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Taihoro Nukurangi

Growth rate, age at maturity, longevity and natural mortality rate of moonfish (*Lampris guttatus*)

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7. Executive summary

Age and growth of moonfish (*Lampris guttatus*) in New Zealand waters was studied from counts of growth bands on cross sections of the second ray of the dorsal 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 3.5–4 times the condyle width above the fin base. Sections were read blind (without knowing the fish length) by two readers. Readability scores were poor. Due to difficulty in interpretation, Reader 1 did a second count knowing the fish length. Age-bias plots showed that Reader 2 produced higher ages, with a mean difference of 1.4 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. Because of this difference between the two readers, two additional readers aged a subset of 25 sections. One of the additional readers generally agreed with Reader 1 and the other with Reader 2.

Length-at-age data did not show any marked differences between males and females. Von Bertalanffy growth curves were fitted to the age estimates of both readers individually, and also to the mean ages of the two readers. We suggest that the mean age provides the best available age estimate for our moonfish samples. However, because of differences between readers, and the unvalidated nature of our estimates, the growth curves must be interpreted with caution, especially for younger fish.

The growth curves suggest rapid early growth. The greatest age estimated in this study was 13 or 14 years depending on the reader, but this is probably an underestimate of true longevity. Using a maximum age of 14 years, Hoenig's method provides an M estimate of 0.30. If moonfish live to 20 years, this would reduce to 0.21. The Chapman-Robson estimate of Z is 0.13–0.14 for ages at recruitment of 2–4 years. However, our sample was not randomly selected and so this is probably unreliable. The best estimate of M may be around 0.20–0.25.

Most of the catch taken by the tuna longline fishery was aged 2 to 14 years, and most (71%) of the commercial catch appears to be of adult fish.

Length and age at maturity could not be accurately determined due to insufficient data, but it appears that fish longer than about 80 cm fork length are mature. The corresponding age at maturity would be 4.3 years. Sexual maturity may therefore be attained at about 4–5 years. A few spawning females were collected in the Kermadec region, and at East Cape, suggesting that moonfish spawn in northern New Zealand. Identification of the location and timing of spawning are important areas of further research and are a pre-requisite for obtaining good estimates of length and age at maturity.

8. Objectives

OVERALL OBJECTIVE

To determine the productivity of non-target fish species caught in the tuna longline fishery

SPECIFIC OBJECTIVE

Objective 1:
To determine the growth rate, age at maturity, longevity and natural mortality rate of moonfish (*Lampris guttatus*)

9. Methods

See attached report.

10. Results

See attached report.

11. Discussion and Conclusions

See attached report.

12. Publications

Nil.

13. Data Storage

Age estimates from this project are stored in the MFish *age* database maintained by NIWA.

INTRODUCTION

Moonfish (*Lampris guttatus*) is a member of the family Lampridae, which comprises moonfish and opah (*L. immaculatus*). Moonfish has been confused with opah, and prior to recognition of the two as separate species, moonfish was sometimes referred to as 'opah' (Parin & Kukuyev 1983). The common names still appear to be confused, with both being applied to either species. Moonfish is regularly caught in New Zealand waters, whereas opah is only caught occasionally, and sometimes recorded as 'moonfish'.

Moonfish occur in tropical and temperate waters of all the major oceans, including the Mediterranean and Caribbean seas, while opah are known only from colder Southern Hemisphere waters (Roberts & Stewart 1998, Paul 2000). They are pelagic in surface waters to depths of about 500 m (Roberts & Stewart 1998) and typically occur well offshore (Hawn et al. 2002).

Moonfish are widely distributed around New Zealand (Francis et al. 1999, O'Driscoll et al. 2003). They are regularly caught as bycatch on tuna longlines throughout the Exclusive Economic Zone, especially in Fisheries Management Areas 1 and 2 (north-eastern and eastern North Island) (Anon 2003). Catch rates of moonfish are highest in the north and decrease with increasing latitude (Francis et al. 1999). Moonfish are always caught beyond the continental shelf, and small moonfish are found in the same areas as adults (O'Driscoll et al. 2003).

On tuna longlines, moonfish are the eighth to ninth most abundant species caught, comprising about 2% of the catch by number (Francis et al. 1999, 2000, 2004, Ayers et al. 2004). Longline catches of opah are restricted to the west coast of the South Island south of 45°S and in much smaller numbers, approximately 0.01% of the catch by number (NIWA unpublished data).

Annual landings of moonfish reported by processors on Licensed Fish Receiver Returns (LFRRs) were 137–355 t per year in the 5-year period 1996–97 to 2000–01 (Anon 2003). Most moonfish are caught by surface longline, but some are taken by midwater trawl, bottom trawl and bottom longline (Anon 2003).

There have been no studies on moonfish in New Zealand, and very little is known about the species worldwide. The average size in New Zealand is reported to be 80–120 cm (Paul 2000), but elsewhere moonfish apparently attain a maximum length of 200 cm and a weight of 270 kg (Gon 1990).

Many pelagic fishes have small, fragile otoliths and can be difficult to age. Some species have been successfully aged using fin rays. This includes use of anal fin rays to age swordfish (Sun et al. 2002, Young & Drake 2004), dorsal fin rays for bigeye tuna (Sun et al. 2001), and dorsal and anal fin rays for albacore (Beamish 1981).

There is no information, in New Zealand or elsewhere, on the age, growth, longevity, or size and age at maturity, of moonfish. This report aims to address these information gaps in order to provide a scientific basis for determining the productivity of moonfish.

METHODS

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.

Otoliths

Otoliths were collected from three moonfish caught on the west coast of the South Island, and examined in the laboratory to assess their utility for age estimation. The otoliths proved unsuitable for ageing, and were not processed further.

Fin rays

The fins of lamprid fishes contain no spines, being composed solely of flexible rays. Dorsal fin ray samples (Figure 1) were collected by observers on tuna longline vessels during 2003 and 2004. Samples were collected from fish caught mainly on the west coast of the South Island, the east coast of the North Island, and north of the Three Kings Islands (Figure 2). Associated data included fork length (FL), sex, and date. The target sample size was 250.

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, 2, 4, 6 and/or 9 times CW from the base of the ray. It was established that a section of the second ray taken at approximately 4 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 3 and 4 times CW above the base. The 4x CW face was polished and embedded downward on a microscope slide. The upper, 3x CW, face was sequentially ground until growth bands became apparent under a stereomicroscope at a magnification of 10–40x. Final section thickness was about 500–800 μm.

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 reading was carried out by Reader 1 with knowledge of fish lengths, due to the difficulty in counting the bands. Two additional readers then independently read a subsample of 25 fin rays.

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). This method has been shown to be better at detecting reader bias than other frequently used techniques (Campana et al. 1995). 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.

Growth rate estimation

Nothing is known about the timing of spawning of moonfish in New Zealand (or elsewhere). Similarly, nothing is known about the timing of fin ray band deposition. We therefore did not assign a theoretical birthday for ageing New Zealand moonfish, and we did not correct ages for the time of year during which specimens were caught.

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 in the graphical and statistical package SAS.

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. This was overcome by selecting randomly within age classes (A. Dunn, NIWA, pers. comm.).

