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Size, maturity and length composition of blue sharks observed in New Zealand tuna longline fisheries

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Pelagic sharks are routinely taken as bycatch in New Zealand's surface longline (SLL) fisheries. The blue shark (*Prionace glauca*) is the most commonly caught pelagic shark, with estimated catches of about 600–1000 t per year between fishing years 2004 and 2013, followed by a large drop to 117 t in 2014. The current Total Allowable Commercial Catch is 1860 t. Due to their migratory nature, management is done on a regional basis with New Zealand being responsible for monitoring its fisheries and providing these data to regional fisheries management organisations. This study assesses the catch composition of blue sharks taken by SLL in New Zealand waters using data and samples collected by observers. Data were stratified by fleet (chartered Japanese or New Zealand domestic vessels) and region (North region = Fisheries Management Areas 1, 2, 8 and 9, and Southwest region = FMAs 5 and 7). Length-frequency distributions were scaled up to estimate the size composition of the commercial catch for the fishing years 2007 to 2015. Maturity and reproductive status were assessed from observer data collected between 2011 and 2015. The proportions of mature animals in the catch were estimated by applying the median length at maturity to the scaled length-frequency distributions (by sex).

Observer sampling of length data was compromised by their inability to measure every shark caught, and evidence that unmeasured, discarded sharks may have a different size composition from measured, discarded sharks. The proportion of blue sharks discarded or released alive under Schedule 6 of the Fisheries Act continued to increase, reaching nearly 100% of the catch in 2015. In the North region, the proportion of blue sharks measured dropped to 3–4% in 2014–2015, and observer coverage was low. High observer coverage of the Japanese charter fleet resulted in about 18–22% of blue sharks being measured in 2014–2015 in the Southwest region, but this was a big decline from about 60% in previous years. The recent big changes in proportions discarded and measured reflect economic and freight problems in the shark fin market in 2014 and the introduction of a ban on shark finning at the beginning of the 2015 fishing year. Those changes make it difficult to assess recent patterns of size composition, sex ratio, and maturity composition.

The SLL blue shark catch was dominated by juveniles, with most sharks being shorter than 200 cm fork length, and an estimated 90% of males and 95% of females being immature; however, these proportions may have been over-estimated if significant numbers of large mature adults were being discarded unmeasured. Mature females are not considered vulnerable to the New Zealand SLL fishery, although they may be taken by other fleets in international waters.

Vertebrae were examined whole or sectioned and X-rayed to estimate age, but growth bands were ambiguous and uninterpretable. Differences among readers resulted in either 'low' or 'high' band counts. Low band counts occurred when multiple individual bands were aggregated into fewer broader bands. Low band counts were more consistent with blue shark growth curves from around the globe, including the only previous New Zealand study. High band counts were not consistent with other studies. However, there have been few attempts at validation of blue shark ageing techniques, and most of them have been limited in scope and scale, and were inconclusive. In the absence of adequate validation, vertebral ageing remains subjective. It was therefore impossible to develop an objective ageing protocol for New Zealand blue shark. Nevertheless, growth curves developed previously for New Zealand blue sharks are consistent with those produced for most other parts of the world and may be reasonably reliable. Further validation is required to determine whether other studies may have under-estimated the ages of large, old blue sharks. Such age under-estimation has been seen in a growing number of shark species, and has been attributed to the merging of small marginal vertebral bands, and may prove to be a common feature among older slower-growing sharks.

1. INTRODUCTION

Pelagic sharks are routinely taken as bycatch in New Zealand's tuna longline fisheries, and to a lesser extent midwater trawl fisheries (Clarke et al. 2013; Francis 2013; Griggs & Baird 2013). The blue shark (*Prionace glauca*) is the most commonly caught pelagic shark, with estimated catches of about 600–1000 t per year between fishing years 2004 and 2013, followed by a large drop to 117 t in 2014. The current Total Allowable Commercial Catch is 1860 t (Ministry for Primary Industries 2015). Highly migratory species (HMS), including blue sharks, are managed by Regional Fisheries Management Organisations (RFMOs). The important RFMO for New Zealand blue sharks is the Western and Central Pacific Fisheries Commission (WCPFC). As a member of WCPFC, New Zealand has numerous obligations, including the provision of specific data and submission of annual reports describing the fisheries and research activities. Within New Zealand fisheries waters, New Zealand implements the objectives of the WCPFC's conservation and management measures via catch limits for the main HMS shark species.

Due to their HMS nature, assessments for these stocks are done on a regional basis with New Zealand being responsible for monitoring its fisheries and providing these data to WCPFC. In addition to the requirement for assessments, quantitative data on elasmobranch catches are also useful for monitoring the New Zealand component of these stocks, particularly as New Zealand fishes the southern extreme of the geographical range for most HMS. The National Plan of Action − Sharks (Ministry for Primary Industries 2013) additionally requires that New Zealand fills some of the current data gaps in information on its shark fisheries.

Historically, most biological information for HMS species has been collected by observers at sea in the tuna longline fishery (Francis & Duffy 2005; Francis 2013, 2015). The low levels of domestic observer coverage result in low quantities of data being collected, and the need for multi-year sampling to answer key questions. Low observer coverage rates greatly reduce our ability to quantitatively monitor the components of the stock that migrate through or reside in New Zealand waters. Under a recent Ministry for Primary Industries research project (HMS2010-03), Francis (2013) characterised the fisheries for blue sharks (and also shortfin mako and porbeagle sharks), documented observer collections of vertebral samples and data on maturity and fin weights, analysed time series of length-frequency, maturity and sex ratio data from tuna longline catches, and made recommendations for improved data and sample collection. This study extends and builds on the previous project by attempting to age blue shark vertebrae collected by observers in 2011–15, estimating the length and age composition of tuna longline catches, and updating previous analyses of maturity composition and sex ratio. The results will be used as inputs to future stock assessments being undertaken by WCPFC.

The objectives of this study were:

1. To develop an ageing protocol for blue sharks from vertebrae collected by fishery observers.
2. To analyse the sex, maturity state, length and age structure of the commercial catch for blue sharks.
3. To develop an ageing library from the material used in this study.

2. METHODS

2.1 Collecting biological data

A set of instructions was prepared for observers on sampling pelagic shark length, sex, maturity, vertebrae and fin weight (Appendix 1). Vertebrae were inventoried and archived in a freezer, and maturity and fin data were punched. From 2014, observers were also asked to record the presence or absence of spermatozeugmata (packages of spermatozoa) in the ampulla epididymis (seminal vesicle) of males (Pratt & Tanaka 1994). Spermatozeugmata occurrence is a useful complement to clasper development when determining the maturity status of male blue sharks (Francis & Duffy 2005). Other observer data were punched and loaded using routine processes into the *COD* database managed by NIWA for the Ministry for Primary Industries (MPI).

2.2 Analysis of observer data

The analyses in this report were based on data and specimens collected by observers. Most data and all specimens came from surface longline (SLL) vessels targeting tunas. A total of 349 SLL observer trips made between April 1993 and September 2015 were included. Twenty-seven observer trips were omitted from length-frequency and proportion mature analyses because their length measurements showed a strong bias towards numbers ending in zero (more than 20% of lengths ending in zero compared with the expected 10%). This indicates that either the sharks were not measured accurately, or measurements were rounded to 10 cm intervals. Nineteen further trips by the same observers were also omitted because of uncertainty about the accuracy of their length measurements. Thus 46 observer trips (13.2%) were omitted from blue shark length-frequency analyses (but were included in other analyses such as sex ratio). Five additional trips (1.4%) were omitted from all analyses because of known species identification problems, or data quality issues.

Observer data were stratified into fleets (chartered Japanese or New Zealand domestic vessels) and regions because previous studies have identified spatial variation in pelagic shark length-frequency distributions (Francis et al. 2001; Francis 2013, 2015). The North region comprised Fisheries Management Areas (FMAs) 1, 2, 8 and 9, and the Southwest region comprised FMAs 5 and 7. Fork length (FL) was adopted as the measurement standard in this study. Hereafter, all references to years are for fishing years (1 October to 30 September) and each year is labelled after the second of the pair of calendar years (e.g. the 2012−13 fishing year is labelled as 2013).

When large numbers of blue sharks are caught on SLL sets, observers may not be able to record data from individual fish. In these cases, observers ‘tally’ (count) the sharks but do not measure and sex them or record other data such as the time of landing, fate, or processing method. Furthermore, many blue sharks that were individually recorded (69.8% of 177 720 sharks) were not measured.

Observer length-frequency distributions were scaled up to estimate the size composition of the commercial catch using NIWA’s catch-at-length-and-age program CALA v2.0-2015-01-28 (rev. 371) (Francis, R. I. C. C. et al. 2014). Measured sharks were aggregated into four strata (Charter North, Charter South, Domestic North and Domestic South) and scaled up to the fishing year catch by SLL using the proportion of hooks observed in each stratum. Annual length-frequency distributions were then further scaled to the total catch for the years 2007−2015 using the ratio of the number of hooks set by the entire fleet in each year to the number of hooks set in 2008 (the year with the lowest fishing effort in the time series). Years before 2007 were not included because they had low observer coverage in the important Domestic North fishery (maximum 4.7% coverage but usually less than 3% and sometimes zero) (Griggs & Baird 2013). Coefficients of variation (CVs) for each length class, and mean weighted CVs (MWCVs) across all length classes, were estimated by bootstrap re-sampling (N=1000 samples) with replacement at the stratum level. No re-sampling was done at the year level.

Maturity and reproductive status were assessed from observer data collected between 2011 and 2015. Maturity was scored on a 3-stage elasmobranch scale (immature, maturing and mature; see Appendix 1). Three additional stages (4−6) were used to classify mature females into reproductive stages (gravid I and II, post-partum). Immature and maturing sharks (classes 1 and 2) were combined as 'immature' and mature sharks (classes 3−6) were combined as 'mature'. Maturity ogives were fitted to the proportions of sharks that were recorded as mature after grouping them into 5-cm length classes. Logistic regressions (binomial error structure with a logit link function) were fitted to the data using the GLM function in R statistical software (R Development Core Team 2008).

2.3 Ageing blue sharks

A block of 3−4 vertebrae was removed from beneath the first dorsal fin of each shark, trimmed of neural and haemal arches, muscle and connective tissue, and then frozen. Sex was recorded and FL was measured in a straight line from the tip of the snout to the fork in the tail, rounded down to the centimetre below actual length. Sharks were aged from their vertebrae using methods previously developed and used successfully for New Zealand blue sharks (Manning & Francis 2005). The vertebral blocks were defrosted, the largest visible vertebra was dissected out, and it was briefly bleached (about 15 min), washed, and air dried overnight. Vertebrae from sharks shorter than 150 cm FL were read whole under a microscope. Vertebrae from larger sharks were glued to small wooden blocks with epoxy resin, and sectioned with a Struers Secotom-10 diamond blade saw. Vertebrae were sectioned in the frontal plane (Wilson et al. 1987) by making two cuts with a single diamond-edged blade to produce a section about 0.6 mm thick. This produced 'bowtie' sections (Figure 1), although these frequently broke into two pieces at the focus. No grinding, polishing or staining was performed. Sections were stored in 70% ethanol. Sections were then X-rayed at 50 kV and 5 mA at various exposure times onto Industrex M100 X-ray film. Developed films were examined under a stereomicroscope and growth bands visible on the films were counted using either transmitted light or from captured images.

