MINISTRY OF FISHERIES

Te Tautiaki i nga tini a Tangaroa

Growth rate, age at maturity, longevity, and natural mortality rate of swordfish (*Xiphias gladius*)

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EXECUTIVE SUMMARY

Age and growth of swordfish (*Xiphias gladius*) in New Zealand waters were studied from counts of growth bands on cross sections of the second ray of the anal fin. Fin samples were collected by Ministry of Fisheries observers working on tuna longline vessels. Observers also collected maturity data, and length-frequency data were obtained from the longline observer database.

Thin sections were cut from fin rays 1.5 times the condyle width above the fin base. Sections were read blind (without knowing the fish length) by two readers. Readability scores were poor, but slightly better than have been achieved elsewhere for swordfish. Age-bias plots showed that Reader 2 produced higher ages, with a mean difference of 0.8 bands between readers. This was largely due to a difference in interpretation of the first band. Interpretation was also difficult at the outer edge of rays from large fish, where there appeared to be a number of thin bands.

Both sexes had similar length-at-age up to about 6 years, after which there were few males. Other studies have shown that female swordfish grow larger and faster than males, with the growth curves diverging after about 3–4 years. Our results are consistent with that conclusion, but the paucity of males older than 8 years means that we could not demonstrate a significant difference between the sexes.

The greatest age estimated in this study was 15.3 years, but this probably underestimates true longevity because of the small sample size and the fact that the population has been fished. Longevity may be about 20 years in the southwest Pacific Ocean.

The best estimate of M using Hoenig's method may be about 0.2. The best Chapman-Robson estimate of Z is 0.25 (assuming full recruitment at 5 years). This suggests that Z is not substantially greater than M, and that fishing mortality is not high. This conclusion is preliminary, and needs verification.

Due to problems with the gonad staging scheme (i.e., the non-separation of immature and resting fish), and the paucity of data, it was not possible to determine length at maturity from our data. However, swordfish from eastern Australia reach 50% maturity at about 221 cm for females and 101 cm for males. These lengths correspond to ages of 9.9 years and 0.9 years respectively. Thus males mature at a very young age, and females mature at a moderate age. Based on the preliminary results from this study, swordfish appear to be moderately productive, having a moderate female age at maturity, moderate longevity, and moderate natural mortality rate (relative to other fish species). Almost all of the commercial catch of males is likely to be mature, but about two-thirds of the females, which are mainly 2–12 years old, are probably immature. Swordfish may spawn rarely in northern New Zealand waters, but most spawning probably occurs in subtropical and tropical waters further north.

1.   INTRODUCTION

Swordfish (*Xiphias gladius*) is the only member of the family Xiphiidae. They are found in tropical, temperate, and sometimes cold waters of all oceans. The latitudinal range extends from 50° N to 45° S in the western Pacific Ocean. Swordfish distribution is largely governed by water temperature. It is a pelagic and oceanic species found in surface waters warmer than 13 °C. Swordfish occur in a wider range of water temperatures than any other billfish, 5–27 °C (Nakamura 1985).

The swordfish found in New Zealand are part of the same stock as others in the southwest Pacific Ocean, and possibly the whole Pacific. In New Zealand they commonly occur around the North and South Islands, especially north of 38° S (Francis et al. 1999, Murray et al. 1999, Bagley et al. 2000). Tagging studies show that swordfish are able to undergo long distance migrations (Ward & Elscot 2000). Swordfish make diurnal vertical movements between the surface at night and deeper water during the day, to about 650 m, although they may dive to 1000 m (Caton et al. 2002, Takahashi et al. 2003). The distribution of swordfish depends on size and sex, and also varies with seasonal fluctuations in water temperature and prey abundance (Ward & Elscot 2000).

Swordfish are the ninth to eleventh most abundant species caught on tuna longlines in the New Zealand EEZ, making up about 1.5% of the catch by number from 1986–87 to 2001–02 (Francis et al. 1999, 2000, 2001, Ayers et al. 2004).

In New Zealand, annual landings of swordfish reported by processors on Licensed Fish Receiver Returns were 283–1102 t per year in the 5-year period 1996–97 to 2000–01 (Anon 2003). Most swordfish are caught as bycatch in the surface longline fishery.

There have been no specific studies on age, growth, reproduction, or maturity of swordfish in New Zealand, but Young & Drake (2002) included New Zealand fish in their study of reproduction of swordfish from Australia. Anal fin rays have been used for determination of age and growth in swordfish elsewhere (Berkeley & Houde 1983, Tserpes & Tsimenides 1995, Sun et al. 2002, Young & Drake 2004). This report aims to address the information gaps for New Zealand swordfish in order to provide a scientific basis for determining their productivity.

This report addresses objective 3 of Ministry of Fisheries project TUN2003/01:
To determine the growth rate, age at maturity, longevity, and natural mortality rate of swordfish (*Xiphias gladius*).

2.   METHODS

2.1   Size composition of tuna longline catches

Length-frequency data collected by Ministry of Fisheries observers were extracted from the tuna longline database *l_line* (Mackay & Griggs 2001), and analysed by year and sex. The usual length measurement made on swordfish by observers is the lower jaw fork length (LJFL), measured as the distance between the tip of the lower jaw and the tail fork. In this report, all length measurements are given as LJFL. The term "fork length" refers to LJFL when used in this report.

2.2 Fin rays

Swordfish fins do not contain spines, and are composed solely of flexible rays. Anal fin ray samples (Figure 1) were collected by observers on tuna longline vessels during 2003 and 2004. Samples were collected on all trips from May 2003 to June 2004, and this covered 20 trips. Observers were instructed to collect fin rays and maturity information from as many swordfish as possible, including both males and females and a range of sizes. Samples were collected mainly from the west coast of the South Island, the east coast of the North Island, north of the Three Kings Islands, and around the Kermadec Islands (Figure 2). Associated data included LJFL, sex, and date. In the laboratory, a subsample of 261 fin rays was selected for ageing that was representative of the size and sex distribution of swordfish caught in the years sampled.

Fin samples were kept frozen until preparation for sectioning. After thawing, individual fin rays were dissected from their encapsulating tissue sheath and immersed in household-strength bleach for 10–15 minutes to remove any residual adherent tissue, then washed in water and allowed to air dry. Rays were then embedded in epoxy resin in a mould.

Initial trials were carried out to determine the optimum position for taking a cross section, using the condyle width (CW) to measure the distance from the base of the ray. The second and third rays were assessed at distances of 0.5, 1, 1.5, 2, 2.5, 3, and/or 3.5 times CW from the base of the ray. A section of the second ray taken at about 1.5 times CW from the base gave the best readability.

Resin blocks were sectioned using a dual-bladed petrographic sectioning saw to remove a section of ray between 1.5 and 2 times CW above the base. The 1.5x CW face was polished and embedded downface on a microscope slide. The upper, 2x CW, face was sequentially ground until growth bands became apparent under a stereomicroscope at a magnification of 10–40x.

Growth bands in the ray sections were counted under a stereomicroscope. The slides were read blind (without knowing fish length, sex, or date of collection) by two readers. A second blind reading was carried out by Reader 2.

The readability of each fin ray section was scored on a 5-point scale:
1. Clear
2. Good
3. Adequate but moderate uncertainty
4. Unclear and considerable uncertainty
5. Essentially unreadable but an estimate can be made

The blind readings by Readers 1 and 2 were used to assess between-reader bias from age-bias plots (Campana et al. 1995), a method that has been shown to be better at detecting reader bias than other frequently used techniques. An index of average percentage error (APE) and mean coefficient of variation (CV) across all age classes were calculated to enable comparison among sets of age determinations (Campana et al. 1995):

$$APE_j = 100 \times \frac{1}{R} \sum_{i=1}^{R} \frac{|x_{ij} - x_j|}{x_j}$$

$$CV_j = 100 \times \frac{\sqrt{\sum_{i=1}^{R} \frac{(x_{ij} - x_j)^2}{R-1}}}{x_j}$$

where x_{ij} is the ith age determination of the jth fish, x_j is the mean age of the jth fish, and R is the number of times each fish is aged. When APE_j and CV_j are averaged across many fish, they become an index of average percent error and the mean coefficient of variation respectively. The CV index is numerically 1.414 times greater than the APE index.

