, pers. comm.), overlaid with the assumed distribution for recruiting oysters — normal with mean 15.5 mm and c.v. 0.4.

3.3.2 Growth tag data and growth estimates

Growth increment data (Dunn et al. 1998b) were available for two samples of oysters marked and retained in cages anchored to the sea floor in Foveaux Strait in 1979 and 1981 (n = 259 and 395 respectively with lengths at release 10–84 mm). The samples were subsequently re-measured in 1980–1982 and 1982 respectively.

Dunn et al. (1998b) estimated growth rates from that experiment using a modified, length-increment von Bertalanffy growth model based on maximum likelihood mixed effects models. However, growth estimates from Dunn et al. (1998b) were seasonal, and allowed for areal, yearly, and breakage effects. The complexity of these processes cannot easily be reproduced within the population model and hence the data were re-fitted using the 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, $\sigma_{\min}$ is the minimum standard deviation, and μ_i 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 annual growth increment measurements only 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 in Figure 4, overlaid with the growth model (and 95% confidence intervals) used in the population model.

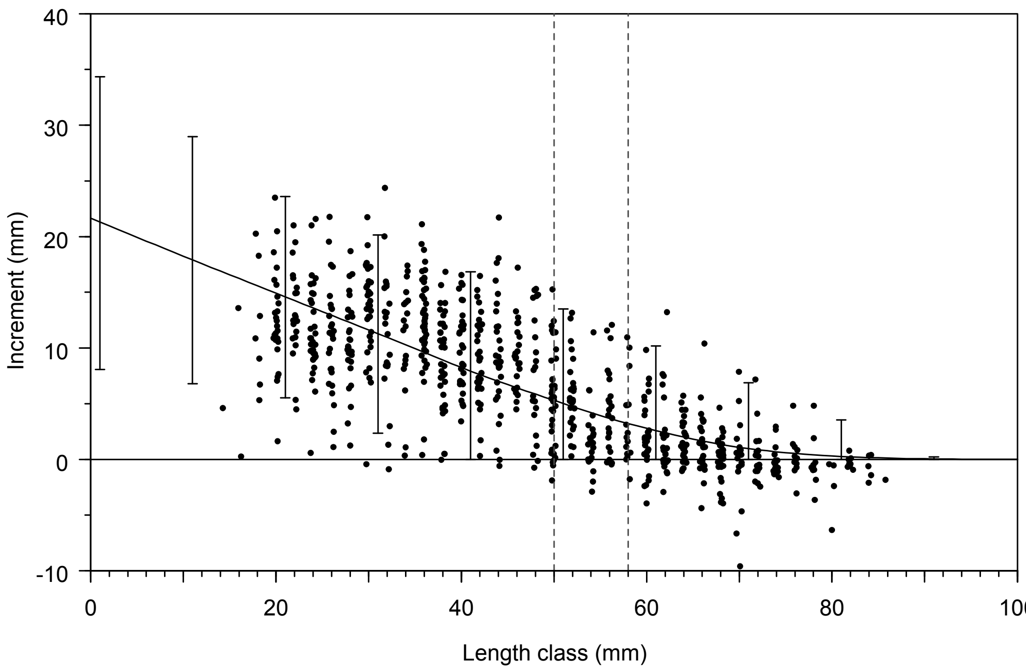

Figure 4: Initial size and mean annual increment data from Dunn et al. (1998b). Lines (and 95% confidence intervals) indicate the growth model assumed in the population model, and dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

In the revised 2007 model, Dunn (unpublished) estimated growth using the tag-recapture data. Observations of the length of the recaptured caged oysters, given their release length and time at liberty, were fitted with a multinomial likelihood, and were based on the observed proportions-at-length given the expected proportions-at-length from the marked population with the sample size equal to the number of individuals observed, i.e.,

$$-\log\left(L_t\right) = -\log\left(N_t!\right) + \sum_i \left[\log\left(\left(N_t O_{ti}\right)!\right) - N_t O_{ti}\log\left(E_{ti}\right)\right],$$

where N_t = the number of observed oysters at time t, O_{ti} = proportion of oysters at length i that were observed at time t, and E_{ti} = expected proportion of oysters at length i in the population at time t.

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.

3.3.3 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 (10–12%) breed as females (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. Figure 5 shows the estimated proportions mature (i.e., proportions of oysters with presence of female ova) by length class, along with exact 95% confidence intervals.

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. 2008).

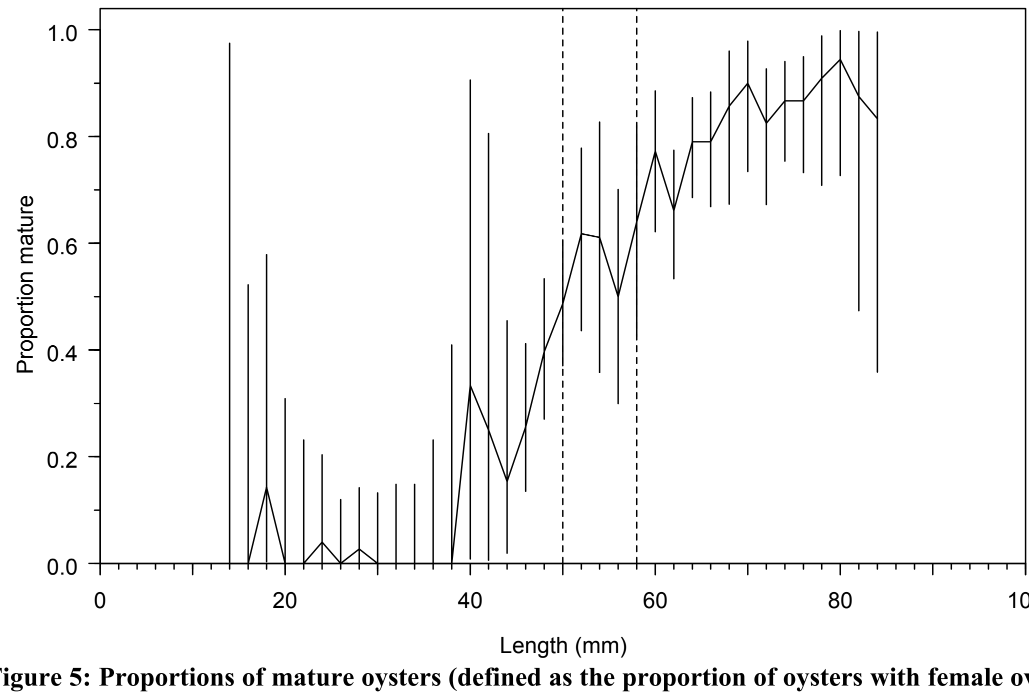

Figure 5: Proportions of mature oysters (defined as the proportion of oysters with female ova) by length (Jeffs & Hickman 2000). Vertical bars give exact 95% confidence intervals, and dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

3.3.4 Natural mortality

Dunn et al. (1998a) estimated natural mortality M for the years 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 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* plus *F* was not high, as at least two oysters lived to recruit size and survived a further 26–29 years.

3.3.5 Disease mortality

Data on disease mortality events are limited. Anecdotal reports exist of a mortality event during the late 1940s (H.J. Cranfield, 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 1907–48 (the period before any abundance estimates); 1952–59 (to allow for disease mortality in the late 1940s); 1967–84 (to allow for disease mortality in the early 1960s); and 1996–99 (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).

At the time of the model by Dunn (2005a), there were no studies that quantified the relationship between disease mortality, oyster length, or oyster maturity. Dunn (2005a) assumed that it was the same as the maturity ogive. He based this on the relationship 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), and data published by Stead (1971b) on relative catches of live oysters and clocks in the 1960–64 survey (Figure 8). We assume that the disease ogive was equal to the maturity ogive in the 2007 basic model and 2009 model runs.

B.K. Diggles (NIWA, unpublished data) analysed 500 oysters from a survey in January 2004 for *B. exitiosa* infection, sex, and maturity with lengths between 24 and 81 mm. These data provide information on the disease selectivity of oysters, and can be used to determine a length-based selectivity of *B. exitiosa* (Figure 9). These data are included within the revised 2007 model and the revised 2009 model only and used to estimate the disease selectivity ogive.

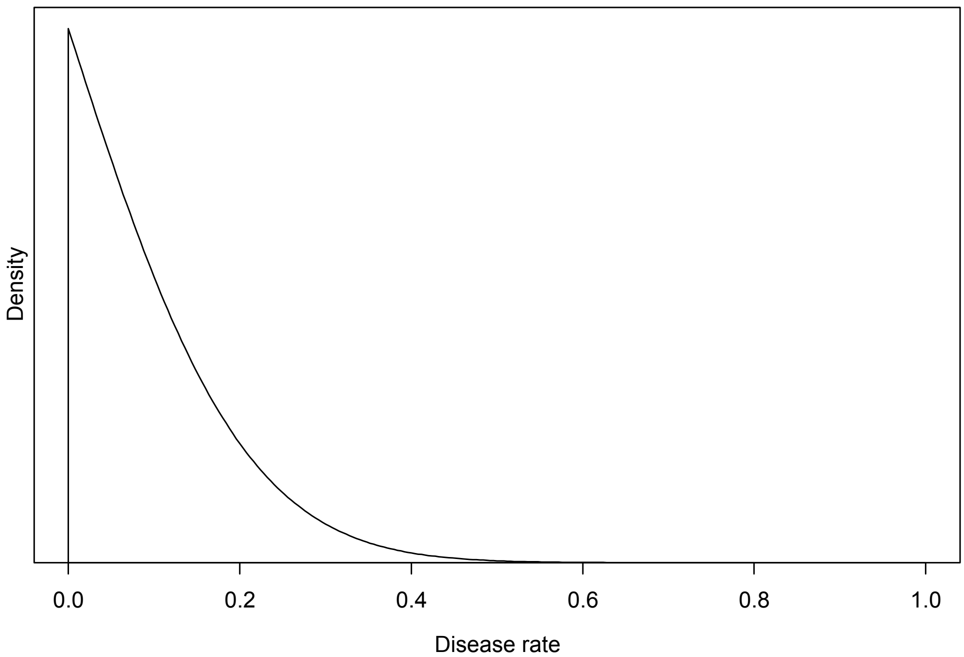

Figure 6: Prior assumed for the rate of disease mortality (normal with mean –0.2, standard deviation 0.2, and bounds [0.0–0.8]).

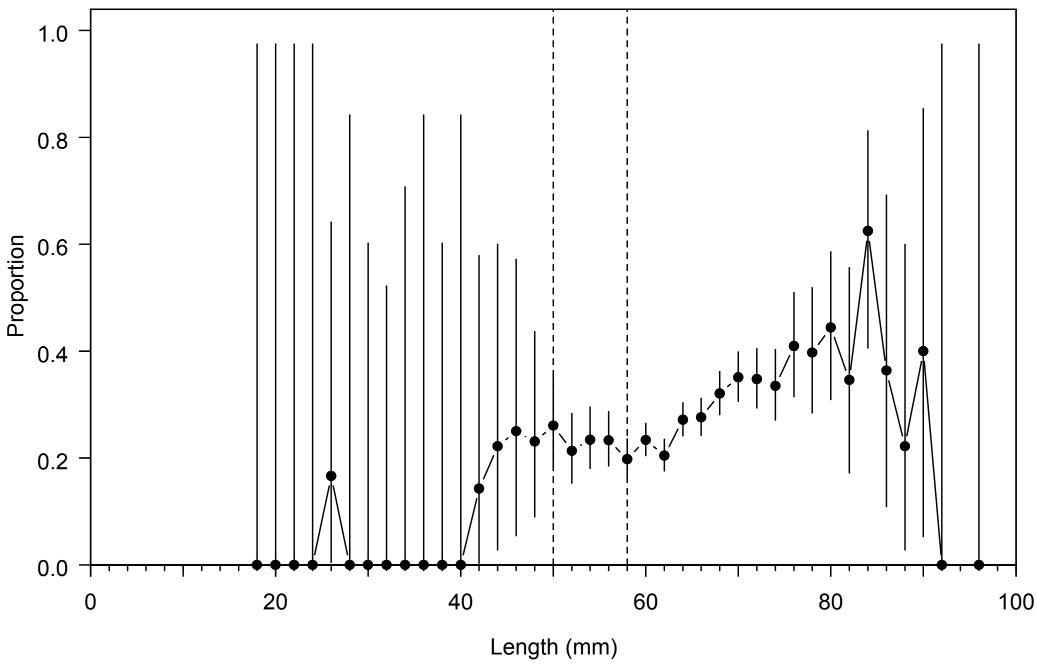

Figure 7: Proportions of oysters (and 95% confidence intervals) with a *B. exitiosa* infection of level 1+ from *B. exitiosa* sampling in the October 2001, January 2002, March 2002, and October 2002 surveys by length. Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit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

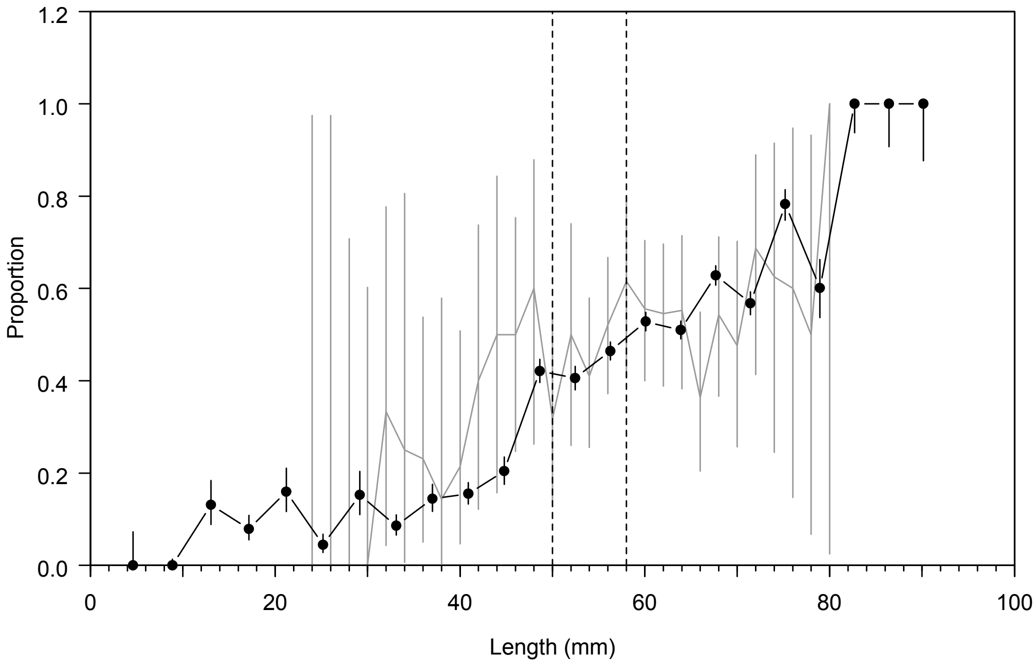

Figure 8: Proportions of clocks (and 95% confidence intervals) in the catch from the 1960–64 survey by length (solid circles and lines, data reproduced from a figure in Stead 1971b), overlaid with the proportion of mature oysters (and 95% confidence intervals) by length derived from Jeffs & Hickman (2000).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

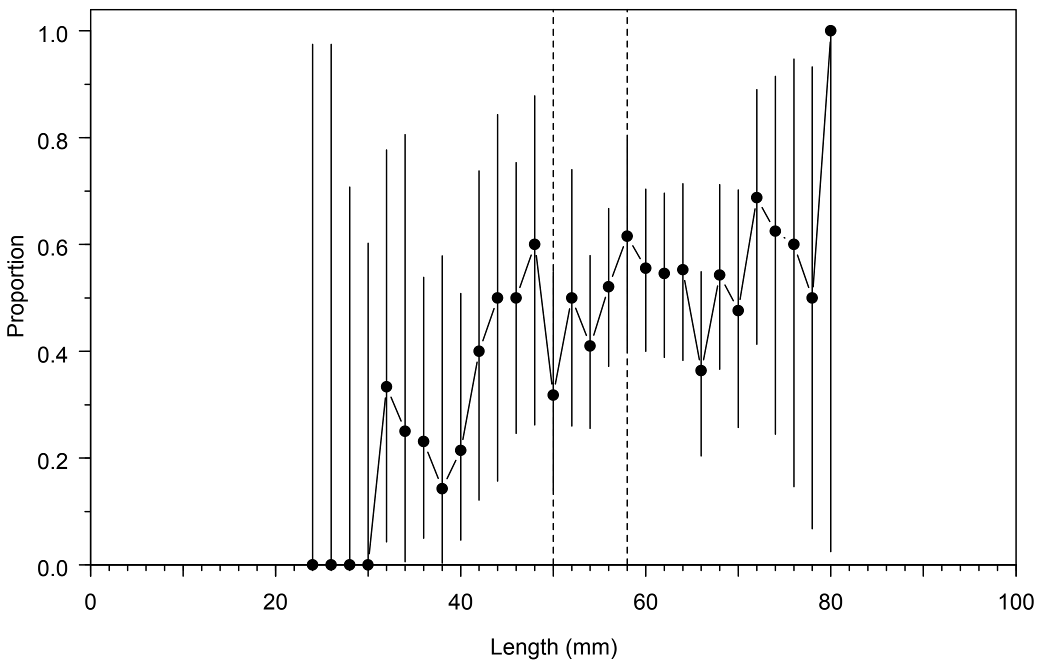

Figure 9: Proportions of oysters (and 95% confidence intervals) with a *B. exitiosa* infection of level 1+ from *B. exitiosa* histological sampling from the January 2004 surveys by length (B.K. Diggles, NIWA, unpublished data). Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

3.4 Commercial catch data

3.4.1 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 Table 2 and Figure 10.

Table 2: Total fishing season (winter) landings of Foveaux Strait oysters 1901–2009 (millions of oysters; sacks converted using numbers assuming a conversion rate of 774 oysters per sack for 1909–92). (Data from 1901–71 from Marine Department Annual Reports, 1972–94 MAF (Fisheries), 1996–2008 QMS.), 2009 assumed. '–' denotes not available.

Year	Catch	Year	Catch	Year	Catch	Year	Catch	Year	Catch
1901	–	1926	21.54	1951	70.15	1976	89.06	2001	14.79
1902	–	1927	16.26	1952	72.51	1977	92.14	2002	14.45
1903	–	1928	30.03	1953	55.44	1978	96.40	2003	7.46
1904	–	1929	30.44	1954	51.29	1979	88.36	2004	7.48
1905	–	1930	33.11	1955	60.84	1980	88.41	2005	7.48
1906	–	1931	28.28	1956	58.63	1981	89.04	2006	7.47
1907	18.83	1932	29.01	1957	60.14	1982	87.98	2007	7.37
1908	17.34	1933	32.64	1958	64.44	1983	89.06	2008	7.49
1909	19.19	1934	40.44	1959	77.00	1984	89.01	2009[1]	7.50
1910	18.20	1935	38.48	1960	96.85	1985	81.79		
1911	18.90	1936	49.08	1961	84.30	1986	60.22		
1912	19.00	1937	51.38	1962	53.42	1987	47.64		
1913	26.26	1938	52.05	1963	57.86	1988	67.81		
1914	19.15	1939	58.16	1964	73.51	1989	65.81		
1915	25.42	1940	51.08	1965	95.30	1990	35.69		
1916	22.61	1941	57.86	1966	124.14	1991	41.80		
1917	17.20	1942	56.87	1967	127.20	1992	4.51		
1918	19.36	1943	56.59	1968	113.93	1993	0		
1919	16.56	1944	49.50	1969	51.30	1994	0		
1920	20.67	1945	58.85	1970	87.92	1995	0		
1921	19.01	1946	69.16	1971	89.08	1996	13.41		
1922	21.11	1947	63.09	1972	77.43	1997	14.82		
1923	22.28	1948	73.10	1973	97.45	1998	14.85		
1924	18.42	1949	75.34	1974	92.47	1999	14.94		
1925	20.01	1950	58.09	1975	88.78	2000	14.96		

1 Assumed for 2009

The conversion rate of 774 oysters per sack was reported by Cranfield et al. (1999). 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, while 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.

Before 1929 the minimum takeable size limit was defined as 44.45 mm (1.75 inches) minimum diameter, increased to 50.8 mm (2.0 inches) in 1929, then increased again to 53.975 mm (2.125 inches) in 1941. In 1969, a takeable size limit of 57.15 mm (2.25 inches) 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 2002–08. 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 1929 to 1940, and 3.175 mm (0.125 inches) for 1941 to 1968.

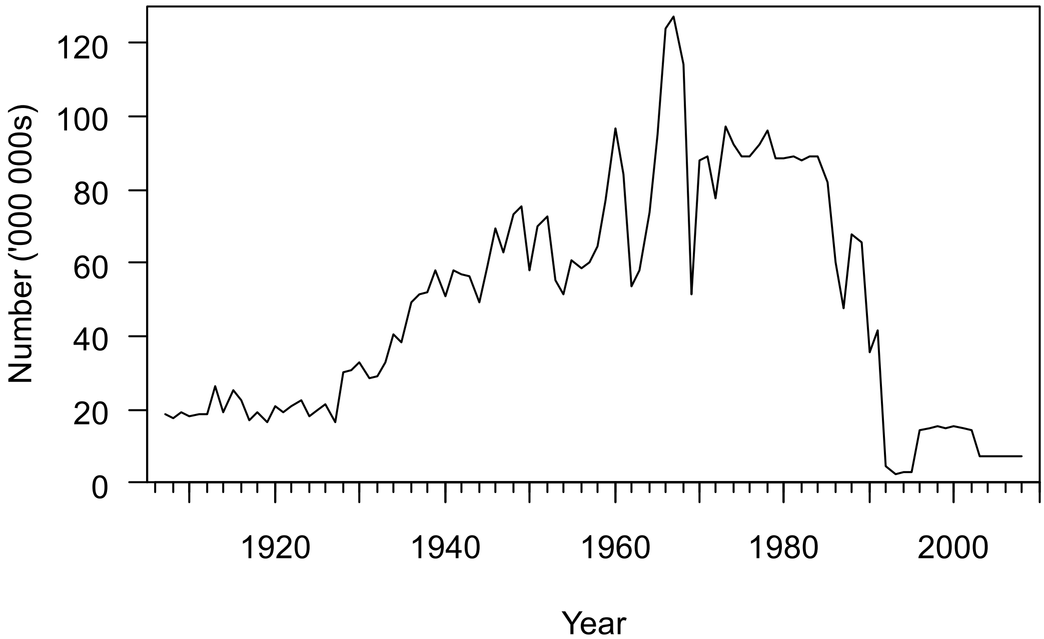

Figure 10: Total commercial catch (winter and summer) by year (millions of oysters), 1907–2008.

3.4.2 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 period (November–February), and were in addition to the usual commercial catch (Table 3).

Table 3: Reported oyster catch of vessels fishing under special permits for Bluff Oyster Management Company Ltd. 1992–93 to the 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	Number (millions)
1993	2.43
1994	3.09
1995	3.03
1996	0.93
1997	0.20
1998	0.72
1999	0.00
2000	1.00

3.4.3 Length frequency of the winter season commercial catch

Length samples from the commercial catch were taken during the 2002 (Michael et al. 2004a), 2003, 2005 (Dunn & Michael 2006), 2006 (Dunn & Michael 2007), 2007 (Dunn & Michael 2008), and 2008 (Dunn. et al 2009) fishing seasons. In 2002, 15 580 oysters were measured (15 269 recruited and 311 pre-recruits); in 2003, 18 940 oysters were measured (18 189 recruited and 751 pre-recruits); in 2005, 6509 oysters were measured (6339 recruited and 170 pre-recruits); in 2006, 6801 oysters were measured (6635 recruited and 166 pre-recruits); in 2007, 6829 oysters were measured (6734 recruited and 94 pre-recruits); and in 2008, 6831 oysters were measured (6733 recruited and 98 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 the length frequency from each stratum up to the total catch to yield length frequencies by stratum and overall (Figure 11). 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 4. (See also Appendix A, Figure 43 for a plot of the relationship).