Maturity

Observers aboard tuna longliners recorded moonfish 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 mature fish: in the non-spawning season, the gonads of mature fish that have previously spawned and are reproductively 'resting' look very similar to the gonads of immature fish that are maturing for the first time. 'Immature' and 'resting' fish are combined in the observer staging scheme. The distributions of gonad stages by sex and length were investigated.

Natural 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) 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.

RESULTS

Size composition of tuna longline catches

Length-frequency distributions of moonfish 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 (1992–2004), are shown in Figures 3 and 4. Nearly all moonfish were in the length range 47–125 cm FL. Only five fish in the database were longer than 125 cm, and they were 138, 146, 158, 158, and 206 cm FL respectively. Fin ray samples were available for the three fish longer than 150 cm, and, based on their sizes and band counts, all appeared to have come from smaller fish (i.e., the recorded lengths were probably erroneous). Thus the usual maximum length for moonfish in New Zealand is probably 125 cm FL, though they possibly reach 150 cm.

The moonfish sampled for fin rays were similar in size composition to the moonfish measured by observers during the same years (Figure 3), indicating that our aged sample was representative of the catch. The length range of moonfish was wide in all years between 1992 and 2004, with most fish 65–110 cm FL (Figure 4). However the relative proportions of small fish (less than 80 cm) and large fish were quite variable among years. There is some evidence of progression of small fish through to larger size classes (e.g., from 1997 to about 2003), but length-frequency modes were not clearly distinguishable and the observed patterns may have been fortuitous. It is possible that males grow slightly larger than females: of 94 moonfish longer than 110 cm in the observer database, 71 (76%) were males.

Otoliths

Moonfish otoliths were very small, friable, and fragile, and they lacked a suitable sectioning axis (Figure 5). They are not suitable for ageing, and were not examined further in this study.

Fin rays

A total of 272 moonfish were aged using dorsal fin rays, comprising 127 males, 121 females, and 24 unsexed fish. Seven samples were not used as length was not recorded.

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 2 to 5, and were mostly 3 or 4 (Table 1). Figure 6 shows an example of a 'good' moonfish ray section, and indicates the growth bands counted by both readers. Figure 7 shows some more difficult examples.

Reader 2 tended to count more bands than Reader 1 up to age 10 (Figure 8). The mean difference was 1.4 bands for fish aged up to 10 years by Reader 1. This difference was a result of Reader 2 tending to count more inner bands (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. This accounted for the higher counts by Reader 1 in the oldest fish (Figure 8). Because of these differences between the two readers, two additional readers (Readers 3 and 4) aged a subset of 25 sections. One of the additional readers generally agreed with Reader 1 and the other with Reader 2.

The average APE index for the between-reader comparison was 12.7%, and the mean CV was 18.0%. However measures of precision are inflated by between-reader ageing bias (Campana et al. 1995). This can be demonstrated by recalculating APE and CV after subtracting the mean bias for fish up to 10 years old (1.4 years) from all of Reader 2's ages. APE and CV then dropped to 8.8% and 12.5% respectively. These values are still high relative to a CV of about 5% often achieved for fishes of moderate longevity and reading complexity (Campana 2001), indicating that moonfish fin rays were difficult to age.

It is not known whether the age estimates of Reader 1 or Reader 2 are more accurate. The bias between readers is the result of two separate processes, related to inner and outer bands respectively. Thus it is possible that neither set of estimates is accurate over the full age range. In the absence of any validation studies, we used the mean of the two readers' ages as our best estimate of the age of each fish. However we also explored the effect of using the individual readers' age estimates to generate growth curves.

Growth rate estimation

Length-at-age data did not show any marked differences between males and females (Figure 9). Length-at-age plots for Reader 2 suggested that males may be slightly longer than females at a given age in fish older than nine years, and that males may live slightly longer. However the differences were minimal and possibly due to the small samples sizes of fish older than nine years; no such pattern was apparent for Reader 1. A randomisation test showed that von Bertalanffy growth curves were not significantly different between the two sexes for Reader 1 ($p = 0.18$), but were significantly different for Reader 2 ($p = 0.02$). Further work is needed to determine if growth differs between the sexes. In developing final growth curves we ignored potential differences and combined the two sexes.

Figure 10 shows length-at-age relationships by reader with fitted von Bertalanffy growth curves. The shapes of the growth curves were similar between readers, with Reader 2's curve shifted right relative to that of Reader 1. The growth curve fitted to the mean ages is considered the best available description of growth, and details are shown in Table 2. The covariance matrix of parameter estimates is given in Table 3.

All growth curves intersected the length axis at positive values (about 20 cm for the mean age curve). There are several possible reasons for this:

- Our counts underestimate true age;
- Fishing gear selectively captures 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 data for fish shorter than 50 cm means that the left-hand ends of the growth curves are poorly defined;
- Failure to convert fin ray band counts to chronological ages using the time difference between spawning and capture resulted in underestimation of ages (bias would be less than one year).

Maximum age

The greatest age estimated in this study was 13 or 14 years depending on the reader, but this probably underestimates true longevity because of the small sample size and the fact that the population has been fished. Moonfish are reputed to reach 200 cm FL (Gon 1990, Roberts & Stewart 1998), but that length is exceptional. There are few moonfish longer than 125 cm in the tuna longline observer database, and at least some of these appear to have been incorrectly measured. In the New Zealand region, it seems that moonfish do not grow much larger than 125 cm, but it is not clear whether larger, and potentially older, fish occur elsewhere. Nevertheless, our estimate of longevity is likely to be conservative.

Natural mortality

Using a maximum age of 14 years, Hoenig's method provides an M estimate of 0.30. If moonfish live to 20 years, this would reduce to 0.21. The Chapman-Robson estimate of Z is 0.13–0.14 for ages at recruitment of 2–4 years. However, our sample was not randomly selected and so this is probably unreliable. The best estimate of M may be around 0.20–0.25.

Maturity

Gonad stage was recorded for 147 males and 157 females (Figure 11). Most males (66%) were immature/resting, 19% were maturing and 15% were spent. Most females (61%) were immature/resting, 27% were maturing, 4% were ripe, 3% running ripe, and 6% were spent. 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. However, from the length distribution of spent fish, it appears that many moonfish longer than about 80 cm FL are mature. From the von Bertalanffy growth curve, the corresponding age at maturity is 4.3 years. Sexual maturity may therefore be attained at about 4–5 years in both sexes.

Gonad width was measured for 127 males and 129 females (Figure 12). There was no abrupt change in gonad width at 80 cm, or any other length, that would support or refute the above estimate of length at maturity.

Immature/resting fish were found in all areas where moonfish were caught (see Figure 2). Most of the maturing or mature fish were found north of 40 °S. Three of four females recorded as running ripe were caught in the Kermadec Islands region, and one was caught off East Cape. Time of spawning is not clear and differences were seen in the two collection years. The three running ripe females from the Kermadecs region were caught in July 2003 and five spent female fish were recorded in June–July 2003, while all of the ripe (3), running ripe (1) and spent fish (4) caught in 2004 were caught in March. The number of spent males increased from May to July in 2003 and no spent males were recorded in 2004. It appears that moonfish spawn in autumn, at least, but there are insufficient data to define the spawning season.