2.3 Growth rate estimation

In eastern Australian waters, swordfish have an extended spawning season in September–May; however, the peak occurrence of females with ripe eggs (hydrated oocytes) is in December–March (Young & Drake 2002, Young et al. 2003). Since New Zealand swordfish are probably part of the same stock that occurs off eastern Australia, we defined the theoretical birthday to be 1 February. One opaque and one hyaline band probably form annually in swordfish fin rays (based on marginal increment analysis of Australian fish), but the composition of the margin can vary among fish: narrow or wide opaque bands, or hyaline bands, may occur in any month of the year (Young & Drake 2004). Thus the timing of band formation is difficult to define, and variable. Therefore we did not correct the ages of the fish in this study for the time of year in which bands are deposited. New Zealand fish were caught between March and August, with most (91%) being caught in April–July. Ages were assigned to fish by adding the time elapsed between 1 February and the date of capture to the fin ray band count.

Growth curves were fitted to the length-at-age data using the von Bertalanffy growth model:

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

where L_t is the expected length at age t years, L_∞ is the asymptotic maximum length, K is the von Bertalanffy growth constant, and t_0 is the theoretical age at zero length. Growth curves were fitted separately to the length-at-age data for each sex using non-linear regression techniques based on the Marquardt-Levenberg least squares algorithm.

Growth curves were compared between the two sexes using likelihood ratio tests. Cerrato (1990) used Monte Carlo simulations to investigate the performance of a variety of methods (likelihood ratio test, t-test, univariate chi-squared test, and Hotelling's T^2 test) for comparing von Bertalanffy growth curves. He concluded "The likelihood ratio test is the most accurate of the procedures considered in this study and whenever possible it should be the approach of choice." Likelihood ratio tests are usually based on Kimura's (1980) maximum likelihood method of minimising the sum of least squared residuals. However, Kimura's method depends on an assumption that the residuals from the fitted von Bertalanffy curves are additive, normally distributed, and have constant variance. Instead, we used a distribution-free randomisation technique, which is not constrained by the distribution pattern of the residuals. A problem occurs if the two data sets being compared have different age frequencies; e.g., one data set may have mainly old fish and the other mainly young fish. The randomisation process might result in inappropriate allocation of fish to each data set, and this was overcome by selecting randomly within age classes (A. Dunn, NIWA, pers. comm.).

2.4 Maturity

Observers aboard tuna longliners recorded swordfish gonad development stages between April and August in 2003, and between March and July in 2004, from locations shown in Figure 2. The gonad staging scheme is shown in Appendix 1. Unfortunately this staging scheme does not distinguish between immature and resting fish: in the non-spawning season, the gonads of mature fish that have previously spawned and are reproductively 'resting' are histologically identical to the gonads of immature fish that are maturing for the first time (Young & Drake 2002). 'Immature' and 'resting' fish are combined in the observer staging scheme. The distributions of gonad stages by sex and length were investigated.

2.5 Natural and total mortality

The maximum age of fish in the samples provides a measure of longevity, albeit a biased one. Actual longevity is likely to be greater than that recorded in a relatively small sample, particularly if the population has been fished. An estimate of the natural mortality coefficient, M, was obtained using a technique based on an observed empirical relationship between M and longevity (Hoenig 1983). Hoenig (1983) compared published estimates of mortality rates and life spans for fishes, cetaceans, and molluscs and found a significant negative relationship between the two variables that explained (for fishes) 68% of the variability in M:

$$\log_e M = 1.46 - 1.01[\log_e(t_{max})]$$

where t_{max} is the maximum age reached by the species. The oldest fish in our aged samples was used as a minimum estimate of t_{max}.

We also estimated the total mortality rate (Z) from the aged sample of the population using the Chapman-Robson estimator (Chapman & Robson 1960):

$$Z = \log_e\left(\frac{1 + \bar{a} - 1/n}{\bar{a}}\right)$$

where $\bar{a}$ is the mean age above the recruitment age and n is the sample size. Dunn et al. (1999, 2002) showed that this estimator performed better than other catch curve methods in most situations. However, in this study, our sample size was small and unlikely to be a random sample from the population. Under ideal conditions (no annual variation in recruitment or mortality and no ageing error), the variance of the Chapman-Robson estimator is given by

$$Var(Z) \approx \frac{(1 - e^{-Z})^2}{ne^{-Z}}$$

The standard error of Z was calculated as the square root of the variance.

3. RESULTS

3.1 Size composition of tuna longline catches

Length-frequency distributions of swordfish that were (a) aged in this study, (b) measured by observers in the sample collection period (2003–2004), and (c) measured by observers during the period covered by the entire observer longline database (1987–2004), are shown in Figures 3 and 4. Cumulative frequency plots are shown in Appendix 2.

The swordfish aged in this study were similar in size composition to the swordfish measured by observers during the same years (Figure 3), indicating that our aged sample was representative of the catch. Swordfish measured by observers from 1987 to 2004 ranged in length from 68 to 330 cm (Figure 4). Females grow larger than males, ranging from 78 to 330 cm, with a mean of 186.6 cm, while males were in the range 76–289 cm, with a mean of 162.9 cm.

The relative proportions of small fish (less than 130 cm) and large fish were quite variable among years, e.g., there were a lot of small fish in 2001. There is some evidence of progression of small fish through to larger size classes, but length-frequency mode progression was not clearly distinguishable, except perhaps in 1992–94.

3.2 Fin rays

A total of 261 swordfish were aged using anal fin rays, but three samples were not used for growth analysis as length was not recorded, and a further six outliers were not used because they appeared to have incorrect lengths. The final sample used for growth analysis was 252 fish, comprising 75 males, 167 females, and 10 unsexed fish.

Fin ray sections showed alternating light and dark bands, but their relative width varied considerably. Bands were often difficult to count: readability scores ranged from 1 to 5 for one reader and 2 to 5 for the other reader, and scores were mostly 3 or 4 (Table 1).

A 'good' swordfish ray section is shown in Figure 5. Figures 6 and 7 show some more difficult examples.

Reader 2 counted, on average, 0.8 more bands than Reader 1 up to age 10 (Figure 8). This difference was a result of Reader 2 tending to count one more inner band (near the centre of the ray). Interpretation was also difficult at the outer edge of rays from large fish, where there appeared to be a number of thin bands, but sample sizes were too small for older fish to determine whether the ageing bias was also present in them. Figure 8 also shows an age-bias plot for the two readings by Reader 2, showing within-reader comparison. The second readings were generally a bit lower for swordfish older than 6 years.

The average APE index for the within-reader comparison was 7.1%, and the mean CV was 10.0%. These values are high relative to a CV of about 5% often achieved for fishes of moderate longevity and reading complexity (Campana 2001), indicating that swordfish fin rays were difficult to age. However, our results are slightly more precise than the APE of 8.35% achieved for eastern Australian swordfish and 8.9% for western Australian swordfish (Young & Drake 2004), and 8.5% achieved for Taiwanese swordfish (Sun et al. 2002). We consider our precision acceptable, and that improved consistency would result from increased experience with this species (the present study was the first time the readers had read swordfish fin rays).

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We used Reader 2's ages for growth rate estimation because there is evidence from other swordfish ageing studies that the first annual band may be missing or overlooked in older fish, resulting in age underestimation (Berkeley & Houde 1983, Sun et al. 2002). The older ages of Reader 2 are therefore likely to be more realistic. We used the second of Reader 2's two readings because the experience gained during the first reading assisted with the interpretation of the banding pattern during the second reading.

3.3 Growth rate estimation

Both sexes had similar length-at-age up to about 6 years, after which there were few males (Figure 9). A randomisation test showed that von Bertalanffy growth curves were not significantly different between the two sexes ($p = 0.256$), but a high proportion of the 499 randomisations failed to converge successfully within the maximum number of iterations. Inspection of the von Bertalanffy parameter estimates showed that the male L_∞ was implausibly high and had a very high standard error (Table 2). This was apparently caused by two outliers, a 255 cm male aged 7.2 years, and a 285 cm male aged 15.2 years (Figure 9). These two fish are very large for males (see Figure 3), and may have been females that were incorrectly sexed. Von Bertalanffy growth curves were re-fitted after removal of these two outliers, resulting in improved parameter estimates (Table 2) and a slightly flatter growth curve (Figure 9), but the growth difference between males and females was still non-significant ($p = 0.17$). Other studies have shown that female swordfish grow larger and faster than males, with the growth curves diverging after about 3–4 years (Berkeley & Houde 1983, Sun et al. 2002, Young & Drake 2004). Our results are consistent with that conclusion, but the paucity of males older than 8 years means that our significance test lacks power. We consider it likely that New Zealand females grow faster than males, and recommend that the growth parameters for females, and males excluding outliers (Table 2, bold rows), be used to model growth in this species. The covariance matrix of parameter estimates is given in Table 3.