Table 4: 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	11 795
2003	18 940	12 740
2005	6 509	5 072
2006	6 801	4 818
2007	6 829	5 383
2008	6 831	5 177

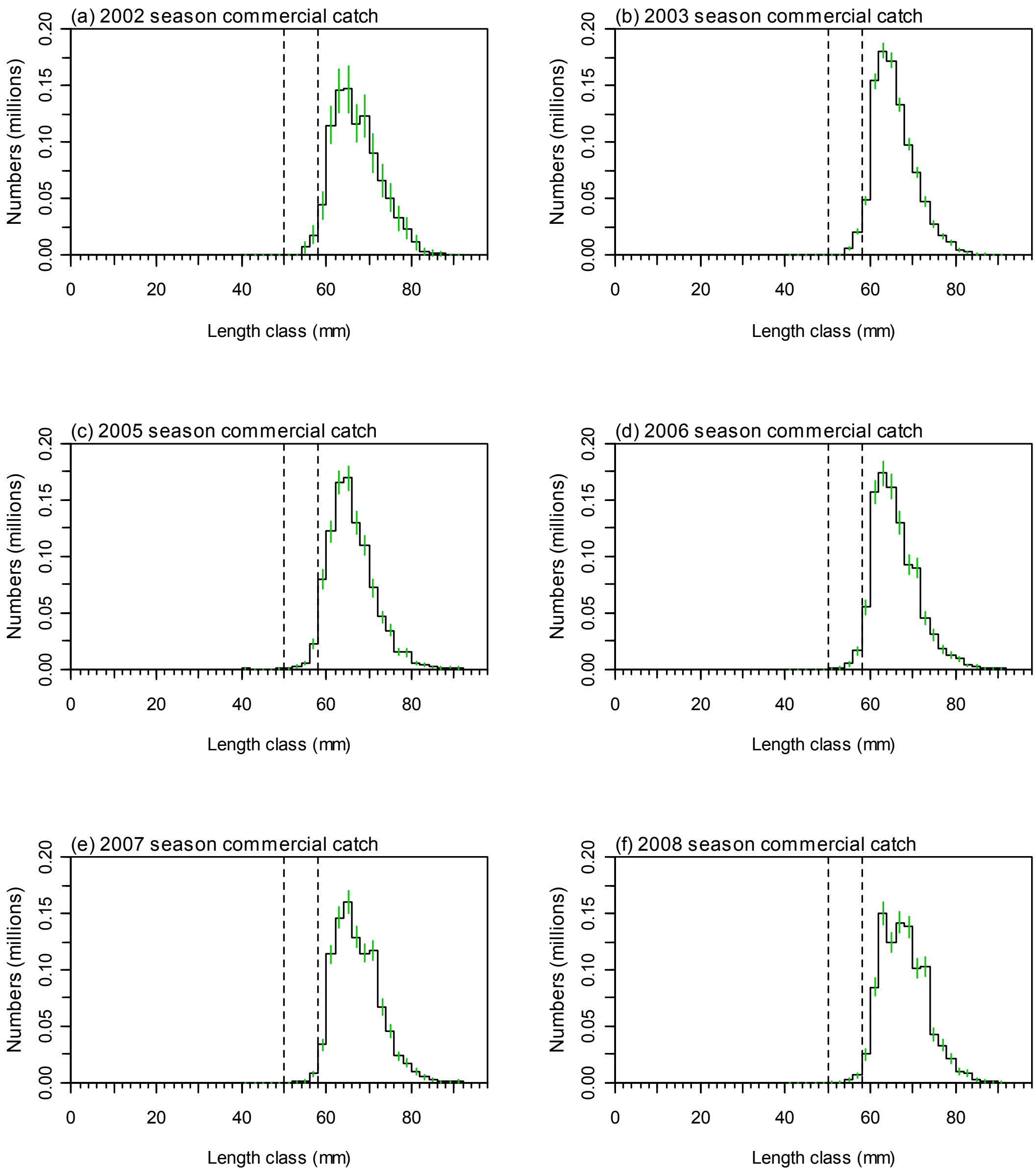

Figure 11: Numbers of oysters in the commercial catch by length class for the (a) 2002 (b) 2003, (c) 2005, (d) 2006, (d) 2007, and (f) 2008 seasons. Vertical bars give approximate 95% confidence intervals. Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

3.5 Non-commercial catch

The non-commercial catch is made up of recreational, customary, and illegal catch (described below). Estimates of non-commercial catch are poor, but suggest that it may be as high as 8% of the commercial catch in recent years (Figure 12).

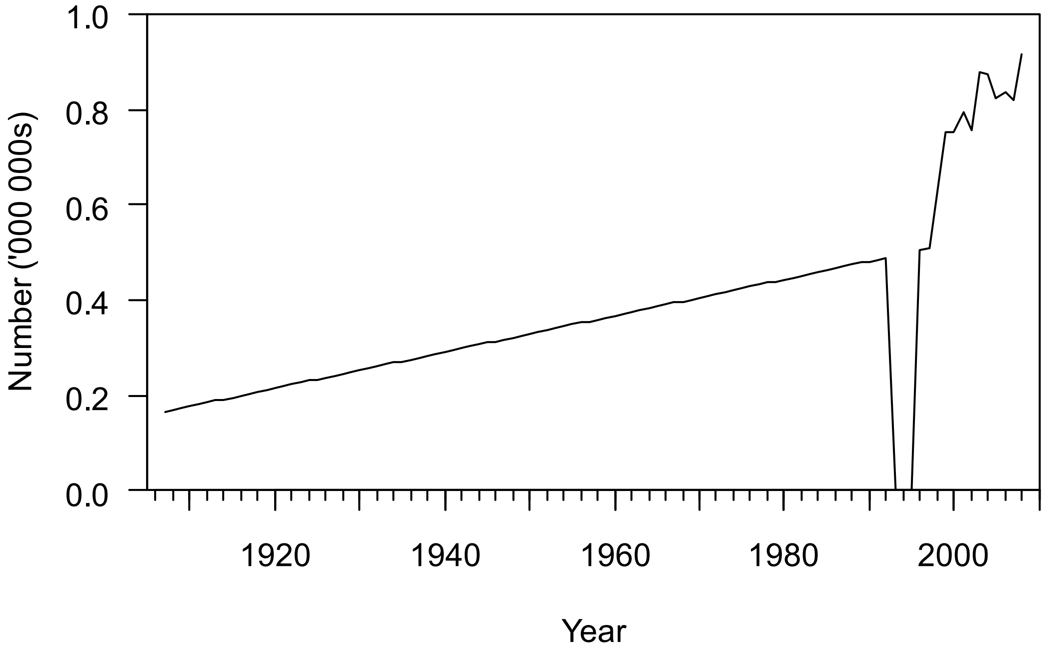

Figure 12: Total non-commercial catch (winter and summer) by year (millions of oysters), 1907–2008.

3.5.1 Recreational catch

The Ministry of Fisheries commissioned two surveys of recreational fishing, 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) (Ministry of Fisheries Science Group 2006). Ministry of Fisheries officials believe the catch has increased significantly since (Ministry of Fisheries Science Group 2006).

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 recreational catch of 50 oysters per fisher per day). Hence, the best estimate of the total recreational catch is about 430 000 (500 sacks) (Ministry of Fisheries Science Group 2006). 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, and linearly since —except that the recreational catch in 1993–95 (when the fishery was closed) was assumed to be zero. Further, the recreational harvest was assumed to take place over the winter season with a selectivity equal to the commercial fishing selectivity.

3.5.2 Customary catch

Reporting of Maori customary harvest is specified in the Fisheries (South Island Customary Fisheries) Regulations 1999. Ngai Tahu reports customary catch of Foveaux Strait oysters to the Ministry of Fisheries quarterly (Table 5). 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 5). Further this is assumed to take place with a selectivity equal to the commercial fishing selectivity.

Table 5: Reported customary catch (numbers) between 1 July 1998 to 31 December 2007 by year and quarter from Kaitiaki data collected by Ngai Tahu. '–' denotes not available (source: Ministry of Fisheries Science Group 2008).

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	0	184 335
2003	1 560	85 920	45 840	0	157 980
2004	26 546	9 820	91 342	0	127 708
2005	43 320	25 920	7 224	0	76 464
2006	–	–	–	–	85 312
2007	–	–	–	–	65 400

3.5.3 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 (Ministry of Fisheries Science Group 2006).

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, this is assumed to take place over the winter season with a selectivity equal to the commercial fishing selectivity.

3.5.4 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 less 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 Results) was also low, the effects of incidental dredge damage or mortality are ignored in this model.

3.6 Resource surveys and other abundance information

3.6.1 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 6). This process is described in more detail below.

In general, resource surveys counted the number of “takeable” oysters. Early surveys often used un-calibrated dredges, and/or failed to document the survey methodology. Later surveys also estimated the number of pre-recruit sized oysters (50 mm to 58 mm) and small oysters (less than 50 mm), 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 ligaments of oysters break 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. Then 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.

3.6.2 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). 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).

The Doonan & Cranfield (1992) 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.

3.6.3 Pre-1960 surveys

No abundance data from the early surveys of Foveaux Strait (i.e., 1906, 1926, 1927, and 1945) are available and no abundance estimates from these surveys were reported. However, individual length data were collected on the 1926–27 surveys by M.W. Young, and reported by Sorensen (1968) (see Section 3.7).

3.6.4 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 where 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 greater than or equal to 53.975 mm 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 methodology (Figure 13). These data were used to estimate the dredge efficiency of the 1960–64 sampling, and calculate an absolute abundance. Estimates of c.v.s were also made by bootstrapping. Survey stations outside the 1999–2002 survey boundary were ignored, and the remainder used to calculate a calibrated survey absolute abundance (for recruit sized oysters) estimate 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 heaver 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) (see Section 3.7).

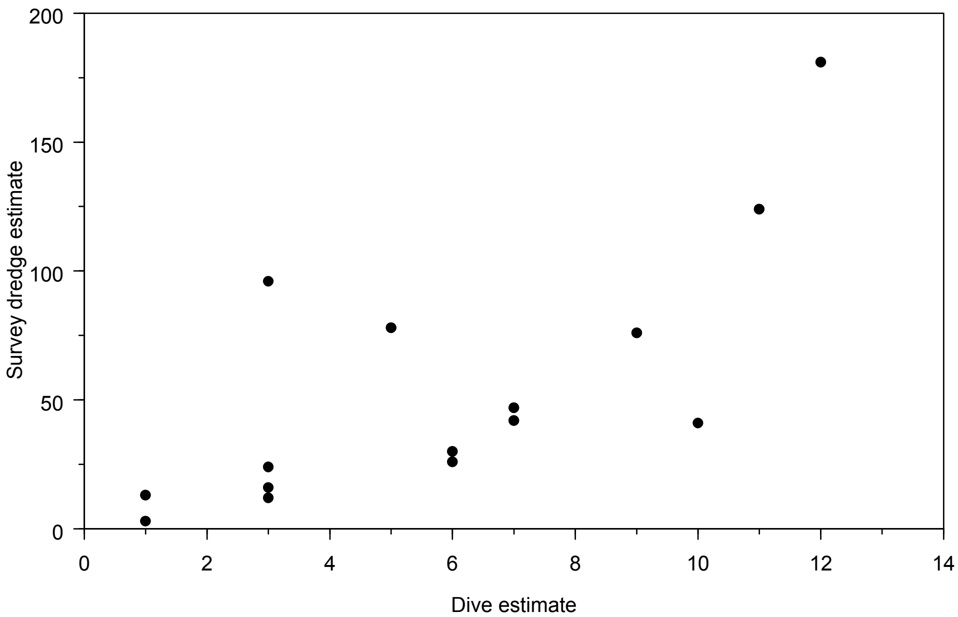

Figure 13: Data used to calibrate the 1960–64 dredge survey. Estimated number of "takeable" oysters sampled by divers on 1 m^2 quadrats (x-axis) and from 5 minute survey tows using the 0.9 m-wide survey dredge (y-axis) (reproduced from data in Stead 1971b).

Table 6: Summary of Foveaux Strait dredge oyster survey data 1906–2005 (numbers of live, new clocks, and old clocks in millions). '–' indicates unknown.

Date	Design[1]	Area (km^2)	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 et al. 1987)
Jan 1987	Specific	–	67	F	*Recruit*	–	–	–	–	–	–	(Dinamani et al. 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 1906–2005.

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)
Jan 2005	SR	1 055	80	G*	*Recruit*	408	0.13	3	287	Yes	–	(Michael et al. 2006)
		1 055	80	G*	*Pre-recruit*	415	0.15	4	152	Yes	–	(Michael et al. 2006)
		1 055	80	G*	*Small*	1 345	0.12	–	–	Yes	–	(Michael et al. 2006)
Feb 2006	Specific	407	44	G*	*Recruit*	242	0.14	13	148	Yes	–	(K.P. Michael, unpublished)
		407	44	G*	*Pre-recruit*	257	0.17	9	72	Yes	–	(K.P. Michael, unpublished)
		407	44	G*	*Small*	622	0.13	–	–	Yes	–	(K.P. Michael, unpublished)
Feb 2007[6]	SR	1 070	103	G*	*Recruit*	624	0.10	11	222	Yes	–	(Michael et al. 2008)
		1 070	103	G*	*Pre-recruit*	464	0.11	4	72	Yes	–	(Michael et al. 2008)
		1 070	103	G*	*Small*	848	0.09	–	–	Yes	–	(Michael et al. 2008)
		1 055	101	G*	*Recruit*[7]	622	0.10	11	222	Yes	–	Re-analysed estimate
		1 055	101	G*	*Pre-recruit*[7]	463	0.11	4	72	Yes	–	Re-analysed estimate
		1 055	101	G*	*Small*[7]	842	0.09	–	–	Yes	–	Re-analysed estimate

Table 6 (continued): Summary of Foveaux Strait dredge oyster survey data 1906–2005.

Date	Design[1]	Area (km^2)	Stations	Type[2]	Category	Live	c.v.	New clocks	Old clocks	*B. exitiosa.*	Lengths	Reference
Feb 2008	Specific	671	40	G*	*Recruit*	694	0.11	18	136	Yes	–	(K.P. Michael, unpublished)
		671	40	G*	*Pre-recruit*	269	0.10	5	42	Yes	–	(K.P. Michael, unpublished)
		671	40	G*	*Small*	702	0.13	–	–	Yes	–	(K.P. Michael, unpublished)
Feb 2009[8]	SR	1 070	105	G*	*Recruit*	725	0.08	17	170	Yes	–	(K.P. Michael, unpublished)
		1 070	105	G*	*Pre-recruit*	358	0.10	4	68	Yes	–	(K.P. Michael, unpublished)
		1 070	105	G*	*Small*	910	0.10	–	–	Yes	–	(K.P. Michael, unpublished)
		1 055	101	G*	*Recruit*[7]	720	0.08	16	166	Yes	–	Re-analysed estimate
		1 055	101	G*	*Pre-recruit*[7]	354	0.10	4	67	Yes	–	Re-analysed estimate
		1 055	101	G*	*Small*[7]	889	0.10	–	–	Yes	–	Re-analysed estimate

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, while '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 being 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.
6. The February 2007 included an additional stratum in north Foveaux Strait. Re-analysed estimates ignore this stratum, and hence are estimates of abundance over an area comparable to earlier surveys.
7. Two errors in the length of tows resulted in a revised estimate of the number of recruits and small oysters for the February 2007 survey. Model runs presented below used values of 661 recruits and 877 smalls for the February 2007 abundance indices, instead of the corrected values of 663 and 879 respectively.
8. The February 2009 included an additional stratum in north Foveaux Strait. Re-analysed estimates ignore this stratum, and hence are estimates of abundance over an area comparable to earlier surveys.

3.6.5 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.

3.6.6 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 based on data 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 impact 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.

3.6.7 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 were made (see Table 6).

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 1990–97 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 to 2005, and re-analysed with the revised dredge efficiency estimates (Table 6, Figures 14 and 15).

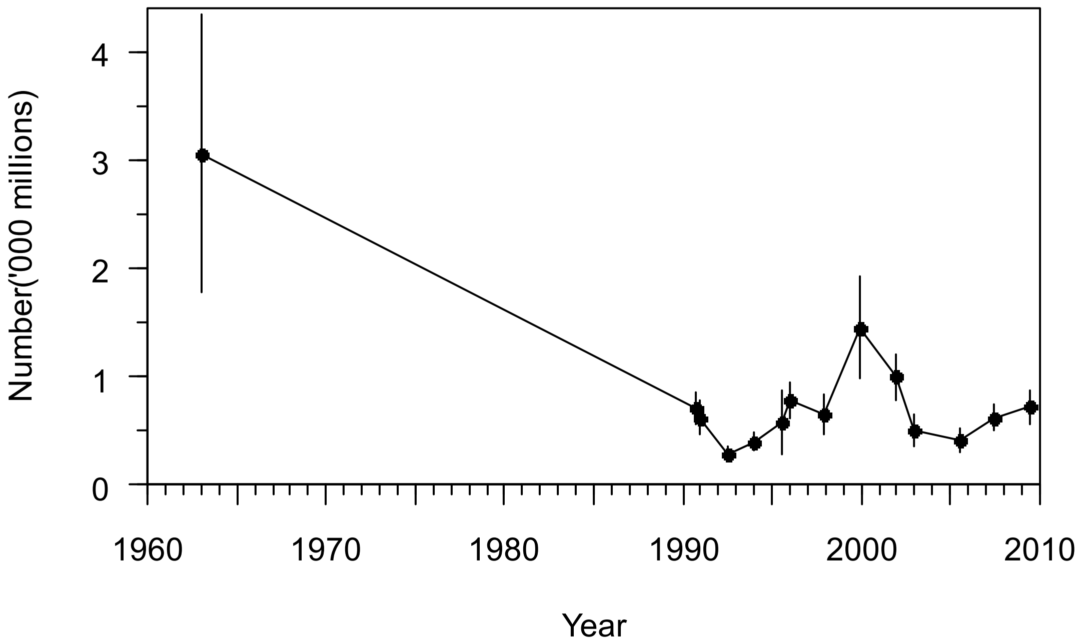

Figure 14: Revised estimates of the recruit-sized absolute abundance from surveys between 1962 and 2009. Vertical lines show approximate 95% confidence intervals.

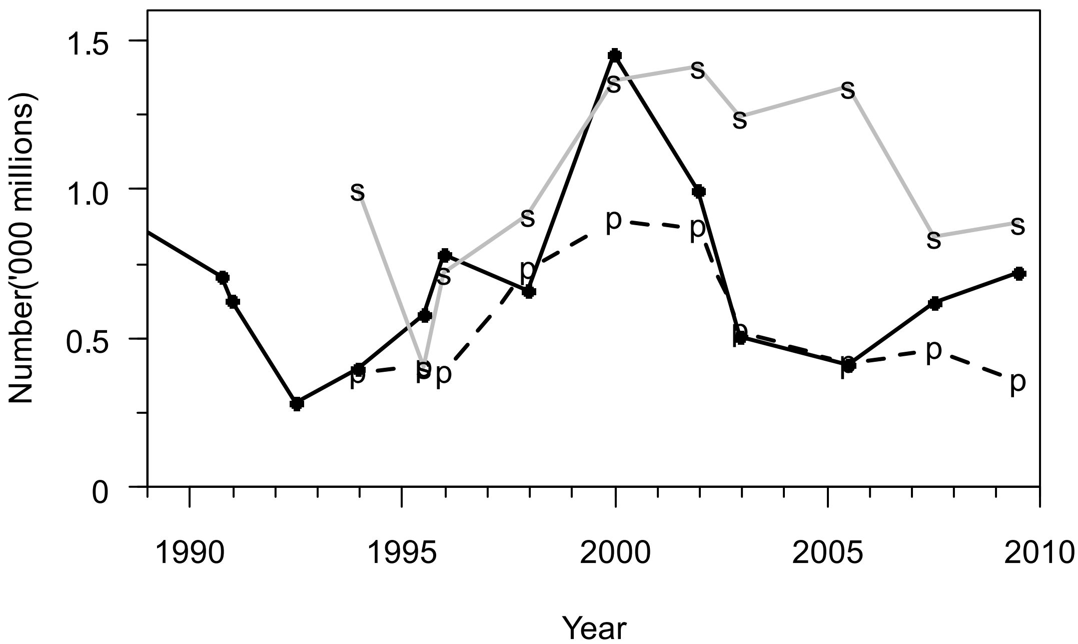

Figure 15: Estimated numbers of recruit (dots), pre-recruit (P), and small (S) oysters found in the biomass surveys between 1990 and 2009.

3.6.8 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.

3.6.9 2005, 2007, and 2009 surveys

The abundance surveys in January 2005, February 2007, and February 2009 occurred at different time from previous surveys (typically these have been in either March or October). In this model we assume that that these surveys are a measure of the beginning of fishing season biomass, and hence include it within the population model as a biomass index at the end of the first time step, in March 2005, 2007, and 2009 respectively.

In addition, the February 2007 and February 2009 surveys covered a slightly larger region than that used to standardise previous surveys (i.e., 1070 km^2 versus 1055 km^2 – see Table 6), by the inclusion of one additional stratum. We ignore the strata that were outside the 2002 region, and hence use the estimates of abundance for the equivalent 2002 region (Table 6).

3.6.10 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 to 1994 by MAF (Fisheries), and since then by the Ministry of Fisheries (Ministry of Fisheries Science Group 2006).

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 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 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 7 and Figure 16).

Dunn (2005a) presented an analysis of the raw catch-rate and a standardised CPUE analysis for the years using CELR data and logbook data. He found that the standardised and unstandardised indices showed very similar trends, with only slight differences discernible between data sets or methods of analysis. Hence, he used the unstandardised indices as an index of fishable abundance in the stock model, with a lognormal likelihood and assumed c.v.s of 0.25. We use the same CPUE data (i.e., series A, B, and C) updated to include data for 2007 and 2008.

Table 7: Reported catch rate estimates and revised estimates from source records for series A, B, and C, for Foveaux Strait oysters 1901–2008 (sacks per hour). (Data from 1948–1971 Marine Department annual reports, 1972 MAF (Fisheries) Annual Report, 1973–2008 Ministry of Fisheries Science Group (2008).)

Year	Series	Reported	Revised	Year	Series	Reported	Revised	Year	Series	Reported	Revised
1948	A	14.7	14.7	1969	B	6.5	9.3	1990	C	6.4	9.7
1949	A	14.6	14.6	1970	B	7.3	7.7	1991	C[4]	5.8	5.8
1950	A	14.2	14.2	1971	B	6.9	6.6	1992	C[5]	3.4	3.2
1951	A	12.6	12.6	1972	B	6.7	6.7	1993	C[6]	–	–
1952	A	13.7	13.7	1973	B[1]	10.0	10.0	1994	C[6]	–	–
1953	A	12.6	12.6	1974	B[1]	11.5	10.8	1995	C[6]	–	–
1954	A	11.0	11.0	1975	B	11.9	11.9	1996	C	5.9	5.4
1955	A	12.2	12.2	1976	B	13.4	13.3	1997	C	7 0	6.4
1956	A	10.0	10.0	1977	B[2]	15.9	15.4	1998	C	8.3	6.3
1957	A	9.0	9.0	1978	B[2]	17.1	15.6	1999	C	7.5	6.3
1958	A	9.5	9.5	1979	B	16.6	14.5	2000	C	7.2	6.6
1959	A	10.7	10.7	1980	B	15.2	15.2	2001	C	7.0	6.5
1960	A	10.5	10.5	1981	B	13.4	13.4	2002	C	3.2	3.2
1961	A	10.5	10.5	1982	B	13.2	13.2	2003	C	2.3	2.4
1962	A	8.0	8.0	1983	B	12.3	12.3	2004	C	2.2	2.2
1963	A	6.0	6.0	1984	B	13.8	13.8	2005	C	1.7	1.8
1964	A	6.8	6.8	1985	C	12.1	12.1	2006	C	1.9	1.9
1965	A	7.9	8.0	1986	C[3]	10.5	10.5	2007	C	–	2.4
1966	A	10.6	10.6	1987	C	10.9	9.1	2008	C	–	3.3
1967	A	9.3		1988	C	10.0	10.0				
1968	A	7.7		1989	C	10.7	–				

1. Landings include catch given as incentive to explore “un-fished” 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.