DISCUSSION

Readability

Both readers found fin sections from this species difficult to interpret and readability scores were poor. 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, if either, set of age estimates is more reliable. Consequently, we used the mean of the two readings as the best available estimate of age. We recommend that the 'mean age' growth curve presented in Table 2 be used as an interim estimate of growth of moonfish, but it should be used with considerable caution. A validation study is required before we can develop a more certain growth curve. Future work should also attempt to obtain moonfish shorter than 50 cm FL in order to define the left-hand end of the growth curve better.

Productivity

Moonfish appear to grow very rapidly in their first two years, regardless of which set of age estimates is used. Length and age at maturity could not be estimated adequately because maturity data for ripening and running ripe fish were too few. However, moonfish seem to mature at a relatively young age of 4–5 years. The greatest age estimated in this study was 13 or 14 years depending on the reader, but this probably underestimates true longevity. Based on the preliminary results from this study, moonfish appear to be moderately productive, having a relatively young age at maturity, moderate longevity, and moderate natural mortality rate.

Gonad stage data indicate that spawning occurs in northern New Zealand waters, but it is possible that the main spawning areas are further north in subtropical or tropical waters. Determination of the location and timing of spawning are important areas of further research, and are a pre-requisite for obtaining good estimates of length and age at maturity.

Future work

Use of fin rays to age fish has many advantages: they are easy to collect, and can be collected without sacrificing the fish. Insight into how to interpret the early and late bands in fin rays might be provided by examination of other hard parts, for example vertebrae or the cleithrum.

It would also be useful to verify that fin ray sections give comparable counts to those from other structures. In other species, such comparisons produced variable results. Brennan & Cailliet (1981) compared a range of ageing structures including pectoral fin rays, clavicles, cleithra, opercula, medial nuchals, and dorsal scutes in white sturgeon, and concluded that fin rays gave good results and were the most practical. Paragamian & Beamesderfer (2003) suggested that fin ray counts in white sturgeon underestimated ages, based on comparison with estimates from tagged fish. Barber & McFarlane (1987) reported higher counts in otoliths than in anal or pectoral rays of Arctic char. Erickson (1983) obtained similar ages from dorsal spines, scales, and otoliths of Manitoban walleyes, but considered that otoliths were superior for older fish because the overcrowding of outer annuli was not as pronounced as in scales and dorsal spines.

Validation of our ageing technique and estimates is highly desirable, but considerable resources would be required to implement a tag-recapture study incorporating a fluorescent marker such as oxytetracycline. The feasibility of this approach remains to be determined, but about three-quarters of moonfish caught on tuna longlines are alive when the line is retrieved (Ayers et al. 2004), suggesting that the tagging phase could be achievable.

Collection of more maturity data would help refine our estimates of length at maturity and time and place of spawning. Such data can easily be collected by observers, and we recommend that this work be continued. Distinguishing between immature and resting fish would add considerable value to the data, so it would be useful if the 7-stage scale used on research vessels was employed in future. However, distinguishing between immature and resting fish can be difficult for inexperienced observers, especially when the appearance of these stages in moonfish has not yet been adequately defined.

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

	Reader 1					Reader 2		
	Readability score					Readability score		
Band count	2	3	4	5	Band count	2	3	4
2		11	6		2		1	
3		17	16		3	1	5	1
4	2	9	17		4	1	23	3
5		15	22		5		26	4
6	2	11	21		6	4	30	2
7	4	11	26		7	2	27	8
8	2	14	11	1	8		22	8
9	2	10	9	1	9		32	5
10	2	7	7		10	1	21	1
11		7	2		11		25	1
12	2	1	1		12		13	1
14		2	1		13		4	
Total	16	115	139	2	Total	9	229	34

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. Moonfish growth curve parameters by reader, and for the mean age of both readers (both sexes combined). SE, standard error. We recommend that the growth parameters for the mean ages be used to model growth in this species.

Otolith reading	Sample size	$L_\infty \pm$ SE (cm)	$K \pm$ SE	$t_0 \pm$ SE (years)
Reader 1	272	52.29 ± 0.59	0.226 ± 0.022	–2.44 ± 0.53
Reader 2	272	118.4 ± 3.2	0.206 ± 0.027	–0.61 ± 0.44
Mean age	272	119.3 ± 2.4	0.218 ± 0.021	–0.78 ± 0.30

Table 3. Correlation matrices for the Von Bertalanffy growth parameters for the mean age (see Table 2).

	L_∞	K	t_0
L_∞	1.000	–0.956	–0.845
K	–0.956	1.000	0.956
t_0	–0.845	0.956	1.000

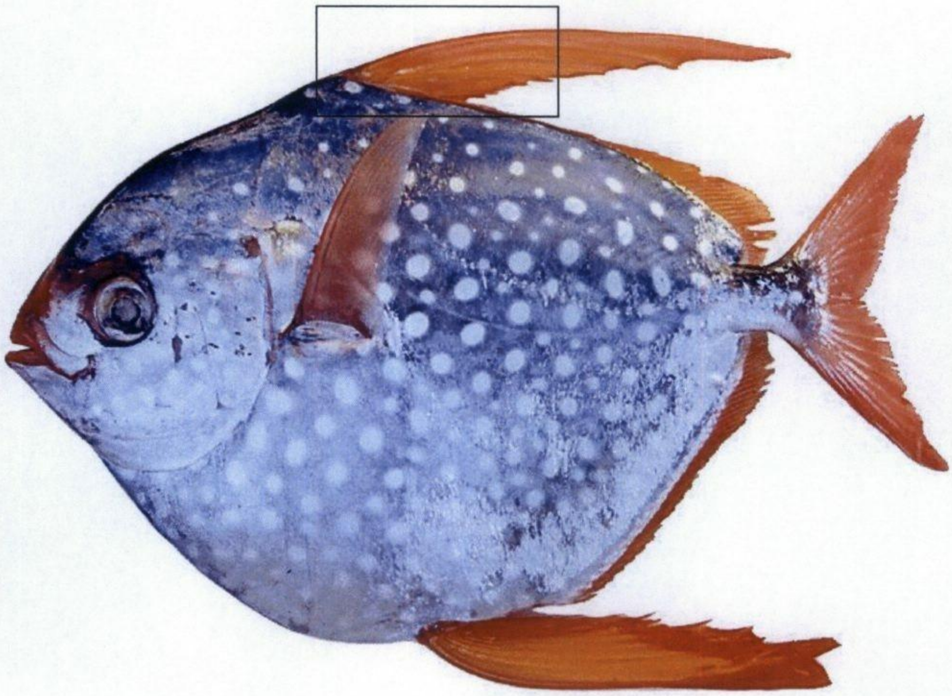


Figure 1: Moonfish showing location of dorsal fin rays sampled for ageing.