All growth curves intersected the length axis at positive values (about 75–90 cm) (Figure 10). Most other studies of swordfish growth have suffered from the same problem (Sun et al. 2002, Figure 10). There are several possible reasons for this.
- Our counts underestimate true age.
- Longlines selectively capture only the larger fish from each of the youngest age groups, biasing mean lengths upwards.
- Fish grow very fast during the first year of life, and the lack of fish shorter than 80 cm means that the left-hand ends of the growth curves are poorly defined.
- Failure to account for the timing of growth band formation resulted in underestimation of ages (bias would be less than one year).

There is good evidence that swordfish grow very rapid initially, reaching 100 cm or more within the first year (Ehrhardt 1992, Megalofonou et al. 1995, Young & Drake 2004). Furthermore, there is evidence that the first annual band may be missing in older fish, resulting in age underestimation (Berkeley & Houde 1983; Sun et al. 2002).

Attempts have been made to fit growth models other than the von Bertalanffy model to swordfish data in order to overcome the problem of high positive length-axis intercepts (and strongly negative t_0 values) (Sun et al. 2002). But although more realistic models have been generated, the lack of age data for swordfish younger than 1+ means that the alternative models are essentially artificial extrapolations of the data.

3.4 Maximum age

The greatest age estimated in this study was 15.3 years, but this probably underestimates true longevity because of the small sample size and the fact that the population has been fished. Swordfish have been aged to 15 and 18 years in western and eastern Australia respectively (Young & Drake 2004). Longevity may be about 20 years in the southwest Pacific Ocean.

3.5 Natural and total mortality

Using maximum ages of 15 and 20 years, Hoenig's method provides M estimates of 0.28 and 0.21 respectively (Table 4).

The age composition of the sample of aged swordfish is shown in Figure 11. The mode of the distribution was 5–6 years, suggesting full recruitment by that age. However, our sample was probably not a random sample of the swordfish population and so this remains uncertain.

The Chapman-Robson estimates of Z were 0.25–0.28 for ages at recruitment of 5–6 years (Table 5). The standard errors of these estimates are probably unrealistically low, because the assumptions underlying them are unlikely to have been met. Annual variation in recruitment or mortality and ageing error can inflate the standard errors substantially (Dunn et al. 1999, 2002).

3.6 Maturity

Gonad stage was recorded for 119 males and 247 females (Figure 12). Most males (66%) were immature/resting, 32% were maturing, 3 fish (3%) were recorded as ripe, and there were no running ripe or spent males. Most females (64%) were immature/resting, 34% were maturing, one fish (0.4%) was ripe, one fish (0.4%) running ripe, and three fish (1%) were recorded as spent. These three "spent" fish were probably staged incorrectly as they were all small. Due to problems with the gonad staging scheme (i.e., the non-separation of immature and resting fish), and the paucity of data, it is not possible to determine length at maturity from our data. Gonad width was measured for 110 males and 251 females (Figure 13). There was no abrupt change in gonad width at any particular length.

Immature/resting fish were found in all areas where swordfish were caught (see Figure 2). Most of the maturing fish were found north of 40° S. All of the fish recorded as ripe, running ripe, or spent were caught north of 37° S off the east coast of the North Island, near Three Kings or near the the Kermadec Islands. Time of spawning could not be determined from our data. The ripe female was caught in April 2004 and the running ripe female in March 2004. The three females recorded as spent were caught in June and August 2003 and May 2004. Ripe males were recorded in July 2003 and April 2004.

4. DISCUSSION

Both readers found fin sections from this species difficult to interpret and readability scores were poor. However the precision of our estimates was slightly better than has been achieved for swordfish elsewhere. Due to difficulties in band interpretation, particularly the position of the first band, there were systematic differences between readers. No ageing validation was possible in this study, so we were unable to determine which set of age estimates was more reliable. We used the second reading by Reader 2 as the best estimate of age. The growth curves we generated

for New Zealand swordfish were similar to those from eastern and western Australia (Young & Drake 2004). Since the Australian study produced evidence from marginal increment analysis that fin ray bands are deposited annually (Young & Drake 2004), our New Zealand growth curves are considered reliable, except during the first year of rapid growth. Future work should attempt to obtain swordfish shorter than 100 cm in order to define the left-hand end of the growth curve better.

Anal fin rays have been used to age swordfish in a number of other studies (Berkeley & Houde 1983, Tserpes & Tsimenides 1995, Sun et al. 2002, Young & Drake 2004). Growth curves for New Zealand swordfish fall in the middle of the range reported elsewhere (Young & Drake 2004).

Two swordfish tagged and recaptured in New Zealand waters provide growth information that can be compared with our age-based growth curves. Where necessary, we estimated fish length at tagging or recapture from the weight estimated by fishers (using a length-weight regression). Because sex was not determined for either fish, we estimated age at tagging as the mean of the ages predicted for males and females using the growth curves in Table 2. Age at recapture was calculated from the estimated age at tagging plus the period at liberty. The first fish was tagged in 1991 at an estimated length of 105 cm and age of 1.5 years, and recaptured 10.7 years later at an estimated length of 205 cm and age of 12.2 years. The second fish was tagged in 1996 at an estimated length of 118 cm and age of 2.4 years, and recaptured 8.3 years later at a length of 165 cm and estimated age of 10.7 years. When these values are plotted in Figure 10, the growth of the first fish is close to that predicted for a male swordfish. The growth of the second fish falls below that predicted for males, but is still within the range of the length-at-age data for both sexes (see Figure 9). Thus the growth of both tagged swordfish is consistent with our age-based results.

Swordfish appear to grow extremely rapidly in their first year, probably reaching about 1 m in length. The growth rate declined markedly after about two years, and became almost linear, but declined over time at a very slow rate. Length at maturity could not be estimated adequately because of an almost complete absence of ripe fish. However, swordfish from eastern Australia reach 50% maturity at about 221 cm for females and 101 cm for males (Young & Drake 2002). These lengths correspond with ages of 9.9 years and 0.9 years respectively, based on our growth curves in Table 2. Thus males mature at a very young age, and females mature at a moderate age that is about 50% of the maximum age. This large difference in age at maturity between males and females is the result of the large difference in length at maturity and the rapid decrease in growth rate after about a year, but is consistent with results reported elsewhere. Our estimate of female age at maturity is consistent with the estimate of 10 years from Australia (Young & Drake 2004), which is not surprising given the use of the same length at maturity estimate and similar growth curves.

The techniques we used for estimating M and Z both have strong limitations. The Hoenig method of estimating M is based on a meta-analysis of data from other species. It has a high (but unquantifiable) variance, and it relies on an accurate estimate of the longevity of swordfish. In an exploited population from which a small sample is taken, longevity may be considerably underestimated. The greatest swordfish age estimated in this study was 15.3 years, but longevity may be about 20 years in the southwest Pacific Ocean (see also below). Consequently the best estimate of M using Hoenig's method may be about 0.2.

An alternative method for estimating M involves use of the "life history invariant" relationship between M and the von Bertalanffy constant K (Beverton & Holt 1959, Charnov 1993, Jensen 1996):

$M = 1.5\,K$

Substituting our estimates of K from Table 2 into this equation produces much lower estimates of M of 0.07–0.08. We believe these estimates are unreliable because K has been poorly estimated, as indicated by its large standard errors (see Table 2), the unrealistically high estimates of L_∞, and the very high correlation between K and L_∞ (see Table 3). These problems with estimating the von Bertalanffy growth parameters result from high variance in the length-at-age data, and the slow convergence of the growth curves to an asymptote (Figure 9).