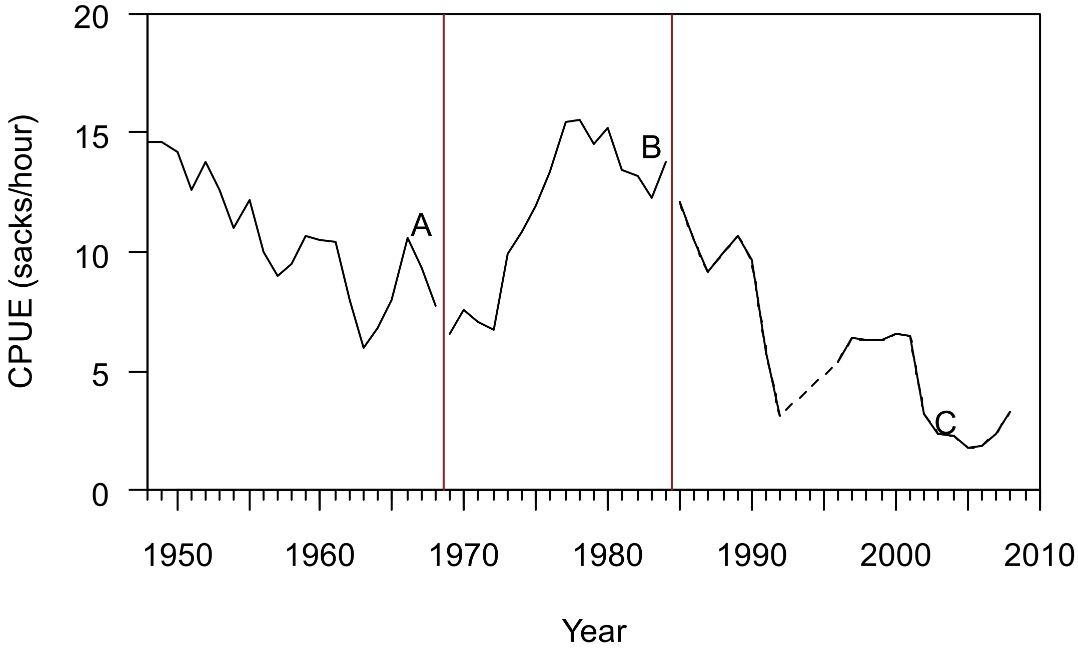

Figure 16: Revised estimates (dark lines) from source records for series A, B, and C, for Foveaux Strait oysters 1948–2008 (sacks per hour). (Data from Table 7.)

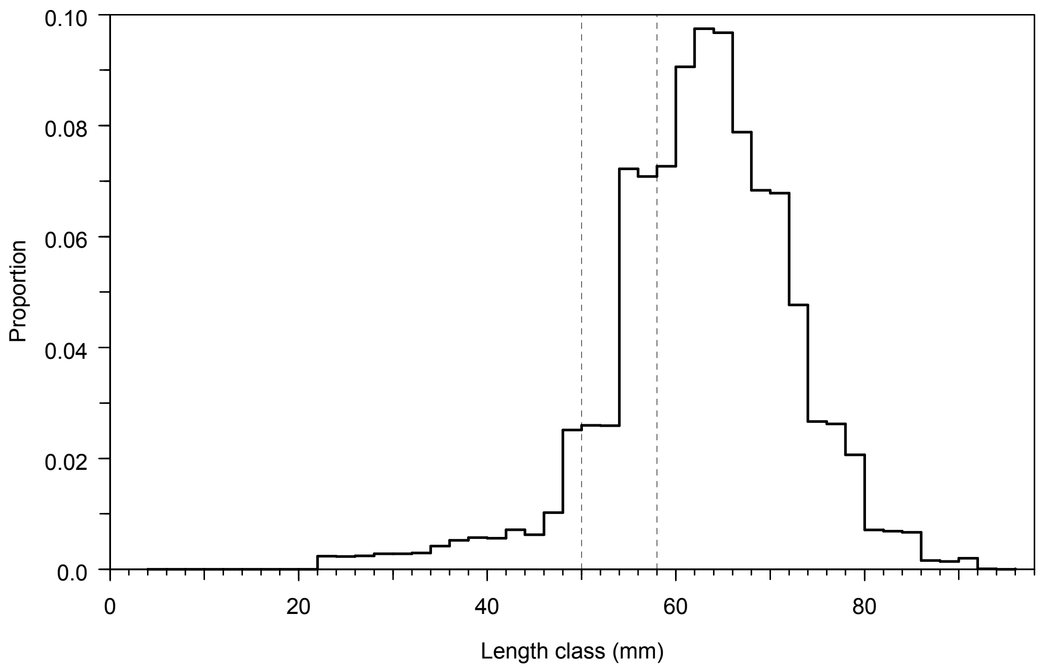

Figure 17: Proportions of oysters by length class from the 1926–27 survey, reproduced from data given in table 3 in Sorensen (1968). Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

3.7 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, ands 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.

3.7.1 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, after converting the length measurements from inches to millimetres.

3.7.2 1960–64 survey

Individual height data were collected on the 1960–64 survey and reported in a graph by 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 2001–03), the height frequencies can be converted to length frequencies, i.e.,

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

where $\varepsilon \sim N(0,\sigma^2)$, and hence we estimated 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.

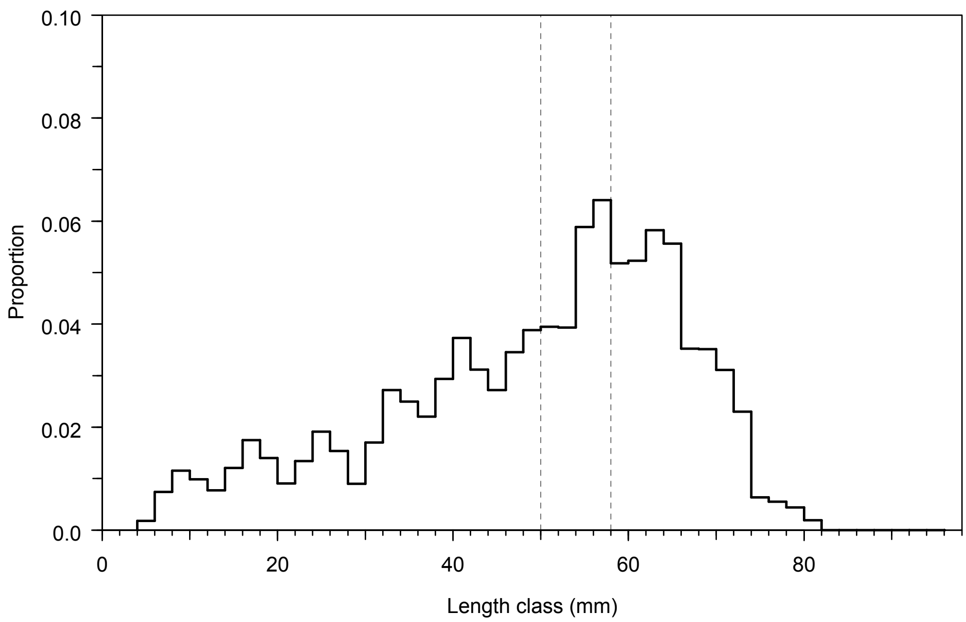

Figure 18: Proportions of oysters by length class from the 1960–64 survey, reproduced from data given in figure 1 in Stead (1971b). Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

3.7.3 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 into the model with 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 *i*th proportion, P_i (Table 8, and Appendix A, Figure 44).

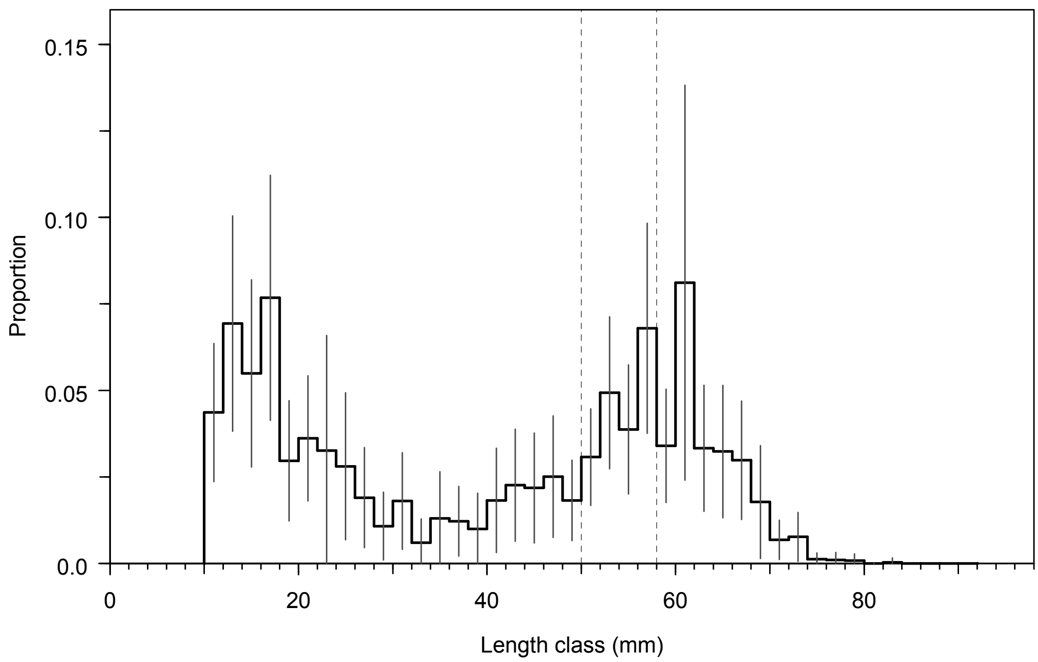

Figure 19: Proportions of oysters by length class from the 1990 dive survey. Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

3.7.4 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 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 $\log(cv_i)\sim\log(P_i)$, where cv_i was the bootstrap c.v. for the *i*th proportion, P_i (Table 8, and Appendix A, Figure 45).

Table 8: 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

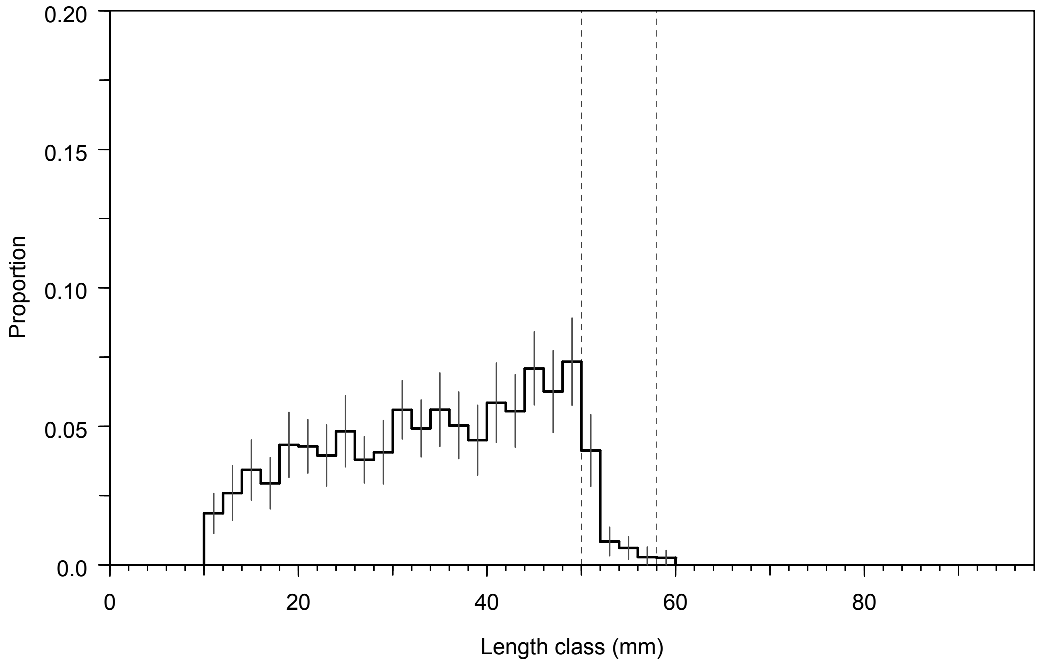

Figure 20: Proportions of oysters classified as "smalls" by length class from the 1999 October resource survey. Vertical bars give approximate 95% confidence intervals. Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

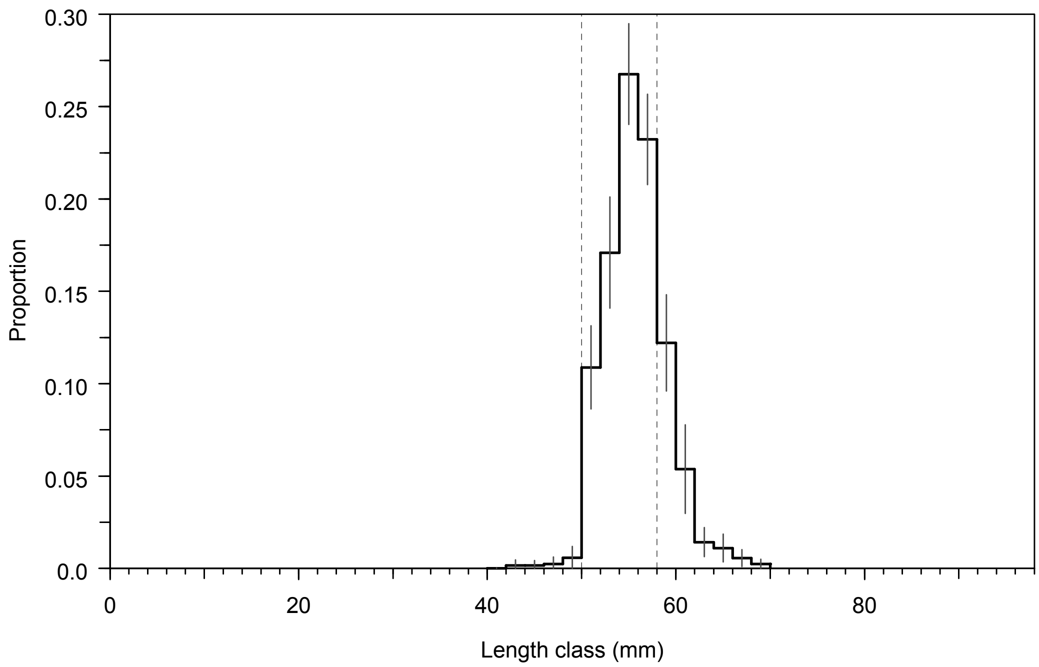

Figure 21: Proportions of oysters classified as "pre-recruits" by length class from the 1999 October resource survey. Vertical bars give approximate 95% confidence intervals. Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

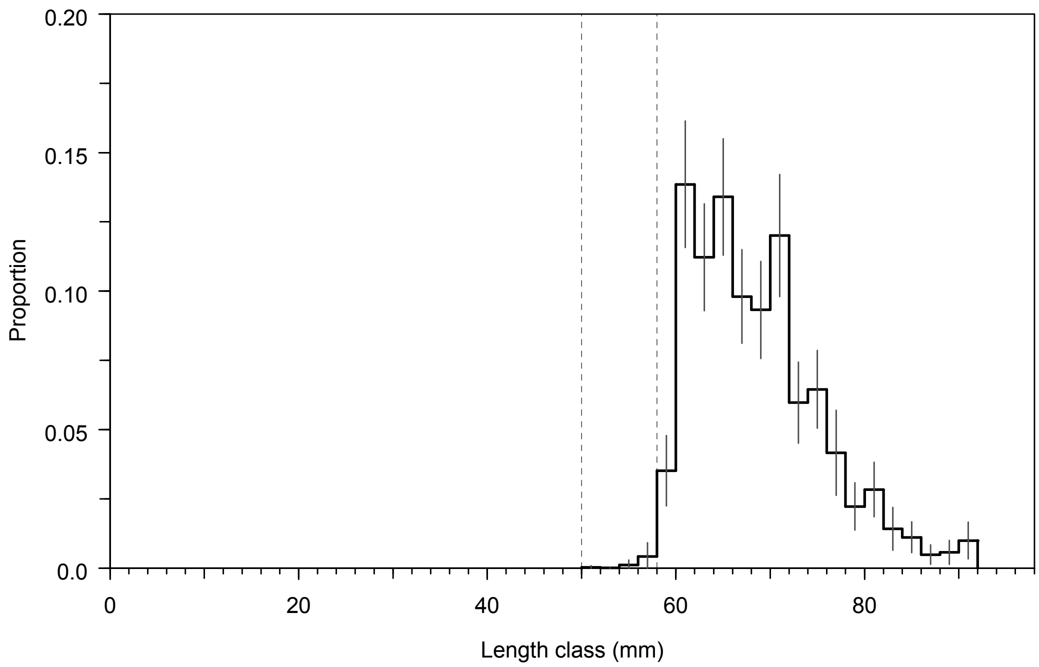

Figure 22: Proportions of oysters classified as "recruits" by length class from the 1999 October resource survey. Vertical bars give approximate 95% confidence intervals. Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

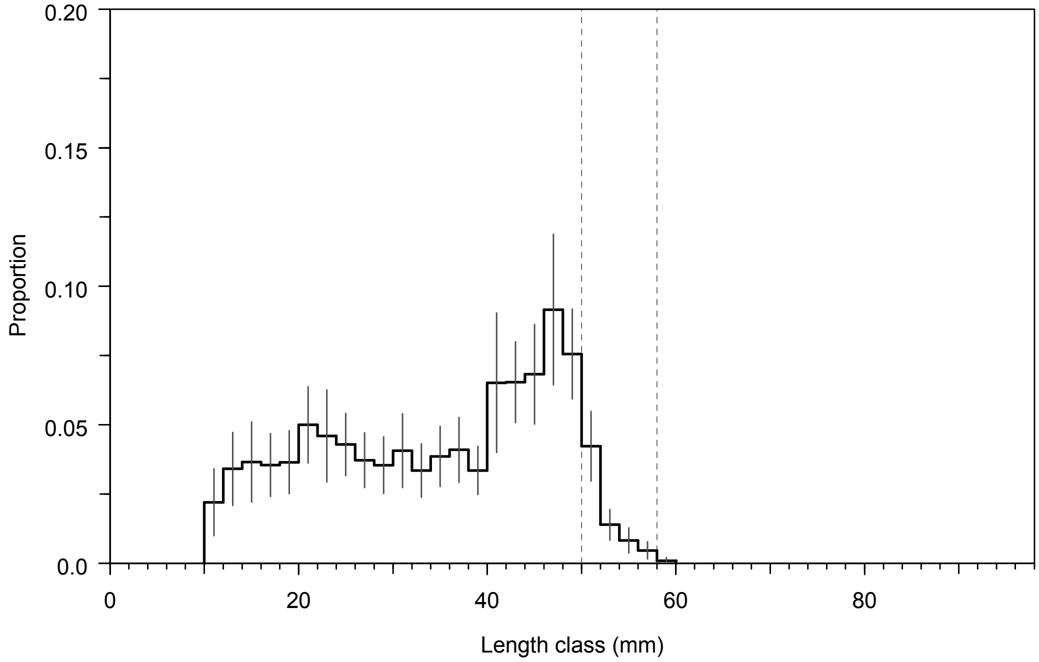

Figure 23: Proportions of oysters classified as "smalls" by length class from the 2001 October resource survey. Vertical bars give approximate 95% confidence intervals. Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

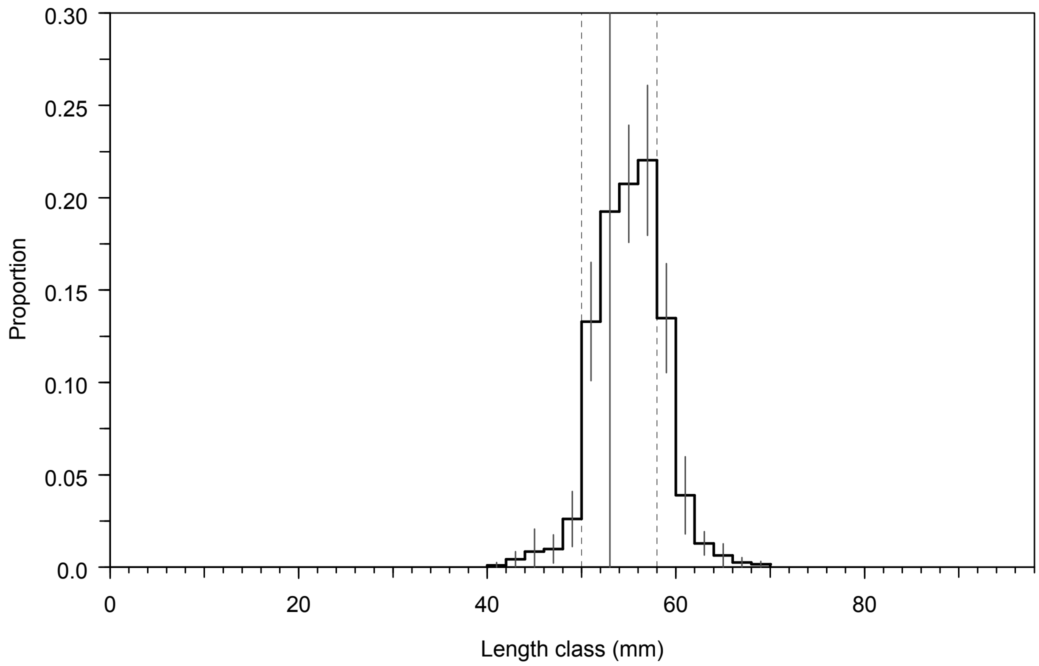

Figure 24: Proportions of oysters classified as "pre-recruits" by length class from the 2001 October resource survey. Vertical bars give approximate 95% confidence intervals. Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

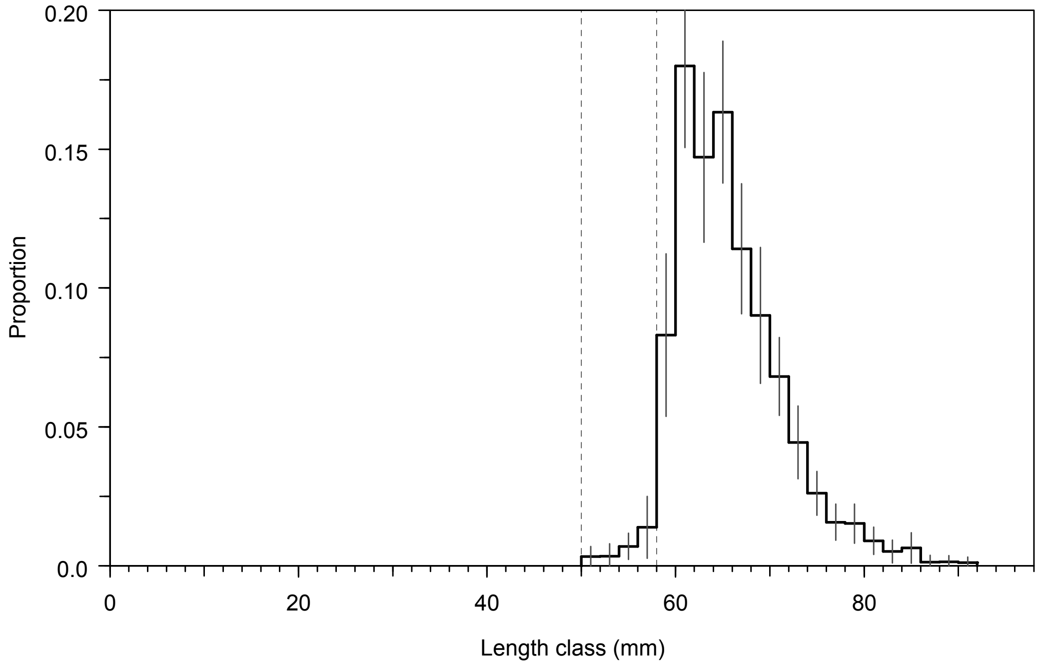

Figure 25: Proportions of oysters classified as "recruits" by length class from the 2001 October resource survey. Vertical bars give approximate 95% confidence intervals. Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

3.8 Process error

The effective sample sizes (in the case of observations fitted with multinomial likelihoods) or c.v.s (for observations fitted with lognormal likelihoods) were assumed to have allowed for sampling error only. Additional variance (here called process error), assumed to arise from differences between model simplifications and real world variation, was added to the sampling variance for each observation.