Vertebral bands were initially counted by two readers (readers 1 and 2). Vertebrae were scored by reader 2 for their readability using a scale from 1 (excellent) to 5 (unreadable). Blue shark vertebrae proved difficult to age, with significant differences in counts between the two readers (see Results). A subset of 16 X-rays of sections was therefore read by two additional readers (readers 3 and 4). The four readers were Malcolm Francis (NIWA, reader 1), Caoimhghin Ó Maolagáin (NIWA, reader 2), Katie Viducic (MSc student, University of Rhode Island, USA, reader 3), and Peter Horn (NIWA, reader 4). Readers 1, 2 and 4 had little or no experience with ageing blue sharks, but were very experienced in ageing a wide range of other sharks and teleosts. Reader 3 was experienced with ageing North Atlantic blue sharks, but from sections viewed under white light rather than from X-rays.

Shark species often display a 'birth band', which is a prominent contrasting band in the centrum deposited about or soon after birth. Identification of this band is important in order to determine where subsequent band counts should begin. The birth band in blue sharks was defined as the first prominent opaque (light on X-rays) band (Figure 1). It was sometimes accompanied by a slight change in the angle of the centrum face (the outer edge of the corpus calcareum). Correct identification of the birth band was assisted by vertebral measurements: Skomal & Natanson (2003) showed that it occurs at about 2.7 mm from the focus in North Atlantic blue sharks.

To estimate precision, Beamish & Fournier (1981) suggested the use of average percent error (APE). Chang (1982) supported the use of this method and also suggested the use of a coefficient of variation (CV). Precision was measured by calculating indices of APE and CV for each set of band counts (Campana et al. 1995; Campana 2001). Within-reader and between-reader age-estimation bias and precision were explored with NIWA R package *AgeCompare* for readings of whole vertebrae by readers 1 and 2. *AgeCompare* produces a plot comparing the two readings, a frequency distribution of the age differences, an age-bias plot (Campana et al. 1995), and plots of the APE and mean CV. CV is numerically $\sqrt{2}$ (= 1.414) times greater than APE.

We were unable to objectively age blue shark vertebrae in this study (see Results). Consequently it was not possible to estimate blue shark growth rate or age composition, nor to develop a reference collection of aged specimens or an ageing protocol.

3. RESULTS

3.1 Observer sampling

All sets from all of the chartered Japanese SLL vessels were observed and sampled in 2011−15 (Table 1, Appendix 2). However, few domestic trips and only 3−7% of the domestic sets were observed, and even smaller proportions were sampled for vertebrae, maturity data or fin weights on domestic trips. Fin weight data were analysed by Francis (2014) and are not considered in this report.

Data and samples were collected from 54 observer trips, 50 of them aboard SLL vessels and four aboard trawlers (Appendix 2). Most vertebrae and data came from SLL vessels operating in FMAs 1, 2, 5 and 7 during April–August. A total of 1152 blue sharks were sampled for vertebrae, 2268 for maturity, and 1161 for fin weights. Only 1 male blue shark was sampled for spermatozeugmata. Comparison of the length-frequency distributions of blue sharks sampled for vertebrae and maturity with the distributions for all blue sharks measured by observers over the same period showed that samples were generally representative of the sharks measured (Figures 2−3). However, small males were under-represented in the maturity samples.

Observers on SLL vessels were not always able to measure every shark, and this may introduce biases into the recorded length-frequency distributions. Potential biases include:

1. Observers may not be able to measure all the sharks that are caught because of other priorities, or because they may not observe an entire haul if it continues beyond the end of a 12-hour day. If large tallied catches represent schools of a particular size group of sharks (e.g. sub-adults[1]), failure to measure them will result in under-estimation of the numbers of that size group.
2. Some sharks may be cut or shaken off the line alongside the boat, and not brought aboard; others are lost during hauling. This issue may be more important on smaller domestic vessels which are less able to bring large sharks aboard, particularly in bad weather. These sharks are not usually measured or sexed.
3. Discarded sharks are often not measured. There are two issues here. First, fishers may selectively discard or release particular size classes; e.g. small sharks have less-valuable fins than large sharks and (up until October 2014 when shark finning was banned) may have been preferentially released. Second, if released sharks are large and lively, they may be difficult and dangerous to measure, leading to fewer measurements of large sharks.

No data are available to assess the magnitude of the first two biases listed above, but only about 30% of the individually-recorded blue sharks were measured in 2011–15. Anecdotal information from observers confirms that those issues exist, and that size-related biases are likely (L. Griggs, NIWA, pers. comm.). There is no way to determine whether discarded sharks differ in length composition from retained sharks. Changes in fisher behaviour might be expected to have occurred at the time of the introduction of the sharks to the QMS (October 2004) and when shark finning was banned (October 2014).

The proportion of blue sharks discarded by observed SLL vessels has increased rapidly from 30–40% in the 2000s to 85% in 2014 and nearly 100% in 2015 (Figure 4). In the North region, the proportion of blue sharks measured by observers has varied greatly (2–47%), with two of the lowest values (3–4%) occurring in 2014 and 2015 (Figure 5). In the Southwest region, the proportion measured fluctuated even more widely (9–69%), and there has been a big decline from about 60% in the early 2010s to 18% and 22% in 2014 and 2015 respectively. The recent big changes in proportions discarded and measured

[1] Sharks often school by size and sex.

reflect economic and freight problems in the shark fin market in 2014 and the introduction of a ban on shark finning at the beginning of the 2015 fishing year.

The proportion of males in the observed catch showed no clear temporal trends (Figure 6). In the North region, there was a slight overall bias towards males (53%) but the sex ratio varied markedly among years. In the Southwest region, blue shark catches were dominated by females, with only 25% males. North catches were slightly skewed towards males because of the presence there of mature males as well as juveniles, while southern catches were dominated by immature females because of the large number of sub-adults (Francis 2013).

Scaled length-frequency distributions for the whole SLL fishery for the period 2007−2015 are shown in Figure 7. Both sexes had a broad size range of mainly immature sharks smaller than 185 cm. Few sharks over 250 cm were recorded for either sex. MWCVs were low (0.08–0.10) reflecting the high sample sizes. For 2007−2015, the ratio of males to females in the scaled EEZ catch was 0.75:1 (42.9% males).

3.2 Maturity

Both male and female blue sharks showed a clear progression in median lengths across maturity classes 1–3 (Figure 8). Males showed good representation of both immature (classes 1 or 2) and mature (class 3) individuals. The largest male shark that was recorded as immature (246 cm) was undoubtedly an error (Figure 8). Most females were immature, with only a small proportion of mature females.

For males, a well-defined logistic growth curve was fitted after removal of the one large immature outlier (Figure 8). The estimated logistic parameters were $\beta_0 = -10.61 \pm 0.74$ (SE) and $\beta_1 = 0.059 \pm 0.004$. The estimated median length at maturity was 179.4 cm (95% confidence limits 175.3–183.6 cm). A paucity of mature females made it impossible to fit a female logistic curve or estimate their length at maturity (Figure 8).

Francis & Duffy (2005) estimated the median length at maturity of male New Zealand blue sharks to be 190–195 cm using a suite of reproductive characters. In blue sharks, unlike in most other shark species, clasper length increases continuously across most of the length range, coming to an asymptote only in very large sharks (Pratt 1979; Francis & Duffy 2005). This makes it difficult to ascertain maturity from clasper length alone. The smallest male blue shark found by Francis & Duffy (2005) with spermatozeugmata in its seminal vesicles was 164 cm, and 50% of males contained spermatozeugmata by 194 cm. Thus although clasper length, which was the main criterion used by observers for determining male maturity in the present study, indicates that males may be able to mate by around 180 cm, their ability to fertilise oocytes probably does not occur until later. Therefore the 190−195 cm size at maturity estimated by Francis & Duffy (2005) remains the best estimate available. Similarly, Francis & Duffy (2005) also provided the best available estimate of length at maturity for New Zealand female blue sharks of 170–190 cm.

These lengths at maturity were applied to the relevant (unscaled) length-frequency distributions to estimate the percentages of sharks that were mature in the 1993−2015 observer time series (Figure 9). Mature male blue sharks made up 19% of the sharks measured in the North region, but the percentage fluctuated markedly among years. The Southwest region had few mature males (1% overall). Few mature females were observed: over the whole time series, estimated percentages mature were 5% in North region and 8% in Southwest region. Based on the scaled length-frequency distributions for 2007−2015 (Figure 7), the percentages of mature blue sharks in the entire New Zealand SLL catch were estimated to be 9.9% for males and 4.5% for females.

3.3 Ageing blue sharks

The sample of vertebrae selected for ageing consisted of 232 sharks (106 males, 125 females and 1 unsexed). Of these, 110 sharks were shorter than 150 cm FL and their vertebrae were aged whole, while

122 were 150 cm FL or longer, and they were aged from X-rayed vertebral sections. Regardless of the ageing method, vertebrae were difficult to read. Reader 2 assigned readability scores mainly at the poor end of the scale: 61.2% of samples were poor readability (readability score = 4), 36.6% were good (3), and only a few (2.2%) were very good (2); none were excellent (1).

A between-reader comparison of the whole-vertebra band counts of readers 1 and 2 for sharks shorter than 150 cm is shown in Figure 10. Readings were highly variable between readers, with an overall CV of 19.8% and APE of 14.0%, and absolute differences (reader 1 minus reader 2) ranging from –1 to 5 years (mean = 0.61 years). Readings of 82% of the vertebrae agreed within ±1 years. However there was a clear age-related trend, with reader 1 counting progressively more bands than reader 2 in larger (older) sharks (Figure 10b, c). Joint inspection of a number of vertebrae (both whole, and X-rayed sections) by the two readers revealed that the vertebrae have a banding pattern that can be interpreted in two different ways: the many relatively narrow bands can be counted, or aggregated into fewer relatively broad bands (with splits or sub-banding) (Figures 1, 11 and 12; note that the images shown in these figures lack the contrast and resolution of sections viewed under a microscope and do not show all the smaller bands). Reader 1 tended to count more narrow bands than reader 2. Variation in lighting direction and source (white light versus X-ray) made little difference to the interpretation, because centra and sections appeared similar in all situations (Figure 11). A number of the larger whole vertebrae were then sectioned and X-rayed to see if the disagreement between the two readers resulted from poor resolution of narrow bands in whole centra, but the result was the same (i.e. reader 1 still counted more bands than reader 2).

Discussion between readers 1 and 2 failed to produce agreed ages, so two further readers (readers 3 and 4) were invited to count growth bands on a subset of 16 thick section X-rays. Pairwise comparisons of readings among all four readers are shown in Figure 13. There were significant positive correlations between all pairs of readings (r = 0.57−0.95, $p < 0.01$). Highest correlations were observed between readers 1 and 2 (r = 0.95), and readers 1 and 4 (r = 0.81), but all comparisons showed displacements or slopes that differed from the expected 1:1 relationship. When band counts were plotted against blue shark fork length, two clusters of points were apparent, with reader 2 producing lower counts than readers 1, 3 and 4 for the same sections (Figure 14). Reader 2's counts fell on or close to the growth curves produced previously for New Zealand blue sharks by Manning & Francis (2005), whereas counts by the other three readers mainly fell to the right of those growth curves (Figure 14).