The Chapman-Robson estimator of Z is affected by sampling bias, ageing errors, and annual variation in recruitment and mortality. The age-structure shown in Figure 11 shows signs of under-representing the older swordfish: for an age at recruitment of 5 years, a Z estimate of 0.25, and a sample size of 190 (as was available for our study), we predict that about nine swordfish between 16 and 20 years should have been present in our samples. Their absence might have been caused by many factors, such as random chance resulting from small sample size; loss of larger (and potentially older) swordfish from the lines; absence of larger (older) swordfish from the region fished; logistical problems for observers in sampling large swordfish for fin rays; increasing natural or fishing mortality for old fish. Loss or absence of larger and older swordfish could have caused both M and Z to be over-estimated. Nevertheless, our best estimate of Z is 0.25 (assuming full recruitment at 5 years). This suggests that Z is not substantially greater than M, and that fishing mortality is not high. This conclusion is preliminary, and needs verification.

Based on the preliminary results from this study, swordfish appear to be moderately productive, having a moderate female age at maturity, moderate longevity, and moderate natural mortality rate (relative to other fish species). Almost all of the commercial catch of males is likely to be mature, but about two-thirds of the females, which are mainly 2–12 years old, are probably immature (see Figure 3).

Young et al. (2003) found only reproductively inactive females around northern New Zealand in January–February 2001, but recorded spawning females off the Queensland coast. They suggested that the water temperature around New Zealand was too low for spawning, even in summer. However, our gonad stage data indicate that spawning may occur rarely in northern New Zealand waters. Nevertheless, the main spawning areas are expected to be further north in subtropical or tropical waters.

Future work
Swordfish appear to grow very fast in their first year, but the left-hand end of the growth curve is poorly defined due to lack of small fish in the sample. More large fish are needed to achieve a better fit at the right-hand end and to obtain a better estimate for maximum age. Other studies have shown a difference in growth rate between males and females, which we believe is likely here. Collection of some more small and large fish could help to clarify these things.

We therefore recommend that observers collect anal fins from the following:
- Males over 150 cm (n=150)
- Females over 230 cm (n=50)
- All swordfish less than 130 cm (n=100)

We also recommend that observers continue to collect maturity data, particularly from the northern region because this study has shown that swordfish spawn occasionally in northern waters, and more information is needed about length at maturity and timing of spawning.

5.   ACKNOWLEDGMENTS

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Table 1: Readability scores for swordfish fin rays by reader.

Band count	Reader 1 Readability score					Band count	Reader 2 Readability score			
	1	2	3	4	5		2	3	4	5
0				3		0				
1	1	3	7	2	1	1		9	1	
2		2	16	6		2	2	11	1	
3	2	5	18	7	1	3	1	16	3	
4	1	4	11	10	4	4	1	10	6	1
5		3	6	5	1	5	1	19	9	1
6		5	11	3		6	2	17	9	3
7		7	12	3	1	7	1	17	4	
8		3	11	2		8	1	12	6	
9		2	6	7	1	9		13	5	1
10		2	7	7	1	10		16	5	3
11	1	1	10	3	1	11		12	3	
12		2	11	1		12	1	11		
13		1	1	1		13		8	1	
14		2	5		1	14		5		
15			1			15		4		
Total	5	42	133	60	12	Total	10	180	53	9

Readability scores: 1, clear; 2, good; 3, adequate but moderate uncertainty; 4, unclear and considerable uncertainty; 5, essentially unreadable but an estimate can be made.

Table 2: Swordfish growth curve parameters for Reader 2. Estimates for males are provided with and without two outliers (see Figure 9). We recommend that the growth parameters for females, and males excluding outliers (bold rows), be used to model growth in this species. SE, standard error.

Sex	Sample size	$L_\infty \pm$ SE (cm)	$K \pm$ SE	$t_0 \pm$ SE (years)
Both	252	576.6 ± 209.7	0.033 ± 0.018	–4.55 ● 1.09
Females	**167**	**434.7 ± 105.8**	**0.053 ± 0.023**	**–3.46 ± 1.18**
Males (all)	75	526.5 ± 457.5	0.030 ± 0.039	–6.07 ± 2.67
Males (excl. outliers)	**73**	**394.4 ± 248.5**	**0.044 ± 0.047**	**–5.86 ± 2.72**

Table 3: Correlation matrices for the von Bertalanffy growth parameters for swordfish.

		L_∞	K	t_0
Both sexes	L_∞	1.000	–0.998	–0.933
	K		1.000	0.952
	t_0			1.000
Females	L_∞	1.000	–0.995	–0.913
	K		1.000	0.947
	t_0			1.000
Males (excl. outliers)	L_∞	1.000	–0.997	–0.949
	K		1.000	0.969
	t_0			1.000

Table 4: Hoenig (1983) estimates of natural mortality rate (*M*) for swordfish using longevities of 15–20 years.

Age (years)	M
15	0.279
16	0.262
17	0.246
18	0.232
19	0.220
20	0.209

Table 5: Chapman-Robson estimates of total mortality rate (*Z*) with standard errors (SE) for various ages at full recruitment.