Estimates of the process error and hence the model sample size for the proportions-at-length observations were made via a two-step process; (a) first, the sample sizes were derived by assuming the relationship between the observed proportions, E_i, and estimated c.v.s, c_i, followed that for a multinomial distribution with unknown sample size N_j as described earlier (see Sections 3.4.3, 3.7.3, and 3.7.4), and (b) by estimating an effective sample size, N_j', by adding additional process error, N_{PE}, to the sample size calculated in (a) above, where,

$$N_j' = 1 \bigg/ \left(\frac{1}{N_j} + \frac{1}{N_{PE}} \right)$$

i.e., from an initial MPD model fit, an estimate of the additional process error was made by solving the following equation for N_{PE},

$$n = \sum_{ij} \frac{\left(O_{ij} - E_{ij}\right)^2}{E_{ij}\left(1 - E_{ij}\right)\left(\frac{1}{N_j} + \frac{1}{N_{PE}} \right)}$$

where n was the number of multinomial cells, O_{ij} was the observed proportions for length class i in year j, E_{ij} was the expected proportions, N_j was the effective sample size estimated in (a) above, and N_{PE} was the associated process error for that class of observations.

Estimates of the effective c.v. for biomass observations were made by fitting the process error within each model run, where the effective c.v. c_i' was determined from the process error c_{PE} and the observed c.v.s c_i by,

$$c_i' = \sqrt{c_i^2 + c_{PE}^2} \; .$$

The relative process error for the 2007 basic model was the same as reported by Dunn (unpublished). We apply the same process error to the 2009 model (labelled 2009 model with 2007 weight), and also updated the process error for the 2009 model and the revised 2009 model using the above methods. In all cases, the additional process error for observations with a lognormal likelihood was estimated to be zero. The initial and final sample sizes assumed for the proportions-at-length data are given in Table 9.

Table 9: Effective sample sizes (N) determined for the multinomial likelihood for the catch and survey proportions at length data and the resulting multinomial sample size used in each model run resulting from the addition of process error.

		2007 basic model	2009 (2007 weight)	2009 model	Revised 2007 model	Revised 2009 model
October 1990 dive	461	198	198	178	258	260
October 1999						
Small	1 273	807	807	944	1 129	1129
Pre-recruit	953	282	282	264	260	261
Recruit	1 277	222	222	233	634	425
October 2001						
Small	1 074	722	722	830	969	970
Pre-recruit	544	231	231	218	215	216
Recruit	887	206	206	216	520	371
Catch-at-length						
2002	10 932	1 228	1 228	1 342	2 502	2 175
2003	15 254	1 268	1 268	1 353	2 675	2 204
2005	4 063	1 032	1 032	1 167	1 804	1 747
2006	5 110	1 089	1 089	1 153	1 984	1 716
2007	5 383		1 101	1 182		1 783
2008	5 177		1 092	1 172		1 760

4. MODEL ESTIMATES AND RESULTS

Model estimates of numbers of oysters were made using the biological parameters and model input parameters described in Section 3.3. The 2009 model was defined as the same structure as the 2007 basic model, but with catch and CPUE data for the 2007 and 2008 fishing years, the inclusion of the February 2009 biomass survey indices, and an assumed catch of 7.5 million oysters in 2009.

The priors assumed for most parameters are summarised in Table 10. In general, ogive priors were chosen to be non-informative and were uniform across wide bounds. The prior for disease mortality was defined so that estimates of disease mortality were encouraged to be low. An informed prior was used when estimating the survey catchability, where a reasonably strong lognormal prior was used, with mean 1.0 and c.v. 0.2.

Summaries of the objective function values (negative log-likelihood) are shown in Table 11. Mode of the posterior distribution (MPD) trajectories for the base and sensitivity cases for the recruit-sized stock abundance are shown in Figure 26. Additional summary plots of the 2009 model MPD fits are given as Appendix A.

Table 10: 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	–	–	$1x10^{-8}$	0.1
Survey q[1]	Lognormal[1]	1.0	0.2	0.10	4.0
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 revised 2007 model and the revised 2009 model run only.

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

Component	2007 basic model	2009 (2007 weight)	2009 model	Revised 2007 model	Revised 2009 model
1976 survey	-1.8	-1.9	-1.9		
1979 recapture data				161.3	160.1
1981 recapture data				77.1	76.4
Bonamia selectivity data				54.9	66.5
CPUE-A	224.6	348.5	358.6	276.7	410.4
CPUE-B	-25.3	-25.0	-25.0	-24.8	-24.8
CPUE-C	-15.8	-15.0	-14.9	-14.3	-14.1
Commercial catch sampling	-12.4	-7.4	-7.3	-10.7	-7.0
Jeffs-Hickman maturity data	63.7	64.1	64.2	63.6	63.6
July survey (recruits)	-2.2	-2.2	-2.2	-2.0	-2.0
Mark-recapture survey (recruits)	-4.0	-5.3	-5.3	-3.8	-4.8
March survey (recruits)	-1.3	-1.7	-1.6	0.4	1.2
March survey (pre-recruits)	2.5	6.0	6.1	2.6	5.8
March survey (smalls)	-2.8	-2.7	-2.7	-2.7	-2.7
October dive survey	80.9	84.5	80.7	82.8	86.0
October survey (recruits)	-6.9	-5.6	-5.8	-4.3	-3.4
October survey (pre-recruits)	66.2	66.4	64.7	65.6	64.5
October survey (smalls)	-6.4	-5.1	-4.9	-8.8	-4.9
October survey length frequency (recruits)	89.8	87.1	88.4	144.3	109.5
October survey length frequency (pre-recruits)	-4.6	-2.9	-2.6	-5.6	-3.9
October survey length frequency (smalls)	155.4	155.5	165.5	160.1	160.1
Subtotal (data)	599.4	737.0	753.9	1012.4	1136.5
Catch limit penalties	0.0	0.0	0.0	0.0	0
Disease smoothing penalty	–	–	–	3.4	3.7
Subtotal (penalties)	0.0	0.0	0.0	3.4	3.7
Priors	104.2	109.2	109.1	104.9	126.3
Total	703.6	846.2	863.0	1117.3	1266.5

A single Monte-Carlo Markov Chain (MCMC) was run on each model, with length $1.5x10^6$ iterations including a burn-in of $0.5x10^6$ iterations for the 2007 basic model and the 2009 model. For the revised models, MCMC chains of length $6x10^6$ iterations including a burn-in of $1x10^6$ iterations were used. Final posterior distributions were derived from systematic sub-sampling ("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 plots indicated reasonable evidence for convergence (Figure 27). In the run in which growth was estimated, three of the four possible growth parameters were estimated (see Bull et al. 2008 for details of the growth model), and the mark-recapture data from Dunn et al. (1998b) were included within the model. The estimation of growth was done by estimating the parameters g_α and g_β (i.e., the mean annual growth increments at reference lengths α and β) and $\sigma_{\min}$, (i.e., the normally distributed variation in growth). Note that the model defines $\sigma = \max(c\mu_i, \sigma_{\min})$, but here we fix c = 0 and hence $\sigma = \sigma_{\min}$.

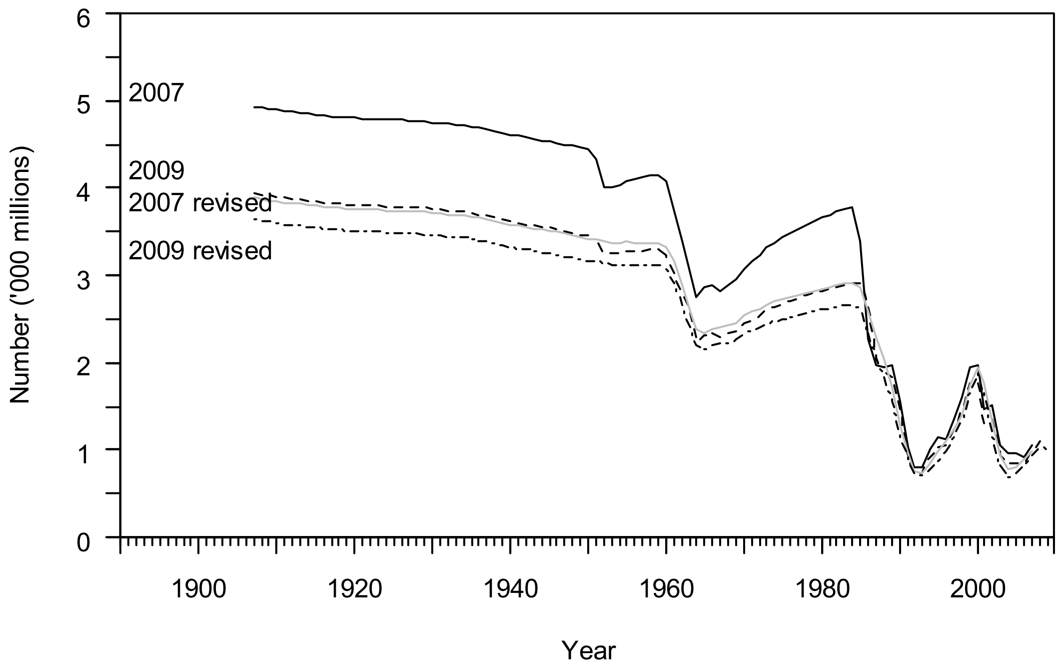

Figure 26: MPD trajectories of SSB for the (a) 2007 basic model, (b) 2009 model, (c) revised 2007 model, and (d) revised 2009 model.

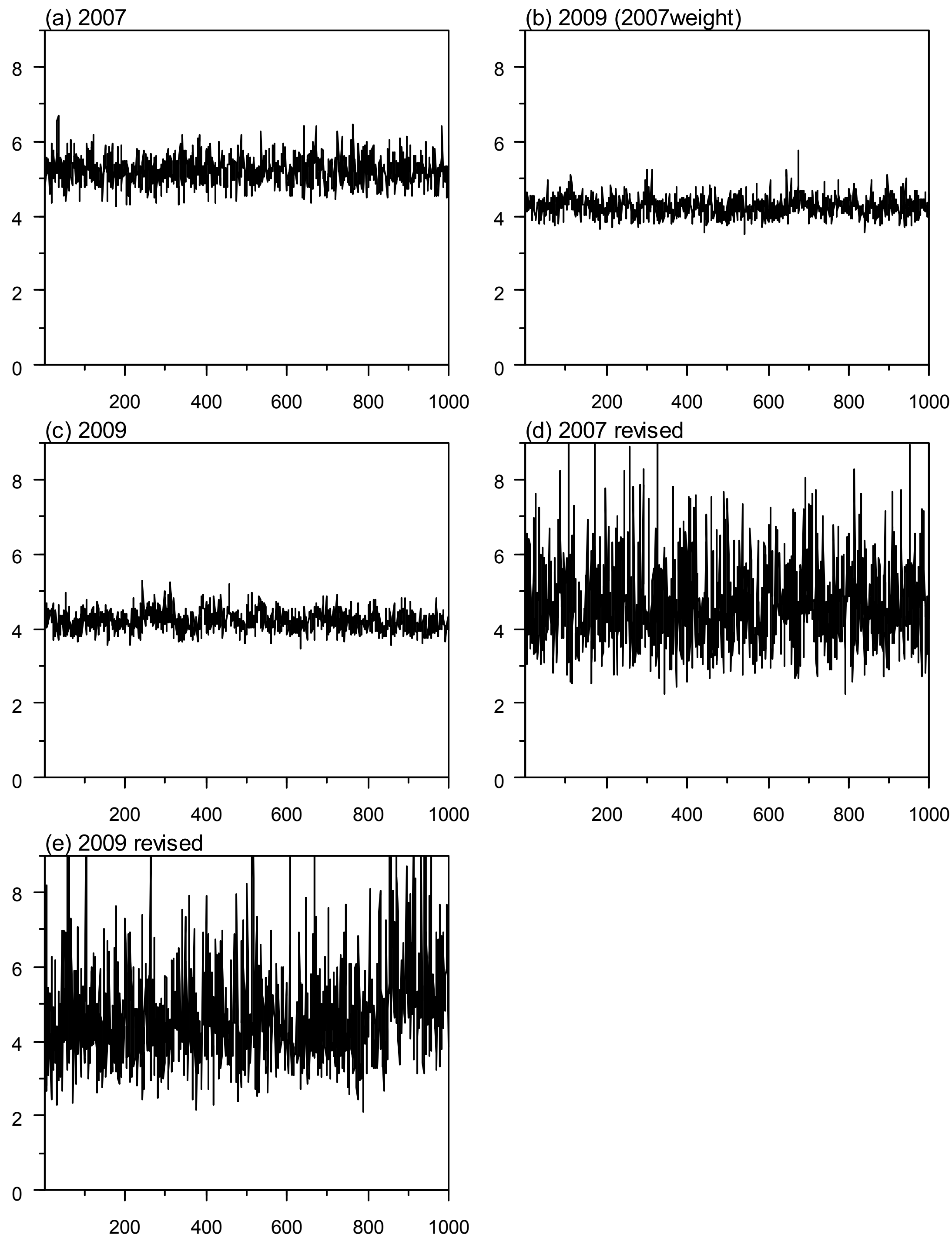

Figure 27: MCMC trace diagnostic plot for the (a) 2007 basic model, (b) 2009 model (2007 weight), (c) 2009 model, (d) revised 2007 model, and (e) revised 2009 model.

4.1 Current status

The 2009 model suggested the virgin equilibrium spawning stock population size to be about 4200 (3720–4800) million oysters, and the current spawning stock size to be 1070 (940–1210) million oysters. The recruit-sized population was estimated as 820 (720–930) million. Model estimates for selected output values are given in Tables 12 and 13.

Figure 28 shows 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). 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 51–55). 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. Estimated CPUE q's showed an increase in relative catchability from series A and B to series C, possibly corresponding to 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 — their q's 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 30–50% of the total abundance available at that time (both of these survey data represent abundance within a smaller survey region than was covered in subsequent surveys). However, posterior distributions for all the catchability constants were relatively narrow.

MPD model fits to abundance indices showed no strong 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. The CPUE increased in 2006 and 2007 as the stock was rebuilding from the last outbreak of *B. exitiosa*, but were still well below the catch rate levels in the early 2000s. However it has been suggested (K. Michael, NIWA, pers. comm.) that there were probably changes in fishing behaviour when fishers have recently been trying to target large oysters in high density patches, which could result in changes in the interpretation of fishing effort and possible bias in the CPUE estimates.

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. Recent recruitment was estimated to be lower than average. However, without other, better, data on historical levels of recruitment, 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., greater than or equal to 58 mm in length) stock abundance.

The revised 2009 model run suggested a similar stock status as the basic model, with slightly higher productivity resulting from a slightly faster growth rate. The relative estimates of B_0 from these model runs suggested much greater 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 36–38). Applying a smoothing penalty to the estimated annual disease mortality rates gave more favourable annual estimates of disease mortality (Figure 39), but had little effect on the key estimated parameters of the model (see Table 13). The fits to the length frequencies of the mark-recapture appeared to be adequate (Figure 40).

Table 12: Bayesian median and 95% credible intervals of B_0 (millions) and SSBs for 2007 and 2009 (millions).

Model	B_0	B_{2007}	B_{2009}
2007 basic model	5 210 (4 510–5 980)	1 090 (940–1 270)	–
2009 (2007 weight)	4 240 (3 790–4 820)	1 020 (880–1 160)	1 070 (940–1 210)
2009 model	4 200 (3 720–4 800)	1 010 (870–1 160)	1 070 (940–1 210)
Revised 2007 model	4 490 (2 830–7 530)	1 080 (660–1 860)	–
Revised 2009 model	4 480 (2 730–7 970)	1 110 (660–2 000)	1 200 (700–2 160)

Table 13: Bayesian median and 95% credible intervals of B_0 (millions), recruit-sized stock abundance rB_{1992}, rB_{2007}, and rB_{2009} (millions).

Model	$B0$	rB_{1992}	rB_{2007}	rB_{2009}
2007 basic model	5 210 (4 510–5 980)	490 (430–580)	730 (620–860)	–
2009 (2007 weight)	4 240 (3 790–4 820)	500 (430–580)	840 (730–960)	820 (720–920)
2009 model	4 200 (3 720–4 800)	510 (440–590)	840 (730–950)	820 (720–930)
Revised 2007 model	4 490 (2 830–7 530)	610 (380–1 040)	830 (510–1 430)	–
Revised 2009 model	4 480 (2 730–7 970)	610 (360–1100)	970 (570–1 760)	990 (570–1 840)

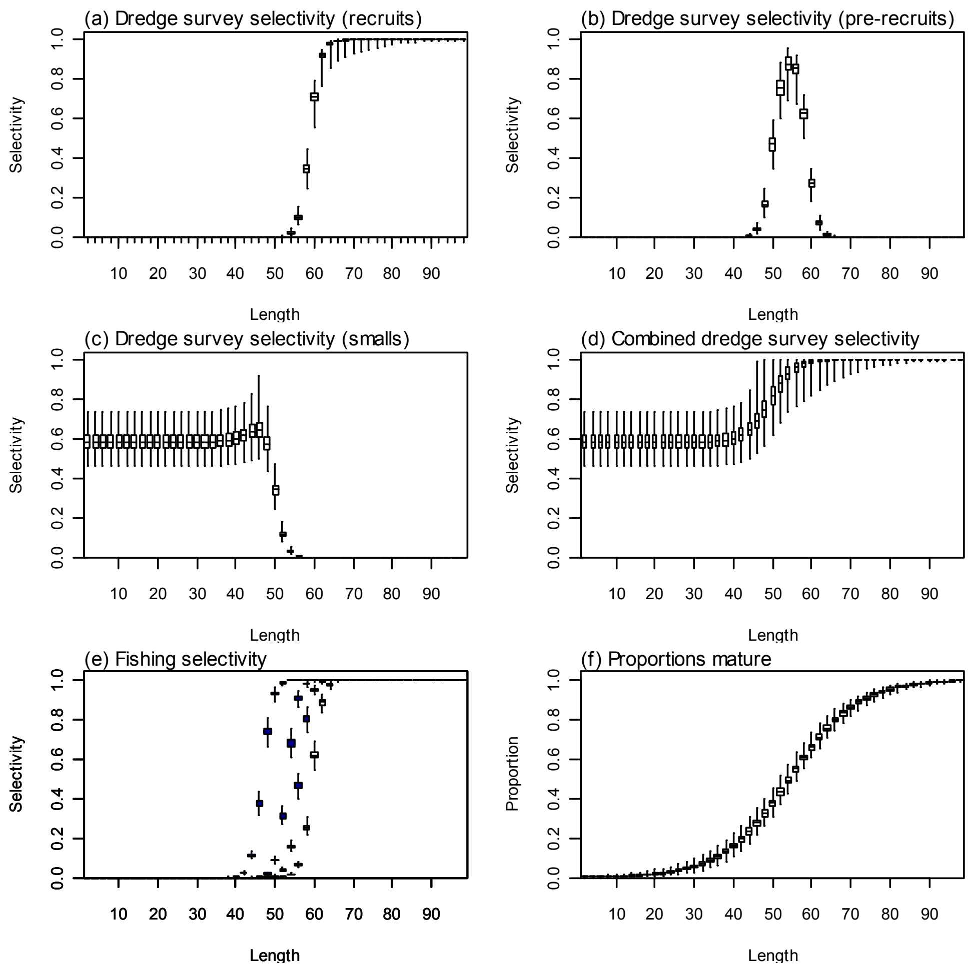

Figure 28: 2009 model estimated posterior distributions of selectivity by length for (a) dredge survey recruits; (b) dredge survey pre-recruits; (c) dredge survey smalls; (d) total recruit, pre-recruit, and small dredge survey selectivities combined; (e) fishing selectivities (greys show shifted selectivities); 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.

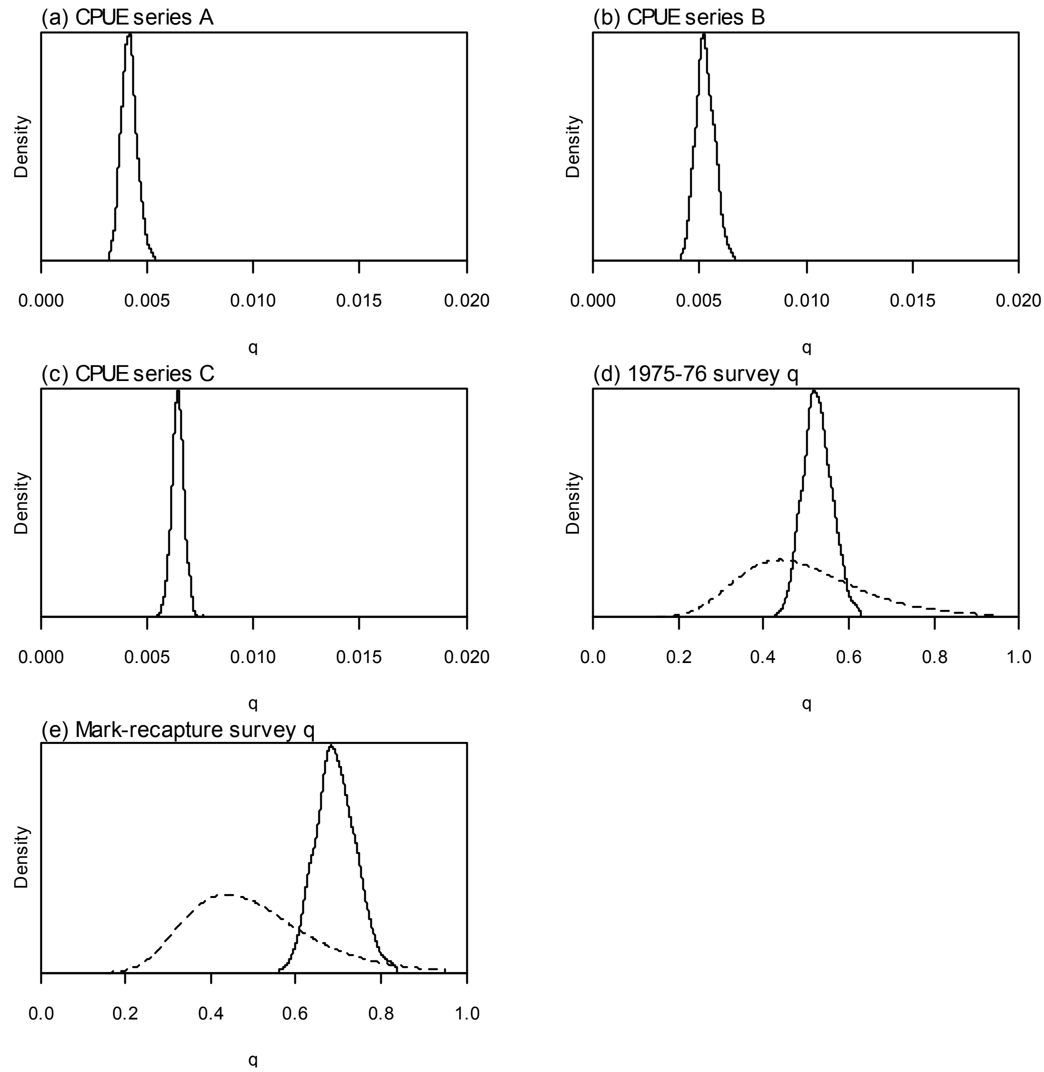

Figure 29: 2009 model estimated posterior distributions (solid lines) and priors (dashed lines) of the (figures a–c) CPUE series A, B, and C (log-uniform priors not shown); (d) 1975–76 survey, and (e) mark-recapture survey relativity constants.

