New Zealand Fisheries Assessment Research Document 98/11

Estimates of biological parameters, total mortality, and maximum constant yield for jack mackerel, *Trachurus declivis* and *T. novaezelandiae*, in JMA 1

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May 1998

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New Zealand Fisheries Assessment Research Document 98/11 38 p.

1. EXECUTIVE SUMMARY

This report summarises the most recent stock assessment work done on jack mackerel (*T. declivis, T. murphyi, T. novaezelandiae*) in JMA 1. Research objectives included determining seasonality and relative proportions of the three species in the commercial purse-seine catch, estimating growth parameters and total mortality of *T. declivis* and *T. novaezelandiae*, and updating *MCY* estimates. Results from previous work are largely restricted to *T. novaezelandiae*. Little is known about *T. declivis* or the effects of *T. murphyi* invasion, which has had a major effect in JMA 1 since about 1990.

Purse-seine landings of *Trachurus* species in JMA 1 were sampled in Tauranga since July 1994. A sampling regime was developed to produce data to estimate proportions of the three species in the catch, to provide biological information for estimating various biological parameters used in stock assessment modelling, and to collect otoliths for ageing.

Descriptions are included of the sampling approach, methods used for otolith preparation and reading, estimation of age structure and species composition of the catch, estimation of von Bertalanffy growth parameters and parameters describing the length–weight relationship, estimation of total mortality, and estimation of maximum constant yield (*MCY*).

The effect of size targeting is evident in the length and age frequencies presented. The estimated age structures show little continuity in patterns of age classes between years, indicating high levels of variability between landings. Total mortality was estimated for both species using catch curve analysis, resulting in values of 0.39 for *T. declivis* and 0.58 for *T. novaezelandiae*. The mean total mortality from the stock reduction analysis over the same period (1988–95) was 0.34. The assumed natural mortality was 0.2.

Proportions of the three species in the catch are presented for the three sampling years, 1994–95, 1995–96, and 1996–97. These proportions are based on two years of targeting large fish (primarily *T. declivis* and *T. murphyi*) and one of targeting small fish (primarily *T. novaezelandiae*). The results are important in developing separate catch histories for the three species from the total catch history in JMA 1.

A deterministic stock reduction model was used to estimate B_0 for *T. declivis* and *T. novaezelandiae* combined. Growth and length-weight parameters, and information on age at recruitment and maximum age estimated during this study, were used as input variables for the model. The resulting B_0 of 40 000 t, and the $F_{0.1}$ of 0.270 estimated from a yield per recruit analysis using the same input variables, were used to produce an *MCY* estimate of 2700 t for the two species combined in JMA 1.

2. INTRODUCTION

2.1 The fishery

The history of the jack mackerel purse-seine fishery in what is now defined as JMA 1 (Figure 1) dates back to 1966, when total landings of 415 cwt (21 t) of mackerel were recorded in the Marine Department Report on Fisheries for that year, probably from Gisborne. Mackerel are defined in the 1956 Marine Department Report as *Trachurus declivis*, and it was not until 1974 that reference was made to the probable presence of more than one *Trachurus* species in the fishery (Anon. 1974).

Over the years the relative proportions of *T. declivis*, *T. murphyi*, and *T. novaezelandiae* in the catch have changed. In the early years, D.A. Robertson (NIWA pers. comm.) noted the absence of *T. declivis*, and Horn's (1993) results indicate its presence at a relatively high proportion. Since the early 1990s the abundance of *T. murphyi* in the area has increased dramatically, according to information recorded by spotter pilots supporting the purse-seine fleet, and the proportion in the catch has also increased (Taylor, unpublished data). An objective of the present study is to produce estimates of the proportions of the three species in the catch, for use as an index of the degree that *T. murphyi* is present in JMA 1 and for separating the total catch history into individual histories of the two New Zealand species for inclusion in their stock assessment.

Since the early 1990s the TACC has been modified twice to allow commercial fishers to capture the increased resource from the *T. murphyi* invasion — in 1993–94 it was raised from 5970 t to 8000 t, and in 1994–95 it was raised further, to 10 000 t. At the time of the second increase, commercial processors undertook a voluntary monitoring of jack mackerel landings in JMAs 1 and 3 to ensure that the increases in TACCs were accounted for by increased landings of *T. murphyi* only. However, results from this monitoring have not been analysed.

Jack mackerel are targeted throughout JMA 1 inside the 200 m depth contour by the purse-seine fleet, although it is within QMA 1 that most effort is expended. Aerial assistance is used to locate appropriate target schools, and, most often, to guide the setting of the gear. Captured fish are loaded into brine tanks or holds of some 20–40 t capacity.

Jack mackerel are targeted by size according to the current market requirements. Jack mackerel tend to school by size and spotter pilots are able to identify, fairly accurately, the size range of schools from the air. The choice of harvest size is therefore well determined.

Because its extent is so much constrained by market requirements and the availability of other more commercially valuable species, the jack mackerel season does not fully reflect the seasonal availability of *Trachurus* species in JMA 1. This information is readily available from the aerial sightings database.

2.2 Factory processing

Generally, two broad size ranges of jack mackerel are sought — small fish in the 200–600 g range, and large fish between about 900 g and 1.3 kg. All jack mackerel landings are graded by weight into two market-based, size-class regimes that differ a little, but can be summarised by the ranges 200–400 g, 400–600 g, 600g–1 kg, and over 1 kg. Occasionally some fish are assigned to a fifth grade of 500–700 g, which overlaps two of the summary ranges and requires special treatment in the present analysis.

At the factory, fish are unloaded by vacuum pump. Its nozzle is lowered into the hold and fish immediately below the hatch are removed to some depth before fish towards the periphery fall down to replace them. This pattern has implications for the choice of sampling regime and is referred to later.

After unloading, fish are distributed on a system of conveyor belts and various sorting and grading regimes are followed — species other than jack mackerel are removed; damaged jack mackerel are assigned to a "rejects" grade; the fish pass through a mechanical grader, which can be adjusted to remove smaller fish; and, finally, the fish pass across the main grading belt or table, where factory staff assign fish to the grades mentioned above. Grading staff frequently use scales to weigh fish, thus minimising incorrect grading. The rate of incorrect assignment is assumed to be low, but has not been quantified.

Fish are usually placed in alloys (moulded aluminium bins) of about 300 kg capacity, although sometimes stacks of plastic fishbins (about 30 kg capacity each) are used. Alloys are labelled and transported to cool storage, where they are stacked by grade. When required, they are taken from storage (in blocks by grade), weighed at the weighbridge (weights are recorded on a PC), and made available for packing line staff. Thus grade weights of all jack mackerel landings are recorded.

2.3 Research

The first stock assessment of jack mackerel in JMA 1 by Robertson (1978) produced yield estimates based on aerial sightings data. Horn (1993) produced growth and mortality estimates for *T. declivis* and *T. novaezelandiae* in JMA 1 based on samples from the purse-seine fleet, though the information for *T. declivis* is based on one sample only. He also presented age validation results for these two species in JMA 1, concluding the presence of annual growth rings for *T. declivis* for at least the first 4 years; and a similar result for *T. novaezelandiae*. Annual growth rings have been validated for *T. declivis* in Australian waters by Webb & Grant (1979) and Stevens & Hausfield (1982).

2.4 Objectives of the present study

The present study is based on market samples of the JMA 1 purse-seine catch at the major point of landing in Tauranga (there are small catches landed elsewhere in Tauranga, but they were not sampled and are unaccounted for here), over the three seasons between 1 July 1994 and 30 June 1997.

The main objective of this study is to update the estimate of *MCY* for jack mackerel in JMA 1.

3. METHODS

Since the beginning of this study, the jack mackerel purse-seine season in JMA 1 has become extremely short, lasting only several weeks during late winter/early spring. The main period of the fishery usually spans the end of the fishing year, and therefore most data are separated in the present analysis into years from 1 July to 30 June.

3.1 Catch sampling

The sampling method for the purse-seine jack mackerel catch was fine tuned over the course of the sampling programme, as the more subtle details of the fishing, unloading, grading, and packing operations became clear. Efficiency was increased as various factors were discovered, and some expectations about what could realistically be achieved were changed. For instance, the original intention to stratify from the hold, so that an account of the uncertainty arising from inter-school variation could be estimated, had to be abandoned because the task was too great for the time available.

The availability of grade weights for all landings was identified early in the programme. These data are an important discovery in terms of reliability of the final results, and the analysis used this information to apply age structure of the various grades to the factory grade-weights for all vessel landings during a given year to produce age structures of the total annual catch for the years over which the programme ran.

Sampling method

During development of the sampling regime two broad variations of fish selection were used — for graded and for ungraded fish. Generally, the approach was similar for both after the initial sampling had been done, but some details of fish selection varied between the two.

Graded fish were selected at random from the top of up to about a dozen alloys after they had been placed on the factory floor for emptying onto the packing line belt. These fish had been graded, but they had not been sorted into species. Ungraded fish were obtained from the end of the conveyor belt at the main grading table when all grading could be temporarily halted for a short period. The graded and ungraded fish so selected are referred to as the sample.

Generally, a single sample was selected for each grade, although several samples were sometimes taken, and the data pooled later to provide a single sample. Because of the randomised manner in which the sampling was done, no bias arises from this approach. The sample size varied somewhat, depending on the grade being sampled, the apparent proportions of the species in the landing or the sample itself (where a species was poorly represented the sample might be larger than where the ratio was higher, say 50:50), or the availability of fish in a grade (certain grades were poorly represented in some landings). Generally, the objective was to include about 300 fish in the sample.

Once selected, the sample was sorted by species. These species-samples were then weighed at the weighbridge, counted to determine the number of fish in each, and the data recorded. Species were distinguished according to known external features as published by Stephenson & Robertson (1977), and Paulin *et al.* (1989).

All these sources were used as reference, particularly near the beginning of the sampling, when clarification about the end of the secondary lateral line relative to the rays of the second dorsal fin was regularly required. The secondary lateral line is an important morphological feature in separating the species, and long immersion in the brine tanks (up to one week) often makes it difficult to see. This, coupled with a tendency for the end point to vary in different ways for each species, resulted in some initial confusion about species identification.

To obtain fish for biological data (length, weight, sex) and otolith extraction, the species-samples were in turn sampled to provide what is referred to as the sub-sample. The sub-sample size varied according to grade, fish availability, and time constraints. Biological data for individual fish from each sub-sample were recorded and their otoliths stored in labelled envelopes.

3.2 Otolith collection and preparation

Otoliths (sagittae) were collected from all sub-samples of *T. declivis* and *T. novaezelandiae* used for recording biological data. The numbers of fish that were aged, by species and fishing year, are shown below.

Fishing year	No. of *T. declivis*	No. of *T. novaezelandiae*
1994–95	251	250
1995–96	220	153
1996–97	138	1284

In preparation for reading, otoliths were baked in an oven at 285 °C for about 4 min., until amber coloured, embedded in epoxy resin (Araldite K142), and sectioned transversely through the nucleus with a revolving diamond-edged saw. The sectioned surface was sanded with P1200 carborundum.

3.3 Otolith reading

Otolith sections were coated with paraffin oil, illuminated with reflected light, and examined under a binocular microscope at X8–72 magnification. A pattern of hyaline (dark) and opaque (light) bands was evident, but the positions of the three inner bands were difficult to determine. To overcome this problem, otoliths from small fish of each species (*T. declivis* and *T. novaezelandiae*) of known age (collected by the Scientific Observer Programme in 1989) were examined, and the distance from the centre of the nucleus to the inner margin of the band was measured. The means and ranges of the band distances were estimated and recorded for both the dorsal and ventral sides of the section.