4. DISCUSSION

This study provides an updated and extended analysis of the composition of the catch of blue sharks in the New Zealand tuna longline fishery. The previous analysis (Francis 2013) was updated by three years to include the 2015 fishing year, and extended by generating scaled length-frequency distributions of the total SLL catch for 2007−2015. The present study therefore provides improved information on blue shark catch composition in the SLL fishery, which accounts for most of the New Zealand blue shark catch (98–99% by weight in 2008−2011 (Francis 2013)).

The quality of the data on which these analyses were based is limited in a number of respects. Observer sampling of length data was compromised by their inability to measure every shark caught, and evidence that unmeasured, discarded sharks may have a different size composition from measured, discarded sharks (Francis 2013). The proportion of observed blue sharks discarded or released alive under Schedule 6 of the Fisheries Act continues to increase, reaching virtually 100% of the SLL catch in 2015. This peak resulted from a decline in the economics of the shark fin trade in 2014 and the introduction of a ban on shark finning at the beginning of the 2015 fishing year. The issue is most acute in the North region, where the percentage of observed blue sharks measured dropped to 3–4% in 2014 and 2015, and observer coverage was low (average 5.8% of hooks observed for the most recent five years 2011–15 for domestic vessels in North region). High observer coverage of the Japanese charter fleet in Southwest region (average 79.9% of hooks in 2011–15) means the situation is much better there, but the percentage of observed sharks measured had dropped to 18–22% in 2014 and 2015. The decline in numbers of blue sharks measured by observers makes it difficult to assess recent patterns of size composition, sex ratio, and maturity composition. The analyses presented here must therefore be interpreted cautiously.

Scaled length-frequency distributions for 2007−2015 showed that the commercial SLL blue catch was dominated by juveniles: an estimated 90% of males and 95% of females were immature. These proportions may have been over-estimated if significant numbers of large mature adults were being discarded unmeasured. However, mature females have always been rare in the observer data (Figure 9; Francis 2013, appendices 2 and 3). Mature females are therefore not considered vulnerable to the New Zealand SLL fishery, although they may be taken by other fleets in international waters. Most measured sharks were shorter than 200 cm FL, compared with a maximum known length for blue sharks of at least 320 cm FL (383 cm TL) (Last & Stevens 2009; Ebert et al. 2013). The scaled distributions differ from previous unscaled distributions (Francis 2013) in being broader with reduced peak heights. This change reflects the increased weight given to North region catches, particularly by domestic vessels, in the scaled distributions.

We were unable to assign ages to blue shark vertebrae in this study. Interpretation of banding patterns was ambiguous, with differences among readers resulting in either ‘low’ or ‘high’ band counts. Low band counts occurred when multiple individual bands were aggregated into fewer broader bands. Low band counts are more consistent with the only previous blue shark growth curves from New Zealand (Figure 14) and also with other growth curves from around the globe (Figure 15). High band counts are not consistent with other studies. Furthermore, although three readers produced high counts, there were substantial differences among their readings. Many studies have reported difficulties in reading blue shark vertebrae, with differences occurring among readers, preparation techniques (whole versus sectioned vertebrae), visualisation techniques (white light versus X-rays) and lighting angle (transmitted versus reflected) (see references in Table 2).

The low vertebral band counts obtained for New Zealand blue sharks are more plausible than the high counts. Elsewhere, blue shark growth curves derived from similar low counts have been corroborated (defined as being supported by independent data (Cailliet 2015)) with growth rate estimates derived from length-frequency and tag-recapture data (Table 2; Stevens 1975, 1976; Nakano 1994; Skomal & Natanson 2003; Manning & Francis 2005; Wells et al. 2016). However, there have been few attempts at validation of blue shark ageing techniques, and most of them have been limited in scope and scale, and were inconclusive. Three studies have used marginal increment analyses (MIA) or Centrum Edge Analysis (CEA), which respectively measure or score the state of the most recently-formed material on the margin of the vertebrae to identify seasonal cycles that might confirm annual band deposition (Campana 2001; Cailliet 2015). Two of the studies found no seasonal cycle (Lessa et al. 2004; Hsu et al. 2011), whereas a third found a weak seasonal MIA cycle and a clear seasonal CEA cycle (Hsu et al. 2012). However MIA and CEA are regarded as poor validation techniques because they rely on subjective determination of the vertebral margin (Campana 2001). Two studies have attempted to validate blue shark vertebral bands using injection of the fluorochemical oxytetracycline (OTC) into tagged and released blue sharks; growth bands formed outside the fluorescent mark can be counted on the vertebrae of recaptured sharks. Unfortunately, both studies had small sample sizes, small age ranges, and short experimental durations, thereby giving inconclusive results. Skomal & Natanson (2003) had only two OTC recaptures of sharks that were liberty for only 0.7 and 1.5 years respectively. Wells et al. (2016) had a larger sample size of 26 OTC recaptures, but only five of their sharks were at liberty for more than one year, only two sharks were older than three years at recapture, and those two sharks were at liberty for only 0.5 and 1 year. A study using radiocarbon dating validated the age of a single 270 cm FL (approximately 330 cm TL) Indian Ocean blue shark as 23 years old (Romanov & Campana 2011). Thus only partial validation of young blue sharks up to a few years of age has been achieved.

In the absence of adequate validation of blue shark vertebral bands in New Zealand or overseas, vertebral ageing remains subjective. It was therefore impossible to develop an objective ageing protocol for New Zealand blue shark in this study. Nevertheless, growth curves developed previously for New

Zealand blue sharks by Manning & Francis (2005) are consistent with those produced for most other parts of the world (Figure 15) and may be reasonably reliable. Although the maximum age derived by most overseas studies does not exceed 16 years, Manning & Francis (2005) reported a maximum age of 22 years for New Zealand blue sharks (Table 2). The latter is consistent with a 23-year old Indian Ocean blue shark validated by radiocarbon dating (Romanov & Campana 2011). Further validation is required to determine whether other studies may have under-estimated the ages of large, old blue sharks. Such age under-estimation has been seen in a growing number of shark species, and has been attributed to the merging of small marginal vertebral bands (Francis et al. 2007; Passerotti et al. 2014), and may prove to be a common feature among older slower-growing sharks.

5. MANAGEMENT IMPLICATIONS

For the first time, this study provides scaled length-frequency estimates of the blue shark catch composition in the SLL fishery, which accounts for most of the New Zealand catch. Subject to caveats about the representativeness of the observer sampling, the scaled distributions show that the catch is dominated by juveniles. Few mature sharks are caught, especially mature females which make up only 5% of the catch (by number). The New Zealand blue shark fishery is therefore mainly a juvenile fishery that has minimal impact on mature breeding females. Mature females are believed to occur and give birth in subtropical and tropical waters around the northern North Island and Kermadec Islands (and other regions in subtropical latitudes) during summer; a similar pattern of sexual- and size-segregation and seasonal migration occurs in the North Pacific Ocean (Nakano 1994; Nakano & Seki 2003). It is likely that mature females are caught by SLL vessels working in international waters beyond New Zealand's EEZ, and efforts should be made to determine the catch composition of such vessels. Tagging indicates that there is considerable movement of blue sharks between New Zealand and the tropical islands to the north of New Zealand, and to a lesser extent to eastern Australia (Holdsworth & Saul 2014).

Fisheries on juvenile sharks can be sustainable if enough juveniles grow through the 'gauntlet' age range to replenish adults dying from natural causes (Simpfendorfer 1999). Currently, SLL fishing effort in New Zealand waters is near its lowest point in over 30 years: about 2 million hooks are set per year compared with over 25 million hooks in the early 1980s (Ministry for Primary Industries 2015). A range of indicators suggest that the population size of blue sharks has either been stable or increased since 2005 (Francis, M. P. et al. 2014). Nevertheless, caution is required because:

- ageing has not been validated, so a conservative approach is required
- blue sharks may live at least 23 years, but few studies have included very large sharks in their samples, suggesting that maximum age may be considerably greater, and natural mortality rate lower, than currently assumed
- stock structure is uncertain, but tagging studies show regular movement around the Southwest Pacific and no tagged sharks have crossed the equator, suggesting that there may be separate North and South Pacific stocks (Holdsworth & Saul 2014; Clarke et al. 2015)
- there is no information on the survival rate of sharks released alive under Schedule 6

6. ACKNOWLEDGMENTS

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8. TABLES

Table 1: Number of surface longline (SLL) vessels and sets, observer coverage, and number of vessels sampled for vertebrae, maturity data or fin weights during 2011−15.

Fishery	Fleet	Fishing year	No. of trips	No. of sets	Observed trips	Observed Sets	% sets observed	Trips sampled
SLL	Charter	2011	4	151	4	151	100.0	4
SLL	Charter	2012	4	164	4	164	100.0	4
SLL	Charter	2013	4	148	4	148	100.0	4
SLL	Charter	2014	4	186	4	186	100.0	4
SLL	Charter	2015	4	181	4	181	100.0	4
SLL	Domestic	2011	568	2736	14	172	6.3	3
SLL	Domestic	2012	560	2617	12	174	6.6	7
SLL	Domestic	2013	510	2497	9	85	3.4	6
SLL	Domestic	2014	430	2106	13	157	7.5	10
SLL	Domestic	2015	412	2043	13	123	6.0	4

Table 2: Summary of literature studies of blue shark age and growth. Total length was the commonest length measurement used in the literature and is adopted here for comparison among methods; TL was estimated from other length measurements as required using regressions provided by Francis & Duffy (2005).

Location	Ocean	Vertebra state	Band visualisation	Light direction	Sample size	Max total length (cm)	Max age (years)	Validation	Corroboration	Comment	Source	Measurement method
England	NE Atlantic	Whole centrum	Silver nitrate staining	Reflected?	82	272	7		Tagging, length-frequency distribution		Stevens (1975, 1976)	TL
California	NE Pacific	Whole centrum	Silver nitrate staining, X-ray	Lateral	130	252	9				Cailliet at al. (1983a,b)	TL
California, Japan	NE and NW Pacific	Whole centrum and thick section	Silver nitrate and haematoxylin & eosin staining	Reflected?	70	280	11				Tanaka et al. (1990)	TL
	N Pacific	Whole centrum	Silver nitrate staining	Reflected?	271	~276	10		Length-frequency distribution		Nakano (1994)	PCL
Ireland	NE Atlantic	Whole centrum	White light	Reflected	159	228	6			Juveniles (only two mature sharks included)	Henderson et al. (2001)	TL
Canada	NW Atlantic	Whole centrum and thick section	White light	Reflected	185	~337	8				MacNeil & Campana (2002)	CFL
USA	NW Atlantic	Thick section	White light	Reflected	411	~365	16	OTC injection	Tagging	Only 2 OTC recaptures after 0.7 and 1.5 years respectively	Skomal & Natanson (2003)	CFL
NE Brazil	SW Atlantic	Thick section	White light	Reflected and transmitted?	236	310	12	Marginal increment ratio		No seasonal cycle in MIR	Lessa et al. (2004)	TL
New Zealand	SW Pacific	Whole centrum and thick section	White light, X-ray	Reflected	428	~360	22		Length-frequency distribution		Manning & Francis (2005)	FL
Mexico	NE Pacific	Whole centrum	Silver nitrate staining	Reflected	184	270	16				Blanco-Parra et al. (2008)	TL
Taiwan	NW Pacific	Thick section	X-ray		431	323	14	Marginal increment ratio		No seasonal cycle in MIR	Hsu et al. (2011)	TL
	Indian	Thick section	White light	Reflected?	2	330	23	Bomb radiocarbon			Romanov & Campana (2011)	TL/FL
	Central-South Pacific	Thick section	X-ray		259	315	15	Marginal increment ratio; marginal increment state		Weak MIR seasonal cycle; clear MIS cycle	Hsu et al. (2012)	TL
South Africa	SW Indian	Whole	White light	Reflected?	197	313	16				Jolly et al. (2013)	TL
California	NE Pacific	Whole centrum	White light	Transmitted	26	~284	8	OTC injection	Length-frequency distribution	Only 5 OTC sharks at liberty > 1 year; only two sharks > 3 years old and they were at liberty 0.5 and 1 year respectively	Wells et al. (2016)	FL