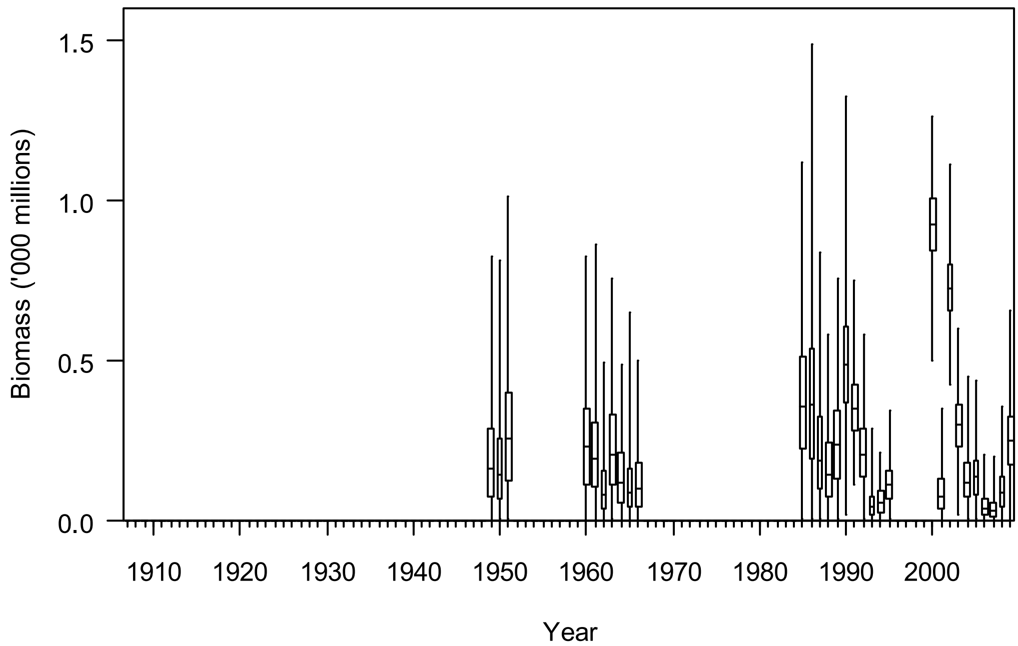

Figure 30: 2009 model estimated posterior distributions of disease mortality (number, '000 millions). Individual distributions show the marginal posterior distribution, with horizontal lines indicating the median.

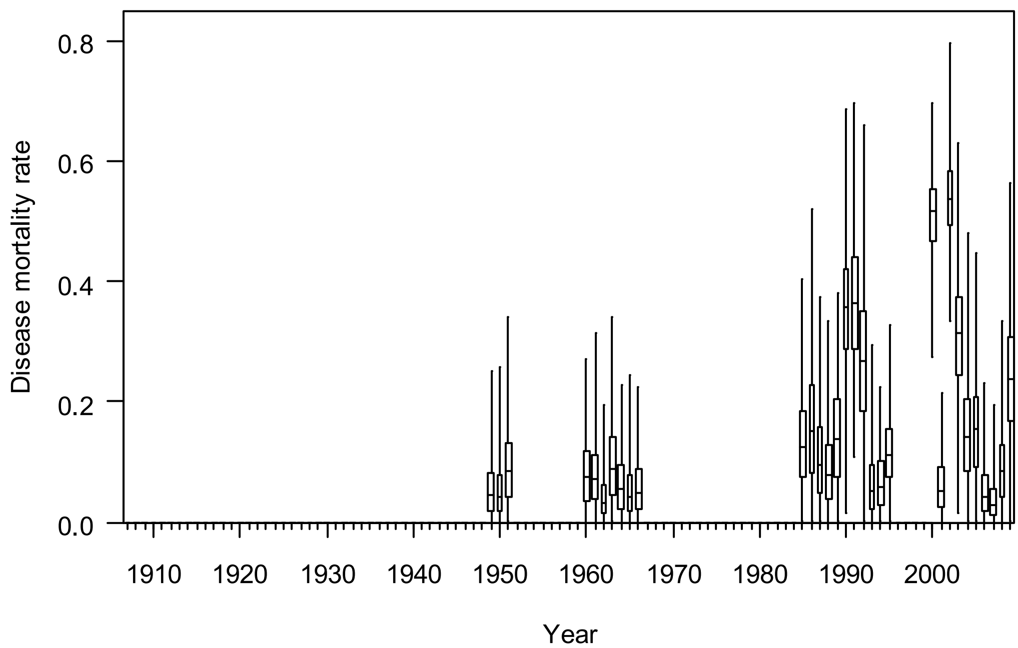

Figure 31: 2007 model estimated posterior distributions of disease mortality rate (y^{-1}). Individual distributions show the marginal posterior distribution, with horizontal lines indicating the median.

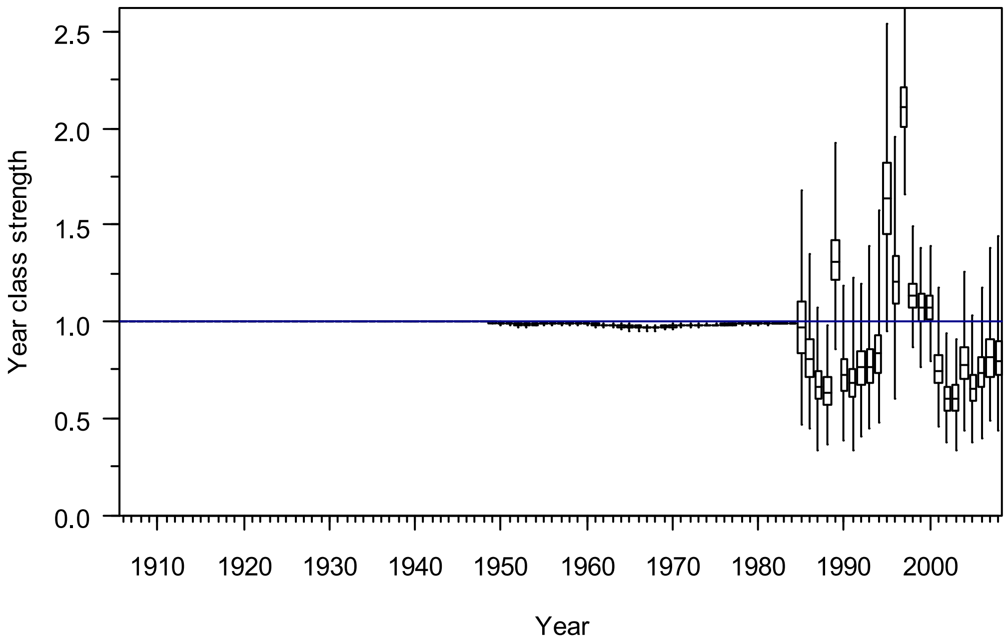

Figure 32: 2009 model estimated posterior distributions of year class strengths. The grey horizontal line indicated the year class strength of one. Individual distributions show the marginal posterior distribution, with horizontal lines indicating the median.

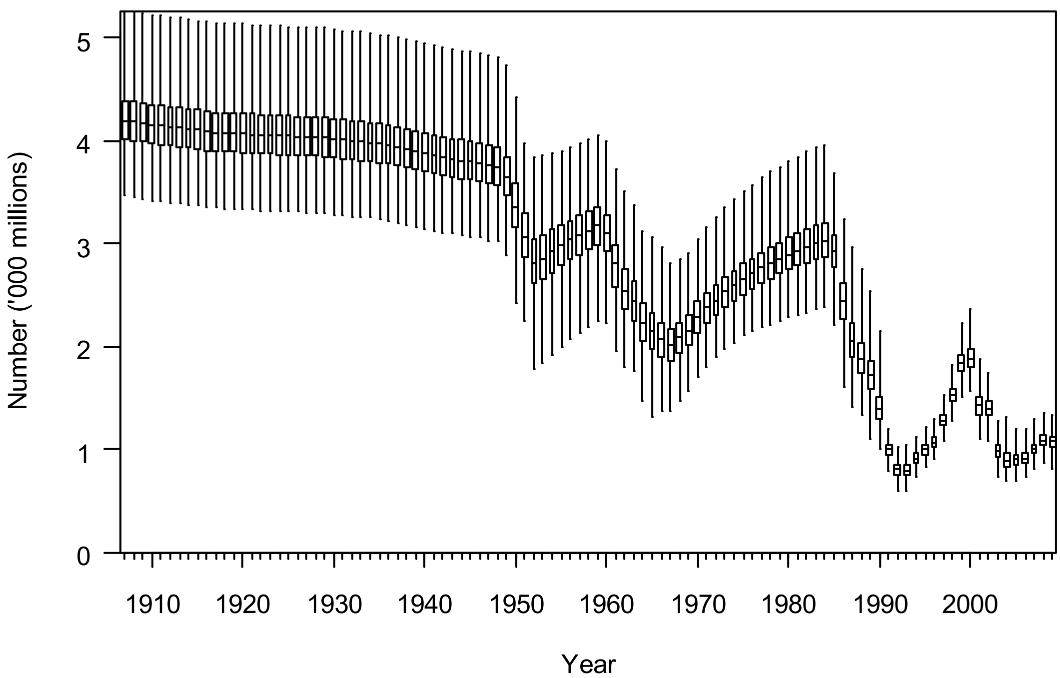

Figure 33: 2009 model estimated posterior distributions of SSBs. Individual distributions show the marginal posterior distribution, with horizontal lines indicating the median.

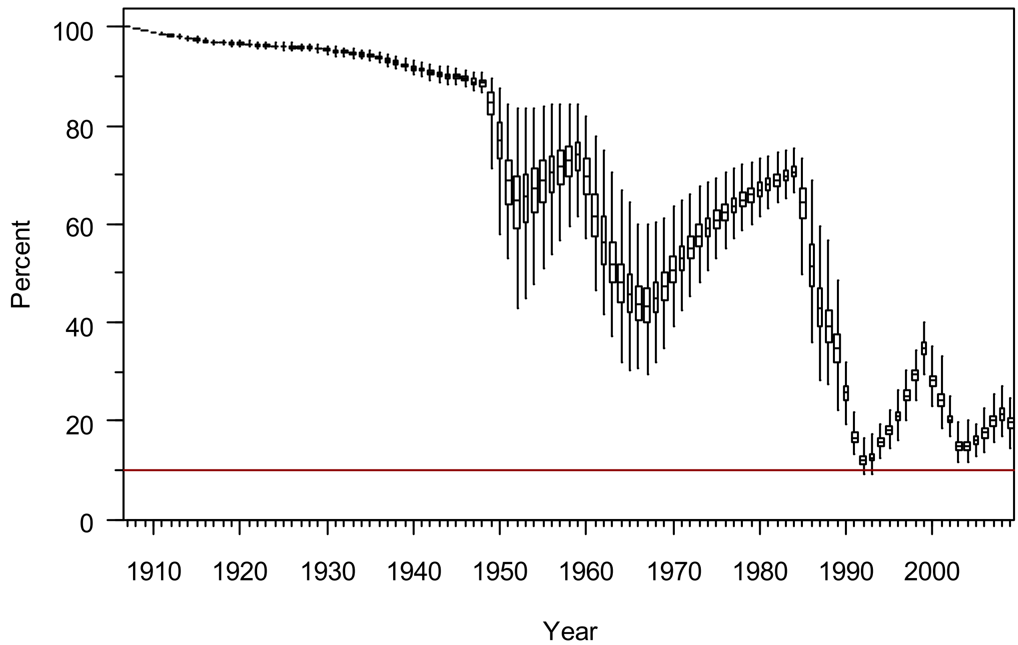

Figure 34: 2009 model estimated posterior distributions of recruit-sized stock abundance. Individual distributions show the marginal posterior distribution, with horizontal lines indicating the median. A solid horizontal line indicates the level equal to 10% of the 1907 stock abundance.

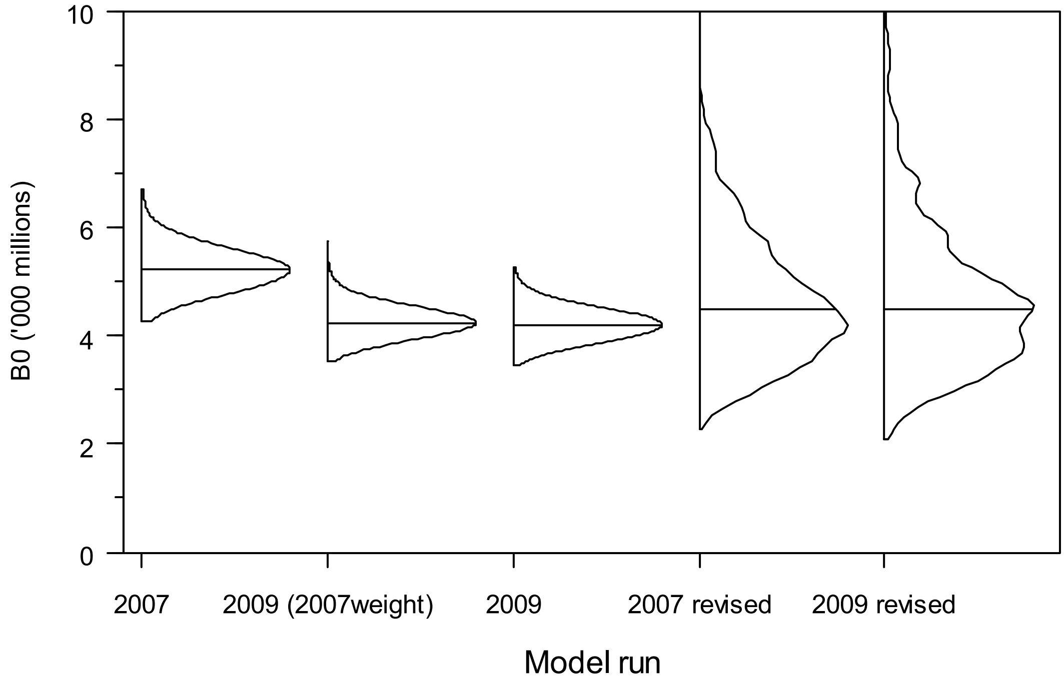

Figure 35: Posterior distributions of B_0 for the 2007 basic model, 2009 model (2007 weight), 2009 model, revised 2007 model, and revised 2009 model.

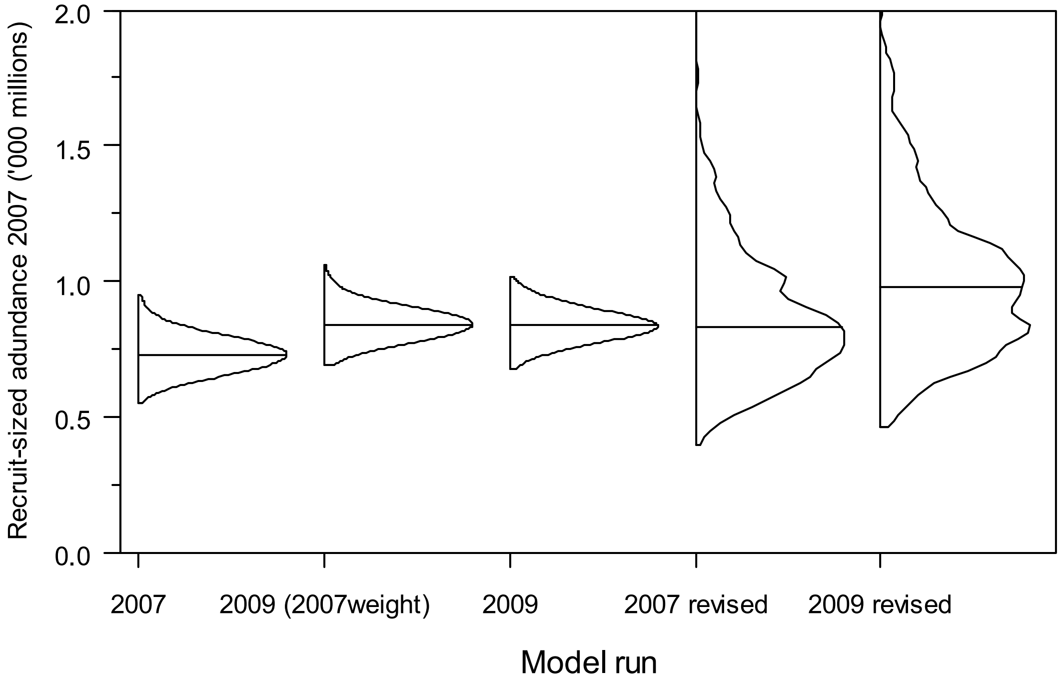

Figure 36: Posterior distributions of recruit-sized abundance (rB_{2005}) for the 2007 basic model, 2009 model (2007 weight), 2009 model, revised 2007 model, and revised 2009 model.

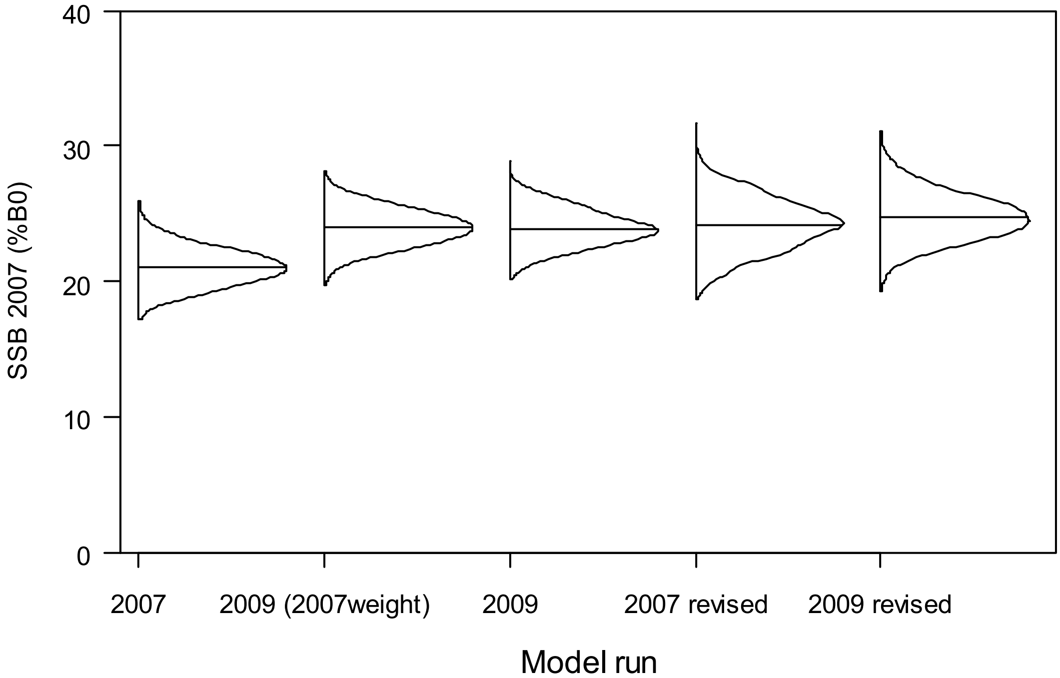

Figure 37: Posterior distributions of SSB_{2007} as a percentage of B_0 (B_{2007}/B_0) for the 2007 basic model, 2009 model (2007 weight), 2009 model, revised 2007 model, and revised 2009 model.

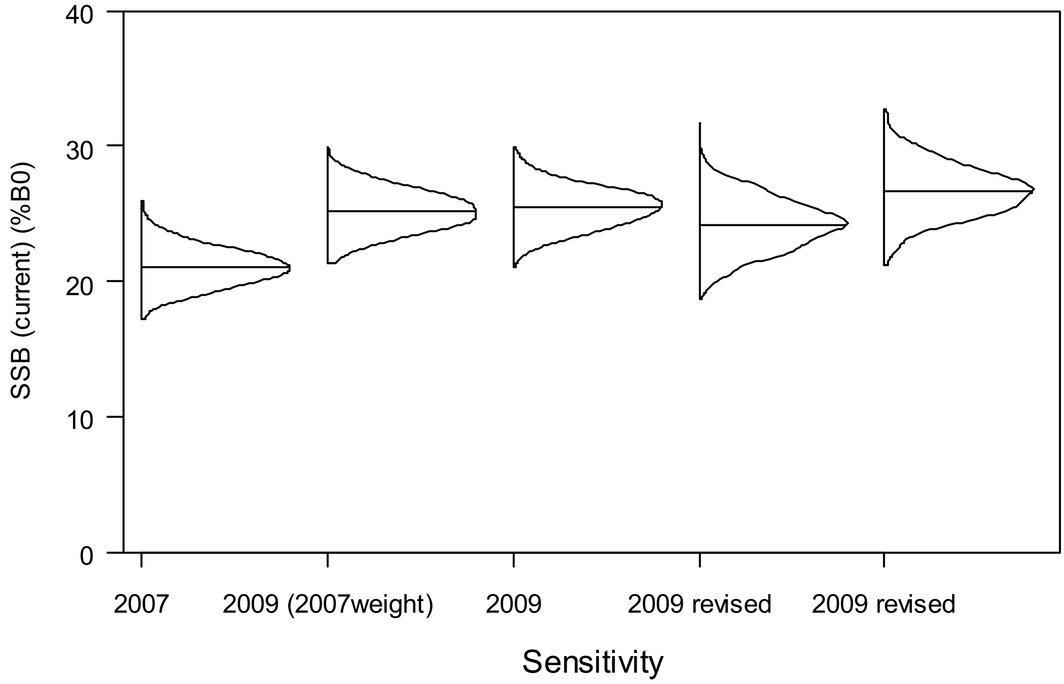

Figure 38: Posterior distributions of $SSB_{current}$ as a percentage of B_0 ($B_{current}/B_0$) for the 2007 basic model, 2009 model (2007 weight), 2009 model, revised 2007 model, and revised 2009 model.

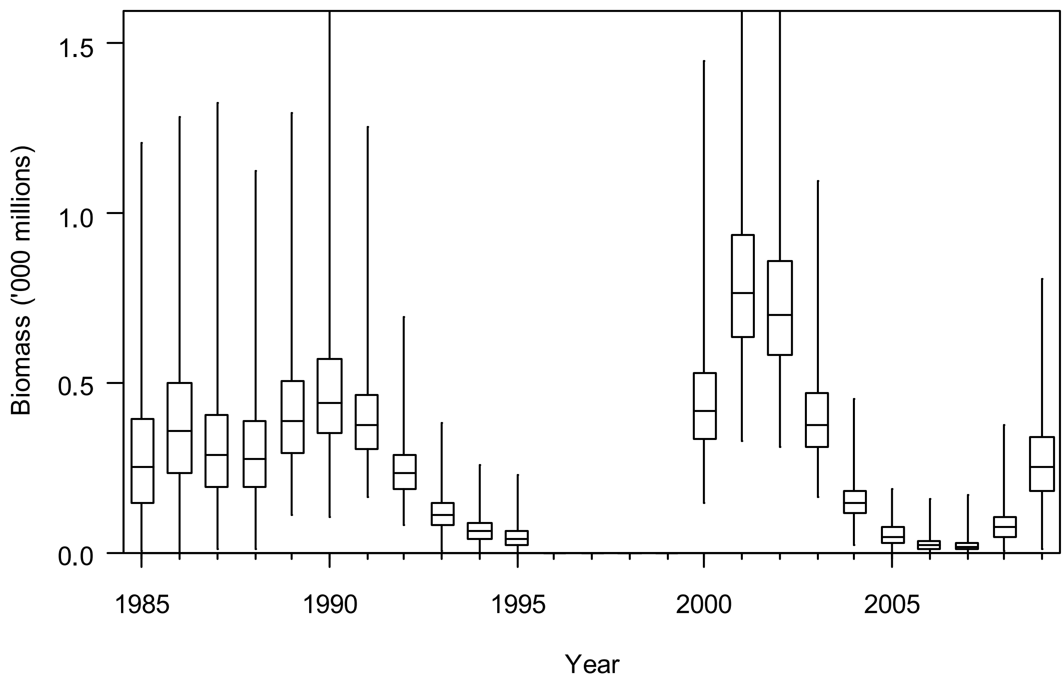

Figure 39: Posterior distributions of the estimated annual disease mortality (1985–2009) for the revised 2009 model.