Returning to the otolith sections, and using the estimated positions of the inner bands as a guide, complete hyaline zones (i.e., dark bands with light material outside them) were counted on each otolith and recorded, according to the method of Horn (1993). Generally the banding pattern was clearer on the ventral side of the section, although reference to the dorsal side was necessary sometimes to clarify interpretation.

Converting otolith band counts to age estimates requires information about the timing of the spawning season, hyaline zone formation, and the sampling date. Jones (1990) summarised information on spawning for *T. declivis*, indicating an extended spawning during spring and summer. This result is largely reinforced by the pattern of *T. declivis* egg frequencies in the Hauraki Gulf described by Crossland (1981), whose work also suggests a similar timing in spawning for *T. novaezelandiae* to that of *T. declivis*. Horn (1993) observed the beginning of formation of the opaque zone in both species during early October, and concluded that the hyaline zone was completed by 1 October. An arbitrary birthdate of 1 January was chosen in the present study, resulting in fish that are 9 months old by completion of the first hyaline band.

This information was used to generate decimal ages of the fish from the band counts obtained from the otoliths. Decimal ages were estimated using

$$a = (n-1) + \left(\frac{m+c}{12} \right)$$

where n is the number of completed hyaline bands, m is the number of months after completion of the most recent band that the fish was sampled, and c is the number of months after the arbitrary birthdate that the first hyaline band was completed (here c = 9).

3.4 Age frequencies

All fish included in the study were aged individually to avoid the use of age-length keys. The method used in applying age structures of the various grades to the total catch of those grades in any year is essentially making use of age-grade keys. Under this definition, age-grade keys were estimated from the ageing data for each year of the study, and applied to the total grade-weights for the appropriate year.

Age data from graded and ungraded fish required different treatment. Ages from a subsample of graded fish can be directly applied to a grade, but ungraded fish must be post-graded to achieve the same result. Included in this category were fish that had been assigned to the fifth grade (i.e., 500–700 g), which overlaps the usual grades. They were treated as ungraded fish, and therefore post-graded. Post-grading was achieved by grouping ungraded fish within the weight ranges of the various grades using their individual weights. Although post-grading does not produce results that are exactly comparable with the results obtained from sampling graded fish (because the assignment of fish is much more strict in the former), the difference is likely to be minimal, considering the care taken in the factory to assign fish to their correct grade.

To estimate the age structure for total annual landings in each year, a series of equations was developed based on the following steps.

a. To estimate the number of individual fish in each grade of the sampled landings

b. To estimate the age frequency of each species in each grade of the sampled landings
c. To estimate the age frequency of each species in each grade of all landings for the year (sampled & unsampled)
d. To estimate the age frequency of each species in the annual landings.

These equations were applied to the data using functions written specifically for the purpose in the New S programming environment. The equations are presented in Appendix 1.

3.5 Growth parameters

Growth parameters were estimated using the von Bertalanffy equation

$$L(t) = L_\infty\left[1 - \exp\left(-K\left(t - t_0\right)\right)\right]$$

which was fitted to the age data using an iterative procedure to minimise the total sum of the squared differences between the predicted and observed values of $L(t)$. For each species, separate equations were derived for each sex and for all fish combined.

3.6 Length frequencies

Size structure of the three species (*T. declivis*, *T. murphyi*, and *T. novaezelandiae*) was estimated using the method described for producing the age frequencies (Section 3.4). Thus, the equations presented in Appendix 1 were used, with the simple substitution of length (cm) for age (plus group). Simple modifications to the S functions allowed their use in processing the data.

3.7 Length–weight relationship

The length and weight variables were linearised using a natural logarithmic transformation, and the transformed weight was then regressed as the dependent variable against the transformed length as predictor (Sparre *et al.* 1989). The analysis produced the two standard parameters (a and b) that describe weight as a function of length according to the relationship

$$w_t = a\left(l_t\right)^b$$

3.8 Mortality

Total mortality was estimated for *T. declivis* and *T. novaezelandiae* using catch curve analysis (Sparre *et al.* 1989). Because of the influence of targeting by size on most catch curves for individual years, the data for all years were pooled to provide summary catch curves for the two species. Age frequencies of the pooled data are given in Figure 2a. The descending arm was taken from age 11 in both species because it was assumed that individuals of both species were fully recruited to the fishery by age 11. In both species recruitment and total mortality were assumed to be constant. Based on these assumptions, the numbers at age are given by

$$N_{11+t} = N_{11}e^{-Zt}$$

where Z is total mortality, t is the period, and 11 is age at full recruitment. N_i is the relative frequency in the catch at age estimate, and is assumed proportional to the number in the stock.

Therefore, linearising for t using natural logarithms we get

$$\ln(N_{11+t}) = \ln(N_{11}) - Zt$$

and total mortality (Z) is estimated using least squares regression.

In applying this method, data above age 22 were ignored to avoid using logarithms of zero which exert unreasonable influence on the least squares regression fit. The method provides an approximate estimate of Z.

3.9 Species composition of the catch

To estimate the species composition of annual landings for the three years of the study, a series of equations were developed, based on the following steps.

a. To estimate species proportions in the sampled landings (y)
b. To estimate average species proportions in the grades of the sampled landings
c. To apply averages to grade totals of the annual catch (y')
d. To estimate proportions of *Trachurus* species in the annual landings.

These equations were applied to the data using functions written specifically for the purpose in the New S programming environment. The equations are presented in Appendix 2.

3.10 Biomass estimation

The model

A deterministic stock reduction model (Francis 1990) was used to produce best estimates of virgin biomass for *T. declivis* and *T. novaezelandiae*. The model required growth and length-weight parameters, an estimate of natural mortality, age at recruitment, maximum age, von Bertalanffy growth parameters, a value for steepness of the Beverton and Holt stock-recruitment relationship, ages at maturity and recruitment, a complete catch history of the fishery, and an index of stock abundance. Usually these input data were derived from the results of this study; natural mortality was taken from Horn (1993). The list of biological parameters and their values used in the model are presented in Table 1. Because the two stocks are being modelled together, the Beverton and Holt steepness parameter had to be constrained to 1 for the model runs. The catch history and stock index were produced specifically for the model, and their derivations are described below.

Catch history

A catch history spanning 53 years (1944 to 1996–97) was generated using data from Marine Department Reports on Fisheries (1944–74), FSU data for 1975–83 from King (1985, 1986), King *et al.* (1986), and FSU, CELR, and LFRR data for 1983–84 to 1995–96 from Annala & Sullivan (1997). These data were converted to tonnes where necessary (early records are in hundredweight), and values assigned to the three *Trachurus* species using factors estimated from the market sampling species proportions. The catch history is presented in Table 2.

For the three years of this study the method was straightforward, and the species proportions estimated from the sampling were applied to the catch. In other years, however, the methods used were a little less direct. In 1992–93, when no sampling was done but grade weights were available from the factory weighbridge, species proportions estimated for the following year were applied to the grade weights to derive estimates of species proportions for the year. These proportions were applied to the annual catch for 1992–93, and also for 1990–91 and 1991–92 for which no information was available, but high increases in catch suggested the presence of *T. murphyi* in the fishery.

Before 1990–91 it was assumed that the catch of *T. murphyi* was zero, and a strategy was developed to apply what information was available to split the recorded landings between *T. declivis* and *T. novaezelandiae*. It was known from discussions with a purse-seine skipper who had been involved with the fishery since at least 1976 that almost all targeting of jack mackerel before 1990 had been of smaller fish (i.e., 200–600 g). To produce a best estimate of the individual catch of the two species, the proportions estimated from the sampling for the two grades covering the range from 200–600 g from 1994–95 to 1996–97 were applied to the catch before 1990.

The stock index

A stock index for *T. declivis* and *T. novaezelandiae* combined was generated using the aerial sightings data (Taylor, unpublished results). Although a number of relative abundance indices have been developed (Bradford & Taylor 1995), this one was chosen because its use of a trimmed mean reduces some of the high level of noise chracteristic of these data.

Applying the model

The model was formulated to allow inclusion of separate biological information and separate catch for the two species while using a single stock index for the two species combined.

Software developed by Chris Francis was used for the analysis. This uses a maximum likelihood approach which determines the level of virgin biomass that best fits the abundance indices, given the catch history and the biological parameters. Using this software, the model is usually applied to two sexes from a single stock. However, there are two species here, each with its own unique set of biological parameters and catch history, but with a single common stock index. Therefore, in addition to virgin biomass, we also need to estimate the proportion of the two species in the population at B_0.

Consequently, different starting proportions (P_{start}) of *T. novaezelandiae* were trialled, and the corresponding maximum likelihood estimates of B_0 and values of maximum likehood (λ) were recorded. These were tabulated together with maximum and minimum proportions of *T. novaezelandiae* and the maximum *F*s, to determine a plausible range of values for B_0. Because of the constraints of the software, the biological parameters for males were used for *T. declivis* and females for *T. novaezelandiae*.

A yield per recruit analysis for the same combined species model was used to produce an estimate of $F_{0.1}$. *MCY* was calculated using method 1 of Annala & Sullivan (1997):

$$MCY = 0.25\ F_{0.1}\ B_0.$$

4. RESULTS

4.1 Average size

A summary of mean lengths (mm) and weights (g) by sex and species from the shed sampling data for the three years combined is given in Table 3.

4.2 Length frequencies

Frequency histograms of the three species, scaled to the total annual purse-seine catch in JMA 1, are presented in Figure 3. The influence of size targeting is evident in the plots, with a broader coverage of size range in the first two years. The bimodal distribution of *T. declivis* in 1994–95 (Figure 3a) is a result of targeting the two size ranges, 200–600 g and 800–1300 g. The plots for 1996–97 (Figure 3a–3c) illustrate the exclusive targeting of 'small' fish known from that year. Apart from a very low take in 1996–97, which is over-represented in the plot (Figure 3b), the catch of *T. murphyi* is restricted to 1994–95 and 1995–96 when the targeting of 'large' fish predominated. In terms of catch, the levels of *T. novaezelandiae* are over-represented in these plots, because the information is presented as numbers of fish and the mean weight *T. novaezelandiae* is about half that of the other two species.

4.3 Positions of otolith inner bands

The estimated positions of the three inner hyaline bands are given in Table 4.

4.4 Age replication

The results of the within-reader comparison (Table 5) show that of the 146 otoliths examined, 118 (81%) are within ± 1 year. This result translates to 83% of the 93 *T. declivis* otoliths read, and 77% of the 53 *T. novaezelandiae* otoliths.

4.5 Age frequency distribution

Pooled age distributions for *T. declivis* and *T. novaezelandiae* are shown in Figure 2a. Distributions of the individual species for each of the sampling years are shown in Figures 2b and 2c.

Catch of *T. novaezelandiae* consistently comprises fish between 5 and 18 years old, with a strong peak between ages 9 and 13. By contrast, the *T. declivis* catch is more bimodal, with a similar peak at age 8–12 and, in some years, a high proportion of 3 and 4 year olds.

A feature of the data is the inconsistency between years, with a marked absence in the continuity of apparently strong year classes. The effect of size targeting is evident in Figures 2b and 2c, and reflects the patterns described in Section 4.2.

4.6 Growth parameters

Growth parameters from the von Bertalanffy fit are presented in Table 6, and growth curves are shown in Figures 4 and 5. The absence of small fish is reflected in the high negative values of t_0, particularly for *T. novaezelandiae*.

