



## **Stock assessment of the Australian east coast tailor (*Pomatomus saltatrix*) fishery**

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## Executive summary

Tailor is a highly migratory fish with an iconic, mainly beach-based fishery on the Australian east coast. There is a pronounced annual, close-inshore run of large schools of tailor from New South Wales, where the fishery peaks in April–June, to Queensland where the Fraser Island fishery at the northern end of the run peaks in August–September. The commercial sector of the fishery developed over the first half of the 20th century while the recreational beach line sector grew strongly from the late 1940s, facilitated by rapid developments in recreational beach-fishing gear.

The recreational sector appeared to have had a pronounced peak in both harvest size and fishing effort in the mid-1990s, after which both the recreational and commercial sectors experienced big falls driven largely by cultural change. Recreational participation rates and fishing effort fell sharply while fishery management implemented measures such as bag limits on the recreational sector and harvest limits and spatial restrictions on the commercial sector.

Information on the tailor fishery is relatively rich in fish length-frequency and ageing data, although data quality greatly improved from the mid-1990s with the introduction of scientific sampling methods. Prior to that time there were no reliable fish ageing data and most length-frequency data came from tagging experiments. The eastern Australian stock of tailor mainly consists of young fish with not many surviving beyond four years of age. The oldest fish aged by Fisheries Queensland's monitoring team were just under seven years of age.

Records on harvest tonnages were available from the 1940s onwards for the commercial sector and from the late 1990s onwards for the recreational sector. Prior to 1997 the recreational harvest had to be estimated from the human population size, except on Fraser Island where records of visitor numbers existed from 1970. The estimated maximum total annual harvest from the fishery was 1794 tonnes in 1996. Estimates since 2010 have been around 300 tonnes.

Tailor abundance from catch rates could be estimated from Queensland fishing-club data from 1954 to 2001 and from commercial logbook data from 1991 to present. The fishing-club catch rates showed a decline of roughly 50% from the 1950s to the 1990s, although these estimates are subject to large experimental errors due to low sample sizes. Commercial catch rates have been fairly steady from the 1990s to present.

The available data were analysed by a new population model that has greater capability to handle random variation in growth than previous models. The tailor fishery has particularly strong length-based vulnerability to both the recreational and commercial fishing sectors, with only the larger individuals of age group 2 (fish aged between one and two years, assumed to be sampled just before their second birthday) vulnerable to ocean-beach fishing. Smaller or slower-growing individuals do not become vulnerable until age-group 3 (fish aged between two and three years). The new model indexes the population matrix by year, age and age at first vulnerability to fishing. The parameter estimates were optimised to match catch rates, length frequency data and age-at-length data.

Results indicate that the exploitable biomass of tailor was around 50% of virgin level from the mid-1980s to 2012. Despite a big fall in the level of fishing, the population appears to have taken a long time to recover from heavy fishing in the 1980s and 1990s, with low estimates of recruitment for many years. The model results suggest that tailor abundance has bounced back strongly since 2012. More years of monitoring data are needed to confirm this prediction.

Estimated harvest rates in the mid-1990s were extremely high, ranging between 60% and 80%. Such high levels may have reduced the number of schools of big fish in the population. Schools of big tailor were present on Fraser Island by early September in 1978 and 1980 but after 1980 they appear in the data only in late September.

Estimates of maximum sustainable yield (MSY) in an average year are around 1350 tonnes per year but could be as low as 1000 tonnes per year. These estimates are inclusive of all fishing sectors and locations in New South Wales and Queensland. The concept of MSY is ill-defined for tailor because the model results show long-term fluctuations in the level of recruitment of new, young fish to the

population. The model estimated high recruitment in the periods 1972–1975 and 1985–1998 and low recruitment in 2003–2011. Long-term fluctuations in recruitment mean that fishing the tailor population at MSY can be unsustainable if there is a long period of low recruitment. Therefore it is advisable that, if a constant limit on annual harvest is desired by management, it should be set well below MSY. Future management procedures need clear targets for indicators of population size, together with flexible operational procedures to meet regional expectations of fishing and needs for sustainability. The model estimated that the harvest exceeded MSY in the 1980s and 1990s but the population was not necessarily overfished because recruitment was high during that period.

It is unknown how much of the fall in recruitment in 2003–2011 is due to fishing and how much is due to environmental variation. It is possible that heavy fishing during the 1990s may have depressed the recruitment for many years afterwards.

Reductions in tailor fishing appear to have allowed the stock to recover from a period of very heavy fishing in the 1980s and 1990s. The assessment's estimation of a recovery in recruitment since 2012 still needs to be confirmed through Fisheries Queensland's annual age–length monitoring in future years.

It is important to recognise that the fishery has a large amount of fishing effort capacity. A recovery in the tailor stock could encourage more fishers to fish and so increase the fishing effort. Any return to fishing effort levels near those of the 1980s and 1990s would run a substantial risk of over-fishing.

In addition to the annual age–length monitoring, the state-wide surveys of recreational catch in both Queensland and New South Wales provided very valuable data for this assessment and it is recommended that they be conducted regularly, preferably no less frequently than every five years.

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# 1. Introduction

## 1.1 Tailor and its fishing history in eastern Australia

Tailor *Pomatomus saltatrix* (Figure 1.1) is widely distributed in subtropical and temperate waters around the world. It is the only species in its family Pomatomidae and is known by various common names including bluefish in North America and Europe; elf, shad and tassergal in Africa; and enchova in South America. Lyman (1987, p. 3) recounts, “Bluefish move through many of the warmer seas of the world as efficient killers—predators supreme ... a match for any fish of their own size and more than a match for most.”

In Australia tailor occurs in two separate stocks on the east and west coasts (Nurthen et al., 1992). The east coast stock (Figure 1.2) has given rise to an iconic fishery rich in folklore, with recreational and commercial components which will be described below.



Figure 1.1: Laboratory photograph of tailor, showing its characteristic silvery coloration and protruding lower jaw. (Older fish develop a green–blue tinge along the back.) Source: DAF archive.



Figure 1.2: Map of the Australian east coast tailor fishery, showing some popular fishing locations, major cities and state borders. The eastern Victorian population (green shading) comes from the same genetic stock but is not covered in this stock assessment due to limited potential to mix with the Queensland and northern New South Wales populations.



In eastern Australia, aboriginal artisanal fishing for tailor using spears and possibly hooks and scoop nets probably dates back many thousands of years (Williams, 1982, p. 14; Pepperell, 2009). After white settlement and before refrigeration became widespread, tailor was recognised as a potential food fish but, although present in fish markets year-round, was not strongly targeted (Pepperell, 2009, pp. 59–60, 80), perhaps because it destroyed fishers' nets or because the flesh begins to decompose quickly after capture (Stead, 1906, pp. 153–157).

By the 1940s, commercial fisheries harvesting hundreds of tonnes per year for tailor had developed in both Queensland and New South Wales (NSW). Records of harvest sizes from that time onward are held by state government agencies. Commercial fishing operates using seine nets which encircle schools of fish swimming off beaches (see Figure 1.3); gillnets which mesh fish around the gills as they swim through; and tunnel nets which are set to capture fish as the tide recedes from suitable beach, sandbank and mud-bank locations.



Figure 1.3: A school of tailor harvested in a beach seine net. Source: DAF archive.

Tailor also occurs in the state of Victoria (see Figure 1.2 above). This stock assessment does not cover Victoria, due to limited potential of tailor to migrate between Victoria and Queensland or northern NSW, and the additional complexity of including a third jurisdiction in the assessment.

In addition to the existing commercial net fisheries, since about 1997 a significant commercial line fishery for tailor has developed in NSW with catches up to about 40 tonnes per year (data held by NSW Department of Primary Industries). We note here that tailor in Queensland and NSW during the fishing season generally occur inshore and line fishing for them, both commercial and recreational, is conducted mainly from beaches or rocks. This is in strong contrast to North America where bluefish occur well offshore and have a sizable boat fishery (Lyman, 1987, ch. 7).

The overall commercial catch in both Queensland and NSW has declined since the mid-1970s, perhaps due initially to a change in public taste, evidenced by the termination of a contract to supply tailor as the primary fish used in Queensland hospitals and institutions (Dichmont et al., 1999, p. 105) and the rise of fast-food outlets other than fish-and-chip shops. The decline is unlikely to be due to falling stocks because tailor were widely available to the recreational fishery which continued to grow after that time (see below). In later years, management measures were implemented for both the commercial and recreational sectors to protect the stock. These are described in the next section.

The recreational beach line fishery for tailor on the Australian east coast developed in earnest from the late 1940s (Claydon, 1996, p. 1). Champion angler Len Thompson wrote in 1966, “It began in

1949, but at the next Australian titles ... in 1951, Al [Sanders] and I had revolutionised surf angling. ... Tailor once were hard to catch. But this new idea [of floating rigs of ganged hooks], plus the introduction of the nylon line by the Americans, changed all that.” (Claydon, 1996, p. 10).

Most recreational tailor fishers, instead of using the floating rigs favoured by competition fishers, either attach sinkers to them or use metal lures; the exact method used depends on wind and sea conditions and light level (day versus night). Post-war development of the recreational tailor fishery was greatly facilitated by developments such as gangs of three or more hooks with baits of garfish (family Hemiramphidae), yellowtail scad *Atule mate* or pilchards (family Clupeidae); nylon fishing line; the sidecast reel; waders; and the increasing availability of four-wheel-drive vehicles (Claydon, 1996, p. 11–15).

Improved barge access to coastal islands in Queensland, such as North Stradbroke Island, Moreton Island and Fraser Island, increased the accessibility of these fishing grounds to recreational anglers. By the late 1970s recreational fishing had become very popular at Fraser Island (Pollock, 1984b), the eastern shore of which is an expanse of about 130 km of ocean beach at the northern end of the spatial range of tailor. Visitor numbers to Fraser Island increased from about 5000 in 1970 to over 300,000 in 1999 (figures from various issues of Moonbi, Fraser Island Defenders Organisation, 2015), although not all of the expansion is related to fishing as the island has also become very popular for non-fishing tourism.

Claydon describes the early development of the recreational fishery (pp. 37–38): “Those of us who were fortunate enough to live on the east coast of Australia, in the area between Bundaberg in the north and Newcastle in the south, in the years between 1940 and 1980, witnessed the development of tailor fishing and had the opportunity to enjoy beach fishing before the crowds arrived. Before the Thompson era, tailor were considered to be a difficult fish to catch in any quantity off a beach or headland. Thommo and Co. were [in the 1940s and 1950s] fishing what were virtually virgin fishing grounds. ...

“The number of four-wheel-drives travelling to Fraser Island in the period from August to October 1980 was evidence that [Claydon believed] our tailor stocks were in trouble. The Rainbow Beach area more resembled Brisbane’s inner city streets than the once deserted beaches of the fifties, sixties and seventies.”

Still the fishery continued to grow and Claydon writes (p. 37), “In 1975 the beaches of Moreton [Island], Double Island and Fraser [Island] were relatively deserted in comparison to the 1990s. There are ten times more anglers chasing tailor in 1995 than there were in ’75.” (See Figure 1.4.)



Figure 1.4: Recreational fishing for tailor on Fraser Island, approx. 2000. Source: Michael O’Neill.

Recreational fishing effort for tailor finally began to decrease from the mid-1990s, according to telephone–diary surveys of participation rates and harvest size in both Queensland and NSW (see section 1.5.2 below). Bag limits (daily or in-possession limits per fisher) were also first applied to recreational fishers at about that time (1993 in NSW, 2002 in Queensland).

## 1.2 Management of the fishery

Various management measures have been applied to the tailor fishery since the late 19th century. Key management measures in Queensland and NSW are summarised in Table 1.1.

*Table 1.1: Management measures applied to the tailor in Queensland and New South Wales waters.*  
Source: Queensland (Qld) and New South Wales (NSW) state government legislation.

Date	State	Measure
1877	Qld	Minimum legal weight 6 ounces
1877–1974	Qld	Various measures relating to fishing gear and practices; e.g., mesh size, net length, allowed species, closed seasons, powers of inspectors
1887	Qld	Minimum legal weight 8 ounces ( <i>Queensland Fisheries Act 1887</i> )
1902–1994	NSW	Various measures relating to fishing gear and practices; e.g., mesh size, net length, closed seasons, prohibition of explosives and poisons
1914	Qld	Minimum legal size 10 inches total length ( <i>The Fish and Oyster Act of 1914</i> )
1957	Qld	Minimum legal size 12 inches total length ( <i>Fisheries Act 1957</i> )
16 Dec 1976	Qld	Minimum legal size abolished ( <i>Fisheries Act 1976</i> )
8 Mar 1990	Qld	Minimum legal size 30 cm total length ( <i>Amendment of Fisheries Organization and Marketing Regulations, 1990</i> )
1 Sep 1990	Qld	Seasonal fishing closure on Fraser Island between 400 m north of Waddy Point and 400 m south of Indian Head, for the month of September
11 Jun 1993	NSW	Minimum legal size 30 cm total length ( <i>Fisheries and Oyster Farms Act 1935—Regulation no. 199, 1993</i> )
11 Jun 1993	NSW	Recreational bag limit 20 fish ( <i>Fisheries and Oyster Farms Act 1935—Regulation no. 199, 1993</i> )
1995	Qld	Closure to commercial net fishing of many beaches around populated areas; most of Moreton Bay (all of Moreton Bay at weekends); Great Sandy Strait at weekends; and the eastern (ocean beach) shore of Fraser Island from 1 April to 1 September ( <i>Fisheries Regulation 1995</i> )
1 Sep 2001	NSW	Commercial net fishing ban, except for incidental catch up to 100 kg per fisher per day taken using ocean hauling nets and 50 kg per fisher per day using any other nets, in the Ocean Hauling and Estuary General Fisheries
1 May 2002	Qld	Recreational bag limit (in-possession limit) 20 fish; 30 for fishers staying on Fraser Island for 72 hours or more
1 May 2002	Qld	Total allowable commercial catch (TACC) 120 t, except for incidental catch up to 100 kg per fisher per day
1 Aug 2002	Qld	Seasonal fishing closure on Fraser Island extended to cover both August and September
1 Sep 2003	Qld	Closure to commercial net fishing on Fraser Island between Tooloora Creek and the northern end of North Ngkala Rocks from 1 April to 1 September (already closed for the rest of the year in 1995)
20 Sep 2003	Qld	Closure to commercial net fishing on northern beaches of North Stradbroke Island from 20 September to 1 April
1 Mar 2009	Qld	<i>Marine Parks (Moreton Bay) Zoning Plan 2008</i> closed many areas near Brisbane to fishing where tailor were commonly caught.
1 Mar 2010	Qld	Minimum legal size increased to 35 cm total length, bag limit (in-possession limit) set at 20 (no variation for extended stay on Fraser Island)
12 Sep 2014	NSW	Bag limit (daily limit) reduced from 20 to 10; in-possession limit (home freezer limit) remains 20.

A minimum legal weight was first imposed in Queensland in 1877, minimum legal size in 1914 (10 inches total length), increased in 1957 to 12 inches (approximately 30 cm) total length, abolished in 1976 and reinstated in 1990. In NSW a minimum legal size of 30 cm was imposed in 1993 and has not changed since then. In Queensland the minimum legal size was raised from 30 cm to 35 cm in 2010.

Recreational bag limits of 20 fish were imposed in NSW in 1993 and Queensland in 2002. The NSW bag limit was reduced to 10 fish in 2014. Queensland also imposed a seasonal finfish fishing closure on part of Fraser Island in 1990; the duration was extended from one month to two months in 2002. No limit has ever been placed on the total number of potential recreational fishers.

Commercial fishing of tailor has been restricted since 2001 in NSW and 2002 in Queensland. Although there are harvest limits and various spatial and temporal closures, the total potential commercial fishing effort is still limited only by the number of licences.

## **1.3 Biology of tailor**

### *1.3.1 General description*

Tailor is a highly migratory fish species with a pronounced annual, close-inshore run of large schools from NSW, where the fishery peaks in April–June, to southern Queensland where the fishery peaks in July–September (fishery data held by state agencies). Over summer the large schools appear to disperse to some extent as many of the fish make their way back south. Tailor on the east coast of Australia, including Victoria (see Figure 1.2 above) is considered a single genetic stock (Nurthen et al., 1992); this does not imply that there is significant mixing of populations on fishery time scales of years or decades, as the time scales over which genetic results apply may be substantially longer. Dispersal of pelagic eggs and larvae with prevailing currents, movement of juveniles into sheltered near-shore or estuarine habitats, and the seasonal migration behaviour of adults, facilitate a genetically homogenous population along the coastline (Zeller et al., 1996; Juanes et al., 1996; Miskiewicz et al., 1996; Ward et al., 2003). Extensive north–south migration of tailor also takes place in other parts of the world, including Western Australia (Lund and Maltezos, 1970; Wilk, 1977; Lyman, 1987, ch. 1–2; Haimovici and Krug, 1996; Shepherd et al., 2006; Smith et al., 2013, p. 7).

Tailor mature in their second year of life and many enter the ocean-beach fishery during this year (Williams, 2002, p. 164). They are reported to be serial spawners and have an extended period of spawning, perhaps from winter through to the following autumn depending on water temperature and latitude but peaking in the spring (Miskiewicz et al., 1996; Ward et al., 2003); a similar pattern occurs in Western Australia and North America (Robillard et al., 2008; Callihan et al., 2008; Smith et al., 2013, pp. 70–71).

A general study of tailor biology was undertaken by Bade (1977), including fecundity analysis on a small sample of fish. Zeller et al. (1996) and Pollock (1984b) cover various aspects on life history of east coast tailor. Halliday (1990), Mann (1992), Morton et al. (1993) and Miskiewicz et al. (1996) further cover the movement and distribution of tailor (eggs, larvae, juveniles and adults) along the east coast. Juanes et al. (1996) compare early life history strategies for populations in different parts of the world. Pollock (1984a) and Broadhurst et al. (2012) cover catch-and-release mortality within the Australian east coast population and Ayvazian (2002) in Western Australia.

### *1.3.2 Ageing*

Tailor can be aged from annual rings in their otoliths (ear bones). A study to validate the ageing procedure in eastern Australia was conducted by Brown et al. (2003). Published ageing studies from other jurisdictions include Smith et al. (2013) from Western Australia, Wilk (1977), Barger (1990) and Robillard et al. (2009) from the USA and Govender (1999) from South Africa. The Western Australian study reported ages up to 5+ (age group 6) with a single fish aged 9+ (age group 10) (Smith et al., 2013, p. 69). The USA studies reported ages up to 13+, 9+ and 13+ years respectively while the South African one recorded up to 6+.

The earlier technique of ageing from scales has also been used for bluefish in the USA (Bluefish Working Group, 2015, pp. 361–363). The technique appears to work tolerably well for this species and data from it were included in the USA stock assessment. For other species scale reading is regarded as less reliable and more likely to underestimate the age of a fish than otolith reading; see, e.g., Robillard and Marsden (1996) and the Introduction and references in Ashford et al. (2001).

Robillard et al. (2009) found substantial differences between ages from otoliths and scales of individual bluefish but did not establish which was more accurate because they had no “ground truth” measurement of age. They stated that ages from scales were biased upward for young bluefish and downward for old bluefish (as judged from otolith ageing). In our opinion, this result is spurious and is an instance of the statistical phenomenon of “regression to the mean” whereby the slope of a regression line is less than one whether scale age is regressed on otolith age or vice versa (see, e.g., Stigler, 1997; Barnett et al., 2005). The authors ascribe absolute accuracy to the otolith ages instead of allowing random variation in them, which invalidates their statistical methods.

The maximum observed age from otoliths sampled from the Australian east coast harvest by the Fisheries Queensland Fishery Monitoring team (data described later) is 6+ (age group 7). Tailor appears to have a much shorter life-span in Australia than in North America. As noted above, in Australia it is also restricted to inshore locations.

Tailor does not exhibit sex change, segregation by sex or significant sex-specific differences in length-at-age.

### 1.3.3 *Formulae for length and weight*

Fishery management usually uses total length of fish whereas scientific measurement uses fork length (measured to the fork of a fish’s tail). It is frequently necessary to convert between the two. The following formulae were found by Bade (1977) for relating total length (TL) to fork length (FL) of tailor, both measured in cm (Leigh and O’Neill, 2004, p. 7):

$$\begin{aligned} \text{FL} &= 0.896 \text{ TL} - 0.1178 \\ \text{TL} &= 1.114 \text{ FL} + 0.1764. \end{aligned}$$

Similarly, fishery models are commonly structured by length (fork length) whereas commercial fishery catches are measured by weight. Bade (1977, p. 78) provides the following formula for converting fork length (measured in cm) to weight  $W$  (measured in kg) (Leigh and O’Neill, 2004, p. 52):

$$W = 1.203 \times 10^{-5} \text{ FL}^{3.01}. \quad (1.1)$$

A growth function to provide length as a function of age is not needed as input to this assessment because growth parameters will be estimate in the population model.

### 1.3.4 *Discard mortality*

When line-caught fish are returned to the sea by fishers, not all of them survive. A discard mortality rate of 0.15 (15% of fish released do not survive) was used in the latest stock assessment in the USA (Bluefish Working Group, 2015, p. 358). In this assessment for eastern Australia we are more conservative and use a value of 0.30 (see Table 5.1, page 45). Discard mortality with an emphasis on Australia was reviewed by Smith (2004).

## 1.4 **Abundance and stock assessment in North America**

The Atlantic coast of North America appears to have the world’s biggest population and longest fishing records of *Pomatomus saltatrix* (bluefish), making it instructive to examine the history of the fishery there. Accounts of fishing for bluefish there go back to at least 1659 (Lyman, 1987, p. 22).

A common observation of bluefish in North America is that its abundance rises and falls enormously over long time scales. Such variation has been recorded for hundreds of years. Sources express unease about how many fish of other species bluefish kill and consider it possible for bluefish to be forced to vacate a region because they have exhausted the local food supply; they also propose that

abundance may vary due to environmental conditions, especially temperature and disease. The following comments highlight such regional and historic variations in the bluefish population along the east coast of North America; they are drawn from Baird (1873, pp. 235–252), State of Rhode Island (1891, pp. 7–27) and Lyman (1987, pp. 13, 22–25):

- “The blue-fish is pre-eminently a pelagic or wandering fish, ... apparently capricious in its movements, varying in numbers at particular localities with the year, and sometimes disappearing from certain regions for a large fraction of a century, again to return as before. The cause of this variation it is impossible to explain, being due in some instances, probably, to the disappearance of its favorite food in consequence of its own voracity, or for other undetermined reasons.” (Baird, 1873, p. 236)
- Bluefish were very abundant around Nantucket from the time of first white settlement in 1659 until 1763, and were caught in great numbers in summer, but disappeared in 1764 until about 1800 when they were again very abundant and very large.
- They were abundant around Woods Hole, Massachusetts until about 1780 or 1790 but were not seen there again until 1831. Baird regards the specified time range of 1780–1790 as unreliable, stemming from the testimony of aged persons who had heard their fathers speak of bluefish; he found no printed records of bluefish in this area between 1764 and 1810.
- Further north in Massachusetts, bluefish were unknown north of Cape Cod before 1837 and around Cape Ann before 1847. They were caught there until 1910 even while the abundance south of Cape Cod declined greatly.
- The abundance around the south coast of Massachusetts fell abruptly between 1870 and 1871 and again between 1871 and 1872.
- Bluefish were not discovered around New York until about 1810, were abundant by 1825 and great numbers were caught in 1841. They remained abundant until at least 1871.
- Bluefish were common between 1850 and 1875 as far north as Massachusetts and extended to Maine and Nova Scotia, but soon after disappeared from Maine and Nova Scotia for almost 100 years before returning in numbers.
- Bluefish apparently were not fished off North Carolina and New Jersey before 1842. Their abundance fell after 1878.
- The greatest abundance of bluefish on the US mid-Atlantic coast between 1800 and 1872 took place around 1850–1860.
- After many lean years, bluefish reappeared in great numbers in east-coast USA in 1947. Abundance was very high in 1951 and stayed high through the 1960s and 1970s, during which time the fish became bigger.

Baird (1873) records that several accounts agree that bluefish of 40–50 pounds (around 20 kg, corresponding to a total length of about 130 cm) were caught in the 18th century.

Since at least 1981 when records of the recreational harvest size began, and probably since at least the 1950s, the fishery for bluefish has been predominantly recreational. Combined landings in the USA declined greatly from a peak of 54,000 t/yr in 1986 to 9600 t/yr in 1999 (Bluefish Working Group, 2015, p. 336). Commercial landings peaked at 7162 t in 1983 and then declined to a low of 1974 t in 2013. Fishery managers implemented a rebuilding plan from 2000 to 2009, after which the stock was declared rebuilt (Feldman, 2013, quoting an unpublished letter from the National Marine Fisheries Service).

The most recent stock assessment of bluefish in the USA (Bluefish Working Group, 2015) concluded that the species was not currently overfished although it apparently had been in the past. The instantaneous fishing mortality rate ( $F$ ) in 1987 was estimated at about  $0.47 \text{ yr}^{-1}$  (Bluefish Working Group, 2015, p. 642); this corresponds to an annual harvest rate of about 0.37, i.e., about 37% of the fish available for exploitation were actually captured in that year. The stock assessment’s reference value for  $F$  (roughly corresponding to maximum sustainable yield, MSY) was  $0.17 \text{ yr}^{-1}$ , roughly a third of the estimated actual level of  $F$  in 1987, indicating that the stock had been overfished then.

The stock assessment took account of the highly migratory behaviour of the species and considered bluefish in the western North Atlantic Ocean to be a single stock.

## 1.5 Scientific data

### 1.5.1 Length-frequency and age-frequency data

Length-frequency data of tailor from the Australian east coast were available from 1976 onwards. Most of these data were fishery-dependent, i.e., samples were taken from recreational and commercial harvests and measured by scientific staff. The sampling procedures improved greatly from 1999 when Fisheries Queensland began routine annual monitoring. The following sources were available:

- Length frequency collected by Bade (1977, p. 20), presumed to be from 1976, the year in the tagging study reported in that thesis was conducted
- DAF tagging experiment conducted on Fraser Island in 1978, 1979 and 1980
- DAF tagging experiment conducted on Fraser Island in 1987, 1988, 1989 and 1990
- Length frequencies from the Sydney Fish Market, 1971 to 1982 and 1987 to 1990
- Length frequencies from the NSW recreational line fishery, 1994 and 1995
- Integrated Stock Assessment and Monitoring Program (ISAMP) in Queensland, 1995, 1996, 1997 (Hoyle et al., 2000)
- Tagging experiment conducted by the Tailor Age Validation project, 2000 (Brown et al., 2003)
- Fisheries Queensland Fishery Monitoring program, every year from 1999 to present (latest 2015)
- Length frequencies from the NSW commercial line and net fisheries, 2009, 2010 and 2014.

Data from the Tailor Age Validation project were not used because they overlapped the Fisheries Queensland monitoring which had more systematic sampling protocols. The other sources prior to the Fisheries Queensland monitoring were used despite their limitations. They provided valuable information from earlier years of the fishery when fishing patterns were different. The NSW samples from 1994–1995 and 2009–2014 (two years and three years respectively) were not used because the numbers of years covered by them were not considered large enough to be informative. Length frequencies can depend on small details of the techniques of fishing and sampling so we preferred not to compare a series to one from a different source. Also tailor school strongly by size: the length frequency for a certain year may come from only a few schools and may depend heavily on the size of fish in the schools that were sampled in that year.

The fish sampled by Bade (1977) came from various locations which are not listed in the thesis. The locations in the tagging study ranged from Indian Head on Fraser Island in the north to Brunswick Heads in northern NSW in the south (see Figure 1.2, p. 1).

The fish sampled in 1978 and 1980 were large (see histograms in section A3.1 of Appendix 3, pages 79 and 80) but we know of no firm evidence that the experiment targeted large fish. Therefore these data were retained. The dates were around the first week in September each year, not at the end of September or early October, the time when tailor over 40 cm fork length (44.7 cm total length) have been common in recent years. Pollock (1984b) states that for this experiment tailor were taken from both Indian Head on Fraser Island (a rocky headland) and beaches within 10 km of Indian Head; Claydon (1996, pp. 22, 26) provides photographs of beach angling from this experiment. The anglers involved were experts.

It appears that schools of large tailor on Fraser Island in early September were frequent in the years 1978–1980, whereas in later years they were not. The 1978–80 sampling events occurred across a short timeframe and narrow geographical range and therefore would each have sampled only a few schools of tailor. Nevertheless, the probability that such an event at that time of year in more recent years would sample so many fish over 40 cm fork length is very low; see histogram of Trip 2 of the Fisheries Queensland Fishery Monitoring team, section A3.2, Appendix 3, page 105.

From 2007 onwards, the Fisheries Queensland monitoring included the commercial fishery and locations other than Fraser Island.

Ageing data associated with the length-frequency data were available for the recreational fishery from 1995–1997 (ISAMP) and 1999–2015 (Fisheries Queensland monitoring), and for the commercial fishery from 1997 (ISAMP) and 2007–2015 (Fisheries Queensland monitoring).

Length frequencies from the Sydney Fish Market predated the introduction of any minimum legal size (MLS) in NSW and hence included some very small fish, some down to about 10 cm. They provided valuable information on the length distribution of tailor harvested from estuaries, including fish that would be discarded and hence not recorded in later years. On the other hand, it is not reasonable to assume that, after the introduction of the MLS, fishers would still net all of these schools of small fish. We decided to include only samples with a median length of at least 29 cm fork length, and exclude all samples with medians smaller than that. The fork length of 29 cm was a natural break in the data, between two modes. It was also slightly over the MLS of 30 cm total length: at a sample median of 29 cm fork length, a majority of the fish from the sample would be retained.

### *1.5.2 Recreational fishing surveys*

Statewide recreational catches of fish in Queensland have been measured by telephone–diary surveys since 1997:

- “RFISH” surveys conducted by Fisheries Queensland in 1997, 1999, 2002 and 2005 (Higgs, 1999, 2001; Higgs et al., 2007; McInnes, 2008)
- Australian national survey (the National Recreational and Indigenous Fishing Survey, NRIFS) in 2000 (diary period 1 May 2000 to 30 April 2001; prior telephone survey of participation), funded by the Australian Government’s Fisheries Research and Development Corporation (FRDC, project number 99/158) (Henry and Lyle, 2003).
- SWRFS State-Wide Recreational Fishing Surveys by Fisheries Queensland using the NRIFS methodology in 2011 (1 October 2010 to 30 September 2011) (Taylor et al., 2012) and 2013 (1 November 2013 to 31 October 2014) (Webley et al., 2015), both with prior telephone surveys of participation.

Two state-wide recreational surveys have been conducted in NSW:

- NRIFS in 2000 (see above)
- Survey using identical methodology to the NRIFS in 2013 (1 June 2013 to 31 May 2014) (West et al., 2015).

All of these surveys consisted of two stages: a preliminary telephone survey to measure the participation rate of residents in each statistical area, followed by a year-long diary survey of telephone respondents who participated in recreational fishing.

The RFISH surveys are regarded as generally providing overestimates of the catch size, mainly due to memory recall bias towards high catches by fishers who participated in them. They were included in the assessment but were adjusted to match the NRIFS and SWRFS catch levels (see section 2.2 below).

All of these surveys were used only to provide the harvest size, not catch rates.

### *1.5.3 Proxies for recreational fishing effort*

Prior to 1997 the recreational catch had to be extrapolated as there were no surveys from which it could be estimated.

For fishing on Fraser Island, there are reliable records of visitor numbers, originally collected by the Queensland National Parks and Wildlife Service and published by the Fraser Island Defenders Organisation (2015). These numbers were taken as a proxy for recreational fishing effort up to 1997.

On the advice of the Project Team, the state-wide human population was used as a recreational fishing effort proxy for Queensland (excluding Fraser Island) and for NSW. State population records were available from the Australian Bureau of Statistics (ABS, 2014) (ABS), record number 3105.0.65.001.



An alternative proxy was the number of motor vehicle registrations, on the premise that fishers needed transport to fishing locations. The Project Team believed that historically fishers managed to get to fishing locations without needing their own motor vehicles. Also when this proxy was investigated, it was impossible to separate motor vehicle registration data from the ABS into four-wheel-drive and non-four-wheel-drive vehicles. The former would have been more relevant to fishing than the latter.

## 1.6 Fishery data

### 1.6.1 Commercial data

The major sources of fishery data were the commercial logbook databases held by the Queensland and New South Wales state governments, which allowed estimation of harvest sizes and standardised catch rates. They contained records of harvest, location and fishing gear by commercial fishers. The data quality and resolution improved through time. The following data were available:

- Queensland estimated harvest sizes from annual reports by the Queensland Fish Board state-owned marketing agency (Halliday and Robins, 2007), 1945–1981
- Queensland daily harvest records by fisher from commercial logbooks, 1988–2014
- NSW estimated harvest sizes from commercial fishery records, 1940–1984
- NSW estimated harvest sizes from commercial logbooks, 1984–1997
- NSW monthly harvest and effort records by fisher from commercial logbooks, 1997–2014
- NSW daily harvest records by fisher from commercial logbooks, 2010–2014.

Queensland commercial harvests between 1981 and 1988 had to be interpolated as no data were available. In the event, the 1981 and 1988 estimates were quite close together so there appeared to be little scope for error in the interpolation. The interpolation was done linearly on the log scale (see section 2.1 below).

NSW logbook data for the period 1984–1997 also contained information from which catch rates could potentially have been analysed, but the Project Team regarded this dataset as being of insufficient quality to provide reliable catch rates. The assessment used only catch rates from 1998 onwards in NSW. The more accurate database began only in July 1997. There were not many records for the second half of 1997, so this database was not used until 1998.

As an illustration of the ranges of daily catches of tailor that can be taken, histograms of the daily catch size taken in a fisher-day are presented in Figure 1.5. We presume that, especially in the beach-seine net sector, the small catches of tailor occurred when fishers were targeting some other species.

Reconstruction of historical harvest sizes is undertaken in Chapter 2, while the analysis of catch rates is undertaken in Chapter 3.

The commercial logbook databases included data from the charter fisheries from both Queensland and NSW. These were not used in the assessment because the harvest size was already included in recreational harvest estimates, and we were concerned about changes in targeting practices by charter fishers which could invalidate catch rate estimates from this sector.

### 1.6.2 Fishing club data

A database of Queensland fishing club trips covering the years 1954–2001 was held by Fisheries Queensland and used to find standardised catch rates over this period. Despite data limitations, this source was very useful because it went back decades before commercial catch rates were available. It contained about 24,000 records from 31 clubs, most of which were based in Brisbane.

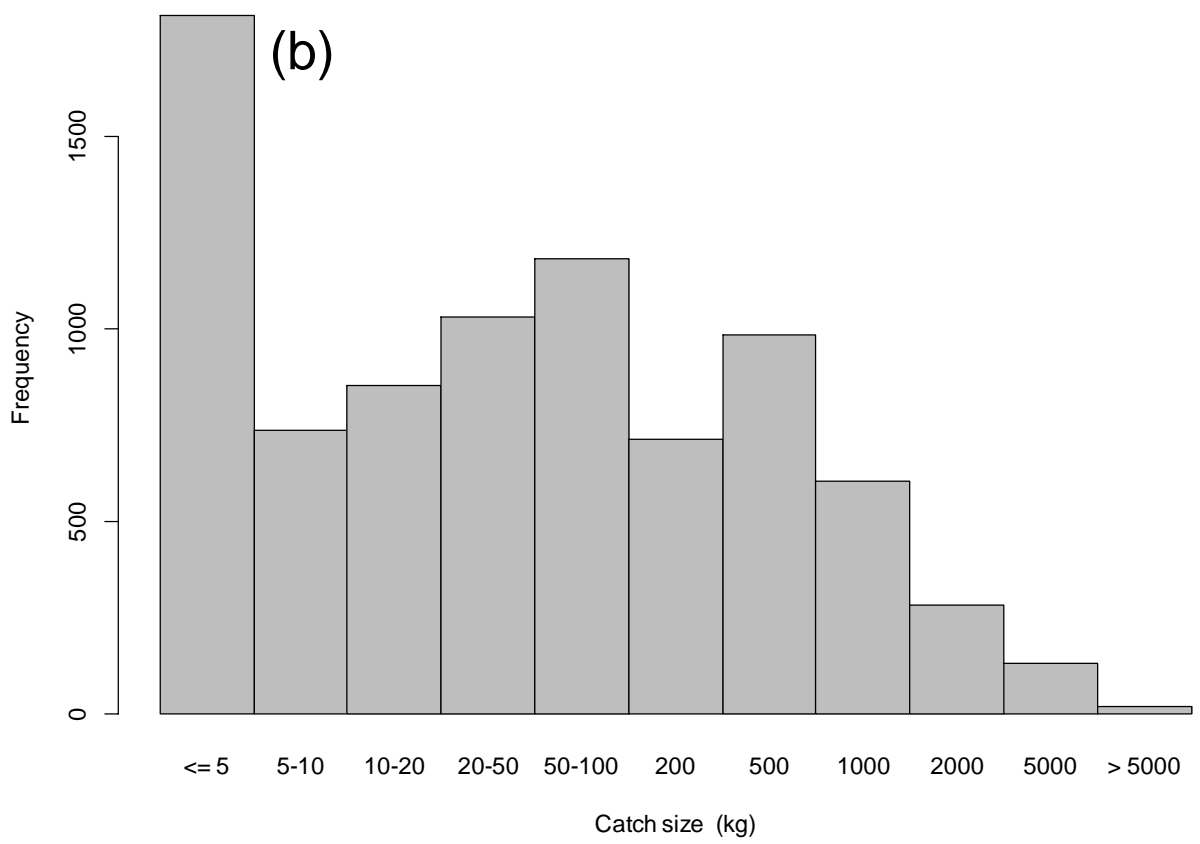
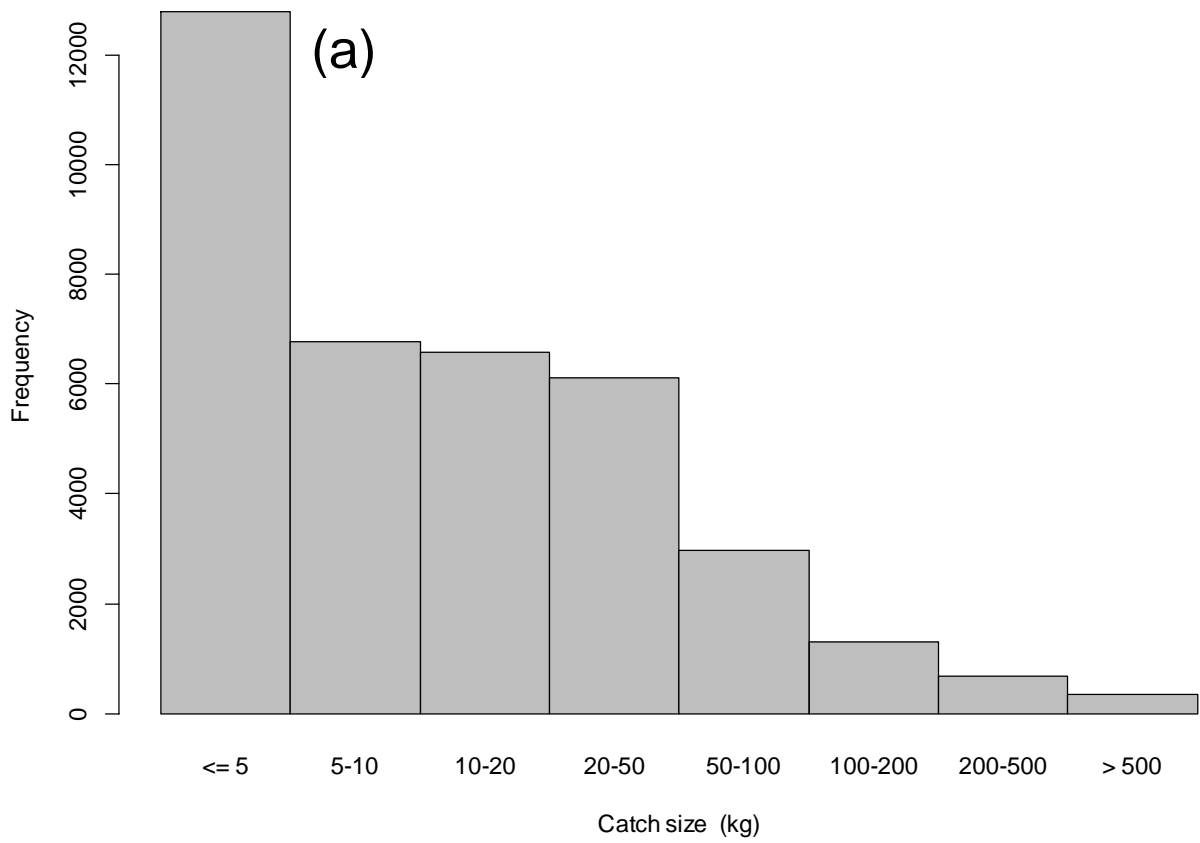


Figure 1.5: Histograms of individual tailor catches per fisher-day for the commercial fishery: (a) Queensland gillnet sector, (b) Queensland beach-seine net sector. Continued on next page.

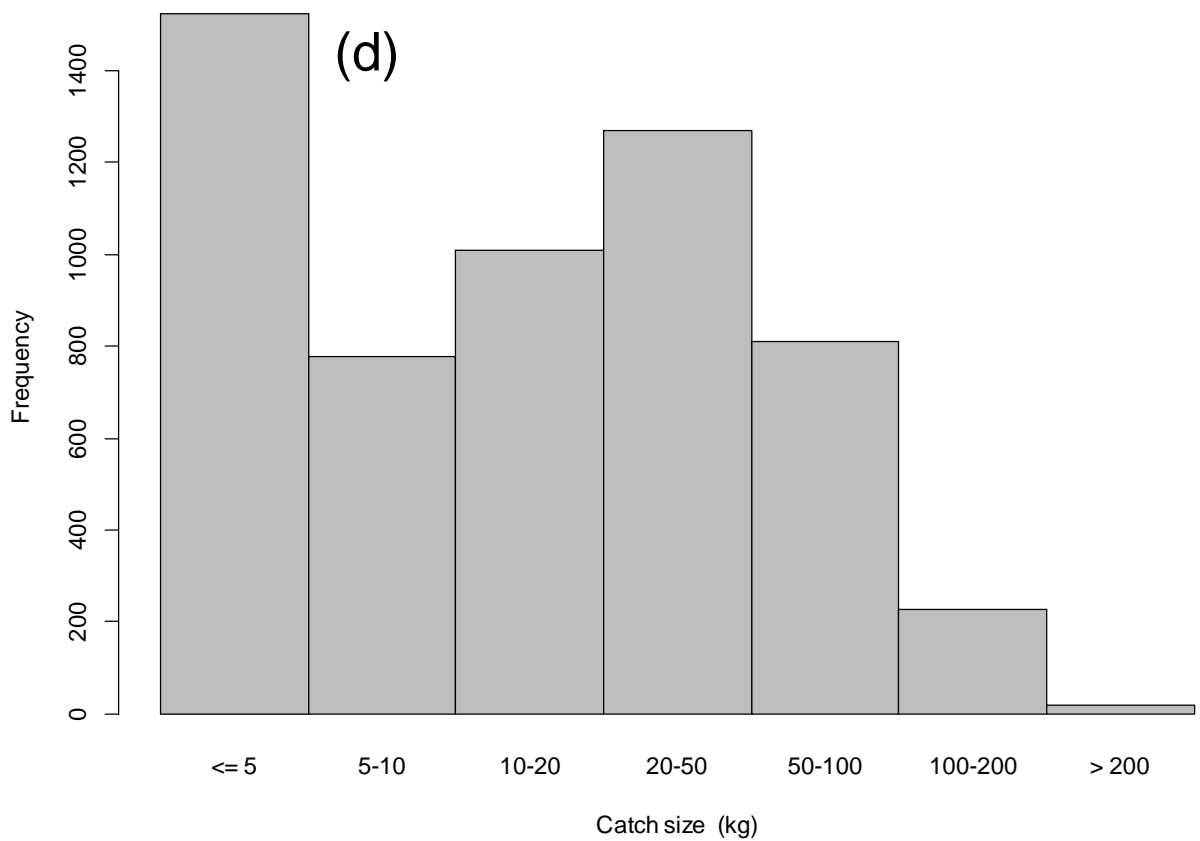
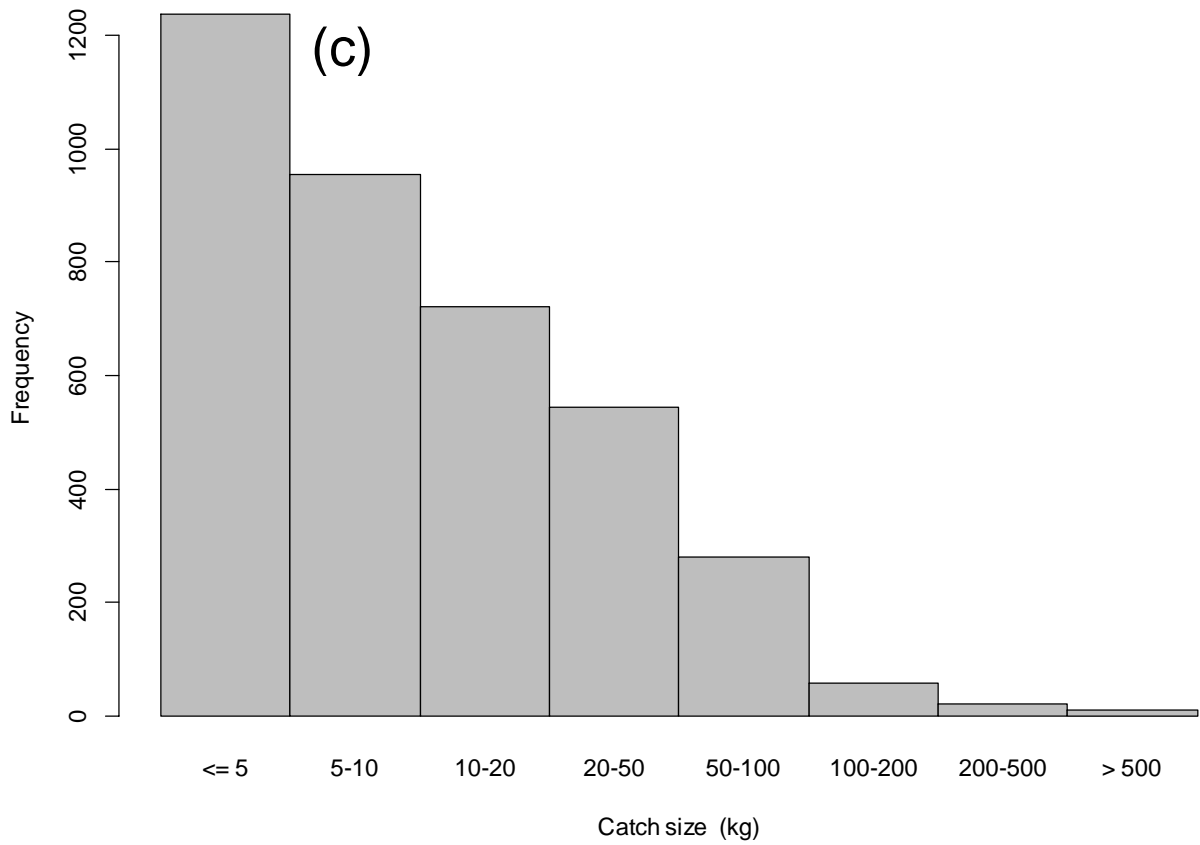


Figure 1.5 (continued): (c) Queensland tunnel net sector, (d) New South Wales line sector.

## 1.7 Data carried forward to the stock assessment

The following data were used in the stock assessment:

- Queensland length-frequency data from various sources, 1976, 1978–1980, 1986–1990, 1995–1997, 1999–2015
- Queensland age-at-length data, 1995–1997, 1999–2015
- NSW length-frequency data 1971–1982, 1987–1990
- Queensland state-wide recreational fishing survey data, 1997, 1999, 2000, 2002, 2005, 2011, 2014
- NSW state-wide recreational fishing survey data, 2000 and 2013
- Records of Fraser Island visitor numbers, 1970–1997
- Queensland and NSW population statistics, 1945–1997
- Queensland Fish Board data on commercial harvest size, 1945–1981
- Queensland commercial logbook data, 1988–2014, used for both harvest size and standardised catch rates
- NSW historical commercial harvest records, 1945–1984 and 1984–1997 (two separate databases)
- NSW commercial logbook data, 1997–2014 (monthly data) and 2010–2014 (daily data), used for both harvest size and standardised catch rates.

The stock assessment was annual over the calendar years 1945–2015.

The Australian east-coast tailor stock was previously assessed in 2004 (Leigh and O’Neill, 2004). Nearly all of the analysis is reworked in this assessment. Also the population model has been completely redesigned to account for individual variation in the asymptotic length  $L_{\infty}$  attained by tailor. Some model inputs are carried over from 2004 without rework.

## 2. Historical harvest sizes of tailor

### 2.1 Background

As described in section 1.6, various data on annual harvest sizes were available. In order to construct an annual time series of harvest size, the following tasks had to be undertaken:

1. Convert historical annual commercial harvests from financial years (July to June) to calendar years (January to December).
2. Interpolate Queensland commercial harvests between 1981 and 1988.
3. Extrapolate the commercial harvests forward to 2015, as the data were acquired at the beginning of the assessment process and did not cover that year.
4. Convert recreational harvest estimates from numbers to weights. This could have been done by the population model described in chapter 4 but would have made little difference to the results. We plan to have the model do it in future assessments.
5. Adjust the RFISH recreational harvest estimates to match the methodology used by NRIFS (Henry and Lyle, 2003).
6. Interpolate recreational harvests in various years between 1997 and 2015 when surveys were not undertaken.
7. Extrapolate recreational harvests backward in time from 1997 back to 1945.

Task 1 was accomplished by assuming that the Queensland harvest was taken in the months July to December and the NSW harvest in the months January to June. This assumption, although obviously not perfect, fitted the annual patterns of when the majority of the commercial catch was taken for each state. Over the duration of the Queensland logbook database, 77.4% (2848 t) of the commercial harvest was taken from July to December and only 22.6% (831 t) from January to June. For NSW the figures are 65.2% (697 t) from January to June and 34.8% (373 t) from July to December. For example, the Queensland harvest for 1980–81 was assumed to have been taken from July to December 1980 and so was assigned to the calendar year 1980. The NSW harvest in that year was assumed to have been taken from January to June 1981 and so was assigned to the calendar year 1981.

For task 2, we interpolated harvests in the years 1981–1987 by fitting a straight line to the logs of the commercial harvests at two endpoints:

- The average of the 1979 and 1980 harvests halfway between 1979 and 1980
- The average of the 1988 and 1989 harvests halfway between 1988 and 1989.

Working on the log scale allowed the interpolation to fit a constant percentage rate of increase or decrease of the harvest over the interpolated period, which we regarded as more realistic than a constant number of tonnes. The fitted interpolation was an annual increase of 0.4% per year between the commercial catches of 212.3 t in 1979–80 and 221.0 t in 1988–89.

For task 3, we assumed that the Queensland commercial harvest in 2015 was equal to the harvest in 2014. For NSW, we used the acquired data which included some but not all data from 2015. This omitted some data for 2015. Both the Queensland and NSW commercial harvests were much smaller than the recreational harvests and we judged that these approximations would have a negligible effect on the assessment. For Queensland, this assumption was very close to the truth: the Fisheries Queensland Qfish database lists the harvest of tailor by net sectors as 57.44 t in 2014 and 54.93 t in 2015.

For task 4 we simply multiplied catch numbers by an average weight of a recreationally caught fish:

- 0.558 kg for Queensland where the most recreational fishing occurs on ocean beaches; this was carried forward from the 2004 assessment (Leigh and O'Neill, 2004) without rework. This could be reworked in future assessments, using regional samples from Fisheries Queensland monitoring data.
- 0.499 kg for NSW fish caught in estuaries (figure supplied by NSW Department of Primary Industries)

- 0.593 kg for NSW fish caught on ocean beaches (figure supplied by NSW Department of Primary Industries).

NSW has much more fishing for tailor in estuaries than Queensland (e.g., the southern locations on the map in Figure 1.2, p. 1), making it desirable to have separate average weights for the two types of location in NSW.

## 2.2 Adjustment of RFISH catch estimates, 1997–2005

As stated in section 1.5.2, the RFISH surveys are thought to overestimate the catch size and to require adjustment to match the NRIFS–SWRFS surveys. The RFISH surveys had less regular prompting of participants, meaning that they had to rely more on their memory. Then they tended to overstate their catches (Lawson, 2015).

Inspection of the RFISH catch estimates from Fraser Island indicated that no adjustment was needed there. The 1999 and 2002 RFISH estimates would have had to be adjusted upwards rather than downwards in order to match the 2000 NRIFS estimate, which was in the opposite direction to the perceived bias in the data. Any adjustment would have been small anyway.

The RFISH catch estimates from locations other than Fraser Island were clearly larger than would be expected from the sizes of the NRIFS and SWRFS surveys. Therefore these were adjusted downwards. The RFISH estimates from all years (1997, 1999, 2002 and 2005) were all multiplied by the factor

$$C_{2000} / (C_{1999}^{2/3} C_{2002}^{1/3})$$

which is the ratio of the NRIFS harvest estimate (denoted  $C$ ) in 2000 to the estimated RFISH harvest in 2000: the latter is a geometric mean of the RFISH surveys before and after, as RFISH was not conducted in 2000. The 1999 RFISH survey received a higher weighting ( $2/3$ ) than the 2002 survey ( $1/3$ ) because it was one year from the target year, as opposed to two years. Only the non-Fraser-Island harvests were used for this calculation.

The assumption implicit in this scaling is that the RFISH estimates were overstated by the same ratio in all years in which they were conducted. We believe this assumption to be reasonable.

In the previous assessment of tailor (Leigh and O’Neill, 2004, p. 10) it was thought that the 1997 RFISH estimate might have been erroneous because it was much larger than the later ones. Since then, the continued decreasing trend through time has shown that there has indeed been a large and continuing fall in recreational fishing effort since 1997. Therefore we no longer regard the 1997 estimate as being especially subject to error. It was included in this assessment, adjusted as above.

## 2.3 Interpolation of recreational harvest, 1997–2015

The above adjustments provided estimates of recreational harvest in Queensland in the years 1997, 1999, 2000, 2002, 2005, 2011 and 2014. Estimates in other years between 1997 and 2015 were calculated by loglinear interpolation of the available harvest estimates. A piecewise linear function (Encyclopedia of Mathematics, 2012) of time was fitted to the logs of the harvest estimates. This function passed through the available log-harvest estimates exactly and changed slope at the years 1999, 2000, 2002, 2005 and 2011. The log-harvest interpolation was then exponentiated (back-transformed) to produce harvest estimates. As in section 2.1, the log scale allowed the interpolation to fit uniform percentage rates of increase or decrease of the harvest over each interpolated period, which we regarded as more realistic than uniform numbers of fish per year. For example, the estimated harvest in 2006,  $C_{2006}$ , was calculated as

$$C_{2006} = C_{2005}^{5/6} C_{2011}^{1/6}.$$

Separate series of estimates were calculated for Fraser Island and Queensland ex Fraser Island.

For NSW, a 1997 estimate was calculated by assuming that the ratio of the 1997 harvest to the 2000 harvest was the same as in Queensland ex Fraser Island. This provided NSW recreational harvest estimates from 1997, 2000 and 2013. As for Queensland, a piecewise linear function was fitted to these estimates, on the log scale, in order to interpolate the other years.

Separate series of estimates were calculated for NSW estuarine and NSW oceanic recreational harvests.

## 2.4 Backward extrapolation of recreational harvest, 1945–1997

Three series of recreational harvests prior to 1997 were calculated:

1. Fraser Island
2. Queensland ex Fraser Island, and
3. New South Wales.

Recreational harvests were assumed to be proportional to the following respective effort proxies, except that they were adjusted for estimated recreational fishing power (see section 3.1 below):

1. Visitor numbers to Fraser Island, recorded in various issue of Moonbi newsletter (Fraser Island Defenders Organisation, 2015); assumed to be zero prior to 1970
2. Human population size in Queensland (ABS, 2014)
3. Human population size in NSW (ABS, 2014).

Only the trends in these proxies were important, not the magnitudes of them: we did not assume that all persons in the population were fishers, although the use of these proxies involves the assumption that the participation rate and the per-person time spent fishing remained the same up to 1997.

In principle, it would be more accurate to make fishing effort, rather than harvest, proportional to an effort proxy. Time did not permit that to be included in the model for this assessment but it could be considered for future assessments. This change would require a more complex population model, in which commercial sectors were driven by catch size but recreational sectors were driven by effort. Moreover, the effort-driven nature of recreational sectors would apply only prior to 1997. From that year onwards, recreational sectors would have to be driven by catch size. We don't know of any effort proxy that would reflect the big falls in recreational effort since 1997. For example, it would be difficult for the measured effort from recreational surveys to capture a trend towards family-oriented holidays on Fraser Island in recent years, in preference to fishing-focussed holidays in past years.

## 2.5 Complete time series of estimated harvest size

The estimated time series of harvest size is plotted in Figure 2.1. It shows a pronounced peak in the mid-1990s, followed by a sharp decline. The maximum estimated total harvest was 1794 t in 1996.

It is known from the telephone–diary surveys in both Queensland and NSW that after the 1996 peak there was a decline in fishing participation and effort in the recreational sectors. There was also increased regulation of the commercial sectors (see Table 1.1, page 4). The decline in the commercial harvest actually began from the mid-1970s, possibly due to decreased public demand for tailor (see section 1.1). From the harvest-size data alone it is not clear to what extent, if any, the fall in total harvest after the mid-1990s was related to a shortage of fish to catch.

The time series of harvest size in Figure 2.1 is a critical input to the population model and the results of the stock assessment. It is assumed to be accurate but is particularly sensitive to two assumptions:

1. Recreational fishing effort increased with human population size until the mid-1990s, when recreational catch surveys began. It is known that recreational fishing for tailor was a very popular activity until the mid-1990s, but whether it actually increased sharply up to that time before falling sharply immediately afterwards is not known for certain. The fact that bag limits were introduced in NSW in 1993 and Queensland in 2002 supports the concept of a change in fisher behaviour and cultural attitude around the mid-1990s.
2. Recreational catch surveys capture the whole recreational catch. Hence the fall in recreational harvest since the mid-1990s is real. It is a potential problem that people who no longer have home telephones are not captured in the surveys, although surveys of fishers outside tackle shops have not yet found that to be a problem (Teixeira et al., 2016).

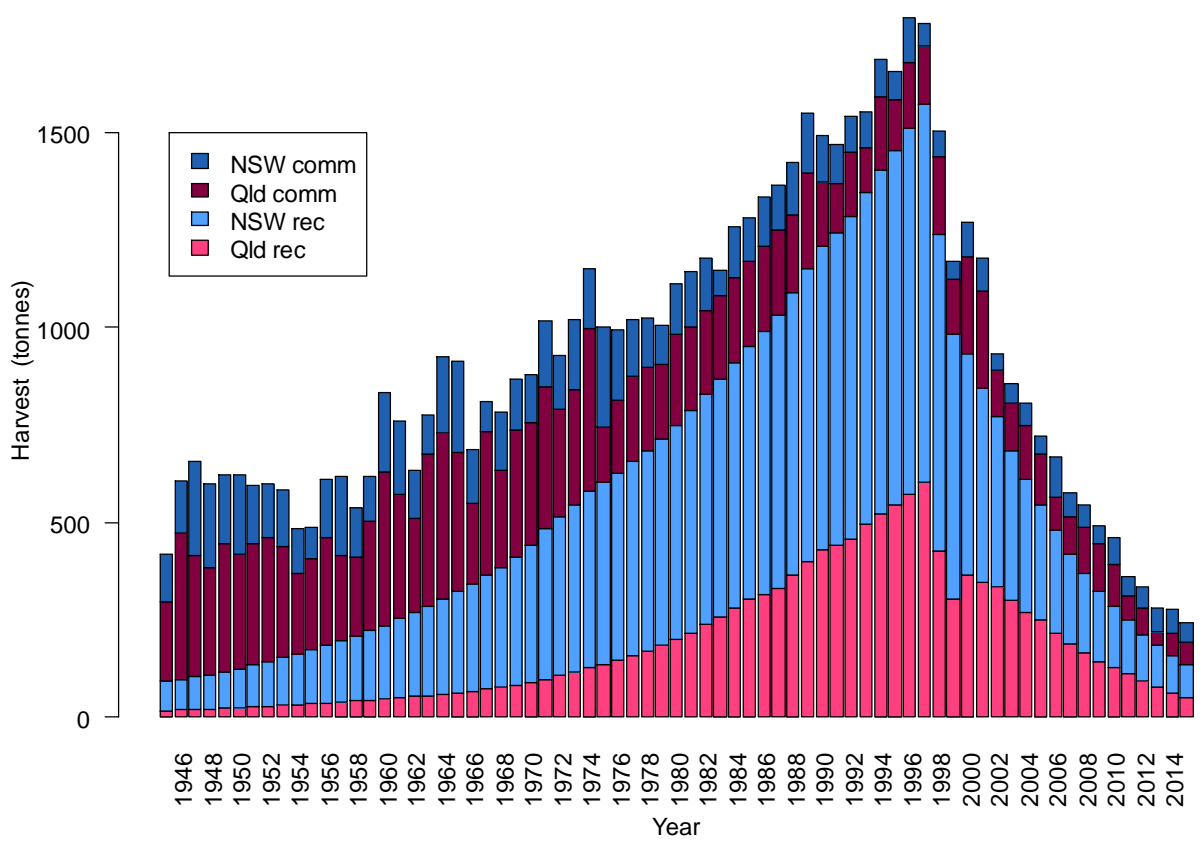


Figure 2.1: Estimated harvest size, 1945–2015. Sectors from bottom to top are Queensland recreational, New South Wales recreational, Queensland commercial and New South Wales commercial. Recreational catch estimates are based on the proxies of human population prior to 1997, the first year in which a state-wide survey was conducted in Queensland.