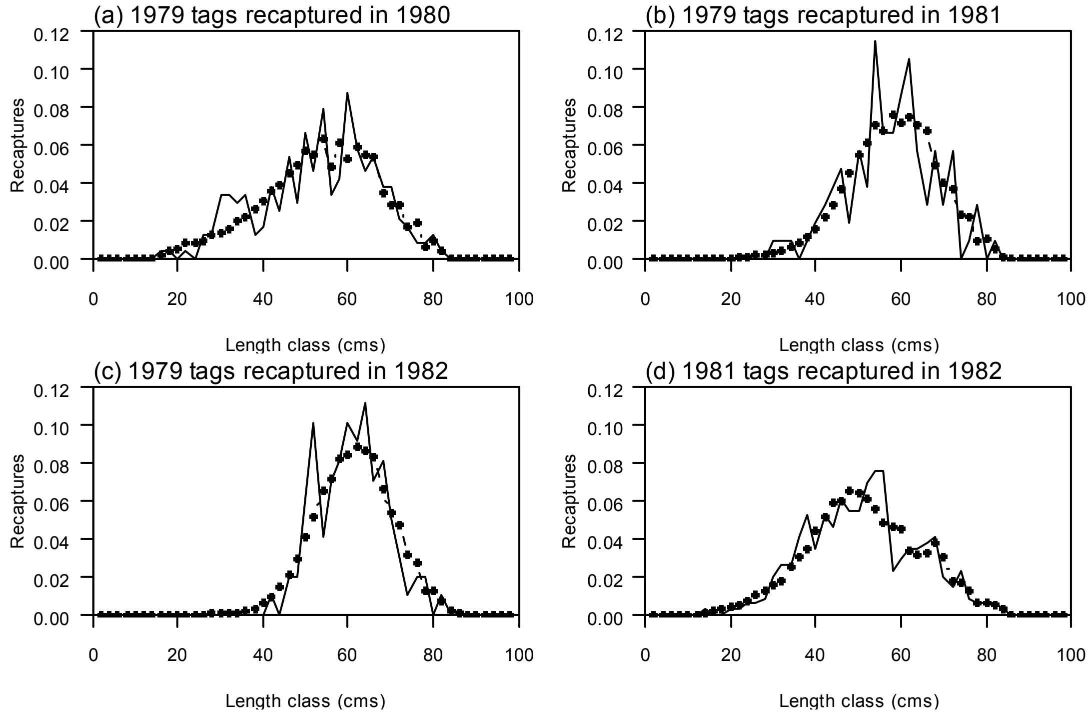

Figure 40: Revised 2009 model MPD estimates of the observed and expected length frequencies of the mark-recapture data for (a–c) 1979 marked fish recaptured in 1980–81, and (d) 1981 marked fish recaptured in 1981.

4.2 Projected stock status

For the 2009 model and the revised 2009 model, 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 2006 (i.e., 0.34 with 95% range 0.29–0.39). Projections were made assuming no future disease mortality and with future disease mortality assumed to be 0.0 y^{-1}, 0.10 y^{-1}, and 0.20 y^{-1}. Two future catch levels were considered each with 7.5 million oysters in 2009, and a future annual commercial catch of either 7.5 or 15 million oysters. Future customary, recreational, and illegal catch were assumed equal to levels assumed for 2009. Projected output quantities are summarised in Tables 14–17. The plots of the median expected recruit sized population are given in Figures 41 and 42.

Under the assumptions of future disease mortality, model projections of commercial catch at either 7.5 or 15 million showed little difference in expected population size. For example, the projected population size in 2012 with a commercial catch of 7.5 million was less than 1% higher than that with a commercial catch of 15 million oysters. Depending on the level of assumed disease mortality, projected status in 2012 ranged from about 34% more than current levels (assuming no disease mortality) to a level about 23% less than the current level (assuming disease mortality of 0.2 y^{-1}) for the 2009 basic model, and from about 29% more than current levels (assuming no disease mortality) to a level about 12% less than the current level (assuming disease mortality of 0.2 y^{-1}) for the revised 2009 basic model.

Table 14: 2009 model median and 95% credible intervals of current spawning stock biomass 2009 (B_{2009}), and projected spawning stock biomass for 2010–12 (B_{2010}–B_{2012}) as a percentage of B_0 with an assumption of a future catch of 7.5 million oysters in 2009 and 7.5 or 15 million oysters in 2010–12, and disease mortality rate of 0.0, 0.1, or 0.2 y^{-1}.

Disease mortality	Catch (millions)	B_{2009} (% B_0)	B_{2010} (% B_0)	B_{2011} (% B_0)	B_{2012} (% B_0)
0.00	7.5	25.9 (22.3–29.6)	25.4 (20.2–31.7)	29.8 (23.9–37.3)	34.4 (27.5–43.1)
	15.0	25.9 (22.3–29.6)	25.4 (20.2–31.7)	29.7 (23.7–37.1)	34.1 (27.3–42.8)
0.10	7.5	25.9 (22.3–29.6)	24.7 (19.6–30.8)	26.1 (20.8–32.7)	27.5 (22.0–34.8)
	15.0	25.9 (22.3–29.6)	24.7 (19.6–30.8)	26.0 (20.7–32.6)	27.2 (21.8–34.6)
0.20	7.5	25.9 (22.3–29.6)	24.0 (19.1–29.9)	22.9 (18.3–28.9)	22.4 (17.7–28.7)
	15.0	25.9 (22.3–29.6)	24.0 (19.1–29.9)	22.8 (18.1–28.8)	22.2 (17.5–28.5)

Table 15: 2009 model median and 95% credible intervals of expected recruit-sized stock abundance for 2009–12 with an assumption of a future catch of 7.5 million oysters in 2009 and 7.5 or 15 million oysters in 2010–12, and disease mortality rate of 0.0, 0.1, or 0.2 y^{-1}.

Disease mortality	Catch (millions)	rB_{2009}/rB_{2009}	rB_{2010}/rB_{2009}	rB_{2011}/rB_{2009}	rB_{2012}/rB_{2009}
0.00	7.5	1.00 (1.00–1.00)	0.99 (0.81–1.16)	1.16 (0.95–1.38)	1.33 (1.09–1.63)
	15.0	1.00 (1.00–1.00)	0.99 (0.81–1.16)	1.15 (0.94–1.38)	1.32 (1.08–1.62)
0.10	7.5	1.00 (1.00–1.00)	0.95 (0.82–1.09)	1.01 (0.86–1.20)	1.07 (0.89–1.33)
	15.0	1.00 (1.00–1.00)	0.95 (0.82–1.09)	1.00 (0.85–1.19)	1.06 (0.88–1.32)
0.20	7.5	1.00 (1.00–1.00)	0.88 (0.76–1.01)	0.82 (0.70–0.98)	0.78 (0.64–0.98)
	15.0	1.00 (1.00–1.00)	0.88 (0.76–1.01)	0.81 (0.69–0.97)	0.77 (0.63–0.97)

Table 16: Revised 2009 model median and 95% credible intervals of current spawning stock biomass 2009 (B_{2009}), and projected spawning stock biomass for 2010–12 (B_{2010}–B_{2012}) as a percentage of B_0 with an assumption of a future catch of 7.5 million oysters in 2009 and 7.5 or 15 million oysters in 2010–12, and disease mortality rate of 0.0, 0.1, or 0.2 y^{-1}.

Disease mortality	Catch (millions)	B_{2009} (% B_0)	B_{2010} (% B_0)	B_{2011} (% B_0)	B_{2012} (% B_0)
0.00	7.5	27.9 (23.2–33.5)	26.8 (31.4–36.0)	31.4 (24.6–42.3)	36.0 (27.9–48.3)
	15.0	27.9 (23.2–33.5)	26.8 (20.8–35.5)	31.3 (24.5–42.2)	35.8 (27.7–48.1)
0.10	7.5	27.9 (23.2–33.5)	26.2 (20.3–34.6)	28.3 (22.0–38.1)	30.1 (23.2–40.7)
	15.0	27.9 (23.2–33.5)	26.2 (20.3–34.6)	28.1 (21.9–38.0)	29.9 (22.9–40.5)
0.20	7.5	27.9 (23.2–33.5)	25.6 (19.8–33.9)	25.5 (19.7–34.5)	25.5 (19.4–34.7)
	15.0	27.9 (23.2–33.5)	25.6 (19.8–33.9)	25.4 (19.6–34.4)	25.4(19.3– 34.5)

Table 17: Revised 2009 model median and 95% credible intervals of expected recruit-sized stock abundance for 2009–12 with an assumption of a future catch of 7.5 million oysters in 2009 and 7.5 or 15 million oysters in 2010–12, and disease mortality rate of 0.0, 0.1, or 0.2 y^{-1}.

Disease mortality	Catch (millions)	rB_{2009}/rB_{2009}	rB_{2010}/rB_{2009}	rB_{2011}/rB_{2009}	rB_{2012}/rB_{2009}
0.00	7.5	1.00 (1.00–1.00)	0.96 (0.83–1.13)	1.13 (0.95–1.37)	1.29 (1.08–1.60)
	15.0	1.00 (1.00–1.00)	0.96 (0.83–1.13)	1.13 (0.95–1.37)	1.29 (1.07–1.59)
0.10	7.5	1.00 (1.00–1.00)	0.96 (0.87–1.08)	1.04 (0.92–1.21)	1.12 (0.96–1.36)
	15.0	1.00 (1.00–1.00)	0.96 (0.87–1.08)	1.03 (0.91–1.21)	1.11 (0.95–1.36)
0.20	7.5	1.00 (1.00–1.00)	0.91 (0.82–1.02)	0.88 (0.78–1.03)	0.88 (0.75–1.08)
	15.0	1.00 (1.00–1.00)	0.91 (0.82–1.02)	0.88 (0.77–1.03)	0.87 (0.74–1.08)

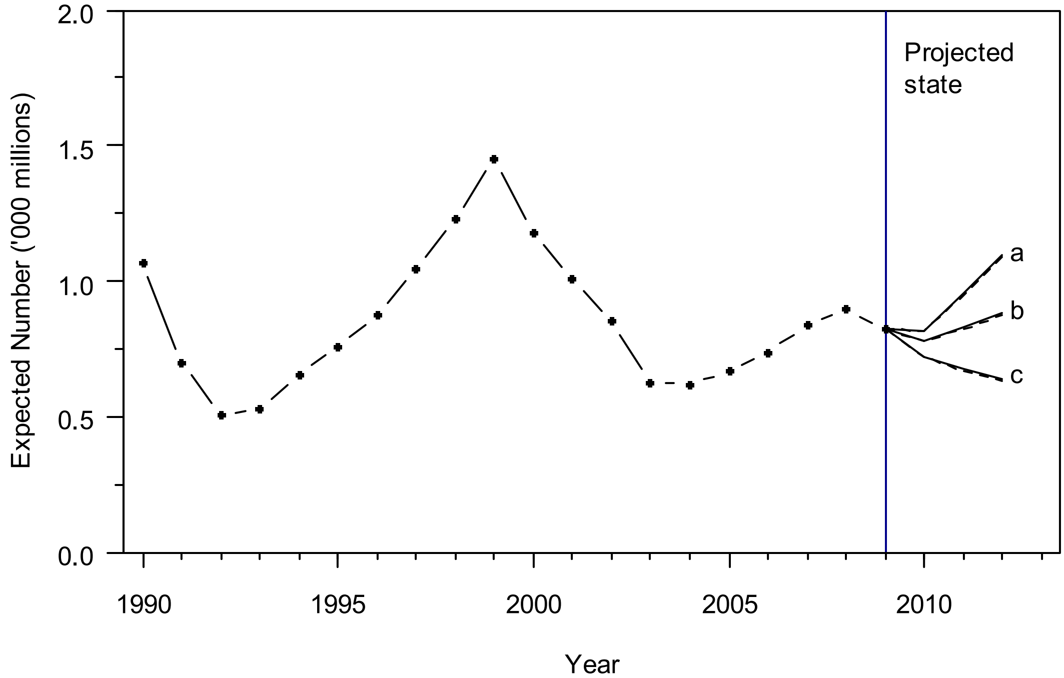

Figure 41: 2009 model estimates of recent recruit-sized stock abundance and projected recruit-sized stock abundance for 2010–12 with catch of 7.5 (black) and 15 million oysters (grey), under assumptions of (a) no disease mortality, (b) disease mortality of 0.10 y^{-1}, and (c) disease mortality of 0.20 y^{-1}.

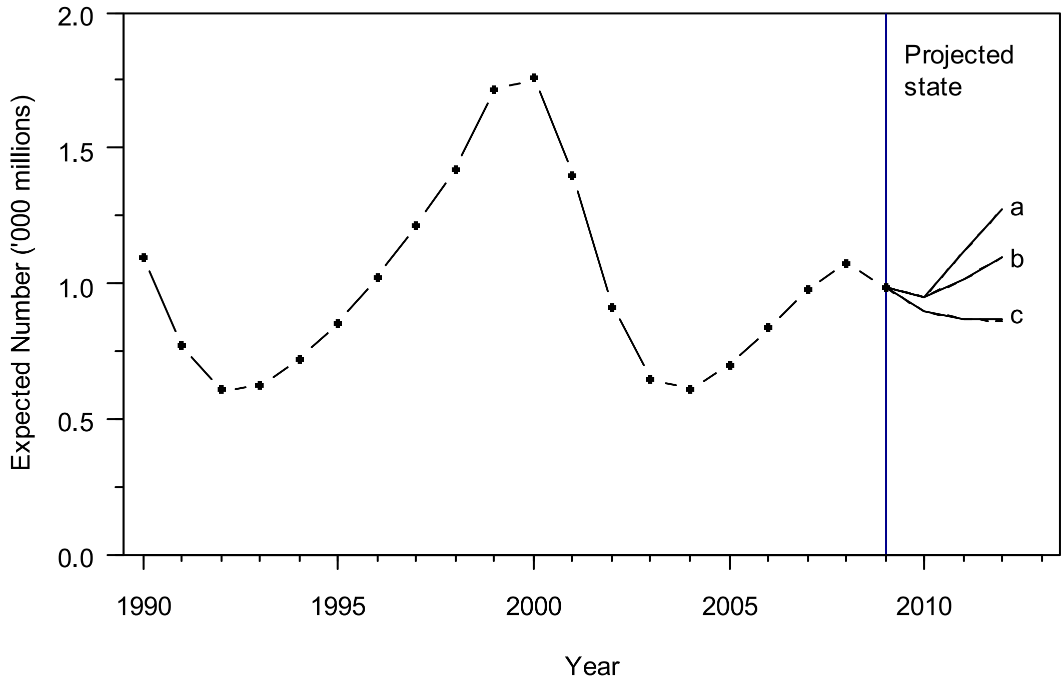

Figure 42: Revised 2009 model estimates of recent recruit-sized stock abundance and projected recruit-sized stock abundance for 2010–12 with catch of 7.5 (black) and 15 million oysters (grey), under assumptions of (a) no disease mortality, (b) disease mortality of 0.10 y^{-1}, and (c) disease mortality of 0.20 y^{-1}.

5. DISCUSSION

Dunn (2005b) concluded that there has been a dramatic reduction in the vulnerable abundance of oysters since the outbreak of the recent *B. exitiosa* epizootic, but fishing exploitation rates had been low. The 2007 assessment suggested reduced levels of *B. exitiosa* mortality in recent years, and the current spawning stock size was 20% (18–23%) B_0 and recruit-sized stock abundance (rB_{2007}) was about 14% (12–17%) of initial state (rB_{1907}). That assessment also stated that there was considerable uncertainty about the possible level of future recruitment and *B. exitiosa* related mortality, with the future stock status depending primarily on the level of future disease mortality.

The updated model estimates presented here suggest a similar state, with *B. exitiosa* mortality remaining low and the stock appearing to rebuild in recent years. Model estimates of spawning stock population in 2009 were about 25% (23–28%) B_0, and recruit-sized stock abundance (rB_{2009}) was about 20% (17–23%) 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 between 7.5 and 15 million oysters are unlikely to have any significant impact on future stock levels. Instead, future disease mortality will determine future stock status. Depending on the level of assumed disease mortality, projected status in 2012 ranged from about 34% more than current levels (assuming no disease mortality) to a level about 23% less than the current level (assuming disease mortality of 0.2 y^{-1}).

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 on 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.

As with earlier models, the models presented here, while fairly representing some of the data (e.g., the biomass indices), also show some signs of poor fit. It is unlikely 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 in predicting absolute outcomes.

The rate of natural mortality is also unknown, and possibly may vary with age, size, and between years. Previous attempts (Dunn 2005a) to estimate natural mortality failed to produce reasonable estimates of M (typically in the range 0.25–0.35 y^{-1}), possibly because of confounding with mortality from *B. exitiosa*. Simulation experiments also suggested estimates of M were likely to be biased (Dunn 2005b).

Estimates of disease mortality appeared reasonable, but the yearly variation, in particular in 1987, suggested further investigation is required. The estimate of the disease rate in 2009 is likely to be a model artefact, though evidence from the fishery suggests a recent increase in *B. exitiosa* mortality. 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). The estimates of mortality, assuming that all clocks observed in a single survey represent the total (natural plus disease) mortality over the preceding year are shown in Figure 42. Also shown are the estimates of total (natural plus disease) annual mortality estimated within the model. This suggests that the disease effects estimated between 1985 and 2009 were of a similar order of magnitude to those suggested by the counts of clocks — although the model allocated most of the disease mortality at the start of the epidemics. 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/or inclusion of clock data within the model may provide better estimates. Smoothed estimates of disease mortality suggested more plausible annual disease rates, and the revised 2009 model run suggested that the use of a smoothing penalty had little effect on the output parameters.

The selectivity and epidemiology of *B. exitiosa* is not well understood, and few data have been collected on the size and maturity status of oysters (particularly pre-recruit and small sized oysters) that have been infected with or have died from *B. exitiosa*. However, using the new data on *B. exitiosa* infection of oysters from the histological sampling from the January 2004 surveys suggested that the pattern of disease infection was very similar to that assumed for maturity. This remains consistent with the current hypothesis of the disease epidemiology (see Hine 1991a, 1991b, 1992, 1996, Hine & Wesney 1992, 1994a, 1994b).

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 high or nil future disease mortality, ranged between 80% and 130% of current levels.

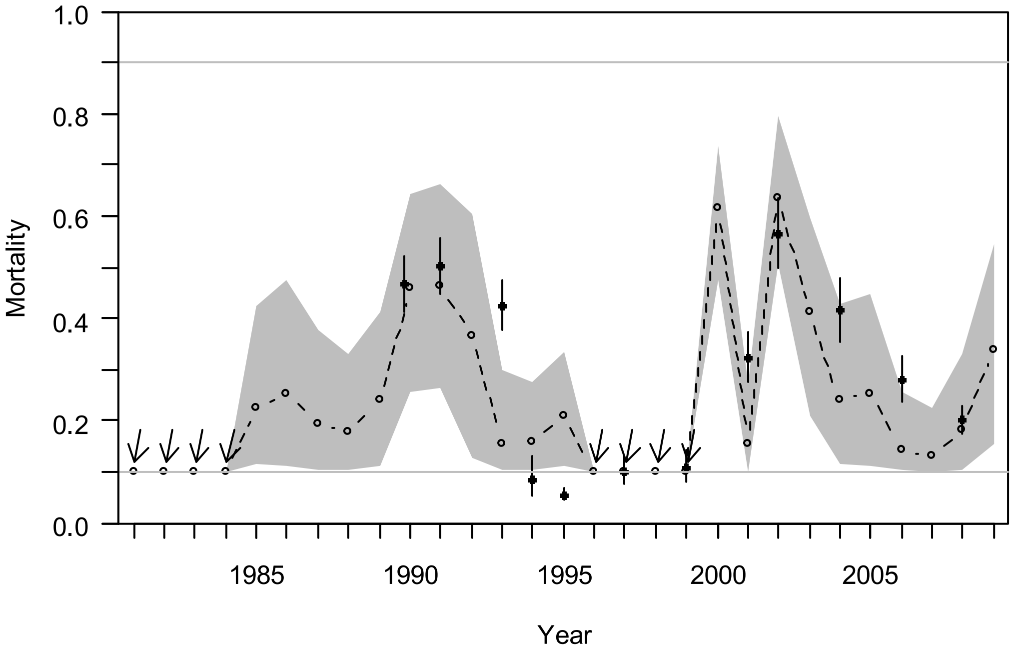

Figure 42: Estimated median MCMC mortality (natural plus disease) rate (dashed line with open circles) and 95% credible intervals (shaded region) for the 2009 model, and estimated mortality (and 95% confidence intervals) from the ratio of new and old clocks from survey sampling (closed circles). Arrows indicate values that were constrained within the model.

6. ACKNOWLEDGMENTS

We thank the many NIWA staff who were involved in the collection of oyster data. Keith Michael provided helpful advice on aspects of the oyster fishery. The project was funded by the Ministry of Fisheries under project code OYS2008/01.

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APPENDIX A: SUMMARY MPD MODEL FITS

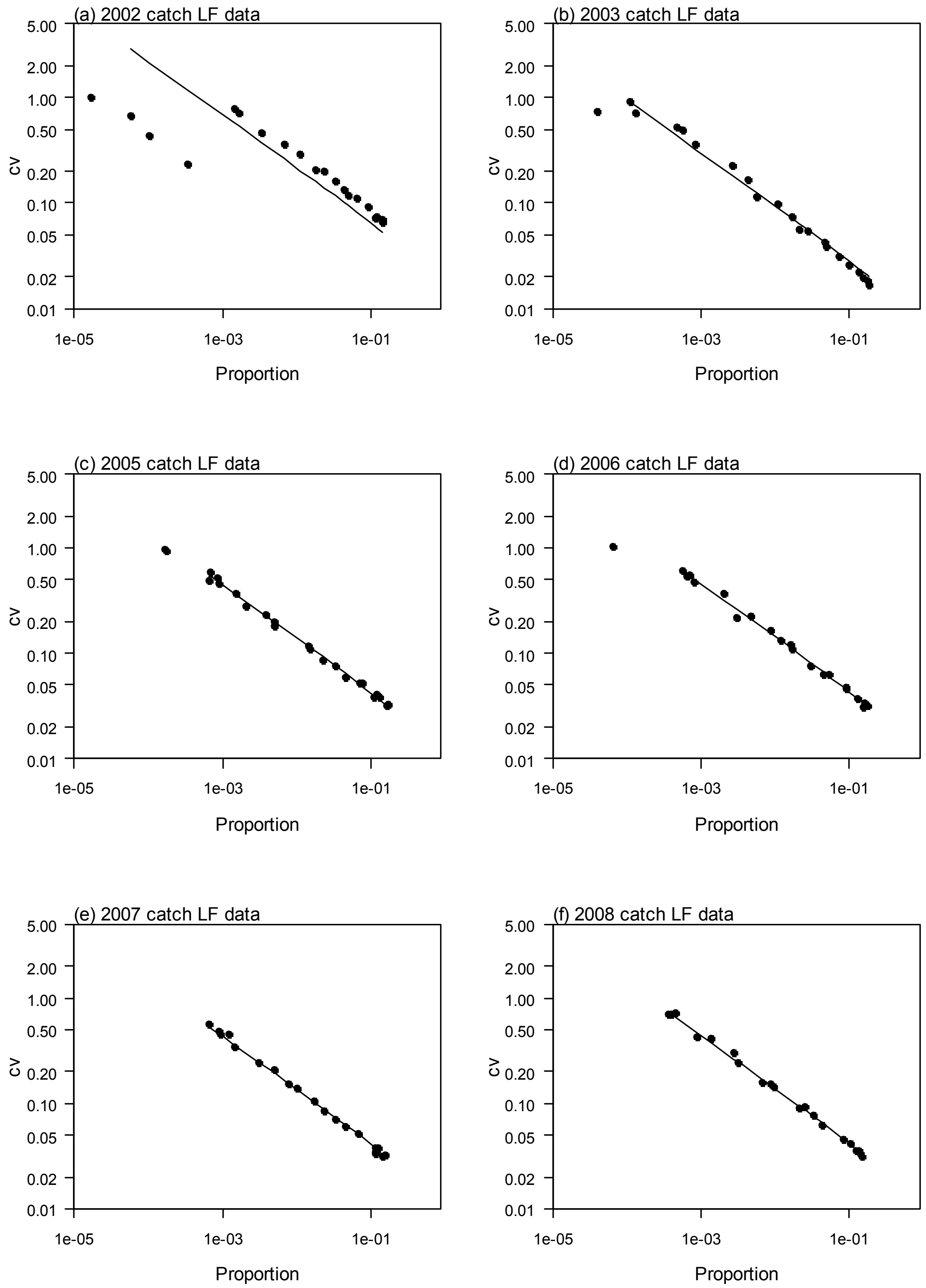

Figure 43: Estimated proportions versus c.v.s for the commercial catch length frequencies for (a) 2002 (b) 2003, (c) 2005, (d) 2006, (e)2007, and (f) 2008. Lines indicate the best least squares fit for the effective sample size of the multinomial distribution.