9. FIGURES

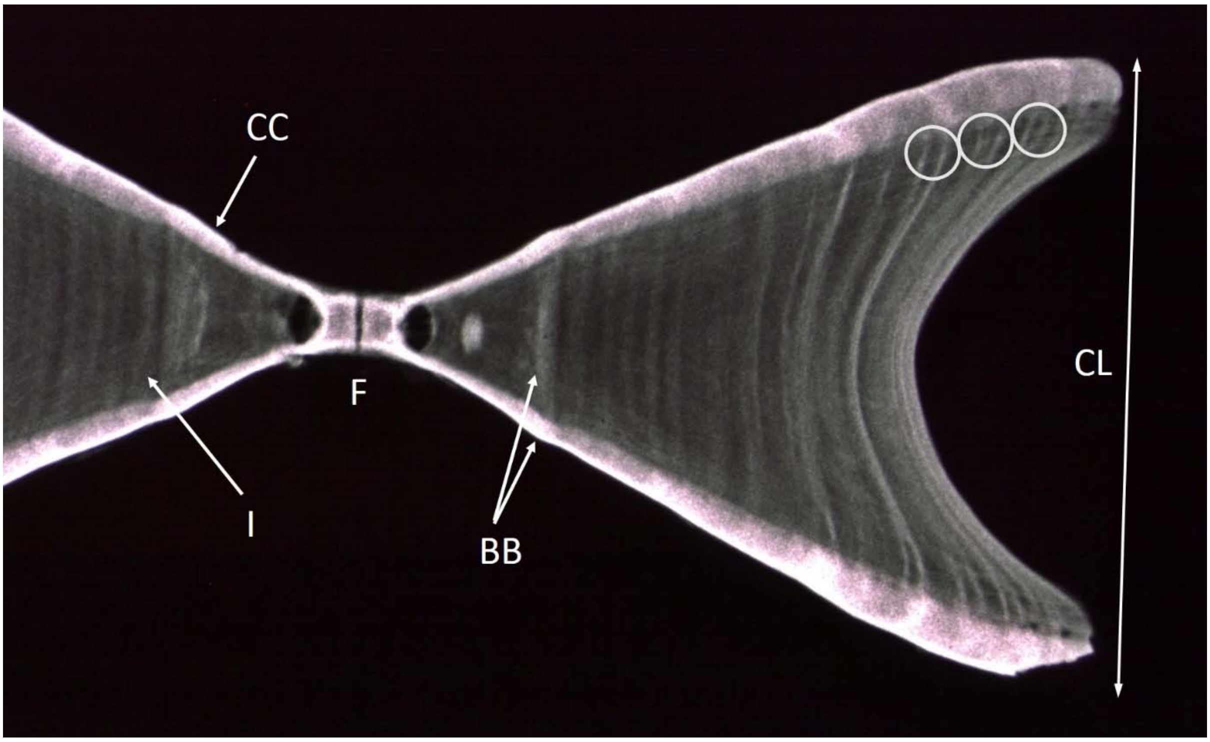

Figure 1: X-ray of three-quarters of a bow-tie thick section from a vertebral centrum of a 146 cm female blue shark (bws484). The two halves of the section meet at the focus (F). The X-ray-opaque areas (bright white) around the outside of the section are the highly-calcified corpus calcareum (CC), which forms the anterior and posterior centrum cones that articulate with adjacent vertebral centra. The less-opaque (grey) wedges between the arms of the corpus calcareum are the intermedialia (I). The birth band (BB) is identified as the first opaque band outside the focus, and is often accompanied by a change in angle of the corpus calcareum. White circles indicate split bands discussed in the text. Centrum length (CL) ~ 6.5 mm.

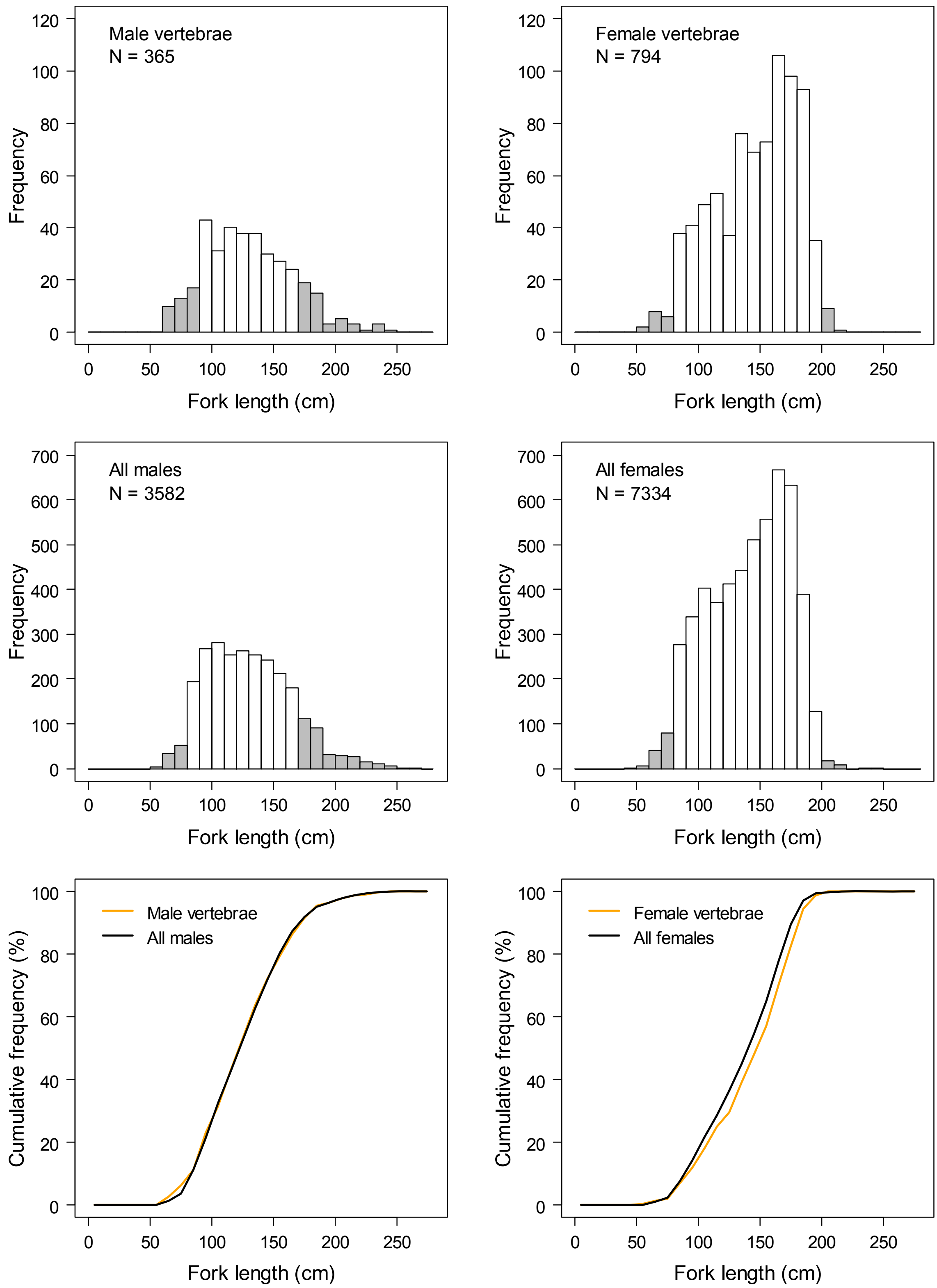

Figure 2: Length-frequency distributions of male and female blue sharks sampled in 2011–15 for vertebrae (top panels) compared with the distributions of all blue sharks measured during the same period (middle panels). The bottom panels show cumulative distribution curves for the data in the top and middle panels.

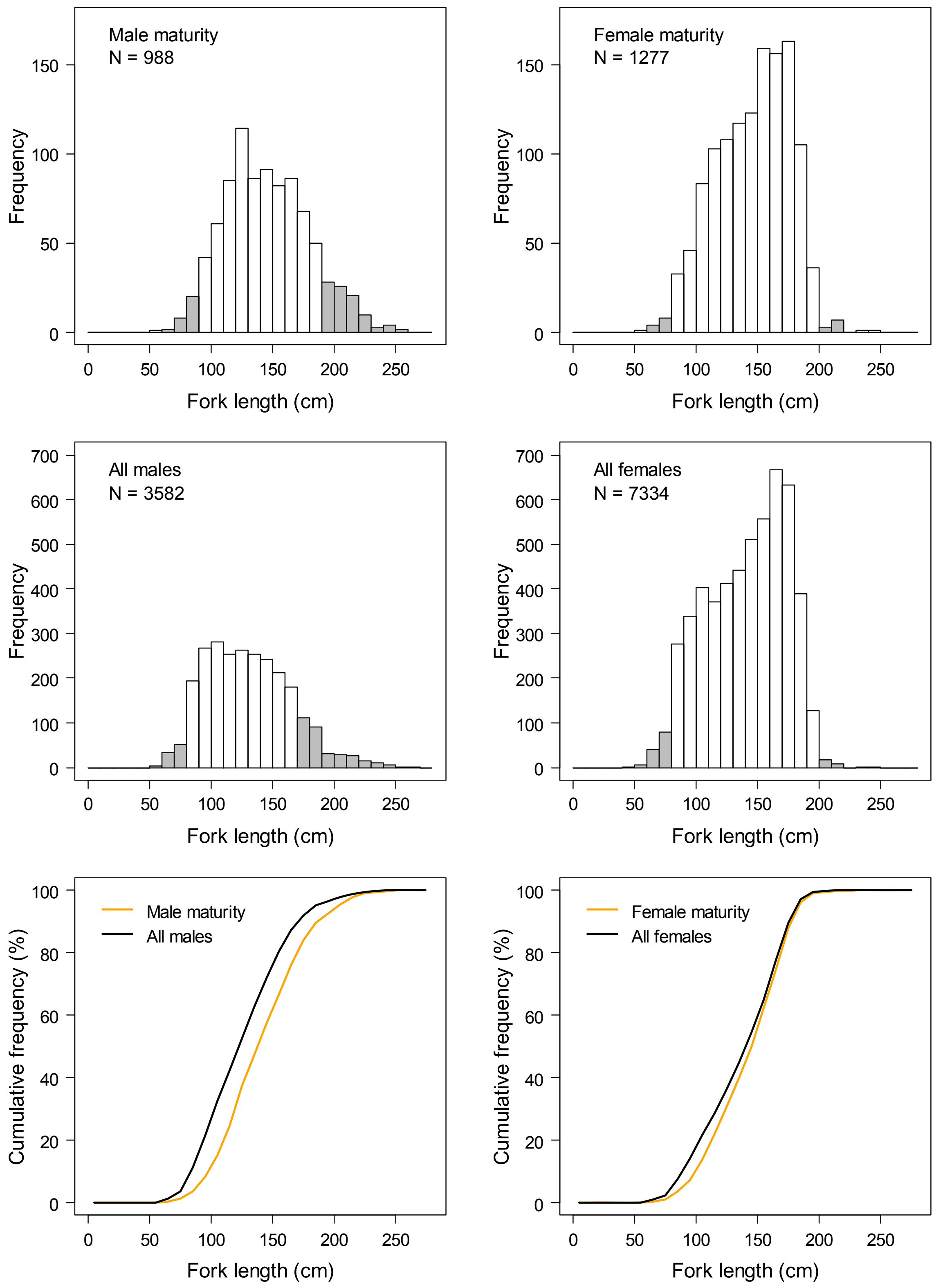

Figure 3: Length-frequency distributions of male and female blue sharks sampled in 2011–15 for maturity (top panels) compared with the distributions of all blue sharks measured during the same period (middle panels). The bottom panels show cumulative distribution curves for the data in the top and middle panels.