4.7 Length-weight relationship

Length-weight parameters are presented in Table 7, and plots in Figures 6 and 7. The absence of small fish has a marked influence on the relationship.

4.8 Mortality estimates

Total mortality, from catch curve analysis, was estimated as 0.39 for *T. declivis*, and 0.58 for *T. novaezelandiae*. However, the level of uncertainty associated with these estimates is high and they should be considered only approximate. Nevertheless, they provide supporting information for the values of M that have been used, both in the present study, as input to the stock reduction model, and in previous studies.

Total mortality was estimated from the output of the stock reduction analysis using the exploitation rates over the same period as the descending arm of the catch curve (1988–95). These exploitation rates were converted to a mean estimate of instantaneous mortality using:

$$\overline{Z} = \frac{\sum_{1}^{n} -\ln(1-y_i)}{n}$$

where $\overline{Z}$ is mean total mortality, y_i is the exploitation rate in the *i*th year of the period, and *n* is the number of years. This estimate for mean total mortality for *T. declivis* and *T. novaezelandiae* combined was 0.34.

4.9 Species composition of the catch

Estimated species proportions by weight are as follows:

Fishing year	*T. declivis*	*T. murphyi*	*T. novaezelandiae*
1994–95	0.35	0.57	0.08
1995–96	0.18	0.47	0.35
1996–97	0.04	0.03	0.93

4.10 Estimation of biomass, $F_{0.1}$ and yield

Biomass

A range of starting values (30–71%) for the percentage of *T. novaezelandiae* in the population was tried (Table 8). Two minima were obtained for λ, at P_{start} values of 37 and 68%, but neither were acceptable fits of the model: the lower value indicated high levels of *F* with an associated reduction of the proportion of *T. novaezelandiae* in the population to zero; the higher value had a high P_{max} value associated with it, in this case predicting a collapse of the *T. declivis* portion of the stock. A range of plausible results was obtained between P_{start} values of 50 and 65%, and the corresponding value of B_0 ranged from about 39 900 to 41 500 t. An arbitrary value of 60% with the B_0 of 40 132 t (rounded to 40 000 t) was chosen as the best estimate.

A plot of biomass and stock index is included in Figure 8 to show their relationship and the small variation that would occur if stock indices for 1976 and 1977 were omitted because of uncertainty about the consistency of sightings data in the early years.

Estimation of $F_{0.1}$

Running the yield-per-recruit analysis in the model, using a P_{start} of 60%, produced an $F_{0.1}$ value of 0.270.

Estimation of *MCY*

The resulting *MCY* estimate for *T. declivis* and *T. novaezelandiae* combined, based on Method 1 of Annala and Sullivan (1997), in JMA 1, is

$$MCY = 0.25*0.270*40000 = \mathbf{2700\ t.}$$

5. DISCUSSION

The main objective of the present study was to improve the previous estimate of *MCY*, using the stock reduction model of Francis (1990) to produce estimates of $F_{0.1}$ and B_0 for input into method 3 of Annala & Sullivan (1997). Uncertainty in this approach arises from possible violation of assumptions when separating the catch history of jack mackerel into histories for the three contributing species, assumptions about separating the *T. murphyi* component from the aerial sightings stock indices, and general assumptions about estimating indices of relative abundance using aerial sightings data that are gathered opportunistically.

The extent of *T. murphyi*'s influence on the two longer established species is unknown, and neither is the effect of expending most fishing effort on one component of a two species aggregate that is managed as a single species. That these two "phases" of the fishery are so well advanced causes complexities that are difficult to unravel using simple approaches. One possible concern is that the effects of increased levels of inter-specific competition, represented by the invasion of *T. murphyi*, might impact synergistically on a species (*T. novaezelandiae*) that is already reduced to some relatively low value of B_0.

The results from the two species model used here, however, do not support this concern, and actually provide parameters for estimation of an *MCY* that produces a 12% increase on that estimated previously. No account is included in this model of the presence of *T. murphyi*. Information on its influence may now be critical to management of the jack mackerel fishery.

In its present form, the model used in this study is restricted in the range of outputs that it can produce. It is not flexible enough to allow any variation from a value of 1 for the recruitment steepness parameter. Because it was originally intended for modeling two sexes of the same species, it is constrained to a constant value of stock-recruitment for *both* species, and cannot allow varying recruitment as the relative proportions of the two stocks change over time. Future modification will allow varying recruitment in a two species approach, making it possible to model a stock-recruit relationship.

The difficulties associated with producing data that are representative of the population from samples of purse-seine catches are well known (Wada & Matsumiya 1990, Hilborn & Walters 1992, Matsuishi *et al.* 1993), although there is little information available on targeting by size. In the present context, the effect of targeting by size is evident from the length frequency distributions, particularly in *T. declivis* where the size range spans all the grade sizes but intermediate sizes are poorly represented, resulting in marked bimodality in the distribution. This deficiency undoubtedly affects the age frequency of *T. declivis*, and is probably responsible for the poor representation of age classes from 5 to 11.

The age frequency of *T. novaezelandiae* is potentially more immune to this problem because a continuous range of its size classes lies within the target category 'small fish'. However, the extremes are more or less well represented in different years, and there is also variability in the degree to which intermediate size classes are represented.

These variations undoubtedly affect the age distributions, though the effect is probably not as pronounced as it was for *T. declivis*.

Generally, the effect of these deficiencies arising from size targeting is to provide estimates of steepness for the descending arm of the catch curve that have relatively high levels of uncertainty. Consequently, the estimates of total mortality from catch curve analysis for *T. declivis* and *T. novaezelandiae* produced by this study also have high levels of uncertainty associated with them.

The difference in the estimates of total mortality between the two species is extremely marked. Total mortality from catch curve analysis was 0.39 for *T. declivis* and 0.58 for *T. novaezelandiae*, suggesting recent fishing mortalities (based on an assumed natural mortality of 0.2) averaging 0.2–0.4. While there is a relatively high level of uncertainty about these estimates, they do support different exploitation rates for the two species, with *T. novaezelandiae* being affected about twice as heavily as *T. declivis*.

The implications of this result are unclear, considering the timing of changes in exploitation of the two species. According to anecdotal information from people who have worked in the fishery, smaller fish were targeted for the 14 years leading up to the appearance of significant numbers of *T. murphyi* in JMA 1, suggesting a higher exploitation of *T. novaezelandiae* during this period. One effect of the *T. murphyi* invasion, and the change in targeting that it has induced, is an increased exploitation of larger *T. declivis*, which are often mixed with *T. murphyi* in single schools. Ultimately, however, the age structure of this fishery does not support the idea of high rates of exploitation. Catches of both species are supported by older age classes, resulting in a fishery that is not recruitment driven.

Uncertainty in the age structure arising from size targeting also affects the choice of recruitment parameters for the stock reduction analysis. The aggregated age structures of the two species suggest the presence of selection ogives, rather than the knife-edge recruitment assumed for the model. The details of the ogive are clearer in *T. novaezelandiae*, where it seems that recruitment continues from 4 to 11, and something similar may be true for *T. declivis*. However, the uncertainties in the age structure described above reduce the certainty with which an appropriate selection ogive can be chosen for either species. Development of these ogives requires a greater understanding of how random the fishing is within a target range. Given the bimodal character of the *T. declivis* length frequency and how this relates to variations in targeting, it may not be possible to collect adequate information to determine the details of a selection ogive in this case.

Estimates of von Bertalanffy growth parameters (especially t_0) and length-weight parameters, suffer from the absence of small fish in the samples (*See* Figures 4–7). Data from small fish would change the shape of the growth curves by increasing the steepness of the rising portion, and causing t_0 values to become less negative. While small fish are sometimes available and are graded into a size class of under 200 g, this seems to be relatively uncommon, and has not been picked up by the sampling so far. Their presence suggests that the age at recruitment may be considerably lower than the values of 4 and 5 years for *T. declivis* and *T. novaezelandiae* evident from Figures 4 and 5, but the vulnerability of these very small fish is undoubtedly much lower than that of the larger size classes, and they cannot be considered as fully recruited to the fishery.

Information about some small fish are available from other sources (e.g., collections by scientific observers). Otoliths from these fish were used for determining the positions of the three inner bands during the ageing work. It is possible that including their biological information might overcome the problems caused by the absence of small fish, but they were collected outside JMA 1 and may introduce bias to the lower end of the growth curve.

6. ACKNOWLEDGEMENTS

I commend the extremely helpful attitude of *everybody* on the staff at Sanfords Tauranga. In particular, I thank Ian van der Nagle, Faye Anderson, and Ian Hughes (now deceased), who organised things to run as smoothly as possible, and Lolita Libeau for her data extracts. I am especially grateful for the guidance given by Dave Gilbert throughout the course of this study, and I thank Chris Francis for his help and advice. Many thanks to Stuart Hanchet for reviewing the manuscript. This work was funded by the Ministry of Fisheries as the research project PIJM01, Stock assessment of jack mackerels.

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Table 1: Biological parameters used in the stock reduction model fitting *Trachurus declivis* and *T. novaezelandiae* combined. Knife-edge recruitment was assumed, and the fit was deterministic with constant stock–recruitment.

Species	Parameter	Symbol	Value
Both	Maximum age		27
	Recruitment model	$B \& H$	3
	Recruitment steepness	h	1
	Natural mortality	M	0.2
T. novaezelandiae	von Bertalanffy parameters	L_∞	38.379
(males)		k	0.129462
		t_0	-5.400
	Length–weight parameters	a	3.2e-08
		b	2.8352
	Age at recruitment	A_r	5
	Gradual recruitment	S_r	0
	Age at maturity	A_m	5
	Gradual maturity	S_m	0
T. declivis	von Bertalanffy parameters	L_∞	46.488
(females)		k	0.203385
		t_0	-1.497
	Length–weight parameters	a	9.51e-09
		b	3.0555
	Age at recruitment	A_r	4
	Gradual recruitment	S_r	0
	Age at maturity	A_m	4
	Gradual maturity	S_m	0

Table 2: Catch history (t) and stock index of jack mackerel (all species) in JMA 1. Sources: 1944–74, Marine Department Reports on Fisheries; 1975–83, FSU data; 1983–96, FSU, CELR and LFRR data. Species assignment criteria are discussed in the text. The stock index is from aerial sightings data and is an estimate of the tonnes sighted per hours flown

	Totals		Landings			
Year	All species	*T. declivis & T. novaezelandiae*	*T.declivis*	*T. novaezelandiae*	*T.murphyi*	Stock index
1944	8	8	1	7	0	0
1945	7	7	1	6	0	0
1946	4	4	1	3	0	0
1947	12	12	1	11	0	0
1948	0	0	0	0	0	0
1949	0	0	0	0	0	0
1950	0	0	0	0	0	0
1951	2	2	1	1	0	0
1952	0	0	0	0	0	0
1953	0	0	0	0	0	0
1954	3	3	1	2	0	0
1955	0	0	0	0	0	0
1956	0	0	0	0	0	0
1957	0	0	0	0	0	0
1958	0	0	0	0	0	0
1959	2	2	1	1	0	0
1960	0	0	0	0	0	0
1961	0	0	0	0	0	0
1962	2	2	1	1	0	0
1963	5	5	1	4	0	0
1964	5	5	1	4	0	0
1965	13	13	2	11	0	0
1966	46	46	6	40	0	0
1967	213	213	26	187	0	0
1968	137	137	16	121	0	0
1969	124	124	15	109	0	0
1970	72	72	9	63	0	0
1971	324	324	39	285	0	0
1972	321	321	39	282	0	0
1973	389	389	47	342	0	0
1974	1255	1255	151	1104	0	0
1975	164	164	20	144	0	0
1976	621	621	75	546	0	332
1977	1167	1167	140	1027	0	414
1978	1166	1166	140	1026	0	821
1979	2125	2125	255	1870	0	819
1980	2499	2499	300	2199	0	473
1981	2795	2795	335	2460	0	361
1982	1601	1601	192	1409	0	477
1983	1457	1457	175	1282	0	403
1984	3684	3684	442	3242	0	256
1985	1857	1857	223	1634	0	212
1986	1173	1173	141	1032	0	378