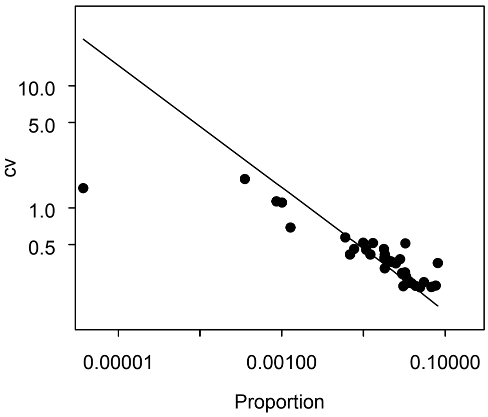

Figure 44: Estimated proportions versus c.v.s for the October 1990 dive survey length frequencies. Lines indicate the best least squares fit for the effective sample size of the multinomial distribution.

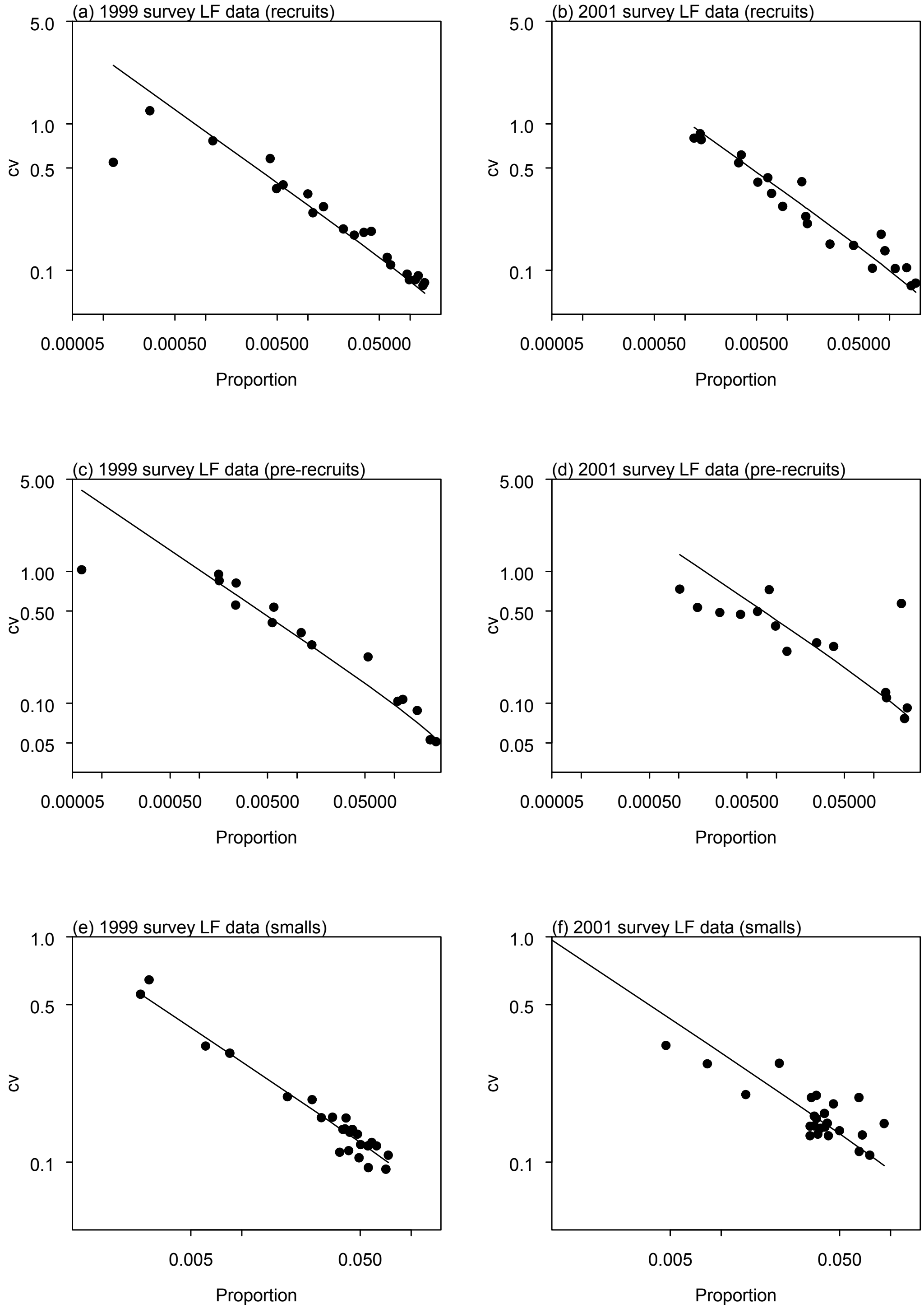

Figure 45: Estimated proportions versus c.v.s for the 1999 and 2001 October survey length frequencies for (a–b) recruits, (c–d) pre-recruits, and (e–f) smalls. Lines indicate the best least squares fit for the effective sample size of the multinomial distribution.

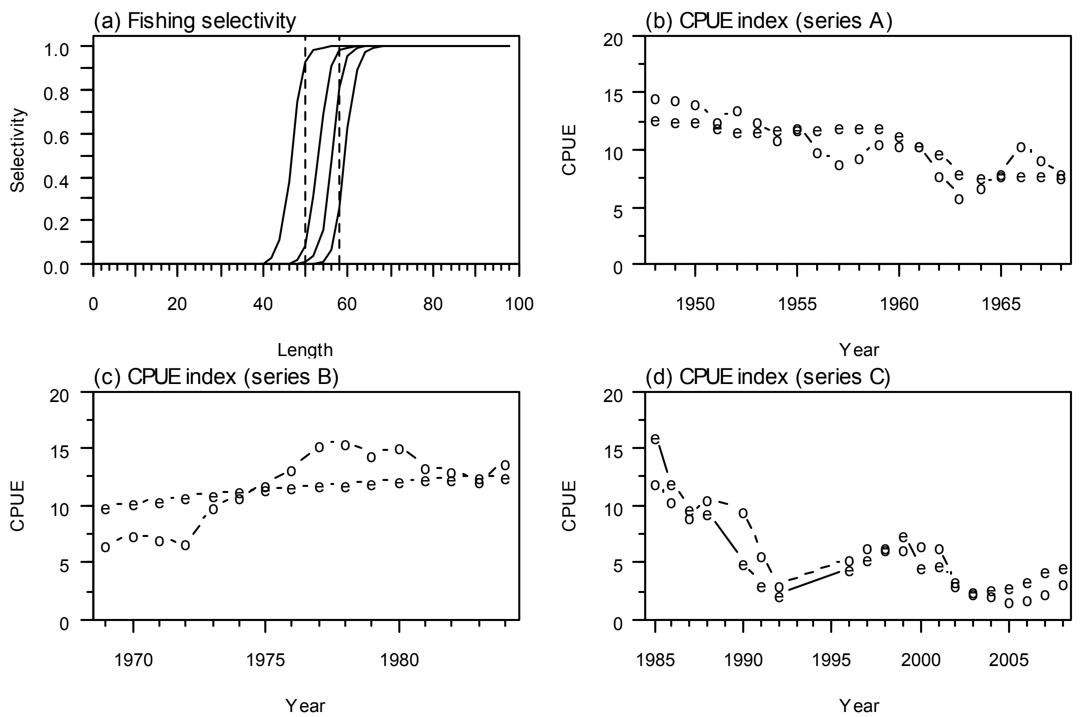

Figure 46: 2009 model MPD estimates of (a) fishing selectivity and model fits to (b) series A, (c) series B, and (d) series C CPUE indices ("e"=expected and "o"=observed). Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

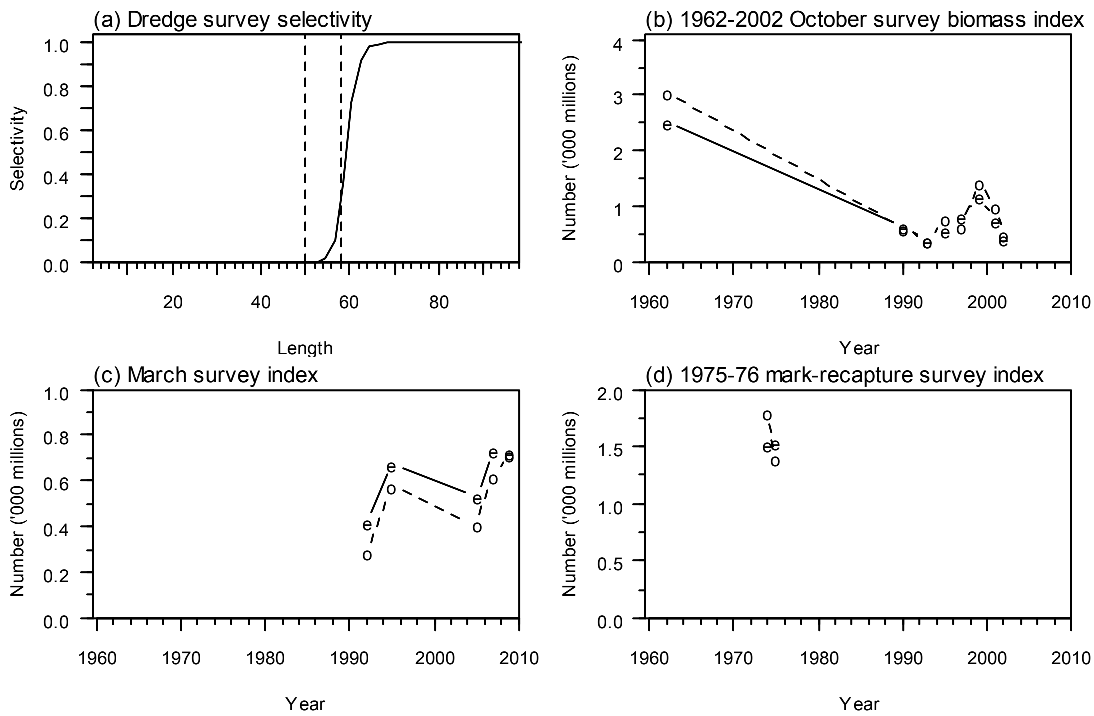

Figure 47: 2009 model MPD estimates of (a) recruit-sized dredge survey selectivity and model fits to recruit-sized abundance indices for the (b) October surveys 1964–2002, (c) March surveys 1992–2009, and (d) 1975–76 mark-recapture survey ("e"=expected and "o"=observed). Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

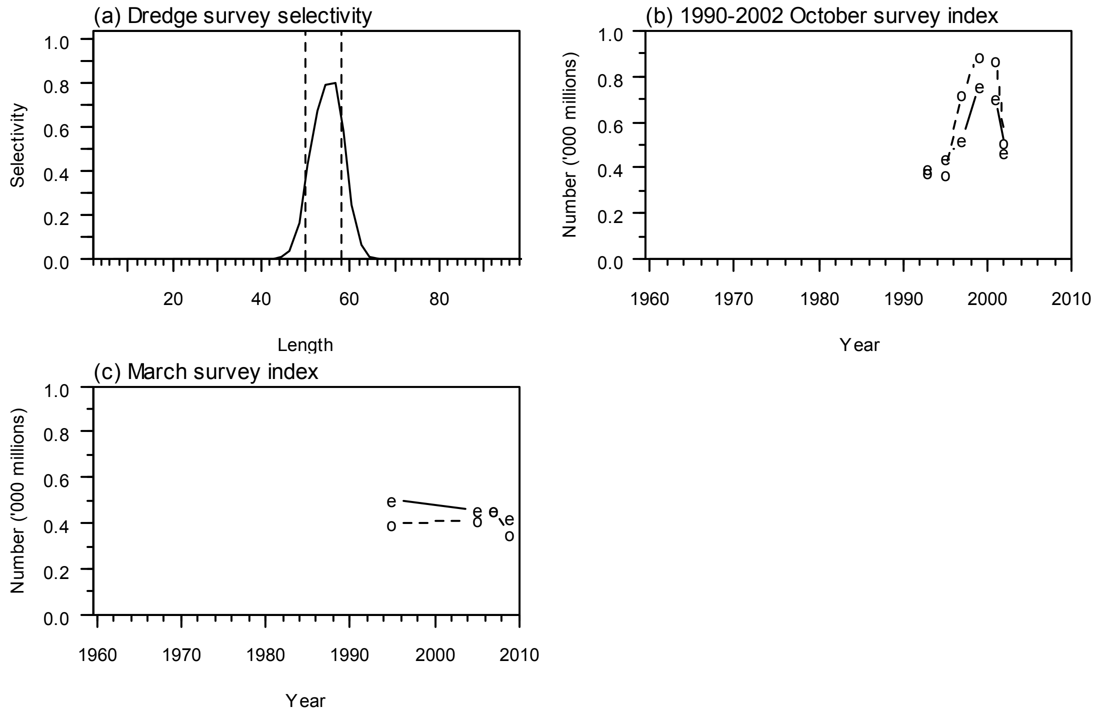

Figure 48: 2009 model MPD estimates of the (a) pre-recruit-sized dredge survey selectivity and model fits to pre-recruit-sized abundance indices for the (b) October surveys 1990–2002, and (c) March surveys 1995–2009 ("e"=expected and "o"=observed). Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

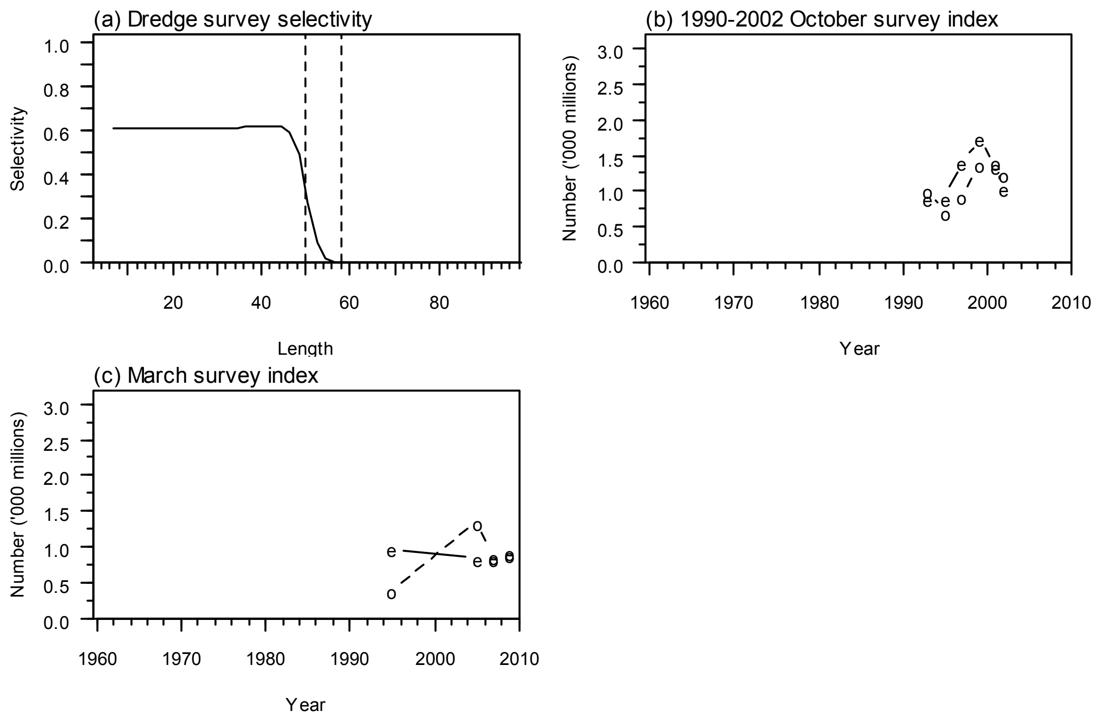

Figure 49: 2009 model MPD estimates of small-sized dredge survey selectivity and model fits to small-sized abundance indices for the (b) October surveys 1990–2002, and (c) March surveys 1995–2009 ("e"=expected and "o"=observed). Dashed lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

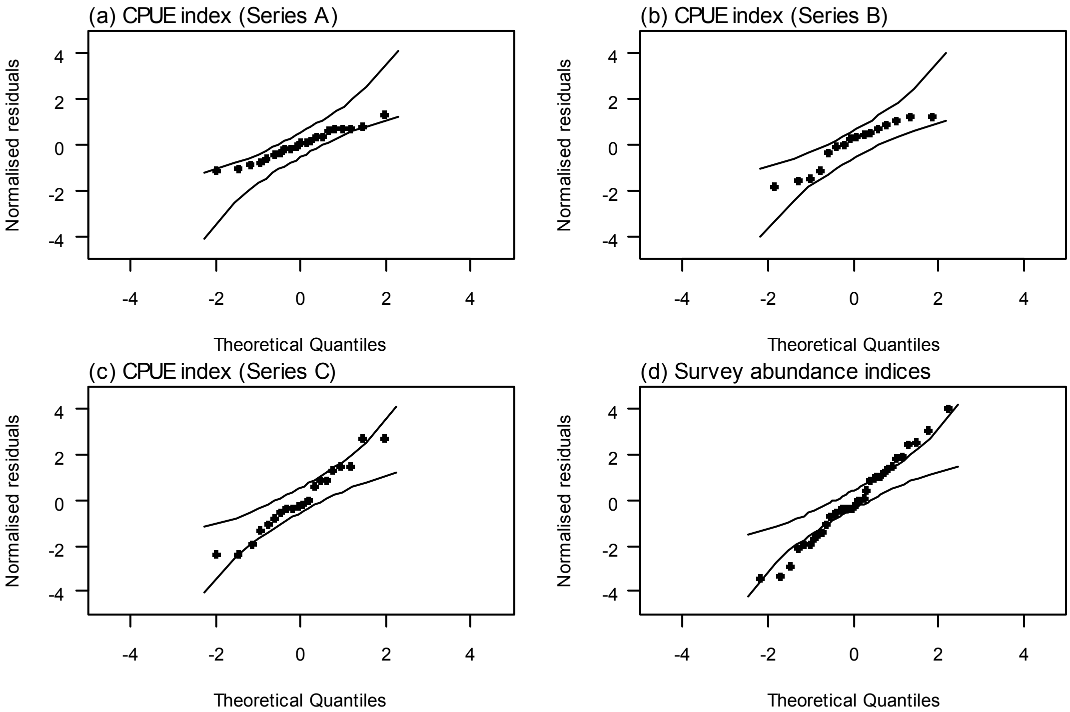

Figure 50: 2009 model MPD estimates of fits (normal quantile-quantile plots) to the (a) series A, (b) series B, (c) series C CPUE indices, and (d) 1964–2007 survey abundance indices combined. Curved lines show 95% confidence envelopes for a true normal distribution.

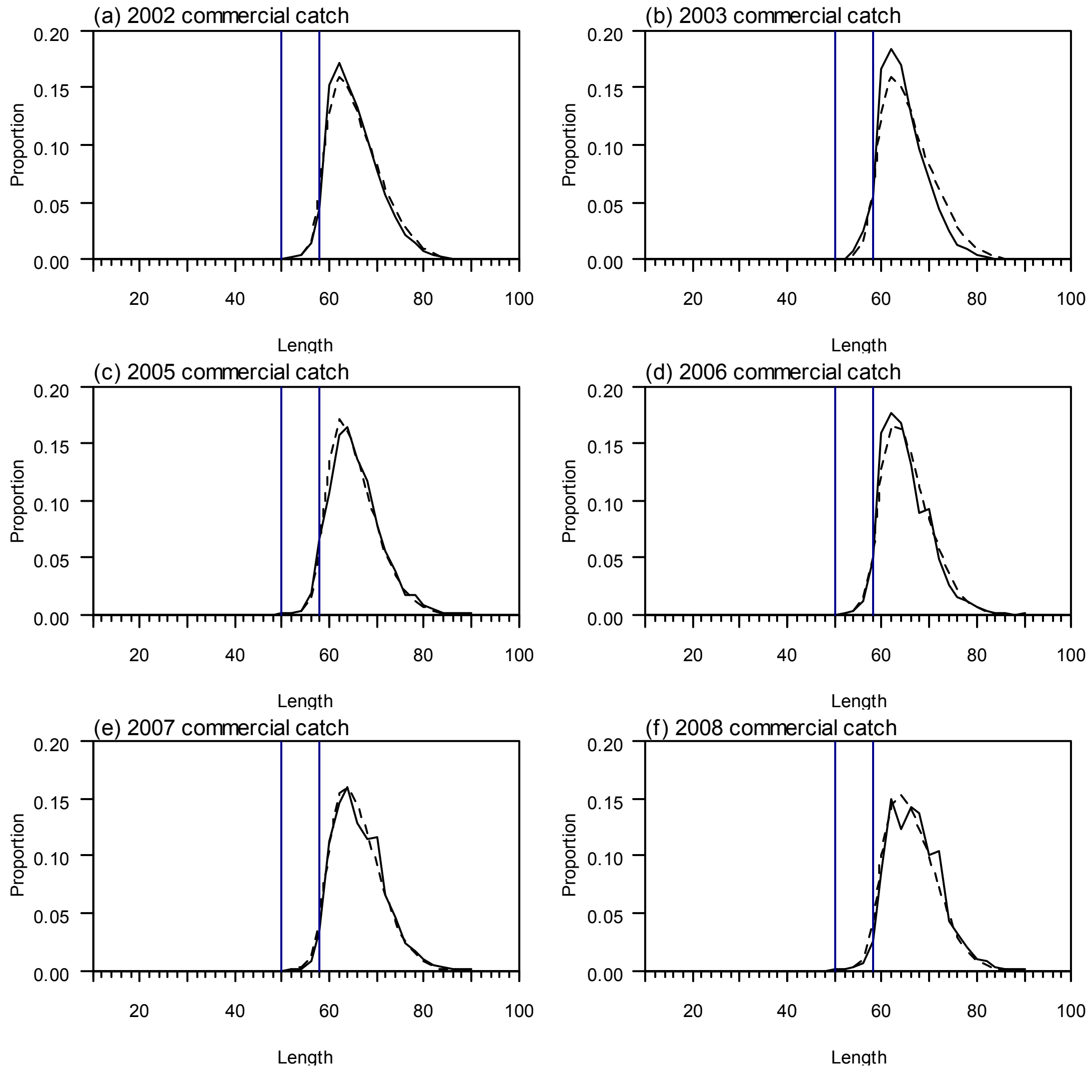

Figure 51: 2009 model MPD estimates of fits to the (a) 2002, (b) 2003, (c) 2005, (d) 2006 , (e) 2007, and (f) 2009 commercial catch length frequencies. Vertical lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