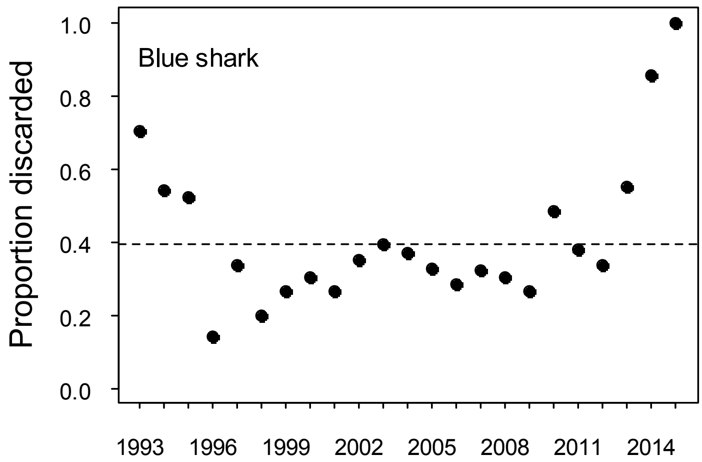

Figure 4: Proportion of blue sharks discarded from surface longline vessels, 1993−2015. The horizontal dashed line indicates the overall discard rate for the whole time series.

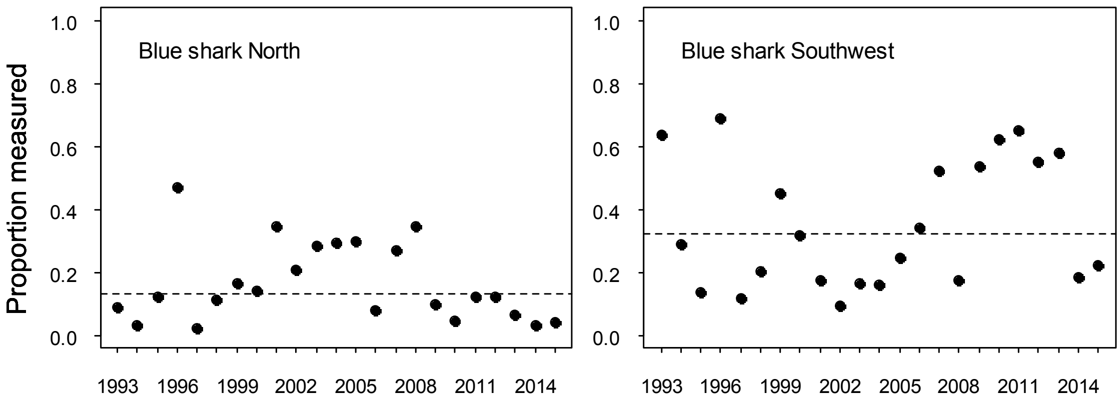

Figure 5: Proportion of blue sharks measured from surface longline vessels in North and Southwest regions, 1993−2015. The horizontal dashed lines indicate the proportion measured for the whole time series.

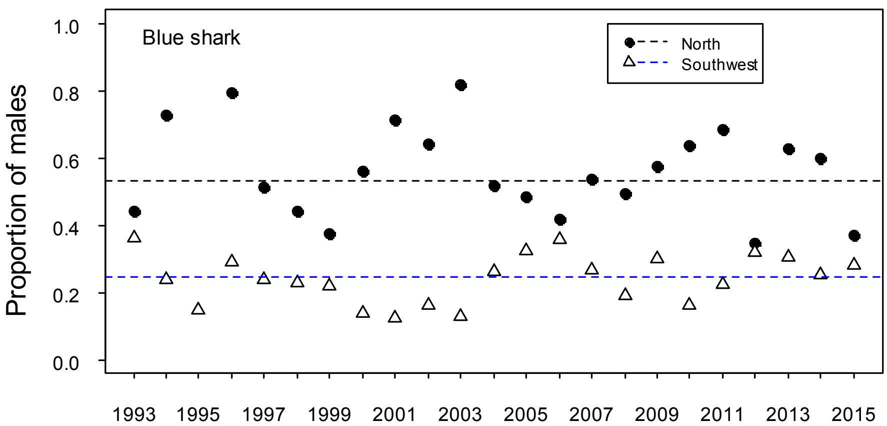

Figure 6: Proportion of male blue sharks by region from surface longlines, 1993−2015. The horizontal dashed lines indicate the proportions of males for the whole time series in each region. Only sample sizes greater than 50 are shown.

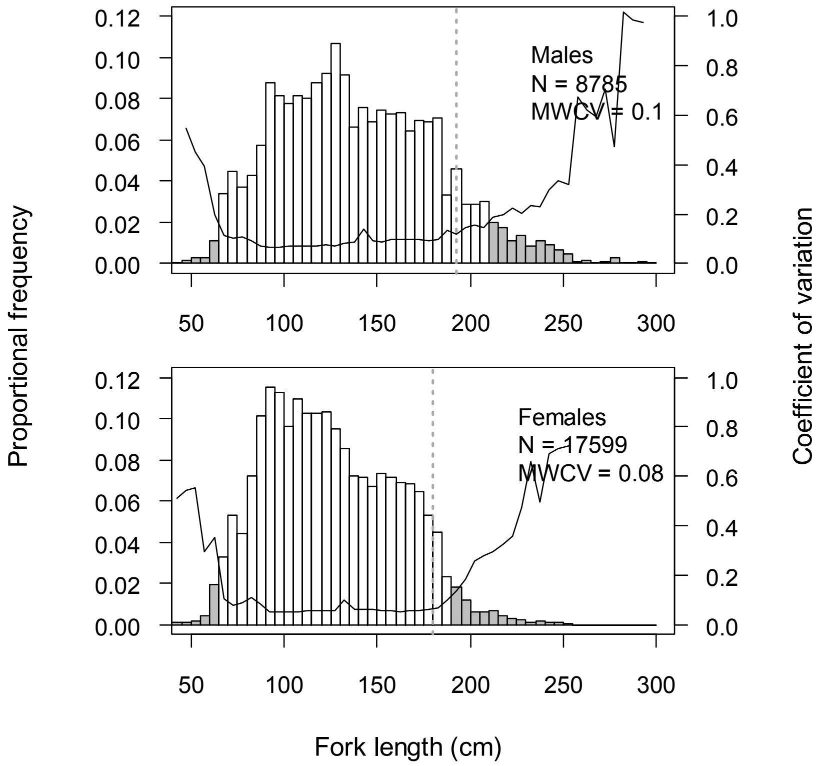

Figure 7: Blue shark scaled length-frequency distributions by sex with bootstrapped coefficients of variation (CV, solid lines) and mean weighted CVs (MWCV). Sample sizes are the number of sharks measured and sexed. Dashed lines indicate the median size at sexual maturity (Francis & Duffy 2005).

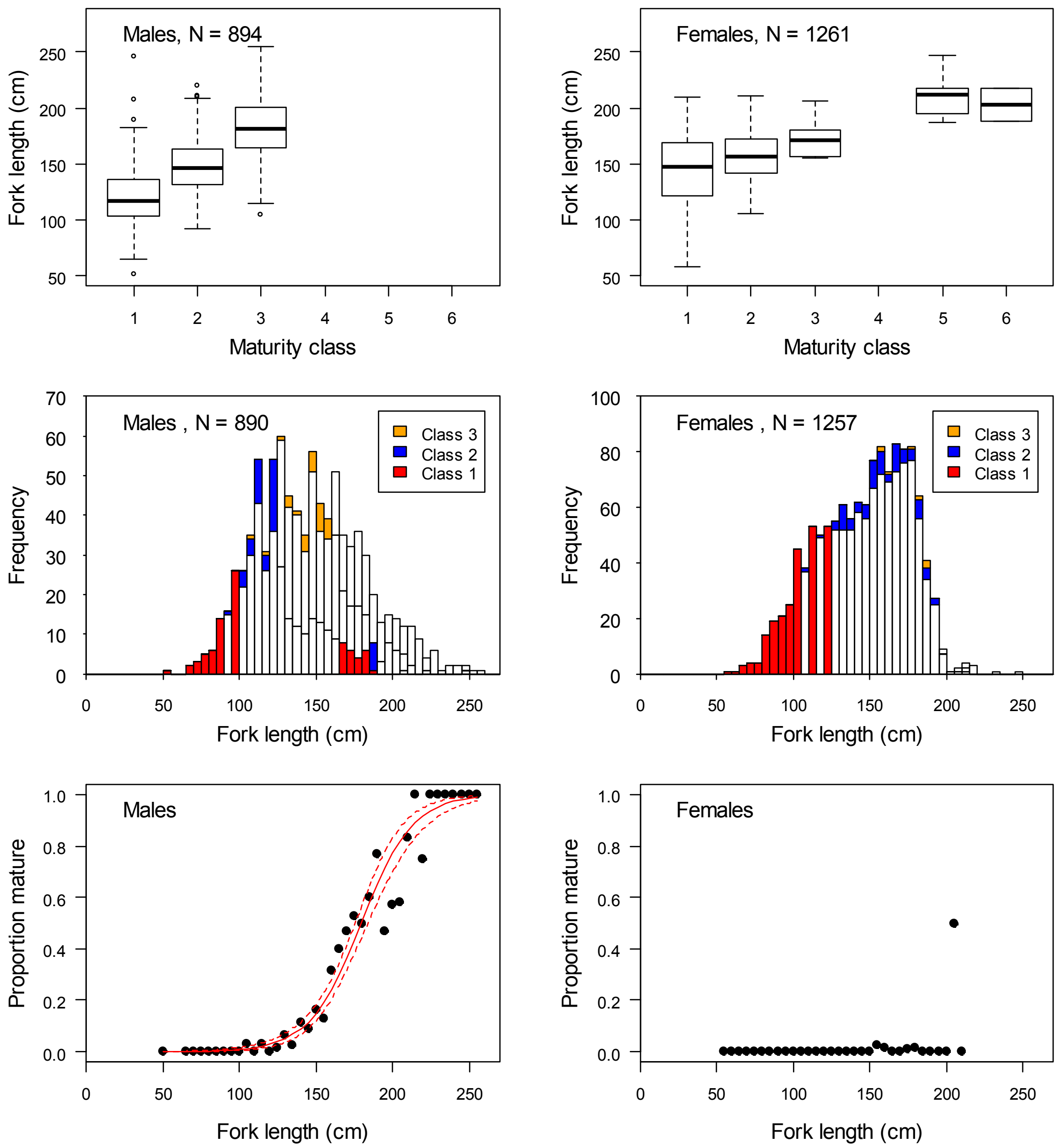

Figure 8: Maturity data collected from male and female blue sharks, 2011–15. Top panels: Box plots of fork length classified by maturity stage (see Appendix 1 for stages). The central black bar is the median, the box spans the first to third quartiles, and the whiskers extend to the most extreme data point which is no more than 1.5 times the interquartile range from the box. Middle panels: Length-frequency distributions classified by maturity class. Bottom panels: Proportion of sharks that were mature (in 5 cm length intervals) with fitted logistic regression for males (no fit was possible for females). Dashed lines are 95% confidence intervals. One large male (246 cm) classified as maturity class 1 was omitted from the bottom left panel.