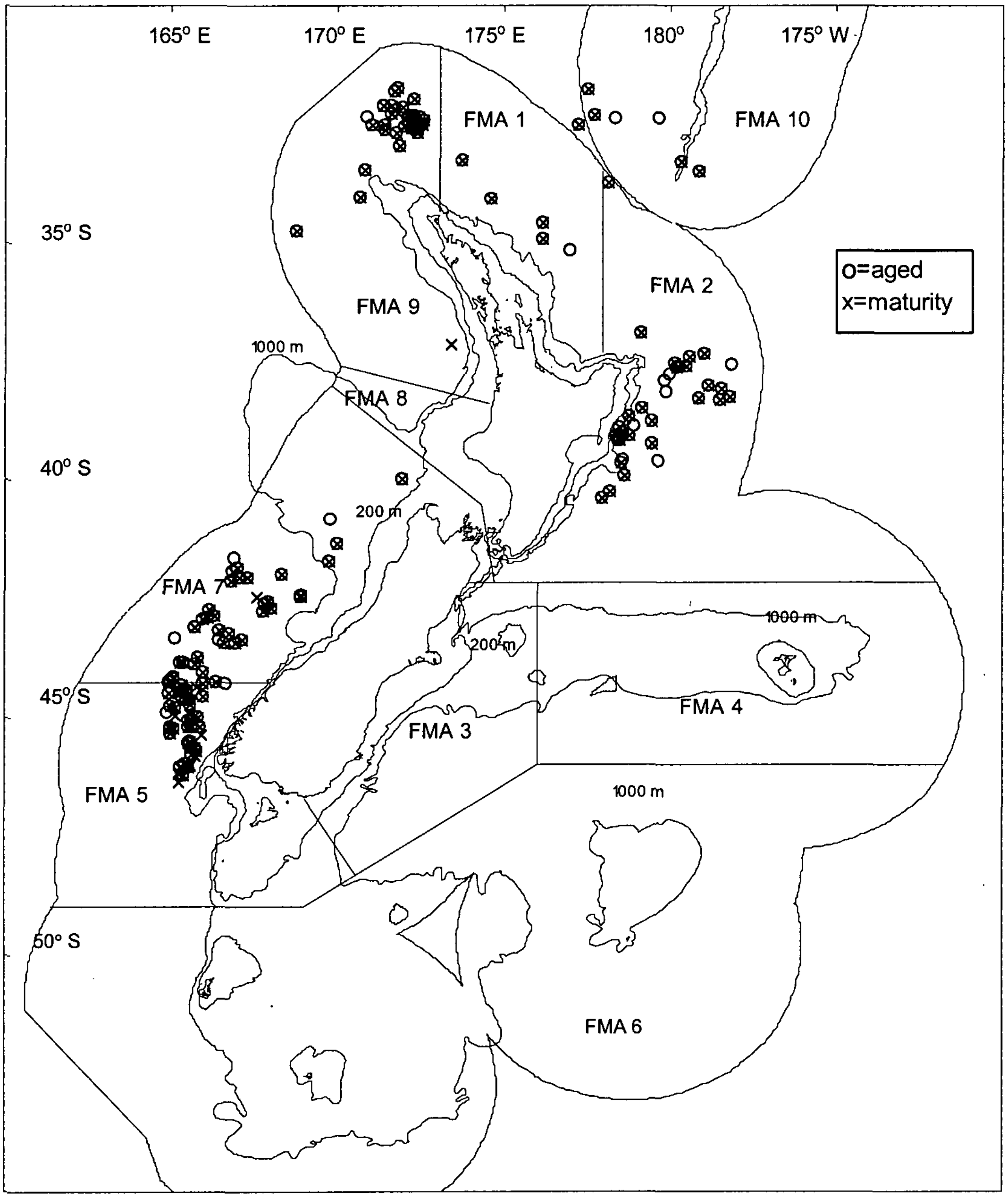


Figure 2: Capture locations for moonfish that were aged and assessed for gonad maturity

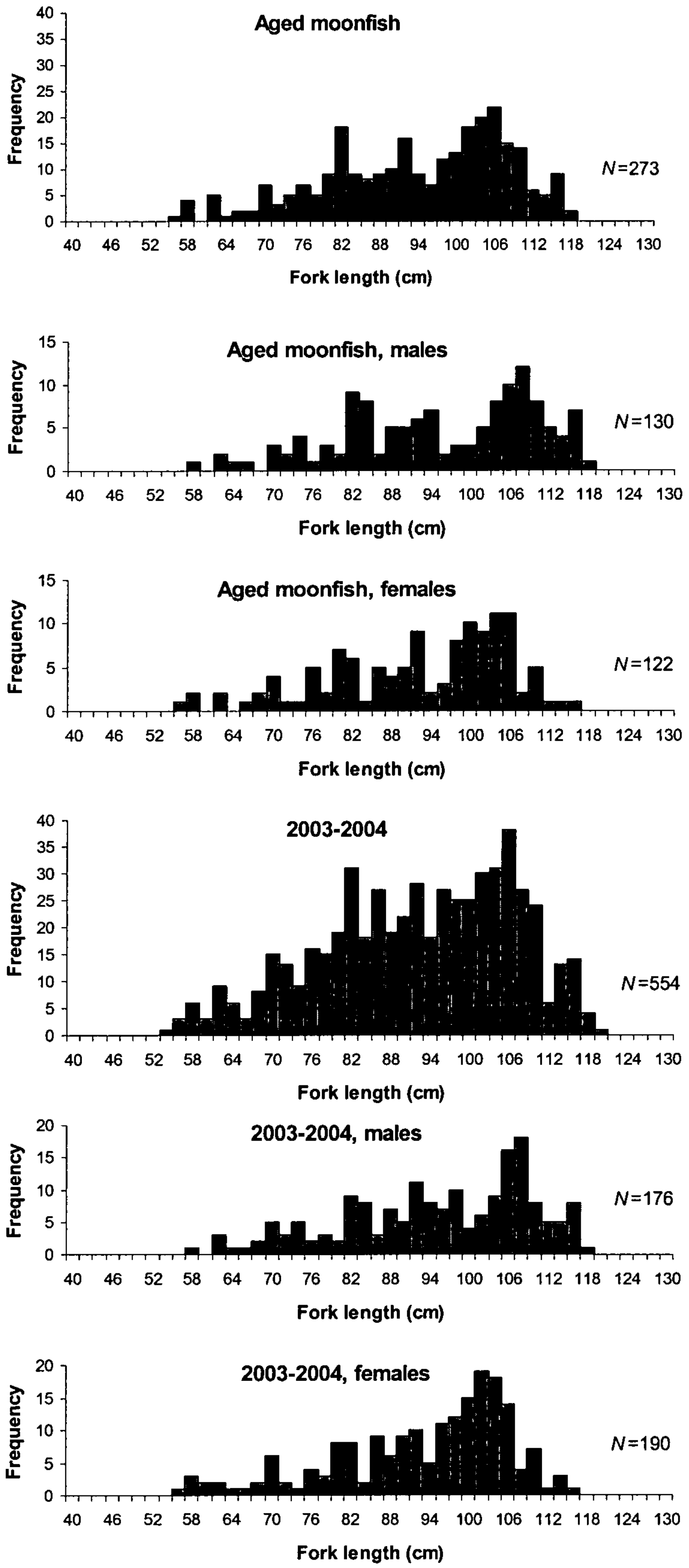


Figure 3: Length-frequency distributions for moonfish that were aged in this study, compared with distributions for all moonfish measured by observers in 2003–2004.