### 3. Catch-rate analysis

#### 3.1 Queensland fishing club data

Queensland fishing club data were available from 1954 to 2001. The dataset was the same as analysed in the previous assessment (Leigh and O'Neill, 2004). The analysis also was taken from the previous assessment. It could be revisited in a future assessment to see whether it could be simplified.

The analysis was conducted in a mixture of R (R Core Team, 2016) and Genstat (Payne et al., 2009). Genstat was used to run a generalised linear mixed model (GLMM) which fitted random effects for club, trip and fisher but fixed effects for year, month and location. All other analysis and data manipulation were conducted in R. The model used was a Poisson model with log link, i.e., multiplicative effects for all the explanatory variables. The dispersion parameter was estimated so as to provide accurate standard errors on the parameter estimates.

Two analyses were run: one for the total of all species combined that were caught on the fishing trips, and another for tailor.

The first analysis (Figure 3.1) aimed to quantify the increase in recreational fishing power during the development of the fishery. Many new fishing techniques and technological improvements were introduced during the 1950s, 1960s and 1970s, as described in section 1.1 above, and it was expected that these would substantially increase the efficiency of recreational fishing over that time.

The second analysis (Figures 3.2 and 3.3) estimated the standardised catch rates of tailor. These could then be adjusted for fishing power using the results of the first analysis, to provide an index of abundance of tailor.

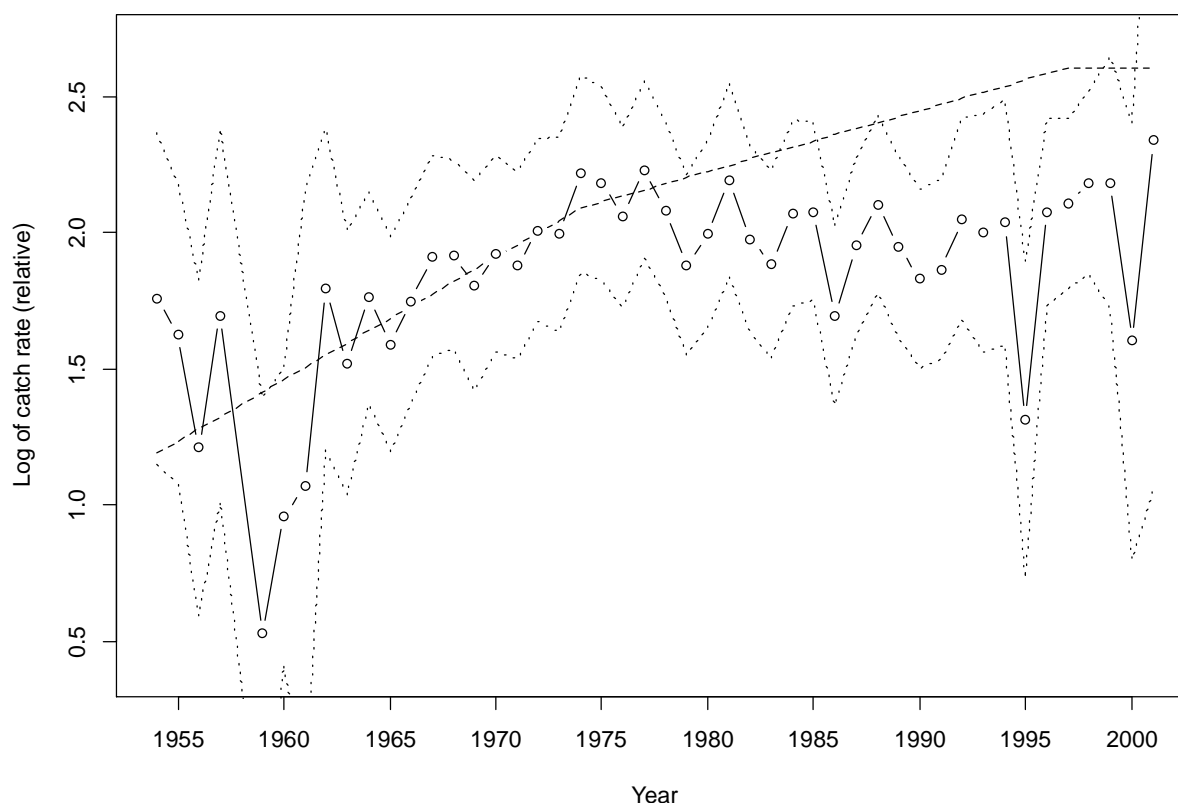


Figure 3.1: Standardised catch rate of all species combined from Queensland fishing club data, to estimate recreational fishing power. Circles and solid lines show the log of standardised catch rate, while dotted lines show 95% confidence limits. Catch rates rise steadily to 1974, which we ascribe to fishing power increase (dashed line). We considered it prudent to continue the fishing power increase at half the previous annual rate until 1997 to allow for increased catchability.

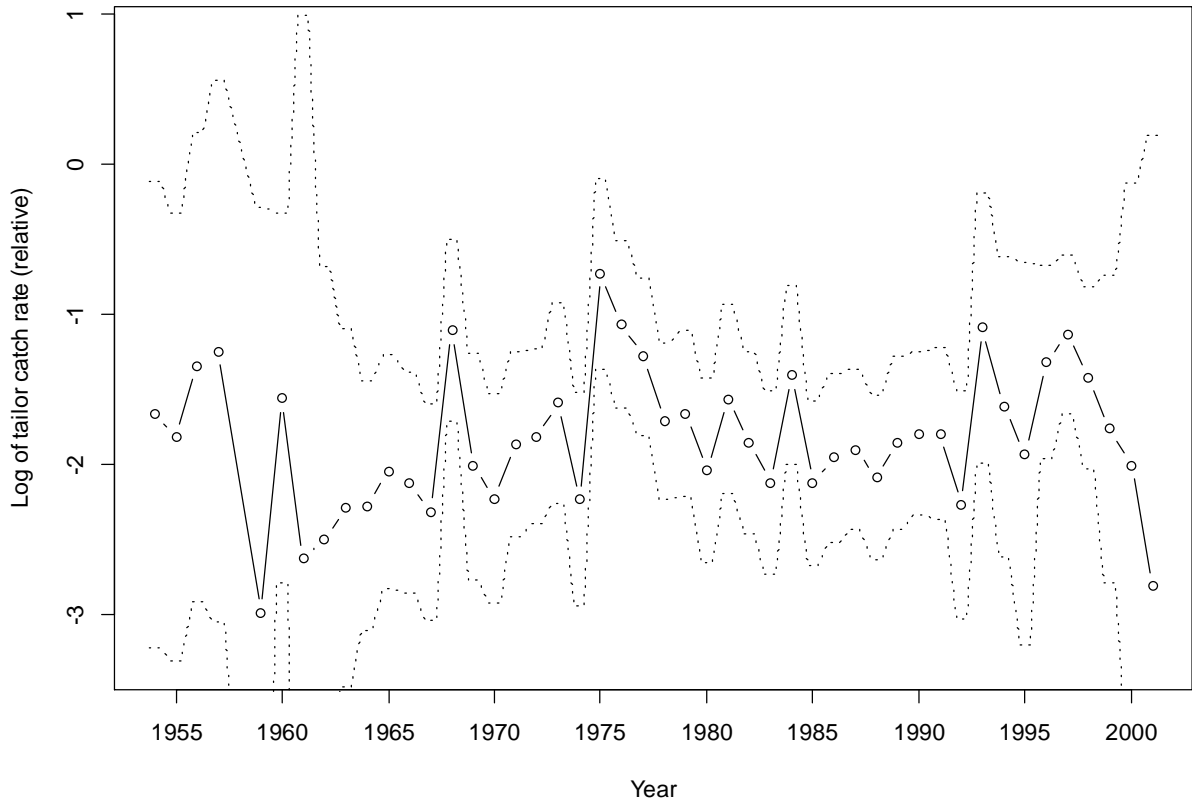


Figure 3.2: Standardised catch rate of tailor from Queensland fishing club data, before correction for fishing power. Dotted lines are 95% confidence intervals.

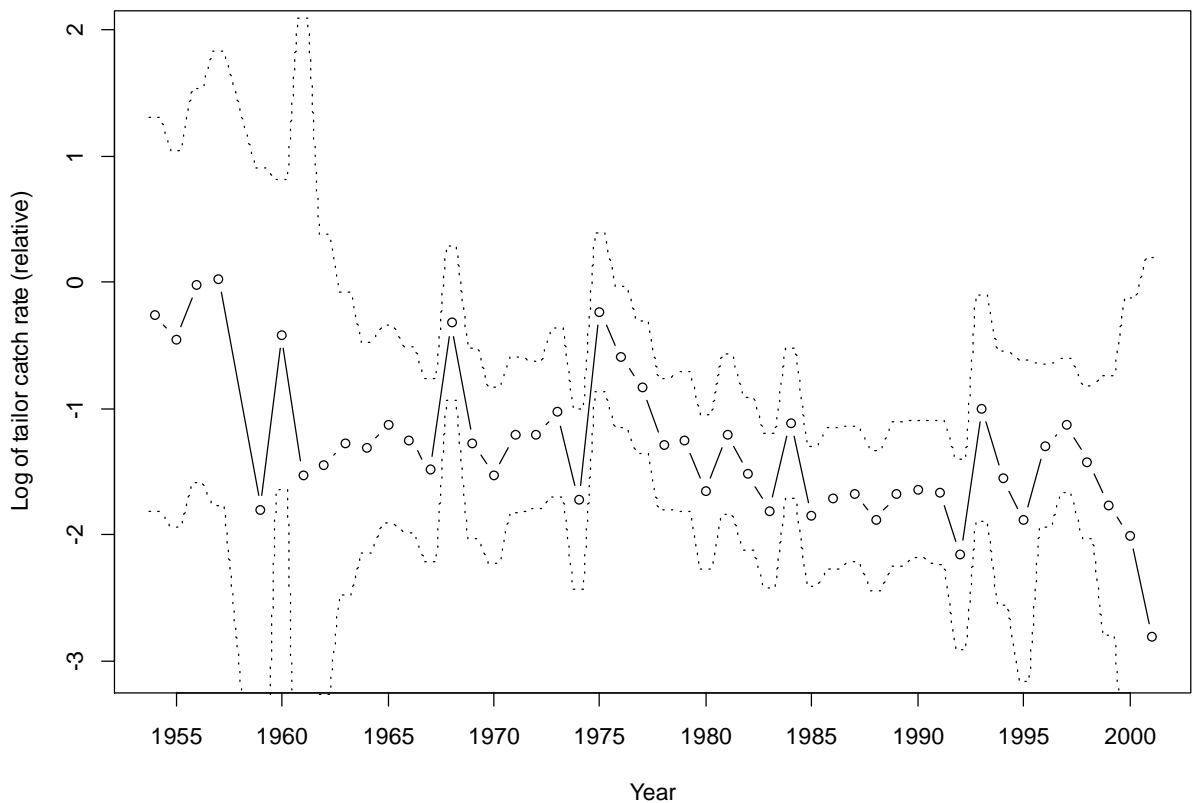


Figure 3.3: Standardised catch rate of tailor from Queensland fishing club data, after correction for fishing power according to the dashed line in Figure 3.1. Dotted lines are 95% confidence intervals.

The results had wide confidence limits, especially near the beginning and end of the data. This was a consequence of the amount of variation in the data, especially the variation of skill levels of fishers and average skill levels of clubs, and the fact that many clubs tended to contribute data for some years and then drop out.

The analysis of all species combined shows a strong increase to 1974, which we ascribe to fishing power increase (about 4.6% per year). After 1974 we considered it prudent not to assume a sudden stagnation of recreational fishing power and we continued it to 1997 at half the previous rate (about 2.3% per year) (Figure 3.1). The year 1997 was chosen as the year in which the fishery harvest was highest (Figure 2.1, page 17). After 1997 there was a drop-off in participation in recreational fishing which made it harder to argue that fishing power would continue to increase. The introduction of bag limits in NSW in 1993 and Queensland in 2002 also would have reduced fishing power (see Table 1.1, page 4).

The standardised catch rate of tailor before correction for fishing power (Figure 3.2) showed little overall trend. After correction for fishing power (Figure 3.3) it shows a downward trend.

The estimated fishing power from Figure 3.1 was also used as an additional scale factor in the recreational fishing effort proxies used to extrapolate the recreational harvest size prior to the commencement of telephone–diary surveys (see section 2.4). The fishing effort proxy of human population size could roughly provide the number of people fishing but did not take into account their levels of skill and technology. Therefore we applied the fishing-power adjustment to better estimate the *effective* recreational fishing effort. This adjustment embodied the assumption that fishing power could be transferred from fishing clubs, whose members may tend more to be expert fishers at the leading edge of technology, to the broad recreational fishing community. We believed that making this assumption was preferable to not applying any fishing power adjustment.

## 3.2 Queensland commercial data

Although the commercial logbook database began in Queensland in 1988, the quality of the data in the first few years (1988–1990) was strongly affected by lower participation rates and inconsistent catch reporting. For tailor in this period, it is also possible that some fishers did not record small retained catches of tailor when they were targeting other species.

We also note that a minimum legal size (MLS) was introduced in Queensland in 1990 and NSW in 1993, which would have produced at least some of the fall in the catch rate. The population model (see chapter 4) accounted for such effects by allowing the MLS to vary by year; the model did not automatically associate a lower catch rate with lower abundance if the MLS changed. Changes in MLS could, however, also affect fishers targeting behaviour; e.g., a higher MLS for tailor may cause fishers to either not fish (ocean-beach operators) or to target other species in preference to tailor. The population model was not able to account for changes in catch rate caused by changes in targeting.

Most of the recorded commercial harvest of tailor was taken by either gillnet or beach seine net. Beach seine data were not well suited to catch-rate analysis because the major form of fishing effort was search time, waiting for a school of fish to appear, and this was not recorded. It may be possible to estimate search time from the total daylight hours over which suitable weather applied, but this would be subjective. The beach seine data were susceptible to hyperstability: the average size of a school of tailor, and hence the catch per record of tailor, may remain the same even if the number of schools in the sea and the total population size increase or decrease substantially.

Therefore catch-rate analysis was undertaken only for the gillnet data. The analysis took the form of a Poisson generalised linear model (GLM) with log link and estimated dispersion parameter. It was carried out in the software R, which refers to the Poisson GLM with non-integer data as a “quasi-Poisson” model. This model with non-integer data is an instance of a quasi-likelihood model (developed by Wedderburn, 1974; see McCullagh and Nelder, 1989 p. 326 for the Poisson version).

The gillnet fishery is a mixed-species fishery in which tailor is only one component. It was considered beneficial for the analysis to include zero catches of tailor when species commonly associated with tailor were caught.

The goal in including zero catches is to include them only when it is reasonable to expect that tailor might have been caught in a particular fishing session. The advantage of this approach is that the abundance estimate falls in years in which schools of tailor are scarce, which is highly desirable but may not happen if zero catches are excluded. A disadvantage is that it is subjective and a judgement has to be made of when nonzero catches of tailor might be expected but don't actually occur.

An exploratory analysis of fishers who had at least 500 kg total catch of tailor provided the average catch weights of tailor per fisher–day listed in Table 3.1.

*Table 3.1: Tailor catches associated with catches of other taxa in the Queensland gillnet fishery. The final column lists the average catch of tailor per nonzero record of the taxon in the first column.*

<b>Taxon</b>	<b>Records</b>	<b>Total harvest (t)</b>	<b>Total tailor (t)</b>	<b>Av. tailor (kg)</b>
Tailor	28253	1085.1	1085.1	38.4
Trevally	10445	939.7	177.1	17.0
Shark	23454	954.1	182.9	7.8
Mackerel	19248	2194.9	141.7	7.4
Flathead	50751	748.0	263.6	5.2
Bream	43745	1450.8	221.6	5.1
Garfish	6115	179.9	27.7	4.5
Whiting	62620	3210.8	283.0	4.5
Mullet	74295	10230.5	314.0	4.2
Other	42793	1389.8	217.5	5.1

On this measure, by far the strongest association of tailor with any other taxon is with the trevally family (Carangidae, several species of which are known as dart). Therefore, the catch-rate analysis included records of trevally, even when the tailor catch was zero. It did not include zero catches of tailor associated with any other taxon. We note that trevally are generally caught all-year-round while the tailor fishery peaks in the winter. The inclusion of a “month” term in the GLM accounted for this phenomenon.

The data were extensively pre-processed to make one record per fisher-day:

- Similar fishing methods were grouped together; e.g., “anchored gillnetting”, “drifting gillnetting” and “ring netting” were all grouped into “gillnetting” because logbook data usually did not distinguish the exact type of gillnetting.
- In the early years of the database, in which fishing methods were not well distinguished, beach-seine netting in the early years was identified based on whether the fisher held the appropriate “K” licence and used a net length of 400 metres or less.
- Records for the same fisher fishing on the same day were combined into a single record.
- Each of these fisher–day records was given a field for each major taxon in the logbook data; e.g., the taxa listed in Table 3.1.
- When a fisher fished in multiple locations on the same day, the location for a fisher–day record was defined to be the location with the greatest total catch (all species combined) of the multiple locations.
- Records with missing data in important fields were omitted, e.g., location, mesh size, net length.
- Records with duration of more than one day were omitted.
- Fishers who fished in only one year were omitted, because their data would not make any contribution to the trend in catch rates.
- Fishers who had low total catches of tailor (less than 500 kg when summed over all years for a particular fishing method) were omitted. These fishers would contribute very little to the catch-rate estimates from the Poisson GLM; they might for models such as the lognormal model which were not used in this assessment. Omitting these fishers simplified the GLM by reducing the number of parameters in it, which also made the results easier to interpret.

Harvest sizes were calculated earlier: records omitted from catch-rate analysis were included in the calculation of harvest size.

The catch-rate GLM included effects for fisher, year, month, location, net mesh size and net length. All terms in the GLM were treated as factors, i.e., variables with discrete levels. The location factor had 12 levels: five 30-minute latitude bands in bay (sheltered) locations and seven in beach (unsheltered) locations. Mesh size had three levels and net length had 11 levels. These variables were not analysed as continuous variables because their relationships to catch size are often complex.

The year effect from the GLM was used as an index of abundance. This is plotted in Figure 3.4. Confidence limits were calculated from the mean deviance of the location–month interaction, not from the model’s residual mean deviance, as we believed that the interaction would provide a more accurate indicator of the true scale of variation.

The first three years 1988–1990 were not input to the population model due to doubts over whether small retained catches were recorded in those years.

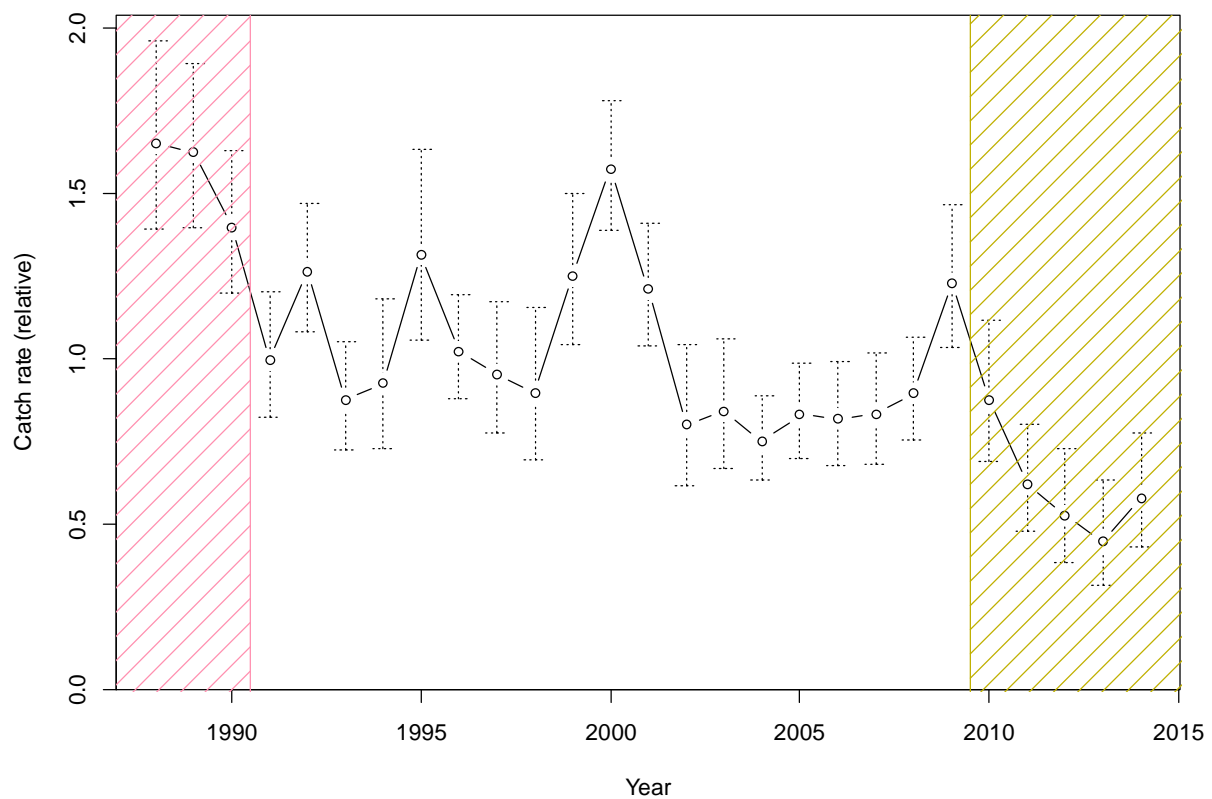


Figure 3.4: Standardised catch rates from the Queensland commercial gillnet fishery, with 95% confidence limits. The first few years may have been subject to incomplete participation by fishers in the logbook system (red shading). A minimum legal size (MLS) was introduced in 1993 and increased in 2010 (bronze-coloured shading). The population model took changes in MLS into account when correlating catch rates to abundance; it did not automatically associate a lower catch rate with lower abundance if the MLS changed.

### 3.3 New South Wales commercial data

Commercial data from NSW were suitable for catch-rate analysis starting from 1998 (see section 1.6.1). One database contained monthly records of catch and effort from 1998 onwards, while the more recent Fish Online database provided daily records from 2010 onwards.

The NSW commercial fishery has a substantial line-fishing component, which the Queensland commercial fishery does not. Line fishing provided additional catch-rate time series. The mesh net component (predominantly gillnet fishing) was also analysed, as in Queensland.

Again, the analysis took the form of Poisson generalised linear models (GLMs) with log link and estimated dispersion parameter, conducted in the software R. For the daily records (2010 onwards), the data were pre-processed to make one record per fisher-day. The GLMs included terms for year, month, fisher and location, all of which were treated as factors with discrete levels.

For analysis of monthly data (1998 onwards), we fitted a parameter to estimate the effectiveness of the second and subsequent days of effort relative to the first day of effort in the month. When fishers report just one day of effort, we can be sure that they actively fished on that day. When they report multiple days of effort, however, the total may be an overestimate: they may report the length of an interval within which they fished but they may not have been actively fishing on each day within that interval.

Inclusion of the effort-effectiveness parameter in the GLM for monthly data allowed for full effort for one day in the month but, on average, a lesser amount of effective effort on each other reported day. A value of one denotes perfect recall of the number of days fished, i.e., fishers were fully active for all reported days fished, while a value much less than one denotes a poor correlation between effort and catch. Actual estimates of this parameter were 0.4771 for line fishing and 0.09288 for mesh-net fishing, indicating that the effort data were useful for line fishing but had a poor correlation with catch for mesh-net fishing.

Effort data were also contained in the daily datasets but were not found to have any correlation with reported catches and hence were omitted from the analyses of daily data.

The location categories used in NSW included 12 ocean regions and 66 estuarine locations. The fishing method was recorded in the data, and records other than line fishing and mesh netting (e.g., ocean-beach haul netting) were excluded from catch-rate analysis.

The daily data included many fishers and locations with very small total reported harvests. Whether these fishers and locations are included or excluded has little effect on the results of a Poisson GLM, as this model automatically downweights small catches. They would have had a big effect if we had used a different model such as a lognormal model (ordinary linear model using log catch) or a gamma GLM, neither of which downweights small catches. For those models, the decisions on exact values of catch thresholds would have been very difficult and would have had a big effect on the results.

Inclusion of the fishers and locations with small total harvests would, however, have greatly increased the number of parameters in the GLM and complicated the analysis, because a separate parameter had to be fitted for each fisher and for each location. Therefore we omitted them. The thresholds were that, to be included in the analysis, a fisher had to report at least 100 kg of tailor in total over all years, while a location had to provide at least 1000 kg (line-fishing analysis) or 300 kg (mesh-fishing analysis). We considered these thresholds to be low, favouring the inclusion of all data that could help with the estimation of coefficients in the GLMs.

The daily datasets also provided the opportunity to include zero catches of tailor, as they contained all the catch records for every fisher that ever caught tailor. It is debatable whether zero catches should be included: on the one hand they provide valuable information when fishers may have tried to catch tailor but no tailor were present, but on the other hand they may indicate occasions on which fishers had no wish and made no attempt to catch tailor. We included the zero catches in the analyses. We note however, that the abundance trends were somewhat different when the zero catches were omitted; this may indicate a change in fishers' targeting behaviour over the period 2010–2014, which could render the abundance estimates inaccurate whichever way they are done. The catch rates with nonzero tailor catches only are shown in Figure 3.7.

The coefficients of variation (CVs, standard errors divided by the estimates) of the abundance estimates for input to the population dynamic model were set to 0.1 in all years in all the analyses, except for the monthly line fishing analysis in 1999 and 2000 when there were fewer data; then they

were set to 0.15. For the monthly analyses, these CV values roughly matched the estimates from the GLMs. For the daily analyses, they were about 1.5 times the GLM estimates and accounted for additional variation caused by potential year-to-year changes in the behaviour of the fish, which could not be estimated by the GLMs.

Final estimates of abundance are plotted in Figures 3.5 and 3.6. They show a slight increasing trend over the period 1988–2014, and that abundance in 2010 appeared to be higher than in 2011–2014.

Only the 1998–2014 abundance estimates (derived from monthly data) were used as inputs to the population dynamic model, as the 2010–2014 time series were not regarded as long enough to be useful yet. They can be included in future assessments when the time series will be longer.

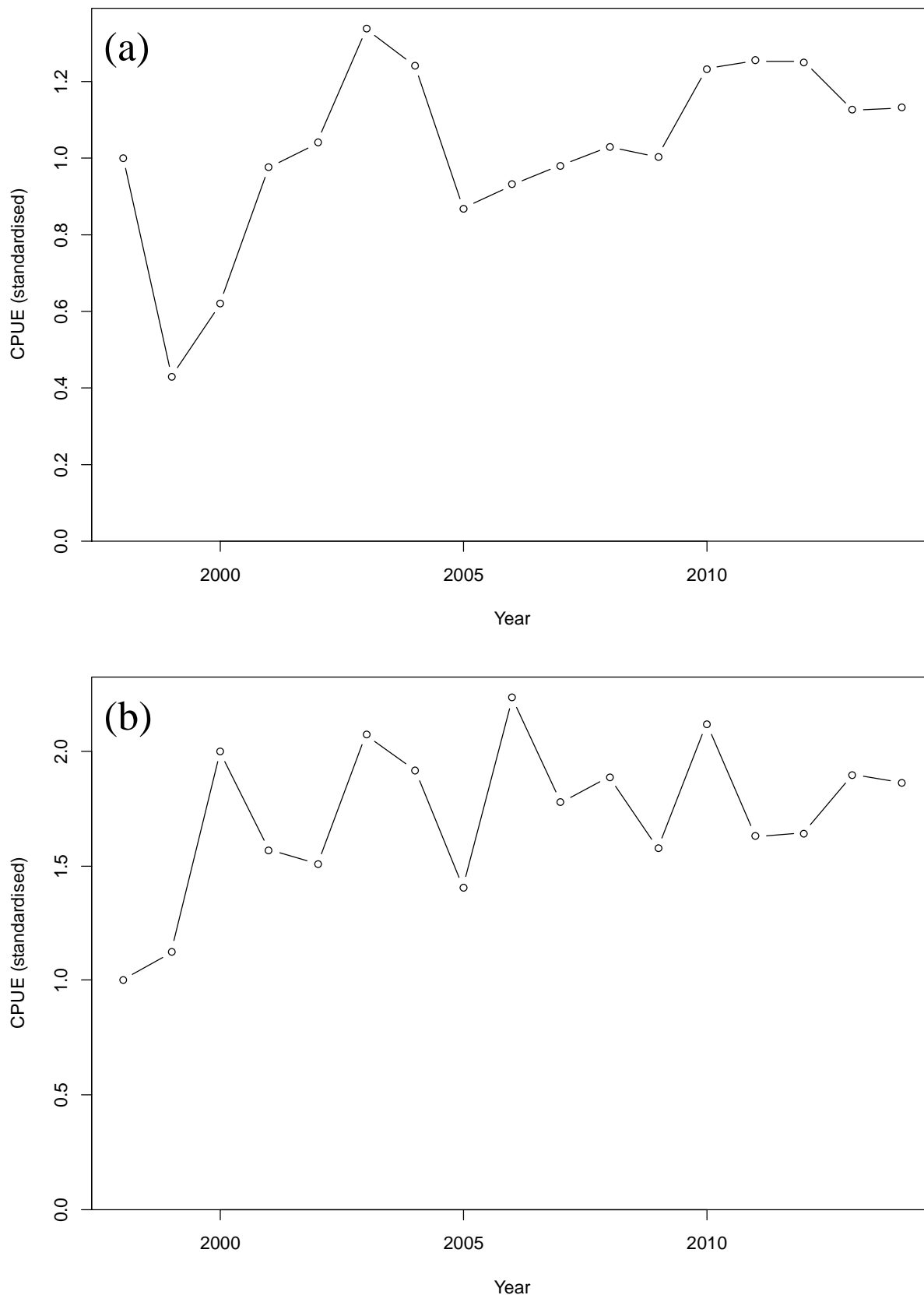


Figure 3.5: New South Wales commercial catch rates (catch per unit effort, CPUE) from monthly data, 1998–2014: (a) line fishery; (b) gillnet fishery. Coefficients of variation (CVs, standard errors divided by the estimates) were about 0.09 for line fishing, except in 1999 and 2000 where there were fewer data and they were about 0.15; and 0.08 for mesh fishing. CVs input to the population model were not allowed to go below 0.10 as estimates could be affected by annual environmental variation.



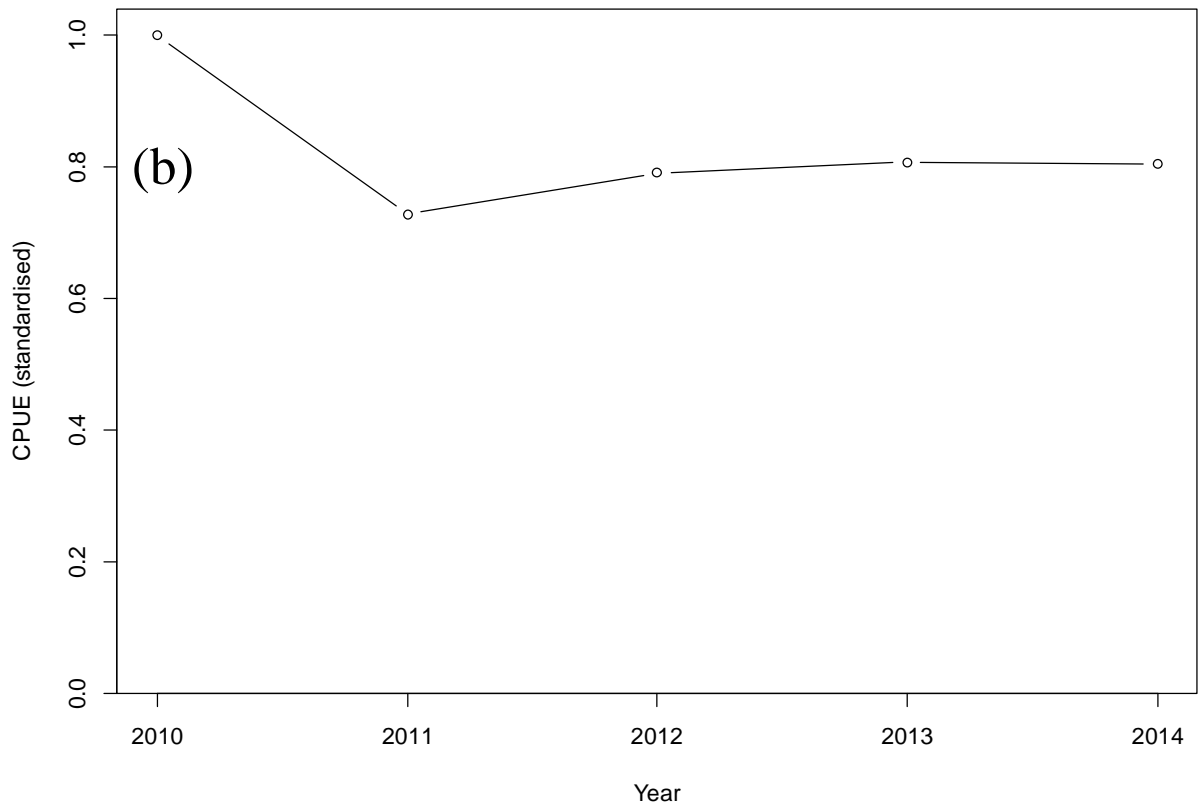
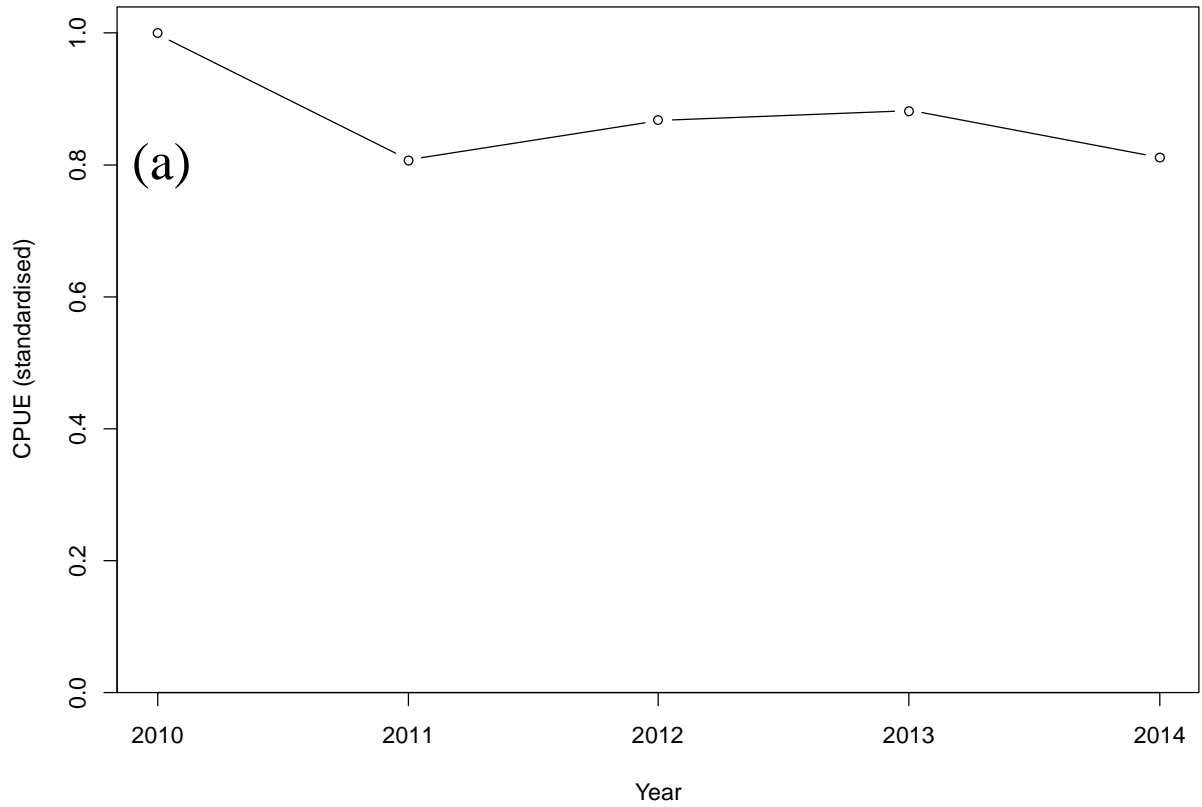


Figure 3.6: New South Wales commercial catch rates (catch per unit effort, CPUE) from daily data, 2010–2014: (a) line fishery; (b) gillnet fishery. Coefficients of variation were about 0.035 for line fishing and 0.04 for mesh fishing. CVs input to the population model were not allowed to go below 0.10 as estimates could be affected by annual environmental variation.

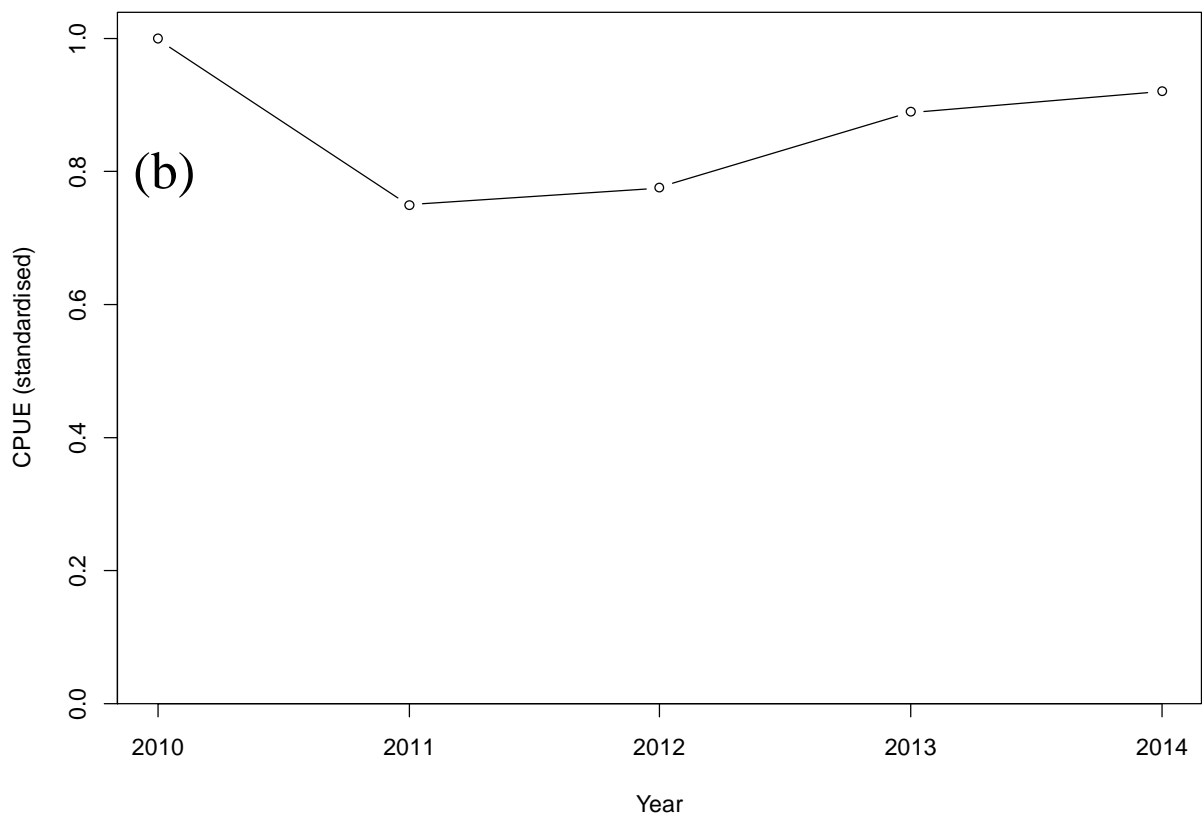
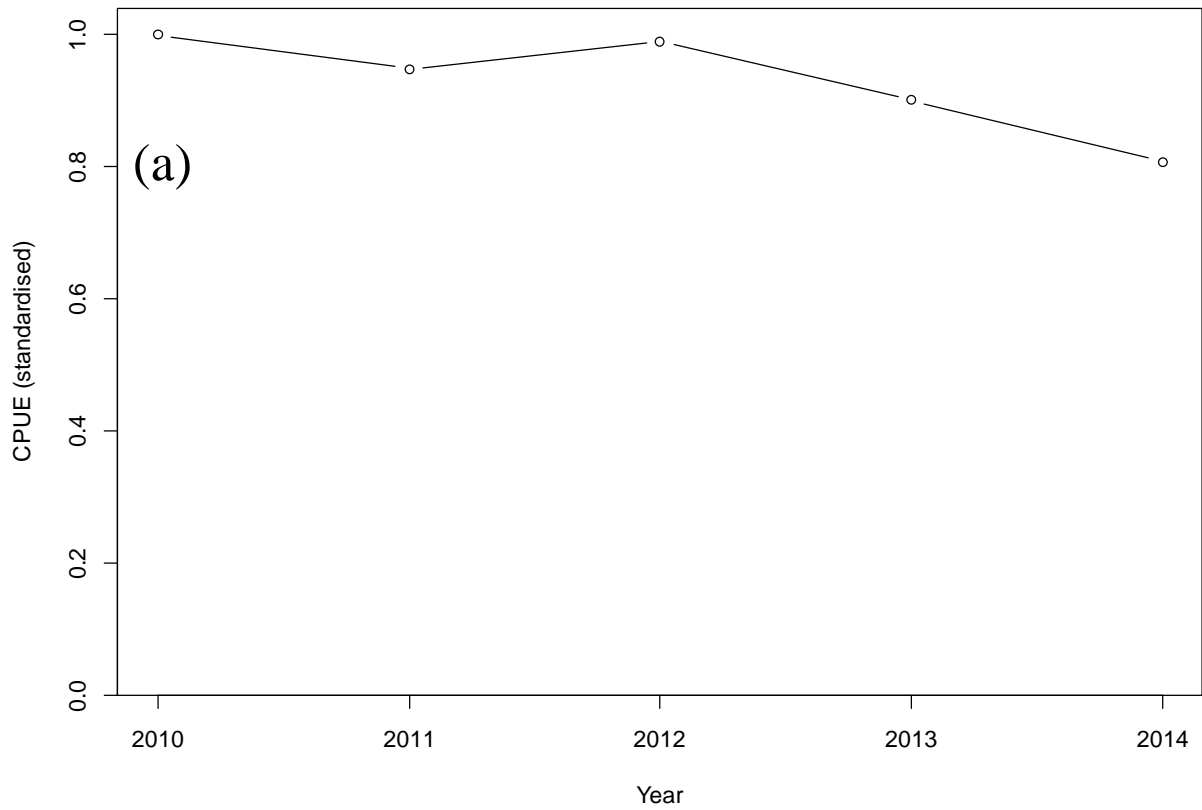


Figure 3.7: NSW commercial catch rates from daily data, nonzero tailor catches only, 2010–2014, for comparison to Figure 3.6: (a) line fishery; (b) gillnet fishery.

## 4. New population model

### 4.1 Size variation and vulnerability to fishing

Fishery populations are commonly subject to size-dependent vulnerability to fishing (Beverton and Holt, 1957; Gulland, 1957; Holt, 1957). Individuals in a population are typically born not at the same time of year but throughout an extended spawning season (Hickling and Rutenberg, 1936; Hempel, 1965). It has also been recognised that some animals may be genetically pre-destined from birth to reach different asymptotic sizes. To model the latter phenomenon, Punt et al. (2001) introduced discrete growth-type groups, each with its own distinct value of the asymptotic size  $L_\infty$ .

Flexible modern population dynamic models take the form of “integrated models” which maintain an age-structured “population matrix” of the number of animals alive of each age at each time step (Fournier and Archibald, 1982; see review in Punt et al., 2013). Alternatively, models may be structured by size (Sullivan et al., 1990), or by both age and size to maintain a matrix of population numbers by age and size at each time step (Frøysa et al., 2002). These different approaches recognise the competing effects of biology which may be predominantly age-dependent and fishing which is often size-dependent.

Inclusion of growth-type groups adds an additional dimension to the population matrix if random size variation from other sources is to be retained. Punt et al. (2001) used just five levels of  $L_\infty$  for their growth-type groups. Walters and Martell (2004, p. 120, Box 5.3) suggest 21 levels.

Existing models that include size structure typically use a “growth transition matrix” to specify the probability that an animal will move from one size class to another in a model time step. These models have the problems not only of large size of the population matrices and the associated computations, but also of how the elements of the transition matrix are to be calculated or estimated (Punt et al., 2016). An annual growth increment is generally a fractional multiple of the model’s size interval, which causes errors that can compound when approximations are applied over multiple years.

This chapter proposes a new population model that is fundamentally different to existing models. It has greater capability to handle random variation in growth from various sources and uses smaller arrays with fewer computations to track the population.

The new model indexes the population matrix by time ( $t$ ), age ( $a$ ) and age at first vulnerability to fishing ( $v$ ). The final index  $v$  ranges from the lowest age at which any animals become vulnerable to fishing, through all the ages of partial vulnerability, up to the lowest age at which all animals are vulnerable. In many applications  $v$  may have only two or three levels because all animals may become vulnerable at a relatively young age.

The model structure is facilitated by the assumption that once an animal becomes vulnerable to fishing, it remains vulnerable for the rest of its life. Moderate departures from this assumption can be accommodated, although they can produce negative intermediate biomasses in the model calculations.

Equivalent capability from existing length-transition models (e.g., the Fleksibest model of Frøysa et al., 2002) would require four dimensions: time ( $t$ ), age ( $a$ ), size ( $L$ ) and growth-type group (GTG). That would still offer only an approximation to the desired population dynamics, due to the discrete nature of both the size intervals and the growth-type groups, and would require the elements in the growth transition matrix to be estimated somehow.

Sex and regional populations can be added as extra dimensions if needed, as they can for existing models. For tailor, sex does not need to be distinguished because the sexes do not appreciably segregate or follow different growth curves, and regional populations are not needed because the fish are highly migratory.

### 4.2 Model assumptions and terminology

The model is based on the following assumptions:

1. The size  $L_0$  of an animal at age zero, defined as the middle of the first full year of life, is normally distributed with some mean  $\mu$  and variance  $\sigma^2$ .
2. Each animal grows according to an individual von Bertalanffy growth function. The growth rate  $K$  is constant and asymptotic size  $L_\infty$  is normally distributed, independently of  $L_0$ , with some mean  $\lambda$  and variance  $\rho^2$ .
3. The weight and fecundity of an animal are parametric functions of size. For simplicity in describing the model, we assume that fecundity is proportional to weight. We assume this for tailor but it does not have to be the case. Fecundity can also depend on age and sex.
4. The proportion of animals mature,  $m_a$ , depends on age but not size. Size dependence, if desired, can be handled through the fecundity function.
5. The instantaneous natural mortality rate  $M$  does not depend on size but may, if desired, depend on age or time.
6. The proportion of animals vulnerable to fishing is the product of a parametric function of size,  $V(L)$ , with a function of time, sex and age. For simplicity in describing the model, we omit the function of time, sex and age here, and assume that vulnerability depends only on size.
7. Once an individual animal becomes vulnerable to the size-dependent component of vulnerability fishing,  $V(L)$ , it remains vulnerable for life. Furthermore,
  - (a) An animal vulnerable to being caught and discarded in one year is vulnerable to being caught and reported the following year; i.e., it will have grown over the minimum legal size in the intervening time; and
  - (b) If the fishery has multiple fishing sectors, which we call “fleets”, with different vulnerability functions, an animal vulnerable to either discarding or reporting by any fleet in one year is vulnerable to reporting by all fleets the following year.
8. Fishing takes place in a pulse in the middle of each year, over a short enough period that natural mortality, although it happens all year round, can be neglected over the duration of the fishing season; i.e., the fishery is a Type 1 fishery in the terminology of Ricker (1975, p. 10).

Assumption 7 underpins the new model and we believe that it will be valid for many fisheries. Its major requirement is that the size-based vulnerability function  $V(L)$  from assumption 6 should be a monotonic increasing function size, a common example of which is the logistic function

$$V(L) = 1 / \left[ 1 + \exp\left\{ -(\log 19) (L - L_{50}) / (L_{95} - L_{50}) \right\} \right], \quad (4.2)$$

where  $L_{50}$  is the size at 50% vulnerability and  $L_{95}$  is the size at 95% vulnerability (see, e.g., Haddon, 2001, p. 353). Violation of assumption 7 can produce negative intermediate biomasses of animals of age  $a$  that became vulnerable at some age  $v$ , although these do not necessarily invalidate the model if the total biomass of age  $a$ , when summed over  $v$ , remains positive.

It is possible, although we do not consider it practicable, to relax assumption 7 and maintain strict validity of the model by considering large numbers of cases in which animals are vulnerable at some ages but not others, or are vulnerable to some fleets but not others. The design of the model requires it to track every potential fishing history of an animal. For example, if the fishery exists only inshore and there is a very strong size-dependent effect that animals move offshore as they grow larger, the model could consider every possible combination of the recruitment-age at which an animal could come into the fishery, and the exit-age at which it could leave the fishery. The exit-age would add an extra dimension to the population matrix.

In the above example, the original model, indexing only by recruitment-age, would be valid if the movement offshore were age-dependent instead of size-dependent. We expect that age-dependence would adequately represent many such fisheries.

Most of the parameters in the model are allowed to depend on time, age and sex if desired. For simplicity we have omitted this dependence in the model description. The growth parameters  $\mu$ ,  $\sigma$ ,  $\lambda$  and  $\rho$  may depend on sex and cohort (time minus age) but not time and age individually. The parameters of  $V(L)$  may depend on time, age and sex although  $V(L)$  should still satisfy assumption 7. Assumption 7 does not have to hold for the final vulnerability in which  $V(L)$  may itself be multiplied by a function of time, age and sex. For example, animals may move offshore out of the fishery as they become older; such an effect should be a function of age only, not size within an age class.

Typically, spawning seasons are annual and we refer to a model time-step as a “year”, but it does not have to be a year. For animals such as prawns, a monthly time step may be used; then the stock–recruitment relationship (see section 4.3.8 below) could easily include a time lag of several months between spawning and subsequent recruitment to the population.

By “vulnerability” we mean the combination of all processes that result in an animal’s being caught by fishers. In the terminology of Parrish (1957) this is a combination of “availability” defined as being in the vicinity, “vulnerability” as exposure to the fishing gear when in the vicinity and “selectivity” as propensity to capture when exposed to the gear.

### 4.3 Elements of the model

#### 4.3.1 Growth equations

Growth of an animal follows the von Bertalanffy growth function: its size at age  $a$  is

$$L_a = L_\infty \{1 - e^{-K(a-a_0)}\} \quad (4.3)$$

where the third model parameter  $a_0$  is the theoretical age at size zero; parameters  $L_\infty$  and  $K$  were introduced in the previous section. We define  $L_0$  to be the length at age zero and will use it as a growth parameter in the von Bertalanffy function in place of  $a_0$ : setting  $a = 0$  in (4.3),

$$L_0 = L_\infty (1 - e^{Ka_0})$$

from which

$$a_0 = \log(1 - L_0/L_\infty)/K.$$

Substituting this expression for  $a_0$  into (4.3) provides the von Bertalanffy growth function in terms of the parameters  $(L_0, L_\infty, K)$  as

$$L_a = \gamma^a L_0 + (1 - \gamma^a) L_\infty \quad (4.4)$$

where  $\gamma = e^{-K}$ . As stated in assumptions 1 and 2 above, we assume that  $L_0$  and  $L_\infty$  follow independent normal distributions. For any other age  $v$ , the von Bertalanffy growth function also satisfies the more general equation

$$L_a = \gamma^{a-v} L_v + (1 - \gamma^{a-v}) L_\infty, \quad (4.5)$$

although it must be borne in mind that if  $v > 0$ ,  $L_v$  and  $L_\infty$  are correlated and not independent.

We define the variable

$$X_a = -(1 - \gamma^a) \rho^2 L_0 + \gamma^a \sigma^2 L_\infty \quad (4.6)$$

so that it is uncorrelated with  $L_a$ , as can be seen from taking the covariance with equation (4.4). Because  $L_a$  and  $X_a$  follow a bivariate normal distribution, being uncorrelated also means that they are independent. Solving the  $2 \times 2$  linear system given by equations (4.4) and (4.6) yields  $L_\infty$  in terms of  $L_a$  and  $X_a$ :

$$L_\infty = \{(1 - \gamma^a) \rho^2 L_a + \gamma^a X_a\} / \{(1 - \gamma^a)^2 \rho^2 + \gamma^{2a} \sigma^2\}. \quad (4.7)$$

Replacing  $a$  by  $v$  in (4.7) and substituting the resulting expression for  $L_\infty$  into the right-hand side of (4.5),  $L_a$  can be written in terms of  $L_v$  and  $X_v$ . After some manipulation,

$$L_a = \frac{\{(1 - \gamma^v)(1 - \gamma^a) \rho^2 + \gamma^{a+v} \sigma^2\} L_v + (\gamma^v - \gamma^a) X_v}{(1 - \gamma^v)^2 \rho^2 + \gamma^{2v} \sigma^2} = p_{av} L_v + q_{av} X_v \quad (4.8)$$

where  $p_{av}$  and  $q_{av}$  are defined for convenience to be the coefficients of  $L_v$  and  $X_v$  in the middle expression in (4.8).

The variables  $L_a$  and  $X_a$  are normally distributed and independent. From (4.4), the mean and variance of  $L_a$  are, respectively,

$$\mu_a = \gamma^a \mu + (1 - \gamma^a) \lambda \quad (4.9)$$

and

$$\sigma_a^2 = \gamma^{2a} \sigma^2 + (1 - \gamma^a)^2 \rho^2, \quad (4.10)$$

while from (4.6) those of  $X_a$  are

$$\mu_{X_a} = -(1 - \gamma^a) \rho^2 \mu + \gamma^a \sigma^2 \lambda \quad (4.11)$$

and

$$\sigma_{X_a}^2 = (1 - \gamma^a)^2 \rho^4 \sigma^2 + \gamma^{2a} \sigma^4 \rho^2. \quad (4.12)$$

### 4.3.2 Vulnerability to fishing

The model handles multiple fishing fleets  $f = 1, \dots, f_{\max}$  with separate size-dependent vulnerability functions  $V_f(L)$ . A commonly used vulnerability function is the logistic one (4.2) which we make fleet-specific:

$$V_f(L) = 1 / \left[ 1 + \exp\left\{ -(\log 19) (L - L_{50f}) / (L_{95f} - L_{50f}) \right\} \right]. \quad (4.13)$$

This function has two parameters  $L_{50f}$  and  $L_{95f}$ . In practice we used the parameters  $L_{50f}$  and  $L_{\text{diff}f} = L_{95f} - L_{50f}$ , because the parameter  $L_{\text{diff}f}$  was a more logical one to which to apply bounds, e.g., a lower bound of zero, than  $L_{95f}$ . The original parameter  $L_{95f}$  can be recovered as  $L_{95f} = L_{50f} + L_{\text{diff}f}$ .

We used the logistic vulnerability function for the recreational components of the tailor fishery. For the commercial gillnet components of the tailor fishery, in which some large fish are too large in girth to be caught, we used a two-parameter symmetric double logistic function:

$$V_f(L) = 4 / \left[ \left( 1 + \exp\left\{ -(\log 19) (L - L_{50f}) / L_{\text{diff}f} \right\} \right) \left( 1 + \exp\left\{ (\log 19) (L - L_{50f}) / L_{\text{diff}f} \right\} \right) \right]. \quad (4.14)$$

The parameter  $L_{50f}$  is now the size at 100% vulnerability and  $L_{50f} \pm L_{\text{diff}f}$  are the sizes at 19% vulnerability. This function is “dome-shaped”, approaching zero at both very small and very large sizes.

The combined vulnerability over all fleets in year  $t$  is defined as

$$V_t^*(L) = \sum_{f=1}^{f_{\max}} U_{tf} V_f(L) / \sum_{f=1}^{f_{\max}} U_{tf}, \quad (4.15)$$

where  $U_{tf}$  is the harvest rate of fleet  $f$  in year  $t$ , i.e., the probability that an animal alive and vulnerable to fleet  $f$  at the beginning of the fishing season in year  $t$  will actually be harvested by that fleet in that year. The combined harvest rate over all fleets in year  $t$  is defined as

$$U_t^* = \sum_{f=1}^{f_{\max}} U_{tf}. \quad (4.16)$$

Technically, use of this equation requires that there be some size at which animals are fully vulnerable to all fleets. This occurs at large sizes if all fleets have monotonic increasing vulnerability such as the logistic function (4.13). The requirement may not be met if one fleet exclusively targets large animals and another fleet exclusively targets small animals, but these targeting effects would have to be extreme to cause a major problem. We note that the combined effect of fishing given by multiplying equations (4.15) and (4.16) is simply the numerator of (4.15) which does not depend on the separation into a combined vulnerability function and a combined harvest rate. The separation is needed only in the detail of the model's population dynamics.

We note also that we define the fleet-specific harvest rate  $U_{tf}$  as catch divided by start-of-season exploitable biomass; see equation (4.31) below. With this definition in the case of multiple fleets,  $U_{tf}$  is not directly related to the instantaneous fishing mortality rate  $F_{tf}$  of fleet  $f$ : equation (4.34) below holds only for all fleets combined, not for individual fleets.

### 4.3.3 Vulnerability adjustments for minimum legal size

Fisheries are commonly subject to a minimum legal size (MLS) below which fishers are not allowed to retain captured animals. Discarded animals, although released, may suffer discard mortality which we assume to be instantaneous. We denote the proportion of discarded animals that die through discard mortality by  $D$ .

We allow the minimum legal size to depend on both year and fleet, and denote it  $L_{tf}^{\text{MLS}}$ . We assume that it is not applied as an exact “knife edge” by fishers but that the probability of retention follows a

logistic function as in (4.13) with parameters  $L_{tf}^{\text{MLS}}$  and  $L_{\text{diff}}^{\text{MLS}}$ . We denote the resulting logistic function  $V_{tf}^{\text{MLS}}(L)$ .

The model contains two versions of the MLS-adjusted vulnerability function:  $V_{tf}^{(K)}(L)$  restricts to animals that are kept by fishers and is used for matching reported harvest sizes, while  $V_{tf}^{(D)}(L)$  includes animals that suffer discard mortality and is used for population dynamics:

$$V_{tf}^{(K)}(L) = V_{tf}^{\text{MLS}}(L) V_f(L) \quad (4.17)$$

$$V_{tf}^{(D)}(L) = D V_f(L) + (1-D) V_{tf}^{(K)}(L). \quad (4.18)$$

The combined vulnerability over all fleets is used only for population dynamics so is the ‘‘D’’ version:

$$V_t^*(L) = \frac{\sum_{f=1}^{f_{\max}} U_{tf} V_{tf}^{(D)}(L)}{\sum_{f=1}^{f_{\max}} U_{tf}}. \quad (4.19)$$

#### 4.3.4 Size-weight relationships

We assume an allometric relationship between the size and mass of an individual animal:

$$W(L) = \alpha L^\beta \quad (4.20)$$

where  $W(L)$  is the mass (weight) of an individual of size  $L$  and  $\alpha$  and  $\beta$  are parameters with known values derived from experimental data. We expect growth to be close to isometric, i.e., animals to roughly retain their shape as they grow and the ratios of length to height to width stay approximately the same. Then the value of the parameter  $\beta$  is close to 3.