Age at recruitment	Z	SE
5	0.252	0.018
6	0.277	0.022
7	0.297	0.026
8	0.339	0.033
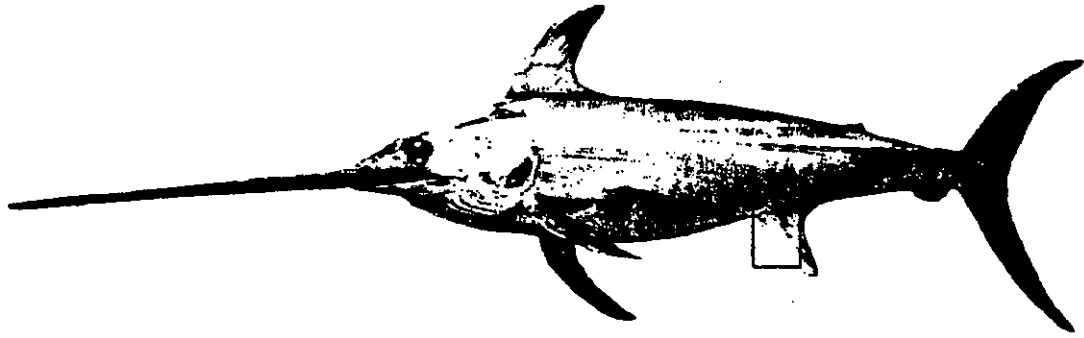
Figure 1: Swordfish showing location of anal fin rays sampled for ageing.
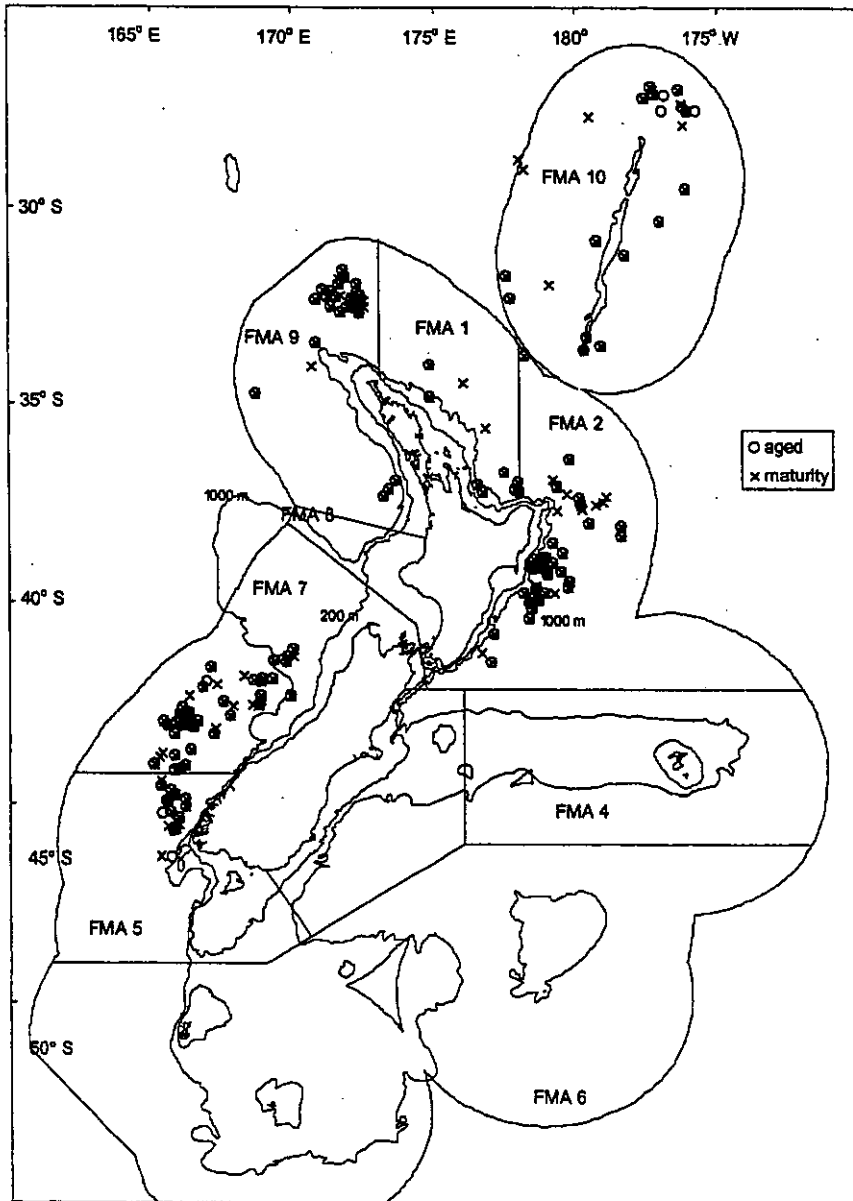
Figure 2: Capture locations for swordfish that were aged and assessed for gonad maturity.
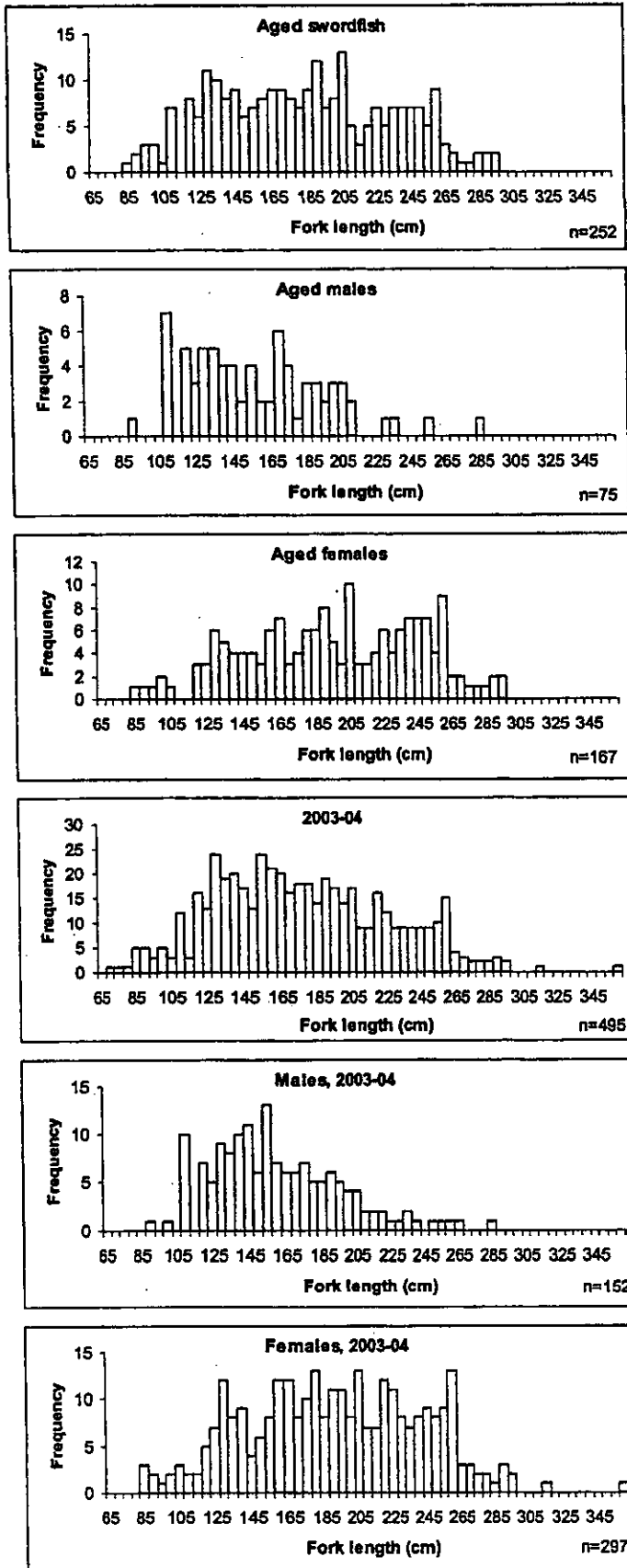
Figure 3: Length-frequency distributions for swordfish that were aged in this study, compared with distributions for all swordfish measured by observers aboard tuna longliners in 2003 and 2004. Fork length = lower jaw fork length (LJFL).

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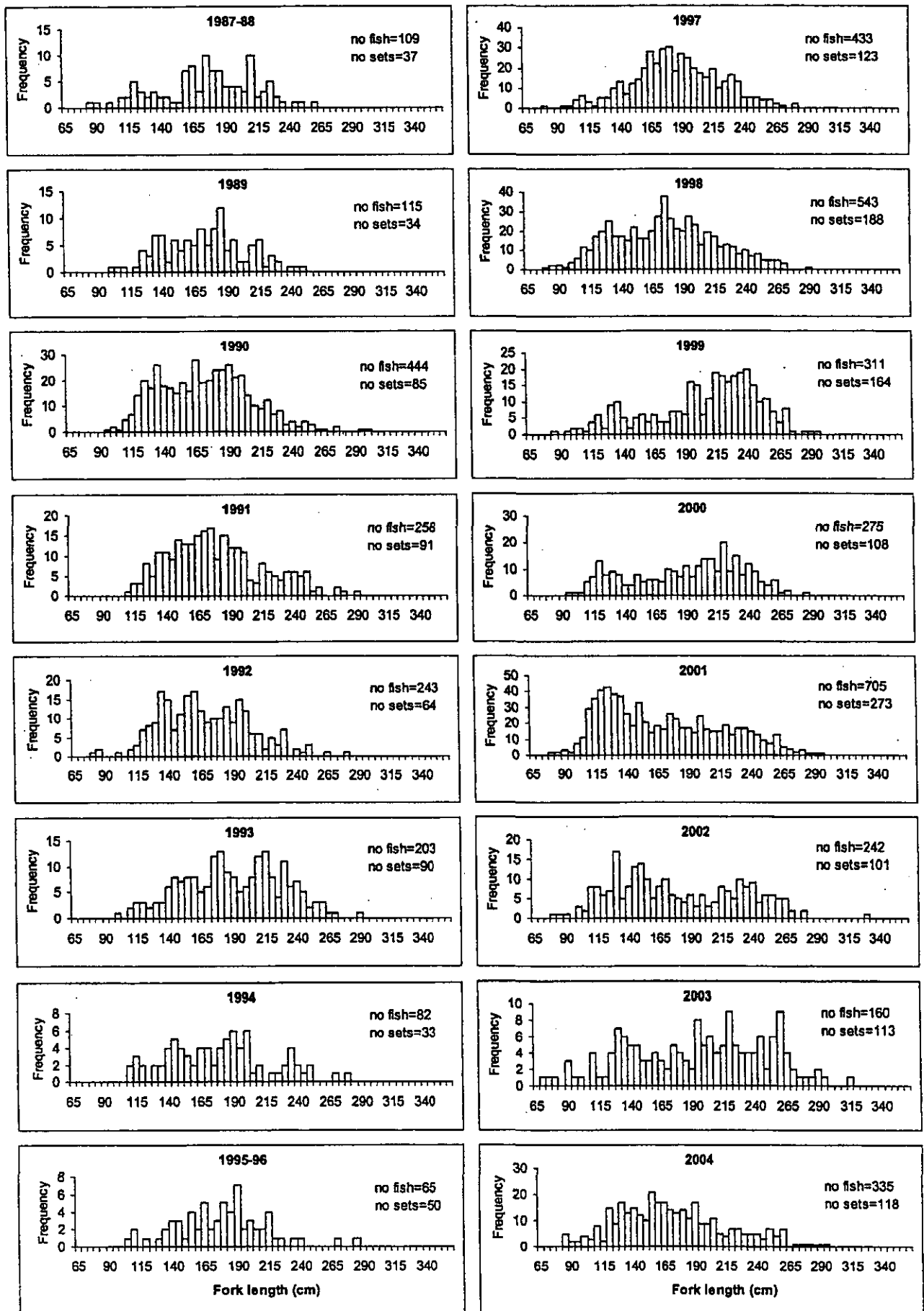
Figure 4: Length-frequency distributions by year for swordfish measured by observers aboard tuna longline vessels, 1987–2004, both sexes combined. Fork length = LJFL. 1987 and 1988, and 1995 and 1996 combined due to small number of fish in these years.
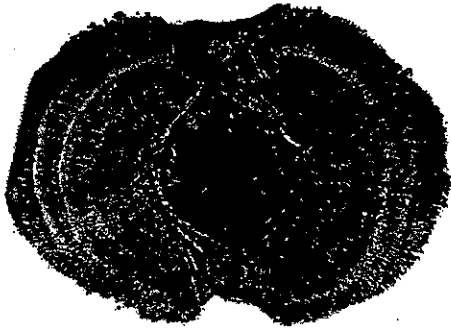
Figure 5: Fin ray section from a 138 cm female swordfish showing growth bands. This section was scored as readability 2 (good) by one reader and 3 (adequate) by the other reader. Age was determined to be 5 years.