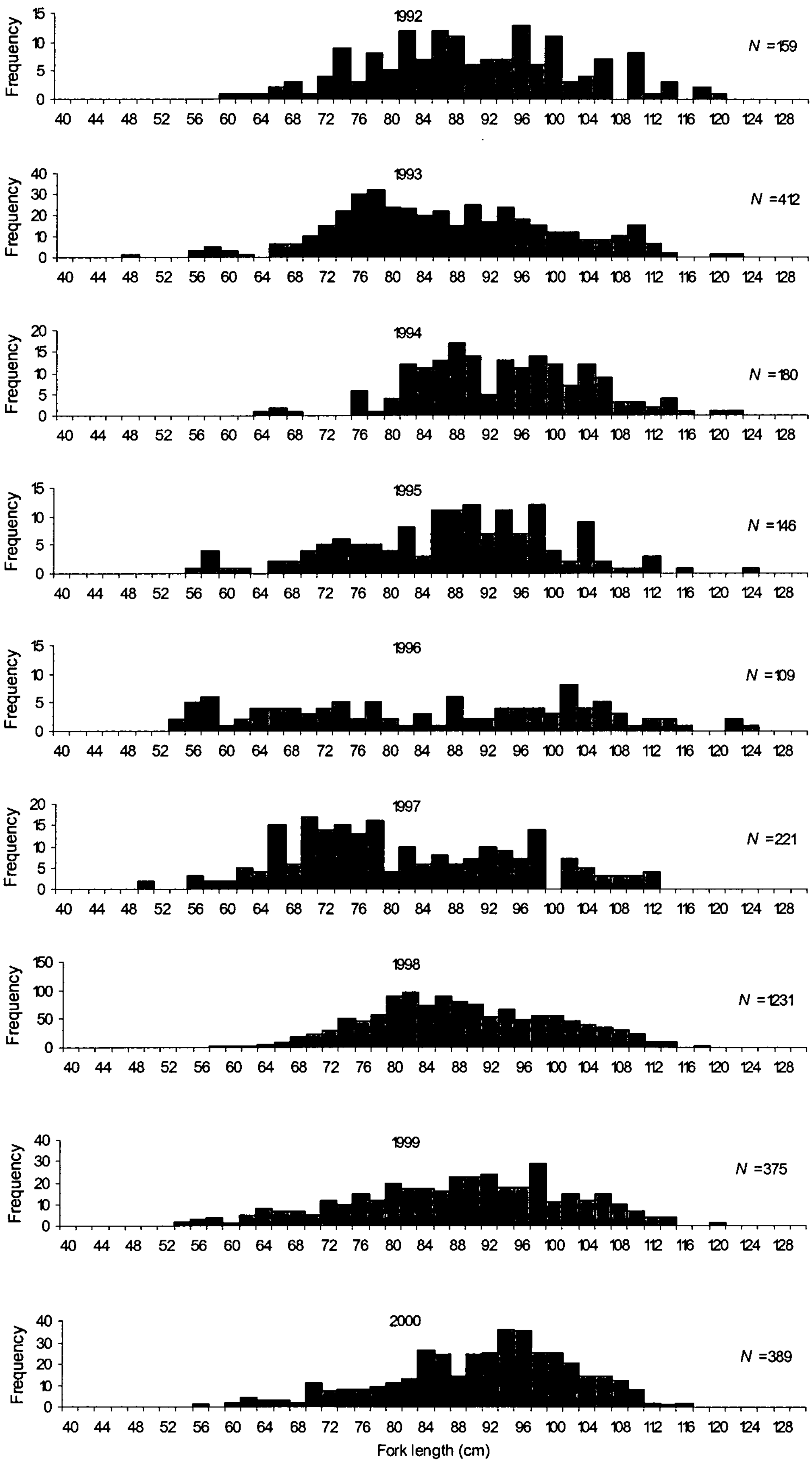


Figure 4: Length-frequency distributions by year for moonfish measured by observers aboard tuna longline vessels, 1992–2004.

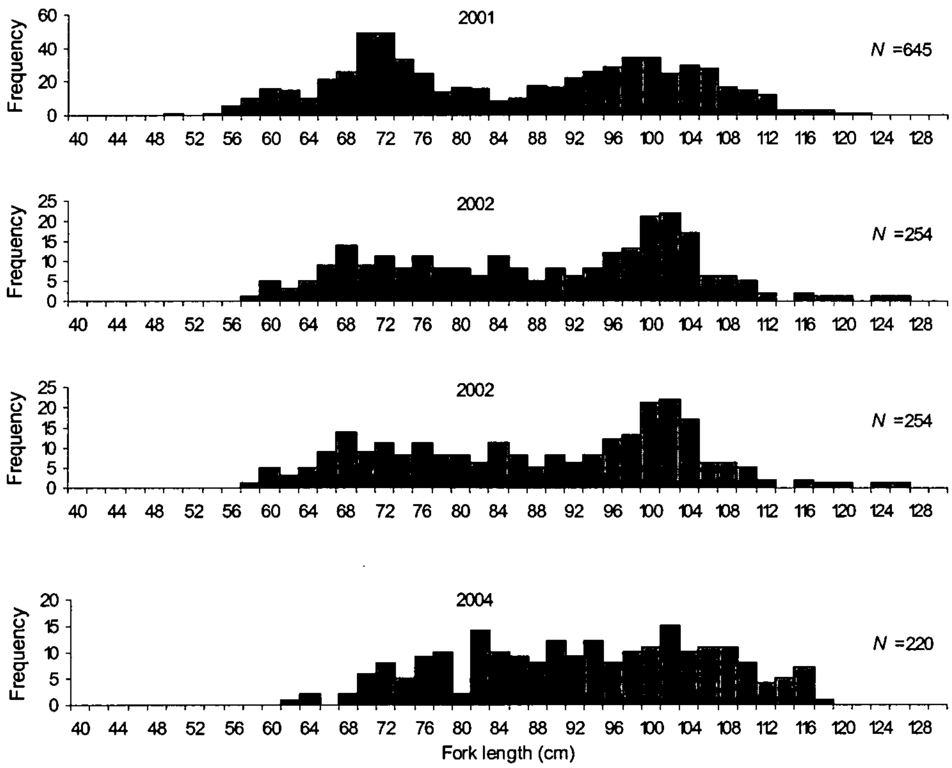


Figure 4 (continued).