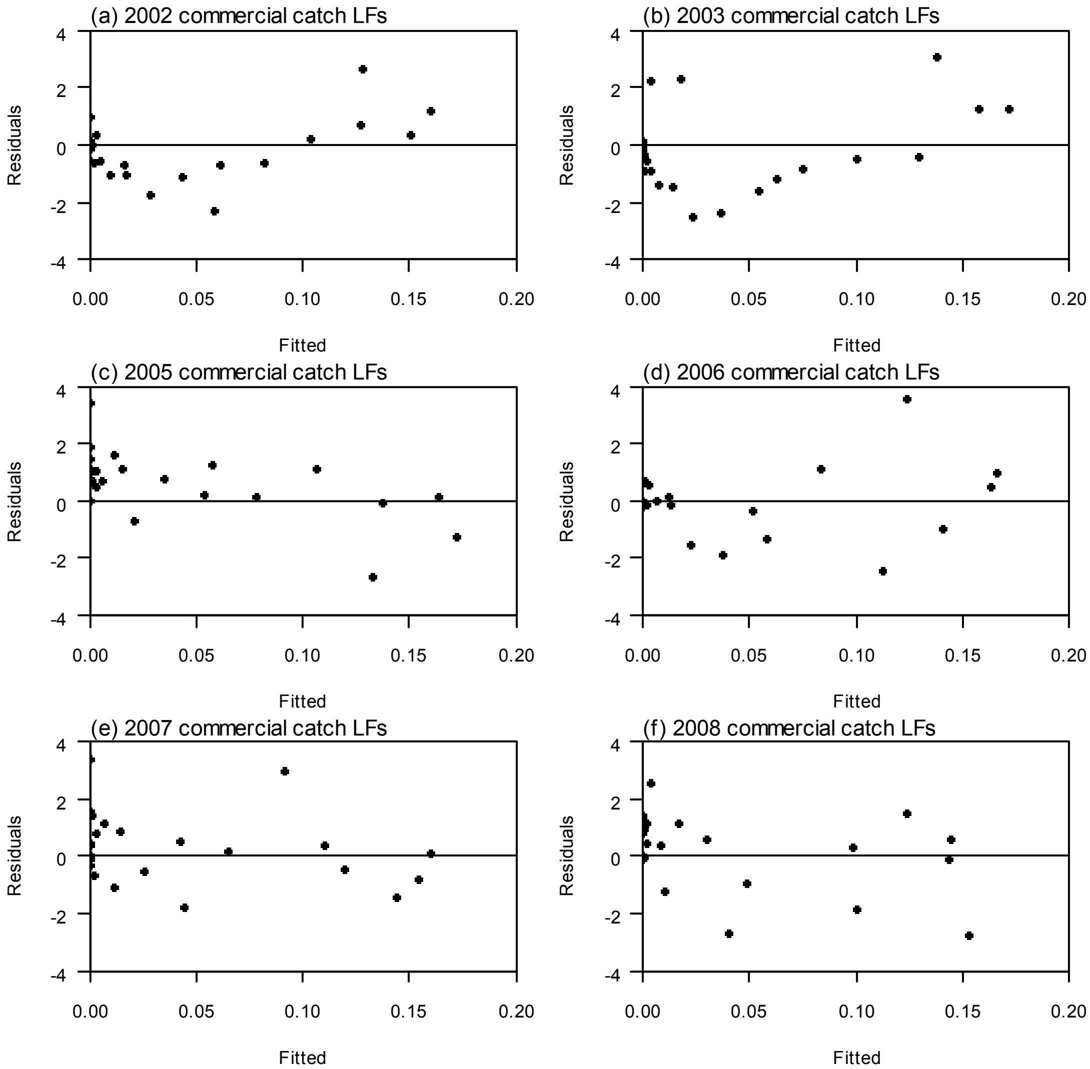

Figure 52: 2009 model MPD estimates of residuals versus fitted values for the (a) 2002, (b) 2003, (c) 2005, (d) 2006 , (e) 2007, and (f) 2009 commercial catch data

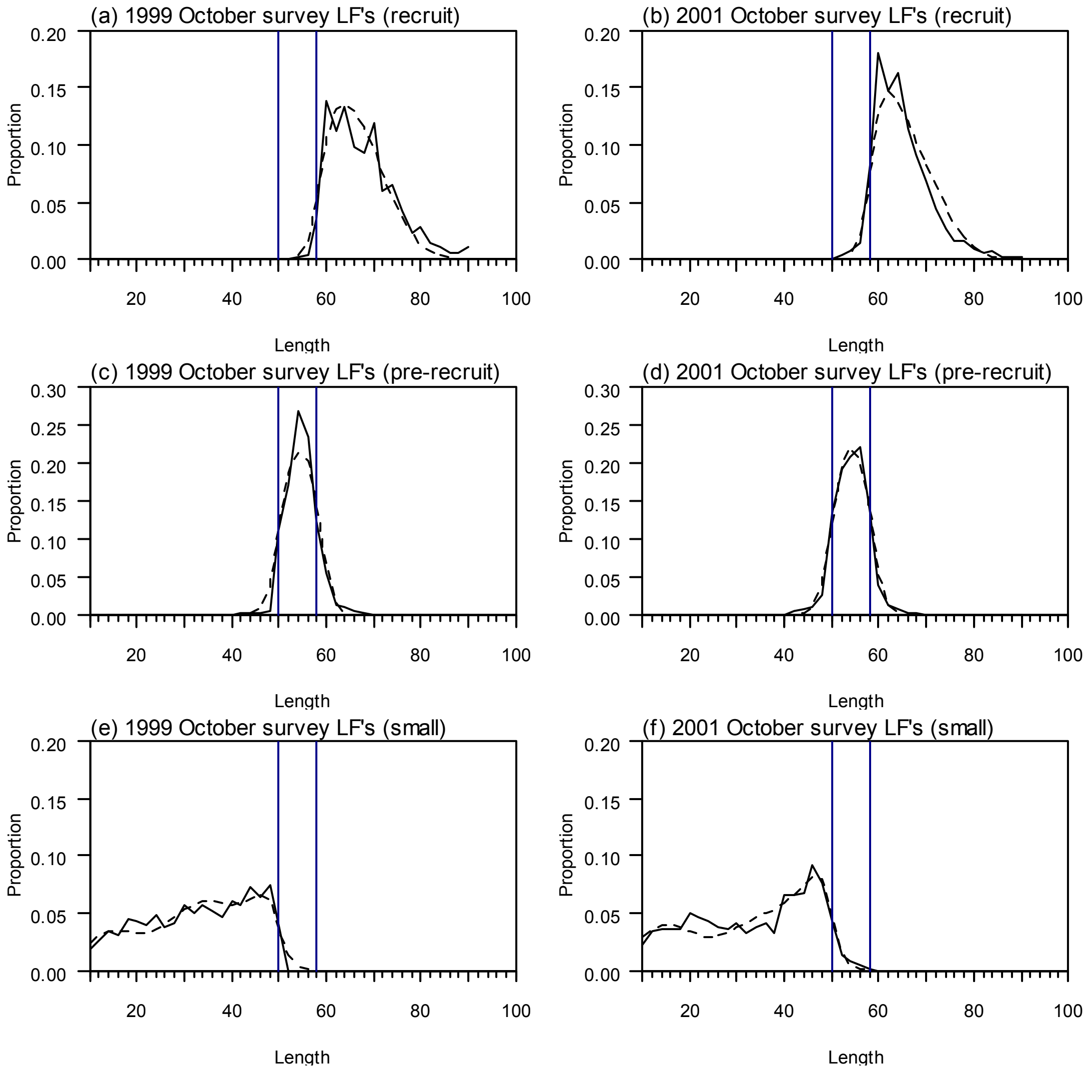

Figure 53: 2009 model MPD estimates of fits to the survey data length frequencies for (a–b) recruit-sized, (c–d) pre-recruit size, and (e–f) smalls from the 1999 and 2001 abundance surveys respectively. Vertical lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

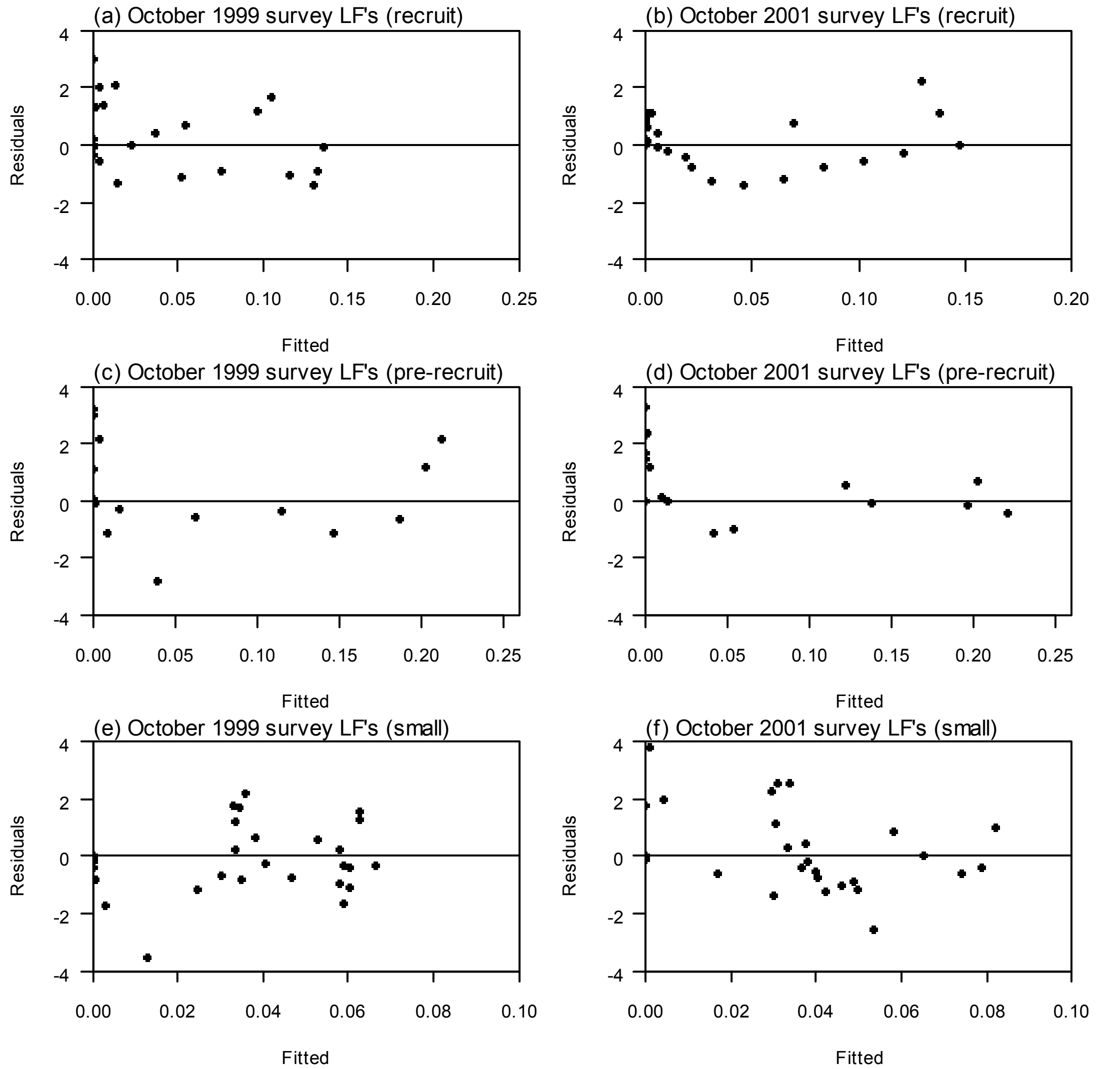

Figure 54: 2007 model MPD estimates of residuals versus fitted values for the survey data length frequencies for (a–b) recruit-sized, (c–d) pre-recruit size, and (e–f) smalls from the 1999 and 2001 abundance surveys respectively (curved lines show 95% confidence intervals for the multinomial distribution).

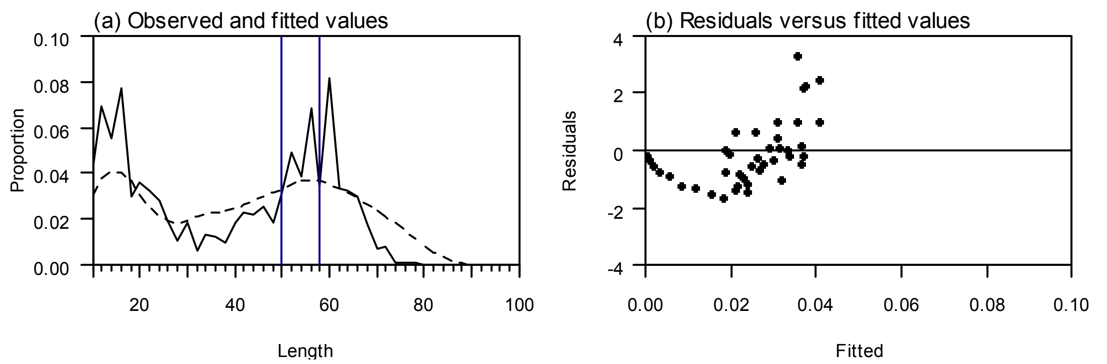

Figure 55: 2009 model MPD estimates for the 1990 dive survey length frequencies (a) observed (solid line) and MPD estimates of fits (dashed line), and (b) residuals versus fitted values (curved lines show 95% confidence intervals for the multinomial distribution). Vertical lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

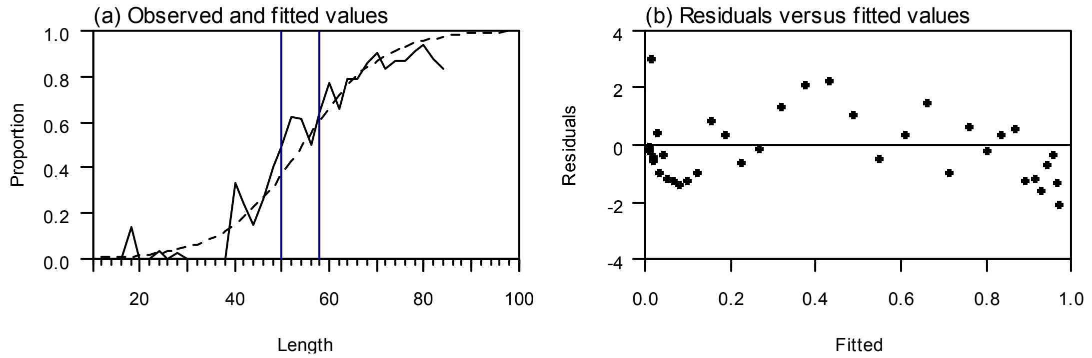

Figure 56: 2009 model MPD estimates for the Jeffs & Hickman (2000) maturity data (a) observed (solid line) and MPD estimates of fits (dashed line), and (b) residuals versus fitted values. Vertical lines separate the small (<50 mm), pre-recruit (≥ 50 mm and <58 mm), and recruit (≥ 58 mm) size groups.

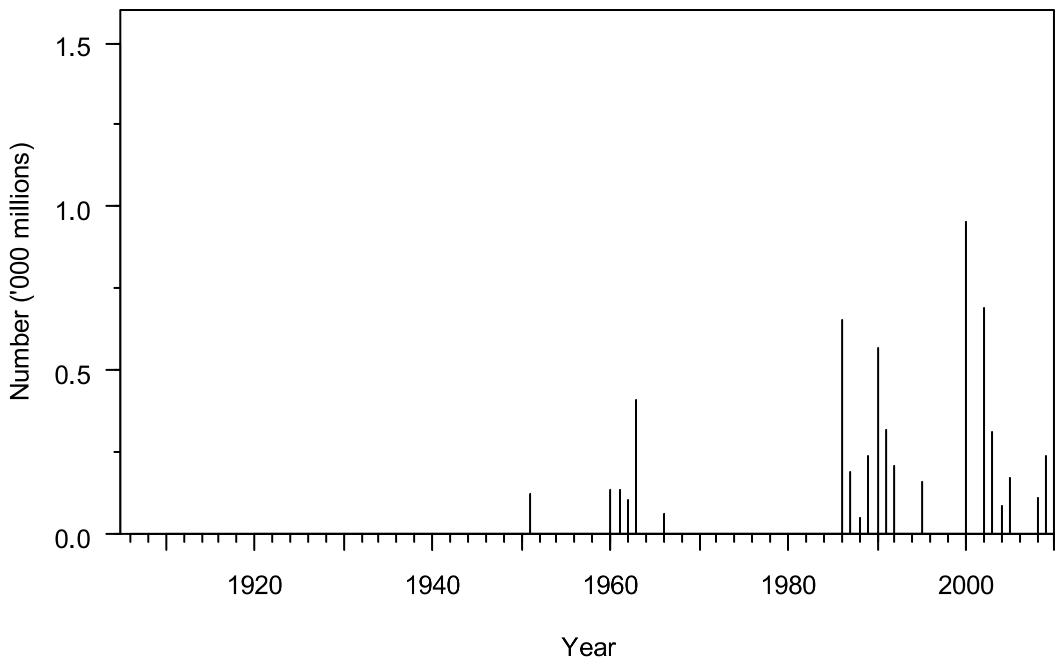

Figure 57: 2009 model MPD estimates of disease mortality, converted to numbers of oysters.

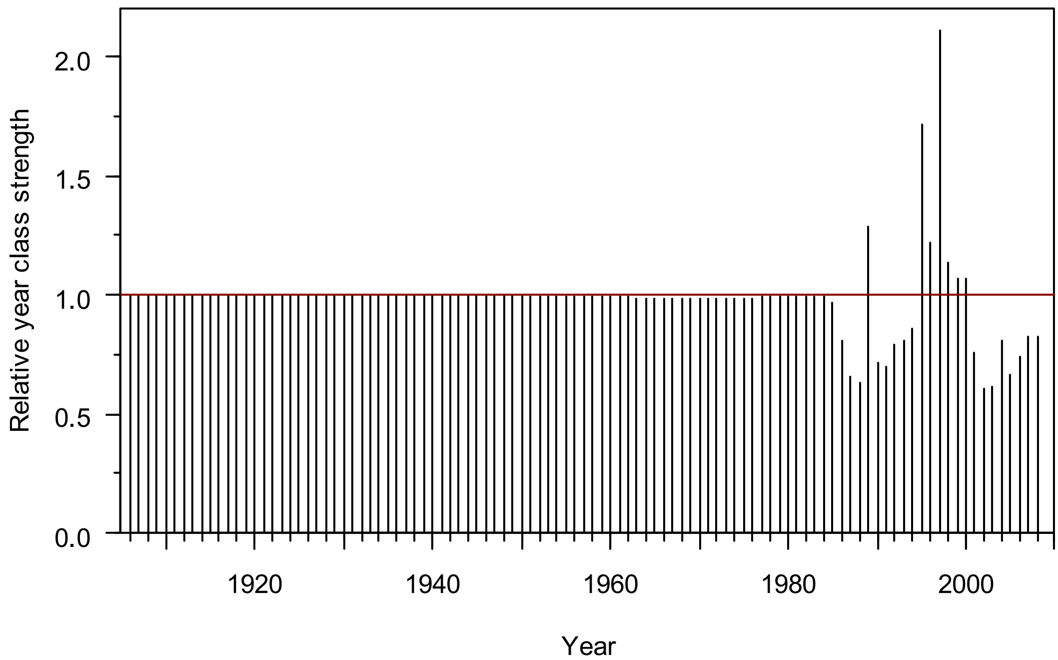

Figure 58: 2009 model MPD estimates of relative year class strengths.

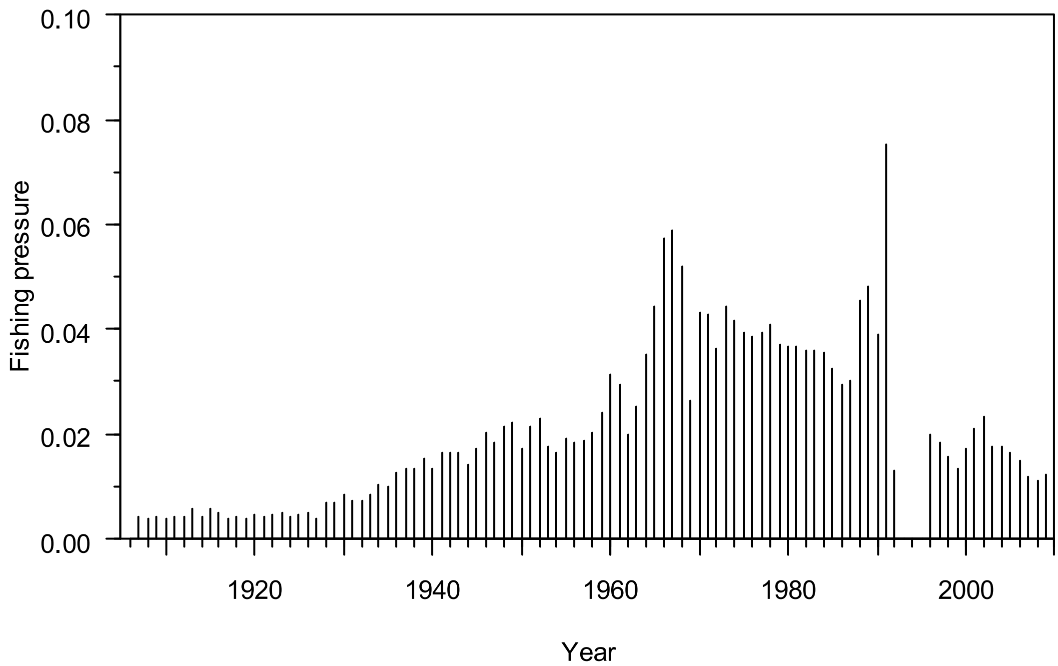

Figure 59: 2009 model MPD estimates of fishing pressure (U_{max}), i.e., catch divided by fishing vulnerable stock size.

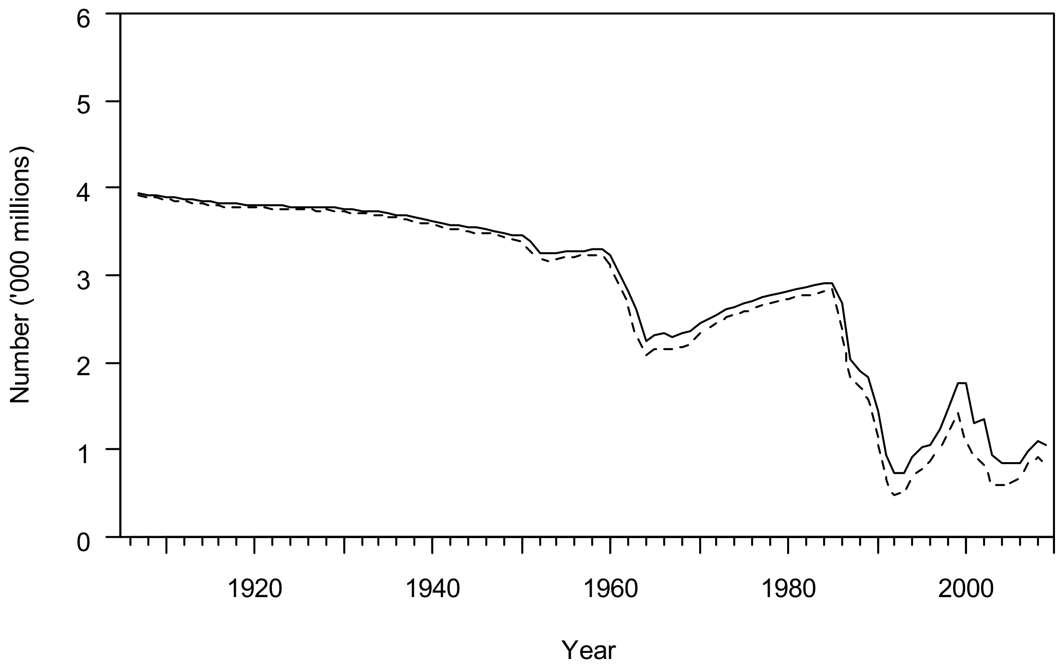

Figure 60: 2009 model MPD estimates of spawning stock size (SSB, solid line) and recruit-sized stock abundance (dashed line).