Table 2 — *Continued*

	Total		Landings			
Year	All species	*T. declivis & T. novaezelandiae*	*T.declivis*	*T. novaezelandiae*	*T.murphyi*	Stock index
1987	4056	4056	487	3569	0	443
1988	3108	3108	373	2735	0	222
1989	2986	2986	358	2628	0	273
1990	4226	4226	507	3719	0	382
1991	6472	5242	1935	3307	1230	344
1992	7017	5684	2098	3586	1333	306
1993	7528	6098	2251	3847	1430	372
1994	14256	6130	5032	1098	8126	191
1995	7832	3368	2765	603	4464	151
1996	6778	3619	1213 18%	2406 35%	3159 47%	172

Table 3: Summary of mean lengths (mm), mean weights (gm), and standard deviations (σ) of *Trachurus declivis*, *T. murphyi* and *T. novaezelandiae* from the shed sampling data for the three years (1994–95 to 1996–97) combined, by sex and species

Dataset	Mean length (mm)	σ	Mean weight (gm)	σ
T. declivis-all data	396	74	900	397
T. declivis-males	402	74	929	393
T. declivis-females	390	74	866	399
T. murphyi-all data	476	36	1 165	257
T. murphyi-males	487	37	1 230	269
T. murphyi-females	458	26	1 061	197
T. novaezelandiae-all data	336	28	479	111
T. novaezelandiae-males	339	28	486	109
T. novaezelandiae-females	333	27	472	112

Table 4: Position of the three inner hyaline bands (dorsal & ventral) in *Trachurus declivis* and *Trachurus novaezelandiae*. Positions given as means of a range of distances from the centre of the nucleus to the inner margin of the band. Measurements are in mm, and *n* is the number of otoliths examined

	T. declivis		
	Ventral side of section		
Band #	range	mean	*n*
1	0.47–0.98	0.68	68
2	1.06–1.27	1.15	48
3	1.40–1.82	1.54	27
	Dorsal side of section		
Band #	range	mean	*n*
1	0.65–1.38	0.90	60
2	1.32–1.58	1.46	47
3	1.60–2.1	1.83	26
	T. novaezelandiae		
	Ventral side of section		
Band #	range	mean	*n*
1	0.73–1.08	0.91	59
2	1.02–1.49	1.32	53
3	1.46–1.78	1.62	9
	Dorsal side of section		
Band #	range	mean	*n*
1	0.96–1.37	1.16	54
2	1.32–1.92	1.62	50
3	1.82–2.02	1.92	12

Table 5: Within reader comparison of 146 otoliths (*Trachurus declivis* and *T. novaezelandiae*) showing the numbers and percentages for identical readings and readings differing by various margins from 1 year and more. The bottom line shows the numbers and percentages that lie within a difference of ± 1 year, i.e., including those that are identical and those differing by ± 1 year

	Both species		*T. declivis*		*T. novaezelandiae*	
Level of similarity	Number of otoliths	Percentage	Number of otoliths	Percentage	Number of otoliths	Percentage
identical	56	38	41	44	15	28
± 1	62	42	36	39	26	49
± 2	18	12	11	12	7	13
± 3	8	5	4	4	4	8
± 4	1	1	0	0	1	2
± 7	1	1	1	1	0	0
within ± 1	118	81	77	83	41	77

Table 6: Growth parameters for *Trachurus declivis* and *T. novaezelandiae* from the von Bertalanffy fit

Dataset	L_∞	K	t_0	n
T. declivis, all data	47.11609	0.209991	-1.365482	597
T. declivis, males	47.67420	0.216952	-1.249052	309
T. declivis, females	46.48757	0.203385	-1.496898	288
T. novaezelandiae, all data	38.22913	0.131806	-5.222789	1 644
T. novaezelandiae, males	38.37867	0.129462	-5.400136	804
T. novaezelandiae, females	37.96760	0.136435	-4.961847	840

Table 7: Length–weight parameters for *Trachurus declivis* and *T. novaezelandiae*

Dataset	a	b	n
T. declivis, all data	1.46E-08	2.982522	597
T. declivis, males	2.19E-08	2.915034	309
T. declivis, females	9.51E-09	3.055501	288
T. novaezelandiae, all data	2.27E-08	2.895342	1 644
T. novaezelandiae, males	3.20E-08	2.835233	804
T. novaezelandiae, females	1.49E-08	2.969652	840

Table 8: Output from the stock reduction model for *Trachurus declivis* & *T. novaezelandiae*. The shaded line represents the model run accepted as the best fit according to the criteria discussed in the text; these values for B_0 and $F_{0.1}$ were used in estimating maximum sustainable yield

P_{start}	λ	B_0	P_{max}	P_{min}	Max F	$F_{0.1}$
30	-97.6251	26065	na	0, 1982–1996	>5 from 1982	
37	-96.8267	28782	na	0, 1985–1993	>5 from 1985	
42	-97.4182	30533	na	0, 1988–1993	>5 from 1988	
46	-98.9795	30126	na	0, 1989–1993	≈5 from 1989	
50	-99.6266	41467	40 in 1996	16 in 1993	0.722 in 1993	0.265
54	-99.5131	40781	50 in 1996	23 in 1993	0.551 in 1993	0.270
56	-99.4516	40453	59 in 1996	30 in 1993	0.464 in 1993	0.270
59	-99.4102	40224	67 in 1996	37 in 1993	0.421 in 1994	0.270
60	-99.3930	40132	71 in 1996	40 in 91 & 92	0.441 in 1994	0.270
61	-99.3769	40078	75 in 1996	42 in 1993	0.464 in 1994	0.270
63	-99.3451	39960	81 in 1996	46 in 1991	0.522 in 1994	0.270
65	-99.3082	39860	88 in 1996	50 in 90 & 91	0.678 in 1995	0.275
67	-99.2498	39603	94 in 1996	53 in 90 & 91	>1 in 1995	0.275
68	-99.1321	40186	100 in 1996	56 in 90 & 91	4.9 in 1995	0.280
70	-99.2379	41387	100 in 1996	59 in 90 & 91	5.0 in 1995	
71	-99.3825	41267	100 in 95 & 96	61 in 90 & 91	>5 in 1995	

P_{start}	Percentage of *T. novaezelandiae* in the population
λ	Maximum likelihood value – increasing goodness of fit with decreasing index value (i.e., greater negativity)
B_0	Virgin biomass
P_{max}	Maximum percentage of the population attained by *T. novaezelandiae*
P_{min}	Minimum percentage of the population attained by *T. novaezelandiae*
Max F	The maximum level of fishing mortality on both species combined, attained during the model fit
$F_{0.1}$	Reference fishing mortality estimated from the yield per recruit analysis; defined as the level of fishing mortality at which the slope of the yield-per-recruit curve is 0.1 times the slope at F=0

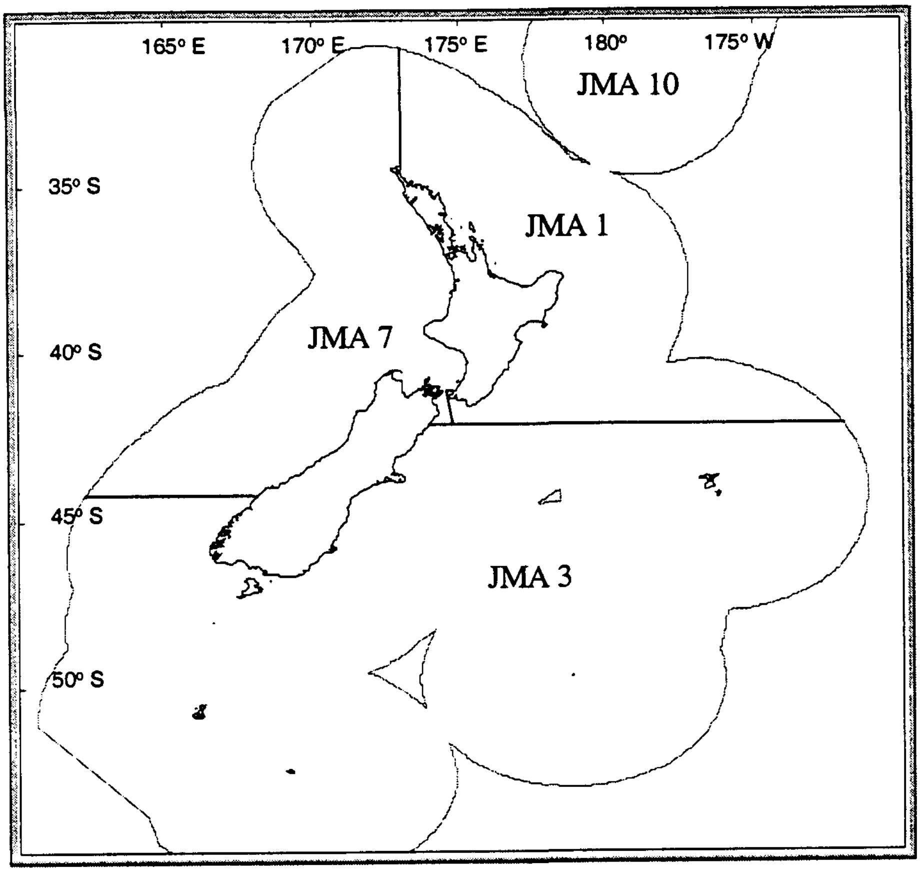


Figure 1: Jack mackerel quota management areas.