Conditional on having size  $L$  at age  $v$ , the size  $L_a$  at age  $a$  is given by equation (4.8): it is normally distributed with mean

$$p_{av} L + q_{av} \mu_{Xv}$$

and variance

$$q_{av}^2 \sigma_{Xv}^2$$

where  $\mu_{Xv}$  and  $\sigma_{Xv}^2$  are given by (4.11) and (4.12) respectively. Using this mean and variance and still conditional on having size  $L$  at age  $v$ ,  $L_a$  can be written as

$$L_a = (p_{av} L + q_{av} \mu_{Xv}) + (q_{av} \sigma_{Xv}) z$$

where  $z$  is a standard normal variable with mean zero and variance 1.

Because  $\beta$  is close to 3, the conditional expected mass of an individual at age  $a$  is closely approximated by a second order Taylor series (binomial) expansion:

$$\begin{aligned} E(W(L_a) | L_v = L) &= E\left(\alpha (p_{av} L + q_{av} \mu_{Xv} + q_{av} \sigma_{Xv} z)^\beta\right) \\ &\approx \alpha \left\{ (p_{av} L + q_{av} \mu_{Xv})^\beta + \frac{1}{2} \beta(\beta-1) (p_{av} L + q_{av} \mu_{Xv})^{\beta-2} q_{av}^2 \sigma_{Xv}^2 \right\}. \end{aligned} \quad (4.21)$$

Terms of odd order do not appear because the expectations of odd powers of  $z$  are zero. Subsequent terms with even powers (4 or more) contain a factor of  $\beta - 3$  which helps to make them very small; e.g., the coefficient of the fourth-power term is  $\frac{1}{24} \beta(\beta-1)(\beta-2)(\beta-3)$ .

#### 4.3.5 Expected vulnerable weight at age

At age  $a$ , using a vulnerability function  $V(L)$ , the per-individual mass (weight) that was vulnerable at age  $v$  is

$$w_{av} = \int_{-\infty}^{\infty} E(W(L_a) | L_v = L) \left\{ \phi\left(\frac{(L - \mu_v)/\sigma_v}{\sigma_v}\right) \right\} V(L) dL \quad (4.22)$$

where  $\phi(z)$  is the standard normal probability density:

$$\phi(z) = \exp\left(-\frac{1}{2} z^2\right) / \sqrt{2\pi}. \quad (4.23)$$

We let  $\nu$  vary between the lowest age at which *any* animals become vulnerable to fishing (including discarding of undersized animals), denoted  $\nu_{\min}$ , and the lowest age at which *all* animals are vulnerable to fishing,  $\nu_{\max}$ .

Once it has been multiplied by  $V(L)$ , the distribution of  $L$  in (4.22) is no longer normal and we need some specialised method to evaluate the integral.

#### 4.3.6 Evaluation of the expected-weight integral

Our method to evaluate the integral (4.22) numerically is based on Gaussian quadrature by Hermite polynomials (Abramowitz and Stegun, 1964, p. 890, formula 25.4.46):

$$w_{a,\nu} \approx \sum_{i=1}^I b_i E(W(L_a) | L_\nu = \mu_\nu + \sigma_\nu z_i) V(\mu_\nu + \sigma_\nu z_i) \quad (4.24)$$

where  $z_i$  are quadrature abscissae,  $b_i$  are quadrature weights and  $I$  is the chosen number of quadrature points. For a given value of  $I$ , corresponding values of  $z_i$  and  $b_i$  for Gaussian quadrature can be looked up in tables such as those presented by Abramowitz and Stegun. A larger value of  $I$  produces greater accuracy but consumes more computing time.

The standard method of Gaussian quadrature is, however poorly suited to integrals of the type (4.22) because it is designed primarily for high-degree polynomials, not sigmoidal (S-shaped) functions such as the vulnerability function  $V(L)$  which ranges between 0 and 1.

Instead we chose the abscissae  $z_i$  to be quantiles of the standard normal distribution. We chose the weights  $b_i$  to be as close to constant as possible but make the integral formula

$$\int_{-\infty}^{\infty} f(z) \phi(z) dz \approx \sum_{i=1}^I b_i f(z_i) \quad (4.25)$$

work exactly when  $f(z)$  is a polynomial of degree 3 or less, because the weight-at-size function is close to a polynomial of degree 3. The solution for  $b_i$  and  $z_i$  is described in Appendix 1, with associated R code (R Core Team, 2016).

We found that model calculations were not highly sensitive to the number of quadrature points,  $I$ , provided that  $I \geq 40$ . We used  $I = 60$ . We expect the effect of this choice on the final results of the stock assessment to be negligible. The major effect of limiting  $I$  is to make the size distributions slightly more centralised than they would be ideally, so that more animals are close to average size and fewer have extremely large or small sizes.

Compared to the amount of computation involved in summing over size in a size-structured model, this numerical integration method is able to focus on the sizes  $\mu_\nu + \sigma_\nu z_i$  that are important at the recruitment age  $\nu$ . It avoids unnecessary calculations; for example, those involving large sizes when  $\nu$  is small and small sizes when  $\nu$  is large. Therefore it can produce more accurate results for the same amount of computation. It also separates this computation from the size intervals that are used in size-frequency data, allowing the user to choose the number of quadrature points  $I$  to achieve a desired level of accuracy.

We note that it is possible to evaluate the integral (4.22) analytically in the case that the coefficient  $\beta$  in equation (4.20) is exactly equal to 3 and the vulnerability function, instead of the logistic function (4.13), is instead a cumulative normal distribution function

$$V_f(L) = \Phi\left(\zeta (L - L_{50f}) / (L_{95f} - L_{50f})\right) \quad (4.26)$$

where

$$\Phi(z) = \int_{-\infty}^z \exp\left(-\frac{1}{2}u^2\right) du / \sqrt{2\pi}$$

and  $\zeta$  satisfies  $\Phi(\zeta) = 0.95$  ( $\zeta \approx 1.6449$ ). This function has a similar shape to the logistic, although with shorter tails. We believe that the difference between whether this function or a logistic is fitted is negligible. An analytic solution would require, however, that the vulnerability not be multiplied by a minimum-legal-size selectivity function  $V_{t,f}^{\text{MLS}}(L)$  such as that described in section 4.3.3.



The analytic formula is described in Appendix 2. The major drawback to it is that it involves a very large number of calculations, making it as slow to evaluate as the numerical integral. The numerical integration method is more flexible, allowing a wide choice of vulnerability functions. The restriction that the parameter  $\beta$  take the value 3 is very minor as the size–weight relationship needs to work only for animals that are large enough to be vulnerable to fishing: a suitable value of the parameter  $\alpha$  in (4.20) could make the relationship accurate over this size range. Terms of degree zero, one and two could also be added into the size–weight relationship if desired and would not appreciably increase the complexity.

#### 4.3.7 Biomass and forward projection

The vulnerable mass per individual (4.22) has “K” and combined versions corresponding to equations (4.17) and (4.19) respectively:

$$w_{tfa v}^{(K)} = \int_{-\infty}^{\infty} E(W(L_a) | L_v = L) \left\{ \phi\left(\frac{(L - \mu_v)}{\sigma_v}\right) / \sigma_v \right\} V_{t-a+v, f}^{(K)}(L) dL \quad (4.27)$$

$$w_{t a v}^* = \int_{-\infty}^{\infty} E(W(L_a) | L_v = L) \left\{ \phi\left(\frac{(L - \mu_v)}{\sigma_v}\right) / \sigma_v \right\} V_{t-a+v}^*(L) dL. \quad (4.28)$$

Subscript  $t - a + v$  is the year in which the animals attained age  $v$  and became vulnerable to fishing.

The per-individual mass at age  $a$  that *first became* vulnerable at age  $v$  is found by subtracting the mass that was vulnerable in the previous year at age  $v - 1$ . When  $v = a$  the mass that has just become vulnerable in year  $t$  is fleet-specific. For fleet  $f$  it is equal to  $w_{tfa a}^{(K)} - w_{t, a, a-1}^*$  because any animal that was vulnerable to any fleet in year  $t - 1$  is vulnerable to fleet  $f$  in the current year (see assumption 7 in section 4.2 above). When  $v < a$  the mass that first became vulnerable at age  $v$  does not depend on the fleet and is equal to  $w_{t a v}^* - w_{t, a, v-1}^*$ .

The population matrix  $N_{t a v}$  records the number of animals of age  $a$  in year  $t$  as if they had all first become vulnerable to fishing at age  $v$ : it does not split the population into different ages of first vulnerability. Let  $B_{tfa}^{(K)}$  denote the reportable biomass of age  $a$  that is vulnerable to fleet  $f$  at the start of the fishing season in year  $t$ , i.e., not including animals that are liable to be caught but discarded. The vulnerability is zero for  $a < v_{\min}$  as no animals of those ages have yet become vulnerable to fishing. If  $v_{\min} \leq a \leq v_{\max}$ ,

$$B_{tfa}^{(K)} = N_{t a a} \left( w_{tfa a}^{(K)} - w_{t, a, a-1}^* \right) + \sum_{v=v_{\min}}^{a-1} N_{t a v} \left( w_{t, a, v}^* - w_{t, a, v-1}^* \right) \quad (4.29)$$

while if  $a > v_{\max}$ ,

$$B_{tfa}^{(K)} = \sum_{v=v_{\min}}^{v_{\max}} N_{t a v} \left( w_{t, a, v}^* - w_{t, a, v-1}^* \right). \quad (4.30)$$

When  $v = v_{\min}$  the mass  $w_{t, a, v-1}^*$ , in which the third subscript is less than  $v_{\min}$ , is defined to be zero.

This biomass is used to calculate the harvest rate  $U_{tf}$  from the recorded harvest  $C_{tf}$ :

$$U_{tf} = C_{tf} / \sum_{a=0}^{a_{\max}} B_{tfa}^{(K)} \quad (4.31)$$

where  $a_{\max}$  is the maximum age in the model.

The harvest rates  $U_{tf}$  are used to find the combined vulnerability function  $V_t^*(L)$  by equation (4.19) and the combined harvest rate by (4.16). The biomass equations (4.29) and (4.30) require the combined vulnerability function and harvest rate only for previous years, thereby avoiding circular definitions.

The population numbers are then projected forward to the next year. When  $a < a_{\max}$  and  $v \leq a$ ,

$$N_{t+1, a+1, v} = e^{-M} (1 - U_t^*) N_{t a v}, \quad (4.32)$$

while for  $v > a$  only natural mortality applies:

$$N_{t+1, a+1, v} = e^{-M} N_{t a v}. \quad (4.33)$$

When  $a = a_{\max}$ , no animals are projected forward to age  $a + 1$ , although if age  $a_{\max}$  is a “plus group” comprising animals of age  $a_{\max}$  and above, the equation for it is

$$N_{t+1, a_{\max}, v} = e^{-M} (1 - U_t^*) (N_{t, a_{\max}-1, v} + N_{t a_{\max} v}).$$

#### 4.3.8 Spawning biomass and recruitment

We assume that spawning takes place in the middle of the fishing season, after half of the fishing mortality has been applied. For a harvest rate  $U$ , the equivalent instantaneous fishing mortality rate  $F$  is defined by the equation for the probability of surviving a season’s fishing:

$$\exp(-F) = 1 - U. \quad (4.34)$$

Applying half the fishing mortality then gives the probability of surviving to the middle of the fishing season as

$$\exp\left(-\frac{1}{2}F\right) = \sqrt{1 - U}.$$

The equation for projecting population numbers of vulnerable animals forward to the middle of the fishing season is similar to (4.32). For  $v \leq a$ ,

$$N_{t a v}^{(\text{mid})} = \sqrt{1 - U_t^*} N_{t a v}. \quad (4.35)$$

For  $v > a$  the animals are not vulnerable to fishing and so

$$N_{t a v}^{(\text{mid})} = N_{t a v}. \quad (4.36)$$

Animals not vulnerable to fishing may still contribute to spawning. In addition to the vulnerable masses per individual from (4.28), we define spawning-only masses  $w_{t a}^{(S)}$ . For  $v_{\min} \leq a < v_{\max}$ ,

$$w_{t a}^{(S)} = \int_{-\infty}^{\infty} W(L) \left\{ \phi\left(\frac{(L - \mu_a)}{\sigma_a}\right) / \sigma_a \right\} \{1 - V_t^*(L)\} dL, \quad (4.37)$$

while for  $a < v_{\min}$ ,

$$w_{t a}^{(S)} = \int_{-\infty}^{\infty} W(L) \left\{ \phi\left(\frac{(L - \mu_a)}{\sigma_a}\right) / \sigma_a \right\} dL. \quad (4.38)$$

The total spawning biomass in year  $t$  is then

$$S_t = \sum_{a=0}^{v_{\max}-1} m_a N_{t a a} w_{t a}^{(S)} + \sum_{a=v_{\min}}^{a_{\max}} m_a \sum_{v=v_{\min}}^{\min(a, v_{\max})} N_{t a v}^{(\text{mid})} (w_{t, a, v}^* - w_{t, a, v-1}^*)$$

where  $m_a$  is the proportion of individuals mature at age  $a$  (see assumption 4 in section 4.2 above).

Recruitment of new individuals to the population is assumed to take place almost one year later. We assume a Beverton–Holt (1957) stock recruitment relationship, parameterised as

$$R_{t+1}/R_0 = \frac{r S_t/S_0}{1 + (r-1) S_t/S_0} \exp(d_{t+1}) \quad (4.39)$$

where  $R_t$  is the recruitment at age zero in year  $t$ ,  $R_0$  is the virgin recruitment,  $S_0$  is the virgin spawning stock size,  $r$  is the recruitment compensation ratio (Goodyear, 1977) and  $d_t$  is a random recruitment deviation. Recruitment deviations for different years are assumed to be independent. To enter the recruits into the population matrix, for  $v = v_{\min}, \dots, v_{\max}$ ,

$$N_{t+1, 0, v} = R_{t+1}.$$

## 4.4 Predictions for matching to data

### 4.4.1 Catch rates

Fishery catch rates (see chapter 3) are fleet-specific and assumed to be proportional to abundance.

For abundance we use a mid-season “K” version of total exploitable biomass calculated similarly to equations (4.29) and (4.30):

$$B_{tf}^{(K, \text{mid})} = \sum_{a=v_{\min}}^{v_{\max}} \left\{ N_{taa}^{(\text{mid})} \left( w_{tfaa}^{(K)} - w_{t, a, a-1}^* \right) + \sum_{v=v_{\min}}^{a-1} N_{tav}^{(\text{mid})} \left( w_{t, a, v}^* - w_{t, a, v-1}^* \right) \right\} + \sum_{a=v_{\max}+1}^{a_{\max}} \sum_{v=v_{\min}}^{v_{\max}} N_{tav}^{(\text{mid})} \left( w_{t, a, v}^* - w_{t, a, v-1}^* \right) \quad (4.40)$$

where  $N_{tav}^{(\text{mid})}$  comes from (4.35).

#### 4.4.2 Age frequency

Predicted age frequencies from the fishery are found by a similar method to biomass (section 4.3.7). The proportion of individuals of age  $a$  in year  $t$  that were vulnerable to fishing by fleet  $f$  at age  $v$  is

$$A_{tfa}^{(K)} = \int_{-\infty}^{\infty} \left\{ \phi \left( (L - \mu_v) / \sigma_v \right) / \sigma_v \right\} V_{t-a+v, f}^{(K)}(L) dL. \quad (4.41)$$

The proportion vulnerable to the combination of all fleets, including by discarding, is

$$A_{tav}^* = \int_{-\infty}^{\infty} \left\{ \phi \left( (L - \mu_v) / \sigma_v \right) / \sigma_v \right\} V_{t-a+v}^*(L) dL. \quad (4.42)$$

We evaluated the integrals numerically by the method described in section 4.3.5.

The total number of animals of age  $a$  vulnerable to fleet  $f$  in the middle of the fishing season in year  $t$ , excluding discards, is, if  $v_{\min} \leq a \leq v_{\max}$ ,

$$N_{tfa}^{(\text{AF})} = N_{taa}^{(\text{mid})} \left( A_{tfaa}^{(K)} - A_{t, a, a-1}^* \right) + \sum_{v=v_{\min}}^{a-1} N_{tav}^{(\text{mid})} \left( A_{tav}^* - A_{t, a, v-1}^* \right), \quad (4.43)$$

and if  $a > v_{\max}$ ,

$$N_{tfa}^{(\text{AF})} = \sum_{v=v_{\min}}^{v_{\max}} N_{tav}^{(\text{mid})} \left( A_{tav}^* - A_{t, a, v-1}^* \right). \quad (4.44)$$

These predicted numbers, when scaled to proportions that sum to 1 over  $a$ , can be compared to the observed age frequency of the retained catch by fleet  $f$  in year  $t$ .

#### 4.4.3 Size frequency

This model does not automatically generate size-frequency predictions. Such predictions have to be calculated separately in each year for which size-frequency data are available. Size-frequency data generally take the form of observed numbers of animals in pre-defined size-classes with equi-spaced midpoints  $L_k^{(\text{LF})}$  ( $k = 1, \dots, n^{(\text{LF})}$ ). We denote the spacing by  $\delta^{(\text{LF})} = L_k^{(\text{LF})} - L_{k-1}^{(\text{LF})}$  for any  $k \geq 2$ .

Suppose that an animal has size  $L$  at age  $v$ . In practice,  $L$  will be a quadrature point used in the numerical integration described in section 4.3.5 and will represent some narrow size interval  $(L^-, L^+)$  where  $L^-$  is halfway down to the next lower quadrature point, and  $L^+$  is halfway up to the next higher quadrature point. The size distribution within this interval is obviously truncated below at  $L^-$  and above at  $L^+$  but we approximate it by a normal distribution in order to facilitate growth calculations.

We use a normal distribution with mean  $L$  and standard deviation  $\sigma_Q (L^+ - L^-)$  with parameter value  $\sigma_Q = \frac{1}{2}$  chosen as a compromise so that the probability density isn't too much lower at  $L^+$  and  $L^-$  than at  $L$ , but at the same time, the distribution is fairly well contained within the interval  $(L^-, L^+)$ . The exact method of approximation makes little difference to the end results because the interval  $(L^-, L^+)$  is assumed to be narrow.

When the animal grows to an age  $a \geq v$ , by equations (4.8) and (4.11) the size  $L$  is transformed to

$$\mu_{Gav}(L) = p_{av} L + q_{av} \mu_{Xv}.$$

Growth also puts in additional normally distributed variation with standard deviation  $q_{av} \sigma_{Xv}$  by equations (4.8) and (4.12) so that the overall standard deviation is

$$\sigma_{G_{av}}(L) = \sqrt{\left\{ \sigma_Q(L^+ - L^-) \right\}^2 + (q_{av} \sigma_{X_v})^2}.$$

It appears that the first standard deviation  $\sigma_Q(L^+ - L^-)$  should be multiplied by  $p_{av}$  in this formula, to account for the growth-related expansion of the distance between quadrature points. We plan to make this correction in future assessments. We believe that it would make a negligible difference to the results of this assessment.

This normal distribution is divided into the size-frequency intervals  $k = 1, \dots, n^{(\text{LF})}$  defined above according to the formula

$$h_{avk}(L) = \delta^{(\text{LF})} \phi\left(\left\{L_k^{(\text{LF})} - \mu_{G_{av}}(L)\right\} / \sigma_{G_{av}}(L)\right) / \sigma_{G_{av}}(L). \quad (4.45)$$

where  $h_{avk}(L)$  is the proportion of animals in size interval  $k$  and  $\phi(z)$  is given by (4.23). The sum of  $h_{avk}(L)$  of  $k$  is approximately equal to 1; the size frequency will be scaled later to sum to 1 exactly. This formula approximates the number of animals in a size interval from the probability density at the midpoint of the interval, an approximation known as the ‘‘midpoint rule’’ (see, e.g., Mysovskikh, 2011). We regard this rule as adequate when size intervals are narrow. If size intervals are wide, a rule such as Simpson’s rule (Abramowitz and Stegun, 1964, p. 886, formula 25.4.5) could be used instead.

From the size-frequency split  $h_{avk}(L)$ , the predicted joint age–size frequency can be calculated as in section 4.4.2. Multiplying and integrating (4.45) similarly to (4.41) and (4.42) provides the proportion of individuals of age  $a$  in year  $t$  that belong to size class  $k$  and were vulnerable to fishing by fleet  $f$  at age  $v$ ,

$$H_{tfa vk}^{(K)} = \int_{-\infty}^{\infty} h_{avk}(L) \left\{ \phi\left(\frac{(L - \mu_v)}{\sigma_v}\right) / \sigma_v \right\} V_{t-a+v, f}^{(K)}(L) dL, \quad (4.46)$$

and the proportion vulnerable to the combination of all fleets, including by discarding,

$$H_{tfa vk}^* = \int_{-\infty}^{\infty} h_{avk}(L) \left\{ \phi\left(\frac{(L - \mu_v)}{\sigma_v}\right) / \sigma_v \right\} V_{t-a+v}^*(L) dL. \quad (4.47)$$

Then the total number of animals of age  $a$  and size class  $k$  vulnerable to fleet  $f$  in the middle of the fishing season in year  $t$ , excluding discards, is, if  $v_{\min} \leq a \leq v_{\max}$ ,

$$N_{tfa k}^{(\text{LAF})} = N_{taa}^{(\text{mid})} \left( H_{tfa ak}^{(K)} - H_{t, a, a-1, k}^* \right) + \sum_{v=v_{\min}}^{a-1} N_{tavk}^{(\text{mid})} \left( H_{tavk}^* - H_{t, a, v-1, k}^* \right), \quad (4.48)$$

and if  $a > v_{\max}$ ,

$$N_{tfa k}^{(\text{LAF})} = \sum_{v=v_{\min}}^{v_{\max}} N_{tavk}^{(\text{mid})} \left( H_{tavk}^* - H_{t, a, v-1, k}^* \right). \quad (4.49)$$

For prediction of size frequencies that contain no information on age, these numbers can be summed over age to produce size-frequency estimates

$$N_{tfk}^{(\text{LF})} = \sum_{a=0}^{a_{\max}} N_{tfa k}^{(\text{LAF})}. \quad (4.50)$$

Finally, these predictions can be scaled to proportions that sum to 1 over  $k$ , and then compared to the observed size frequency of the retained catch by fleet  $f$  in year  $t$ .

#### 4.4.4 Age at size

Age information may be available for some of the animals whose sizes were measured. In the Fisheries Queensland Fishery Monitoring data, the majority of fish aged were considered representative of the overall fishery catch and hence were included in the size frequency, while others were not considered representative (e.g., large ‘‘trophy’’ fish retained by recreational fishers), and were excluded from the size frequency. For the population model it does not matter whether the animals aged are included or excluded from the size frequency, as age is analysed conditional on size.

This information commonly produces age–length keys from which overall age-frequencies can be estimated (Friðriksson, 1934). Here, however, we use the raw age-at-size data which have not been scaled up by any age–length key. We regard our approach as preferable to scaling up by an age–length key because it preserves the numbers of animals that were actually aged. Scaling up results in age frequencies with the same numbers of measured individuals as length-frequencies and implies spuriously high precision in the age frequencies.

We assume that there is no *age* bias in the selection of animals to age. We allow arbitrary *size* biases in the selection.

Age-at-size predictions are accomplished by simply scaling the age–size frequency given by (4.48) and (4.49) so that the sum over age within a size class is equal to the actual number of fish aged in that size class in the ageing data. A separate age frequency is produced for each size class. To avoid very small sample sizes, we combined these age frequencies into coarser size classes as described in section 4.5.3 below.

## 4.5 Matching predictions to data

### 4.5.1 Catch rates

Elements  $Y_{st}$  of a catch-rate time series  $s$  are assumed to follow independent lognormal distributions. Let  $f$  be the fishing fleet from which the series was taken. Let  $\mu_s^{(CR)}$  and  $\sigma_{st}^{(CR)}$  respectively be the mean and standard deviation of  $\log Y_{st} - \log B_{tf}^{(K, mid)}$ , where  $B_{tf}^{(K, mid)}$  is given by (4.40). If  $\mu_s^{(CR)}$  and  $\sigma_{st}^{(CR)}$  are specified, the likelihood of series  $s$  is

$$\prod_t \left[ \exp \left\{ -\frac{1}{2} \left( \log Y_{st} - \log B_{tf}^{(K, mid)} - \mu_s^{(CR)} \right)^2 / \sigma_{st}^{(CR)2} \right\} / \left( \sqrt{2\pi} \sigma_{st}^{(CR)} \right) \right].$$

The negative log-likelihood (NLL), omitting the constant factors of  $\sqrt{2\pi}$  from above, is

$$\ell_{Y_s} = \sum_t \left\{ \log \sigma_{st}^{(CR)} + \frac{1}{2} \left( \log Y_{st} - \log B_{tf}^{(K, mid)} - \mu_s^{(CR)} \right)^2 / \sigma_{st}^{(CR)2} \right\}. \quad (4.51)$$

We set the standard deviation  $\sigma_{st}^{(CR)}$  to the product of a scale factor  $\sigma_{s*}^{(CR)} \geq 1$  with the standard error of the log-catch-rate parameter from the generalised linear model (GLM) used for catch-rate analysis (see chapter 3). Because it is on the log scale, this standard error becomes a coefficient of variation and we denote it  $CVY_{st}$ . The scale factor  $\sigma_{s*}^{(CR)}$  accounts for experimental error in the model, additional to experimental error due to finite sample sizes in the GLM which is already captured in  $CVY_{st}$ . Such additional experimental error may come from changes in environmental conditions or fish behaviour from year to year. The NLL, omitting constant terms, is

$$\ell_{Y_s} = \sum_t \left\{ \log \sigma_{s*}^{(CR)} - \frac{1}{2} \log w_{st} + \frac{1}{2} w_{st} \left( \log Y_{st} - \log B_{tf}^{(K, mid)} - \mu_s^{(CR)} \right)^2 / \sigma_{s*}^{(CR)2} \right\}, \quad (4.52)$$

where  $w_{st} = 1/CVY_{st}^2$ .

Standard estimators of  $\mu_s^{(CR)}$  and  $\sigma_{s*}^{(CR)2}$  in Subregion  $s$  are:

$$\hat{\mu}_s^{(CR)} = \sum_t w_{st} \left( \log Y_{st} - \log B_{tf}^{(K, mid)} \right) / \sum_t w_{st}$$

and

$$\hat{\sigma}_{s*}^{(CR)2} = \sum_t \left\{ w_{st} \left( \log Y_{st} - \log B_{tf}^{(K, mid)} - \hat{\mu}_s^{(CR)} \right)^2 \right\} / (n_{Y_s} - 1), \quad (4.53)$$

where  $n_{Y_s}$  is the number of years of catch-rate data in series  $s$ . Substituting these expressions into (4.52) provides a likelihood that depends only on data ( $Y_{st}$  and  $w_{st}$ ) and model predictions ( $B_{tf}^{(K, mid)}$ ):

$$\ell_Y = \sum_s (n_{Y_s} - 1) \left( \log \tilde{\sigma}_{s^*}^{(CR)} + \frac{1}{2} \frac{\hat{\sigma}_{s^*}^{(CR)2}}{\tilde{\sigma}_{s^*}^{(CR)2}} \right), \quad (4.54)$$

where  $\tilde{\sigma}_{s^*}^{(CR)}$  is the estimate of  $\sigma_{s^*}^{(CR)}$  taking account of its lower bound  $\sigma_{\min}^{(CR)} = 1$ :

$$\tilde{\sigma}_{s^*}^{(CR)} = \max(\hat{\sigma}_{s^*}^{(CR)}, \sigma_{\min}^{(CR)}). \quad (4.55)$$

The factor applied to  $\log \tilde{\sigma}_{s^*}^{(CR)}$  in (4.54) is  $n_{Y_s} - 1$  instead of  $n_{Y_s}$  as a correction for the need to estimate  $\mu_s^{(CR)}$  by  $\hat{\mu}_s^{(CR)}$ . Formula (4.54) is similar to the negative log-likelihood derived by Haddon (2001, p. 89) but includes the adjustment term for the lower bound on  $\sigma_{s^*}^{(CR)}$ .

The “max” function is not suitable for the software ADMB (Fournier et al., 2011) in which the model was written, or indeed for any optimisation method that takes full advantage of derivatives, because its derivative is discontinuous. In fact, it is better not to calculate  $\hat{\sigma}_{s^*}^{(CR)}$  either, but to use its square directly from (4.53), because  $\hat{\sigma}_{s^*}^{(CR)}$  involves a square root which causes trouble if its argument is zero. Therefore we used the following expression for  $\tilde{\sigma}_{s^*}^{(CR)}$ :

$$\tilde{\sigma}_{s^*}^{(CR)} = \sqrt{\frac{1}{2} \left( \hat{\sigma}_{s^*}^{(CR)2} + \sigma_{\min}^{(CR)2} \right) + \sqrt{\frac{1}{4} \left( \hat{\sigma}_{s^*}^{(CR)2} - \sigma_{\min}^{(CR)2} \right)^2 + 4\delta^2 \sigma_{\min}^{(CR)4}}}, \quad (4.56)$$

where  $\delta > 0$  is a smoothness parameter that took the value 0.1. The value  $\delta = 0$  makes (4.56) the same as (4.55), which is the formula that has to be avoided. The smoothing has the side effect of shifting the value of  $\tilde{\sigma}_{s^*}^{(CR)2}$  at  $\sigma_{\min}^{(CR)}$  up to approximately  $(1 + \delta) \sigma_{\min}^{(CR)2}$  instead of the desired value of  $\sigma_{\min}^{(CR)2}$ .

The value  $\delta = 0.1$  shifts  $\tilde{\sigma}_{s^*}^{(CR)2}$  up about 10% and  $\tilde{\sigma}_{s^*}^{(CR)}$  up about 5%, which we believed was a reasonable compromise.

The overall negative log-likelihood for catch rates is the sum of (4.54) over  $s$ , i.e., over all the catch rate series that are available.

#### 4.5.2 Size frequency, age frequency and age at size

Here we describe the likelihood for matching predicted to observed size frequency. Age frequency and age at size were dealt with in identical manner, although age-at-size data were combined into coarser size classes (see section 4.5.3 below).

A size frequency from fleet  $f$  in year  $t$  consists of a number of animals  $y_{tfk}$  measured in each size class  $k$  (see section 4.4.3). When each animal is considered to be independent of all other animals, the likelihood of a size frequency is multinomial:

$$\binom{y_{tf \text{ tot}}}{y_{tf1}, \dots, y_{tf n^{(LF)}}} \prod_{k=1}^{n^{(LF)}} p_{tfk}^{y_{tfk}}, \quad (4.57)$$

where  $y_{tf \text{ tot}}$  is the total number of animals measured in sample  $(t, f)$  (sum of the  $y_{tfk}$  over  $k$ ),  $p_{tfk}$  is the model's predicted proportion from size class  $a$ , and the multinomial coefficient is defined as

$$\binom{y_{tf \text{ tot}}}{y_{tf1}, \dots, y_{tf n^{(LF)}}} = \frac{y_{tf \text{ tot}}!}{\prod_{k=1}^{n^{(LF)}} y_{tfk}!}.$$

In practice, animals sampled from fishery populations are not independent, and instead of the total number  $y_{tf \text{ tot}}$ , the sample has an “effective sample size” which is usually much less (Pennington and Vølstad, 1994; McAllister and Ianelli, 1997; Francis, 2011).

We deal with the problem of effective sample size by adjusting the multinomial likelihood. The approach estimates the effective sample size from the “raggedness” of the size-frequency distribution: a smooth distribution gives a large effective sample size, and a very ragged one gives a small effective sample size. The estimation does not use the actual sample size  $y_{tf \text{ tot}}$ .

We accept the point made by Francis (2011) that this approach can overestimate the effective sample size if the sample distribution is smooth but randomly biased towards either big animals or small animals in particular years, e.g. if the fishing grounds are, by chance, frequented by schools of larger animals in one year but schools of smaller animals in another year. The method proposed by Francis (2011) is extremely complex and we have found it impractical (O'Neill et al., 2014). We regard this as an unsolved problem and have used what we believe is the best practical methodology.

Firstly, we note that zero values of  $y_{t f \text{ tot}}$  in (4.57) make no contribution to the likelihood. Hence we restrict the likelihood to size classes  $a$  for which  $y_{t f k} > 0$ . We let  $q_{t f}$  denote the number of such size classes and  $Q_{t f}$  denote the set of these size classes. Then the likelihood (4.57) becomes

$$\left\{ y_{t f \text{ tot}}! / \prod_{k \in Q_{t f}} y_{t f k}! \right\} \prod_{k \in Q_{t f}} p_{t f k}^{y_{t f k}}. \quad (4.58)$$

We introduce the effective sample size, denoted  $T_{t f}$ , so that an observation of  $y_{t f k}$  animals of size  $k$  in the sample of size  $y_{t f \text{ tot}}$  is transformed to an effective observation of  $\left( T_{t f} / y_{t f \text{ tot}} \right) y_{t f a}$  animals from a sample of size  $T_{t f}$ . We also treat the likelihood (4.58) as a probability density function (p.d.f.) of the  $y_{t f k}$  in  $q-1$  dimensions; the number of dimensions is  $q-1$  rather than  $q$  because the  $y_{t f k}$  are not independent but are constrained to sum to  $y_{t f \text{ tot}}$ . The transformed likelihood has to remain a p.d.f. of  $y_{t f k}$ , not of  $\left( T_{t f} / y_{t f \text{ tot}} \right) y_{t f k}$ , which necessitates multiplying by the factor  $\left( T_{t f} / y_{t f \text{ tot}} \right)^{q-1}$ . Therefore the likelihood (4.58) is transformed to

$$\left( T_{t f} / y_{t f \text{ tot}} \right)^{q-1} \left\{ T_{t f}! / \prod_{k \in Q_{t f}} \left( T_{t f} y_{t f k} / y_{t f \text{ tot}} \right)! \right\} \prod_{k \in Q_{t f}} p_{t f k}^{T_{t f} y_{t f k} / y_{t f \text{ tot}}}. \quad (4.59)$$

When  $T_{t f} y_{t f a} / y_{t f \text{ tot}}$  is not an integer, the factorial function can be replaced by the gamma function, a mathematical special function which is defined for non-integer values and reproduces the factorial function at integer values.

We approximate the factorial function by the well-known Stirling's formula (Encyclopedia of Mathematics, 2015):

$$x! \sim \sqrt{2\pi x} x^x e^{-x}.$$

This approximation becomes extremely close as  $x \rightarrow \infty$ , but for practical purposes is also close for small  $x$ , e.g.,  $x \geq 1$ . For notational convenience, we will simply write  $T$  for  $T_{t f}$  and omit the subscripts  $t$  and  $f$ . Omitting constant factors and factors involving only the data  $y_{t f a}$ , the likelihood (4.59) becomes

$$T^{q-1} \left\{ T^{T+\frac{1}{2}} e^{-T} / \left[ T^{q_{t f}/2} \prod_{k \in Q_{t f}} \left\{ \left( T y_{t f k} / y_{t f \text{ tot}} \right)^{T y_{t f k} / y_{t f \text{ tot}}} e^{-T y_{t f k} / y_{t f \text{ tot}}} \right\} \right] \right\} \prod_{k \in Q_{t f}} p_{t f k}^{T y_{t f k} / y_{t f \text{ tot}}},$$

which, with some algebraic manipulation, can be simplified to

$$T^{(q-1)/2} \prod_{k \in Q_{t f}} \left( p_{t f k} / \hat{p}_{t f k} \right)^{T \hat{p}_{t f k}},$$

where  $\hat{p}_{t f k} = y_{t f k} / y_{t f \text{ tot}}$  is the observed proportion of animals in size class  $k$  in the sample. This produces the negative log-likelihood

$$\ell_{t f}^{(\text{LF})} = -\frac{1}{2}(q_{t f} - 1) \log T + T \sum_{k \in Q_{t f}} \hat{p}_{t f k} \log(\hat{p}_{t f k} / p_{t f k}). \quad (4.60)$$

The ratio  $p_{t f k} / \hat{p}_{t f k}$  has been replaced by its inverse  $\hat{p}_{t f k} / p_{t f k}$  to reverse the sign of the log factor.

The effective sample size  $T$  is estimated by maximum likelihood, by minimising the negative log-likelihood (4.60):

$$\hat{T} = \frac{1}{2}(q_{t f} - 1) / \sum_{k \in Q_{t f}} \hat{p}_{t f k} \log(\hat{p}_{t f k} / p_{t f k}). \quad (4.61)$$

In the theory of generalised linear models (see McCullagh and Nelder, 1989, 197), this is also the estimate produced by equating the deviance of the multinomial model,  $2T \sum \hat{p}_{t_{fk}} \log(\hat{p}_{t_{fk}}/p_{t_{fk}})$  to its asymptotic, large-sample expectation  $q_{t_{f}} - 1$ . Substituting the estimate (4.61) into the negative log-likelihood (4.60) and ignoring the resulting constant term yields the final negative log-likelihood for the size-frequency sample:

$$\ell_{t_{f}}^{(\text{LF})} = -\frac{1}{2}(q_{t_{f}} - 1) \log \hat{T}_{t_{f}}. \quad (4.62)$$

For every available age-frequency sample, the negative log-likelihood given by (4.62) and (4.61) is added into the overall negative log-likelihood for the model. Using this formulation it would be easy to impose a lower and upper bounds  $T_{\min}$  and  $T_{\max}$  on the effective sample size  $T_{t_{f}}$ . The negative log-likelihood for such a case is

$$-\frac{1}{2}(q_{t_{f}} - 1) \log \tilde{T}_{t_{f}} + \frac{1}{2}(q_{t_{f}} - 1) \tilde{T}_{t_{f}} / \hat{T}_{t_{f}}, \quad (4.63)$$

where  $\tilde{T}_{t_{f}} = \min(\max(\hat{T}_{t_{f}}, T_{\min}), T_{\max})$ . For size-frequencies of tailor we imposed upper bounds equal to the actual sample sizes, with a maximum of 1000. We did not consider it necessary to apply any lower bounds.

#### 4.5.3 Combining age-at-size into coarser size intervals

For age at size we combined some of the size classes in order to prevent the numbers of aged animals in a sample from being too small. We first worked with the original (fine) size classes to generate predicted numbers at age in each size class, as has been described in section 4.4.4. Both the predicted and observed numbers at age within each size class were then summed within coarse size classes to produce age-at-size distributions for the coarse size classes.

In this way the distributions for coarse size classes took into account the exact numbers of animals actually aged in each fine size class: they did not assume random sampling with a coarse size class.

For tailor the sizes were originally measured in 1 cm intervals of fork length. For the coarse size classes we used 5 cm resolution with the first class covering all fish up to 30 cm fork length, the next four going up to 35, 40, 45 and 50 cm, and the final one covering all fish longer than 50 cm.

Again we imposed upper bounds equal to the actual sample sizes. For the age-at-size data we also found it necessary to apply lower bounds equal to half the actual sample sizes. Without the lower bounds, the fits to proportions at age for the older age classes were consistently very poor.

#### 4.5.4 Recruitment deviations

The log-recruitment deviations  $d_t$  (see equation (4.39) above) were assumed to follow a normal distribution with mean zero and standard deviation  $\sigma^{(\text{RD})}$ , although they were constrained to sum to zero. They were treated similarly to the relative abundance indices in section 4.5.1 and produced a single term to add into the overall negative log-likelihood.

When applied to recruitment deviations the negative log-likelihood (4.51) becomes

$$\ell^{(\text{RD})} = \sum_t \left\{ \log \sigma^{(\text{RD})} + \frac{1}{2} d_t^2 / \sigma^{(\text{RD})^2} \right\}. \quad (4.64)$$

The standard estimator  $\sigma^{(\text{RD})^2}$  is:

$$\hat{\sigma}^{(\text{RD})^2} = \sum_t d_t^2 / (n^{(\text{RD})} - 1),$$

where  $n^{(\text{RD})}$  is the number of years for which recruitment deviations are included. We subtract 1 in the denominator because of the constraint that the  $d_t$  have to sum to zero. Substituting into (4.64) provides a data-only version and analogue to (4.54):

$$\ell^{(\text{RD})} = (n^{(\text{RD})} - 1) \left\{ \log \tilde{\sigma}^{(\text{RD})} + \frac{1}{2} \hat{\sigma}^{(\text{RD})^2} / \tilde{\sigma}^{(\text{RD})^2} \right\}, \quad (4.65)$$



where  $\tilde{\sigma}^{(RD)}$  is the estimate of  $\sigma^{(RD)}$  taking account of bounds  $\sigma_{\min}^{(RD)}$  and  $\sigma_{\max}^{(RD)}$  that may be applied to it:

$$\tilde{\sigma}^{(RD)} = \min(\max(\hat{\sigma}^{(RD)}, \sigma_{\min}^{(RD)}), \sigma_{\max}^{(RD)}). \quad (4.66)$$

Analogous to (4.56), a derivative-friendly formula for  $\tilde{\sigma}^{(RD)}$  is

$$2\tilde{\sigma}^{(RD)2} = \sigma_{\min}^{(RD)2} + \sigma_{\max}^{(RD)2} + \sqrt{\left(\hat{\sigma}^{(RD)2} - \sigma_{\min}^{(RD)2}\right)^2 + 4\delta^2\sigma_{\min}^{(RD)4}} - \sqrt{\left(\sigma_{\max}^{(RD)2} - \hat{\sigma}^{(RD)2}\right)^2 + 4\delta^2\sigma_{\min}^{(RD)4}}. \quad (4.67)$$

For tailor we used bounds of  $\sigma_{\min}^{(RD)} = 0.1$  and  $\sigma_{\max}^{(RD)} = 0.25$ .

## 4.6 Data structures

To code the model we defined data structures to reduce rework in the calculations but still use manageable amounts of storage. The following structures highlight the differences of the new model from existing models and may also aid in understanding of the new model:

- Quadrature lengths  $L_v$ ; indexed by  $(v, i)$ , i.e., age at first vulnerability to fishing and quadrature-point index; see equation (4.24).
- Masses of individual animals  $E(W(L_a) | L_v = L)$ ; indexed by  $(a, v, i)$ , i.e., current age, age at first vulnerability and quadrature-point index; see equation (4.21).
- Size-transition matrix  $h_{avk}(L)$  for growth from age  $v$  to age  $a$ , used only to generate size frequencies in years in which they are needed in order to match size-frequency data; indexed by  $(a, v, i, k)$ , i.e., current age, age at first vulnerability, quadrature-point index and size-frequency interval; see equation (4.45).
- Vulnerability function  $V_f(L)$  prior to adjustment for minimum legal size (MLS); indexed by  $(\text{Selex}, v, i)$ , i.e., index of vulnerability function (any vulnerability function applicable to any fishing fleet), age at first recruitment and quadrature-point index; see, e.g., equation (4.13) or (4.14).
- Minimum-legal-size vulnerability functions  $V_{tf}^{\text{MLS}}(L)$ ; indexed by  $(\text{MLS}, v, i)$ , i.e., MLS (any MLS applicable to any fishing fleet in any year that the fishery operated), age at first vulnerability to fishing, and quadrature-point index; see section 0.
- “K” vulnerability function  $V_{tf}^{(K)}(L)$  for retained (kept) animals, adjusted for MLS; indexed by  $(\text{Selex}, \text{MLS}, v, i)$ , i.e., index of vulnerability function, MLS, age at first recruitment and quadrature-point index; see equation (4.17).
- “D” vulnerability function  $V_{tf}^{(D)}(L)$  for discarded animals which may be subject to discard mortality, adjusted for MLS; indexed by  $(\text{Selex}, \text{MLS}, v, i)$  as for the “K” version; see equation (4.18).
- Combined vulnerability function  $V_i^*(L)$  over all fleets; indexed by  $(t, v, i)$ , i.e., year, age at first vulnerability and quadrature-point index; see equation (4.19). This depends on year because it depends on the ratios of harvest rates of the fishing fleets, which are year-specific; also the MLS for each fleet is allowed to depend on year.
- Population matrix  $N_{tav}$  at start of fishing season; indexed by  $(t, a, v)$ , i.e., year, current age and age at first vulnerability; see, e.g., equation (4.29).

## 4.7 List of model parameters

Parameters used in the model are listed in Table 4.1. We attempt to estimate as many of the parameters as possible and not fix them outside the model. Parameters have to be fixed when there are no data or very little data from which they can be estimated, such as the parameters of the minimum-legal-size vulnerability function.

For tailor we attempted to estimate the recruitment compensation ratio  $r$  but it tended to go to either 1 or infinity, neither of which is a sensible value. We had to fix  $r$  to values that produced sensible results, neither an extremely large population on which fishing had a negligible effect, nor a population that was being “mined” over the history of the fishery and was unable to replenish itself. The parameters  $\mu$  and  $\lambda$  also tended to go very low and we fixed them to the minimum values that we considered sensible.

*Table 4.1: Parameters used in the model. The final column states whether the parameter is estimated in the model or fixed outside the model: “Attempted” means that the model attempted to estimate the parameter but it either hit the lower or upper bound or produced nonsensical answers; then the parameter’s value was fixed.*

Symbol	Description	Estimated?
$\alpha, \beta$	Parameters in size–weight relationship; see equations (4.20) and (1.1).	No
$m_a$	Maturity at age (proportion of female fish mature); see section 4.2.	No
$\mu$	Mean of size at age zero, $L_0$ ; see section 4.2.	Attempted
$\sigma$	Standard deviation of size at age zero, $L_0$ ; see section 4.2.	Yes
$\lambda$	Mean asymptotic size, $L_\infty$ ; see section 4.2; actually parameterised as the mean size at the highest age in the model, for ease of guessing initial values.	Attempted
$\rho$	Standard deviation of asymptotic size, $L_\infty$ ; see section 4.2.	Yes
$K$	Growth rate parameter in von Bertalanffy growth function; see eq. (4.3).	Yes
$R_0$	Virgin recruitment; see equation (4.39); actually parameterised as $\log(R_0)$ .	Yes
$r$	Recruitment compensation ratio; see equation (4.39); actually parameterised as $\log(r - 1)$ to give it a distribution closer to normal.	Attempted
$d_t$	Log-recruitment deviations; see equation (4.39).	Yes
$M$	Instantaneous natural mortality rate	Yes
$L_{50}^{(\text{line \& seine})}$	Length at 50% vulnerability to line and beach-seine fishing; see eq. (4.13).	Yes
$L_{\text{diff}}^{(\text{line \& seine})}$	Difference between lengths at 95% and 50% vulnerability; see section 4.3.2.	Yes
$L_{50}^{(\text{gillnet})}$	Length at 50% vulnerability to gillnet fishing; see equation (4.14).	Yes
$L_{\text{diff}}^{(\text{gillnet})}$	Difference between lengths at 95% and 50% vulnerability; see section 4.3.2.	Yes
$L_{50}^{(\text{MLS})}$	Lengths at 50% discarding from minimum legal size (MLS); see sec. 4.3.3.	No
$L_{\text{diff}}^{(\text{MLS})}$	Difference between lengths at 95% and 50% MLS discarding; see sec. 4.3.3.	No

## 4.8 Potential future development

The following suggestions are for potential developments of this model which may be useful to future stock assessments of both tailor and other species:

- Capability for some fleets (e.g., the recreational sector) to be driven by fishing effort instead of catch; then the instantaneous fishing mortality rate  $F$  (see equation (4.34)) is equal to the fishing effort multiplied by a catchability parameter, which becomes another parameter estimated by the model. The annual harvests, instead of being intrinsic to the model’s forward projection of population numbers (see equation (4.31)), become extra data to which the model’s catch predictions have to be matched. A lognormal distribution could be used for the harvest, as in section 4.5.1. Designing this capability is difficult because equation (4.34) applies only to all fleets combined and not to individual fleets: the harvest rate of an individual fleet rate  $f$  with instantaneous fishing mortality rate  $F_f$  is less than  $1 - \exp(-F_f)$  because the other fleets are competing with it.
- Use of gamma distributions for lengths instead of normal distributions, in order to keep the quadrature lengths  $L_v$  in equation (4.24) positive. With normal distributions, any negative quadrature lengths have to be set to zero or some value close to zero, which is not derivative-friendly for optimisation software such as ADMB.

- Consider whether quadrature lengths could be clustered around the  $L_{50}$  point in the vulnerability function, which is where numerical integration is most sensitive. This may produce more accurate numerical integration, but may also greatly complicate the data structures because the quadrature lengths  $L_v$  in the numerical integration formula (4.24) would depend on the vulnerability function. It appears to be of doubtful benefit.

## 5. Application and results of the population model

### 5.1 Model settings

Settings used to run the model are listed in Table 5.1.

Table 5.1: Settings used for the model for the tailor fishery.

Description	Settings used
Size–weight relationship	See equation (1.1).
Age range	Ages 0+ (age group 1) to 6+ (age group 7). The final age group was a “plus group” containing all fish of that age and above. Only three fish of that age were observed in the Fisheries Queensland monitoring data. Young of the year (age group 0) are omitted from the model and are assumed not to be caught in the fishery.
Age at maturity	None mature at age 0+ (age group 0, 1), all mature at age 1+ (age group 2)
Mean length at age zero	Parameter $\mu$ was set to a fork length of 10 cm (total length 11.3 cm) which was the minimum that we considered biologically reasonable. When the model estimated it, it went unreasonably low.
Mean length at final age	Mean length at age 6+ (age group 7) was set to a fork length of 55 cm (total length 61.4 cm) which was the minimum that we considered biologically reasonable. When the model estimated it, it went unreasonably low: the data contained a substantial number of old fish with relatively small lengths which unduly affected the estimated growth curve. The model parameter $\lambda$ (mean $L_\infty$ ) was derived from the mean length at the final age, using the other von Bertalanffy parameters $\mu$ and $K$ .
Recruitment compensation ratio	When the recruitment compensation ratio $r$ (see section 4.7) was estimated, the results obtained were considered highly improbable, corresponding to either extremely large or extremely small population sizes. Therefore $r$ was fixed to three values: 5, 6 and 6.5.
Recruitment deviations	Years 1953 to 2014, i.e., cohorts of age 1+ (age group 2) in any year in which catch-rate data were present. At age 0+ (age group 1) there were insufficient numbers of fish caught in the fishery to provide any information about their year-class strength.
Natural mortality	Instantaneous natural mortality rate $M$ was constrained to lie between a $0.95 \text{ yr}^{-1}$ and $2.5 \text{ yr}^{-1}$ , with uniform prior distribution within this interval. Values below $0.95 \text{ yr}^{-1}$ resulted in extremely low population levels (less than 1% of virgin stock size) in the early 2000s, at which ADMB’s Markov chain Monte Carlo (MCMC) algorithm became “stuck” and unable to produce random samples of values for the parameters. We did not believe that these results were sensible, so used the bound of $0.95 \text{ yr}^{-1}$ .
High harvest rate penalty	Large penalty if combined harvest rate went over 80% in any year
Age at first vulnerability	Some fish became vulnerable to fishing at ages 0+ (age group 1) and 1+ (age group 2); all were vulnerable by age 2+ (age group 3).
Fishing fleets	Four fleets: 1 Qld recreational, 2 NSW recreational, 3 Qld commercial, 4 NSW commercial; commercial harvests were combined over all fishing methods but only gillnet data were used for commercial catch rates and length frequency.
Vulnerability functions	Two vulnerability functions: logistic for line and beach-seine fishing (eq. (4.13)) and double logistic for gillnet fishing (eq. (4.14)). For harvest calculations, all commercial sectors were assumed to follow the gillnet vulnerability because of the difficulty of separating these sectors

Description	Settings used
Minimum legal size	accurately. For size-frequency data, commercial line and beach seine were assumed to follow the line-fishing vulnerability. Minimum legal sizes (MLSs) varied with both time and jurisdiction; see Table 1.1, page 4. The model took account of all variations in MLS.
Discard mortality	Instantaneous discard mortality was assumed to be 0.3, i.e., 30% of released fish died as a result of being caught.

## 5.2 Seasonal variation in age and length distributions

Data on age and length distributions of tailor from the Fisheries Queensland monitoring program (1999–2015) showed a high degree of seasonal variation. Older fish, and larger fish within the same age class, tend to come into the recreational line and commercial beach-seine sectors through the course of the calendar year. Many old and large fish are present by late September but are not present in large numbers prior to that. The estuarine (gillnet and tunnel-net) fishery tends to act as a “feeder” to the ocean-beach fishery, with larger fish from the estuaries appearing to migrate into the ocean-beach zone through the calendar year.

The pattern of variation in age and length structures was complex and we did not regard it as practical to attempt to apply different vulnerability functions to different times of year. Therefore, we stuck to just the two vulnerability functions, each covering the whole year: a logistic one for the line and beach-seine sectors, and a double-logistic (dome-shaped) one for the gillnet sector.

We note that the years 1999–2001 included only two monitoring trips to Fraser Island each year, in mid-August and the end of August. A third trip to Fraser Island was added at the end of September from 2002 onwards, to cover the opening of the extended seasonal closure (see Table 1.1). This trip tended to sample bigger fish because of the time of year.

Sampling prior to 1999 was more opportunistic and less inclined to follow a scientific sampling protocol. It was still valuable and the data were used in the analysis. Samples from 1978 and 1980 contained large fish in the month of August, with no indication that large fish were targeted (see section 1.5.1). These data were also used in the analysis. It appears that the period over which large fish are present at Fraser Island has become compressed over the years, to the final part of the season. This may possibly stem from reduced numbers of large fish due to heavy fishing in 1980s and 1990s.

## 5.3 Coding and operation of the software

The model was coded in parallel in two different software packages: ADMB (Fournier et al., 2011) and R (R Core Team, 2016). The ADMB version was intended to find maximum likelihood estimates and then perform Markov chain Monte Carlo (MCMC) to provide random samples of possible parameter values. The R version was written both as a check on the ADMB version to ensure that both gave the same results for particular values of the parameters, and as a way to summarise and plot the results from the ADMB version.

A separate R script was written to collate all the input data and generate inputs to both the ADMB and R versions of the model.

The optimisation algorithm of the ADMB software worked imperfectly, often coming close but not finding the maximum likelihood solution. Therefore we relied on results from ADMB’s Markov chain Monte Carlo (MCMC). The problems with the optimisation algorithm may have been related to negative quadrature lengths which had to be truncated to zero (see section 4.8). We checked ADMB’s analytic derivatives against derivatives by differences and found that they agreed when the differences in parameter values were very small, but disagreed by a large factor when the differences in parameter values were moderate. A factor of similar magnitude was also reported by ADMB in its convergence criterion. This may indicate an undocumented feature of ADMB in that it magnifies the analytic derivatives when they appear to be too small. We could not find any way to turn it off.

The mixing of the MCMC simulations appeared to be satisfactory when the MCMC did not become “stuck” at low values of the instantaneous natural mortality rate  $M$  (see Table 5.1 above). This provided confidence that the simulations were accurately sampling the parameter space despite the problems with the optimisation.

We ran 420,000 MCMC simulations for each value of the recruitment compensation ratio  $r$  (5, 6 and 6.5) and saved every 30th simulation for a total of 14,000 saved simulations. We then excluded some early simulations until the value of the negative log-likelihood stabilised, and we excluded simulations through which the MCMC moved extremely slowly (i.e., got stuck).

The results presented below are from the MCMC output of ADMB.

## 5.4 Overview of results

The model indicates that the exploitable biomass of tailor was around 50% of virgin level from the mid-1980s to 2012 (Figure 5.1). It appears to have bounced back strongly since 2012, due to high recruitment, but more years of monitoring data are needed to confirm that. The estimates of high recruitment come from the age-length distributions of tailor collected by Fisheries Queensland’s monitoring team, which show large numbers of small fish coming into the fishery from 2012 onwards (see figures in Appendix 3, section A3.1, pages 90–92).

The sharp rise in biomass since 2012 is not yet supported by commercial catch rates. We did not apply any artificial weighting to the different data sources: hence the model has automatically given the most weight to the source with the most data (age-length information) and less weight to catch rates. It does, however, appear to have been strongly influenced by catch rates in the period 2003–2011 (see below).

Estimates of maximum sustainable yield (MSY) are around  $1350 \text{ t yr}^{-1}$  but could be as low as  $1000 \text{ t yr}^{-1}$  or as high as  $2000 \text{ t yr}^{-1}$  (Figure 5.2).

The concept of MSY is ill-defined for tailor because the model results show long-term fluctuations in the level of recruitment (Figures 5.3 and 5.4; see also age-structure plots in Appendix 3). The model estimates high recruitment in the periods 1972–1975 and 1985–1998, and low recruitment in 2003–2011. The presence of long-term fluctuations in recruitment of tailor is in accord with observations of long-term fluctuations in abundance of bluefish in North America (see section 1.4, page 6).

The model’s estimates of recruitment for the period 2003–2011 are sensitive to the catch rate inputs. We have assumed that the catch-rate trends derived in Chapter 3 are accurate in showing little change in overall abundance despite big falls in fishing activity since the early 1990s. The model has estimated that recruitment and fishing activity have both fallen, roughly in parallel, which has kept the abundance fairly constant. This conclusion may not be valid if catch rates are susceptible to hyperstability, whereby catch rates remain fairly constant even if abundance fluctuates greatly. Hyperstability can occur, for example, if fishers can maintain their catch rates by targeting particular schools of fish, even though the total number of schools in the population may decrease. We tried to guard against hyperstability by excluding beach-seine netting from catch-rate analysis, because search time waiting for a school to arrive is not recorded in the beach-seine data. Still it is possible that catch-rates from gillnet and line-fishing data may also experience hyperstability.

Long-term fluctuations in recruitment mean that fishing the tailor population at MSY can still be unsustainable if there is a long period of low recruitment. Therefore it is advisable that, if a constant harvest each year is desired, this harvest be well below MSY. Conversely, the model estimated that the harvest exceeded MSY in the 1980s and 1990s (see section 2.5), but that may not have resulted in overfishing because it occurred in a period of high recruitment.

It is unknown how much of the fall in recruitment in 2003–2011 is due to fishing and how much is due to environmental variation. Heavy fishing of tailor in the 1990s may have affected the wider ecosystem and depressed the recruitment of tailor for many years afterwards, but on the other hand the low recruitment may be unrelated to fishing. The population model is a single-species model and does not attempt to take account of ecosystem effects: any ecosystem effect would be reflected in the

recruitment deviations in equation (4.39) (page 35) plotted in Figure 5.4, not in the recruitment compensation parameter  $r$ , and so would be indistinguishable from an environmental effect.

Estimates of the instantaneous natural mortality rate  $M$  range between  $0.95 \text{ yr}^{-1}$  (the lower bound) and about  $1.45 \text{ yr}^{-1}$ , with a best estimate of about  $1.30 \text{ yr}^{-1}$  (see Figure 5.5). These estimates are high by the standards of most large bony fish and are driven by the lack of old tailor in the Australian fishery compared to, e.g., North America; see section 1.3.2 (page 5).

Estimated harvest rates from the mid-1990s were extremely high, ranging between 60% and 80% for the individual MCMC simulations with the highest likelihoods (Figure 5.6). These values align with harvest-rate levels from the previous assessment of tailor on the east coast (Leigh and O'Neill, 2004). That assessment was conducted before it was established that there had been a big fall in the size of the harvest since the mid-1990s, and hence its results were subject to greater uncertainty.

High harvest rates in the 1980s and 1990s may be at least partly responsible for the absence of schools of big tailor from Fraser Island prior to late September since the 1980s. Such schools appeared to be frequent in early September in the period 1978–80; see section 1.5.1 and caveats on data collection discussed there. Tailor schools comprise fish of similar size. If fishing depleted the total number of large tailor, viable numbers per school could be maintained only by reducing the number of schools of large fish. This reduction may in turn have compressed the period over which schools of large tailor visit Fraser Island.

Sequences of negative log-likelihood (NLL) from the MCMC runs are plotted in Figures 5.7 and 5.8. They show good mixing when the qualitatively different, extremely slow-moving parts are excluded. Those parts corresponded to low values of  $M$  and very low population sizes in the early 2000s.

Parameter estimates from the model are listed in Tables 5.2, 5.3 and 5.4 for the three different values of recruitment compensation ratio  $r$  that we used. The 50% values listed are medians for the parameter values, while the 25% and 75% values make 50% confidence intervals and the 2.5% and 97.5% values make 95% confidence intervals.

## 5.5 Model fit

The age–length frequencies used in the model are plotted in Appendix 3. Because these data were especially important to the fitting of the model, all the samples used are plotted.

Appendix 4 contains plots that show the fit of the model to the input data.

Fits to catch-rate data (section A4.2) are not very close due to conflicting signals between catch-rate, harvest-size and the age–length frequency data. We could have up-weighted the catch-rate data to force the model to fit them more closely. We did not believe that the case for doing this was quite strong enough and we preferred to leave it to the model to fit all the input data as best it could.

The catch-rate data especially do not support the model result of very high recruitment in the last few years. We recommend waiting for some more years of data before drawing any firm conclusions about recruitment in recent years.

Our decision not to impose any data weighting was influenced by the difficulty of obtaining accurate results from catch-rate analysis, due to problems such as hyperstability (see section 5.4). Age–length frequency data appeared to be somewhat less problematic than catch rates. Nevertheless, there were far more age–length frequency data than catch-rate data and it may be considered that the age–length frequency data have dominated the model results.