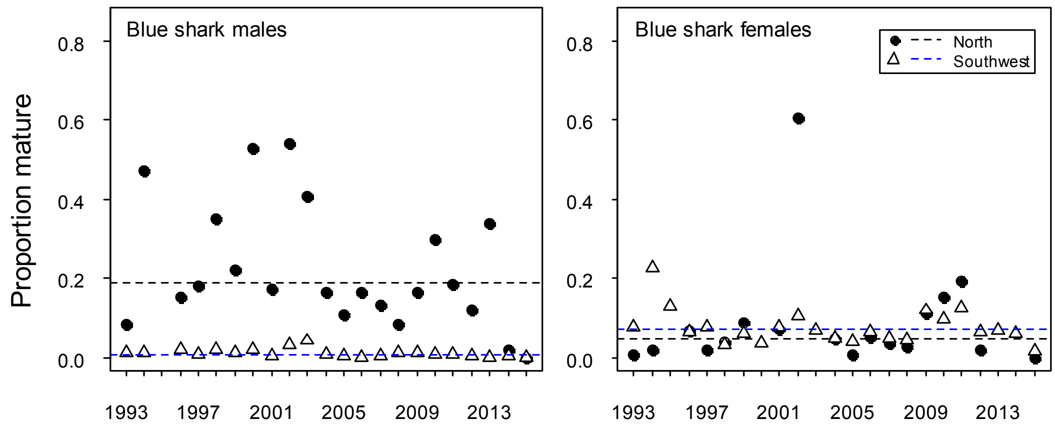

Figure 9: Proportions of observed blue sharks that were estimated to be mature based on length-frequency distributions and median lengths at maturity.

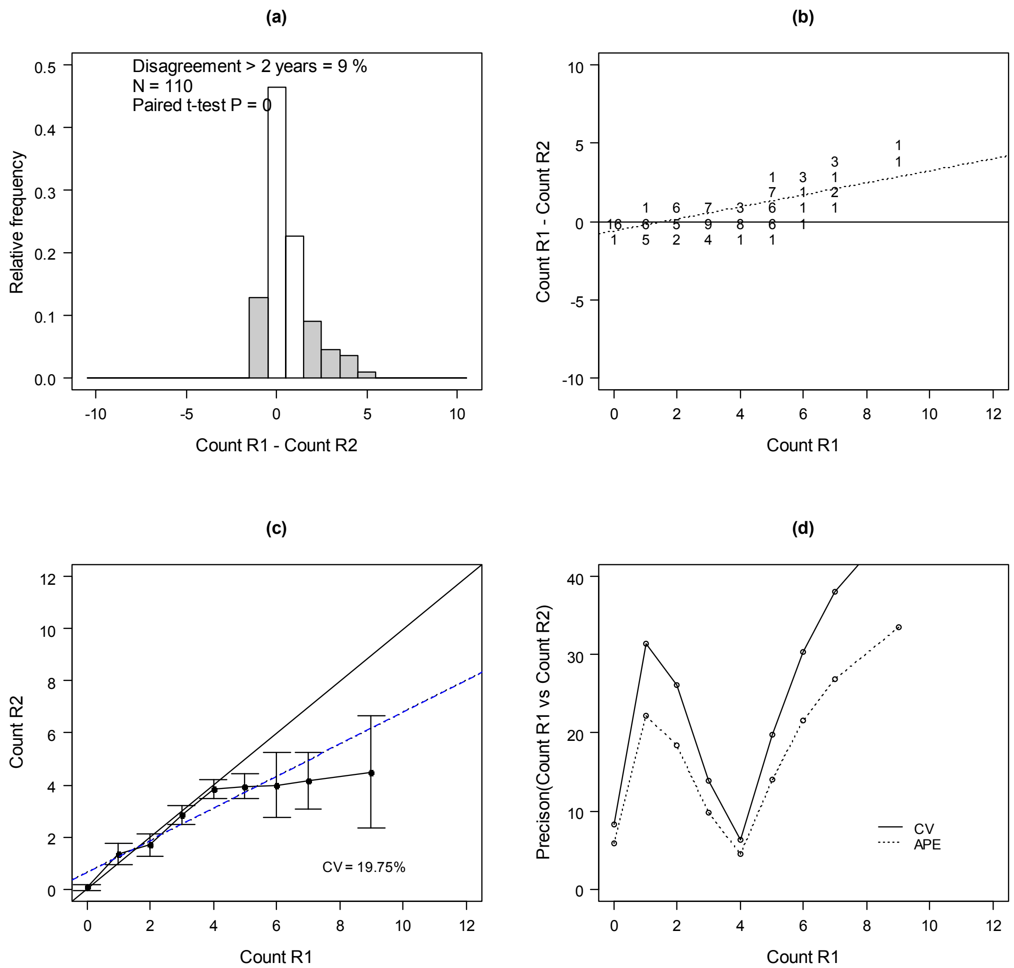

Figure 10: Comparison of vertebral band counts of readers 1 and 2 (R1 and R2). The diagonal black line in (c) is the 1:1 line, and dotted and dashed lines in (b) and (c) are fitted linear regressions. CV, coefficient of variation; APE, average percentage error.

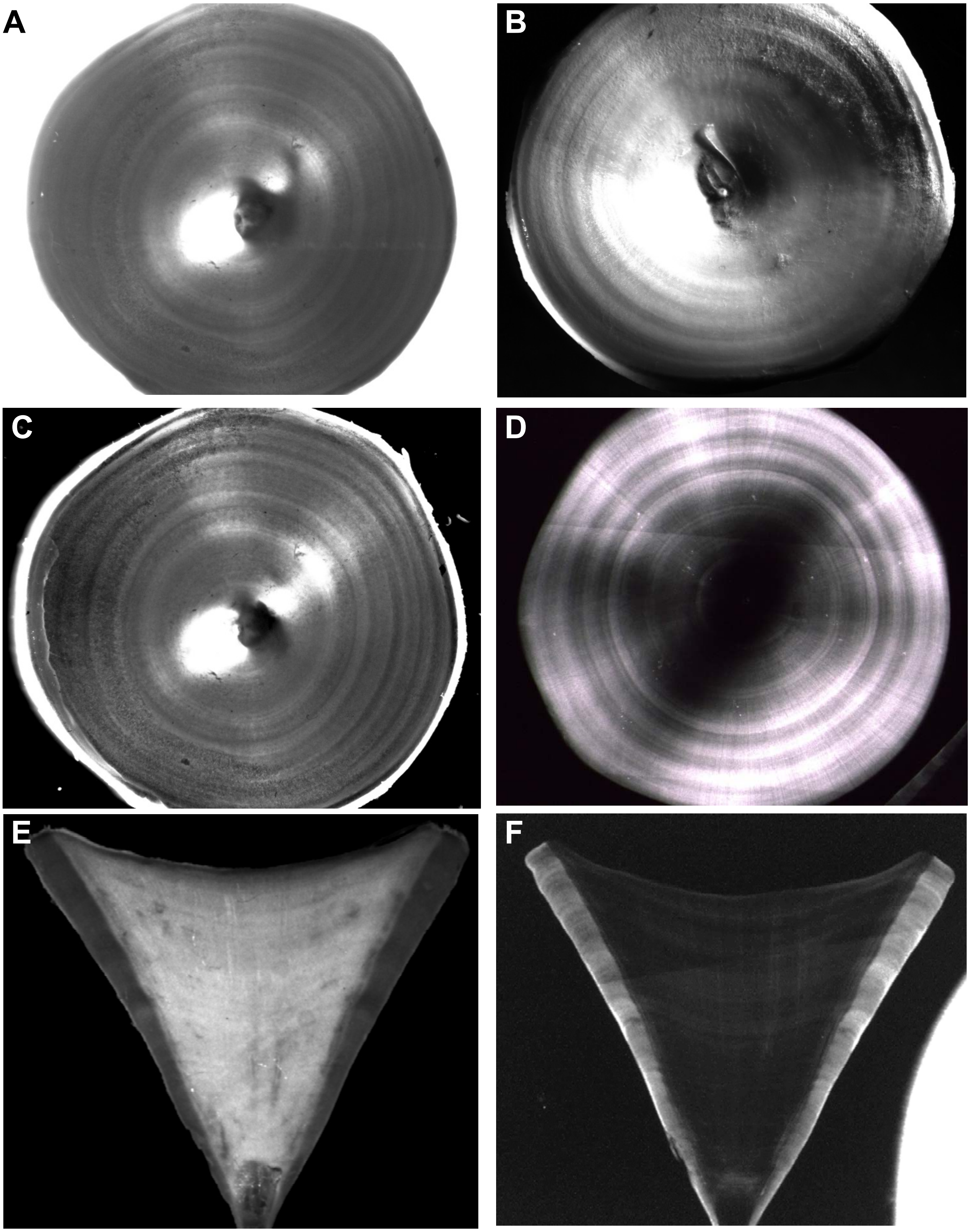

Figure 11: Images of vertebrae from a 191 cm FL female blue shark (bws446) under varying light direction and source. A, half-centrum transmitted light; B, whole centrum reflected light; C, half-centrum horizontal light; D, half-centrum X-ray; E, thick section reflected light; F, thick section X-ray. Images are approximately to the same scale, but not necessarily of the same vertebral centrum or thick section, nor in the same orientation. Centrum diameter (A–D) 20.8 mm; centrum length (E–F) 10.2 mm.