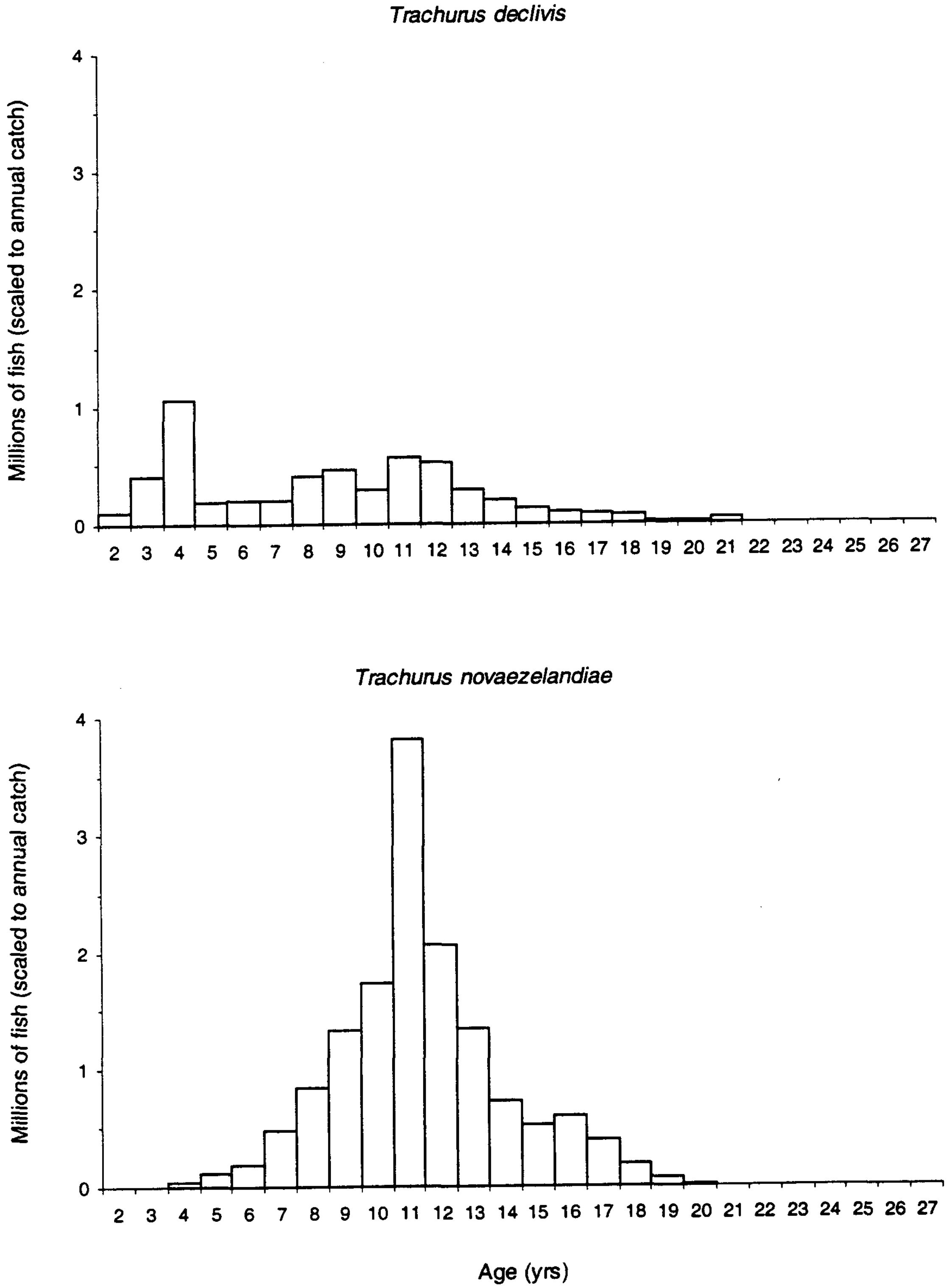


Figure 2a: Age frequencies of *Trachurus declivis* and *T. novaezelandiae* aggregated for all sampling years combined

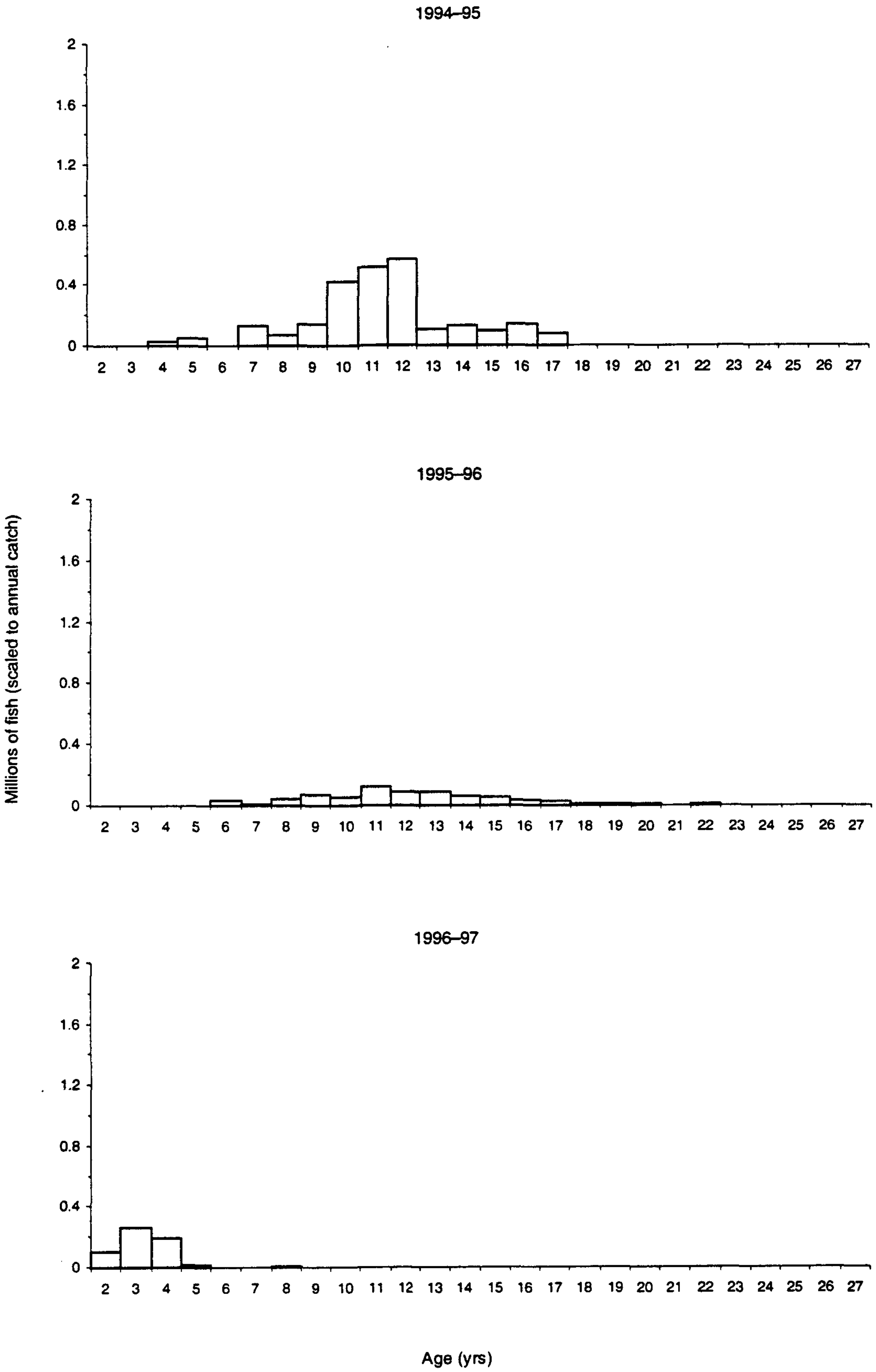
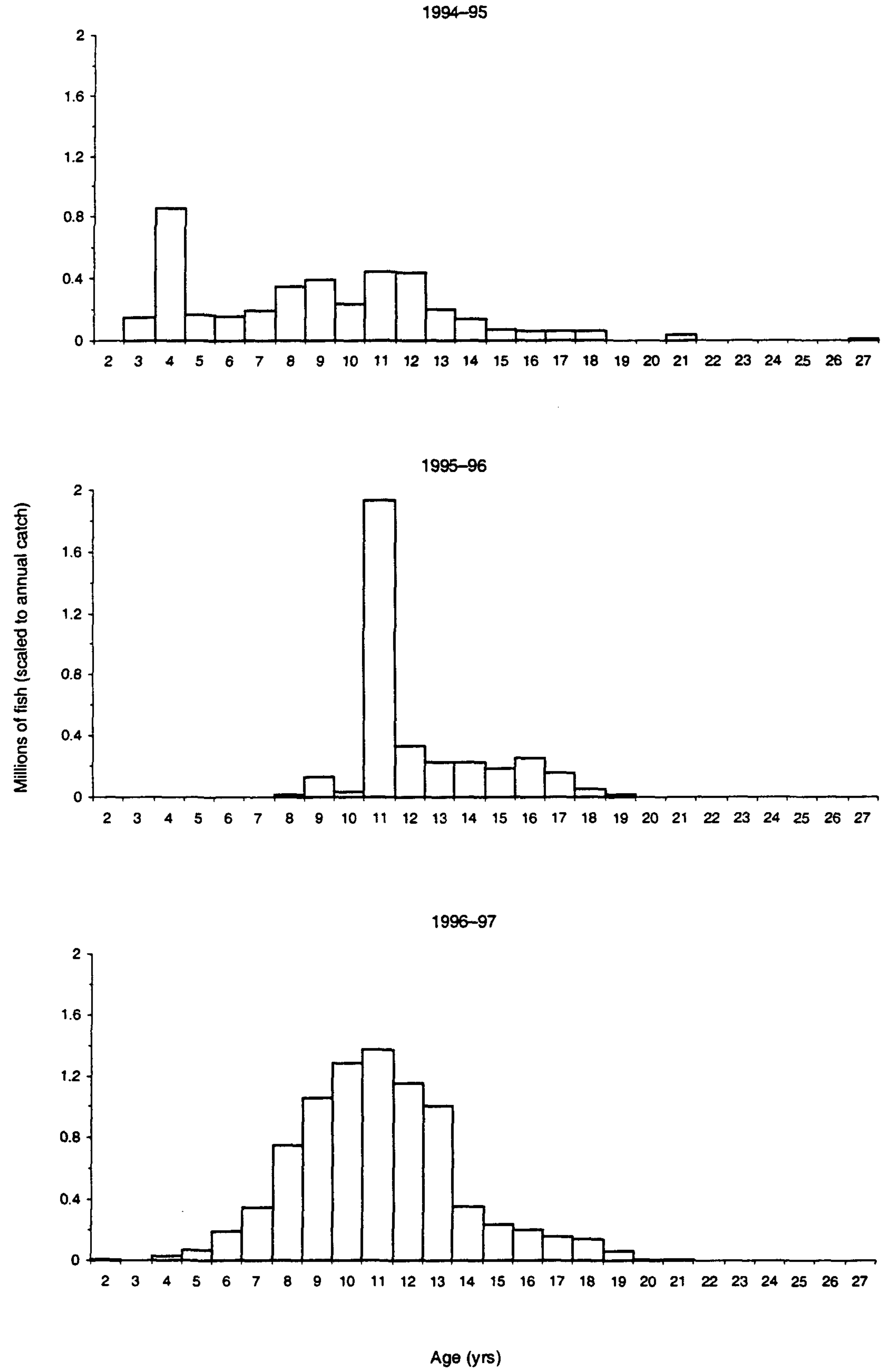


Figure 2b: Age frequencies of *Trachurus declivis* for each sampling year.


1994–95

1995–96

1996–97

Figure 2c: Age frequencies of *Trachurus novaezelandiae* for each sampling year.