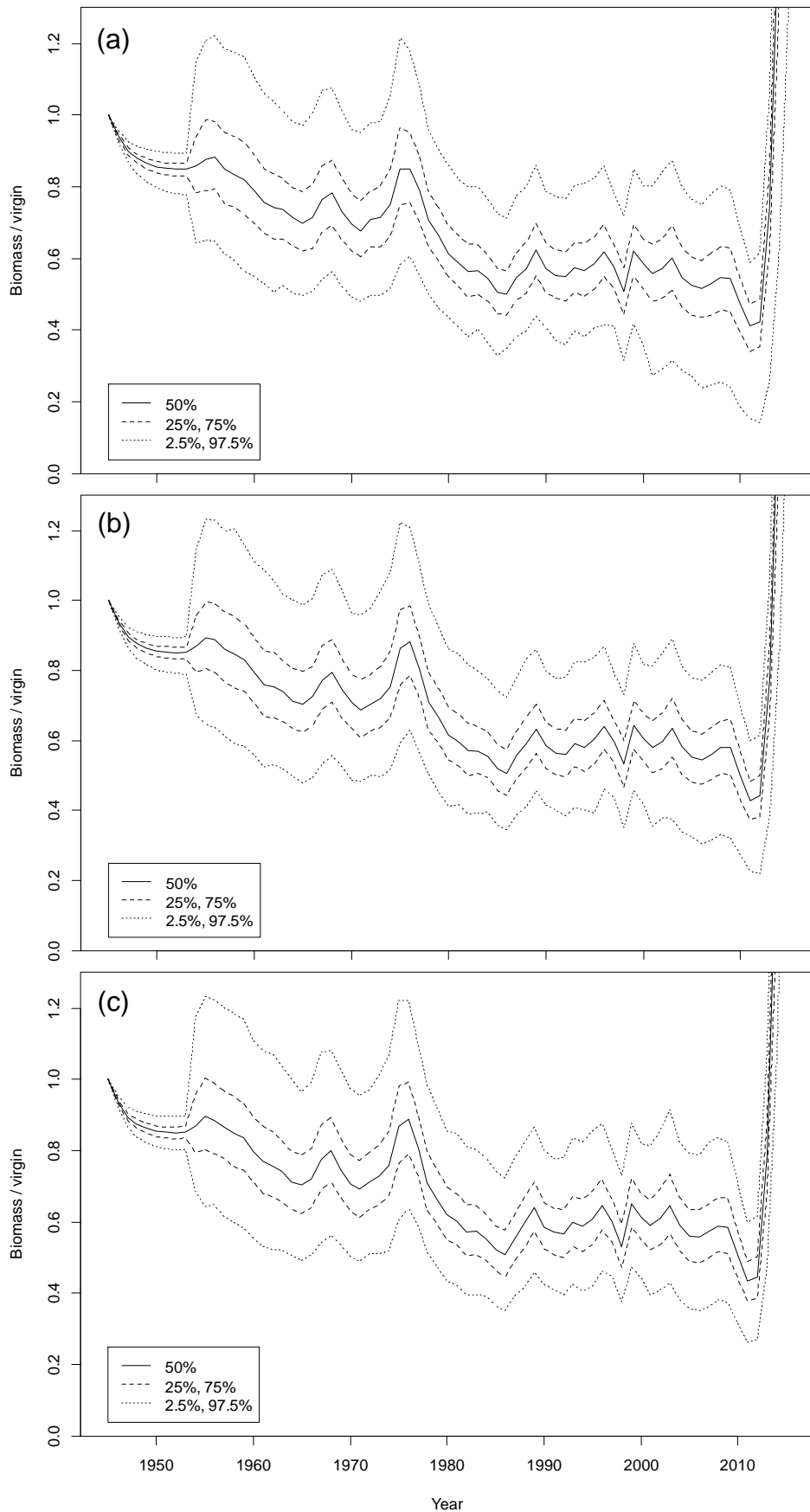


Figure 5.1: Biomass trajectories for different values of the recruitment compensation ratio,  $r$ : (a) 5, (b) 6, (c) 6.5. The solid line is the median of MCMC simulations. Other lines are percentiles as specified in the legends. The rise after 2011 still needs to be confirmed by more years of data.



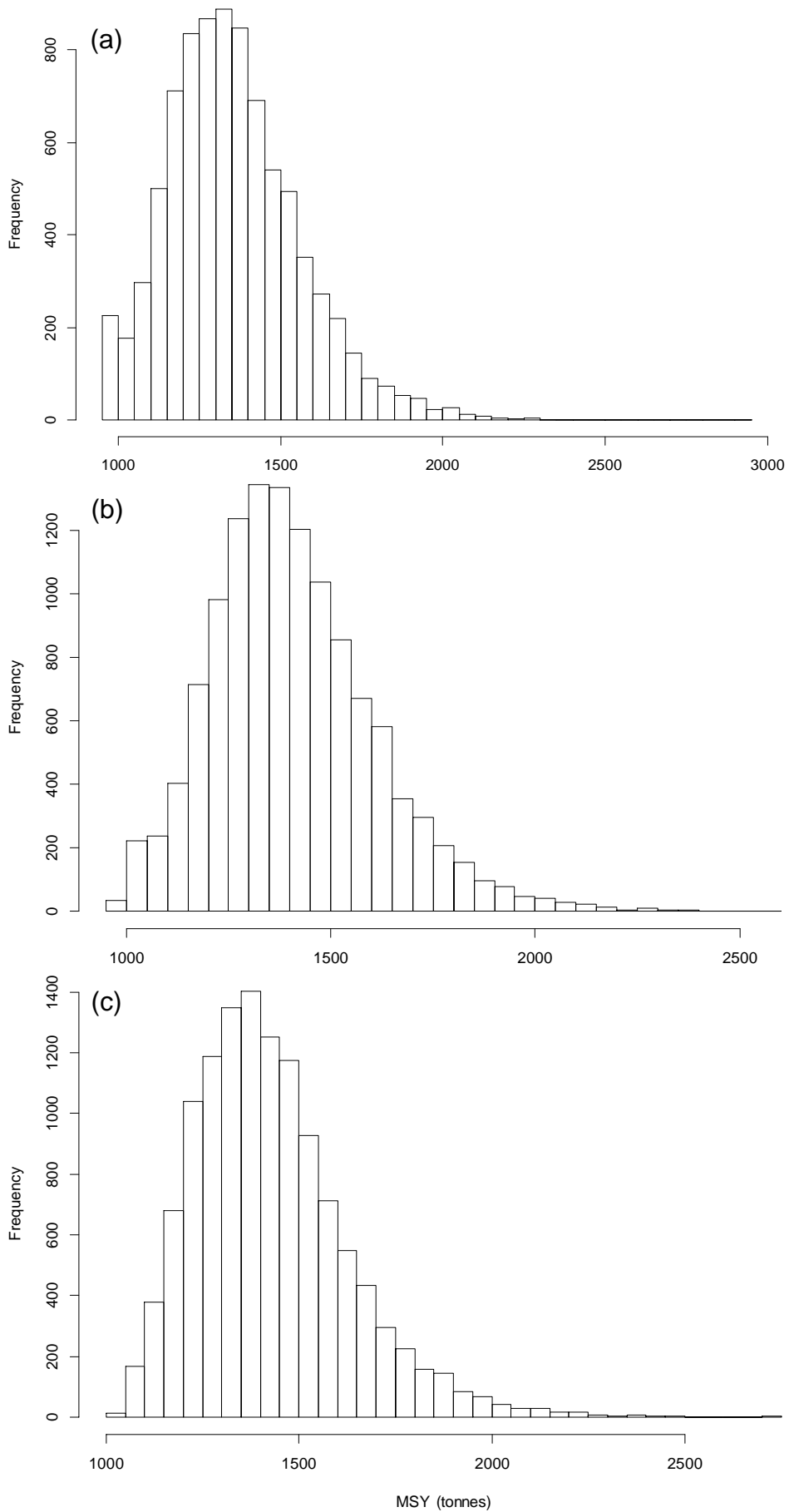


Figure 5.2: Histograms of maximum sustainable yield (MSY) estimates: (a)  $r = 5$  (b)  $r = 6$  (c)  $r = 6.5$ .

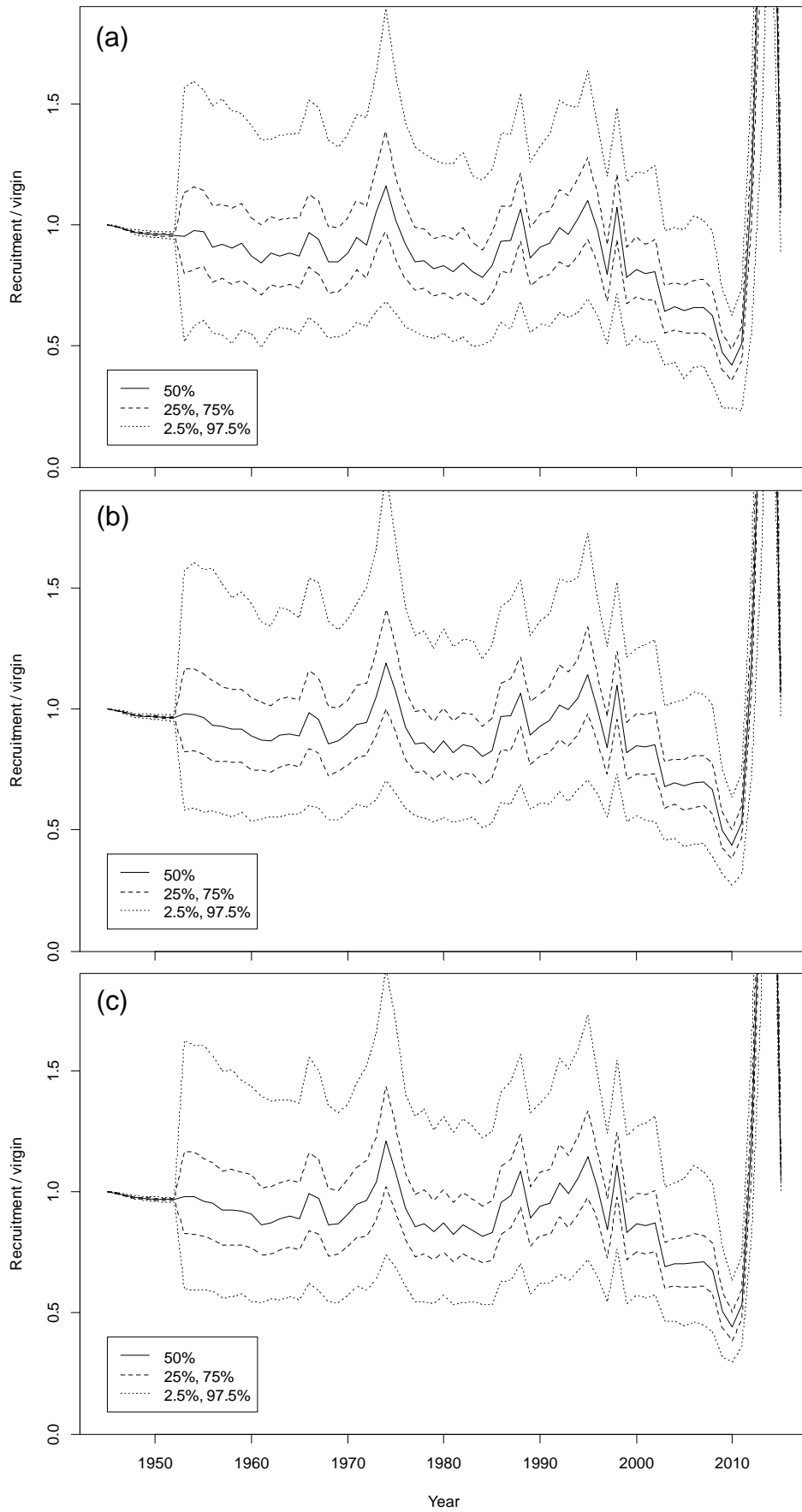


Figure 5.3: Estimated recruitment trajectories showing MCMC medians (50%) and other percentiles: (a)  $r = 5$ , (b)  $r = 6$ , (c)  $r = 6.5$ . The rise after 2011 still needs to be confirmed by more years of data.

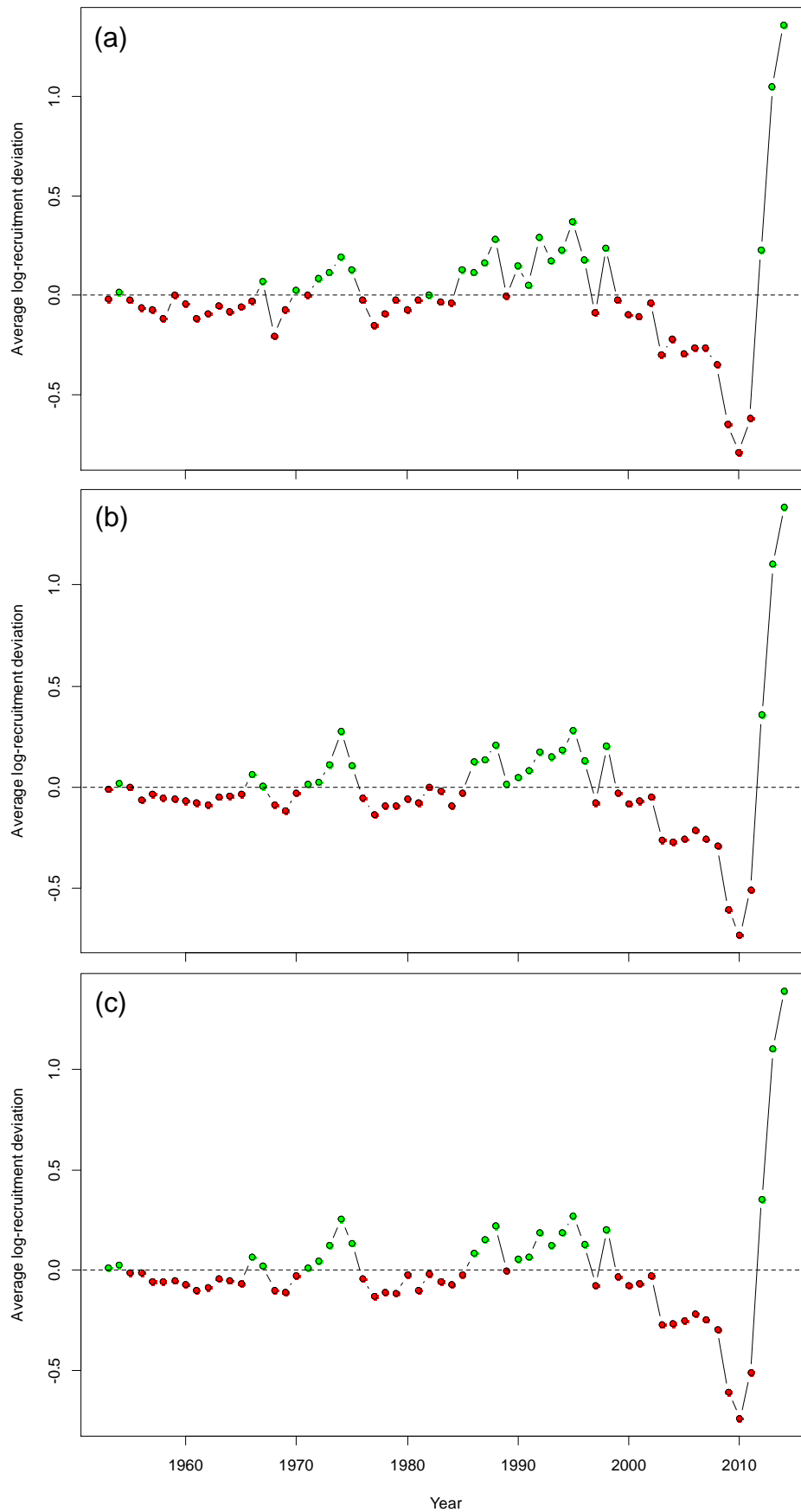


Figure 5.4: Estimated log-recruitment deviations,  $d_t$ : (a)  $r = 5$ , (b)  $r = 6$ , (c)  $r = 6.5$ . Green points are positive deviations and red ones negative. Zero corresponds to a deterministic stock–recruitment relationship (see equation (4.39)). The rise after 2011 needs to be confirmed by more years of data.

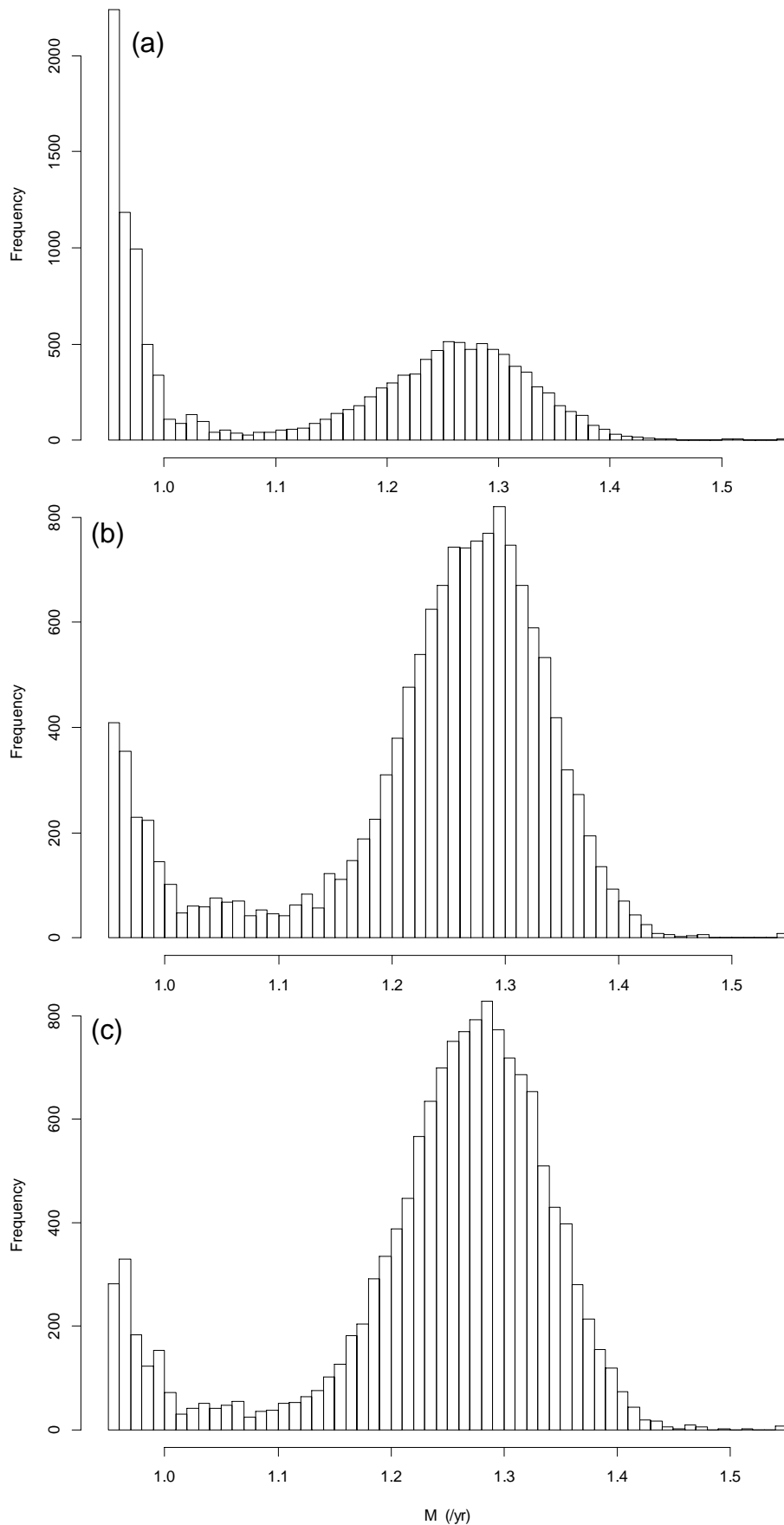


Figure 5.5: Histograms of estimates of instantaneous natural mortality rate,  $M$ : (a)  $r = 5$ , (b)  $r = 6$ , (c)  $r = 6.5$ . A lower bound of  $0.95 \text{ yr}^{-1}$  was applied to prevent the population going unrealistically low in the early 2000s. Results focus on the right-hand mode and largely exclude the left-hand one.

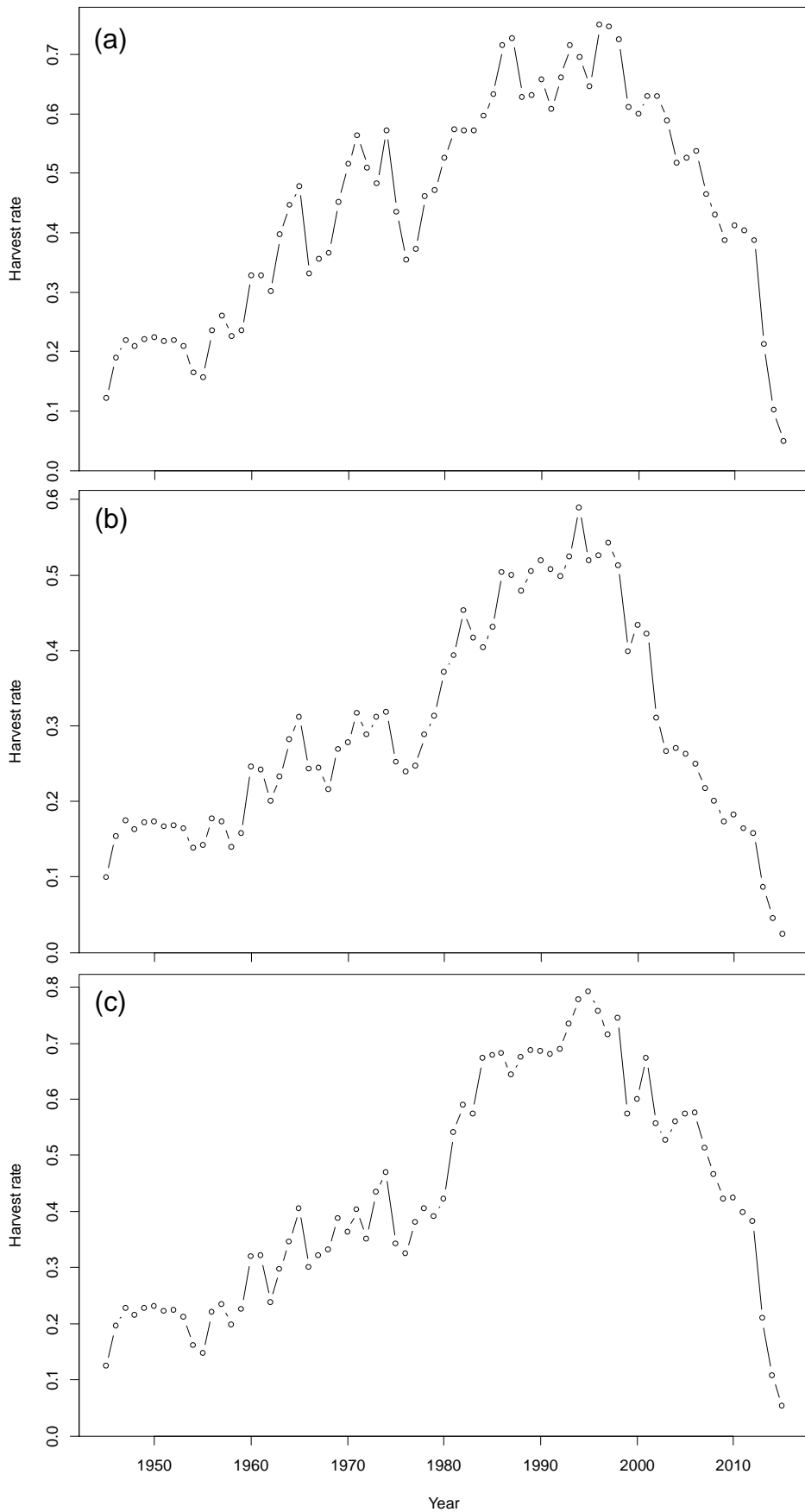


Figure 5.6: Harvest rate trajectories for the MCMC simulation with the highest likelihood value, for different values of the recruitment compensation ratio,  $r$ : (a) 5, (b) 6, (c) 6.5. The falls after 2012 are contingent on very high recruitment estimates which still need to be confirmed by more years of data.

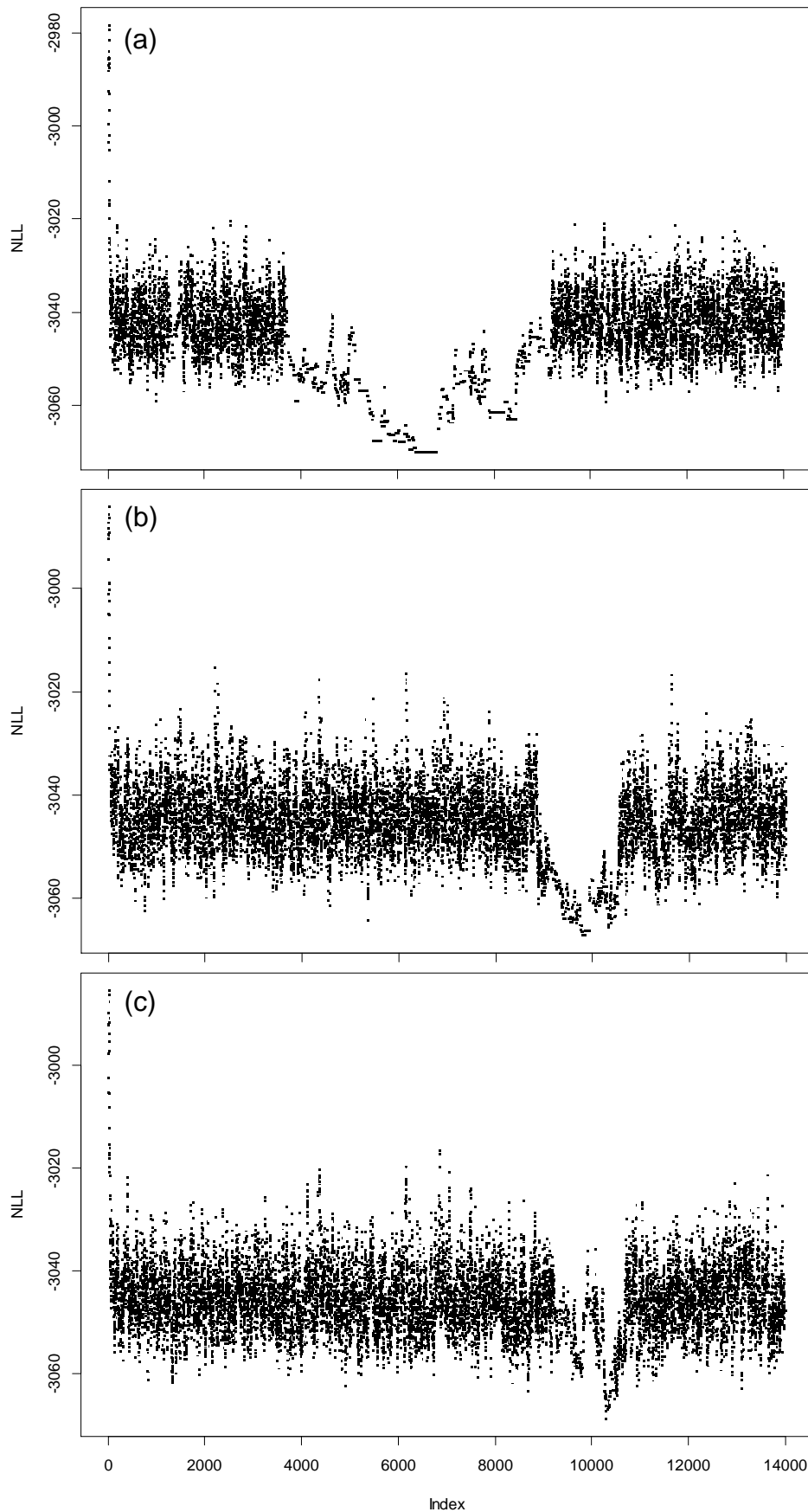


Figure 5.7: Sequences of negative log-likelihood (NLL) values from MCMC, all saved simulations included: (a)  $r = 5$ , (b)  $r = 6$ , (c)  $r = 6.5$ . Sections of poor mixing corresponded to low values of the instantaneous natural mortality rate  $M$  and were removed from further analysis.

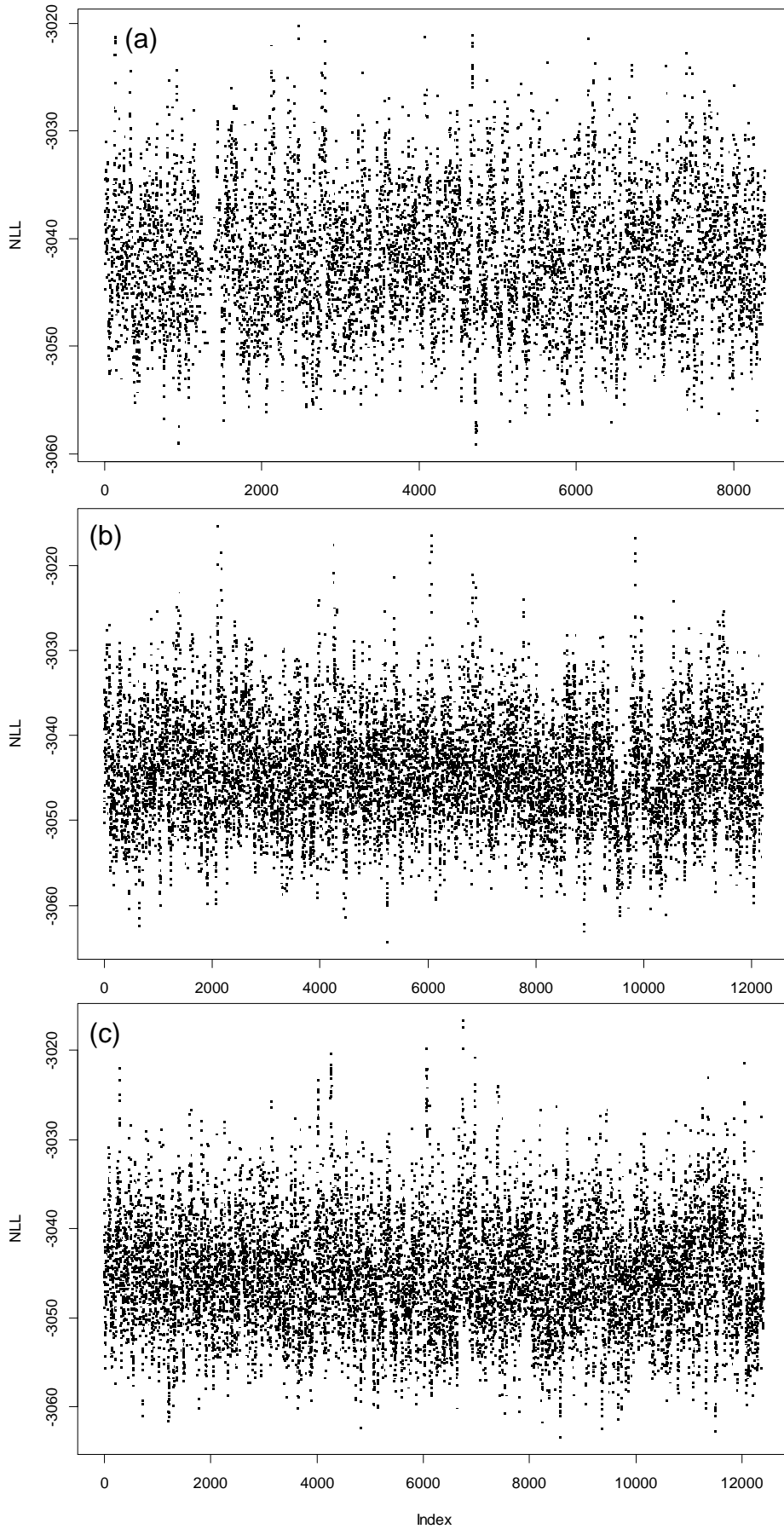


Figure 5.8: Sequences of negative log-likelihood (NLL) values from MCMC, early simulations and extremely slow-moving parts from Figure 5.7 excluded: (a)  $r = 5$ , (b)  $r = 6$ , (c)  $r = 6.5$ .

Table 5.2: Parameter estimates for recruitment compensation ratio  $r = 5$ : mean and percentiles from the model's MCMC simulations. Recruitment deviations have been converted from the model's 61 independent parameters to the 62 year-specific deviations which sum to zero. Names that differ from those in Table 4.1 are  $L_{min} = \mu$ ,  $L_{max} =$  expected length at age 6+ (age group 7),  $SdL_{min} = \sigma$ ,  $SdL_{inf} = \rho$ ,  $\ln\_R0 = \log(R_0)$ ,  $L50R = L_{50}^{(line\&seine)}$ ,  $L95diffR = L_{diff}^{(line\&seine)}$ ,  $L50C = L_{50}^{(gillnet)}$  and  $L95diffC = L_{diff}^{(gillnet)}$ . Length parameters are measured in cm and  $K$  and  $M$  are measured in  $yr^{-1}$ . Parameters  $L_{min}$ ,  $L_{max}$  and  $L95diffR$  hit their lower bounds and were fixed.

Parameter	Mean	2.5%	25%	50%	75%	97.5%
Lmin	10	10	10	10	10	10
Lmax	55	55	55	55	55	55
K	0.4205	0.4087	0.4164	0.4206	0.4246	0.4319
SdLmin	9.9402	9.7697	9.8832	9.9408	9.9975	10.1118
SdLinf	7.1170	6.7128	6.9800	7.1158	7.2558	7.5231
M	1.2518	1.0035	1.2129	1.2619	1.3058	1.3801
ln_R0	17.1723	16.5671	17.0367	17.1861	17.3276	17.5968
r	5	5	5	5	5	5
L50R	29.9349	29.6234	29.8308	29.9343	30.0406	30.2423
L95diffR	1.5	1.5	1.5	1.5	1.5	1.5
L50C	31.5486	30.8947	31.2944	31.5320	31.7799	32.3071
L95diffC	4.2309	3.5008	3.9714	4.2123	4.4784	5.0278
<b>Recruitment deviations by year</b>						
1953	-0.0118	-0.5914	-0.1831	-0.0042	0.1683	0.4936
1954	0.0155	-0.4998	-0.1592	0.0212	0.1928	0.5099
1955	0.0153	-0.4636	-0.1447	0.0207	0.1741	0.4879
1956	-0.0615	-0.5522	-0.2344	-0.0643	0.1114	0.4399
1957	-0.0513	-0.5731	-0.2160	-0.0456	0.1160	0.4509
1958	-0.0675	-0.6103	-0.2323	-0.0601	0.1100	0.4267
1959	-0.0339	-0.5142	-0.2074	-0.0315	0.1333	0.4449
1960	-0.0790	-0.5438	-0.2420	-0.0798	0.0813	0.3983
1961	-0.1125	-0.6267	-0.2794	-0.1051	0.0626	0.3561
1962	-0.0553	-0.5239	-0.2123	-0.0489	0.1085	0.3797
1963	-0.0519	-0.4811	-0.2094	-0.0586	0.1033	0.3980
1964	-0.0410	-0.4847	-0.1967	-0.0445	0.1149	0.4069
1965	-0.0455	-0.4971	-0.2048	-0.0420	0.1126	0.4102
1966	0.0598	-0.3895	-0.0930	0.0569	0.2135	0.5199
1967	0.0261	-0.4476	-0.1390	0.0299	0.1863	0.4962
1968	-0.0951	-0.5627	-0.2584	-0.0935	0.0719	0.3706
1969	-0.1021	-0.5548	-0.2574	-0.0993	0.0516	0.3436
1970	-0.0444	-0.5081	-0.1917	-0.0399	0.1090	0.3961
1971	0.0406	-0.4166	-0.1097	0.0438	0.1930	0.4785
1972	0.0147	-0.4492	-0.1475	0.0172	0.1756	0.4712
1973	0.1367	-0.3542	-0.0234	0.1433	0.3069	0.5816
1974	0.2381	-0.2815	0.0642	0.2422	0.4163	0.7311
1975	0.0933	-0.3813	-0.0750	0.0963	0.2577	0.5673
1976	-0.0414	-0.4856	-0.1982	-0.0434	0.1160	0.4073
1977	-0.1165	-0.5474	-0.2717	-0.1190	0.0338	0.3440
1978	-0.0982	-0.5535	-0.2435	-0.0878	0.0501	0.3243
1979	-0.1068	-0.5467	-0.2522	-0.1046	0.0360	0.3294
1980	-0.0755	-0.4968	-0.2163	-0.0739	0.0689	0.3429
1981	-0.0819	-0.5223	-0.2358	-0.0819	0.0731	0.3689
1982	-0.0239	-0.4933	-0.1842	-0.0272	0.1353	0.4425
1983	-0.0598	-0.4833	-0.1990	-0.0561	0.0843	0.3586
1984	-0.0929	-0.5416	-0.2459	-0.0887	0.0585	0.3438
1985	-0.0183	-0.4883	-0.1768	-0.0169	0.1430	0.4418



Parameter	Mean	2.5%	25%	50%	75%	97.5%
1986	0.1218	-0.3324	-0.0187	0.1286	0.2688	0.5376
1987	0.1174	-0.3538	-0.0274	0.1299	0.2729	0.5341
1988	0.2263	-0.2178	0.0954	0.2353	0.3708	0.6057
1989	-0.0001	-0.4361	-0.1398	0.0074	0.1523	0.3907
1990	0.0249	-0.4028	-0.1142	0.0331	0.1684	0.4221
1991	0.0654	-0.3923	-0.0796	0.0759	0.2169	0.4765
1992	0.1511	-0.2907	-0.0081	0.1503	0.3011	0.6261
1993	0.1317	-0.3108	-0.0249	0.1277	0.2838	0.5927
1994	0.1672	-0.3028	0.0162	0.1751	0.3271	0.5863
1995	0.2483	-0.2134	0.0948	0.2507	0.4087	0.6748
1996	0.1196	-0.3228	-0.0250	0.1260	0.2737	0.5276
1997	-0.1009	-0.5043	-0.2441	-0.1020	0.0434	0.3088
1998	0.2092	-0.2047	0.0802	0.2225	0.3427	0.5556
1999	-0.0515	-0.4534	-0.1944	-0.0494	0.0911	0.3420
2000	-0.0705	-0.4751	-0.2082	-0.0722	0.0736	0.3264
2001	-0.0740	-0.5097	-0.2056	-0.0666	0.0636	0.3202
2002	-0.0398	-0.4620	-0.1769	-0.0339	0.0950	0.3658
2003	-0.2709	-0.6540	-0.4041	-0.2678	-0.1373	0.1031
2004	-0.2657	-0.6422	-0.3927	-0.2639	-0.1351	0.1033
2005	-0.2673	-0.6731	-0.4003	-0.2582	-0.1234	0.1142
2006	-0.2248	-0.6057	-0.3637	-0.2282	-0.0855	0.1828
2007	-0.2166	-0.6213	-0.3530	-0.2115	-0.0794	0.1730
2008	-0.2905	-0.6874	-0.4321	-0.2885	-0.1501	0.1073
2009	-0.5792	-0.9786	-0.7124	-0.5758	-0.4437	-0.1824
2010	-0.6914	-1.0365	-0.8157	-0.6917	-0.5700	-0.3426
2011	-0.4638	-0.7863	-0.5695	-0.4588	-0.3553	-0.1534
2012	0.4024	0.1035	0.3177	0.4060	0.4910	0.6554
2013	1.1459	0.9685	1.0833	1.1425	1.2072	1.3310
2014	1.4040	1.2484	1.3496	1.4044	1.4579	1.5609

Table 5.3: Parameter estimates for recruitment compensation ratio  $r = 6$ . Descriptions are identical to Table 5.2.

Parameter	Mean	2.5%	25%	50%	75%	97.5%
Lmin	10	10	10	10	10	10
Lmax	55	55	55	55	55	55
K	0.4204	0.4089	0.4169	0.4210	0.4253	0.4332
SdLmin	9.9505	9.7831	9.9013	9.9611	10.0186	10.1377
SdLinf	7.0968	6.6988	6.9583	7.0912	7.2260	7.5048
M	1.2682	0.9563	1.2048	1.2630	1.3088	1.3836
ln_R0	17.1604	16.4312	16.9586	17.1341	17.2756	17.5477
r	6	6	6	6	6	6
L50R	29.9317	29.6239	29.8381	29.9431	30.0393	30.2523
L95diffR	1.5	1.5	1.5	1.5	1.5	1.5
L50C	31.5542	30.9150	31.3044	31.5159	31.7708	32.2864
L95diffC	4.2299	3.5322	3.9683	4.2130	4.4779	4.9970
<b>Recruitment deviations by year</b>						
1953	0.0119	-0.4987	-0.1593	0.0174	0.1897	0.4875
1954	0.0165	-0.4889	-0.1533	0.0142	0.1882	0.5109
1955	-0.0062	-0.5172	-0.1778	-0.0059	0.1704	0.4901
1956	-0.0351	-0.5195	-0.2158	-0.0422	0.1402	0.4834
1957	-0.0460	-0.5363	-0.2134	-0.0452	0.1208	0.4391
1958	-0.0542	-0.5558	-0.2175	-0.0519	0.1142	0.4158
1959	-0.0459	-0.5169	-0.2080	-0.0461	0.1131	0.4358
1960	-0.0813	-0.5870	-0.2464	-0.0744	0.0882	0.4033

<b>Parameter</b>	<b>Mean</b>	<b>2.5%</b>	<b>25%</b>	<b>50%</b>	<b>75%</b>	<b>97.5%</b>
1961	-0.0839	-0.5448	-0.2410	-0.0874	0.0804	0.3602
1962	-0.0825	-0.5185	-0.2423	-0.0821	0.0744	0.3620
1963	-0.0524	-0.5221	-0.2122	-0.0510	0.1076	0.4135
1964	-0.0407	-0.4980	-0.1947	-0.0402	0.1156	0.4189
1965	-0.0452	-0.4958	-0.2014	-0.0430	0.1125	0.3940
1966	0.0601	-0.4145	-0.0992	0.0620	0.2253	0.5176
1967	0.0290	-0.4530	-0.1300	0.0288	0.1937	0.4874
1968	-0.0974	-0.5530	-0.2597	-0.0975	0.0677	0.3663
1969	-0.0955	-0.5564	-0.2437	-0.0922	0.0569	0.3330
1970	-0.0466	-0.4983	-0.1946	-0.0388	0.1033	0.3838
1971	0.0131	-0.4265	-0.1428	0.0177	0.1676	0.4534
1972	0.0294	-0.4299	-0.1283	0.0297	0.1867	0.4867
1973	0.1204	-0.3878	-0.0417	0.1273	0.2923	0.5873
1974	0.2456	-0.2816	0.0739	0.2481	0.4240	0.7499
1975	0.1268	-0.3533	-0.0358	0.1343	0.2945	0.5882
1976	-0.0471	-0.4922	-0.1975	-0.0427	0.1062	0.3896
1977	-0.1255	-0.5571	-0.2682	-0.1221	0.0216	0.2971
1978	-0.1010	-0.5394	-0.2475	-0.1007	0.0480	0.3309
1979	-0.1225	-0.5507	-0.2694	-0.1250	0.0249	0.3091
1980	-0.0519	-0.5059	-0.2022	-0.0508	0.0981	0.4013
1981	-0.0878	-0.5232	-0.2366	-0.0858	0.0628	0.3441
1982	-0.0459	-0.5019	-0.1928	-0.0407	0.1069	0.3839
1983	-0.0378	-0.4725	-0.1894	-0.0394	0.1148	0.3958
1984	-0.0932	-0.5531	-0.2415	-0.0881	0.0646	0.3222
1985	-0.0525	-0.4986	-0.2049	-0.0540	0.0998	0.3987
1986	0.1139	-0.3395	-0.0323	0.1231	0.2681	0.5293
1987	0.1275	-0.3432	-0.0224	0.1392	0.2888	0.5402
1988	0.1931	-0.2396	0.0613	0.1987	0.3359	0.5808
1989	0.0030	-0.4237	-0.1378	0.0092	0.1511	0.3924
1990	0.0236	-0.3972	-0.1173	0.0310	0.1699	0.4195
1991	0.0662	-0.3722	-0.0767	0.0745	0.2163	0.4714
1992	0.1494	-0.2955	-0.0025	0.1511	0.3048	0.5736
1993	0.1245	-0.3491	-0.0318	0.1293	0.2828	0.5803
1994	0.1564	-0.2910	0.0099	0.1656	0.3090	0.5636
1995	0.2558	-0.2316	0.0981	0.2577	0.4254	0.7016
1996	0.1086	-0.3144	-0.0256	0.1165	0.2508	0.4944
1997	-0.0740	-0.4939	-0.2117	-0.0729	0.0668	0.3343
1998	0.1992	-0.2010	0.0711	0.2087	0.3357	0.5484
1999	-0.0477	-0.4721	-0.1806	-0.0439	0.0922	0.3435
2000	-0.0673	-0.4735	-0.2080	-0.0633	0.0785	0.3202
2001	-0.0595	-0.4963	-0.2015	-0.0549	0.0883	0.3431
2002	-0.0332	-0.4419	-0.1724	-0.0303	0.1095	0.3681
2003	-0.2620	-0.6433	-0.3944	-0.2639	-0.1309	0.1178
2004	-0.2574	-0.6385	-0.3823	-0.2551	-0.1319	0.1167
2005	-0.2558	-0.6862	-0.3931	-0.2514	-0.1116	0.1426
2006	-0.2212	-0.6264	-0.3626	-0.2195	-0.0796	0.1867
2007	-0.2097	-0.6067	-0.3411	-0.2073	-0.0771	0.1793
2008	-0.2751	-0.7068	-0.4130	-0.2682	-0.1315	0.1149
2009	-0.5716	-0.9446	-0.7082	-0.5729	-0.4376	-0.1865
2010	-0.6997	-1.0574	-0.8178	-0.6978	-0.5779	-0.3566
2011	-0.4723	-0.7905	-0.5757	-0.4695	-0.3653	-0.1729
2012	0.3912	0.1174	0.3082	0.3973	0.4812	0.6303
2013	1.1217	0.9147	1.0595	1.1236	1.1888	1.3099
2014	1.3976	1.2324	1.3434	1.3962	1.4540	1.5579

Table 5.4: Parameter estimates for recruitment compensation ratio  $r = 6.5$ . Descriptions are identical to Table 5.2.

Parameter	Mean	2.5%	25%	50%	75%	97.5%
Lmin	10	10	10	10	10	10
Lmax	55	55	55	55	55	55
K	0.4200	0.4082	0.4159	0.4200	0.4242	0.4322
SdLmin	9.9548	9.7838	9.8981	9.9549	10.0112	10.1250
SdLinf	7.0908	6.6872	6.9438	7.0913	7.2334	7.5061
M	1.2732	1.1424	1.2332	1.2755	1.3169	1.3881
ln_R0	17.1545	16.7691	17.0226	17.1505	17.2841	17.5520
r	6.5	6.5	6.5	6.5	6.5	6.5
L50R	29.9273	29.6174	29.8226	29.9283	30.0332	30.2298
L95diffR	1.5	1.5	1.5	1.5	1.5	1.5
L50C	31.5607	30.9232	31.3112	31.5376	31.7888	32.3142
L95diffC	4.2374	3.5287	3.9820	4.2264	4.4823	4.9988
<b>Recruitment deviations by year</b>						
1953	0.0146	-0.4793	-0.1582	0.0122	0.1878	0.5180
1954	0.0131	-0.4911	-0.1593	0.0125	0.1871	0.5049
1955	-0.0062	-0.4896	-0.1724	-0.0131	0.1603	0.5021
1956	-0.0219	-0.5029	-0.1933	-0.0231	0.1408	0.4722
1957	-0.0548	-0.5497	-0.2201	-0.0522	0.1083	0.4344
1958	-0.0483	-0.5397	-0.2142	-0.0467	0.1185	0.4398
1959	-0.0472	-0.5071	-0.2105	-0.0466	0.1161	0.4161
1960	-0.0623	-0.5712	-0.2263	-0.0551	0.1121	0.4042
1961	-0.0936	-0.5645	-0.2530	-0.0969	0.0672	0.3772
1962	-0.0809	-0.5301	-0.2371	-0.0816	0.0760	0.3695
1963	-0.0643	-0.5221	-0.2183	-0.0630	0.0924	0.3835
1964	-0.0459	-0.5104	-0.1964	-0.0432	0.1136	0.3894
1965	-0.0528	-0.5119	-0.2068	-0.0472	0.1054	0.3782
1966	0.0621	-0.3998	-0.1008	0.0690	0.2270	0.5142
1967	0.0305	-0.4616	-0.1260	0.0410	0.1946	0.4819
1968	-0.0953	-0.5540	-0.2554	-0.0947	0.0680	0.3501
1969	-0.0998	-0.5677	-0.2498	-0.0909	0.0573	0.3280
1970	-0.0433	-0.4935	-0.1965	-0.0355	0.1145	0.3767
1971	0.0159	-0.4250	-0.1382	0.0199	0.1701	0.4502
1972	0.0349	-0.4475	-0.1283	0.0376	0.2013	0.4928
1973	0.1087	-0.3767	-0.0524	0.1111	0.2789	0.5706
1974	0.2529	-0.2388	0.0834	0.2570	0.4273	0.7271
1975	0.1333	-0.3232	-0.0265	0.1332	0.2951	0.5875
1976	-0.0406	-0.4656	-0.1842	-0.0373	0.1056	0.3740
1977	-0.1325	-0.5750	-0.2839	-0.1277	0.0186	0.2937
1978	-0.1018	-0.5662	-0.2544	-0.0972	0.0566	0.3434
1979	-0.1121	-0.5442	-0.2562	-0.1104	0.0346	0.3078
1980	-0.0537	-0.4775	-0.2006	-0.0488	0.0945	0.3652
1981	-0.0928	-0.5286	-0.2410	-0.0935	0.0605	0.3353
1982	-0.0451	-0.5088	-0.1919	-0.0391	0.1076	0.3814
1983	-0.0542	-0.4903	-0.2035	-0.0522	0.0955	0.3753
1984	-0.0836	-0.5185	-0.2267	-0.0827	0.0634	0.3358
1985	-0.0584	-0.4966	-0.2079	-0.0539	0.0980	0.3561
1986	0.0951	-0.3303	-0.0553	0.1014	0.2500	0.4992
1987	0.1321	-0.2935	-0.0099	0.1387	0.2794	0.5443
1988	0.2013	-0.2281	0.0628	0.2090	0.3471	0.5863
1989	-0.0073	-0.4305	-0.1497	-0.0013	0.1369	0.3971
1990	0.0307	-0.3808	-0.1058	0.0342	0.1747	0.4128

<b>Parameter</b>	<b>Mean</b>	<b>2.5%</b>	<b>25%</b>	<b>50%</b>	<b>75%</b>	<b>97.5%</b>
1991	0.0604	-0.3618	-0.0843	0.0654	0.2093	0.4670
1992	0.1547	-0.2997	0.0061	0.1573	0.3072	0.5788
1993	0.1142	-0.3442	-0.0353	0.1200	0.2686	0.5506
1994	0.1607	-0.2907	0.0089	0.1638	0.3198	0.5874
1995	0.2452	-0.2230	0.0895	0.2541	0.4079	0.6772
1996	0.1142	-0.3263	-0.0172	0.1222	0.2585	0.5049
1997	-0.0826	-0.5107	-0.2235	-0.0742	0.0620	0.3135
1998	0.2045	-0.1713	0.0809	0.2135	0.3315	0.5514
1999	-0.0494	-0.4821	-0.1875	-0.0437	0.0974	0.3460
2000	-0.0567	-0.4592	-0.1954	-0.0497	0.0866	0.3240
2001	-0.0494	-0.4654	-0.1882	-0.0479	0.0927	0.3474
2002	-0.0217	-0.4255	-0.1606	-0.0192	0.1163	0.3799
2003	-0.2639	-0.6333	-0.3946	-0.2633	-0.1357	0.1100
2004	-0.2619	-0.6618	-0.3918	-0.2616	-0.1271	0.1174
2005	-0.2405	-0.6650	-0.3751	-0.2361	-0.1029	0.1483
2006	-0.2130	-0.6248	-0.3582	-0.2164	-0.0663	0.2114
2007	-0.2152	-0.6472	-0.3499	-0.2101	-0.0712	0.1802
2008	-0.2741	-0.6999	-0.4124	-0.2662	-0.1307	0.1248
2009	-0.5689	-0.9932	-0.7029	-0.5668	-0.4269	-0.1731
2010	-0.7025	-1.0452	-0.8205	-0.7005	-0.5836	-0.3661
2011	-0.4759	-0.7719	-0.5775	-0.4742	-0.3740	-0.1777
2012	0.3849	0.1345	0.3022	0.3897	0.4704	0.6199
2013	1.1132	0.9234	1.0506	1.1132	1.1777	1.2977
2014	1.3972	1.2357	1.3411	1.3966	1.4525	1.5611

## 6. Discussion

### 6.1 Performance of the population model

The new population model (Chapter 4) handles important effects in fisheries that have been difficult with previous models. Tailor especially has very strong length-based vulnerability to recreational fishing from ocean beaches, as can be seen from the age–length frequency plots for this sector in Appendix 3. These plots show that only the larger individuals of age 1+ (age group 2) are caught in this sector. Smaller individuals don't enter the ocean-beach sector until age 2+ (age group 3) and so can spawn once before becoming vulnerable to that sector. The larger fish have an extra year of potentially intensive fishing, to which they become vulnerable before spawning: their numbers are depleted faster than those of smaller fish of the same age. It is important for the population model to treat this effect correctly.

The model has provided sensible results for certain values of the recruitment compensation ratio (Goodyear, 1977),  $r = 5, 6$  and  $6.5$ . Equivalent values of the “steepness” parameter  $h = r/(4 + r)$  defined later (Mace and Doonan, 1988) are  $h = 0.56, 0.60$  and  $0.62$ . We consider these values sensible given that tailor in Queensland and New South Wales mature early in life but don't live long: there are not many tailor in the harvest aged more than 3+ (age group 4), so most fish have only between one and three years to breed during the course of their lives.

This assessment and its population model have used the ageing data on individual fish aged by the monitoring team, instead of scaling them up by an age–length key. This strategy preserves the error structure of the data, in particular the numbers of fish actually aged in the different age classes. Scaling up by an age–length key would instead use the numbers of fish whose lengths were measured, which may bear little relationship to the numbers aged. To use the ageing data, we amalgamated the associated length data into five-centimetre length intervals: we do not regard that as a significant limitation because the numbers of fish in the original one-centimetre intervals were accounted for in the amalgamation, thereby removing potential for biases.

Estimates of recruitment are very high from 2012 onwards. Future years of monitoring and catch-rate data will be needed to confirm this finding and at present it should not be considered accurate. It is unlikely that the recruitment is as high as the model has estimated. Management should consider lower estimates of the current tailor population size.

The presence of old fish that are smaller than expected in the fishery monitoring data should be investigated when tailor is next assessed. It may be correct for the growth curve to have a small value of the asymptotic length parameter  $L_{\infty}$ . For this assessment we fixed the value average length of a fish of age 6+ (age group 7) to a fork length of 55 cm (total length 61.4 cm) which was the minimum that we considered biologically reasonable. We expect this assumption to have increased the biomass of old fish present in the population but there are very few of these fish so the overall effect on biomass would be minimal.

The problem whereby ADMB's optimisation algorithm does not quite find the maximum likelihood point for this model requires further investigation before the model is used for other species. We have, however, accepted ADMB's Markov chain Monte Carlo (MCMC) results for this model, as visually the mixing appeared good (Figure 5.8). We deliberately set the lower bound on the instantaneous natural mortality rate  $M$  ( $0.95 \text{ yr}^{-1}$ ) low enough to show the right-hand tail of a second mode at low values of  $M$  which does not provide sensible results. This second (lower) mode corresponds to extremely low population sizes in the early 2000s. We believe that the level of fishing activity fell at this time for reasons related more to fishery management (Table 1.1) and falling recreational fishing participation (Queensland and NSW telephone–diary surveys) than lack of availability of fish. The occasions on which the MCMC became stuck in Figure 5.7 would not have occurred if our lower bound for  $M$  had been higher.

## 6.2 Recommendations

### 6.2.1 Fisheries Queensland monitoring program

The Fisheries Queensland Fishery Monitoring program has provided a very valuable, long-term data set for this assessment: age and length structure of the harvest over an important period of 17 years of the fishery's history. During this period the level of fishing fell greatly but the population appears to have taken a long time to recover due to many years of low recruitment.

Results from the population model show a recovery after 2012 but more years of monitoring data are needed to confirm that finding. The monitoring program therefore remains important in future years.

Currently, the selection of fish to age takes the form of a cap on the number of fish aged within each one-centimetre length class. This strategy weights the selection towards larger, older fish, because these are less common in the population. The strategy is sound and appears to be functioning well. The numbers of older fish are important in determining mortality rates.

Adequate numbers of fish are currently being aged each year. The current monitoring strategy is sound, putting a limit on the number of otoliths that are aged from each one-centimetre length interval and thereby ageing all of the large fish from which otoliths can be extracted. Also, the numbers of fishers whose catches are sampled appear to be providing accurate results. Model fits to the length data since the monitoring program began in 1999 are far superior to the fits to previous data.

We plan to investigate possible variations to the numbers of fish aged as part of ongoing development of methodology to aid the analysis used for the biennial Status of Australian Fish Stocks (SAFS, 2014). Therefore we do not make recommendations on those elements here.

The monitoring program is fishery-dependent in that it samples catches by recreational and commercial fishers. The alternative of fishery-independent sampling would involve scientific direction of the fishing activities from which samples are drawn. Fishery-independent sampling is expensive and generally impractical for small fisheries, including many fisheries in Australia.

The current fishery-dependent sampling is potentially susceptible to conflicting goals:

- On one hand it sets out to conduct representative sampling of the fishery catch in each year.
- On the other hand, stock assessment requires lengthy time series whose data are comparable between years.

These goals are in conflict if fishers change their fishing locations, times of year or proportions of catch taken by different fishing sectors. There is no simple solution to this problem.

The time series of monitoring data from Fraser Island, dating from the start of the Fisheries Queensland Monitoring Program in 1999 and 1978 in other sources, is by far the longest and most valuable collection of length and age data. Monitoring of the commercial sector and of the recreational sector from locations other than the Fraser Island ocean beach began in 2007. It is important to continue to sample large numbers of fish from Fraser Island for comparison with past years. Trip 3 to Fraser Island (end of September and beginning of October) has been particularly beneficial as it has collected large fish since 2002.

Reducing the duration of each Fraser Island trip, if necessary for Fisheries Queensland's management of limited resources, would be preferable to reducing the number of trips, for the following reasons:

- The size and age distributions of fish collected depend strongly on the exact time of year at which sampling is conducted; see plots in section A3.2, Appendix 3. It is highly desirable to continue the same sampling plan if samples are to be comparable from year to year.
- Tailor swim in large schools and school by size. To best represent the entire harvest, as many separate schools as possible should be sampled, which can be achieved with the maximum practical number of sampling trips. Within each trip there is always a danger of collecting many fish from one school. Fishing takes places right through the fishing season, so sampling at as many different times as possible will best sample the overall harvest.

We recommend that the monitoring program collect time series that can be compared from year to year. Stock assessment has to consider different fishery sectors separately; for example, this assessment has fitted separate vulnerability functions for the recreational ocean-beach sector and the commercial gillnet sector. It is important that each sector that is sampled have its own time series and that each time series be of useful duration (e.g., ten years or more). The Fraser Island recreational sector has the longest time series and so is the most useful one for stock assessment.

The time series begun in 2007 will become more informative in future, as the number of years of data increases.

For tailor the exact times of year at which samples are collected are very important, as the length structure and age structure change greatly even within the peak fishing season. Sampling strategies should specify the times of year, and the seasonal distribution of sampling effort should be the same in each year. We recognise that, despite such a strategy, schools of various-sized fish will appear at sampling locations at different times in different years. A sampling strategy can only minimise the problem by having multiple sampling times and sampling at the same times each year.

This sampling strategy is also important for the caps of fish to age within length intervals. It is desirable that caps not be combined over separate fishery sectors because the fish targeted by different sectors have different age-at-length distributions (i.e., different age-length keys); see plots for the recreational ocean-beach sector and the commercial gillnet sector in Appendix 3. Also it is desirable that caps for small length intervals (in which there are high numbers of fish) should be filled gradually through the fishing season, not filled early in the year, because the age-at-length distribution (age-length key) varies with time of year. For example, a fish with fork length between 40 and 45 cm (total length 44.7–50.3 cm) is much more likely to be aged 1+ (age group 2) in Fraser Island trip 3 than in trips 1 and 2; see plots in section A3.2, Appendix 3. In this assessment, we judged that it was too difficult to model the tailor life-cycle processes that give rise to these differences and consequent seasonal age-length keys. We assumed that the same sampling schemes had been employed in all years.