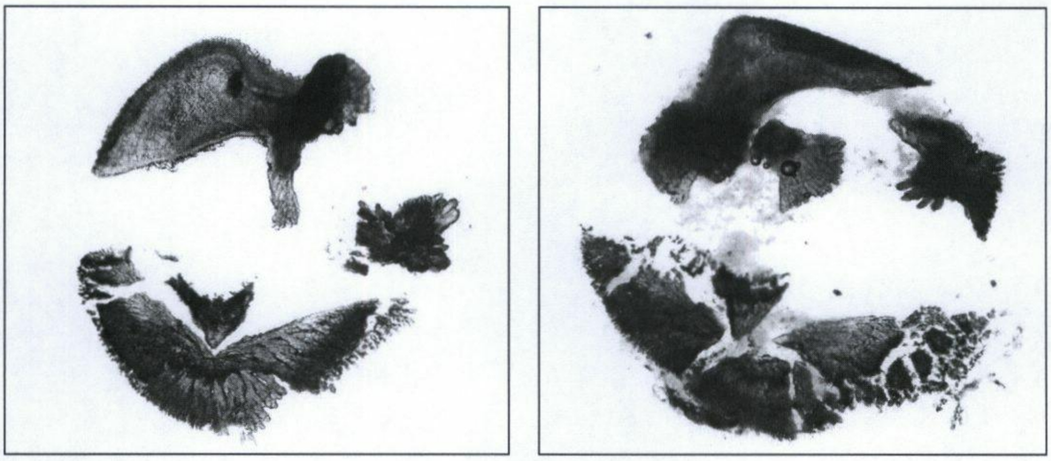


Figure 5: Otoliths from (left) a 101 cm FL female moonfish, and (right) a 115 cm male moonfish. The otoliths are lapillus (top), asteriscus (right) and sagitta (bottom). Note the broken sagitta in both fish.

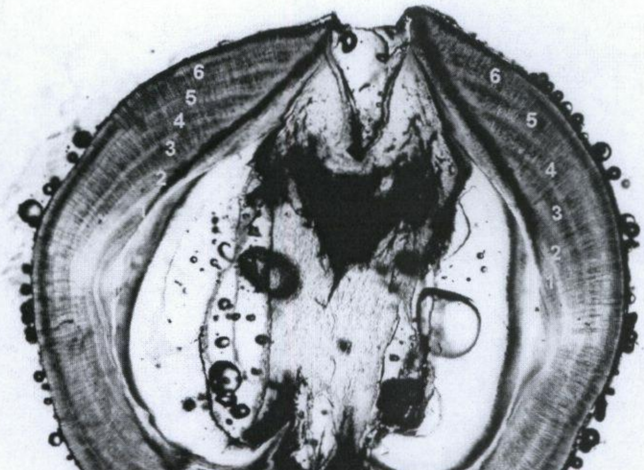


Figure 6: Fin ray section from a 97 cm FL unsexed moonfish showing growth bands. This section was scored as readability 2 (good). The ray measured 3.95 mm in diameter.

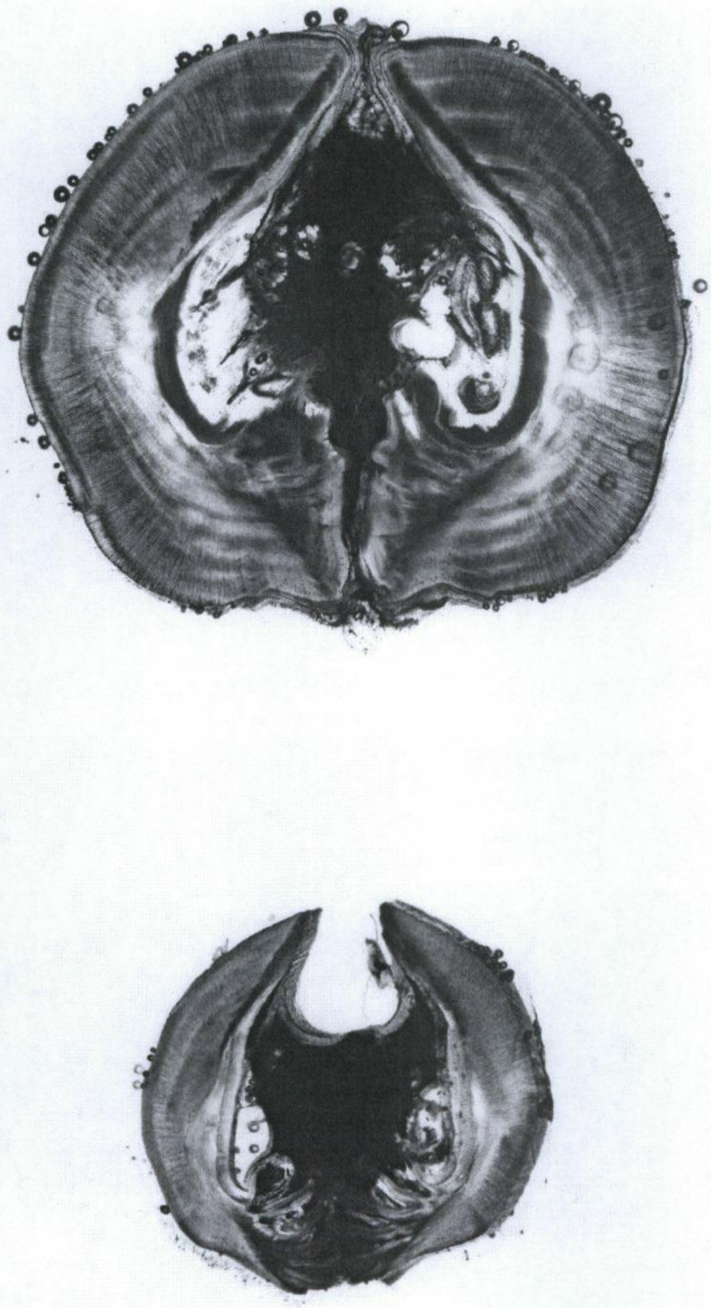


Figure 7: Fin ray sections scored as readability 3 or 4 (adequate to unclear). Sections are from (top) a large 115 cm FL fish, and (bottom) a small 62 cm FL fish. The ray diameters were 4.6 mm (top) and 2.7 mm (bottom).

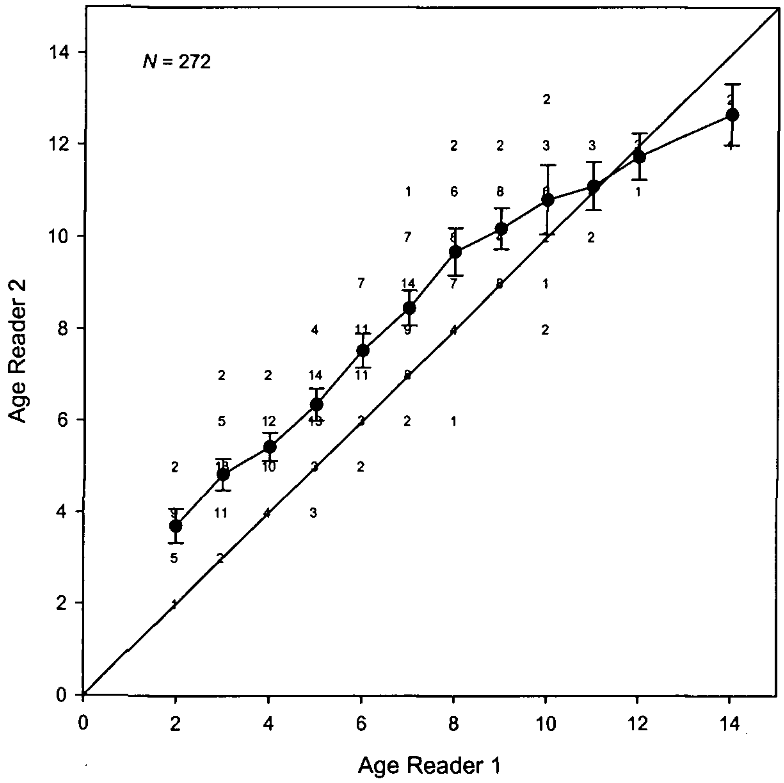


Figure 8: Age-bias plot, comparing fin ray counts by Reader 1 and Reader 2. Symbols with error bars show the mean count of Reader 2 (± 2 standard errors) relative to the counts of Reader 1. Diagonal line indicates the expected relationship. Numbers represent number of fish. *N*, total sample size.