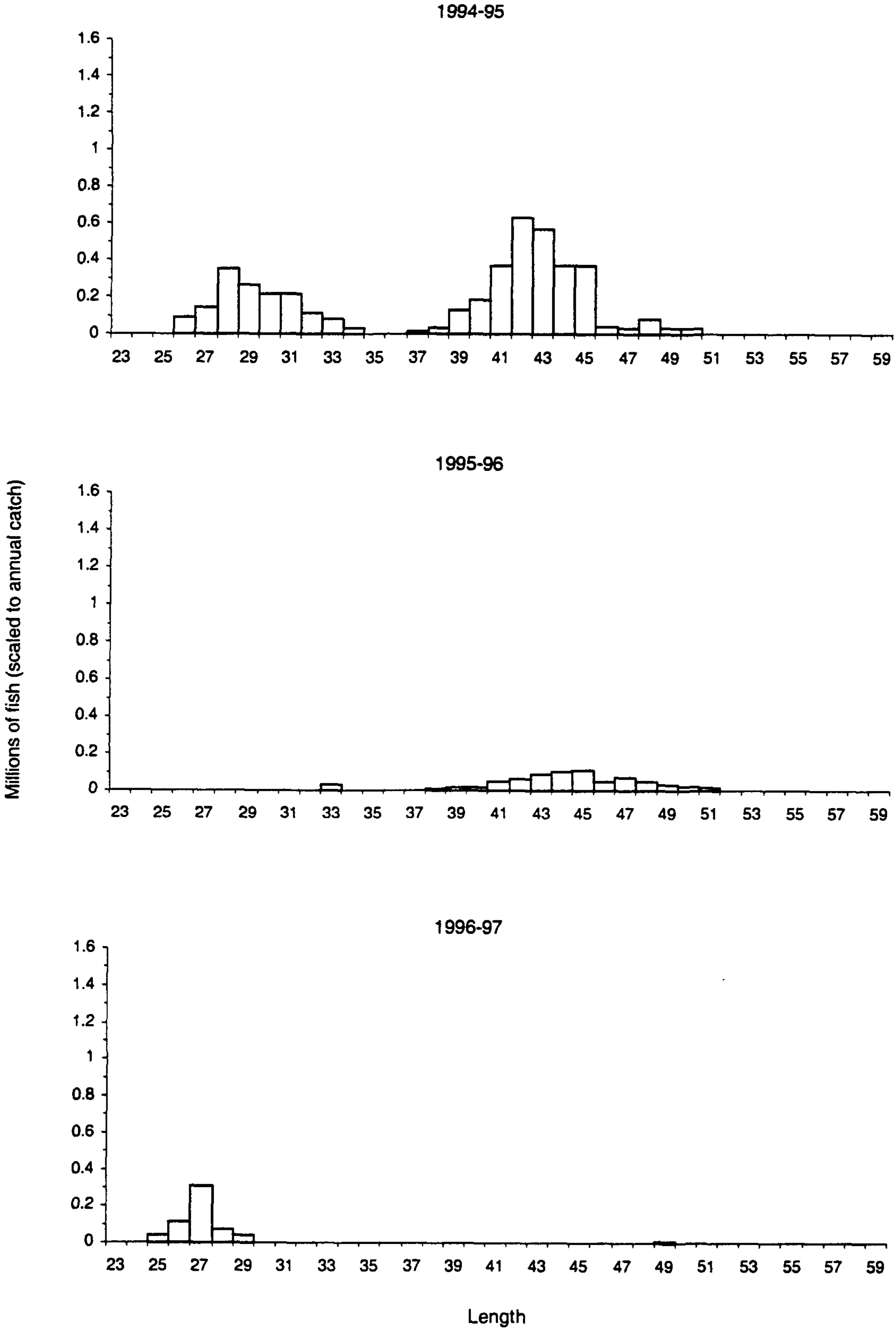
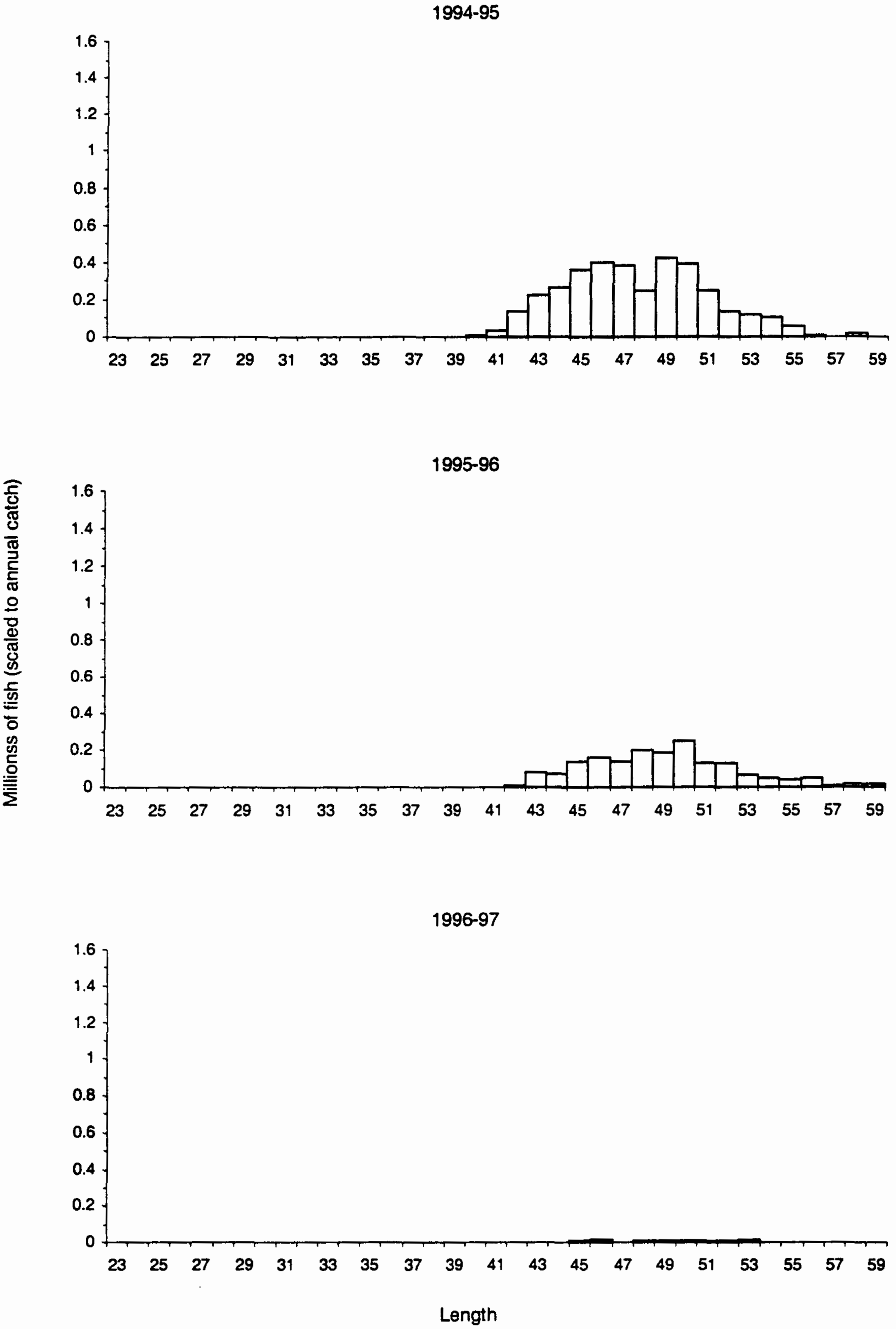


Figure 3a: Length frequencies of *Trachurus declivis* from shed samples of the purseseine target fishery for jack mackerel in JMA 1 between 1994–95 and 1995–96.



1994-95

1995-96

1996-97

Figure 3b: Length frequencies of *Trachurus murphyi* from shed samples of the purseseine target fishery for jack mackerel in JMA 1 between 1994–95 and 1995–96.

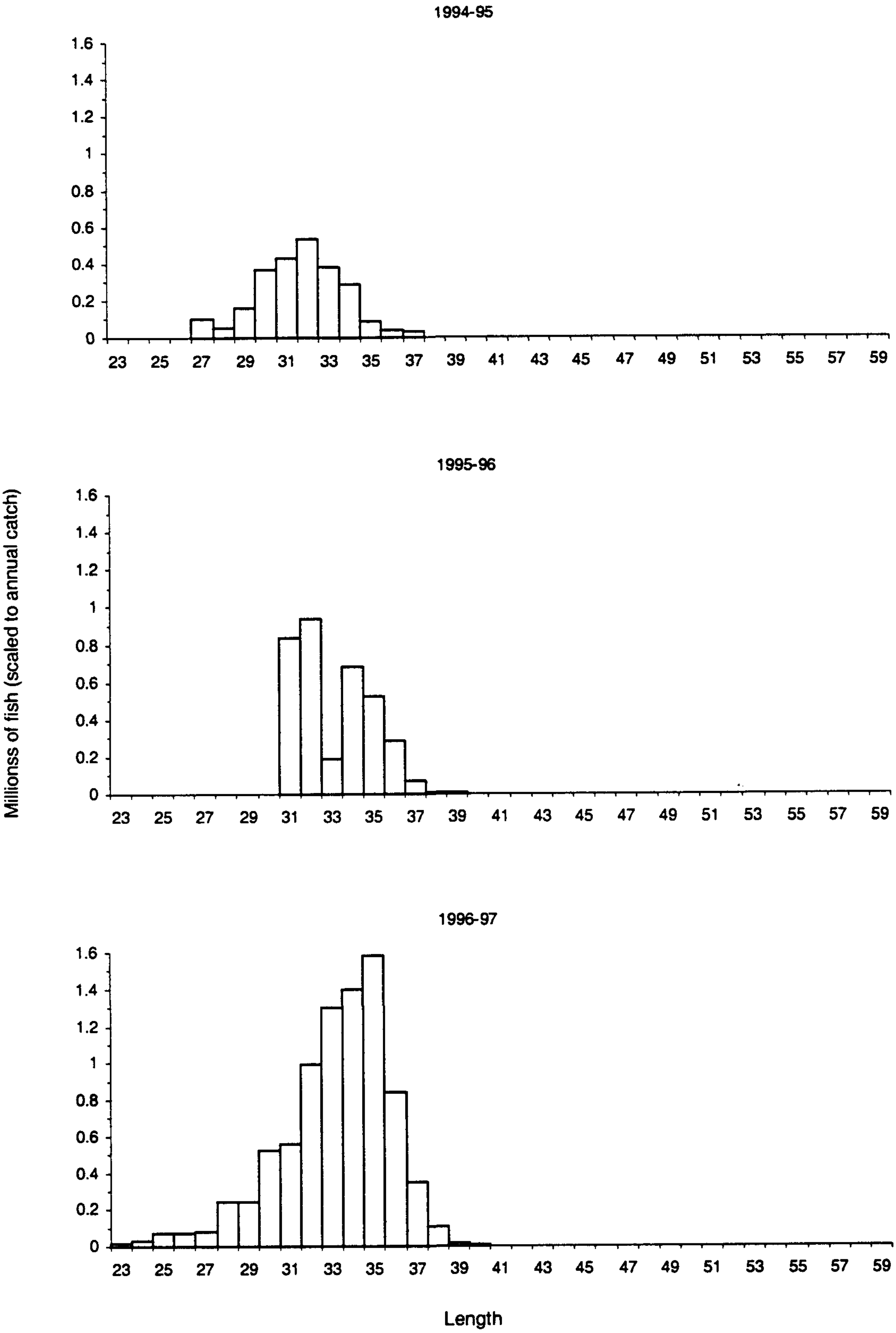


Figure 3c: Length frequencies of *Trachurus novaezelandiae* from shed samples of the purseseine target fishery for jack mackerel in JMA 1 between 1994–95 and 1995–96.