Fishery-dependent sampling, while providing valuable data, has limitations. It is generally impossible to estimate abundance from the Fisheries Queensland sampling methodology, as it does not attempt to record fishing effort. Angler counts were carried out in the past but were subjective and discontinued.

The total mortality rate (fishing mortality plus natural mortality) can be estimated from the age structure. Splitting this into separate fishing and natural mortality components, however, is not possible from monitoring data alone. Such a split requires knowledge of the fishing effort or catch, together with contrast in the data between years of light fishing and years of heavy fishing. We do not recommend the use of estimates of the instantaneous natural mortality rate  $M$  by methods such as Pauly (1980) or Hoenig (1983), as these methods are subject to very large amounts of experimental error.

### *6.2.2 Telephone-diary surveys of the recreational fishery*

Results of the surveys of the recreational fishery in both Queensland and NSW have been vital to this assessment. These surveys have documented the decline in recreational fishing effort and harvest which were critical inputs into the population model used in this assessment.

It is important that the recreational surveys continue in future years, preferably every two to three years and no less frequently than every five years, to show future trends in recreational fishing activity. These surveys also provide valuable data for many species other than tailor.

### *6.2.3 Logbook databases*

The commercial logbook databases in both Queensland and NSW, in addition to providing harvest-size information, have formed the mainstay of the catch-rate analyses to estimate abundance of tailor over 25 years. They will continue to provide valuable information into the future. In particular the NSW daily records, collected since mid-2009, will become much more informative as the number of years of data increases.

Use of new reporting technology may allow recording of extra data in logbook records. If fishers have to learn to use the technology anyway, extra data might be recorded with little extra effort. Useful data could include the following:

- Start time and end time of fishing, excluding setup time
- Search time for schools, especially for the commercial beach-seine sector
- Exact location from GPS
- Number of shots (sets of the gear) or robs (acts of removing fish) conducted
- Sessions in which no fish were caught
- Occasions when fishing had to be stopped due to capacity limitations (too many fish).

Increased information on any of the above would inform future stock assessments involving this species and help to improve the overall accuracy of sustainable yield estimates.

#### 6.2.4 *Fishery management*

Changes in fishing pressure on tailor appear to have allowed the tailor stock to recover from a period of very heavy fishing in the 1980s and 1990s. There is now an opportunity to modernise management mechanisms and consider clear target reference points and operational objectives to meet regional expectations of fishing and needs for sustainability. If changes to TACC, fishing licences, size limits or bag limits are considered, recruitment levels need to be carefully monitored. The economic and social benefits of consistent rules between the Queensland and NSW jurisdictions could also be discussed.

Stock assessment results are highly reliant on the estimated fall in total harvest (Figure 2.1, page 17). It would be wise for management to assume precautionary low values of fish population size, particularly because there has been no rise in commercial catch rates in recent years (Figure 3.4, page 22).

It may be still too early to judge the effect of the increase in minimum legal size (MLS) in Queensland from 30 cm total length (26.8 cm fork length) to 35 cm total length (31.2 cm fork length) in 2010. It would be most effective if fishers avoid fishing at times and locations when most of the fish are undersize. Then the stock would benefit, many individual fish would be able to spawn at least once before becoming vulnerable to fishing, and the recreational fishing experience of catching legal-sized fish would be improved. We acknowledge, however, that tailor usually move into ocean-beach areas, potentially becoming vulnerable to recreational line fishing and commercial beach-seine netting, before they reach 35 cm total length. This may result in higher discard rates than with the old MLS.

If total catch is managed, it should be at a level well below nominal MSY and consider all fishing sectors and their seasonal and regional effects, due to the relatively high probability of long-term fluctuations in recruitment of tailor (see section 5.4). It should be borne in mind that high recruitment of tailor for some years can attract additional fishing effort and result in overoptimistic expectations when recruitment falls again. It may take a few years for this additional fishing effort to leave the fishery, during which time the reduced population may be heavily fished.

It is important to recognise that the fishery has a large amount of latent fishing effort, as there are no restrictions on the total number of fishers or the total amount of fishing gear that may be used. A recovery in the tailor population could encourage more fishers to fish and so increase the fishing effort. Any return to fishing effort levels near those of the 1980s and 1990s would run a substantial risk of over-fishing and adversely affect the quality of the fishing experience (both numbers and size of fish caught).

We recommend that the total allowable commercial catch (TACC) in Queensland should include all tailor harvests of any size. Under current Queensland regulations, individual commercial daily harvests less than 100 kg do not have to be recorded against the TACC, as they are considered to be an incidental allowance (see Table 1.1, page 4, and Figure 1.5, page 11). These harvests still have to be reported in logbooks. The incidental-allowance rule can cause catch rates to become inaccurate if fishers discard the excess over 100 kg, or split their catch reports so that each recorded harvest is less



than 100 kg. This level of incidental allowance is large enough to allow non-reported targeting of schools of tailor and may not be sufficiently restrictive for some fishing areas and gears.

We also recommend that logbook entries be subject to validation from unload or sale receipts. This will improve the accuracy of logbook data. Potential improvements to the Queensland commercial logbook templates have been noted in section 6.2.3 above.

Current tailor bag limits appear to have been a substantial aid to reduce recreational fishing effort on tailor, both directly by limiting the catches of proficient recreational anglers and indirectly by encouraging cultural change towards fishing holidays with objectives other than to catch as many fish as possible. For the commercial sector, the TACC in Queensland and the prohibition on targeting of tailor in NSW are keeping the commercial catch well below the levels from past years such as the 1960s (see Figure 2.1, page 17).

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# Appendix 1: Numerical integration for biomass

## A1.1 Theory

For equation (4.25) to work exactly for polynomials up to order 3, we in fact need to consider only polynomials of orders 0 and 2. The formula works automatically for odd orders because  $b_i$  and  $z_i$  will be symmetric about  $z = 0$ . To make the weights  $b_i$  as uniform as possible, we minimise the sum of squares

$$\sum_{i=1}^I (b_i - 1/I)^2 \quad (\text{A1.1})$$

subject to the constraints

$$\sum_{i=1}^I b_i = 1$$

and

$$\sum_{i=1}^I b_i z_i^2 = 1.$$

We choose  $z_i$  to be the  $1/(2I)$ ,  $3/(2I)$ ,  $5/(2I)$ , ...,  $(2I-1)/(2I)$  quantiles of the standard normal distribution. Then  $b_i$  can be solved by differentiating (A1.1) and using Lagrange multipliers  $\lambda_0$  and  $\lambda_2$  respectively for the constraints. This yields the equation

$$b_i - 1/I = \lambda_0 + \lambda_2 z_i^2. \quad (\text{A1.2})$$

Summing gives the equation

$$I\lambda_0 + \lambda_2 \sum_{i=1}^I z_i^2 = 0,$$

while multiplying by  $z_i^2$  and summing gives

$$\lambda_0 \sum_{i=1}^I z_i^2 + \lambda_2 \sum_{i=1}^I z_i^4 = 1 - \sum_{i=1}^I z_i^2 / I.$$

These equations can be solved for  $\lambda_0$  and  $\lambda_2$ :

$$\lambda_2 = \left( 1 - \sum_{i=1}^I z_i^2 / I \right) / \left\{ \sum_{i=1}^I z_i^4 - \left( \sum_{i=1}^I z_i^2 \right)^2 / I \right\}$$

$$\lambda_0 = -\lambda_2 \sum_{i=1}^I z_i^2 / I.$$

Finally, the weights  $b_i$  are given by (A1.2):

$$b_i = 1/I + \lambda_0 + \lambda_2 z_i^2.$$

## A1.2 R code

The following code shows the inadequacy of Gauss-Hermite quadrature for sigmoidal functions, even with a very high number of points, then finds quadrature abscissae and weights for the method described above.

```
#####
# Gauss-Hermite quadrature, 128 points
# Values from Mathar (2013), low-order moments checked
nQuad = 128
x = c(
  9.798382195581895431377132468618e-02,
  2.939661103002957028133518674044e-01,
  4.899923604154589180890443856367e-01,
  6.860919752173348720452864326905e-01,
  8.822945007929814060005083432269e-01,
  1.078629684810908930471007575703e+00,
  1.275127536089158321432510826233e+00,
```

1.471818385674486000678375605460e+00,  
 1.668732949803723630486601211909e+00,  
 1.865902395140598696649124077990e+00,  
 2.063358406708565977681751367495e+00,  
 2.261133258973062280284208177523e+00,  
 2.459259890565739401936776191993e+00,  
 2.657771983189483996310816219916e+00,  
 2.856704045297405282651849105437e+00,  
 3.056091501202680055957840916841e+00,  
 3.255970786350659346652905677001e+00,  
 3.456379449571737482209434453368e+00,  
 3.657356263235308096230587406178e+00,  
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 4.877506030264814412167551734907e+00,  
 5.083676167489339906735053683003e+00,  
 5.290785481477179576436741808655e+00,  
 5.498890668973909484522189260087e+00,  
 5.708051508768086261774908791132e+00,  
 5.918331175085811675116817434458e+00,  
 6.129796589422162024620595978774e+00,  
 6.342518817001779471729389555727e+00,  
 6.556573515264482889625788942886e+00,  
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 7.207569103387333854417799471093e+00,  
 7.427821529952301115657395520734e+00,  
 7.649874227681006561131849953275e+00,  
 7.873844133535434466787108918844e+00,  
 8.099858421507896075457943481098e+00,  
 8.328055920790146645008020036717e+00,  
 8.558588795064508288960303800717e+00,  
 8.791624544888686406350402914272e+00,  
 9.027348413394788344826655732796e+00,  
 9.265966300296175921853640375173e+00,  
 9.507708323279056576954901826744e+00,  
 9.752833213439168674549426141513e+00,  
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 1.051164732991486861739413692790e+01,  
 1.077368911516144067131166098962e+01,  
 1.104109097601963338424289867191e+01,  
 1.131447164428997791721200284514e+01,  
 1.159457505474145174678208459080e+01,  
 1.188231011887831158083591680926e+01,  
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 1.280431208206713129501371416543e+01,  
 1.313777478802765110106505867185e+01,  
 1.348955641262314182637911777505e+01,  
 1.386520698447624158977684332026e+01,  
 1.427398130478783556250943565636e+01,  
 1.473384247358929905561314471775e+01,  
 1.529181976688274097174678865517e+01)  
 w = c(  
 1.940976118640877569776970287225e-01,  
 1.797730839077992649886979561022e-01,  
 1.542104352983543833635277132836e-01,



1.225032731641356946186646056109e-01,  
9.010867837644891954805743980399e-02,  
6.136072100449006566465106925699e-02,  
3.867395481063690265502488671356e-02,  
2.255431016782442241024982224923e-02,  
1.216691886446933949101663288563e-02,  
6.068862406925887620668014199269e-03,  
2.797839401605789273190803682523e-03,  
1.191563814457167239116805610408e-03,  
4.685515378084113654798021268418e-04,  
1.700140882628094094098971557634e-04,  
5.688743760040241092701878858822e-05,  
1.754048584809390503836776197909e-05,  
4.979924532590987011340992705981e-06,  
1.300747003238199233513755866984e-06,  
3.122872986178903081979449917514e-07,  
6.884581122154350090644062663124e-08,  
1.392190715293517881195788161746e-08,  
2.579397229426394801149805695268e-09,  
4.373186659848403445632172536186e-10,  
6.775780487774553786308396491931e-11,  
9.580316508735857708620663585480e-12,  
1.234214486600556690816236044371e-12,  
1.446347321190416563205909284280e-13,  
1.539049730353545814249810703833e-14,  
1.484223837513856482911895568900e-15,  
1.294548159339371534395456955600e-16,  
1.018933230423292524036582044691e-17,  
7.220107316928292019644377341307e-19,  
4.594007677329721592211726053893e-20,  
2.617457583934811155868731666743e-21,  
1.331367859033589604405994294736e-22,  
6.025984032006454288646569872263e-24,  
2.418403459647664969603905743957e-25,  
8.572830483769353744549325497395e-27,  
2.672923620058073240172664371834e-28,  
7.296545006768404253818687043209e-30,  
1.735103020282061208816016881382e-31,  
3.574378895879421072164570348026e-33,  
6.339913526366489060767539973884e-35,  
9.616708067967506977595218244602e-37,  
1.238085557976368037618838166903e-38,  
1.341497481764369366965568415626e-40,  
1.211779534130591907354349400912e-42,  
9.028040138786644009179615645741e-45,  
5.480217028978796498206162830512e-47,  
2.672743751736067854520219899160e-49,  
1.030486252055694734226723308562e-51,  
3.082077383339298687104255411632e-54,  
6.993072924051955987987474150598e-57,  
1.171978501212980517385598883733e-59,  
1.404467257740487260441865920030e-62,  
1.156155164096375213347254094680e-65,  
6.214244161830313662409307302240e-69,  
2.041585797243985015800692473788e-72,  
3.751215868804724996562746242353e-76,  
3.401230086936637126866928667296e-80,  
1.261249483338538303309322166297e-84,  
1.404689771315088634798657253446e-89,  
2.608172402409111079248851484591e-95,  
1.799065980109284720823363388052e-102)

```

QuadWeight_AS = c(rev(w), w) # Abramowitz and Stegun weights and
# abscissae for function exp(-x^2) instead of exp(-0.5 * x^2), need
# to be transformed.
QuadAbscissa_AS = c(-rev(x), x)
QuadWeight = QuadWeight_AS / sqrt(pi)
QuadAbscissa = sqrt(2.0) * QuadAbscissa_AS

sum(QuadWeight) # 1
sum(QuadAbscissa^2 * QuadWeight) # 1
sum(QuadAbscissa^4 * QuadWeight) # 3
QuadAbscissa
pnorm(QuadAbscissa)

# Even with nQuad = 128 the central interval still ranges from -0.139
# to 0.139 standard deviations and contains 11.0% of the probability
# mass.
# This spacing of abscissae isn't fine enough.

#####
# We really need close spacing for integrands that involve
# vulnerability functions (sigmoidal functions) and we need it to
# work on polynomials only up to order 3 (length-weight
# relationships). In reality this means only up to order 2 because
# the abscissae will be symmetric about the origin.
# Choose normal distribution quantiles as the abscissae. Then we want
# the weights to be as close to constant as possible.
nQuad = 100
QuadAbscissa = qnorm((-0.5 + 1:nQuad) / nQuad)
QuadWeight1 = rep(1 / nQuad, nQuad)
sum(QuadWeight1)
sum(QuadAbscissa)
sum(QuadWeight1 * QuadAbscissa^2) # < 1
# Solve by differentiation using Lagrange multipliers.
# First ensure that abscissae are exactly symmetric.
l1 = QuadAbscissa < 0
l2 = QuadAbscissa > 0
QuadAbscissa[l2] = rev(abs(QuadAbscissa[l1]))
if (nQuad %% 2 == 1) QuadAbscissa[(nQuad + 1) / 2] = 0
s2 = sum(QuadAbscissa^2)
s4 = sum(QuadAbscissa^4)
# Values for Lagrange multipliers
lambda2 = (1 - s2 / nQuad) / (s4 - s2^2 / nQuad)
lambda0 = -s2 * lambda2 / nQuad
QuadWeight = QuadWeight1 + lambda0 + lambda2 * QuadAbscissa^2
sum(QuadWeight) # Should be 1
sum(QuadWeight * QuadAbscissa^2) # Should be 1, and now is!
sum(QuadWeight * QuadAbscissa^4) # Should be 3
sum(QuadWeight * QuadAbscissa^6) # Should be 15
sum(QuadWeight * QuadAbscissa^8) # Should be 105
sum(QuadWeight * QuadAbscissa^10) # Should be 945
plot(QuadAbscissa)
plot(nQuad * QuadWeight)
# We see that higher moments are severely underestimated. Evidently
# it's a matter of horses for courses. We have to be careful to
# specify what we want. We see why the Gauss-Hermite abscissae seem
# so biased towards large values.
# For sigmoidal functions it seems clear that we should have close
# spacing of the abscissae at the expense of matching high-order moments.

```

## Appendix 2: Analytic formulae for integrals

### A2.1 Mean weight at age

The expression

$$E(L_a^3 | L_v = L)$$

can be evaluated from equations (4.8), (4.11) and (4.12). We use the following standard formulae for expectations of powers of a normally distributed variable  $X$  with mean  $\mu$  and variance  $\sigma^2$ :

$$E(X) = \mu \quad (\text{A2.1})$$

$$E(X^2) = \mu^2 + \sigma^2 \quad (\text{A2.2})$$

$$E(X^3) = \mu^3 + 3\mu\sigma^2. \quad (\text{A2.3})$$

From equation (4.8) and using the fact that  $L_v$  and  $X_v$  are independent,

$$\begin{aligned} E(L_a^3 | L_v = L) &= E(\{p_{av}L_v + q_{av}X_v\}^3 | L_v = L) = E(p_{av}^3L^3 + 3p_{av}^2L^2q_{av}X_v + 3p_{av}Lq_{av}^2X_v^2 + q_{av}^3X_v^3) \\ &= p_{av}^3L^3 + 3p_{av}^2q_{av}\mu_{X_v}L^2 + 3p_{av}q_{av}^2(\mu_{X_v}^2 + \sigma_{X_v}^2)L + q_{av}^3(\mu_{X_v}^3 + 3\mu_{X_v}\sigma_{X_v}^2), \end{aligned} \quad (\text{A2.4})$$

where  $\mu_{X_v}$  and  $\sigma_{X_v}^2$  are given by equations (4.11) and (4.12).

Therefore, to calculate the vulnerable masses in equations (4.27) and (4.28) using the vulnerability formulation (4.26), we need to evaluate integrals of the form

$$I_n = \int_{-\infty}^{\infty} (L^n/\sigma_v) \phi(\{L - \mu_v\}/\sigma_v) \Phi(\{L - \xi\}/\eta) dL \quad (\text{A2.5})$$

for powers  $n = 0, 1, 2$  and  $3$ . These evaluations will be taken up below.

### A2.2 Evaluation of integrals

An expression for the integral (A2.5) can be found explicitly as follows, where for convenience we omit the subscript  $v$  in  $\mu$  and  $\sigma$ :

$$I_n = \frac{1}{\sigma} \int_{-\infty}^{\infty} L^n \phi(\{L - \mu\}/\sigma) \Phi(\{L - \xi\}/\eta) dL = \frac{1}{\sigma\eta} \int_{-\infty}^{\infty} L^n \phi(\{L - \mu\}/\sigma) \int_{\xi}^{\infty} \phi(\{L - x\}/\eta) dx dL.$$

Interchanging the order of integration to put the integral with respect to  $L$  on the inside, this becomes

$$\begin{aligned} I_n &= \frac{1}{\sigma\eta} \int_{\xi}^{\infty} \int_{-\infty}^{\infty} L^n \phi(\{L - \mu\}/\sigma) \phi(\{L - x\}/\eta) dL dx \\ &= \frac{1}{2\pi\sigma\eta} \int_{\xi}^{\infty} \int_{-\infty}^{\infty} L^n \exp\left[-\frac{1}{2}\left\{(L^2 - 2\mu L + \mu^2)/\sigma^2 + (L^2 - 2xL + x^2)/\eta^2\right\}\right] dL dx \\ &= \frac{1}{2\pi\sigma\eta} \int_{\xi}^{\infty} \int_{-\infty}^{\infty} L^n \exp\left[-\frac{1}{2}\left\{(\sigma^{-2} + \eta^{-2})L^2 - 2(\sigma^{-2}\mu + \eta^{-2}x)L + (\sigma^{-2}\mu^2 + \eta^{-2}x^2)\right\}\right] dL dx \\ &= \frac{1}{2\pi\sigma\eta} \int_{\xi}^{\infty} \int_{-\infty}^{\infty} L^n \exp\left[-\frac{1}{2}\left\{\frac{\sigma^2 + \eta^2}{\sigma^2\eta^2}\left(L - \frac{\eta^2\mu + \sigma^2x}{\sigma^2 + \eta^2}\right)^2 + \frac{(\mu - x)^2}{\sigma^2 + \eta^2}\right\}\right] dL dx. \end{aligned}$$

The inner integral which is over  $L$  is now the integral of  $L^n$  multiplied by a normal probability density with mean

$$\mu^*(x) = \frac{\sigma^{-2}\mu + \eta^{-2}x}{\sigma^{-2} + \eta^{-2}} = \frac{\eta^2\mu + \sigma^2x}{\sigma^2 + \eta^2}$$

and variance

$$\sigma^{*2} = 1/(\sigma^{-2} + \eta^{-2}) = \sigma^2\eta^2/(\sigma^2 + \eta^2)$$

which does not depend on  $x$ .

With algebraic manipulation and use of equations (A2.1)–(A2.3) above, the double integral reduces to

$$I_n = \frac{1}{\sqrt{2\pi(\sigma^2 + \eta^2)}} \int_{\xi}^{\infty} \exp\left\{-\frac{1}{2} \frac{(x-\mu)^2}{\sigma^2 + \eta^2}\right\} M_n(x) dx \quad (\text{A2.6})$$

where

$$M_0(x) = 1, \quad M_1(x) = \mu^*(x), \quad M_2(x) = \mu^*(x)^2 + \sigma^{*2} \quad \text{and} \quad M_3(x) = \mu^*(x)^3 + 3\mu^*(x)\sigma^{*2}. \quad (\text{A2.7})$$

Again this is the integral of a normal density multiplied by  $M_n(x)$ , although this time one of the limits of integration is finite. Such integrals can be evaluated using the following formulae for indefinite integrals which can be proven easily by integration by parts:

$$\int u\phi(u) du = -\phi(u) \quad (\text{A2.8})$$

$$\int u^2\phi(u) du = \Phi(u) - u\phi(u) \quad (\text{A2.9})$$

$$\int u^3\phi(u) du = -(2 + u^2)\phi(u). \quad (\text{A2.10})$$

By the substitution

$$u = (x - \mu) / \sqrt{\sigma^2 + \eta^2},$$

(A2.6) is converted to

$$I_n = \int_{\tau}^{\infty} \phi(u) M_n(\mu + \sqrt{\sigma^2 + \eta^2} u) du \quad (\text{A2.11})$$

where the integration limit  $\tau$  is given by

$$\tau = (\xi - \mu) / \sqrt{\sigma^2 + \eta^2}. \quad (\text{A2.12})$$

We note that

$$\mu^*(\mu + \sqrt{\sigma^2 + \eta^2} u) = \left\{ \eta^2 \mu + \sigma^2 (\mu + \sqrt{\sigma^2 + \eta^2} u) \right\} / (\sigma^2 + \eta^2) = \mu + \sigma^2 u / \sqrt{\sigma^2 + \eta^2}. \quad (\text{A2.13})$$

From equations (A2.8)–(A2.10) and (A2.12)–(A2.13), with a substantial amount of algebra the following formulae can be derived for the integrals of powers of  $\mu^*$ :

$$\int_{\tau}^{\infty} \phi(u) \mu^*(\mu + \sqrt{\sigma^2 + \eta^2} u) du = \mu \{1 - \Phi(\tau)\} + \sigma^2 \phi(\tau) / \sqrt{\sigma^2 + \eta^2}, \quad (\text{A2.14})$$

$$\begin{aligned} \int_{\tau}^{\infty} \phi(u) \mu^*(\mu + \sqrt{\sigma^2 + \eta^2} u)^2 du &= \mu^2 \{1 - \Phi(\tau)\} + 2\mu \frac{\sigma^2}{\sqrt{\sigma^2 + \eta^2}} \phi(\tau) + \frac{\sigma^4}{\sigma^2 + \eta^2} \{1 - \Phi(\tau) + \tau\phi(\tau)\} \\ &= \left( \mu^2 + \frac{\sigma^4}{\sigma^2 + \eta^2} \right) \{1 - \Phi(\tau)\} + \frac{(\mu + \xi)\sigma^2 + 2\mu\eta^2}{(\sigma^2 + \eta^2)^{\frac{3}{2}}} \sigma^2 \phi(\tau) \end{aligned} \quad (\text{A2.15})$$

and

$$\begin{aligned} \int_{\tau}^{\infty} \phi(u) \{ \mu^*(\mu + \sqrt{\sigma^2 + \eta^2} u) \}^3 du &= \mu^3 \{1 - \Phi(\tau)\} + 3\mu^2 \frac{\sigma^2 \phi(\tau)}{\sqrt{\sigma^2 + \eta^2}} + 3\mu \frac{\sigma^4 \{1 - \Phi(\tau) + \tau\phi(\tau)\}}{\sigma^2 + \eta^2} + \frac{\sigma^6 (2 + \tau^2) \phi(\tau)}{(\sigma^2 + \eta^2)^{\frac{3}{2}}} \\ &= \left( \mu^3 + \frac{3\mu\sigma^4}{\sigma^2 + \eta^2} \right) \{1 - \Phi(\tau)\} + \left\{ \frac{3\mu\sigma^2(\mu\eta^2 + \xi\sigma^2) + (2 + \tau^2)\sigma^6}{(\sigma^2 + \eta^2)^{\frac{3}{2}}} \right\} \phi(\tau). \end{aligned} \quad (\text{A2.16})$$

Finally, substituting (A2.7) into (A2.11) and using (A2.14)–(A2.16) yields

$$I_0 = 1 - \Phi(\tau) \quad (\text{A2.17})$$

$$I_1 = \mu \{1 - \Phi(\tau)\} + \sigma^2 \phi(\tau) / \sqrt{\sigma^2 + \eta^2} \quad (\text{A2.18})$$

$$I_2 = (\mu^2 + \sigma^2) \{1 - \Phi(\tau)\} + \frac{(\mu + \xi)\sigma^2 + 2\mu\eta^2}{(\sigma^2 + \eta^2)^{\frac{3}{2}}} \sigma^2 \phi(\tau) \quad (\text{A2.19})$$

and

$$I_3 = (\mu^3 + 3\mu\sigma^2) \{1 - \Phi(\tau)\} + \frac{3\eta^2(\mu^2 + \sigma^2) + 3\mu\xi\sigma^2 + (2 + \tau^2)\sigma^4}{(\sigma^2 + \eta^2)^{\frac{3}{2}}} \sigma^2 \phi(\tau). \quad (\text{A2.20})$$

## Appendix 3: Age-length frequency plots

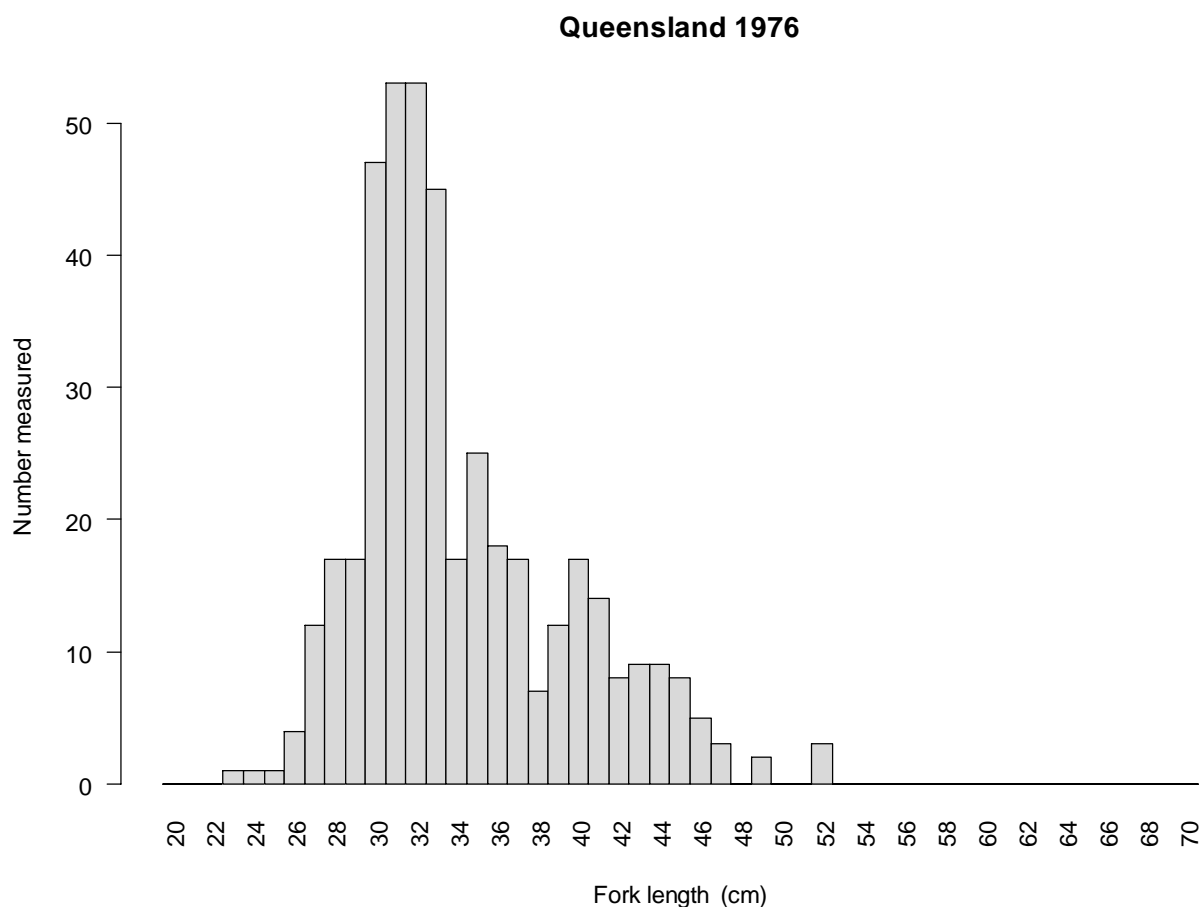
### A3.1 Data used in the model

The following plots summarise the length-frequency and age-at-length data used in the population model. For purposes of illustration they have used age-length keys when ageing data were available. In the model inputs, however, age-length keys were not used: the model fitted length-frequency data and age-at-length data; see sections 4.4 and 4.5.

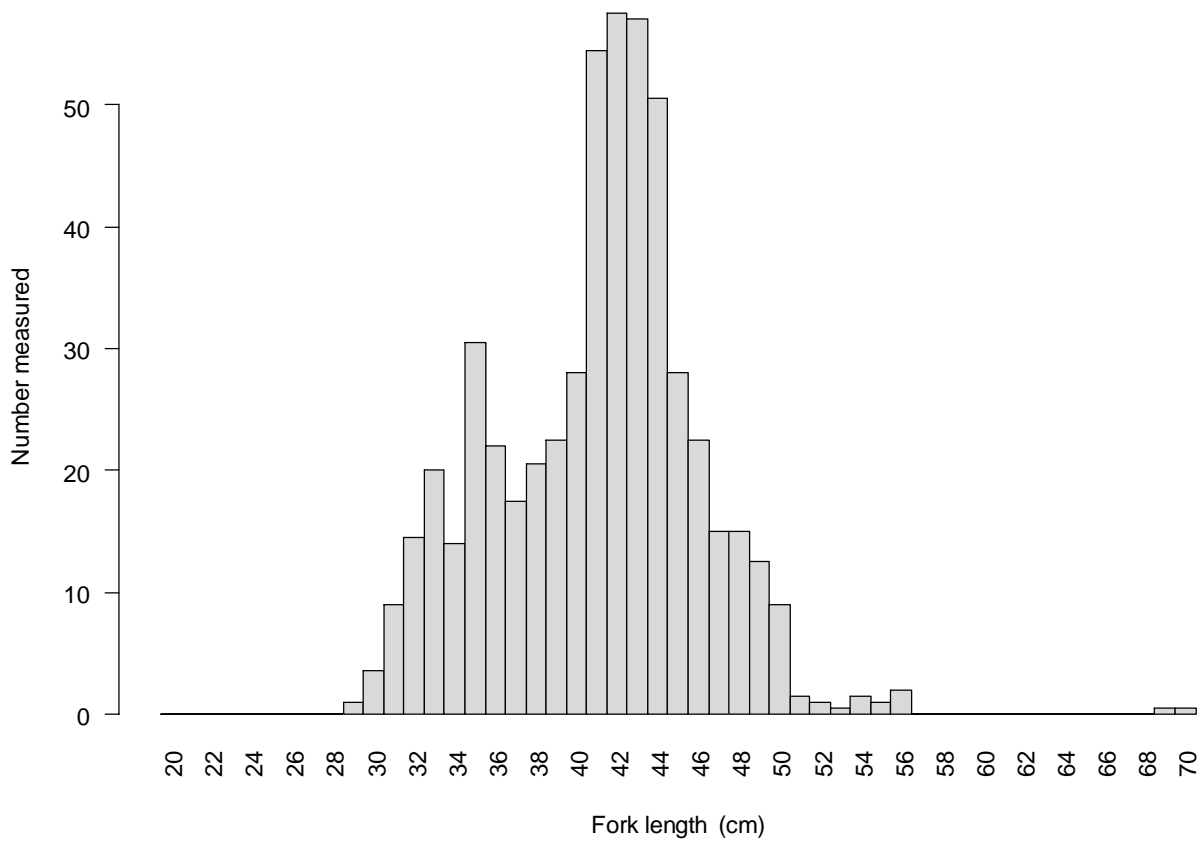
Plots labelled only “Queensland” are from the Queensland ocean-beach recreational fishery and form the mainstay of the length-frequency and age-at-length data used in the model. Data sources have been described in section 1.5.1 (page 8).

Bars in the plots represent length-frequency (number of fish whose lengths were measured). Where ageing data are available, the length-frequency bars are divided into different-coloured segments to show the age distribution within each one-centimetre length interval. Bars are coloured grey when no fish were aged from that length interval in that year and sector.

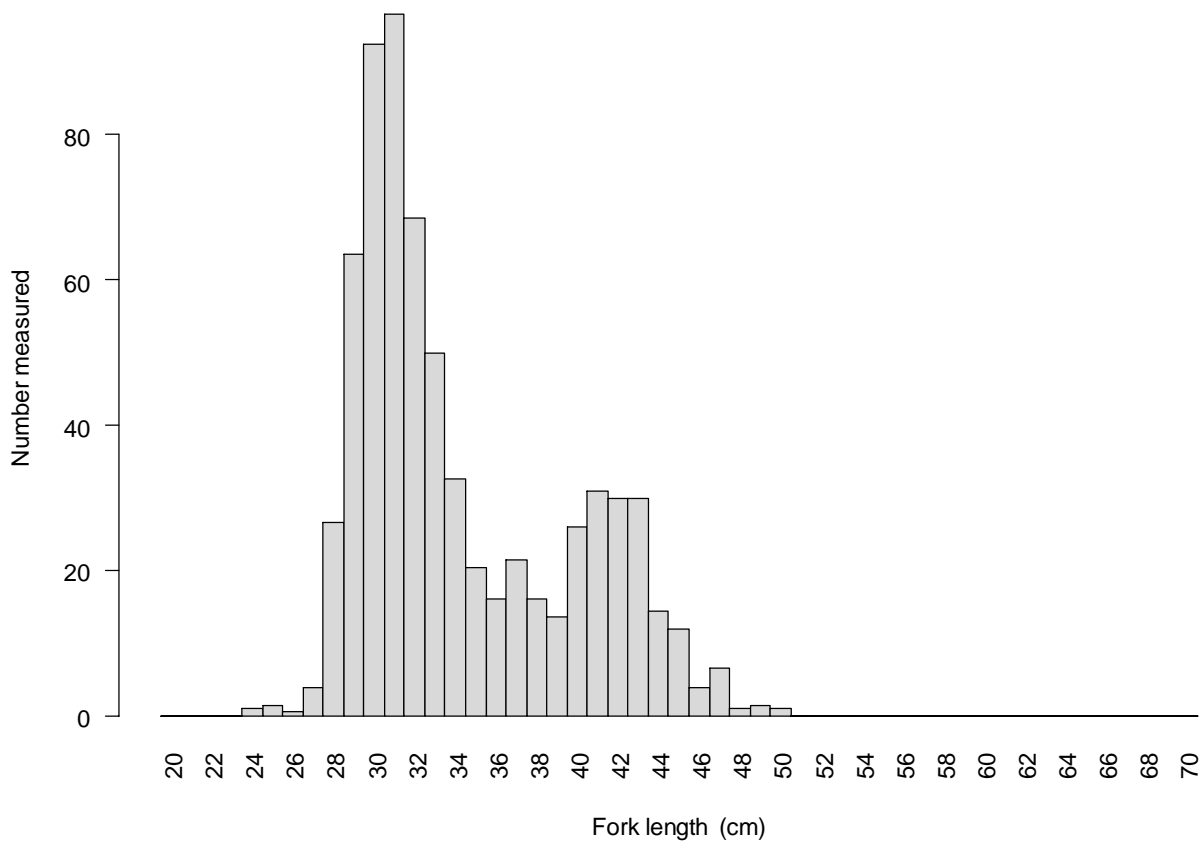
The descriptor “truncated” in the New South Wales commercial length frequencies indicates that only samples with a median fork length of 29 cm or more have been included (see section 1.5.1, page 8).



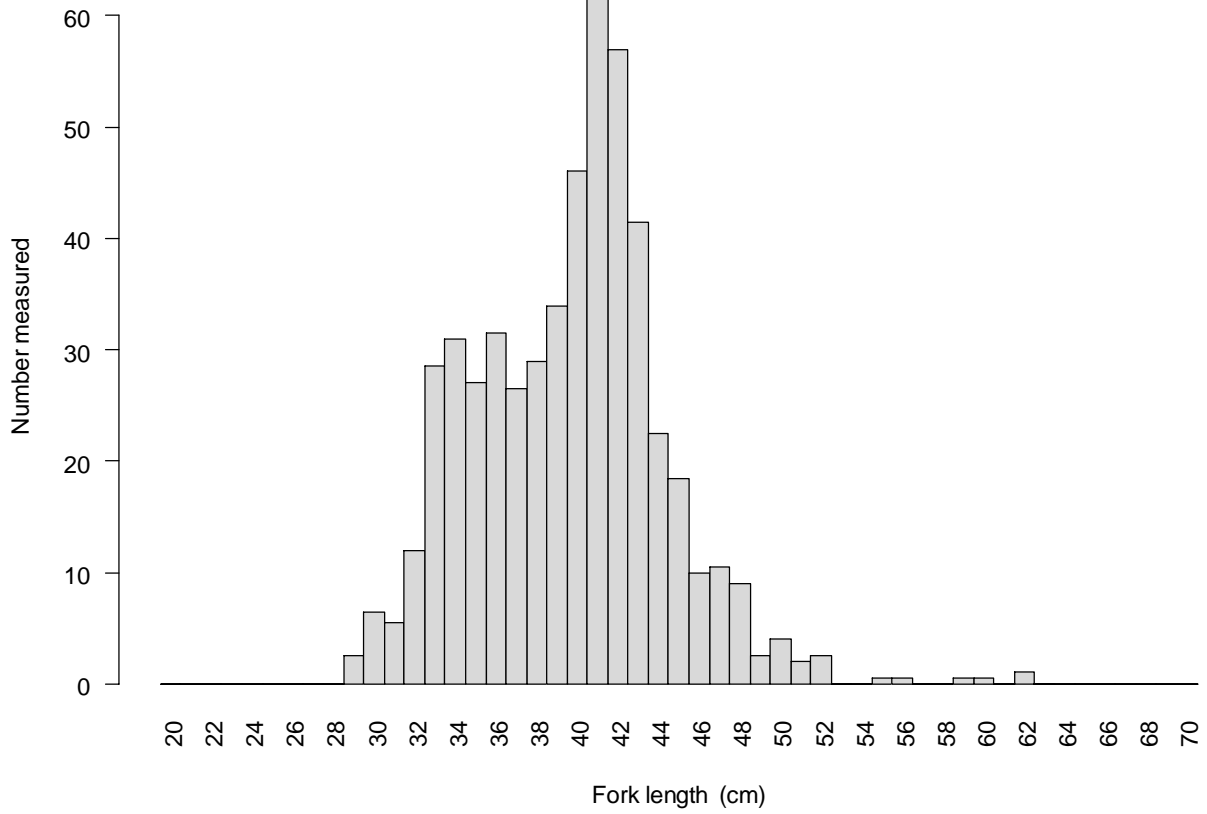
### Queensland 1978



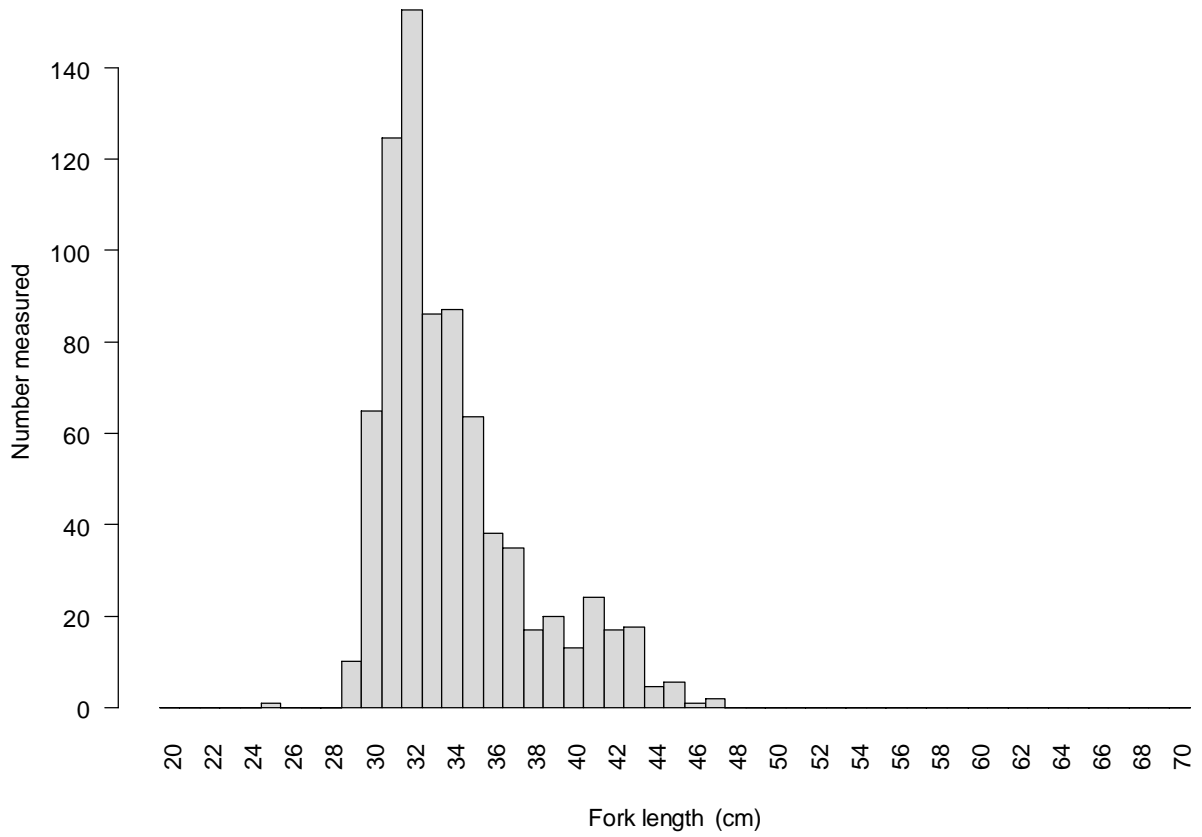
### Queensland 1979



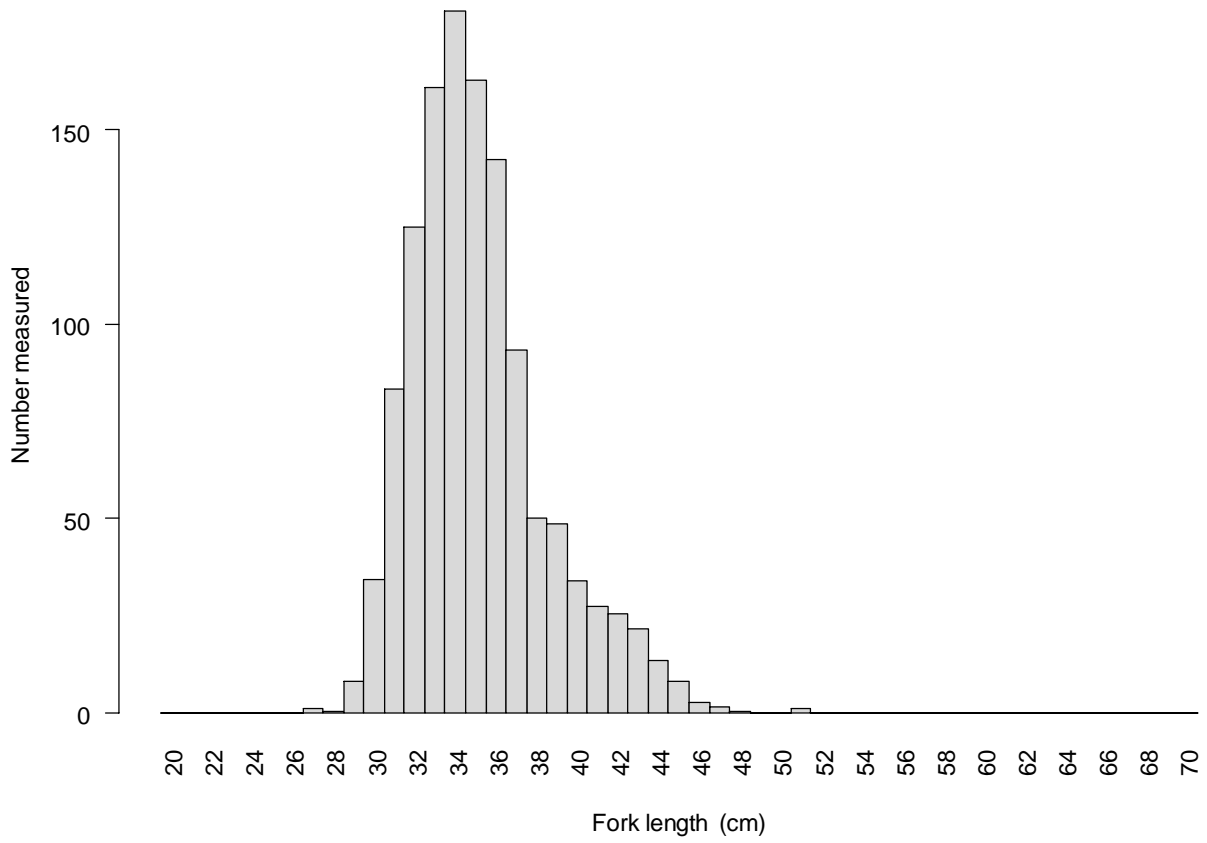
### Queensland 1980



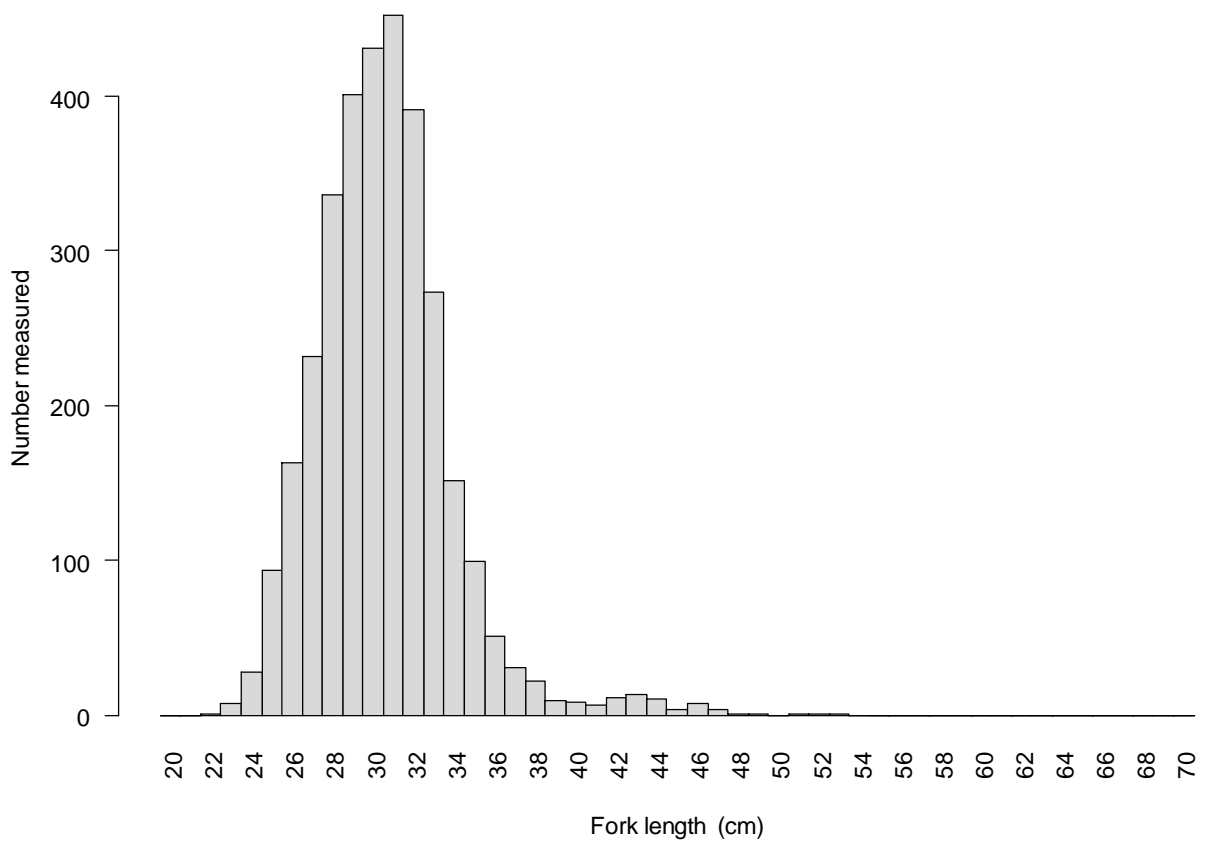
### Queensland 1987



### Queensland 1988

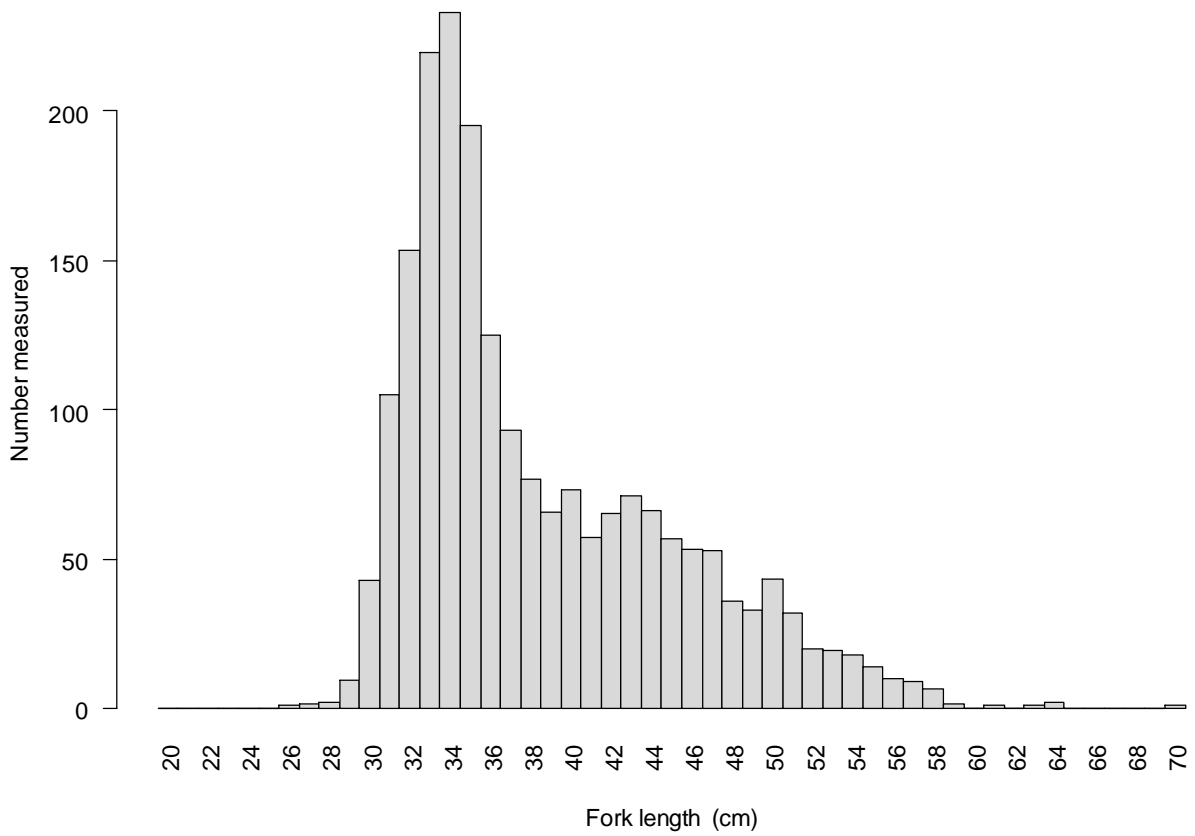


### Queensland 1989

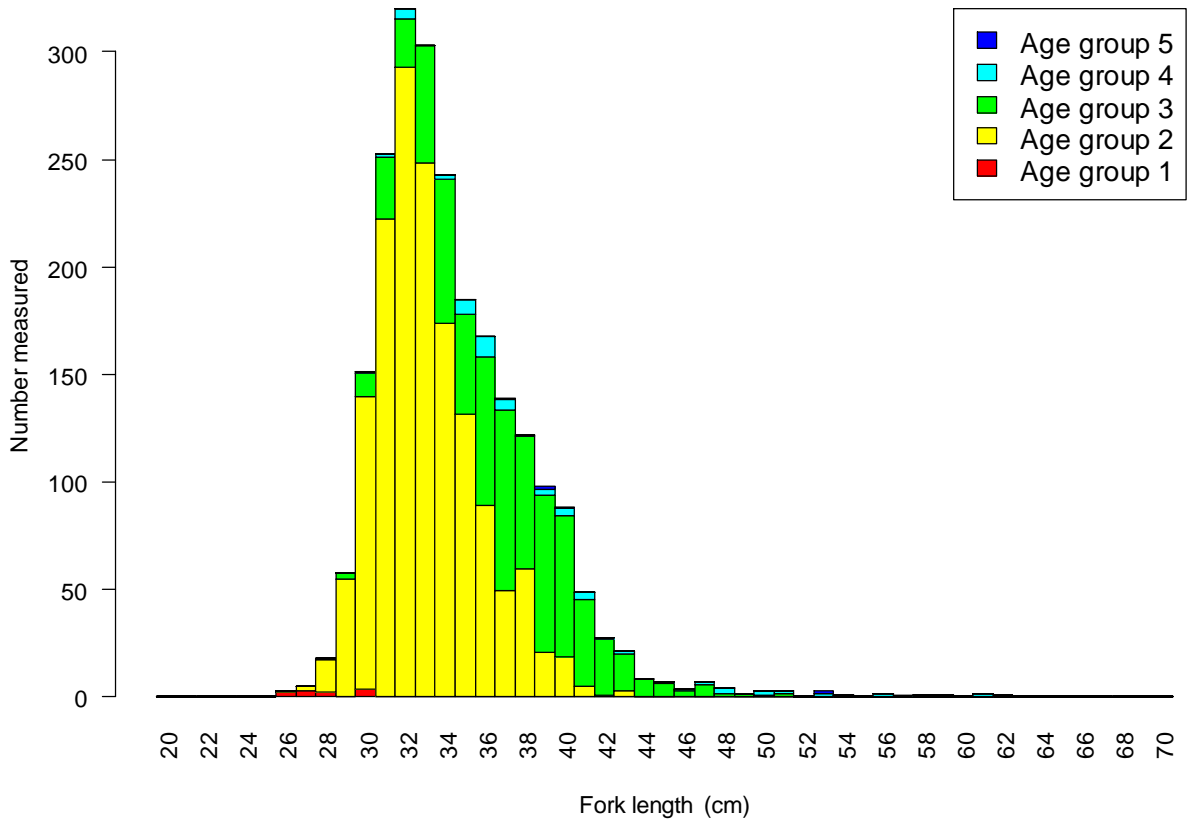




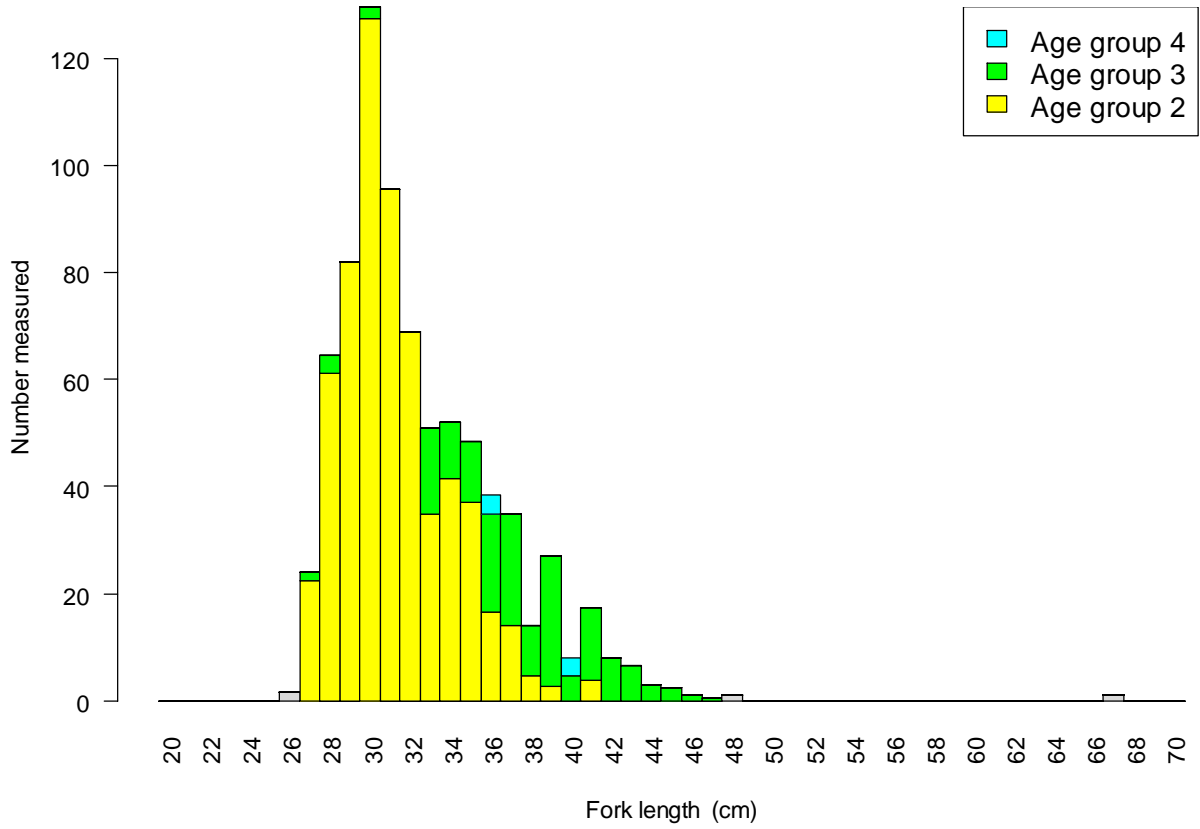
### Queensland 1990



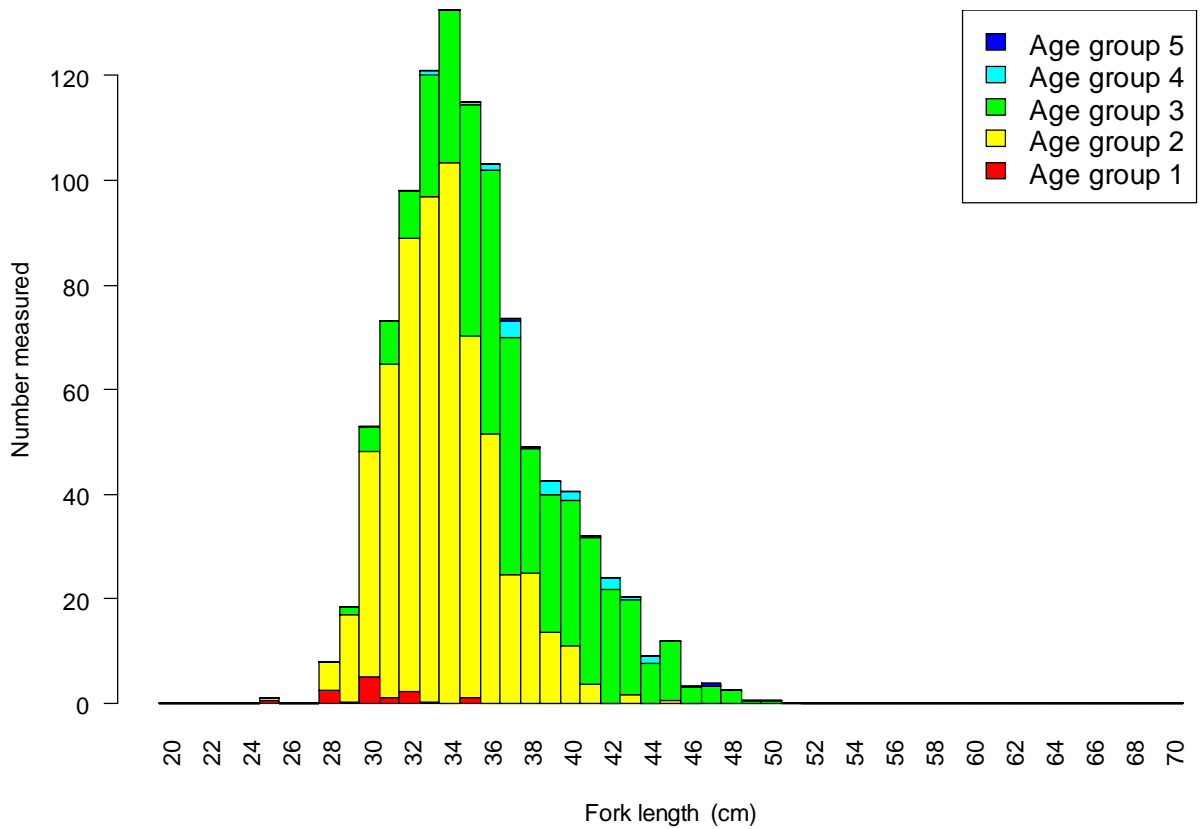
### Queensland 1995

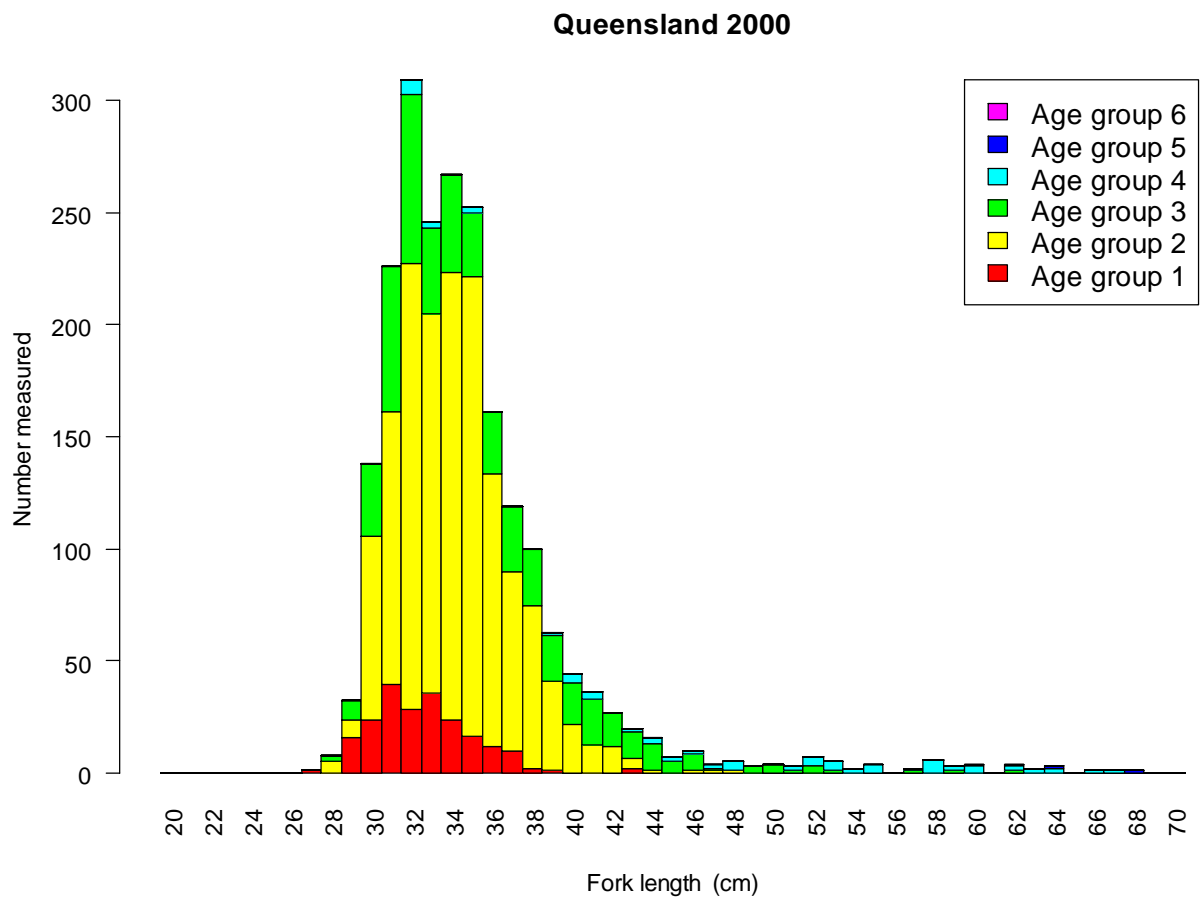
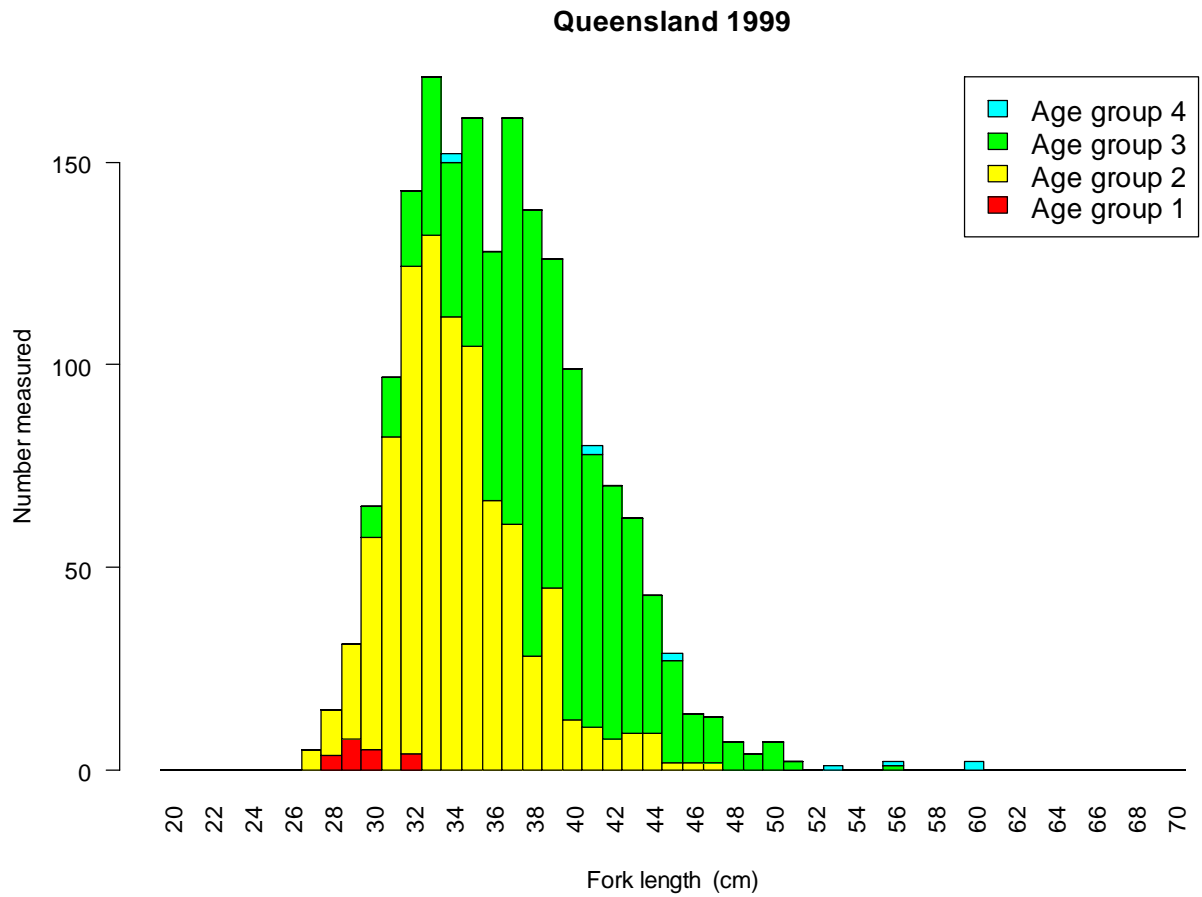