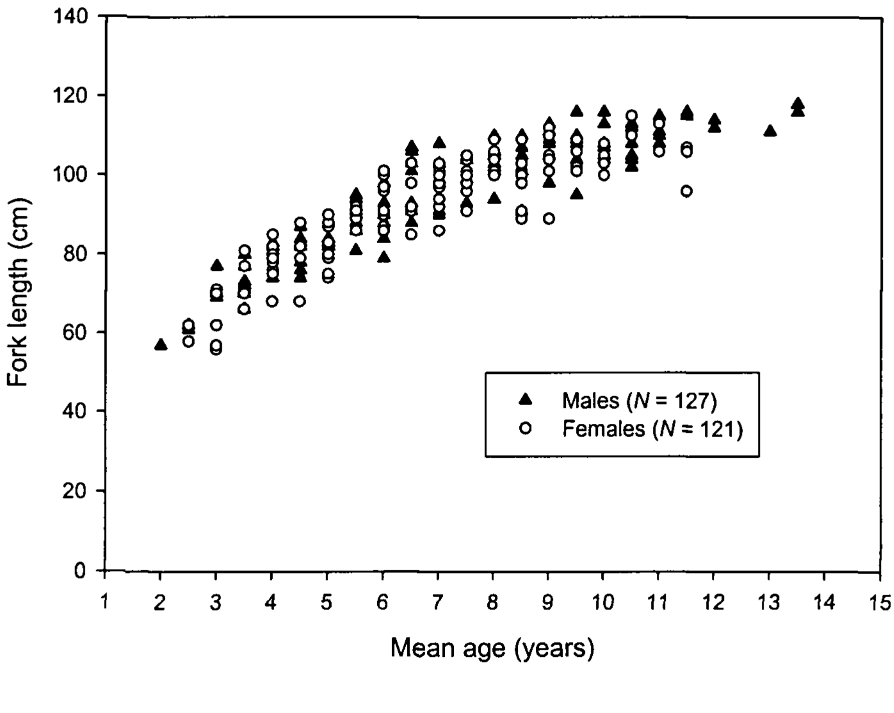


Figure 9: Length-at-age relationships for male and female moonfish.

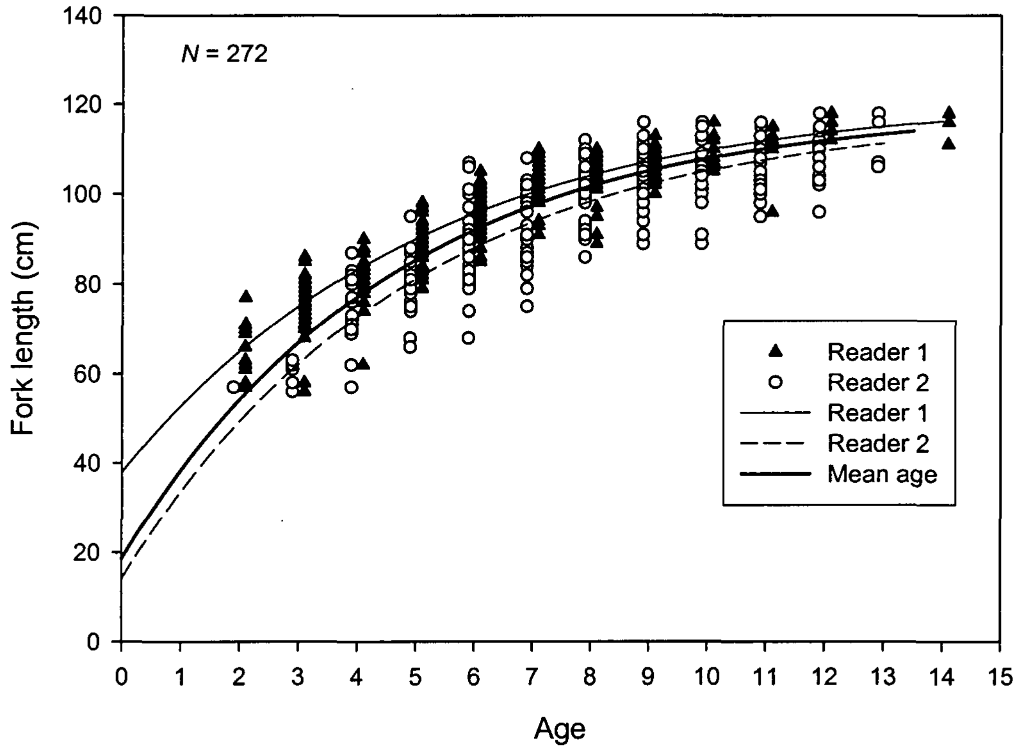
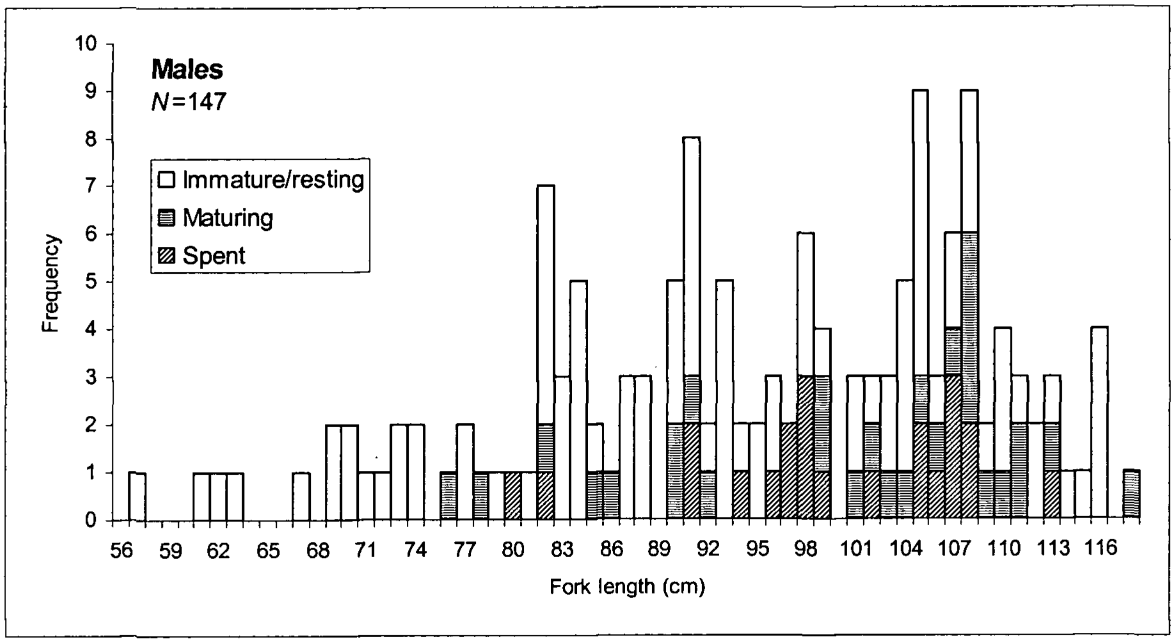


Figure 10: Length-at-age relationships (both sexes combined) for moonfish with fitted von Bertalanffy growth curves for each reader separately, and for the mean age from both readers. Data points are displaced slightly from the axis tick marks for clarity.