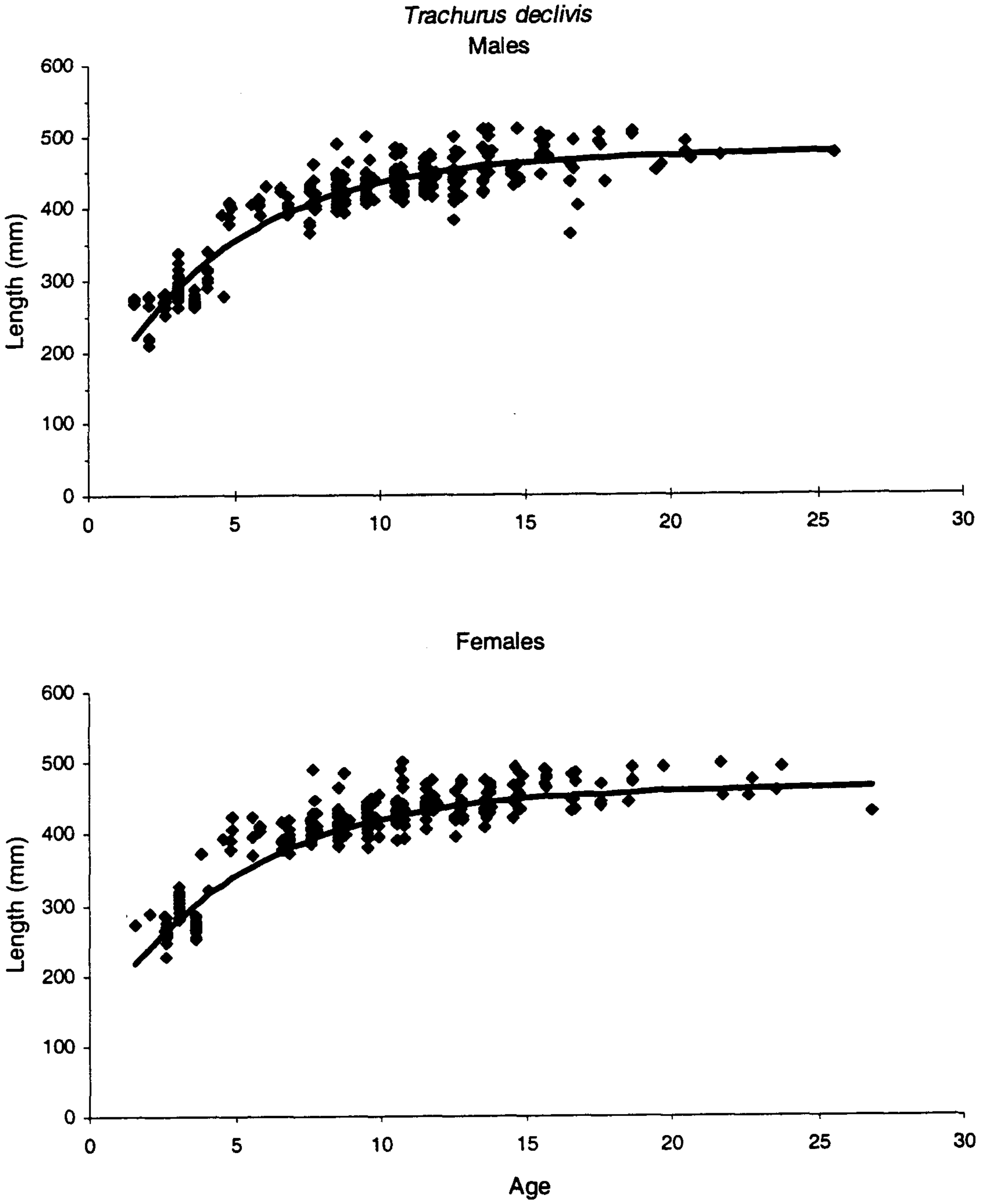


Figure 4: Growth curves for *Trachurus declivis* males and females.

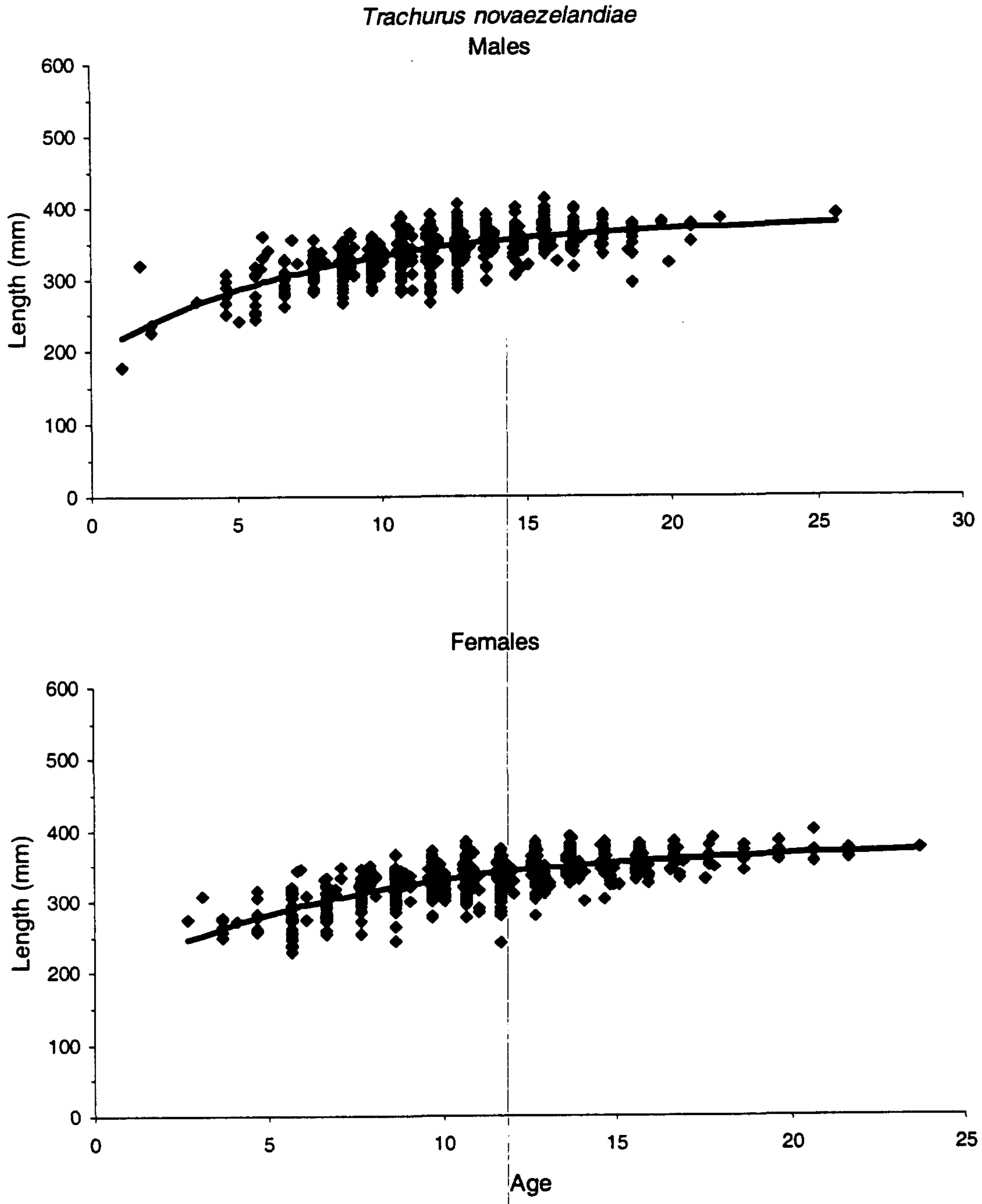


Figure 5: Growth curves for *Trachurus novaezelandiae* males and females.

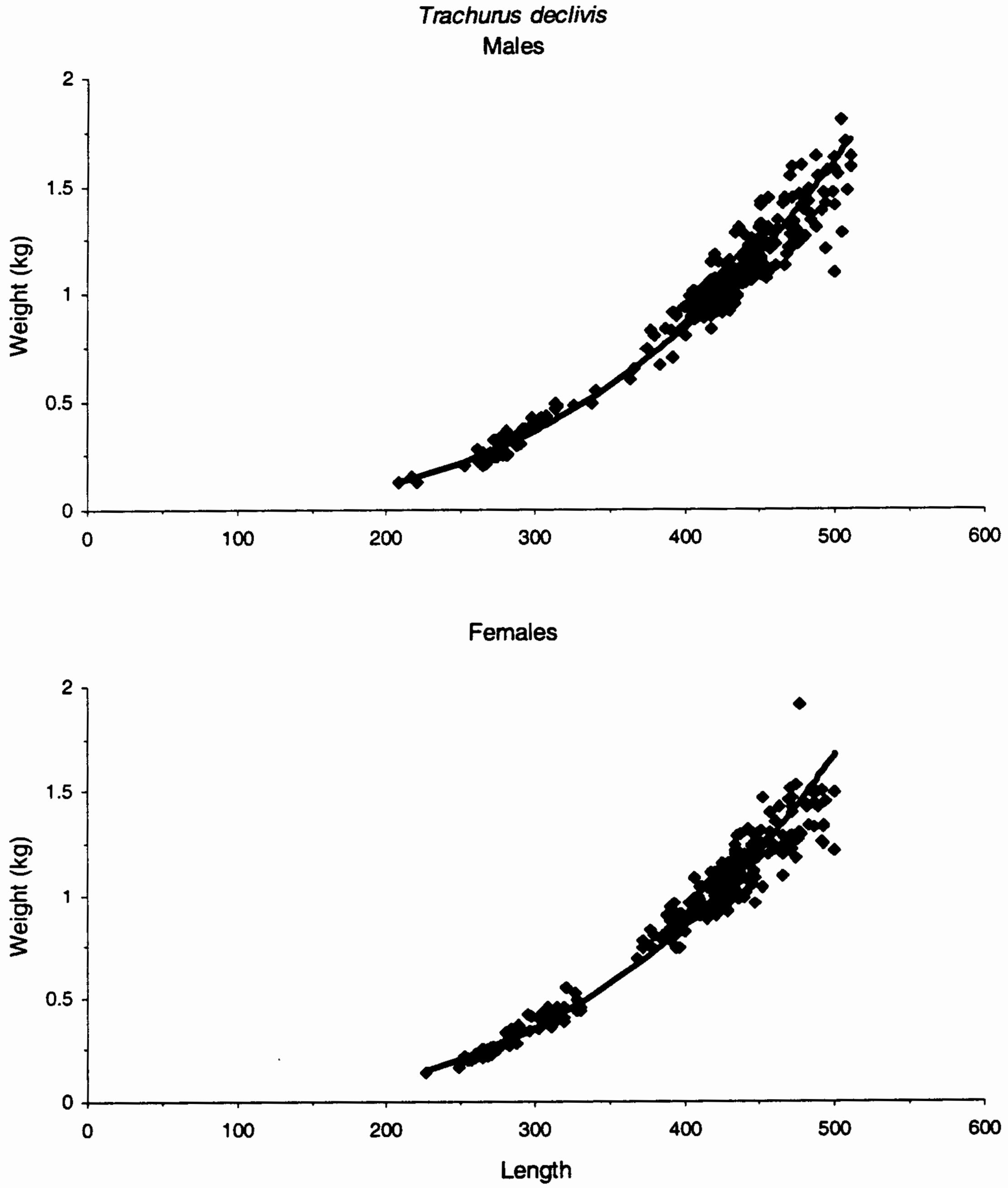


Figure 6: Length-weight plot for *Trachurus declivis* males and females.