### Queensland 1996

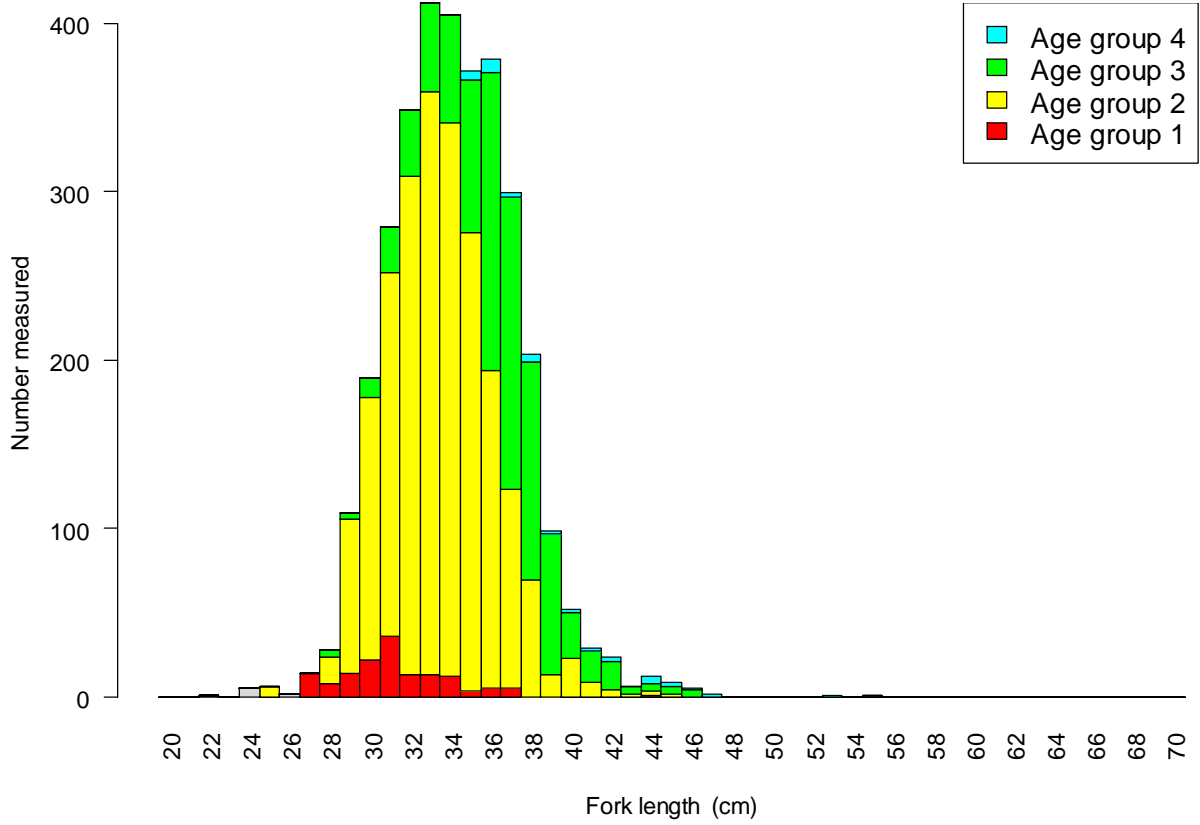


### Queensland 1997

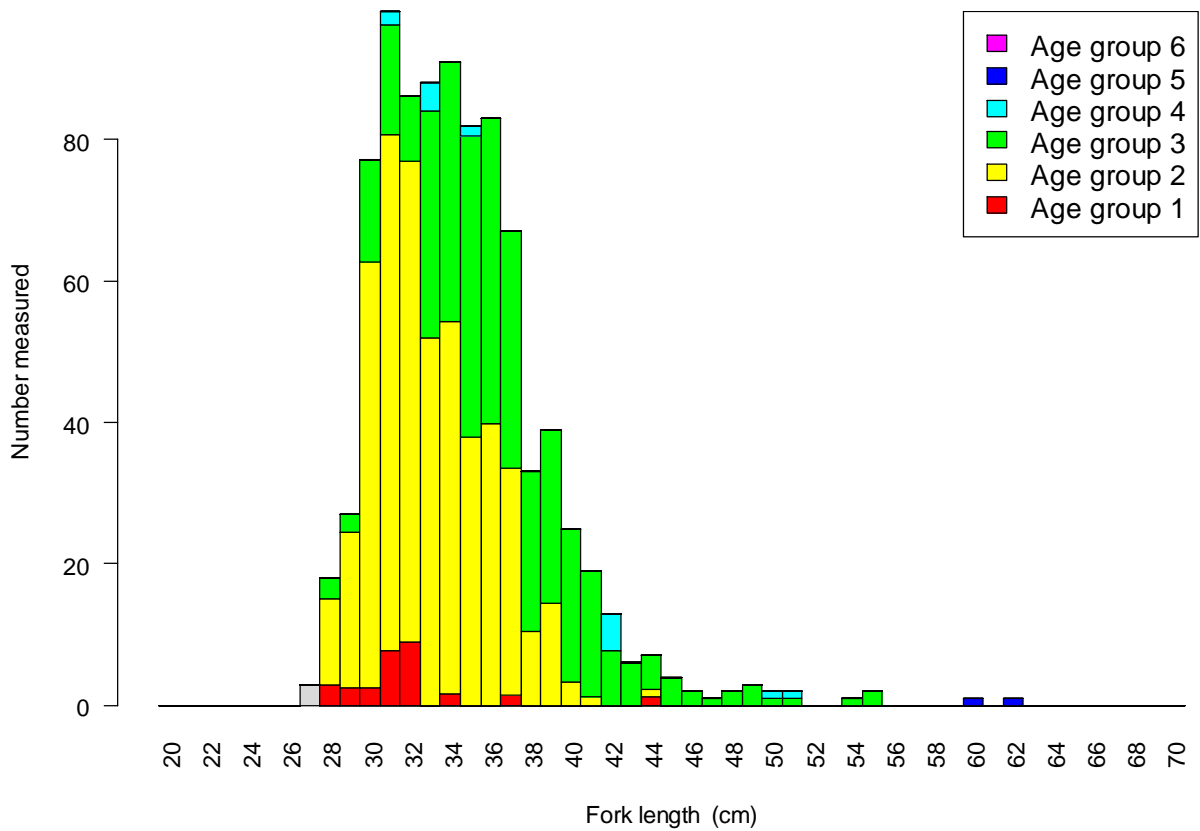




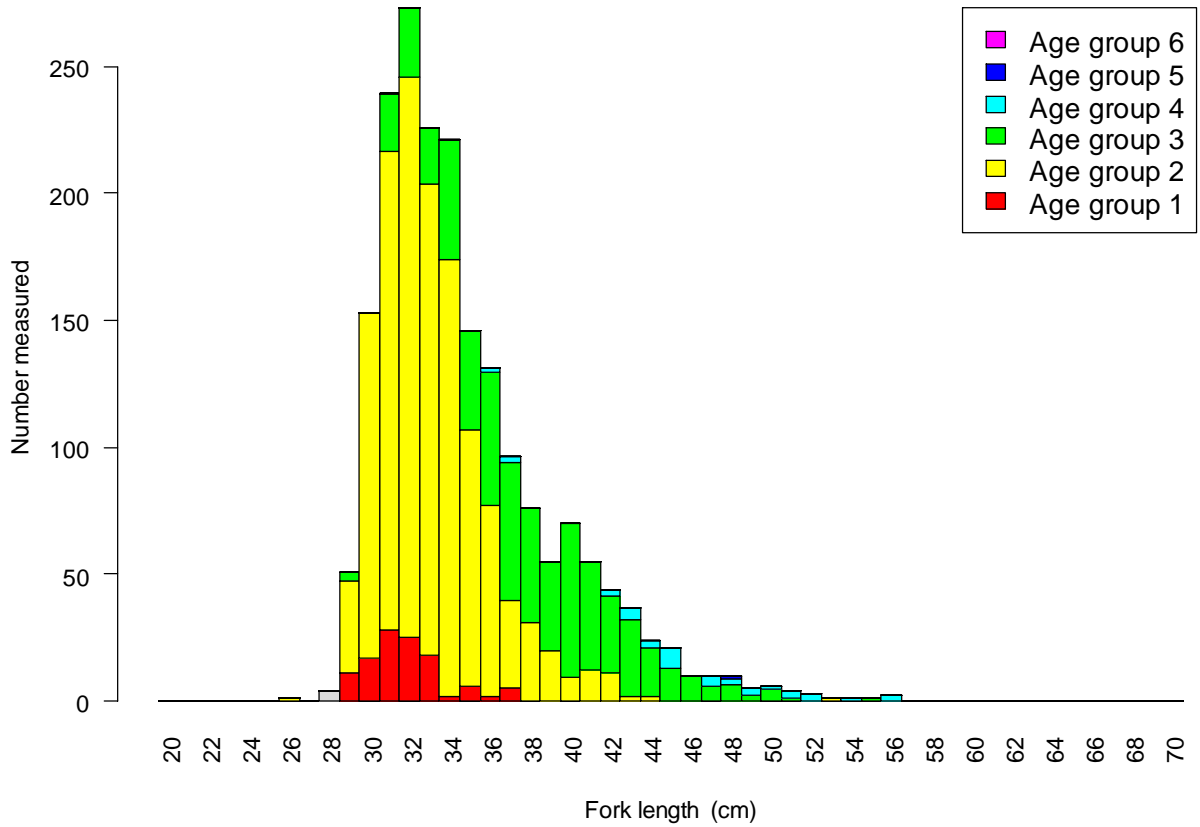
### Queensland 2001



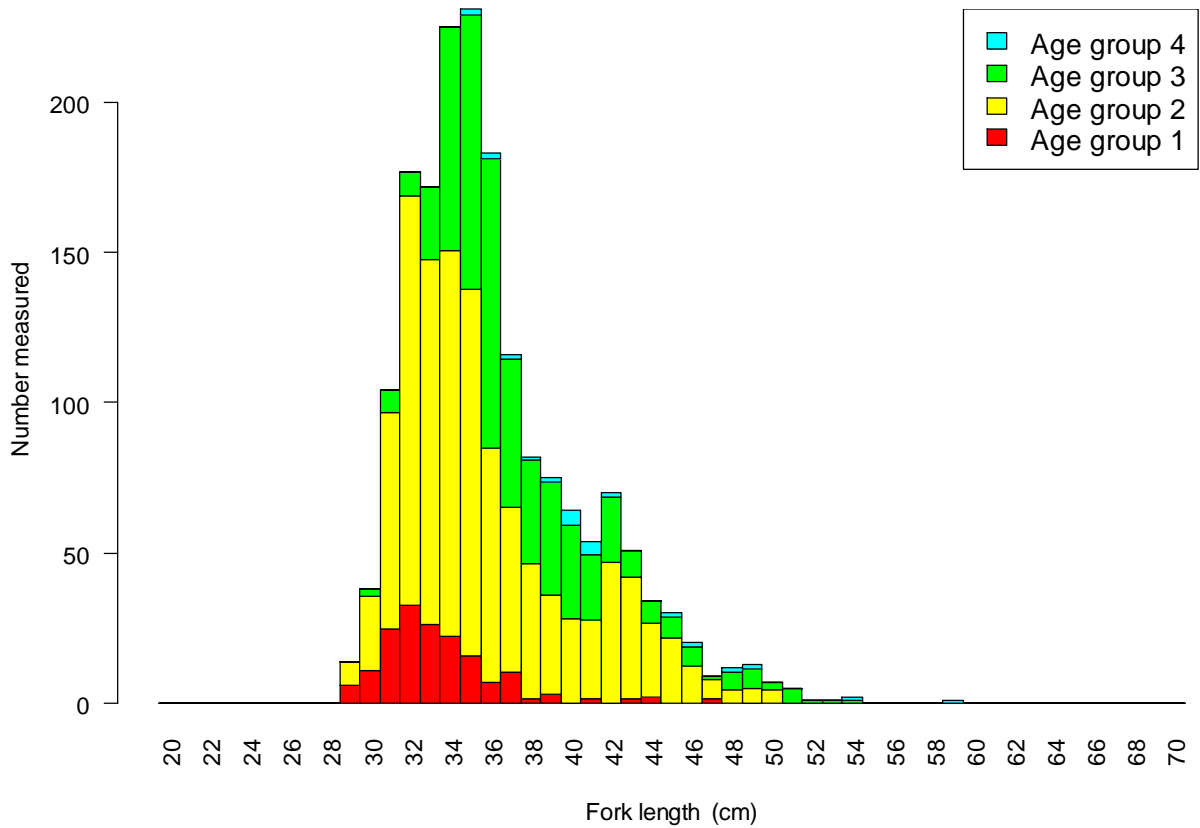
### Queensland 2002



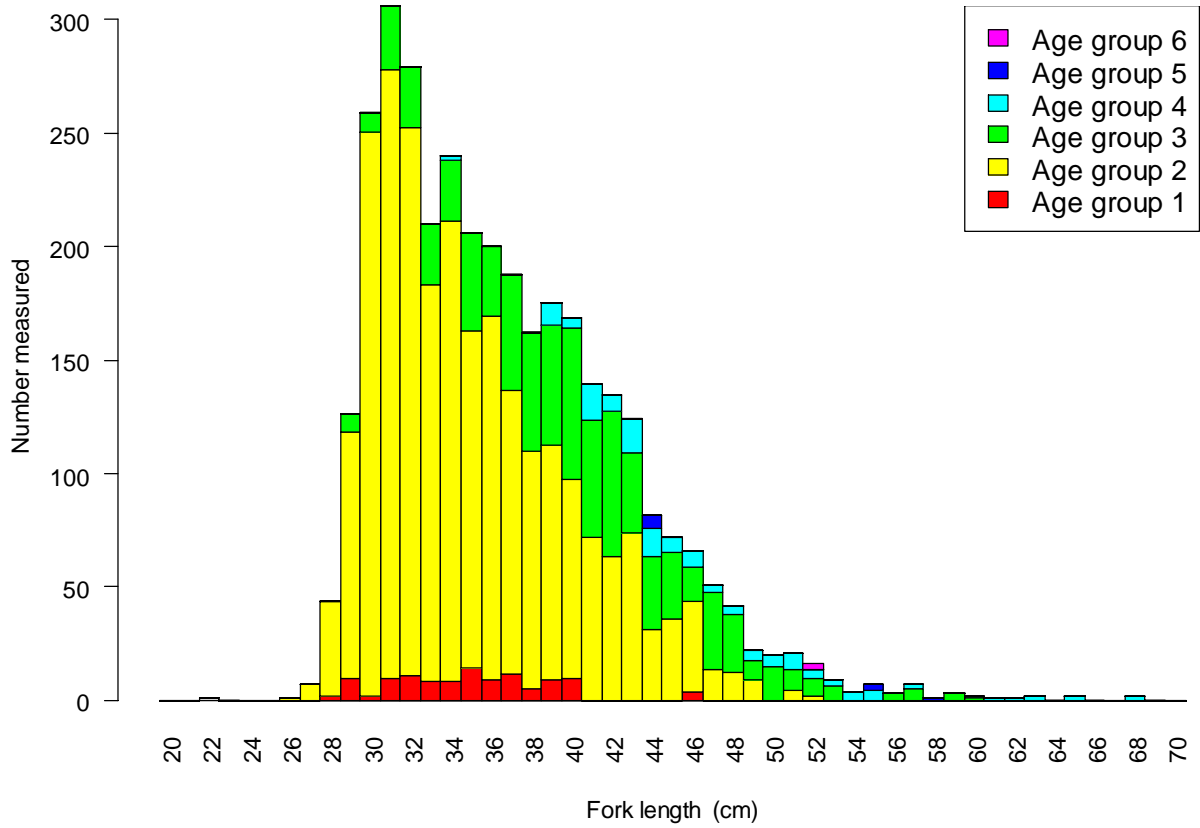
### Queensland 2003



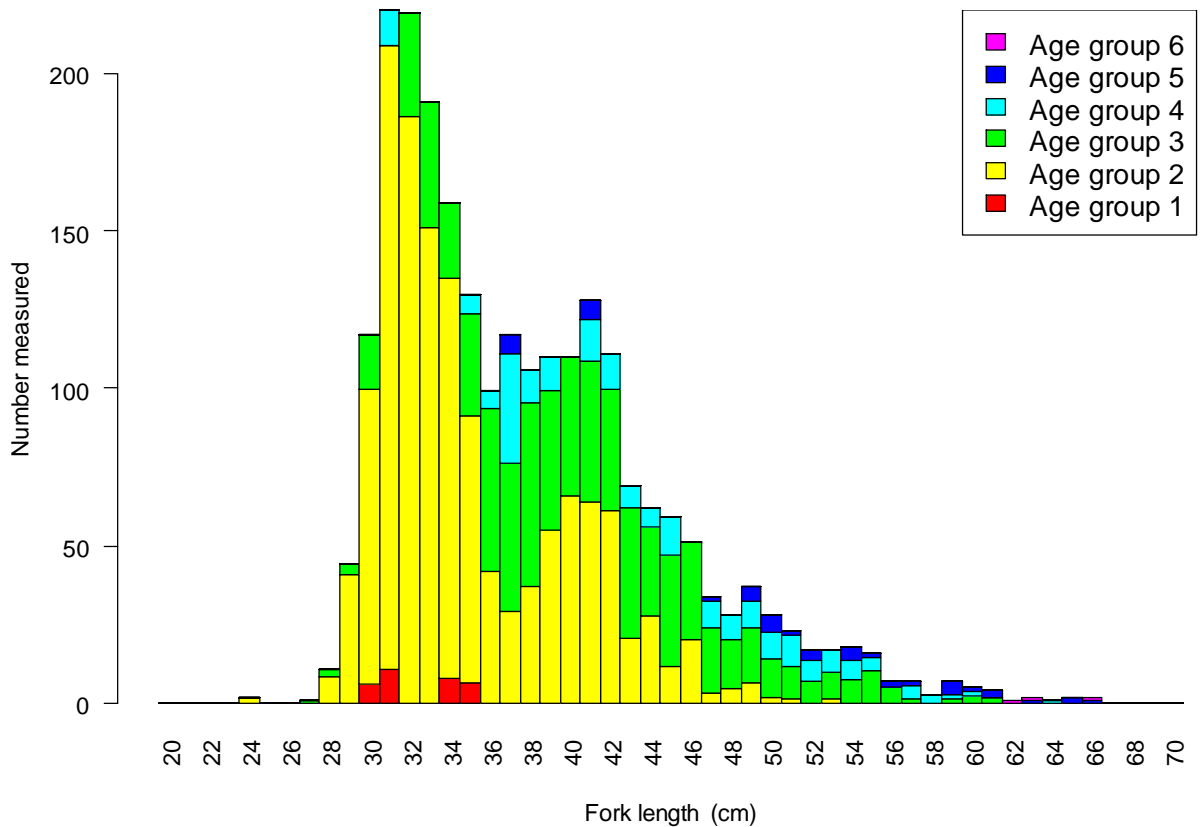
### Queensland 2004



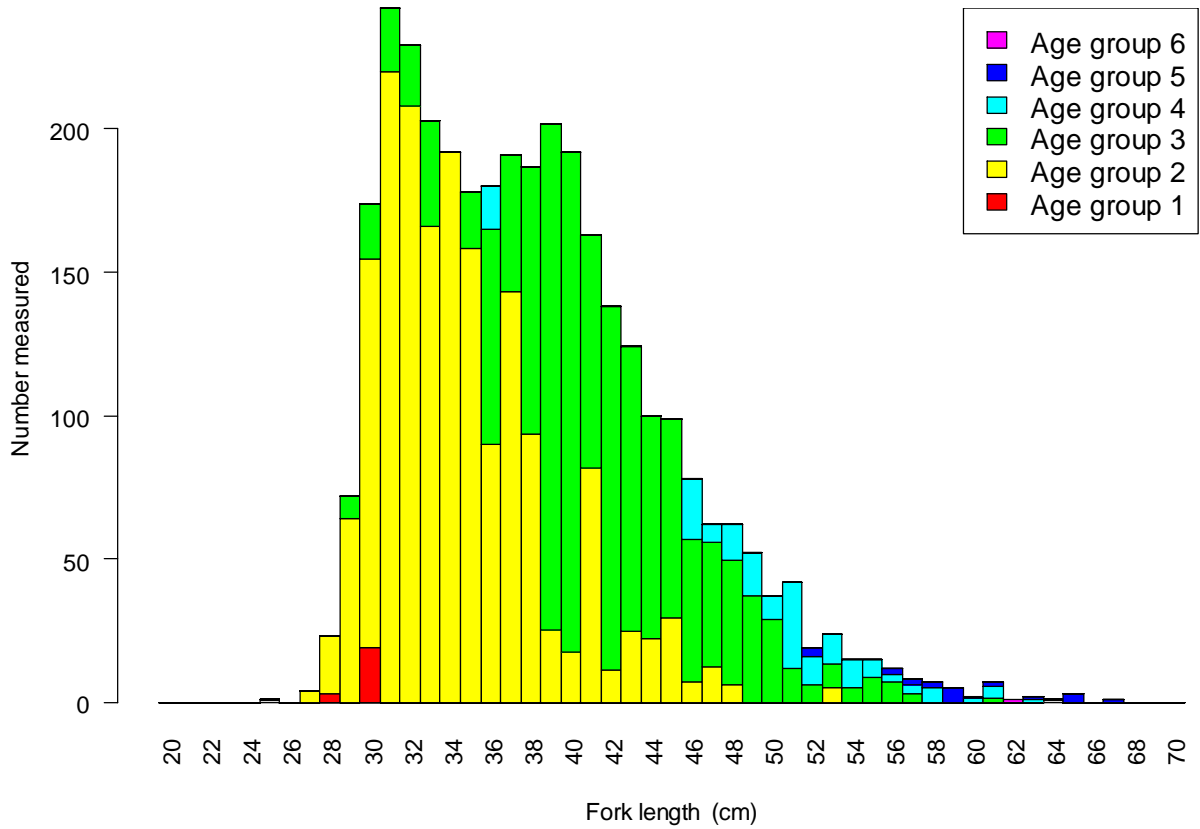
### Queensland 2005



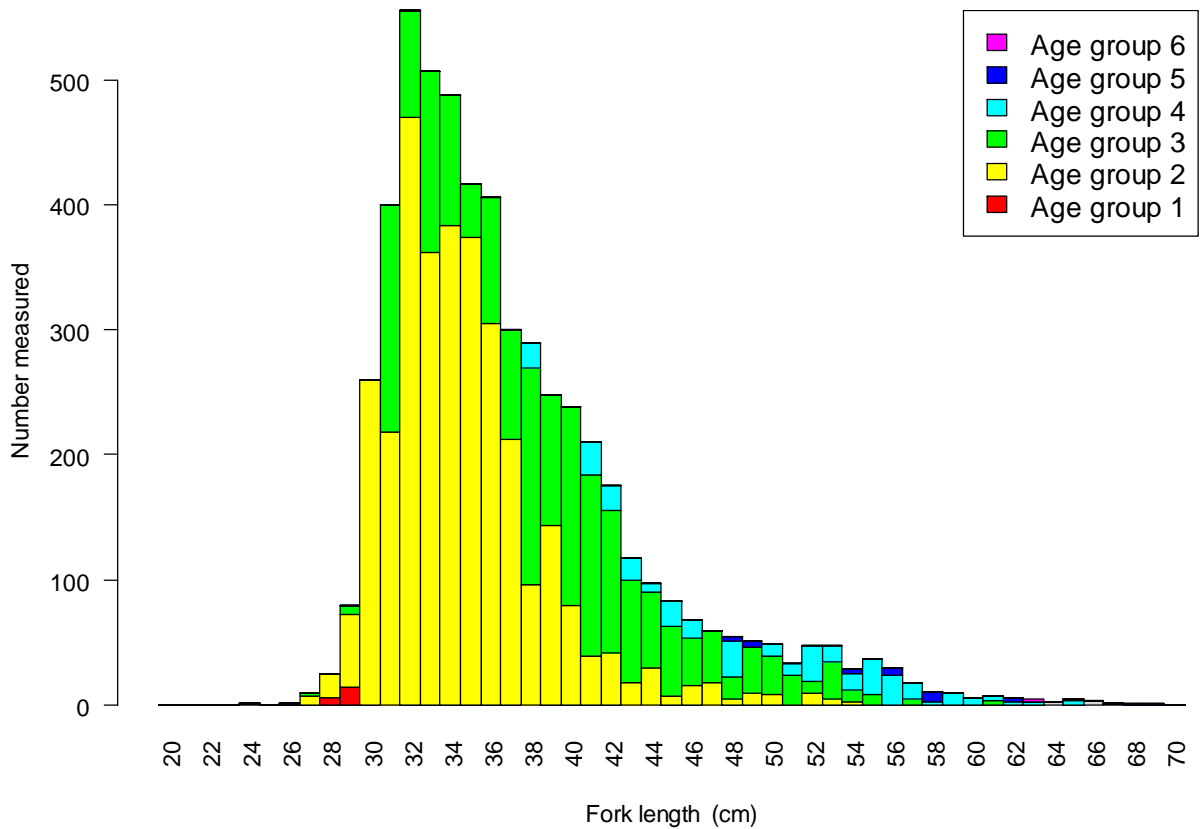
### Queensland 2006



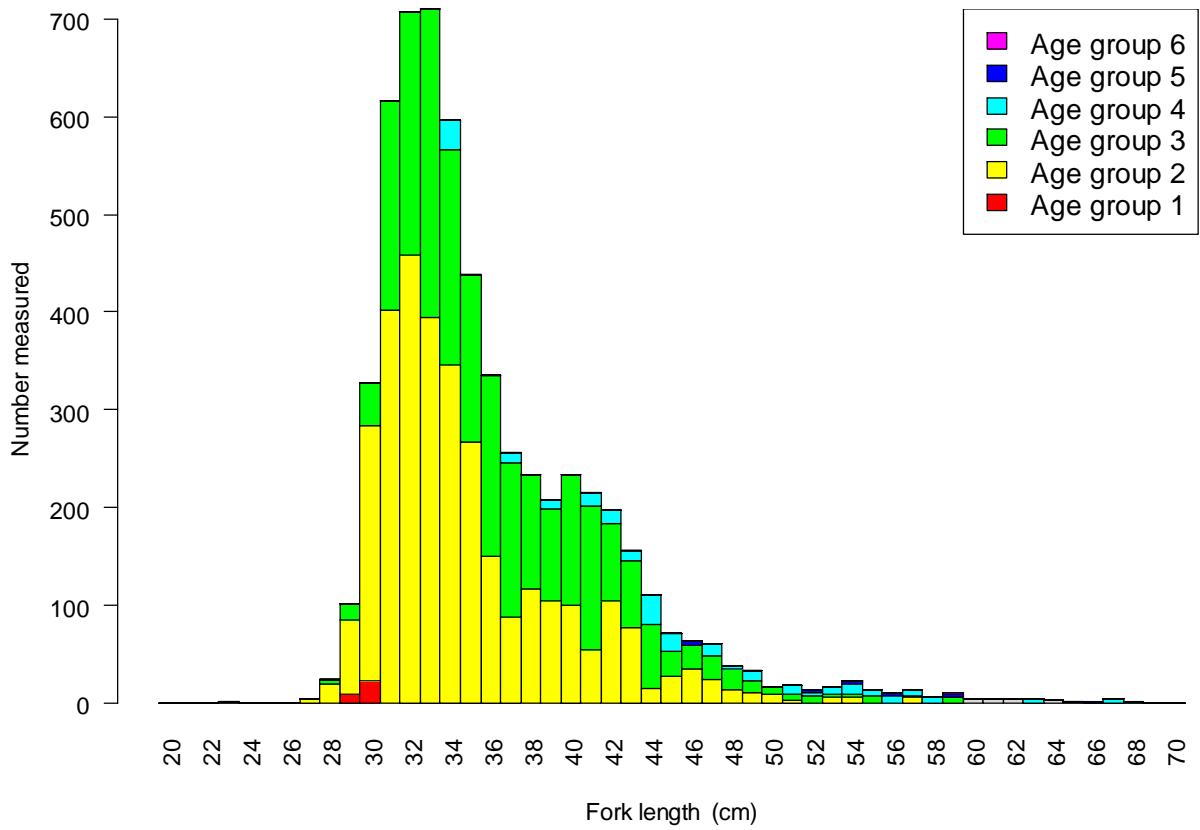
### Queensland 2007



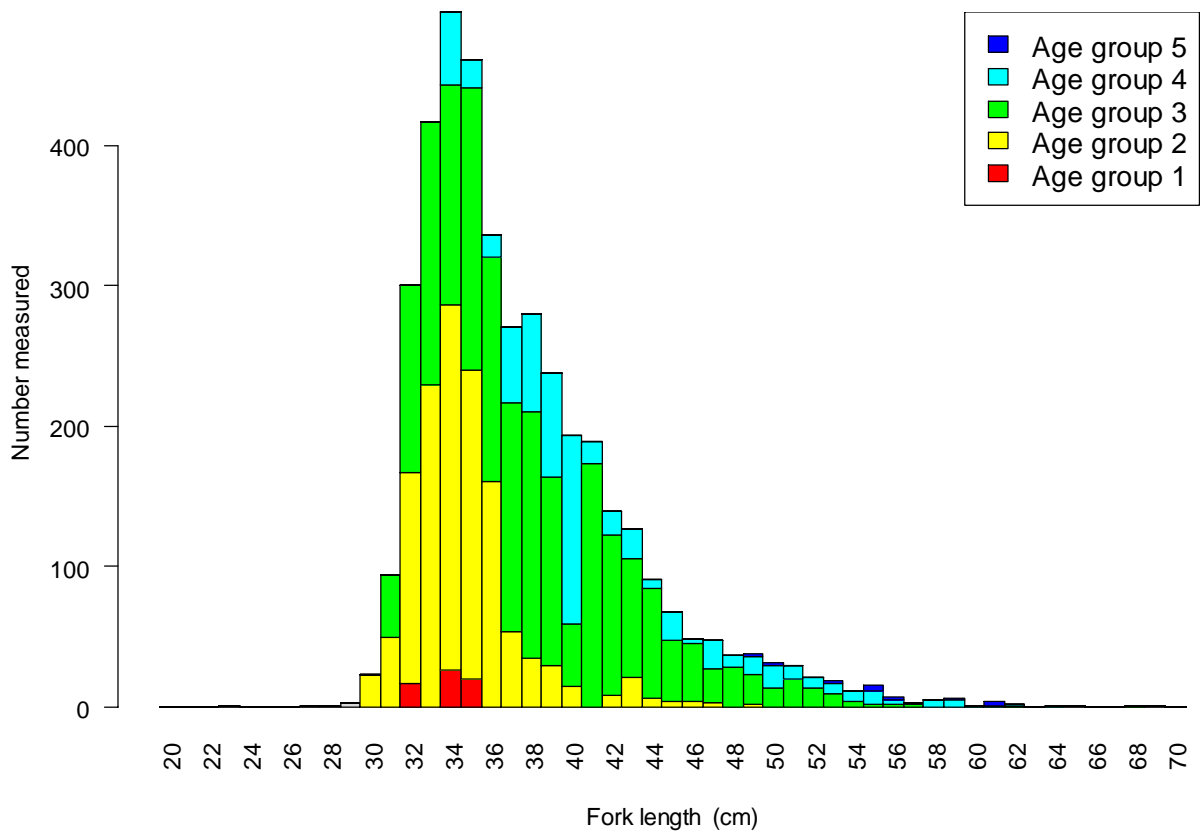
### Queensland 2008



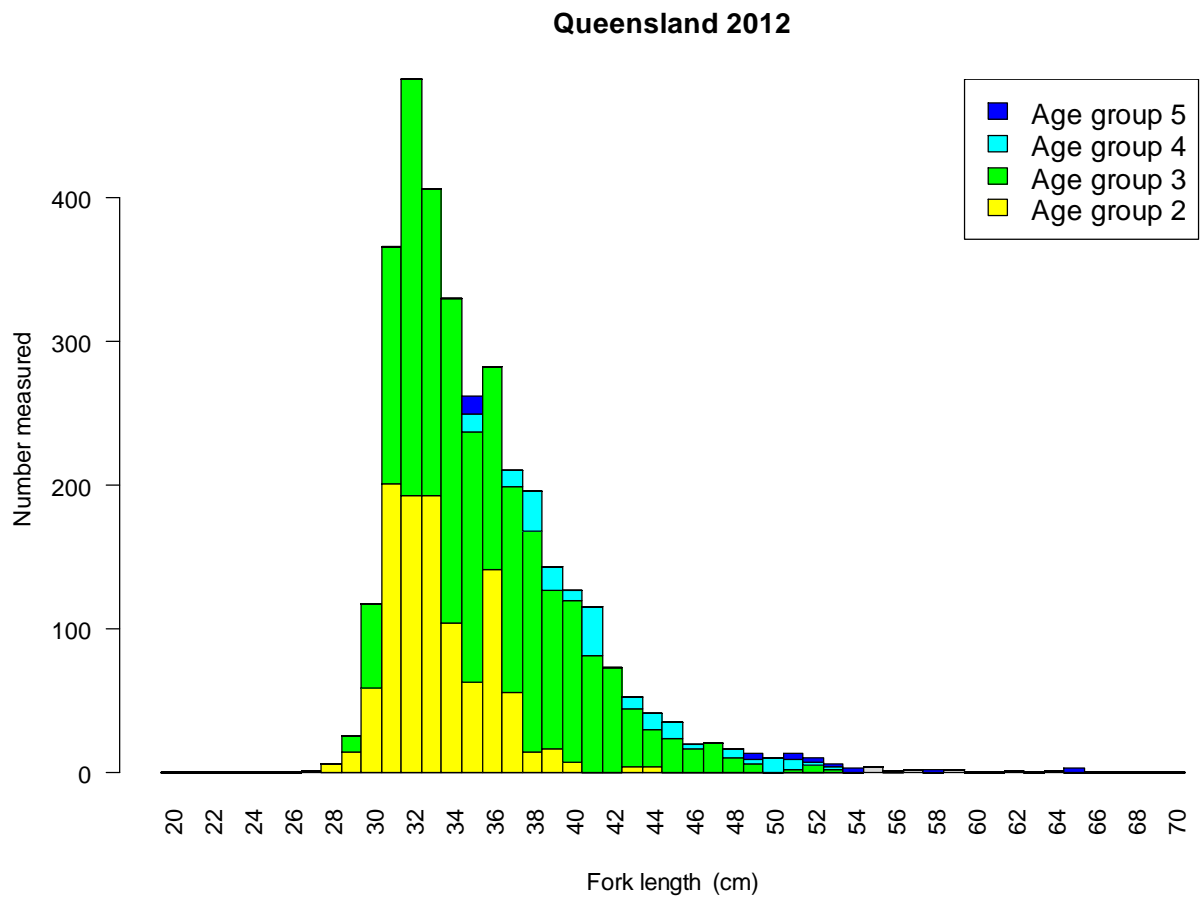
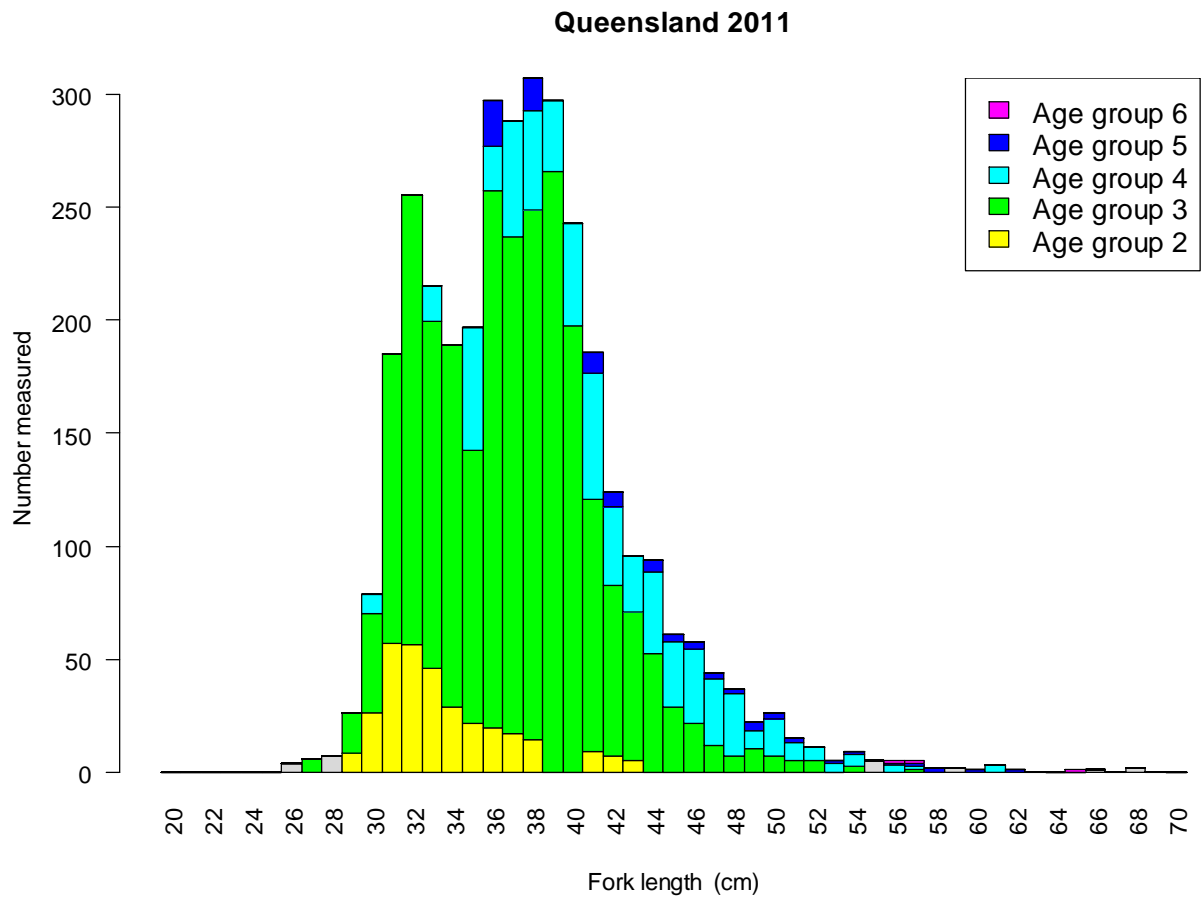
### Queensland 2009