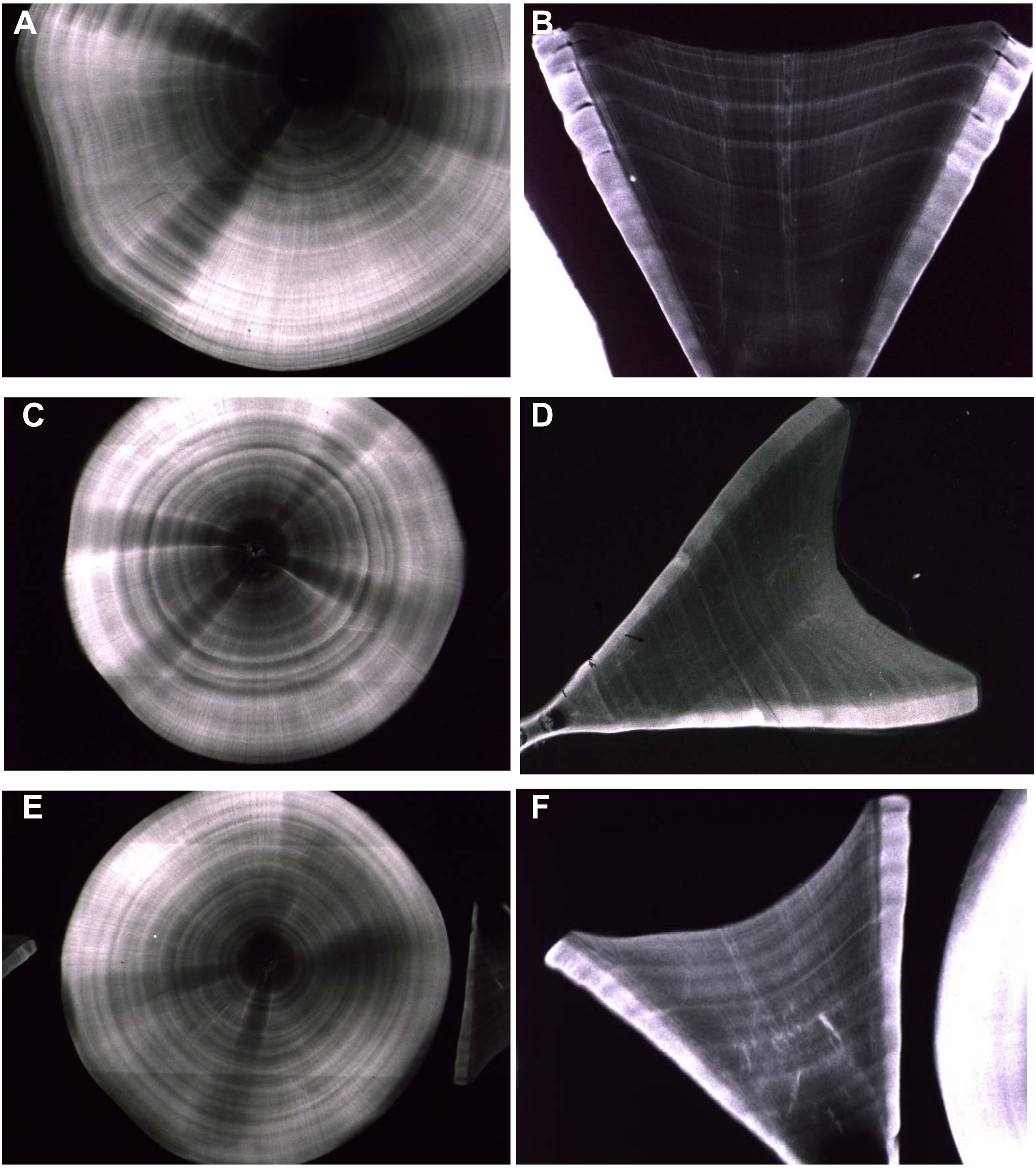

Figure 12: X-ray images of a half-centrum (left) and a thick section (right) from the same shark: A & B, 246 cm FL male blue shark (bws510) (centrum diameter 28.1 mm, centrum length 13.2 mm); C & D, 204 cm FL female blue shark (bws460) (centrum diameter 20.6 mm, centrum length 9.7 mm); E & F, 195 cm male blue shark (bws505) (centrum diameter 20.7 mm, centrum length 11.6 mm).

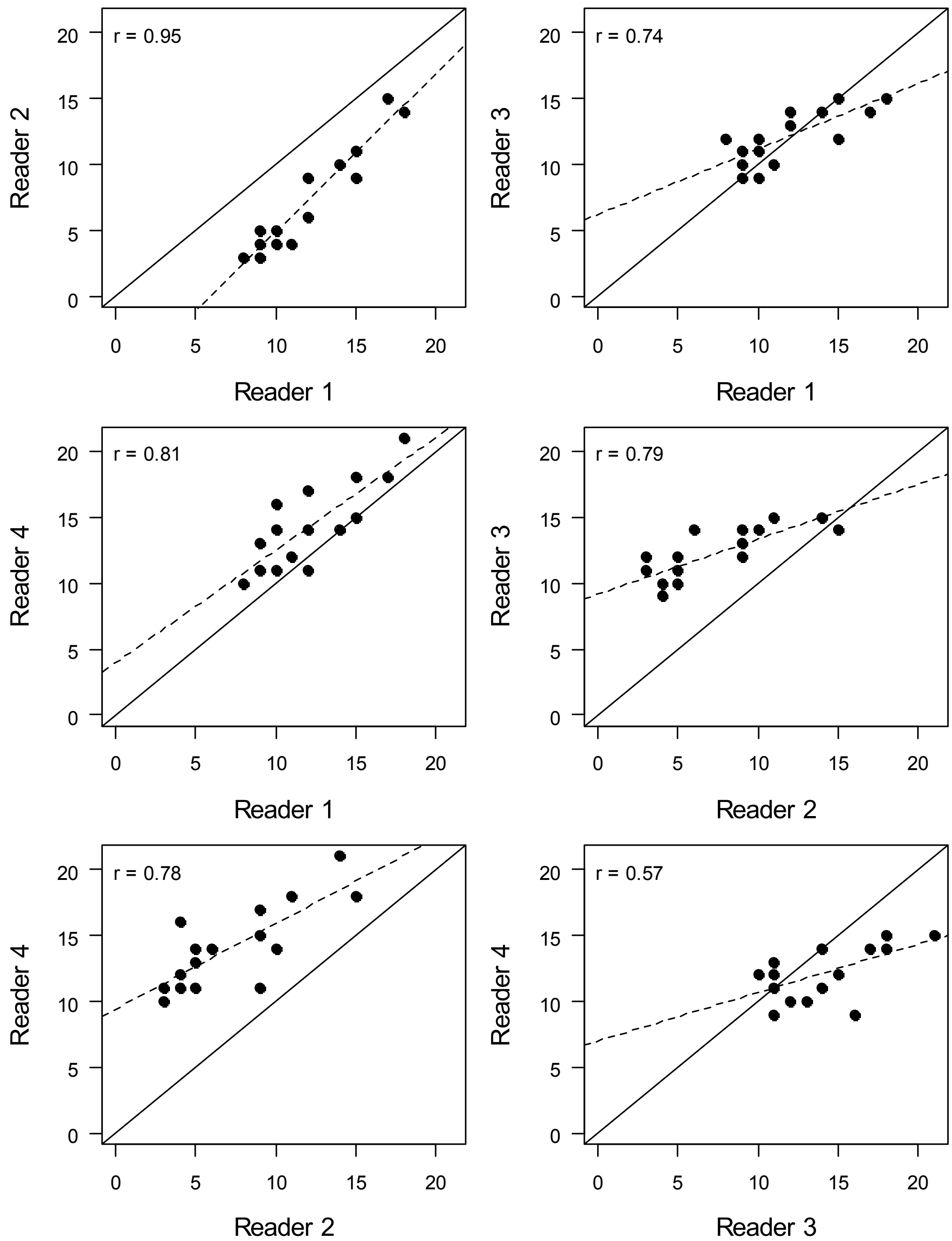

Figure 13: Pairwise comparisons of vertebral band counts by four readers of X-ray images of 16 blue shark vertebral thick sections. The diagonal solid lines are the 1:1 lines, and dashed lines are fitted linear regressions. r is the correlation coefficient.

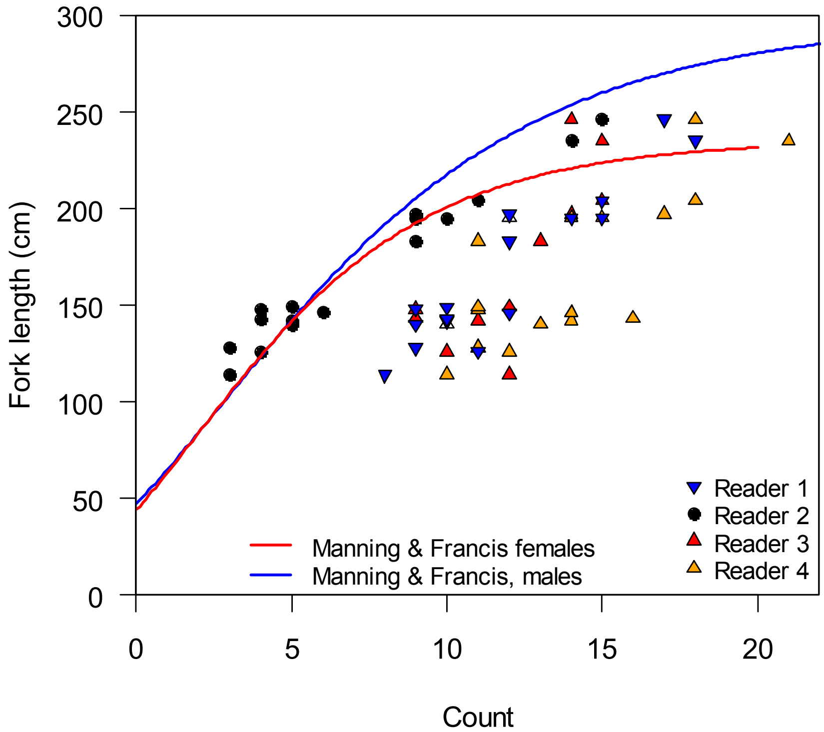

Figure 14: Vertebral band counts by four readers of X-ray images of 16 blue shark vertebral thick sections plotted against fork length. Also shown are the male and female blue shark growth curves generated by Manning & Francis (2005).