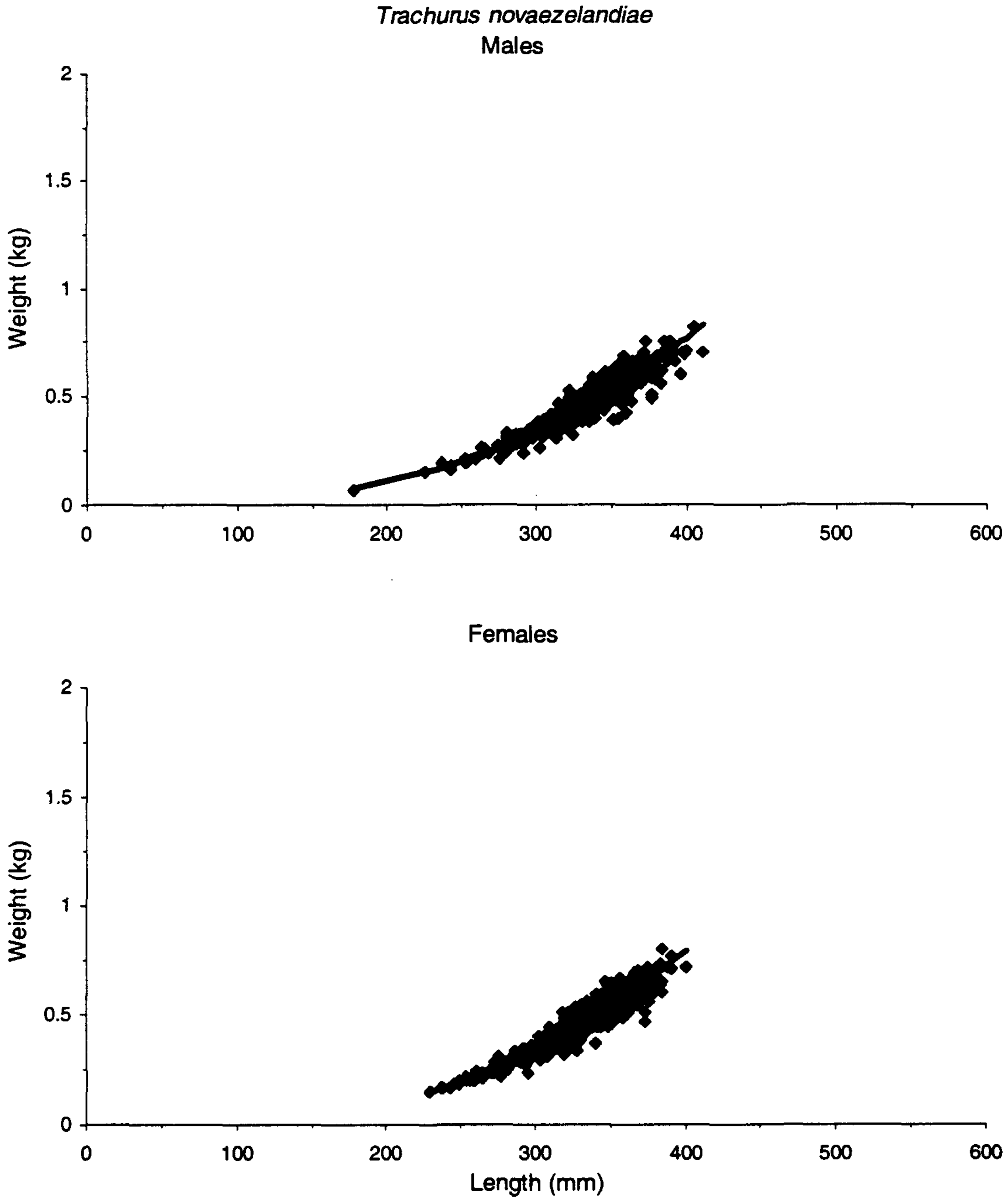
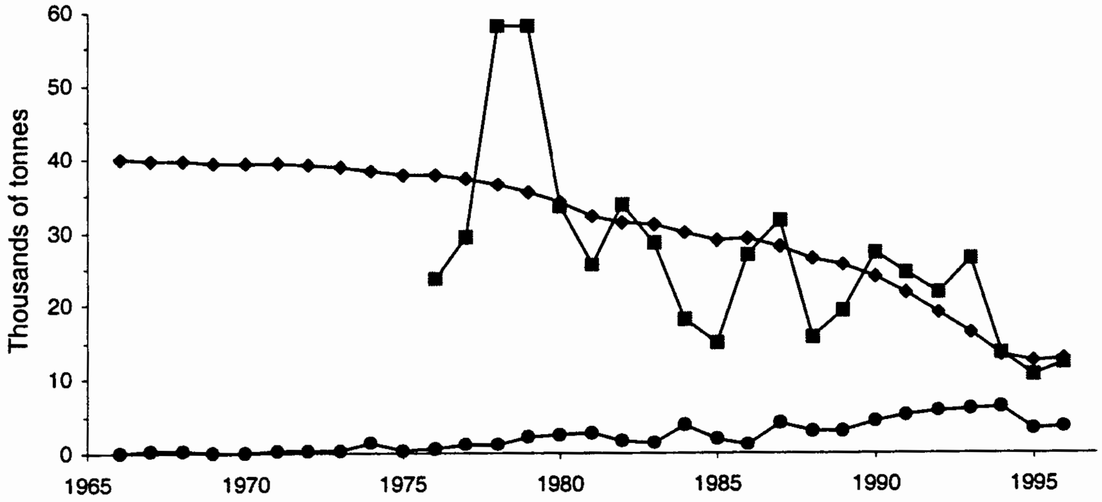


Figure 7: Length-weight plot for *Trachurus novaezelandiae* males and females.

Annual biomass & stock index
With 1976–77 indices



Without 1976–77 indices

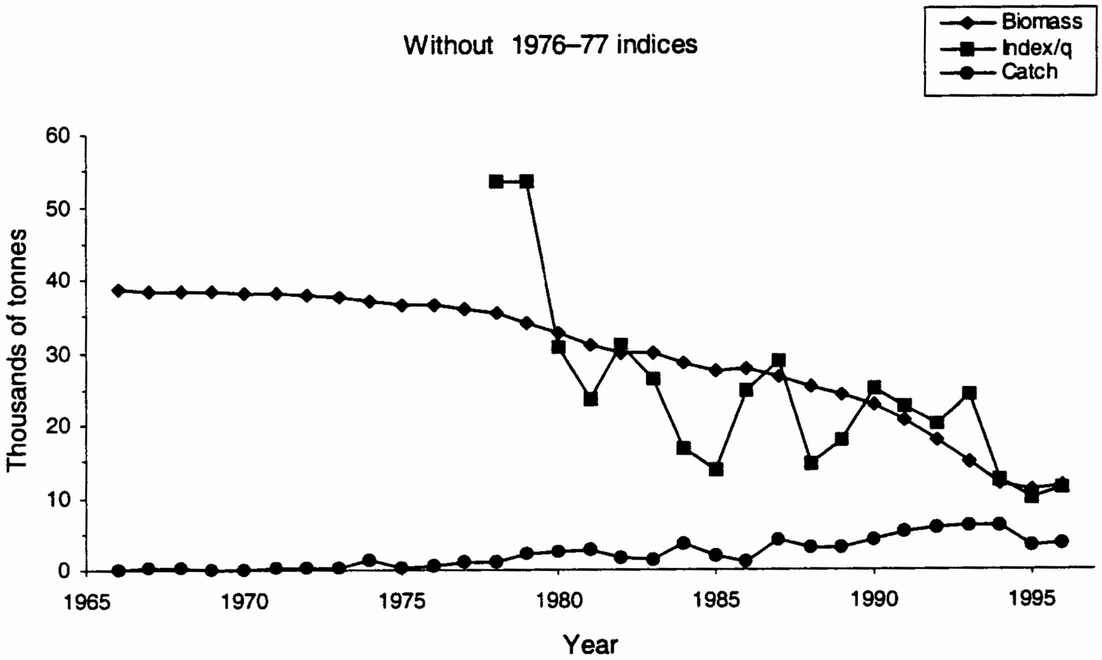


Figure 8: Biomass estimate, stock index, and total catch from deterministic stock reduction fit of *Trachurus declivis* and *Trachurus novaezelandiae* combined

Appendix 1: Estimating an age frequency for the total annual purse-seine catch of *Trachurus* species in JMA 1

Definitions

w_{jkl} is the weight of a sample of species l in grade j and sampled landing k.

n_{jkl} is the number of fish in the sample, of species l from grade j and sampled landing k.

m_{ijkl} is the number of fish of age i, in size group (grade) j, landing k, and species l; referred to as the *sub-sample.*

$W'_{jk'}$ is the weight of size group j, in landing k' of all landings (sampled and unsampled).

W_{jk} is the weight of size group j, in landing k of sampled landings only.

Step a, to estimate the number of individual fish in each grade of the sampled landings

The estimated weight of species l in size group j and landing k = $\dfrac{w_{jkl}}{\sum_l w_{jkl}} \cdot W_{jk}$

and the average weight of species l in size group j in landing k = $\dfrac{w_{jkl}}{n_{jkl}}$.

Therefore, the estimated number of fish in size group j, landing k, and species l is given by

$$N_{jkl} = \frac{w_{jkl} \cdot W_{jk}}{\sum_l w_{jkl}} \cdot \frac{n_{jkl}}{w_{jkl}}$$

$$= \frac{W_{jk} \cdot n_{jkl}}{\sum_l w_{jkl}}$$

Step b, to estimate the age frequency of each species in each grade of the sampled landings

The age frequency for species l in size group j and landing k is given by

$$M_{ijkl} = \frac{m_{ijkl} \cdot N_{jkl}}{\sum_l m_{ijkl}}$$

Step c, to estimate the age frequency of each species in each grade of all landings for the year (sampled and unsampled)

The estimated age frequency for species l in size group j the k'th landing of all landings for the year is given by

$$M'_{ijk'l} = \left(\sum_k M_{ijkl} \right) \cdot \frac{\sum_k W_{jk}}{\sum_{k'} W'_{jk'}}$$

Step d, to estimate the age frequency of each species in the annual landings

The estimated age frequency for species l in the annual catch is given by

$$M_{il} = \sum_j \left[\left(\sum_k M_{ijkl} \right) \cdot \frac{\sum_k W_{jk}}{\sum_{k'} W'_{jk'}} \right].$$

Appendix 2: Estimating species composition (proportions of the 3 jack mackerels) of the total annual purse-seine catch of *Trachurus* species in JMA 1

Definitions

w_{jkl} is the weight of a sample of species l in grade j and sampled landing k.

W_{jk} is the weight of size group j, in landing k of sampled landings only.

Step a, to estimate species in the sampled landings (y)

The proportion of species l in grade j and sampled landing k were based on the counts of the three species from the samples, and were applied to the total weight of grade j in landing k to determine its species composition by weight, using

$$W_{jkl} = \frac{w_{jkl}}{\sum_{l} w_{jkl}} \cdot W_{jk}$$

An estimate of the weight of species l in the sampled landing k is given by $\sum_{j} W_{jkl}$.

Step b, to estimate average species proportions in the grades of the sampled landings

The grade proportional distribution of species l in sampled landing k was estimated using

$$W'_{jkl} = \frac{W_{jkl}}{\sum_{j} W_{jkl}}$$

and the mean value was estimated for all of the sampled landings using

$$O_{jl} = \frac{\sum_{k} W'_{jkl}}{n_k}$$

where n is the number of landings that were sampled.

Step c, to apply averages to grade totals of the annual catch

The mean species proportions were used to estimate the tonnage of species l in grade j of the k'th landing of all landings for the year (sampled and unsampled)

$$W_{ljk'} = O_{jl} * W'_{jk'}$$

Step d, to estimate proportions of *Trachurus* species in the annual landings

The species were summed across each grade to get the totals for each species and these were divided by the grand total (of all species) to estimate the species proportions in the annual catch

$$P_l = \frac{\sum_j W_{ljk'}}{\sum_{ljk'} \sum_j W_{ljk'}}$$