Figure 6: Fin ray section from an 83 cm FL female swordfish, scored as readability 3 or 4 (adequate to unclear). Age was determined to be 0 or 1 depending on reader.

Figure 7: Left side of a fin ray section from a 292 cm FL female swordfish, scored as readability 3 (adequate). Age was determined to be 12 or 15 years depending on reader.

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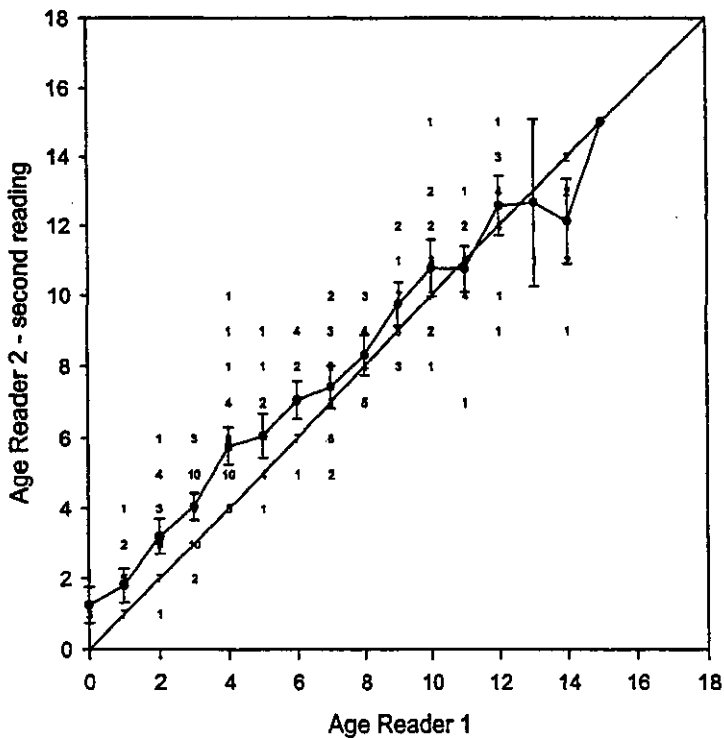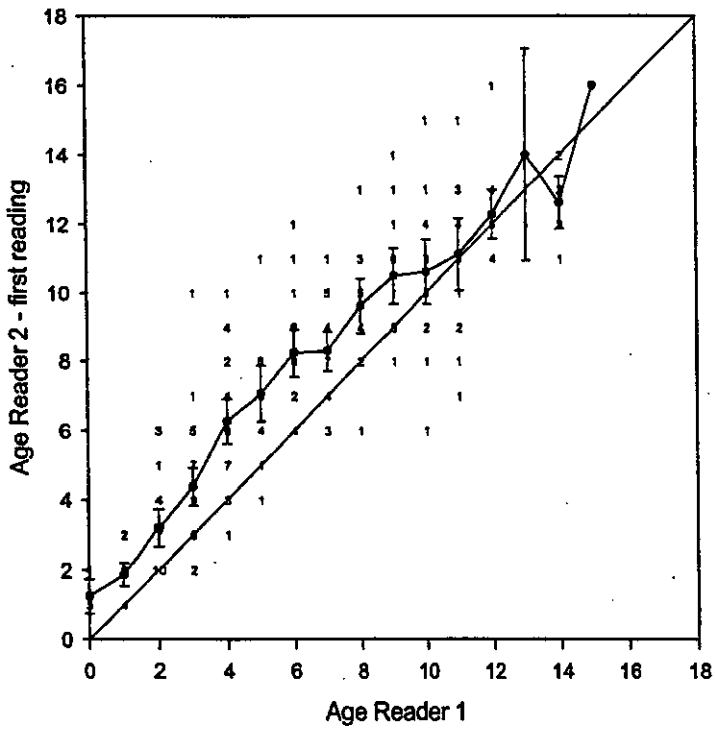
Figure 8: Age-bias plots, comparing both of the fin ray counts by Reader 2 with counts by Reader 1. Symbols with error bars show the mean count of Reader 2 (± 2 standard errors) relative to the counts of Reader 1. Diagonal line indicates the expected relationship. Numbers represent number of fish. Sample size = 261.
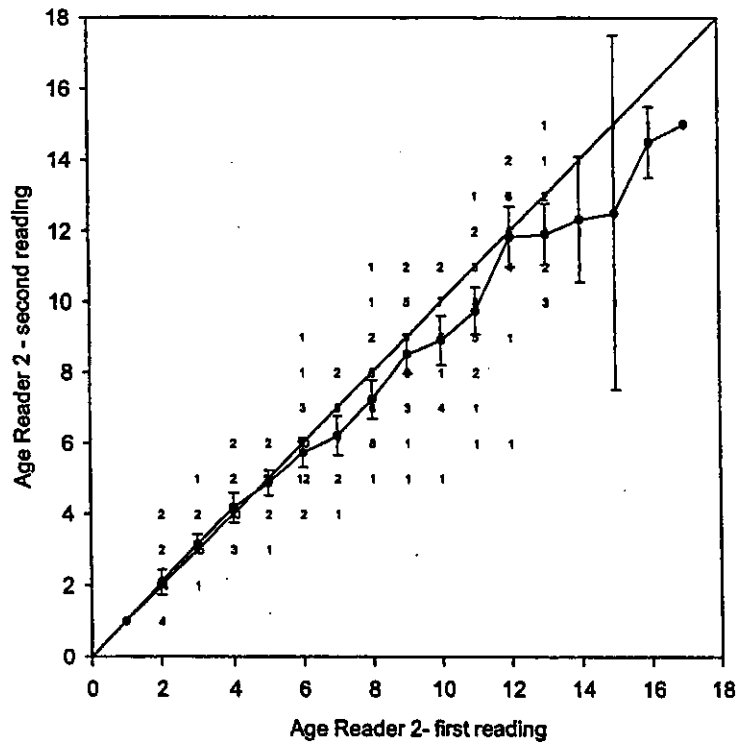
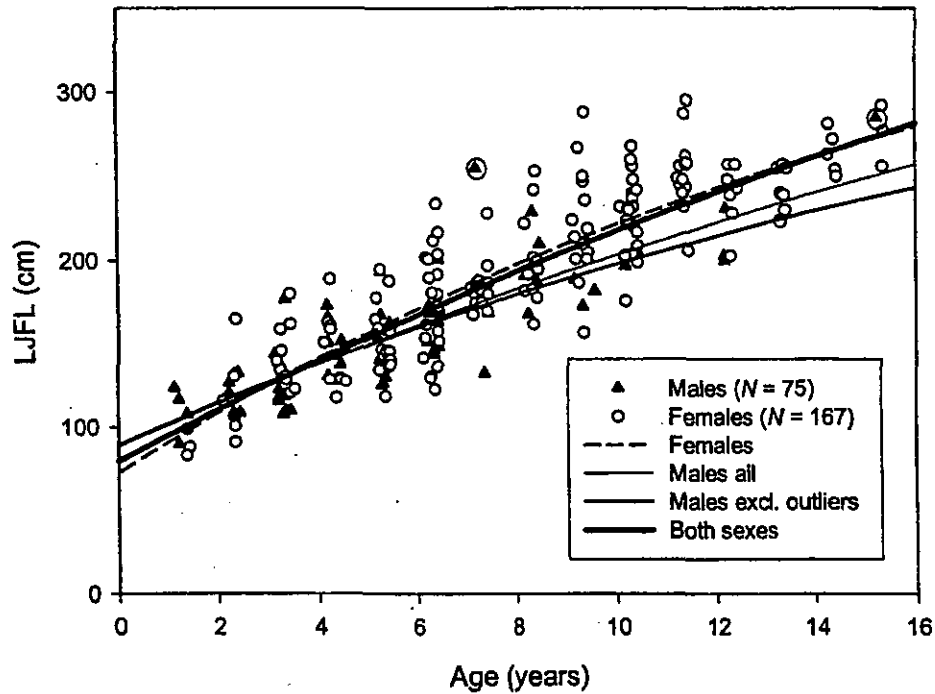Figure 8 (continued): Age-bias plots, comparing two readings of fin ray counts by Reader 2 . Symbols with error bars show the mean count of the second reading (± 2 standard errors) relative to the counts of the first reading. Diagonal line indicates the expected relationship. Numbers represent number of fish. Sample size = 261.