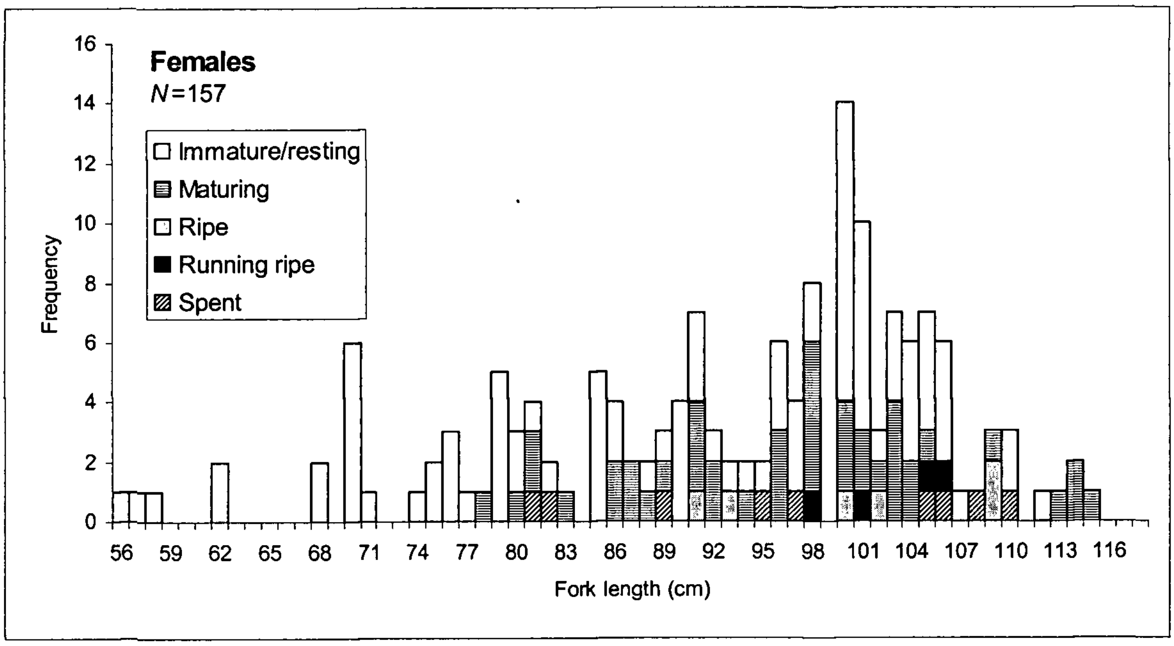


Figure 11: Relationship between gonad development stage and fork length for male and female moonfish.

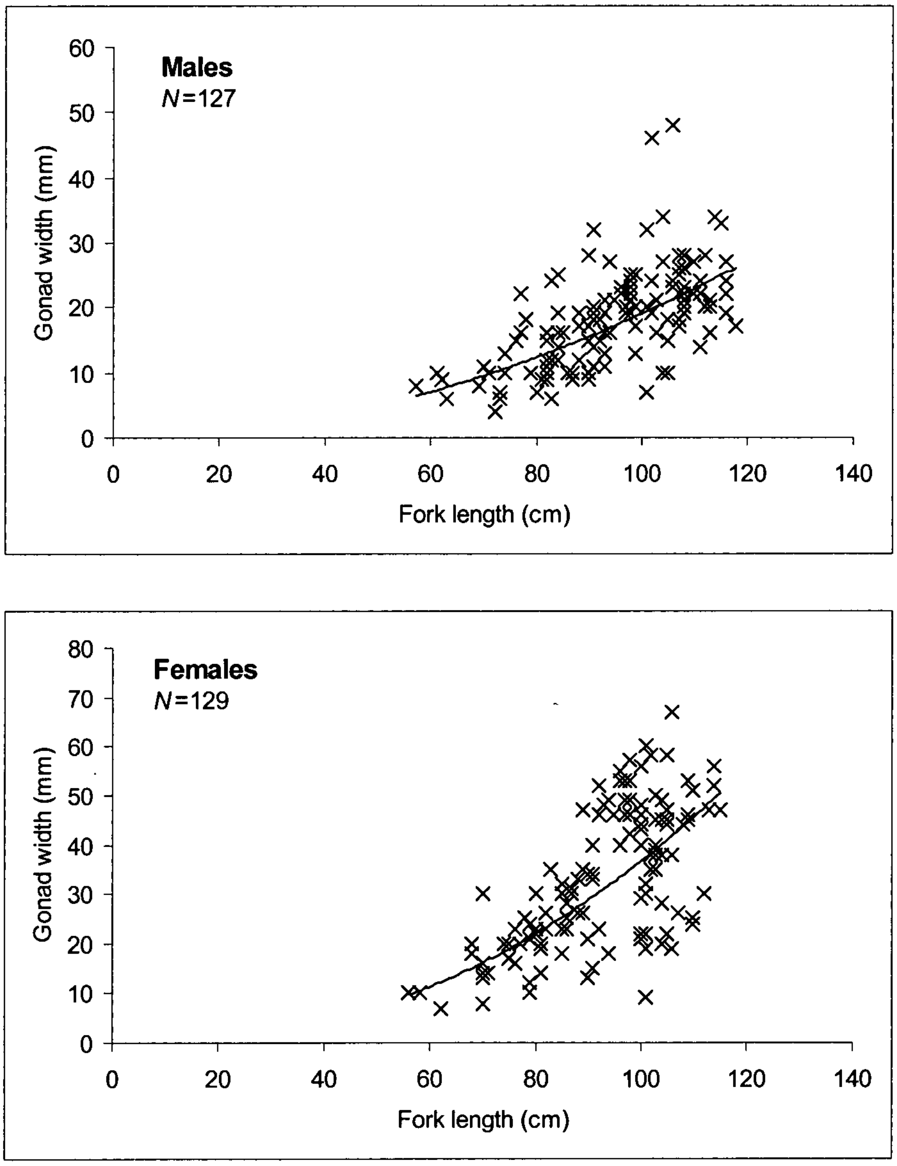


Figure 12: Relationship between gonad width and fork length in male and female moonfish.

Appendix 1. Gonad staging scheme used for moonfish 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