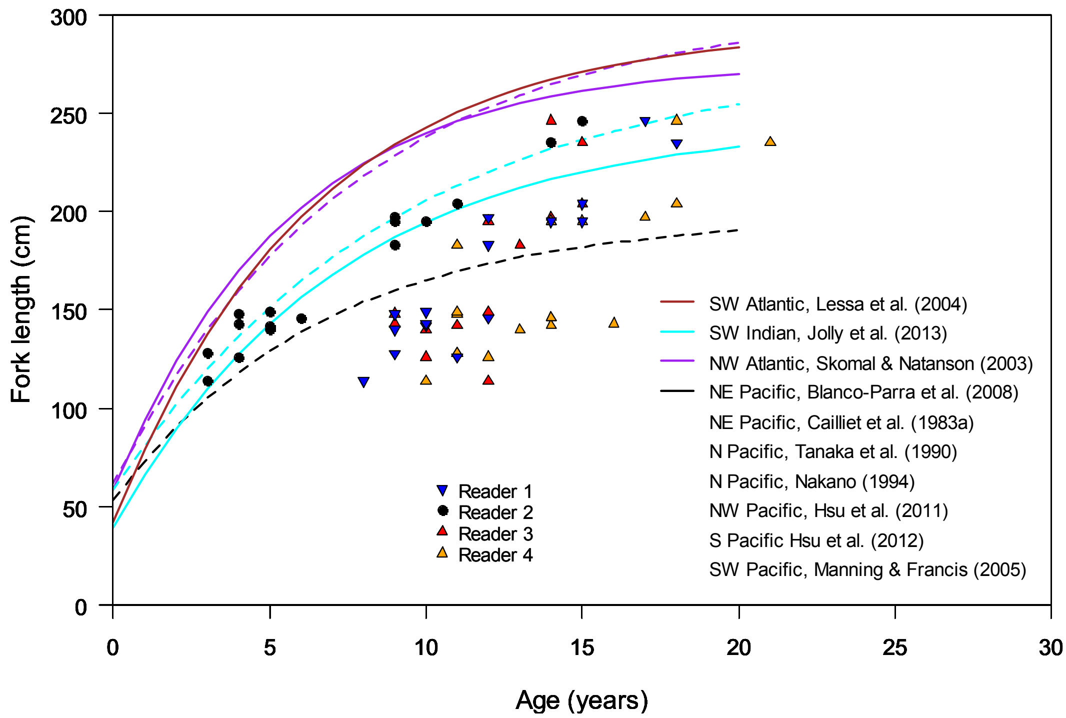

Figure 15: Blue shark growth curves published in previous studies compared with the vertebral band counts by four readers of X-ray images of 16 blue shark vertebral thick sections from the present study. Fork length was estimated from other length measurements as required using regressions provided by Francis & Duffy (2005). Solid and dashed lines of the same colour show male and female growth curves respectively.

APPENDIX 1

Observer instructions for sampling pelagic sharks

Pelagic sharks (blue, mako and porbeagle sharks) are caught mainly in tuna longline and midwater trawl fisheries around New Zealand. A sampling programme has been initiated to obtain information on the catch composition of these sharks in commercial catches, and to develop improved shark fin conversion factors. Size, sex, and maturity data will be collected, along with vertebrae to enable the sharks to be aged. Fins will be weighed at sea and related to shark green weight to obtain fin weight ratios.

Size and sex composition and maturity

For each shark caught, measure fork length and determine sex. Where possible, weigh green weight. For as many sharks as possible, determine maturity status (see shark staging guide below; note that males have a 3-stage maturity scale and females have a 6-stage scale). **Males of all three species can be staged by examining the state of clasper development**. Females have to be opened up to examine the reproductive tract**.**

BWS
For blue sharks use the ovarian egg diameter as indicated in the staging guide to determine female maturity.

Ageing

Remove a section of 3-4 vertebrae from beneath the first dorsal fin. Put a label in with each specimen giving trip, set/tow number, fork length and sex (or sample number). The vertebrae should then be bagged and frozen. Please ensure that all bags are tightly sealed to reduce desiccation in the freezer.

The numbers of sharks to be sampled has been determined according to a monthly sampling schedule and will be advised by the Observer Programme.

Reproductive staging guide for sharks and skates

Stage	Name	Males	Females
1	Immature	Claspers shorter than pelvic fins, soft and uncalcified, unable or difficult to splay open	BWS: Ovaries small and undeveloped. Ova not visible, or small (pin-head sized) and translucent whitish POS: Uterine width about 4-7 mm MAK: Uterine width about 4-15 mm
2	Maturing	Claspers longer than pelvic fins, soft and uncalcified, unable or difficult to splay open or rotate forwards	BWS: Some ova enlarged, up to about pea-sized or larger, and white to cream. POS: Uterine width about 8-10 mm MAK: Uterine width about 16-30 mm
3	Mature	Claspers longer than pelvic fins, hard and calcified, able to splay open and rotate forwards to expose clasper spine	BWS: Some ova large (greater than pea-sized) and yolky (bright yellow) POS: Uterine width > 10 mm MAK: Uterine width > 30 mm
4	Gravid I	*Not applicable*	Uteri contain eggs or egg cases but no embryos are visible
5	Gravid II	*Not applicable*	Uteri contain visible embryos.
6	Post-partum	*Not applicable*	Uteri flaccid and vascularised indicating recent birth

APPENDIX 2

Inventory of vertebral samples, and maturity and fin weight records, collected by observers for blue, porbeagle and mako sharks in the 2011 to 2015 fishing years.

							Vertebrae				Maturity				Individual fin weights			
Trip	Year	Months	Method	Fleet	FMAs	Target species	BWS	POS	MAK	Total	BWS	POS	MAK	Total	BWS	POS	MAK	Total
1	2011	Apr-Jun	SLL	C	5, 7	STN	67	11	0	78	492	12	2	506	221	9	2	232
2	2011	Apr-Jun	SLL	C	5, 7	STN	20	8	3	31	0	0	1	1	12	7	3	22
3	2011	Apr-Jun	SLL	C	1, 5, 7	STN/BIG	51	0	5	56	236	5	5	246	0	0	0	0
4	2011	Apr-Jun	SLL	C	5, 7	STN	41	14	2	57	66	5	2	73	149	22	2	173
5	2011	Jun-Aug	SLL	D	1, 2	STN/BIG/SWO	0	0	0	0	385	41	24	450	0	0	0	0
6	2011	Jun-Jul	SLL	D	1, 2	STN	0	0	0	0	23	3	1	27	0	0	0	0
7	2011	Jul-Aug	SLL	D	1	STN/SWO	0	0	0	0	6	15	7	28	0	0	0	0
8	2011	Aug-Sep	TWL	C	6, 7	HOK/SBW	0	5	0	5	0	0	0	0	0	0	0	0
9	2011	Aug-Sep	TWL	D	3, 7	HOK/HAK/BAR	0	0	0	0	0	3	0	3	0	3	0	3
10	2012	May-Jun	SLL	D	2	STN	0	0	0	0	229	0	9	238	0	0	0	0
11	2012	Apr-Jun	SLL	C	5,7	STN	125	6	5	136	223	6	4	233	146	6	5	157
12	2012	Apr-Jun	SLL	C	5,7	STN	34	8	7	49	0	0	0	0	0	0	0	0
13	2012	Apr-Jun	SLL	C	5,7	STN	80	1	2	83	63	0	0	63	0	1	0	1
14	2012	Apr-Jun	SLL	C	5,7,9	STN/BIG	150	17	6	173	0	0	0	0	57	10	5	72
15	2012	May,Jul-Aug	SLL	D	7,9,1	STN/SWO	0	0	0	0	79	0	7	86	0	1	3	4
16	2012	May-Jul	SLL	D	2	STN	8	13	9	30	8	12	9	29	0	0	0	0
17	2012	Jun	SLL	D	1,2	STN	0	0	0	0	13	0	6	19	0	0	0	0
18	2012	Jun-Jul	SLL	D	1	STN	19	6	2	27	19	6	2	27	0	0	0	0
19	2012	Jun-Jul	SLL	D	7	STN	0	0	0	0	1	0	0	1	0	0	0	0
20	2012	Aug-Oct	SLL	D	1,9	STN/BIG	3	6	11	20	4	6	11	21	0	0	0	0
21	2013	May-Jun	SLL	C	1,5,7,9	STN/BIG	81	5	11	97	79	4	11	94	0	0	0	0
22	2013	May-Jun	SLL	C	5,7,9	STN	113	26	3	142	0	0	0	0	0	0	0	0
23	2013	May-Jun	SLL	C	5,7	STN	20	10	3	33	0	0	0	0	96	9	5	110
24	2013	May-Jun	SLL	C	5,7	STN	90	11	8	109	88	8	10	106	88	8	10	106
25	2013	May-Jun	SLL	D	1	BIG	4	0	1	5	14	0	4	18	0	0	0	0
26	2013	May-Sep	SLL	D	1,9	STN/SWO	23	0	0	23	61	1	0	62	0	0	0	0
27	2013	Jun	SLL	D	7	STN	1	3	2	6	1	3	2	6	0	0	0	0
28	2013	Jul-Aug	SLL	D	1,2	STN	34	10	4	48	33	7	3	43	0	0	0	0
29	2013	Jul-Aug	SLL	D	1	STN	11	2	0	13	0	0	0	0	0	0	0	0
30	2013	Aug	SLL	D	9	BIG	0	0	0	0	38	0	4	42	0	0	0	0
31	2013	Aug-Dec	SLL	D	1,9	BIG/STN	0	0	1	1	0	0	0	0	0	0	0	0
32	2013	Nov-Dec	SLL	D	1	BIG	0	0	0	0	2	4	0	6	0	0	0	0
33	2014	Jan-Mar	SLL	D	1,9	BIG	1	0	18	19	1	0	23	24	0	0	22	22
34	2014	Apr-Jun	SLL	D	7	STN	0	0	1	1	0	42	12	54	0	0	0	0
35	2014	Apr	SLL	D	1	BIG	0	0	1	1	0	0	0	0	0	0	0	0
36	2014	May-Jul	SLL	C	5,7	STN	21	16	5	42	0	1	0	1	112	22	5	139
37	2014	May-Jun	SLL	C	5,7	STN	34	9	4	47	33	8	4	45	0	0	0	0
38	2014	May-Jun	SLL	C	5,7	STN	61	19	5	85	0	1	0	1	77	20	5	102
39	2014	May-Jun	SLL	C	5,7	STN	7	1	2	10	0	0	0	0	203	3	2	208
40	2014	May	SLL	D	7	STN	0	0	0	0	1	0	0	1	0	0	0	0
41	2014	May-Jun	SLL	D	7	STN	0	0	0	0	34	1	1	36	0	0	0	0
42	2014	Jul-Aug	SLL	D	1,2	STN	21	5	1	27	17	10	1	28	0	0	0	0
43	2014	Aug	SLL	D	1	STN	3	0	0	3	0	0	0	0	0	0	0	0
44	2014	Jul-Aug	SLL	D	2	STN/BIG	1	7	1	9	0	0	0	0	0	0	0	0
45	2014	Sept-Oct	TWL	C	3,6	BAR/SBW	0	3	0	3	0	0	0	0	0	0	0	0
46	2014	Sept-Oct	SLL	D	1,9	BIG	0	1	0	1	0	1	0	1	0	0	0	0
47	2015	Dec-Jan	TWL	C	7,8,9	JMA	2	17	5	24	2	17	5	24	0	0	0	0
48	2015	Jan-Feb	SLL	D	1	BIG,SWO	0	0	1	1	0	0	2	2	0	0	0	0
49	2015	Mar-Apr	SLL	D	1	BIG,SWO	0	0	0	0	2	0	1	3	0	0	0	0
50	2015	Apr-Jun	SLL	C	5,7	STN	14	7	0	21	15	4	0	19	0	0	0	0
51	2015	Apr-Jun	SLL	C	5,7	STN	12	2	0	14	0	0	0	0	0	0	0	0
52	2015	Apr-Jun	SLL	C	5,7	STN	0	0	13	13	0	0	13	13	0	0	13	13
53	2015	Apr-Jun	SLL	C	5,7	STN	0	0	1	1	0	0	0	0	0	0	0	0
54	2015	Jun-Jul	SLL	D	1,2	STN	0	9	3	12	0	2	2	4	0	0	0	0
Total							1152	258	146	1556	2268	228	188	2684	1161	121	82	1364