Figure 9: Length-at-age relationships for male and female swordfish, with fitted von Bertalanffy growth curves. Two male outliers that may have been incorrectly sexed are circled. Growth curves are shown for all males, and after excluding the two outliers. LJFL, lower jaw fork length.
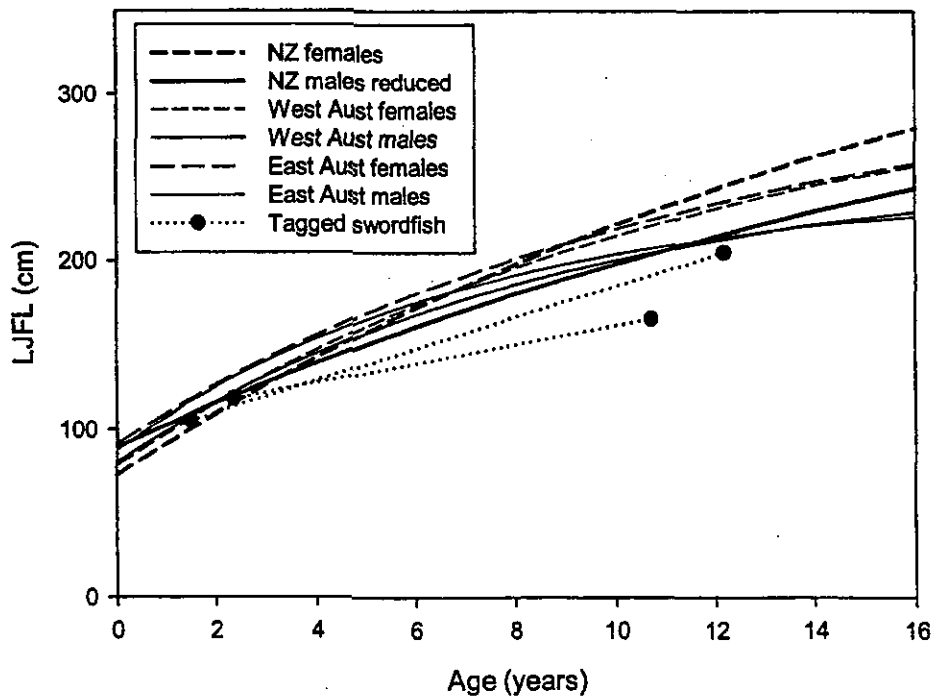
Figure 10: Comparison of New Zealand swordfish von Bertalanffy growth curves (present study) with growth curves from eastern and western Australia (Young & Drake 2004). LJFL, lower jaw fork length. Also shown are the growth increments of two swordfish tagged in New Zealand waters.
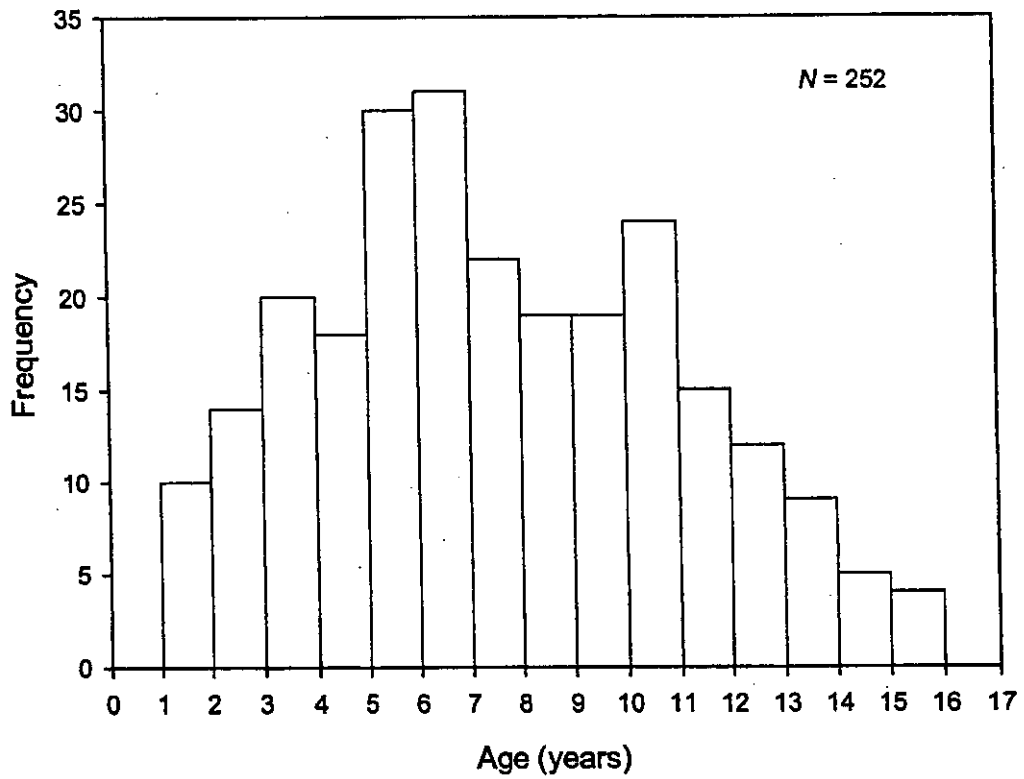
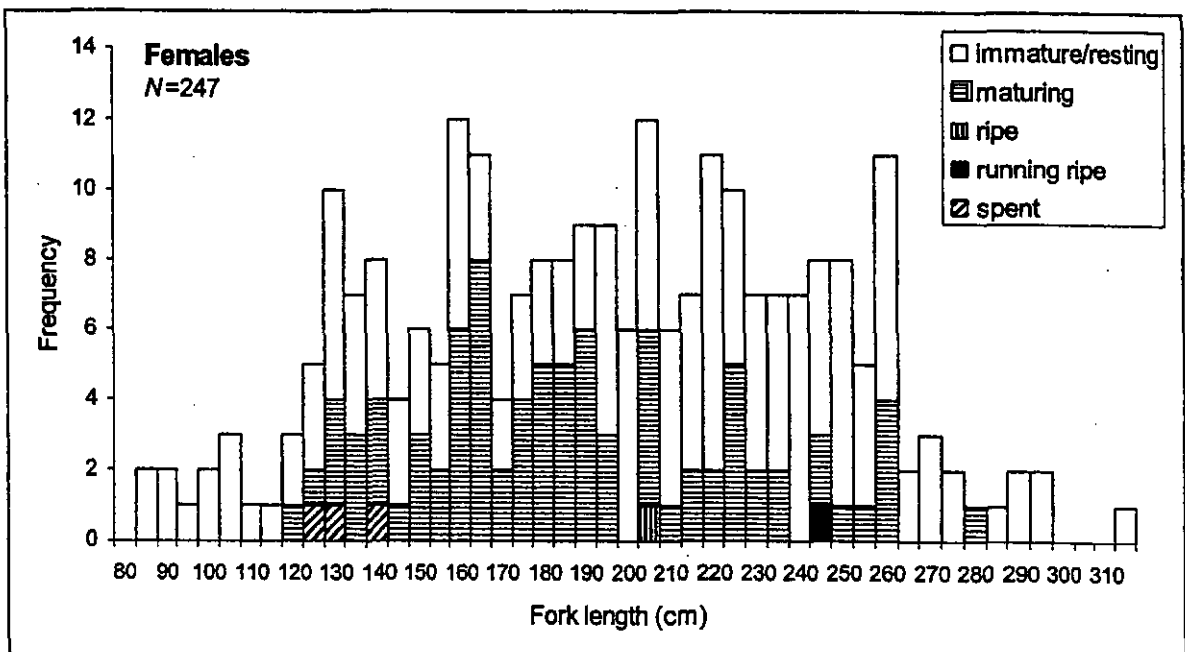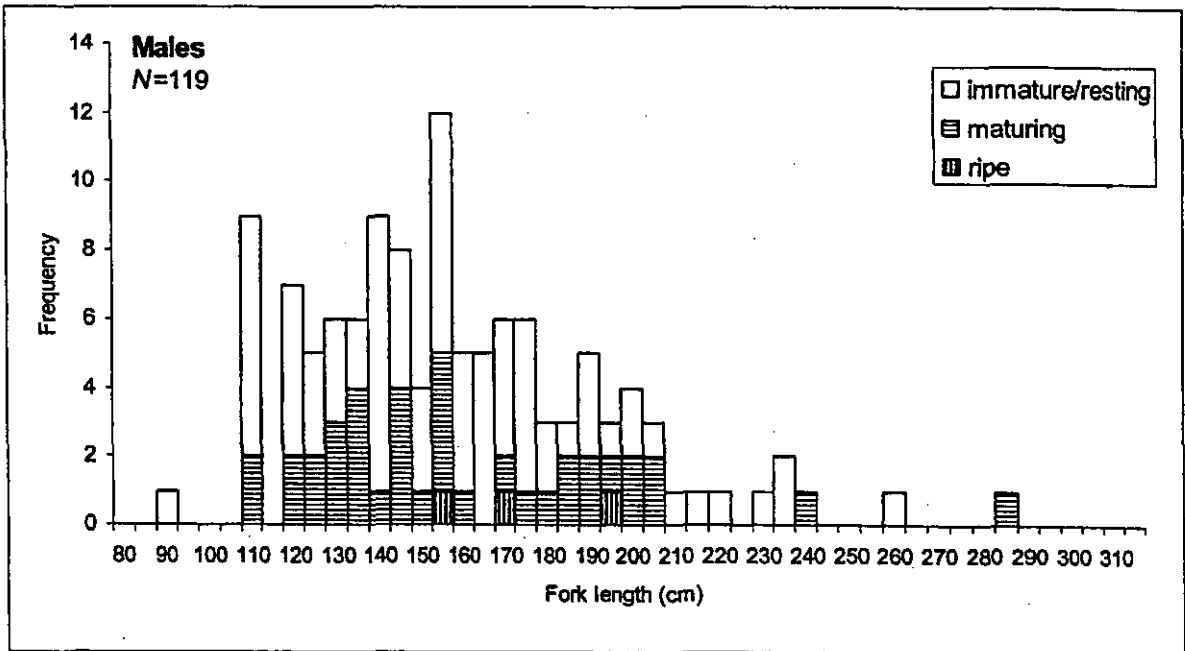Figure 11: Age-frequency distribution for swordfish aged in this study.