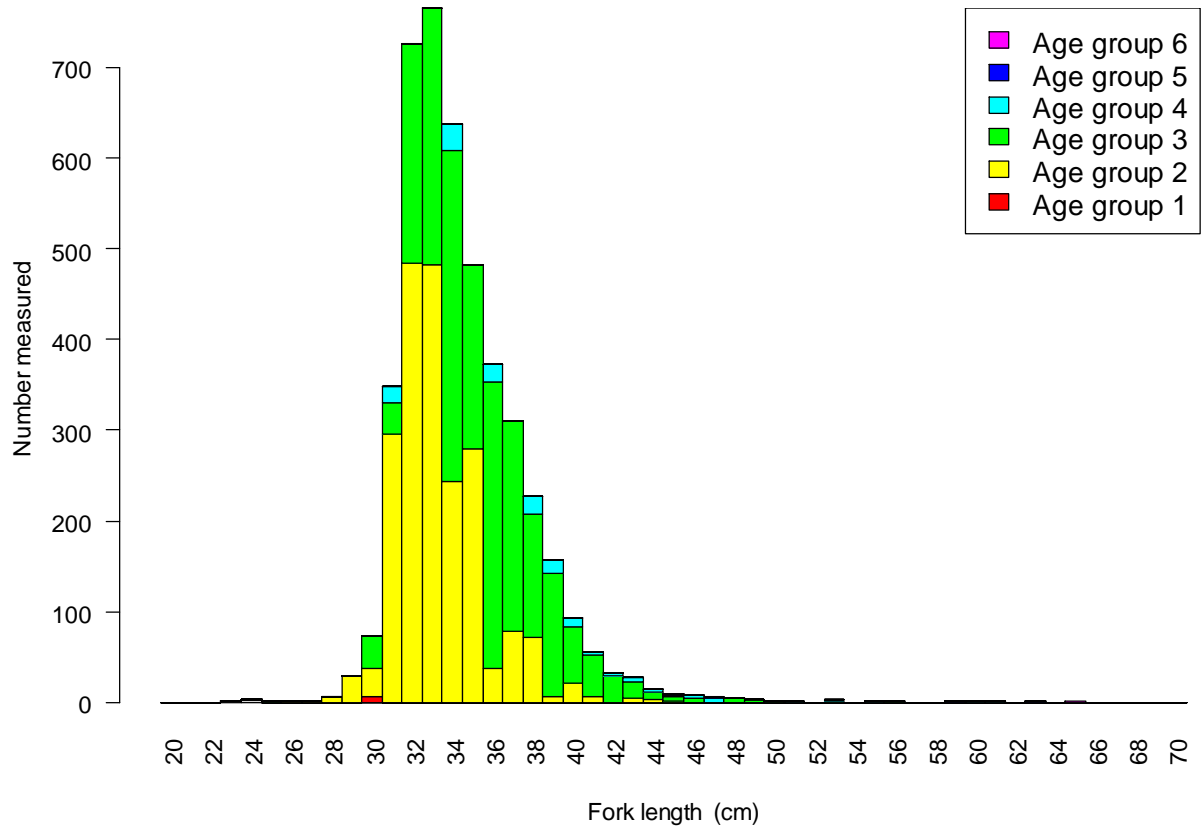
### Queensland 2010



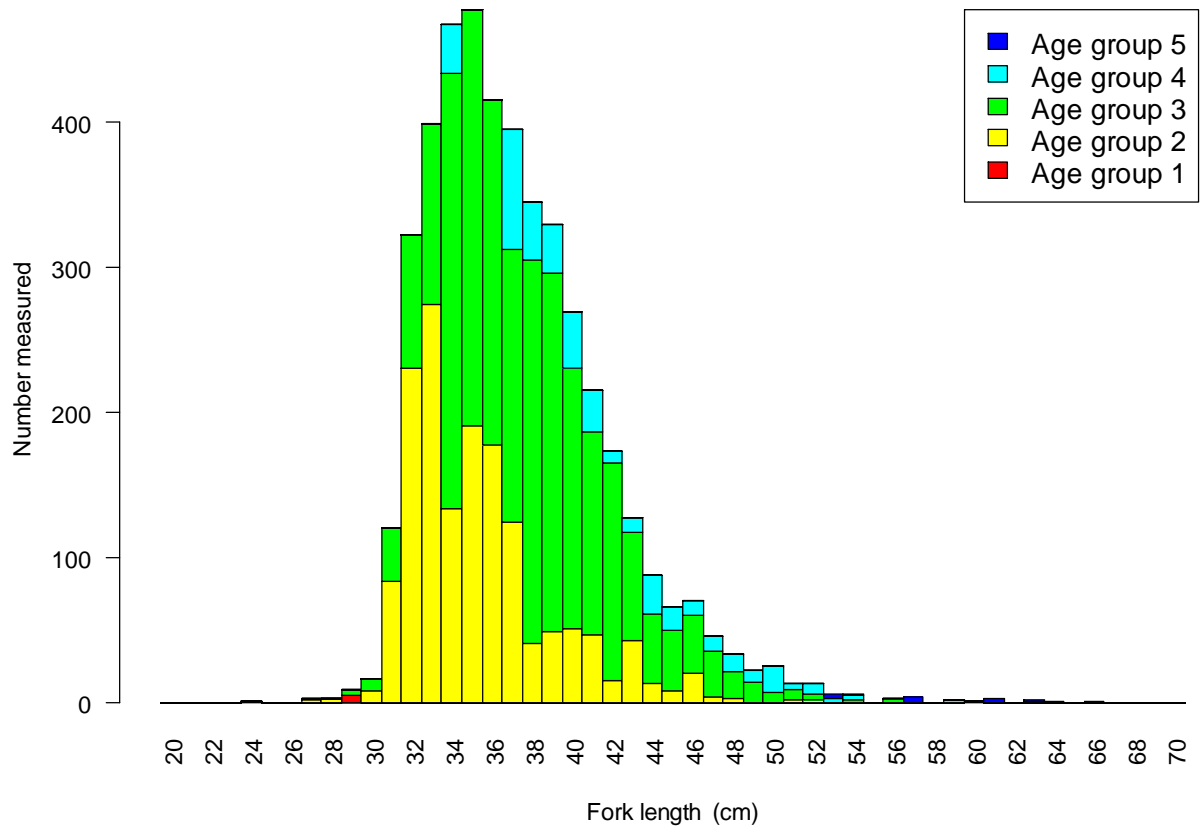




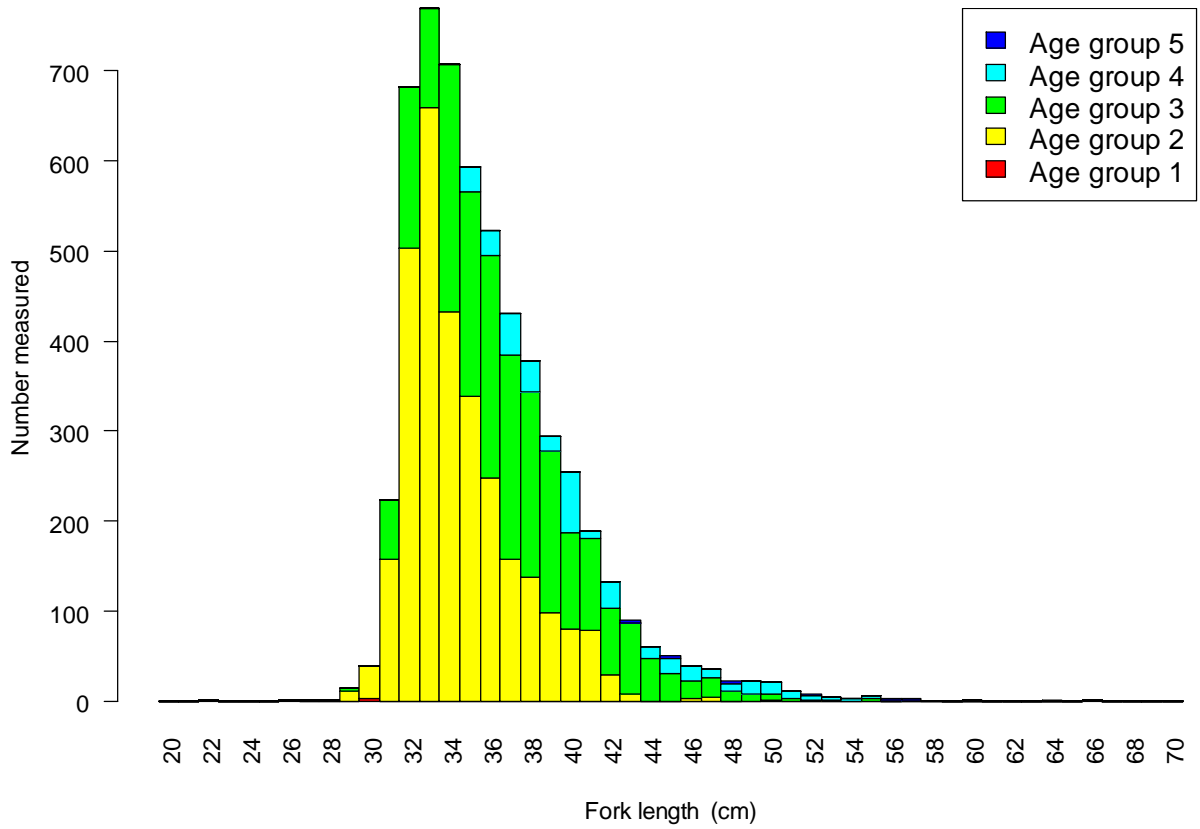
### Queensland 2013



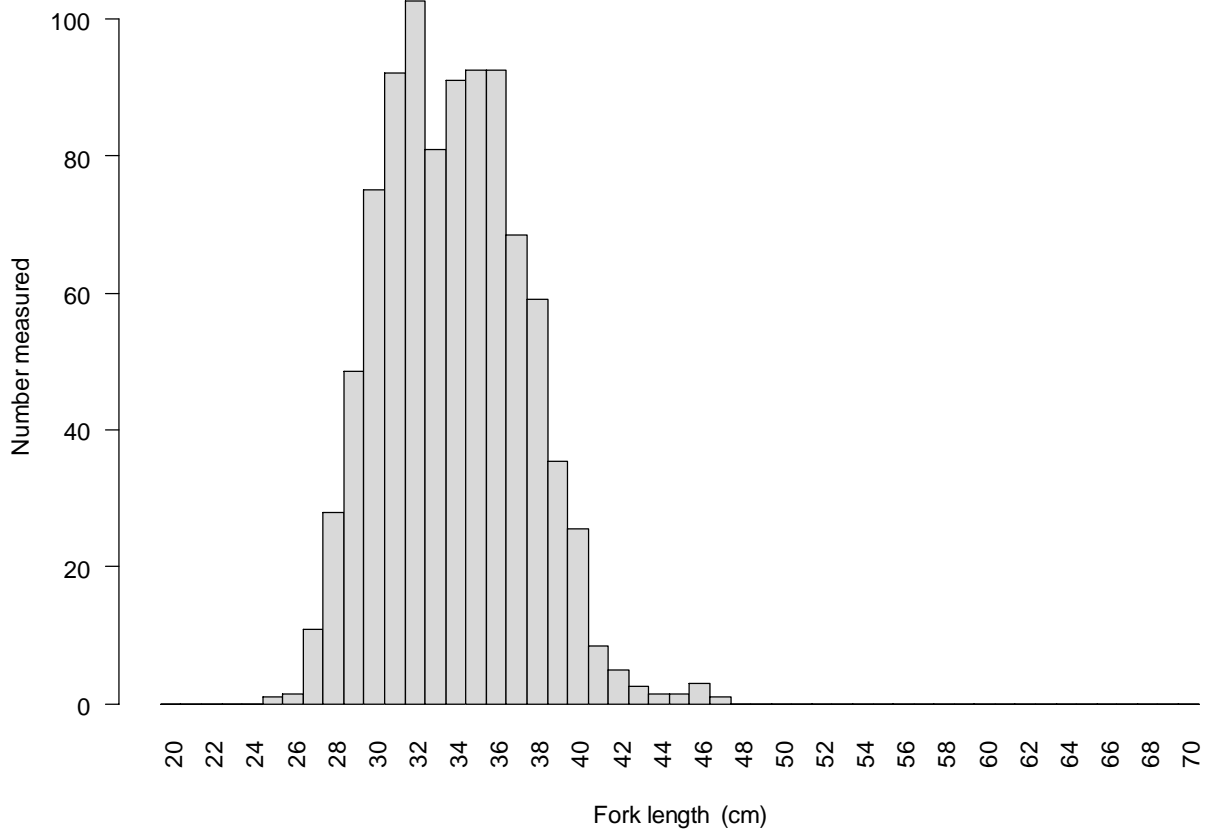
### Queensland 2014



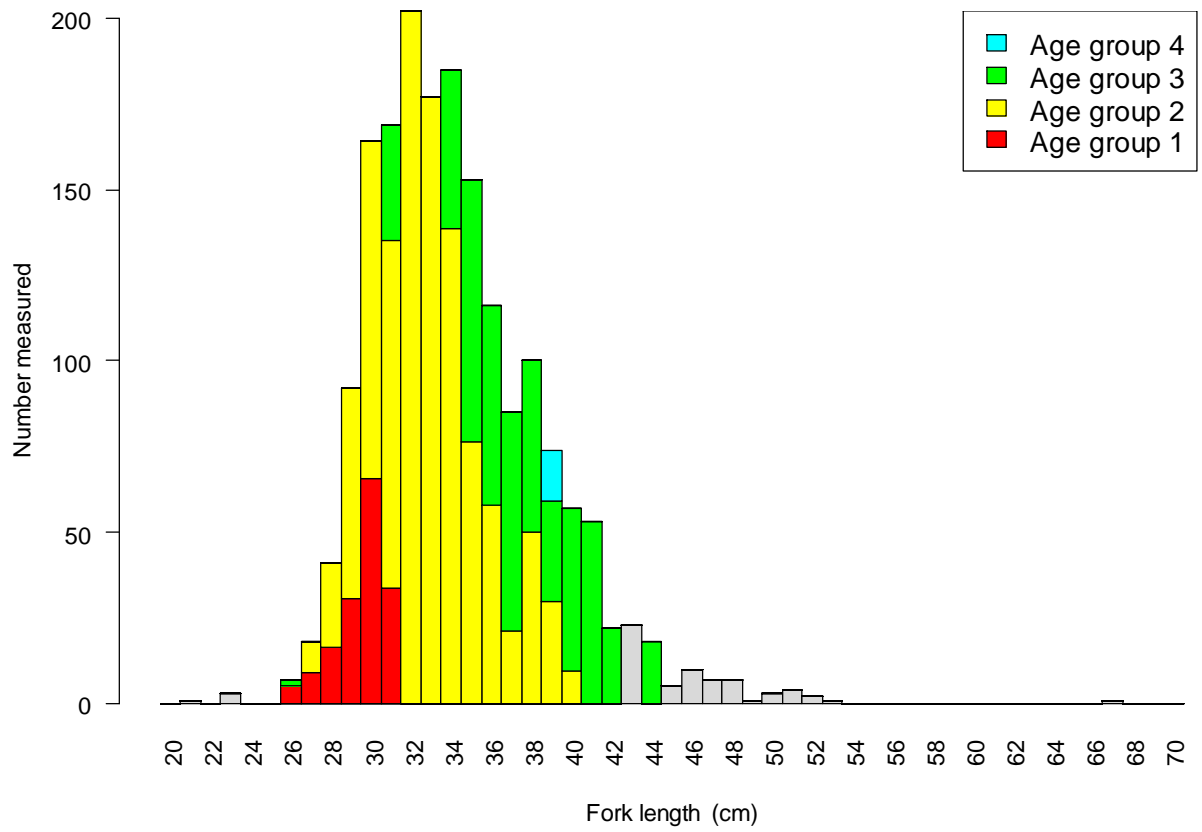
### Queensland 2015



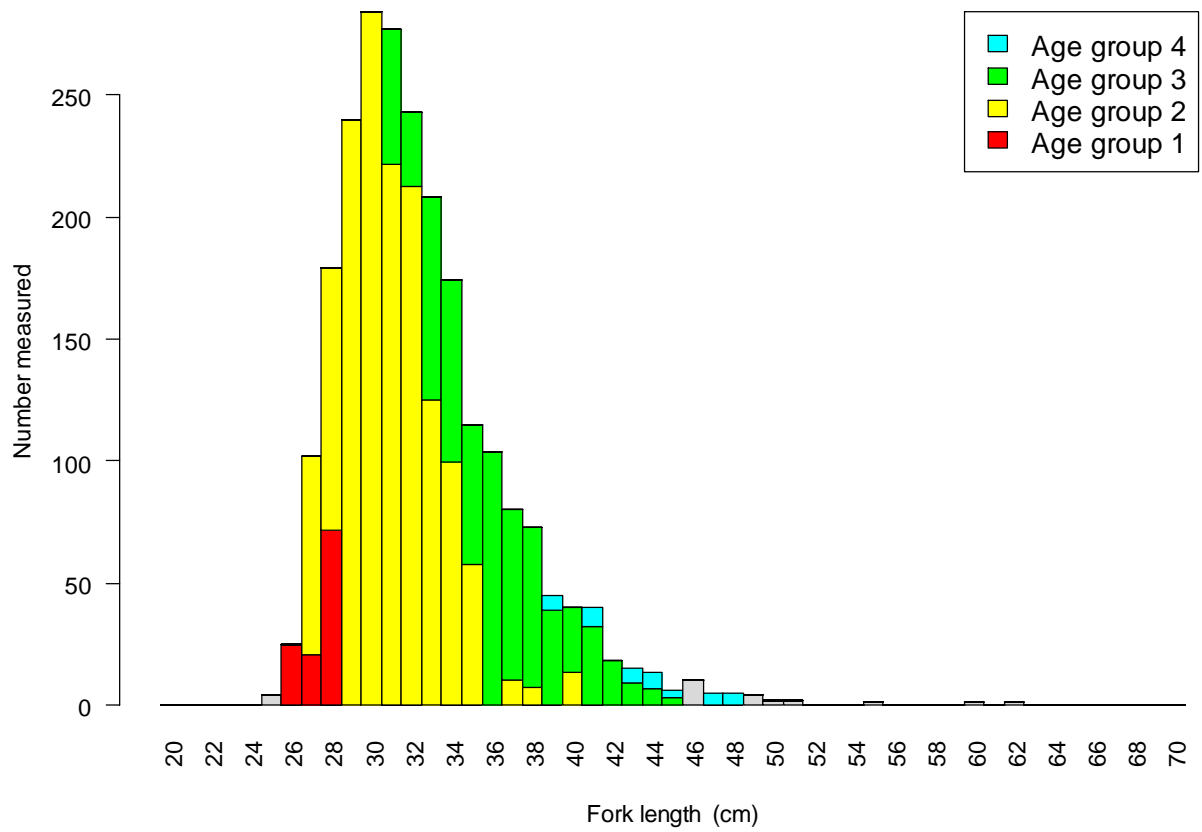
### Queensland ISAMP 1996, gillnet



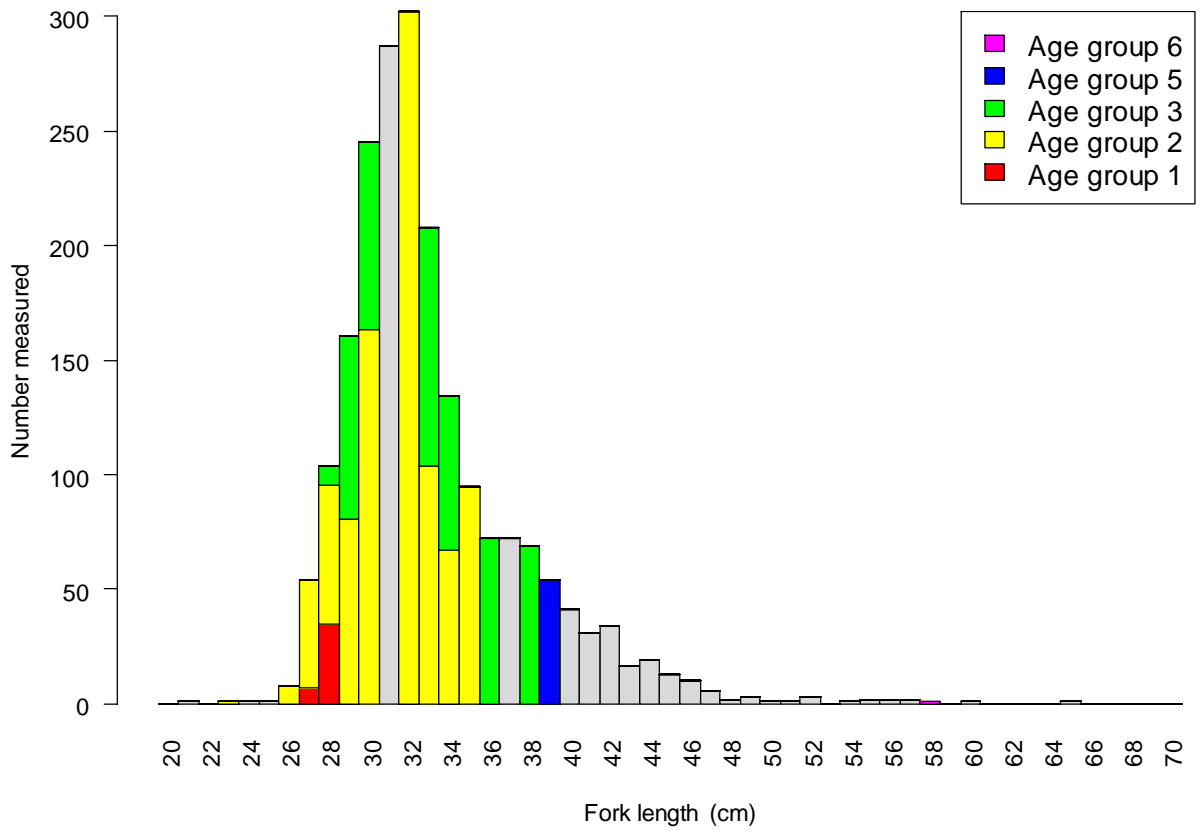
### Queensland gillnet 2007



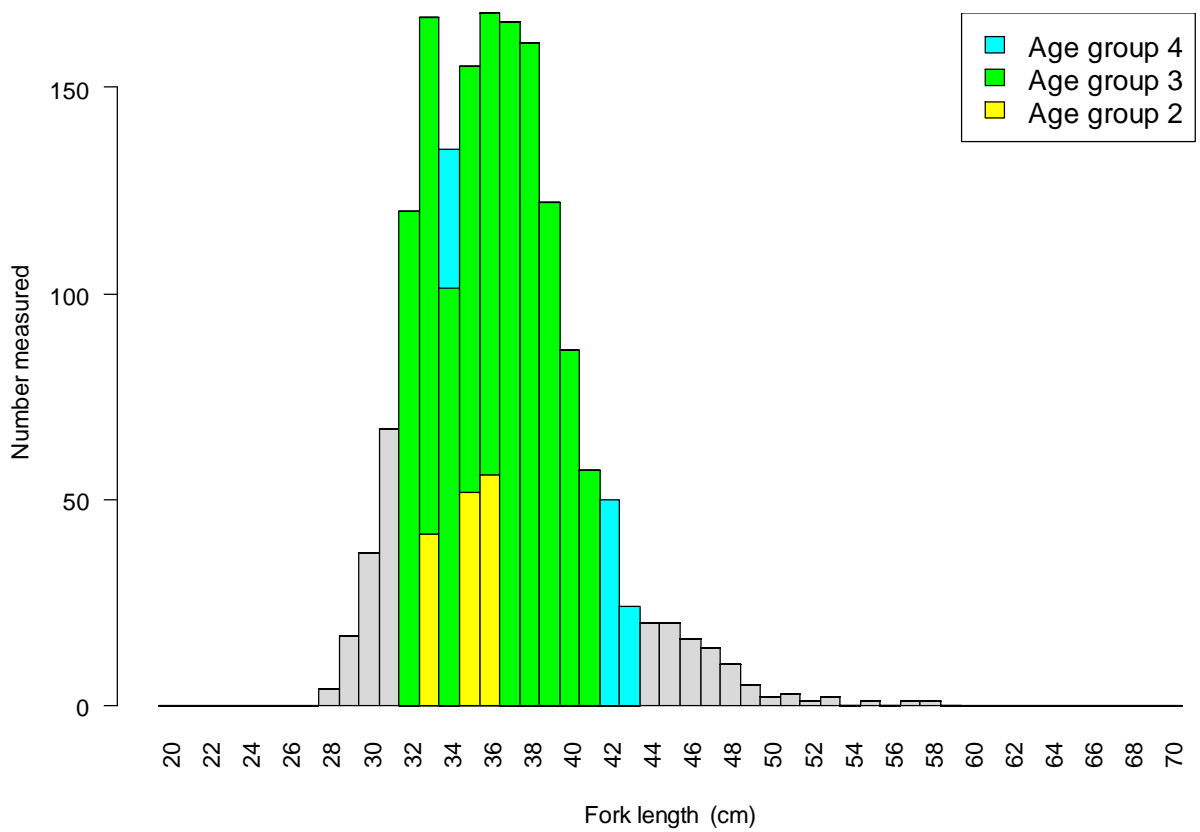
### Queensland gillnet 2008



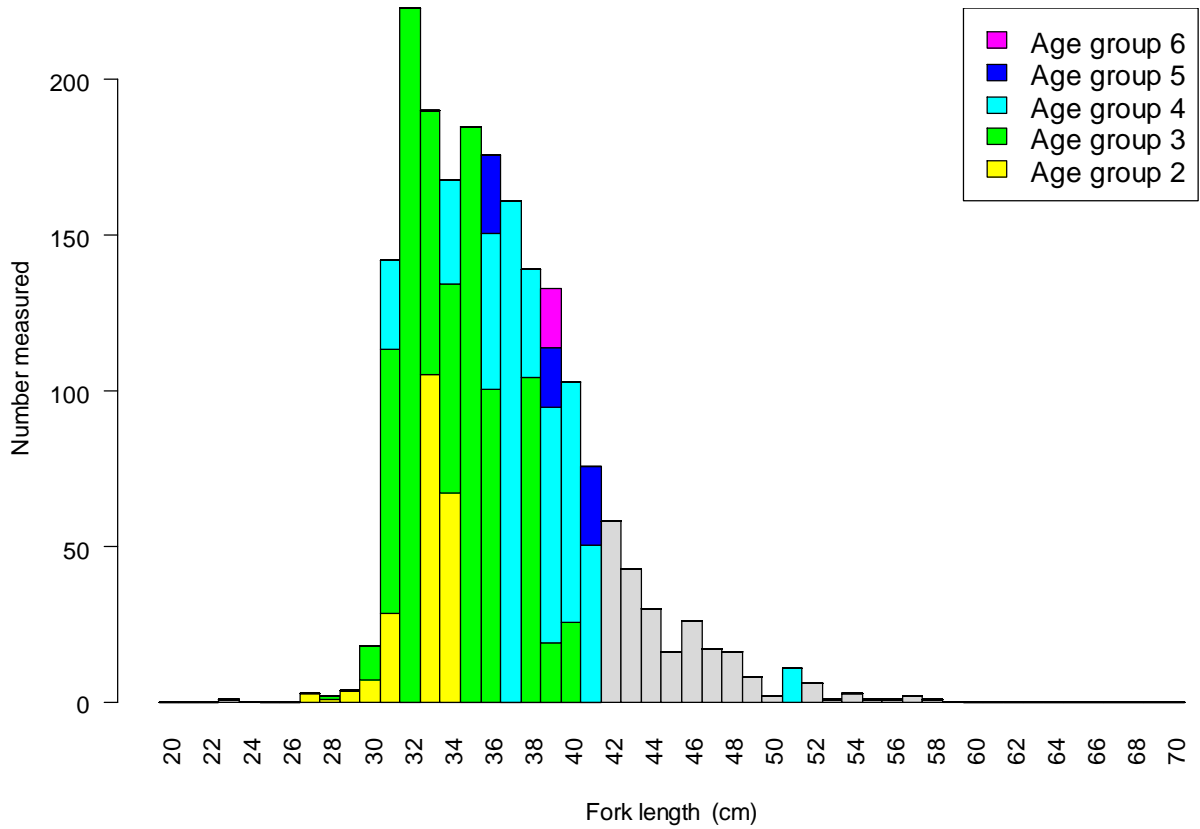
### Queensland gillnet 2009



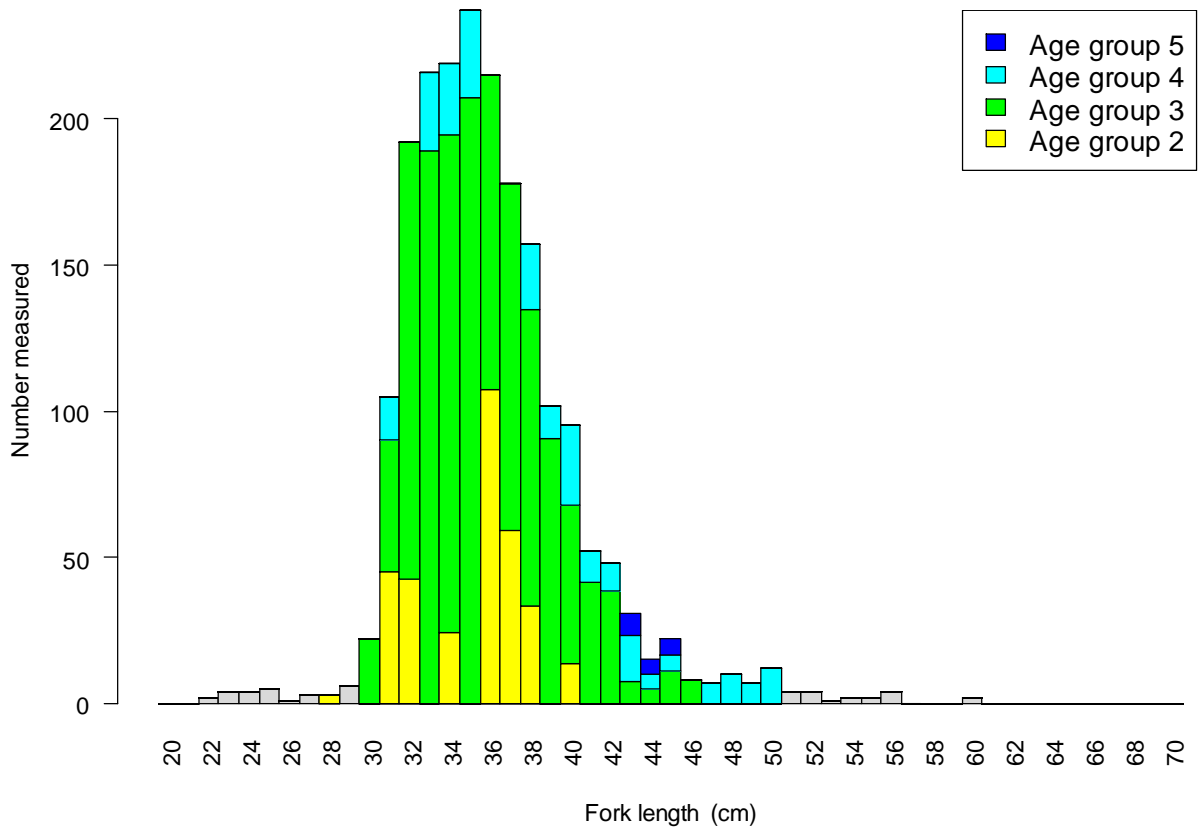
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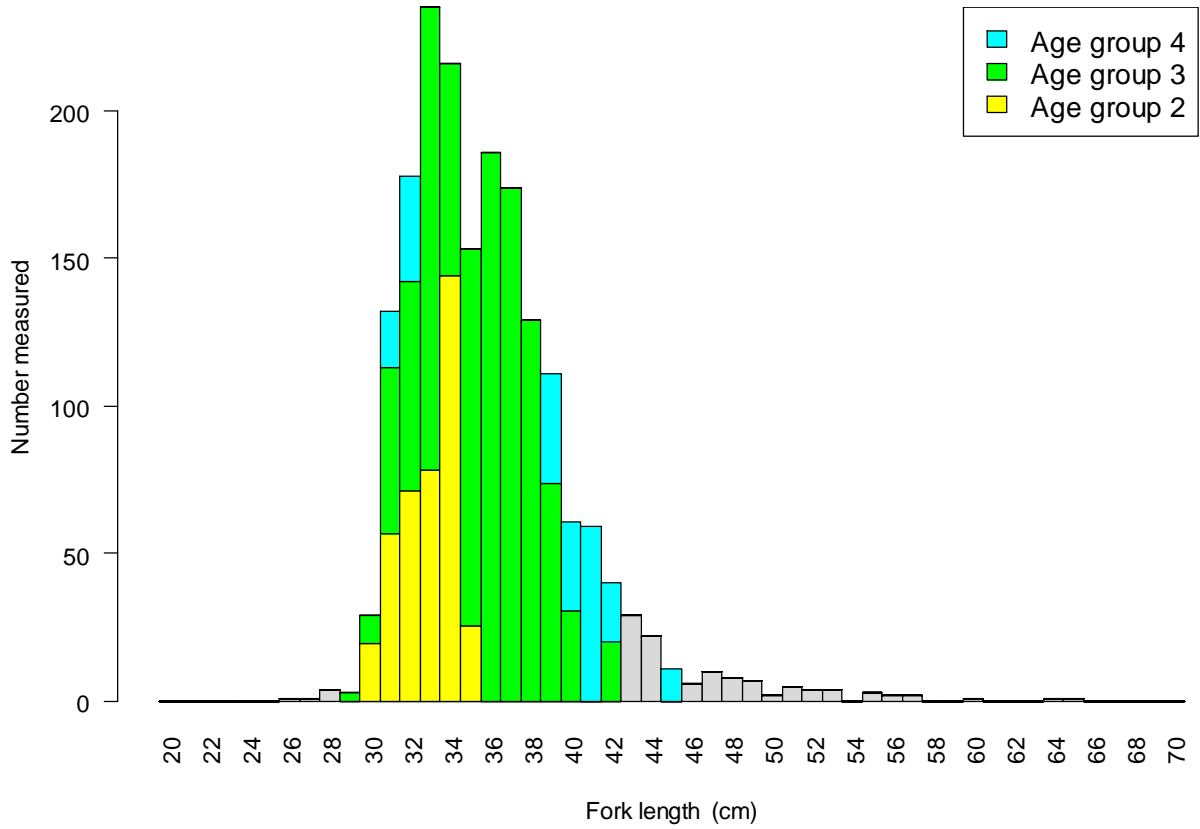
### Queensland gillnet 2011



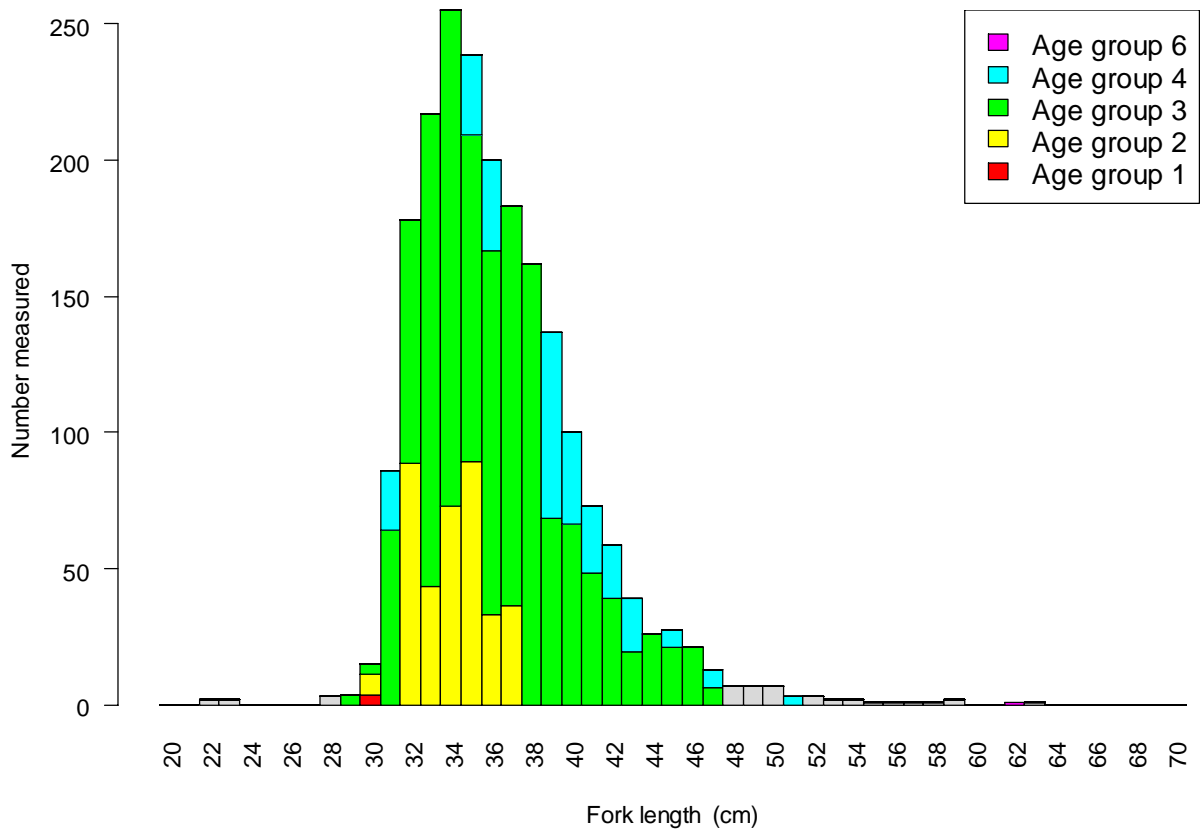
### Queensland gillnet 2012



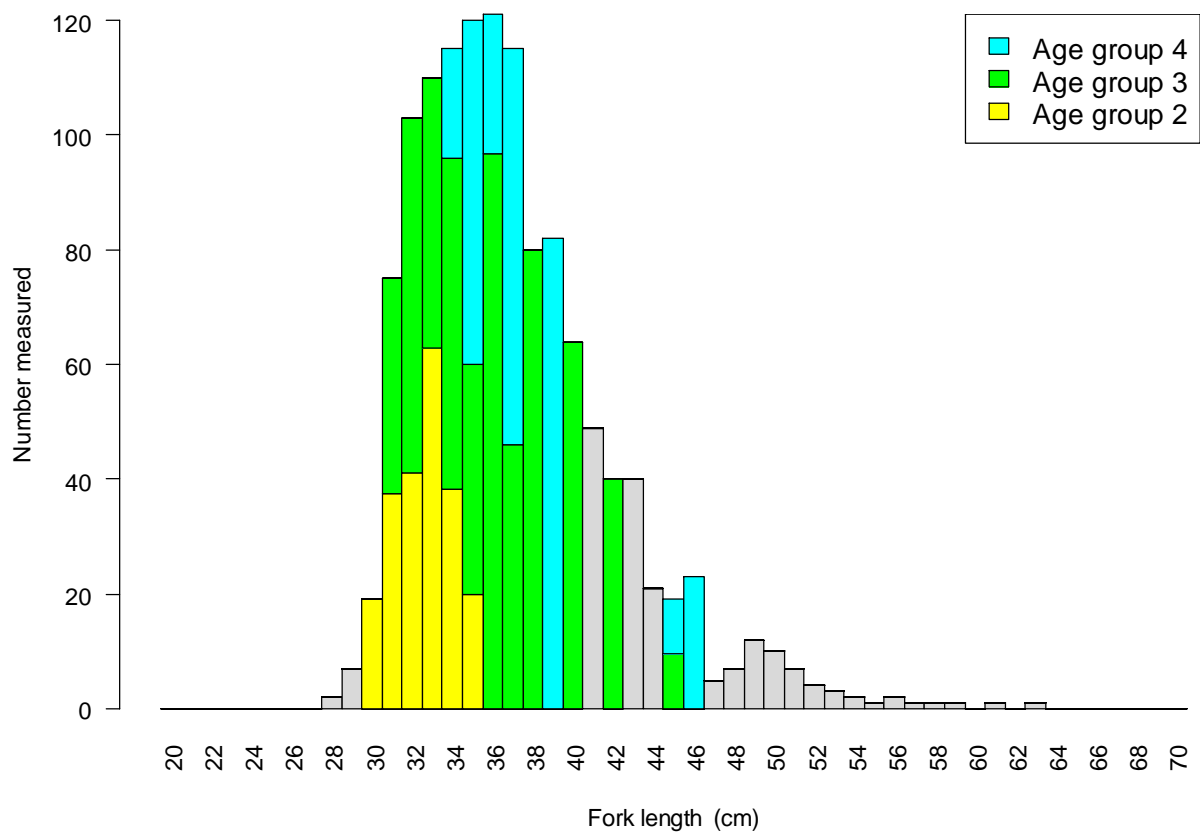
### Queensland gillnet 2013



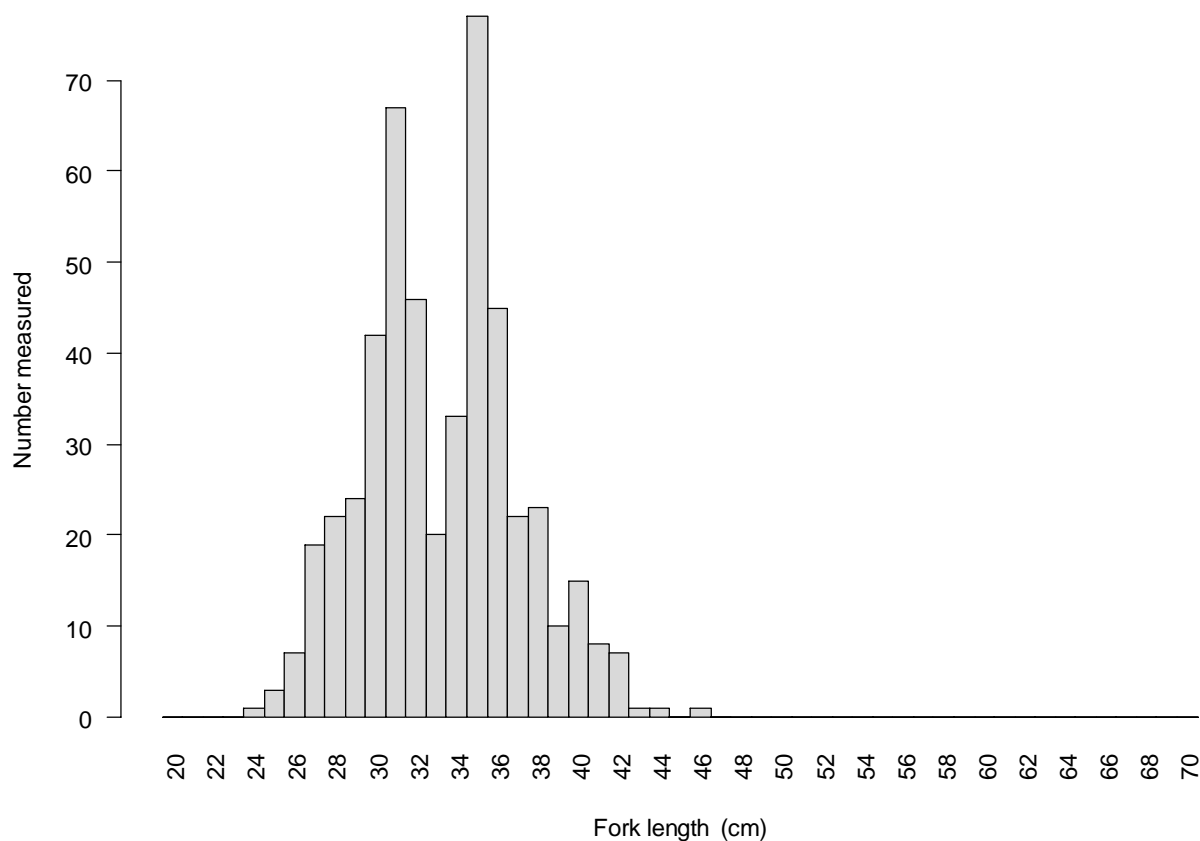
### Queensland gillnet 2014



### Queensland gillnet 2015

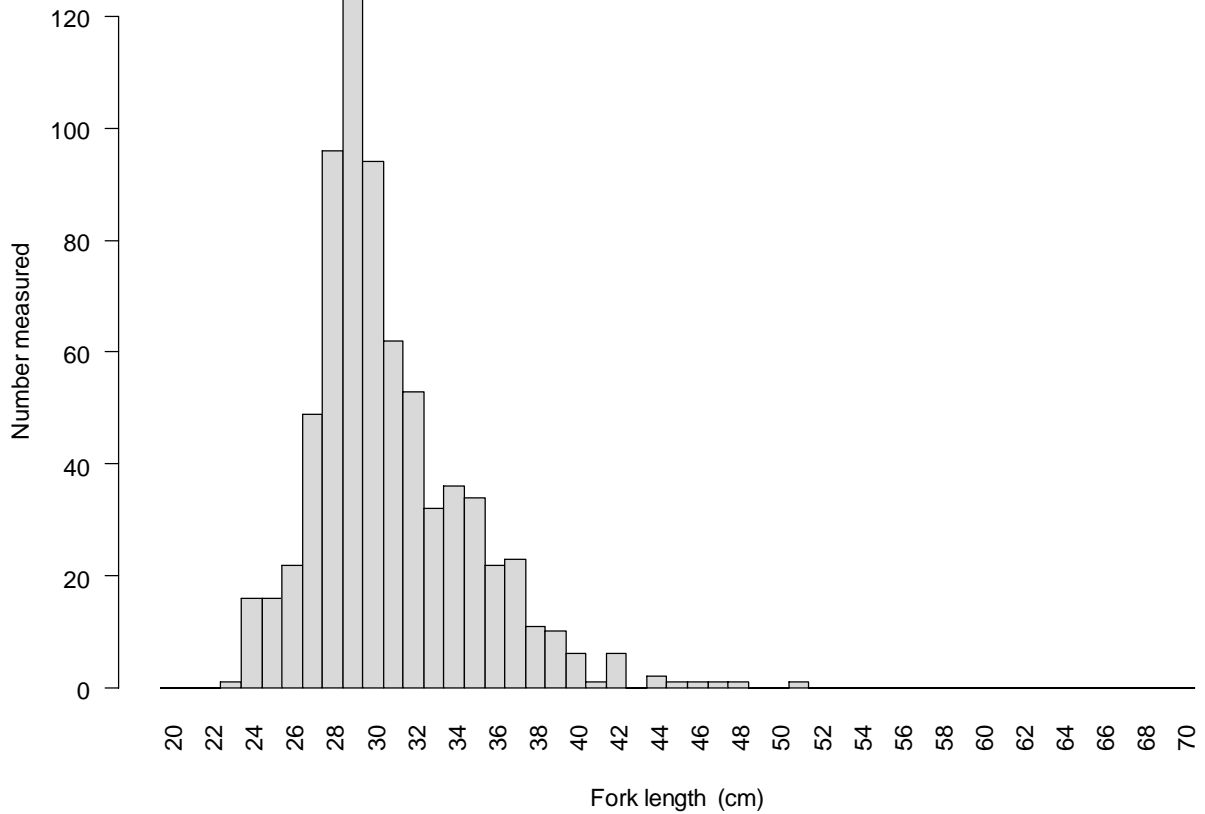


### NSW commercial, truncated, 1971, n = 494 (10 samples)

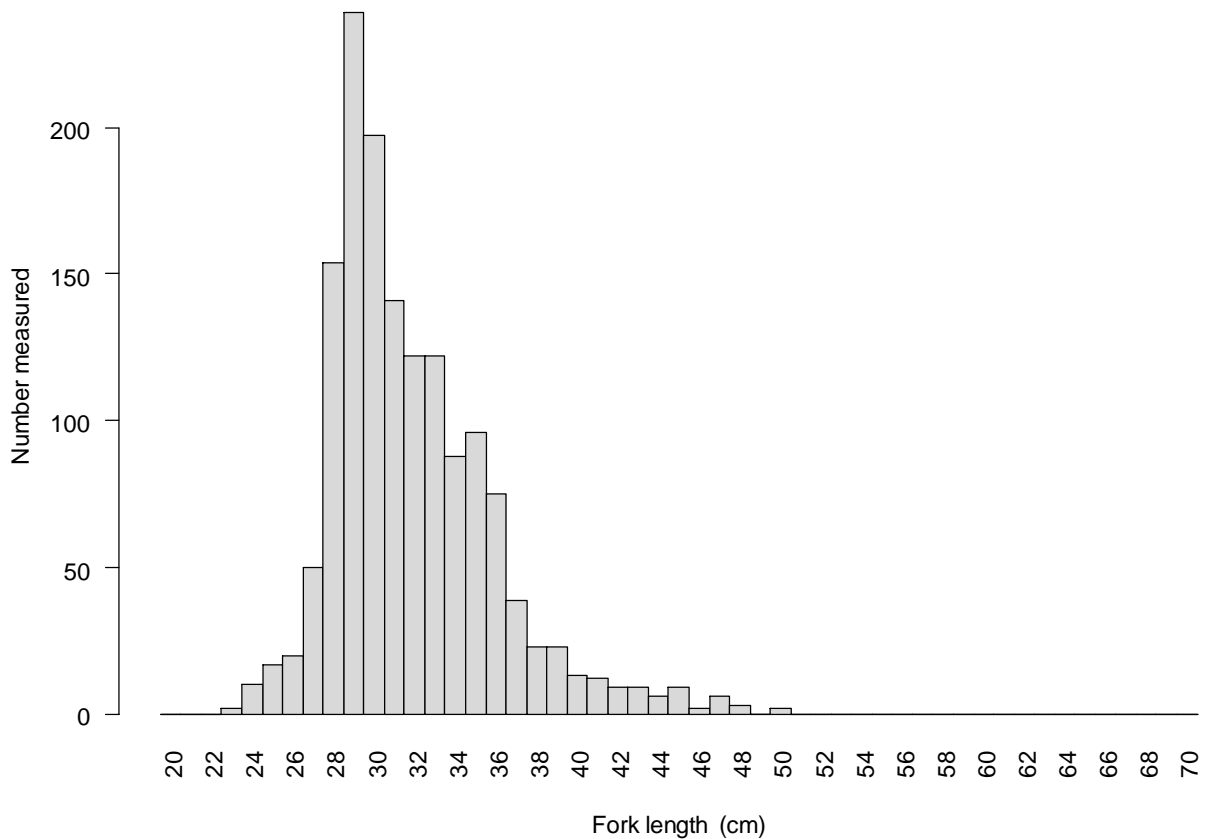




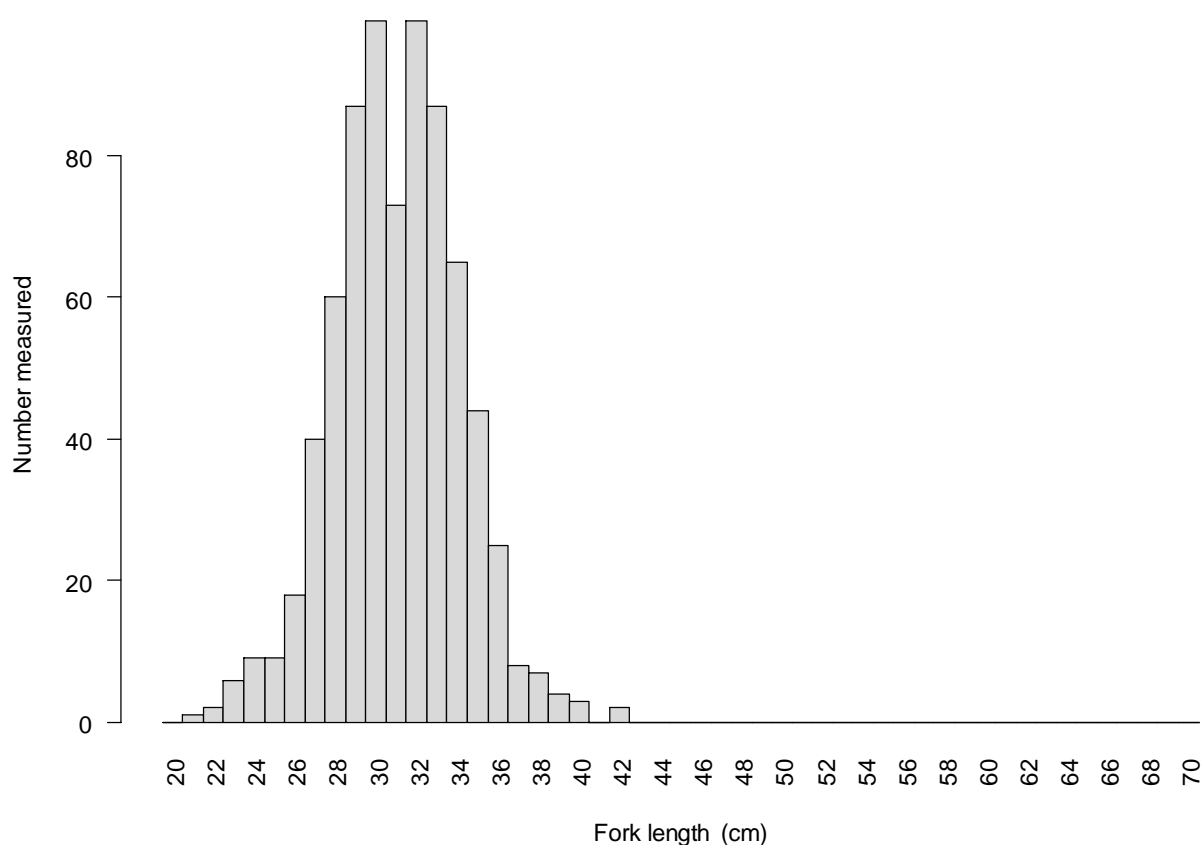
**NSW commercial, truncated, 1972, n = 722 (11 samples)**



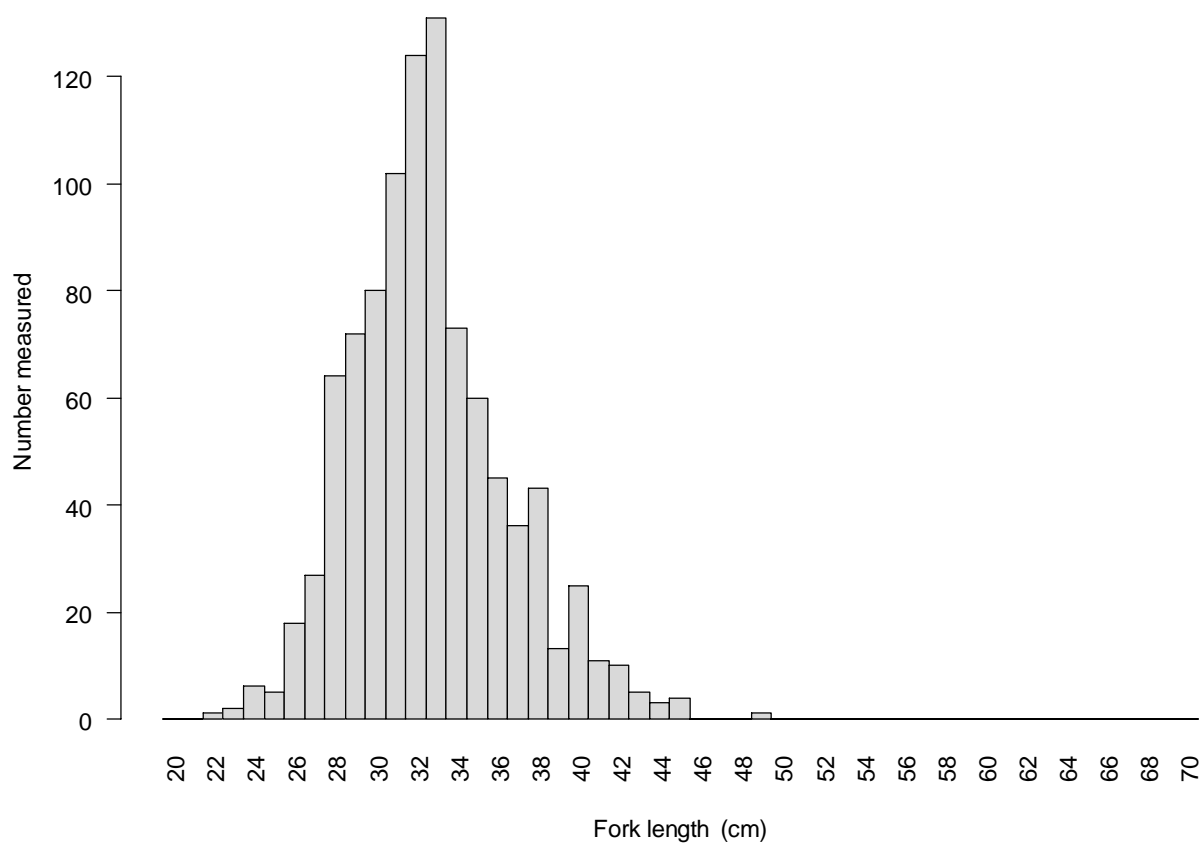
**NSW commercial, truncated, 1973, n = 1489 (21 samples)**



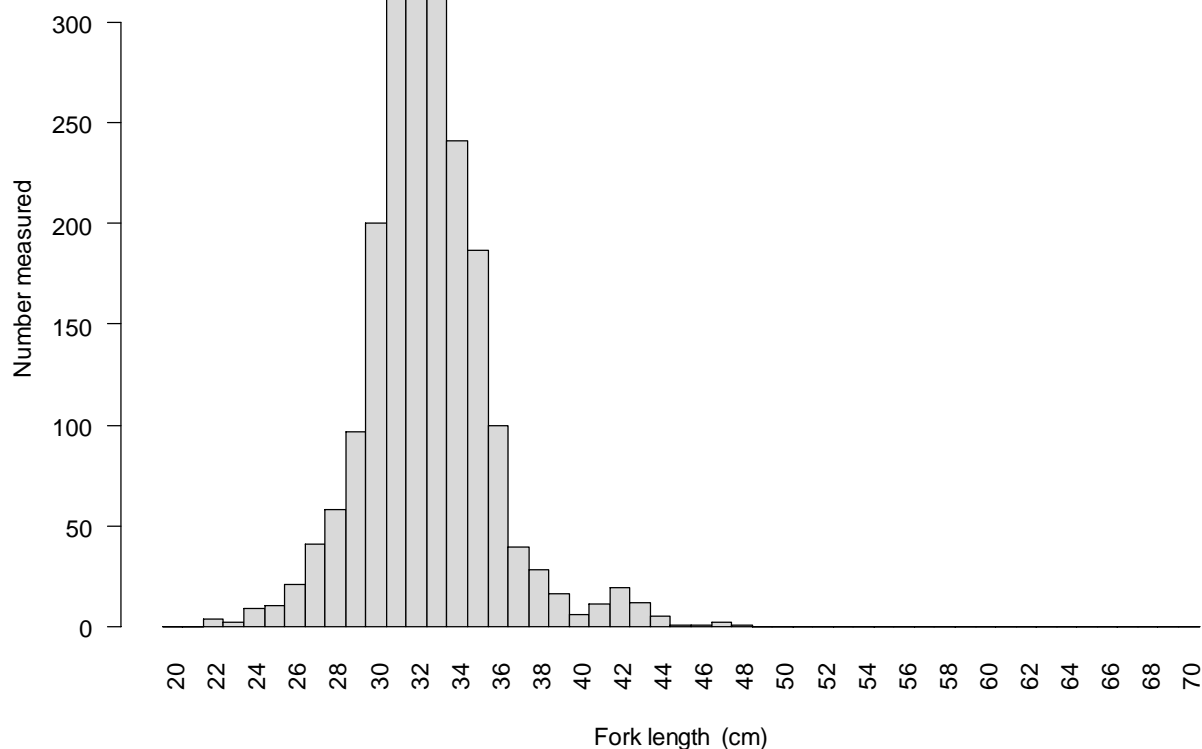
**NSW commercial, truncated, 1974, n = 748 (10 samples)**



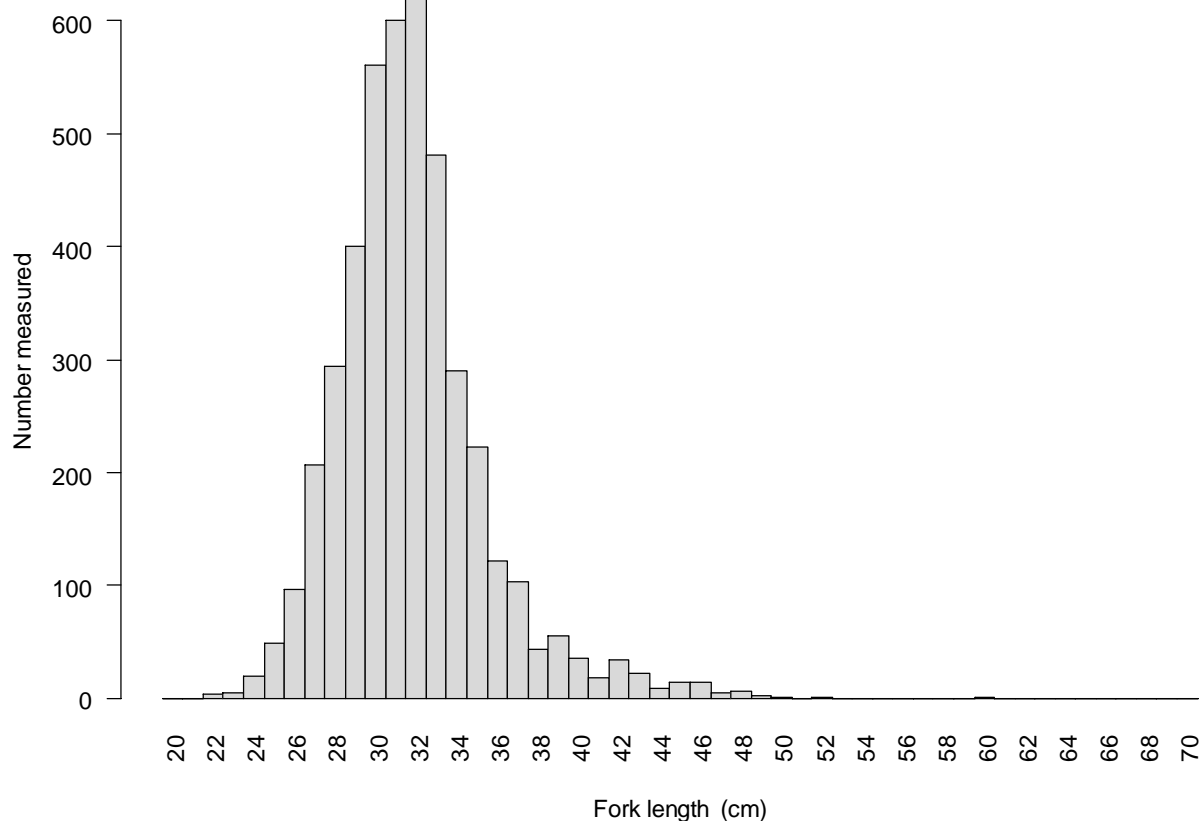
**NSW commercial, truncated, 1975, n = 961 (17 samples)**



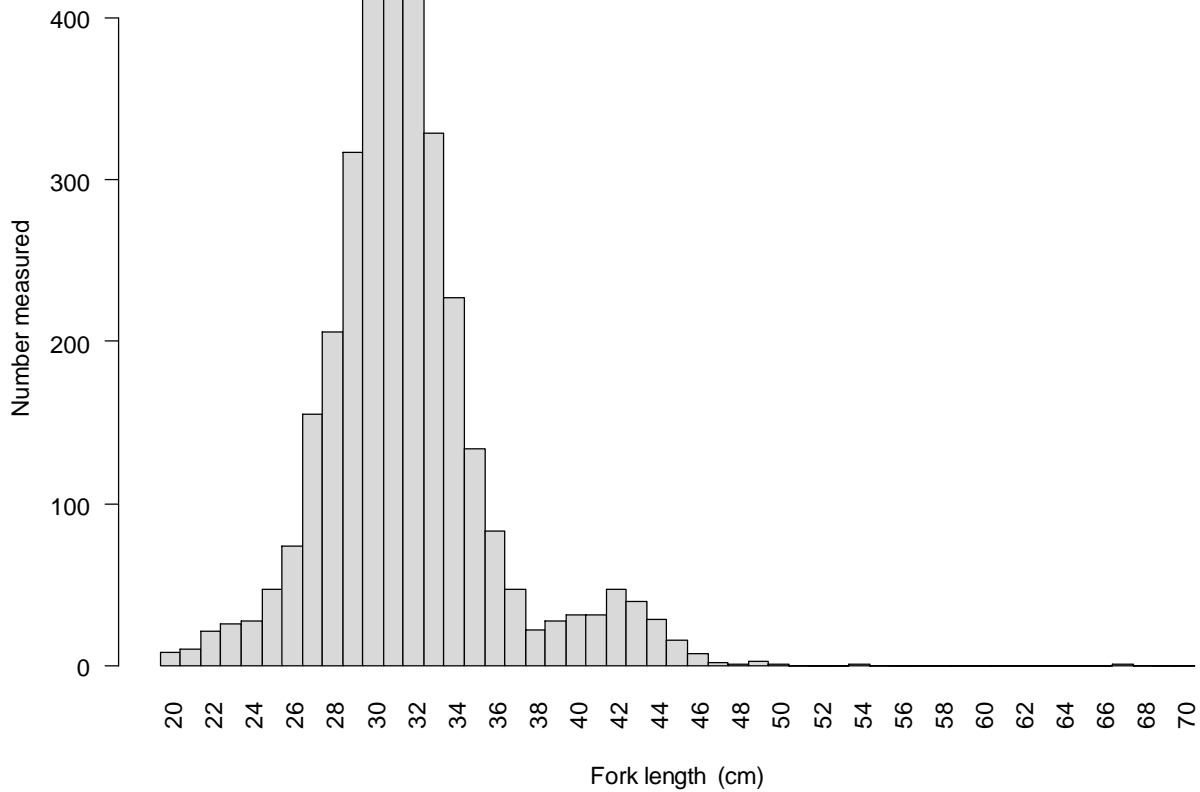
**NSW commercial, truncated, 1976, n = 2141 (10 samples)**



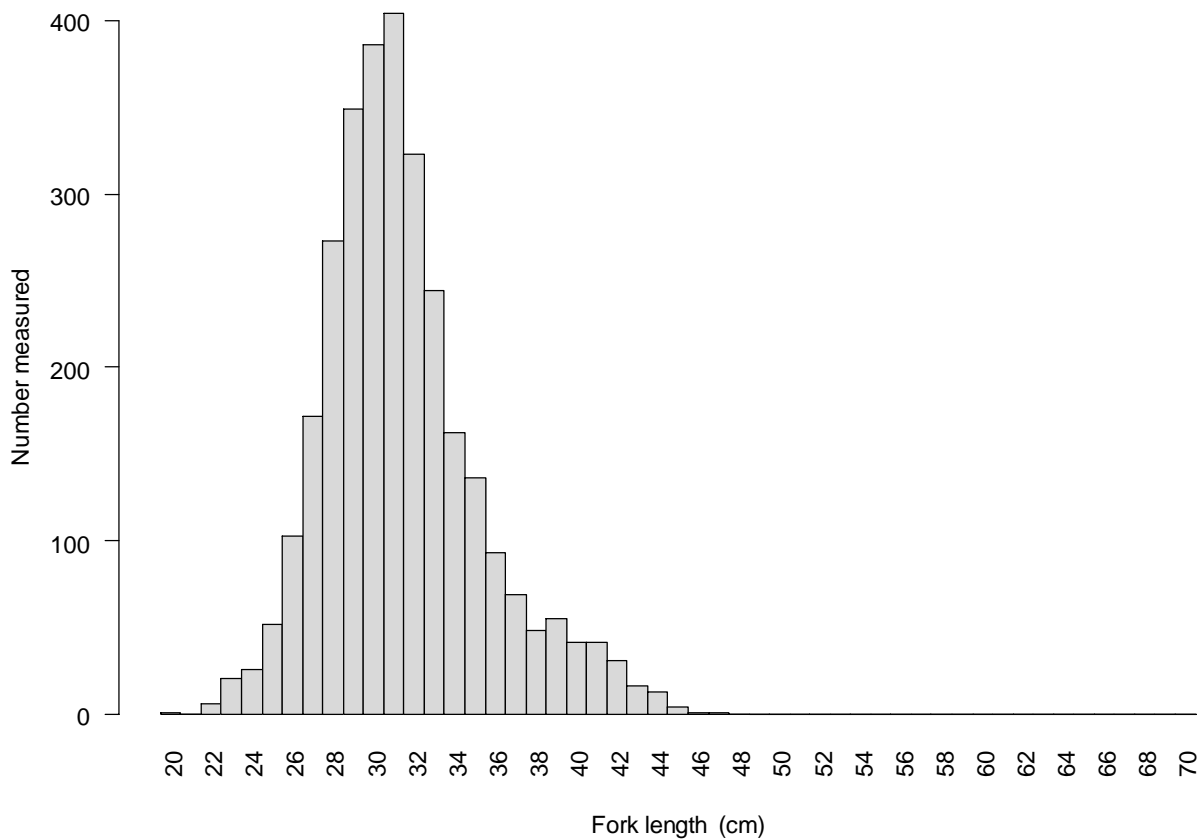
**NSW commercial, truncated, 1977, n = 4344 (32 samples)**



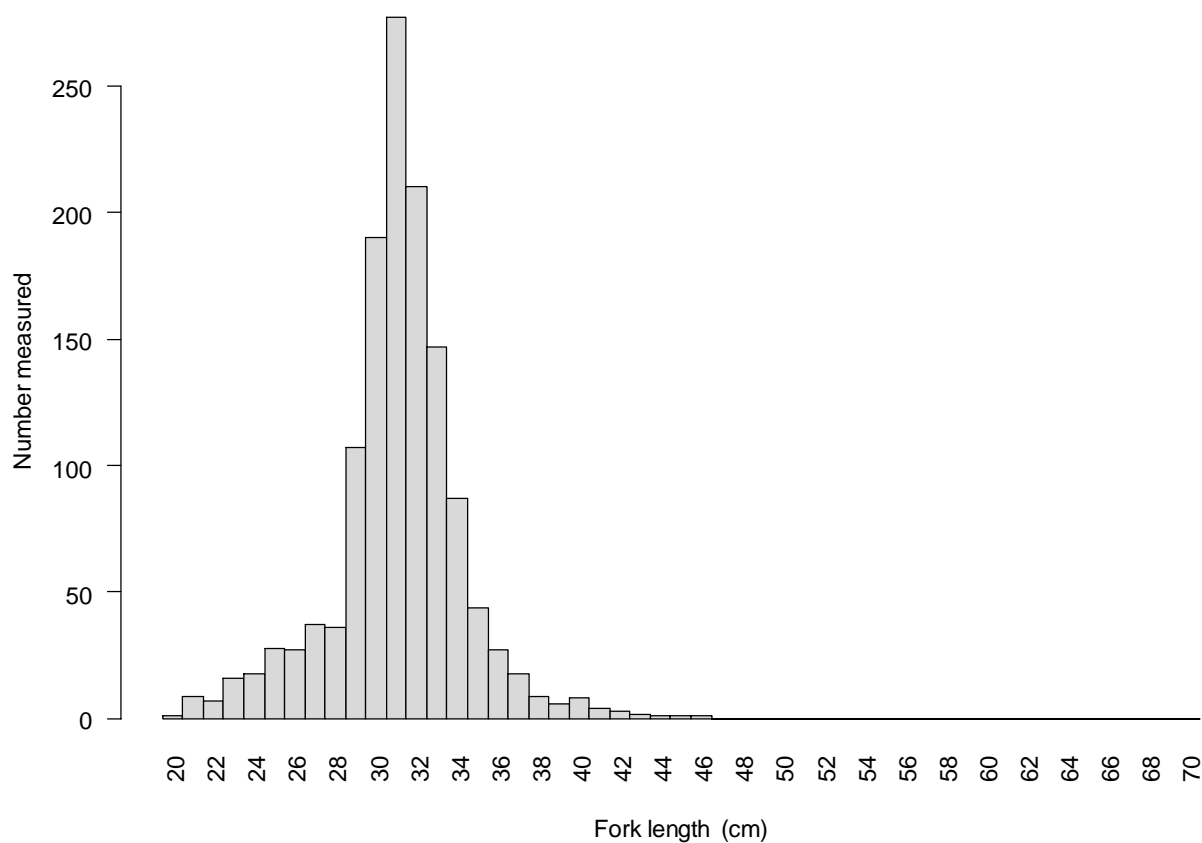
**NSW commercial, truncated, 1978, n = 3250 (24 samples)**



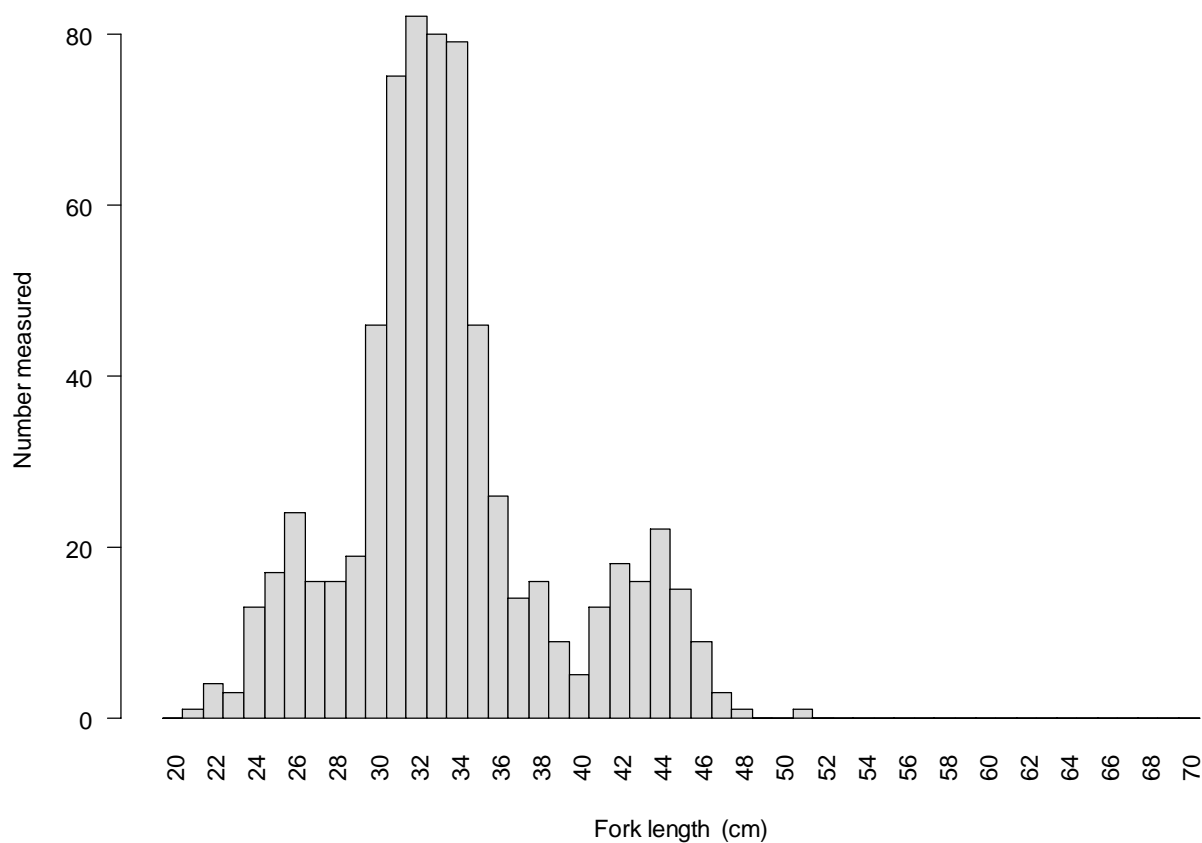
**NSW commercial, truncated, 1979, n = 3071 (17 samples)**