Figure 12: Relationship between gonad development stage and fork length for male and female swordfish. (Fork length = lower jaw fork length).
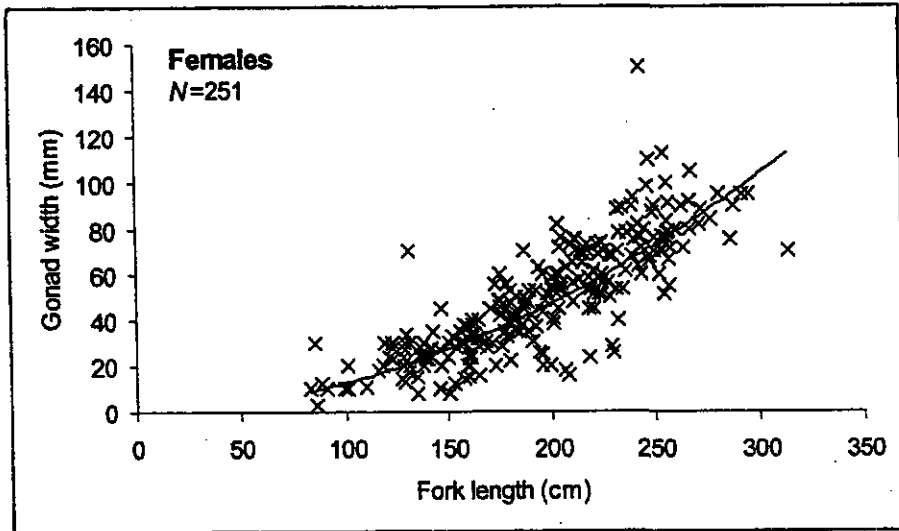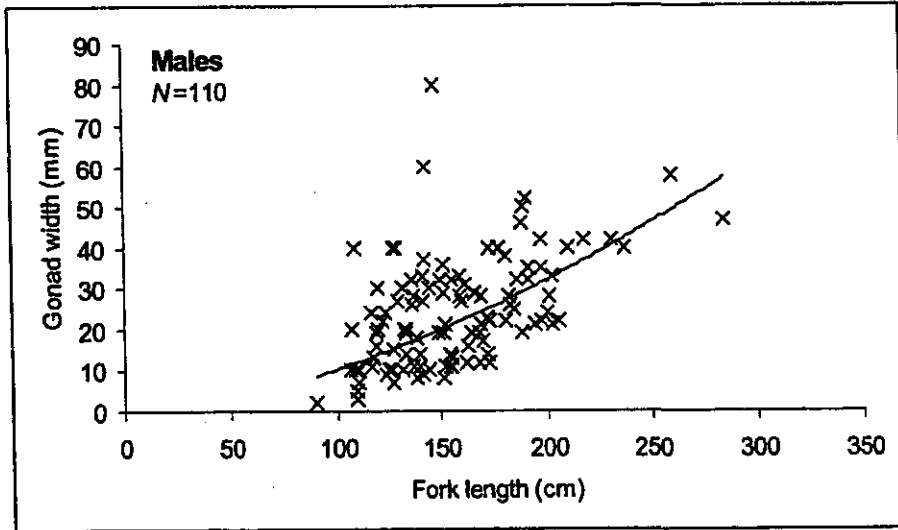
Figure 13: Relationship between gonad width and fork length in male and female swordfish (Fork length = lower jaw fork length).

Appendix 1. Gonad staging scheme used for swordfish by observers on tuna longline vessels

Stage	Description	Males	Females
1	Immature/resting	Testis small, thin (ribbon-like), translucent, colourless	Ovary translucent or pink, small with no eggs visible; can occur in both small and large fish
2	Maturing	Testis becoming swollen, translucent creamy white (though blood vessels may give it an overall pinkish appearance), narrow and angular, milt not expressible from ducts when cut	Eggs visible, opaque/coloured, but not hyaline (clear); ovaries can get quite large and solid in this stage; colour will vary between species, but maturing ovaries are generally creamy white to orange; if held up to the light or cut, a small ovary thought initially to be Stage 1 may show some developing eggs: it is then to be classed as Stage 2
3	Ripening	Testis large, pink-white, milt expressible when cut and squeezed	Ovary large and firm; clear eggs are present (more than just one or two); the ovary can appear quite mottled with clear eggs interspersed with the opaque maturing eggs
4	Running ripe	Testis large, white or bloodshot, milt flows freely with slight external pressure	Ovary large, thin-walled and fragile; large clear eggs flow out freely, or are obvious in large numbers when the ovary is cut
5	Spent	Testis appears shrivelled, thin, hardened, and bloodshot. Milt may still flow from collecting duct when cut and squeezed	Ovary flaccid and bloody, size much reduced from Stage 4; some residual large clear or opaque eggs may still be present

Appendix 2. Cumulative frequency plots of length frequency distributions shown in Figures 3 and 4