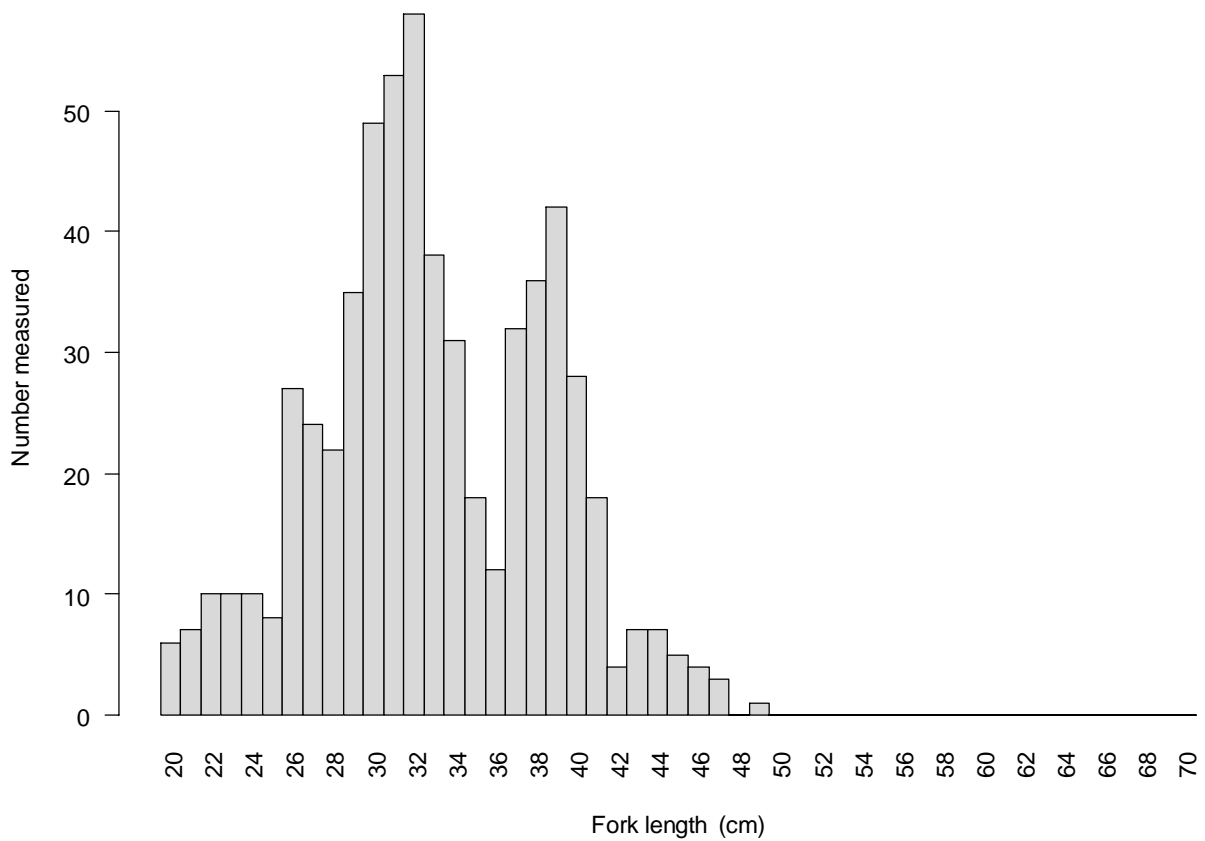
**NSW commercial, truncated, 1980, n = 1321 (8 samples)**



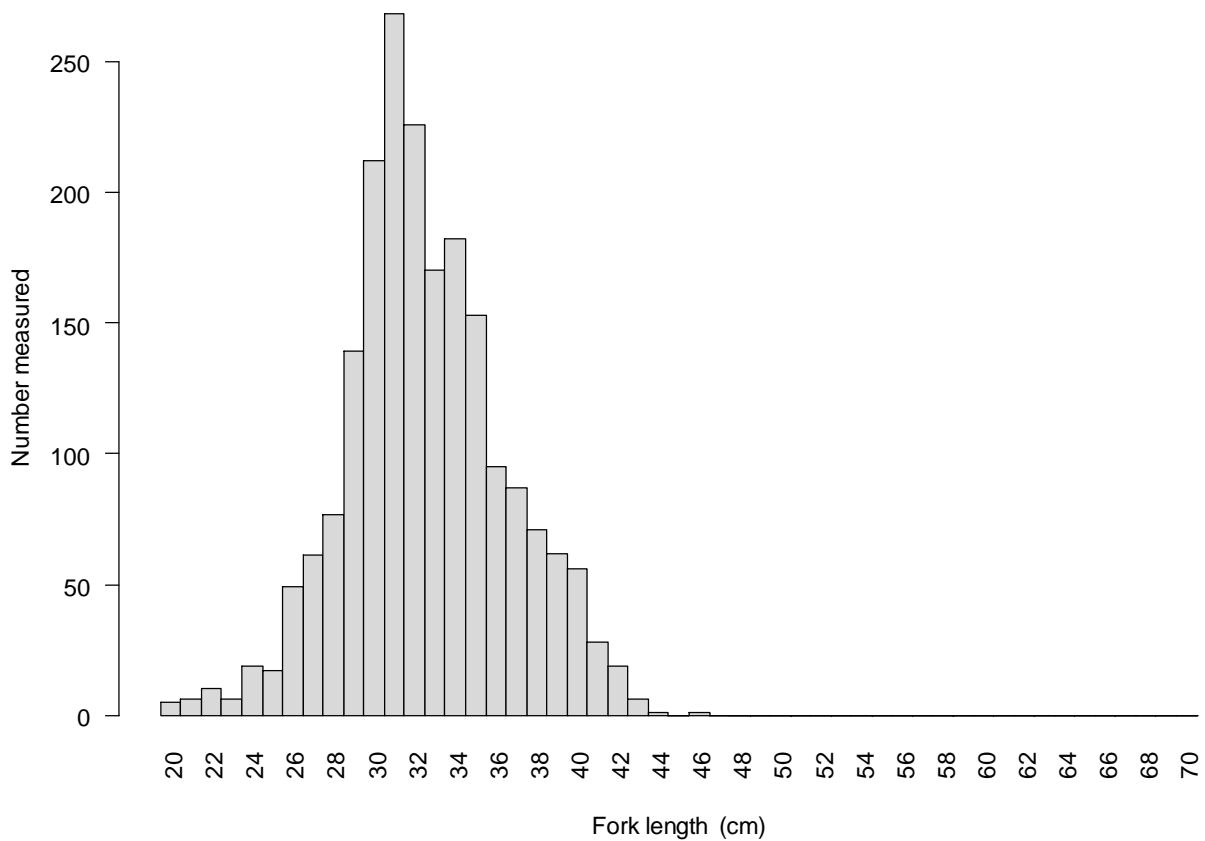
**NSW commercial, truncated, 1981, n = 689 (4 samples)**



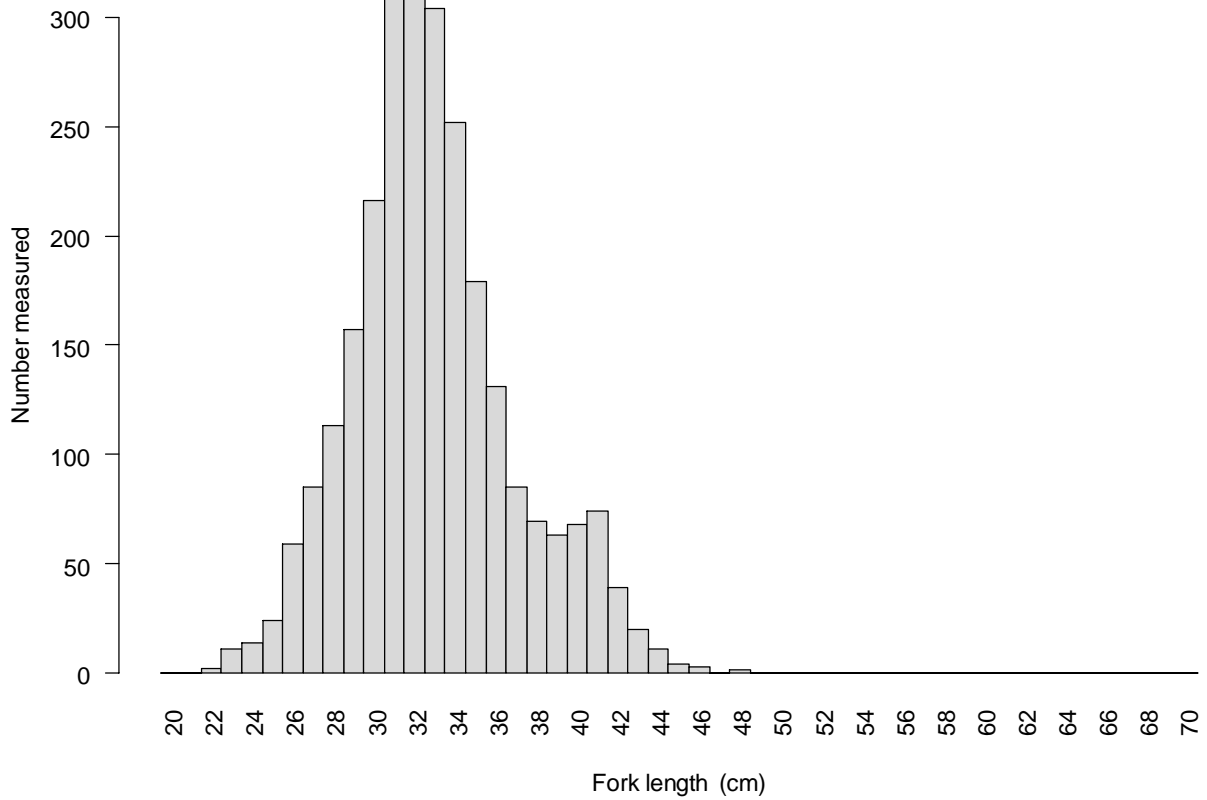
**NSW commercial, truncated, 1982, n = 605 (5 samples)**



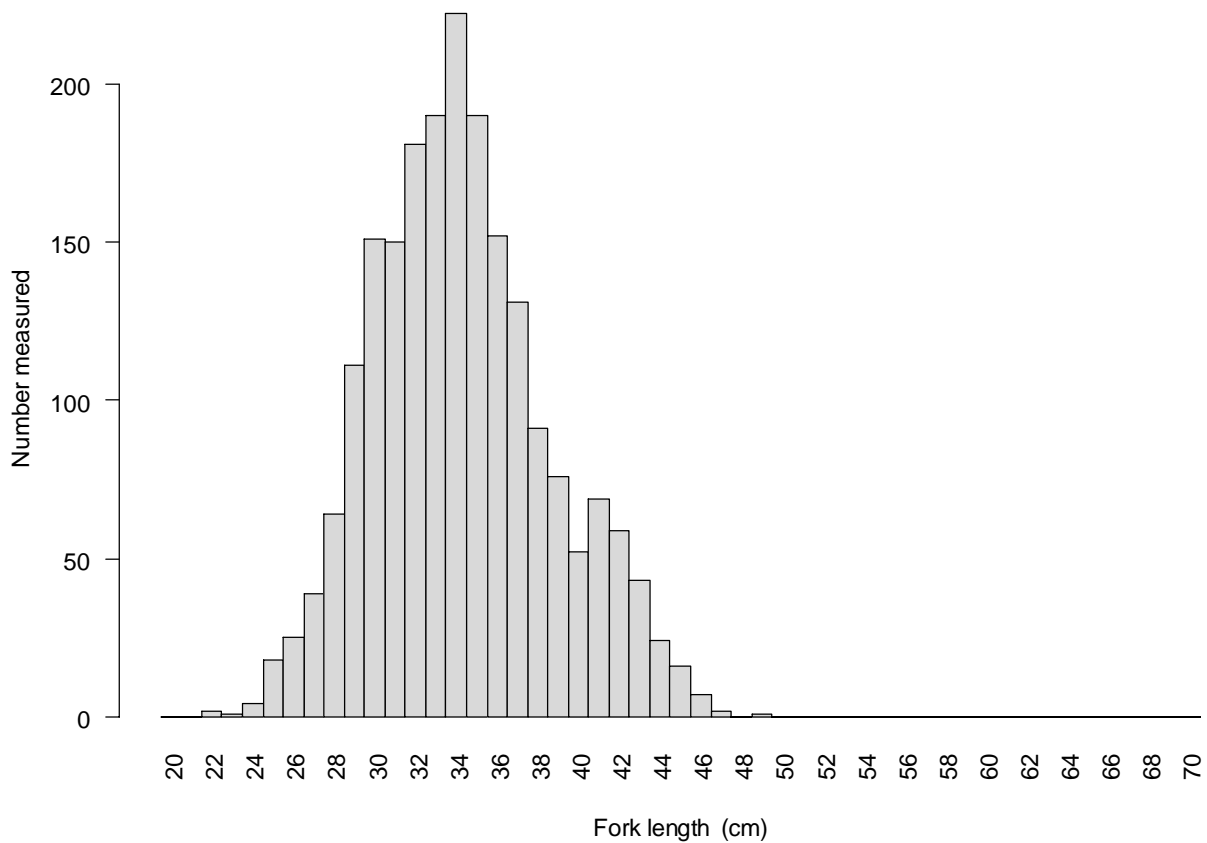
**NSW commercial, truncated, 1987, n = 2026 (14 samples)**



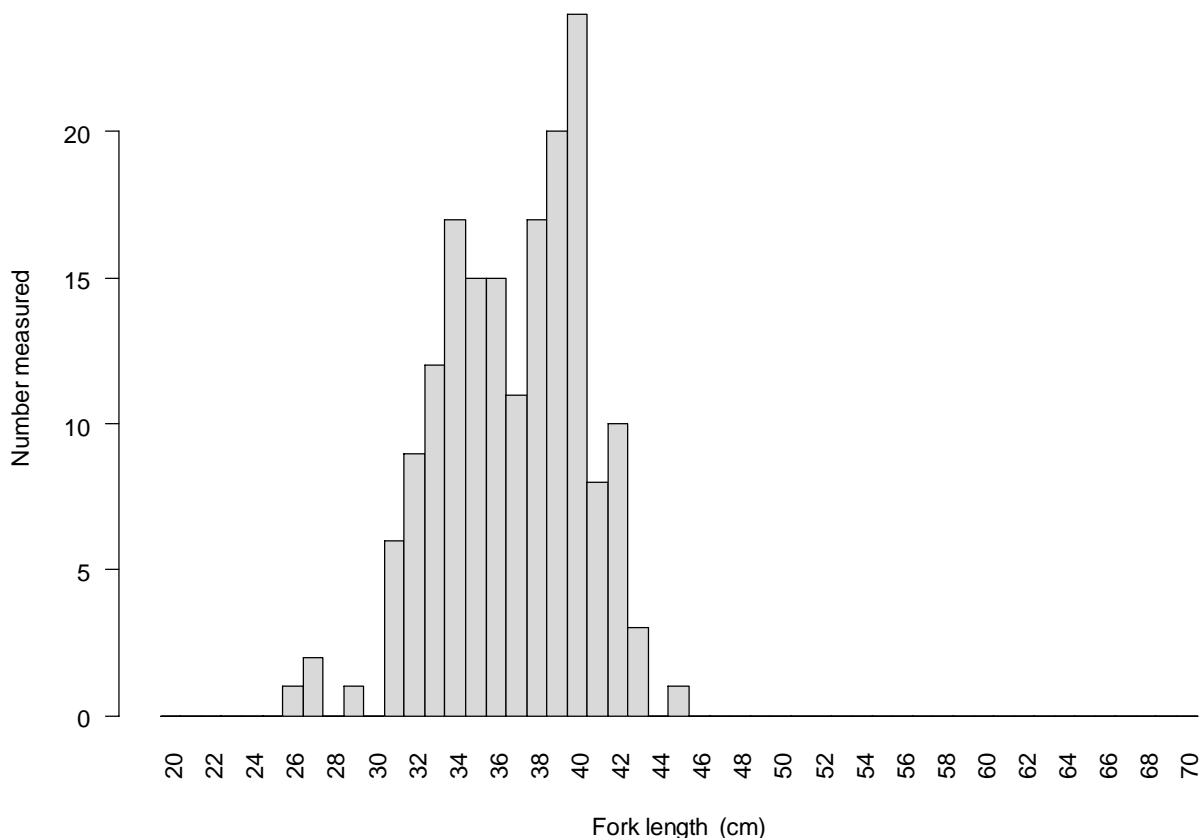
**NSW commercial, truncated, 1988, n = 2617 (20 samples)**



**NSW commercial, truncated, 1989, n = 2071 (18 samples)**



### NSW commercial, truncated, 1990, n = 172 (2 samples)



### A3.2 Comparison of trips to Fraser Island

The following plots show length-frequency of measured fish and age-frequency of aged fish for the regular sampling trips to Fraser Island taken by Fisheries Queensland's monitoring program at three different times of year:

- Trip 1: 7 August to 20 August
- Trip 2: 21 August to 6 September
- Trip 3: 25 September to 5 October.

The numbers plotted are for all years combined. They show the changes in length and age structures with time of year of sampling.

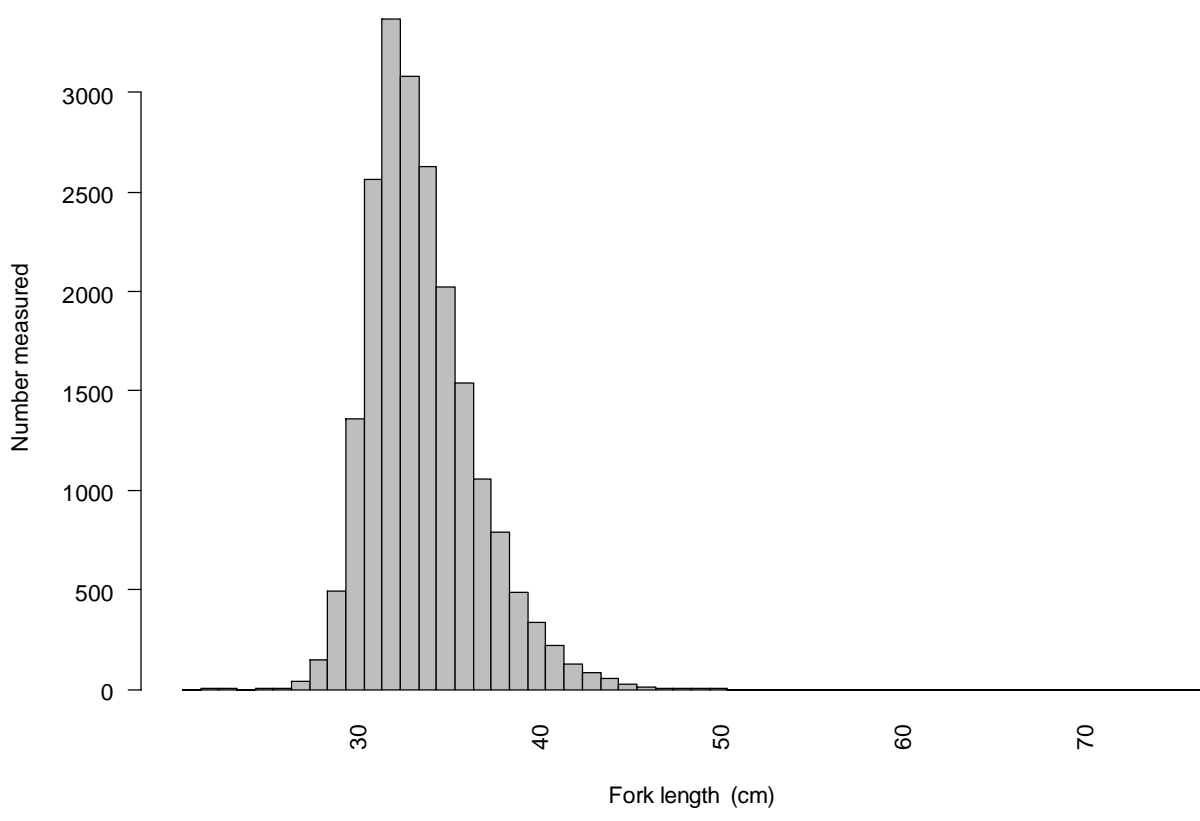
The age-frequency plots are not scaled up by age-length keys. They show only the fish that have been aged: the bars represent only the artificially chosen sample size in each length interval, not the length frequency. They do not accurately represent the length distributions of sampled fish. Only the proportions of fish of different ages in each length interval are important.

Several criteria unrelated to the length frequency determine whether fish have their otoliths removed. The total number of otoliths collected per year is restricted by a cap per length class; hence the number of otoliths collected from each Fraser Island trip depends on how many have already been collected earlier in the year, both in other locations and on previous Fraser Island trips. There is also a cap on the number of otoliths retained per catch for each length class.

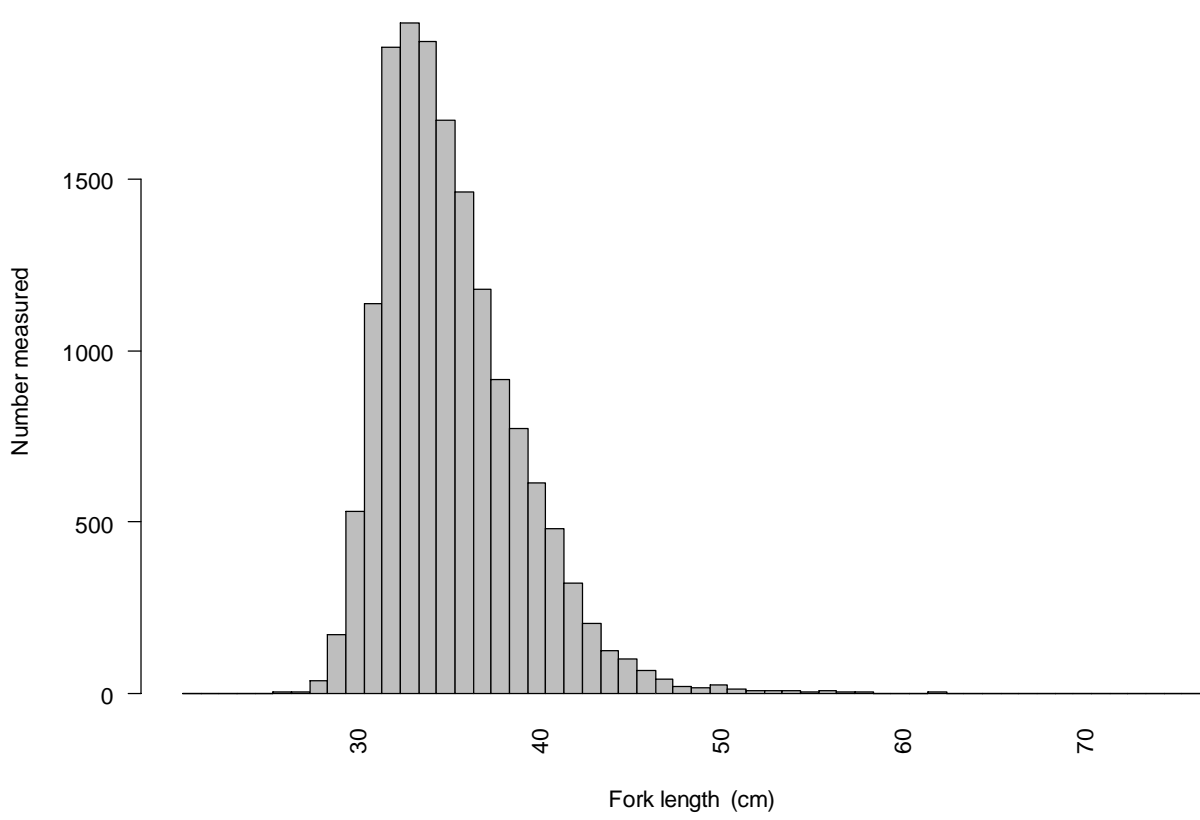
These proportions of age-at-length can be seen to change with time of year. For example, the length at which the proportions of fish aged 1+ (age group 2) and 2+ (age group 3) are the same can be seen to increase with trip number, so that later trips tend to sample younger fish of the same length. Therefore, not only the length distributions (grey plots) but also the age-at-length distributions (colour proportions within the bars) vary seasonally. The differences cannot be explained by growth of fish between trips, as the trips are quite close together in the calendar year.



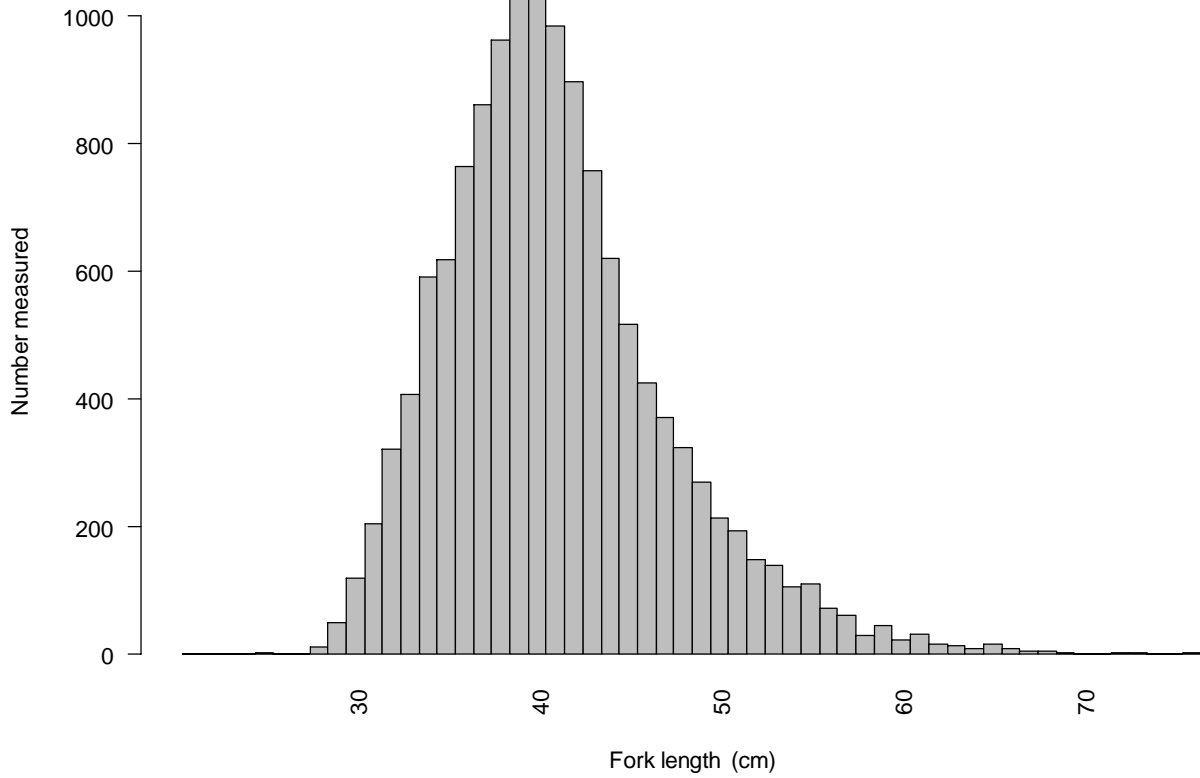
**Trip 1, all years combined**



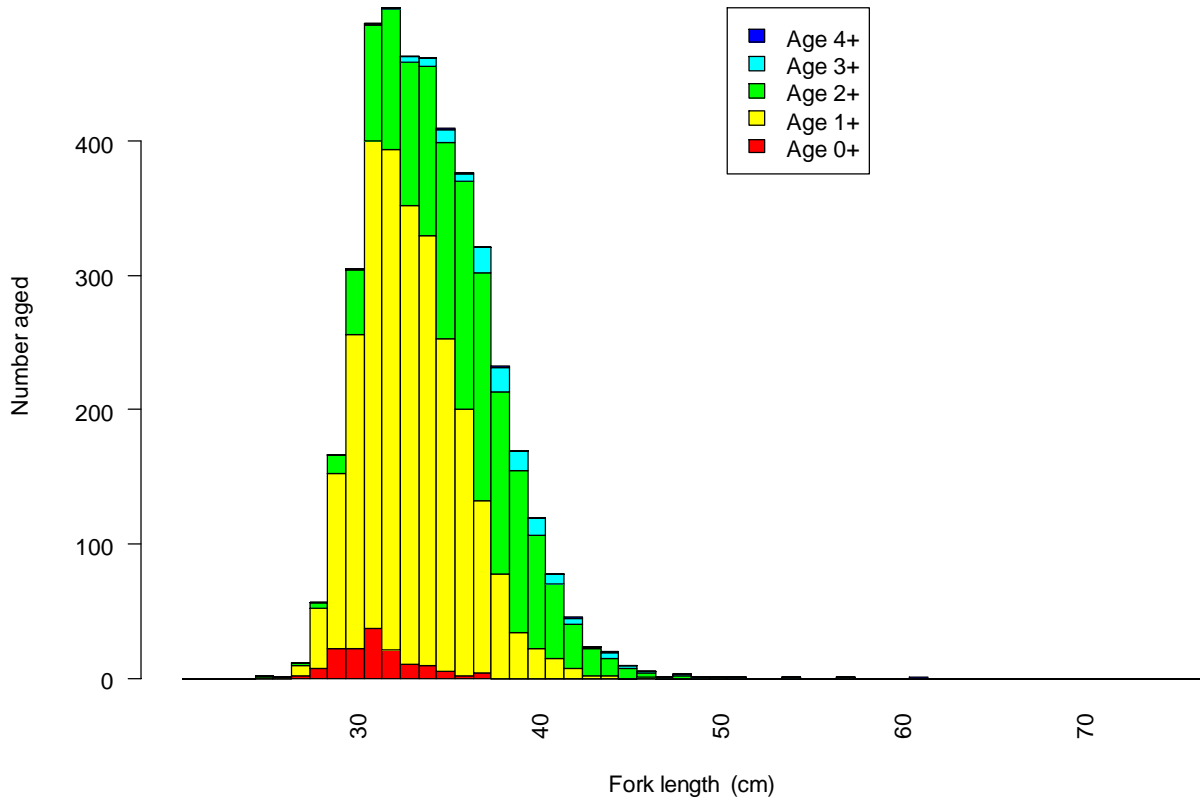
**Trip 2, all years combined**



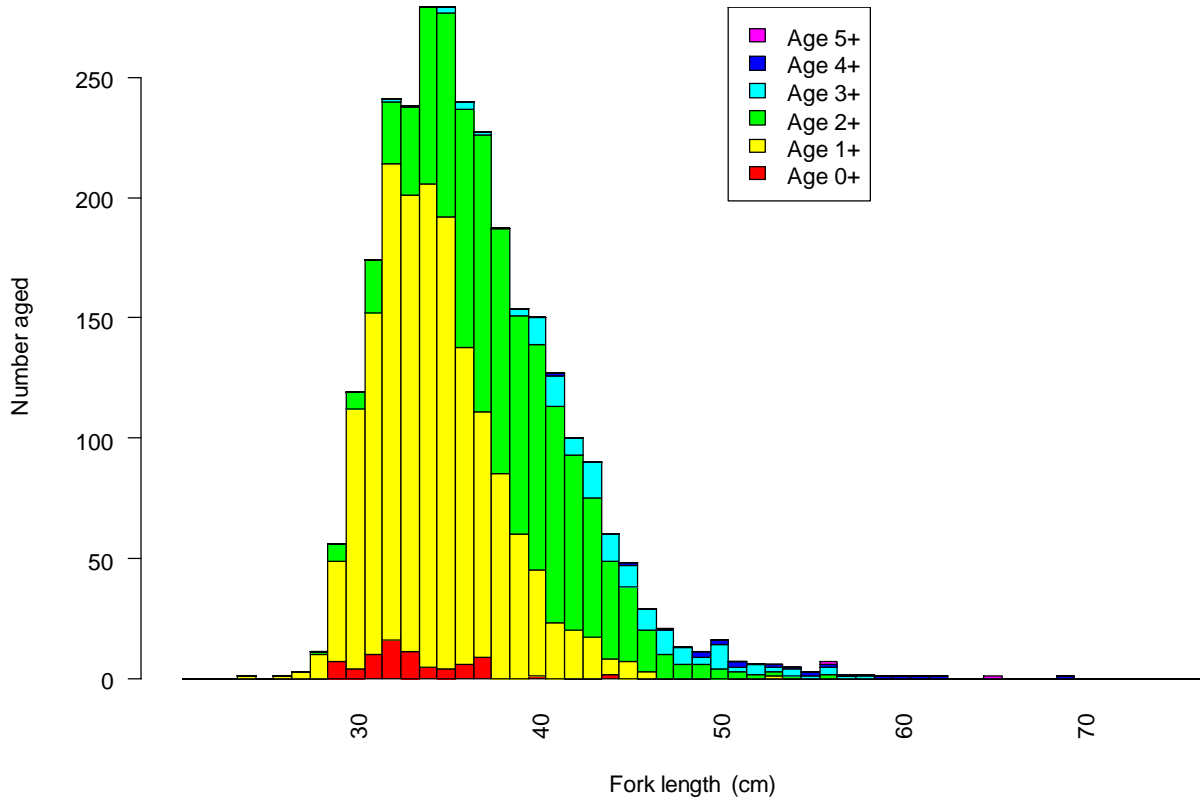
**Trip 3, all years combined**



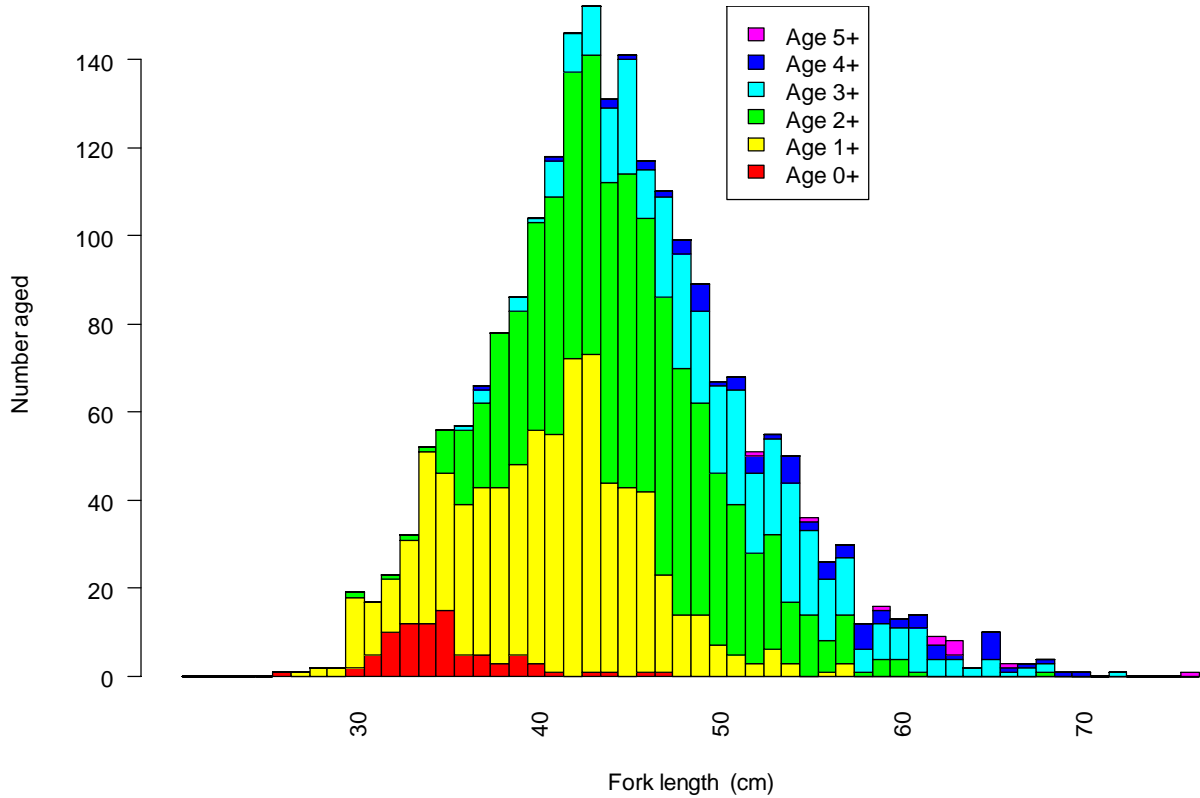
**Trip 1, all years combined**



**Trip 2, all years combined**



**Trip 3, all years combined**



## Appendix 4: Plots of model fit

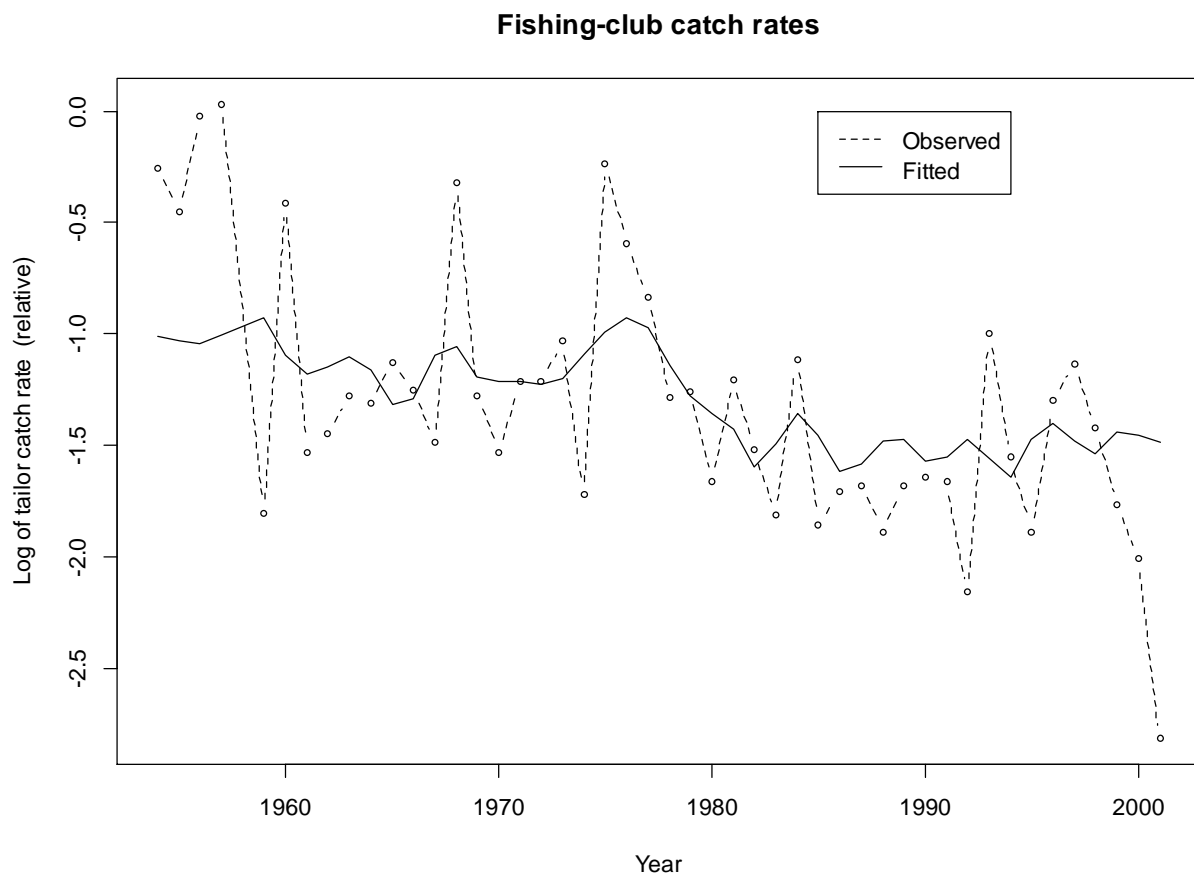
### A4.1 Selection of model run

All the model fits plotted in this appendix come from the MCMC model run with the highest likelihood, with recruitment compensation ratio  $r$  set to 6 (the middle value of the three for which results were obtained). This was the same strategy used to select some of the values plotted in section 5.4. We did not consider it feasible to display the results for all model runs and we believe that this single run provides an accurate impression of how well the model has fitted the data.

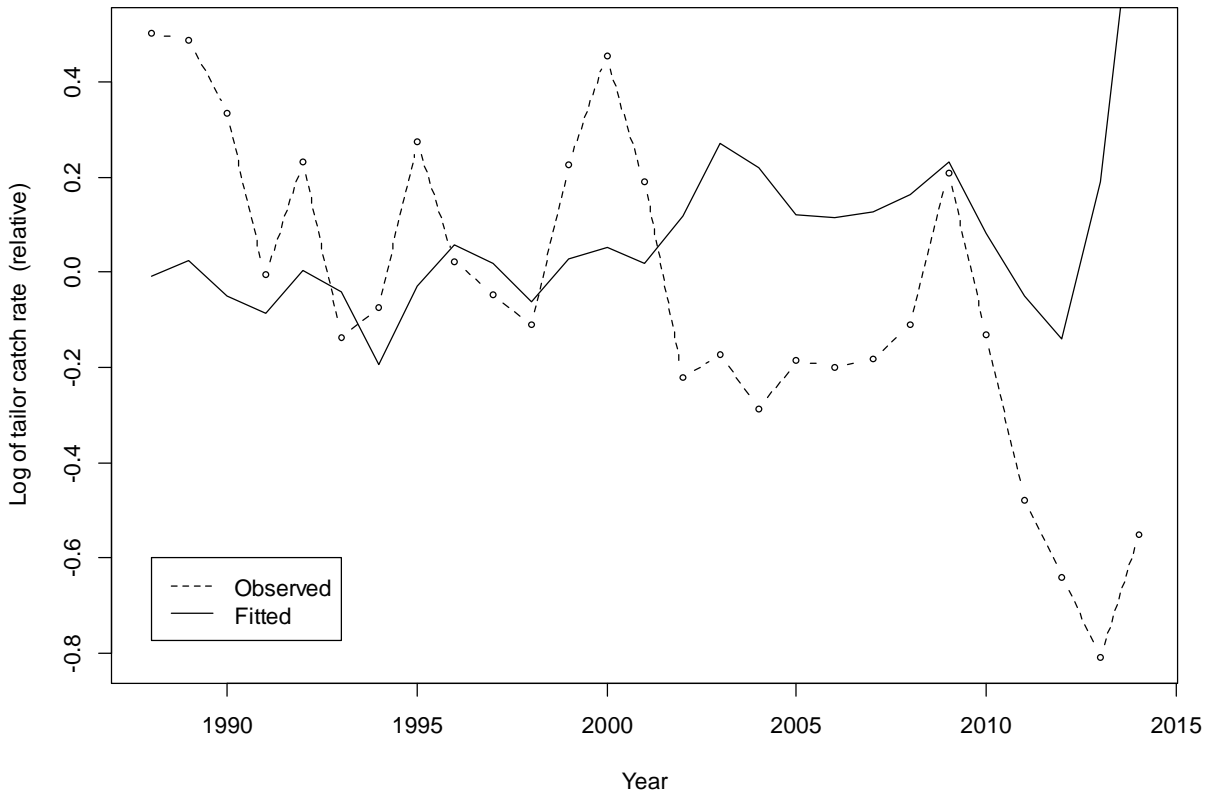
### A4.2 Catch rates

Fits to catch rates are plotted in this section. Four catch-rate time series were input to the model: Queensland fishing club, Queensland gillnet, NSW gillnet and NSW line-fishing.

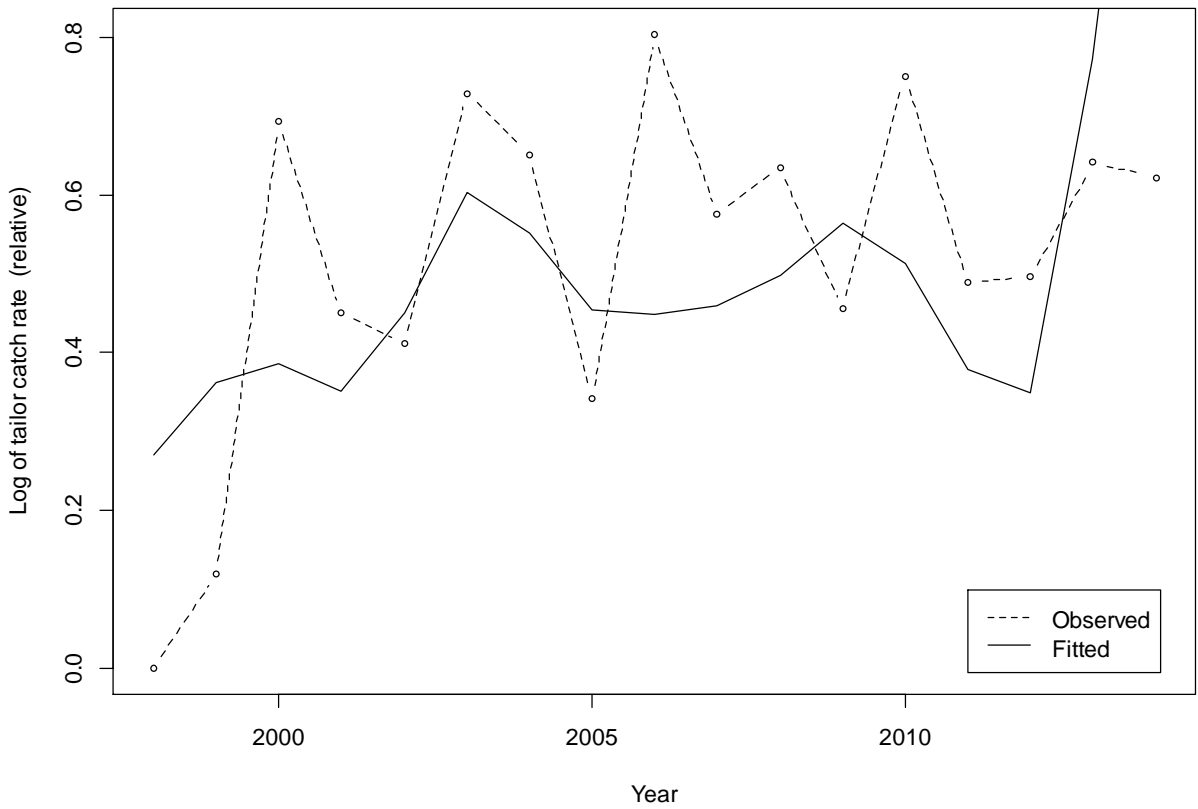
The observed catch rates were previously presented in Figures 3.3, 3.4 and 3.5 in chapter 3. Confidence intervals for the observed catch rates were plotted in Figures 3.3 and 3.4, and described in the caption of Figure 3.5. They are not reproduced here.



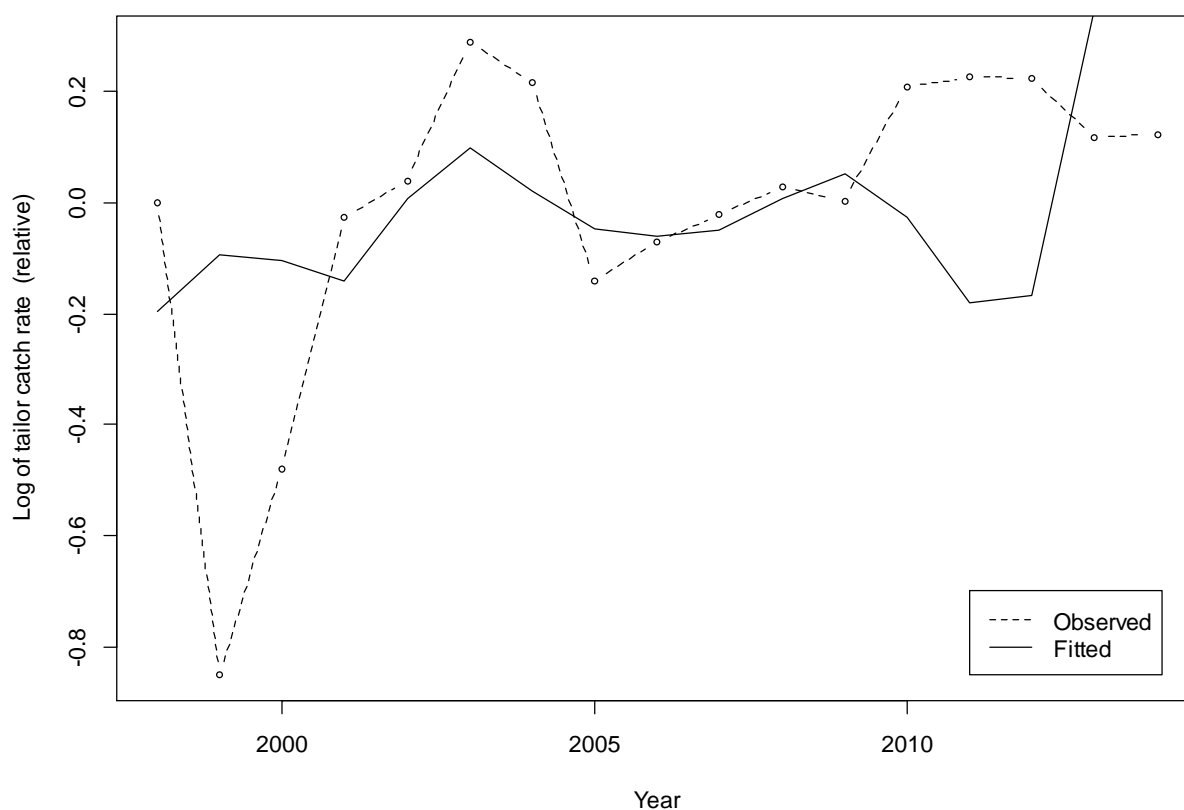
Queensland gillnet catch rates



NSW gillnet catch rates



### NSW line catch rates



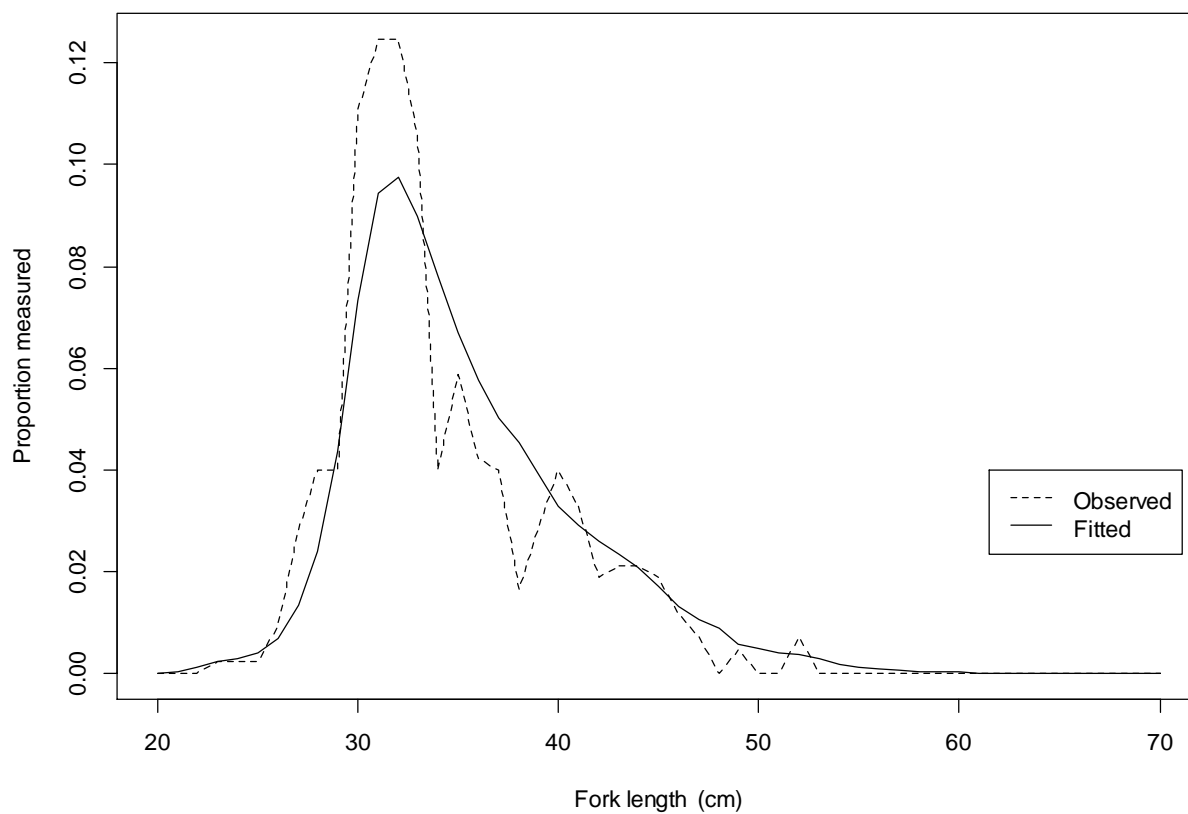
### A4.3 Length-frequency data

This section presents model fits to length-frequency data. The model's estimated effective sample sizes (ESSs) are noted on the titles of the plots. The ESS provides a measure of "goodness of fit" to the data and also shows the relative weighting that the model gave to the sample; the weighting is inversely proportional to the ESS.

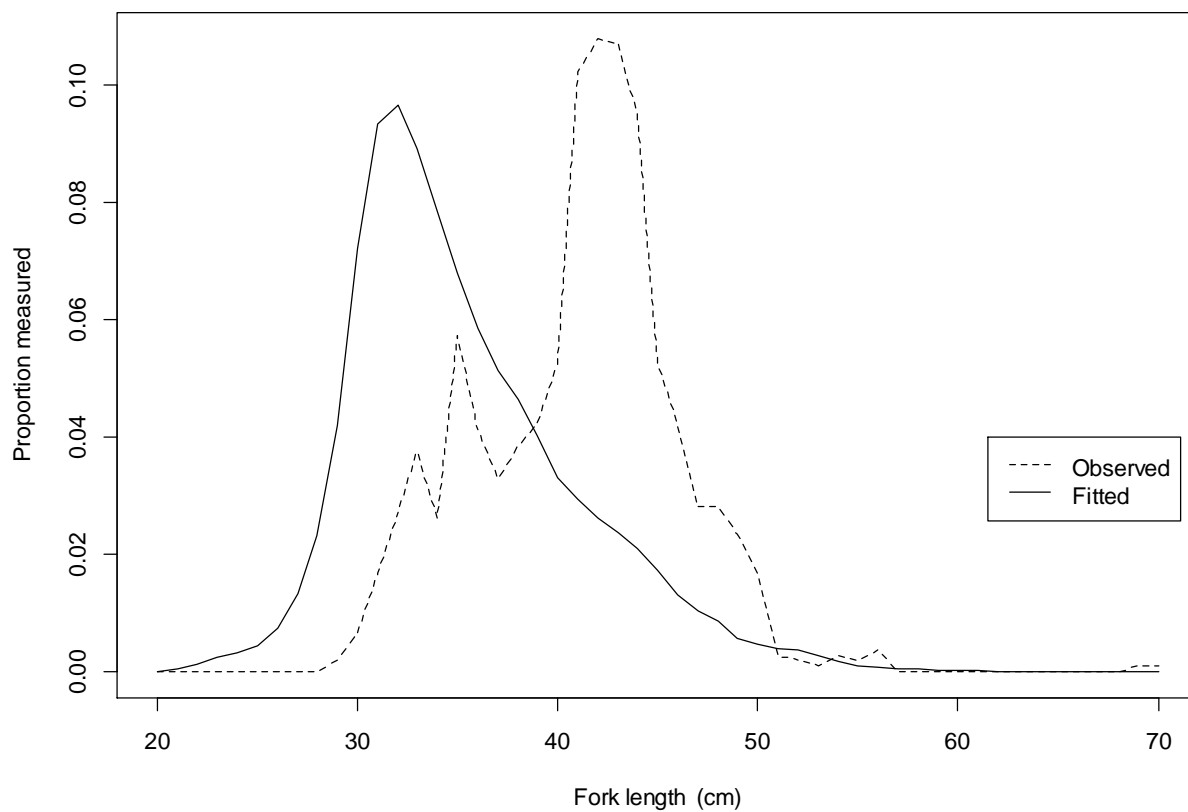
A marked improvement in the fits, quantified by higher ESS values, is evident from the beginning of the official Fisheries Queensland monitoring program in 1999. The sampling under this program has been undertaken according to carefully designed scientific protocols.

Sampling trip 3 to Fraser Island has been carried out by the Fisheries Queensland monitoring team in every year since 2002. This trip tends to sample bigger fish which are lacking in trips 1 and 2. Therefore samples prior to 2002 tend to lack big fish. This is especially evident in 2001. The fish were evidently smaller in 2001 than in other years, but some schools of big fish may still have come to Fraser Island late in that year when the monitoring team was not present.

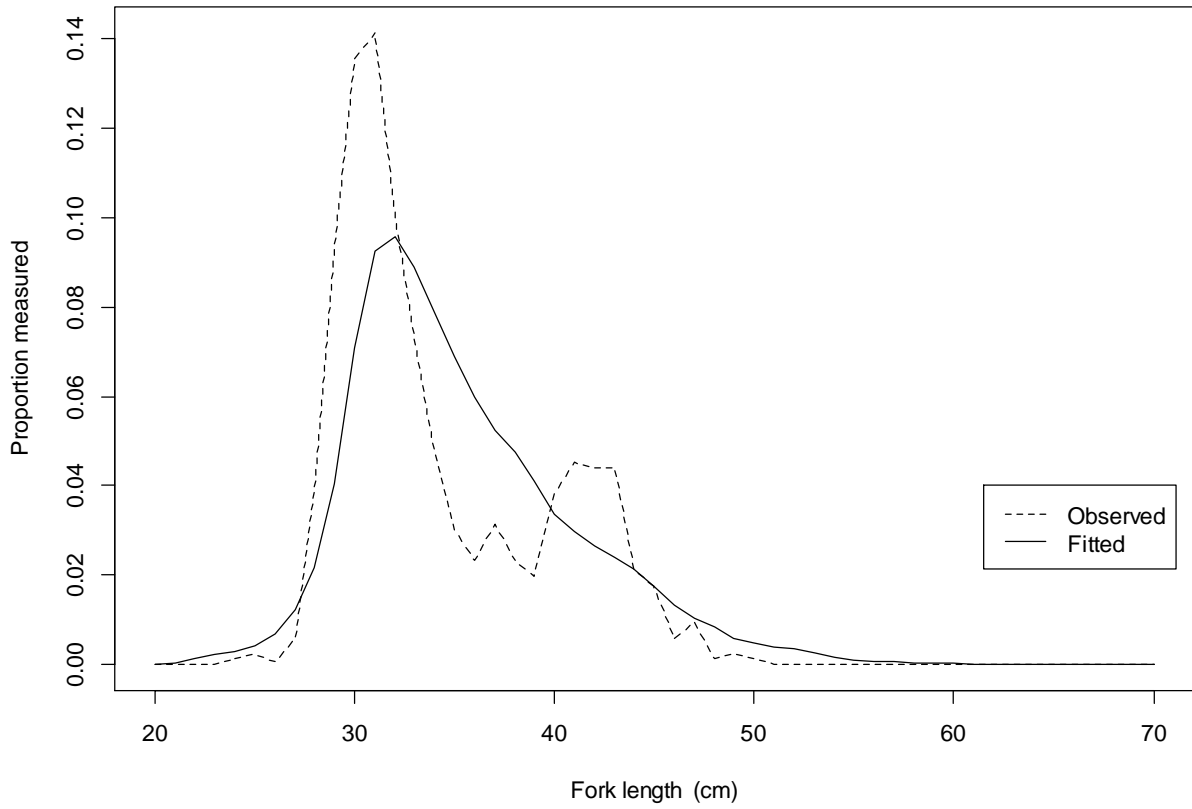
**Queensland recreational, 1976, ESS = 153.3**



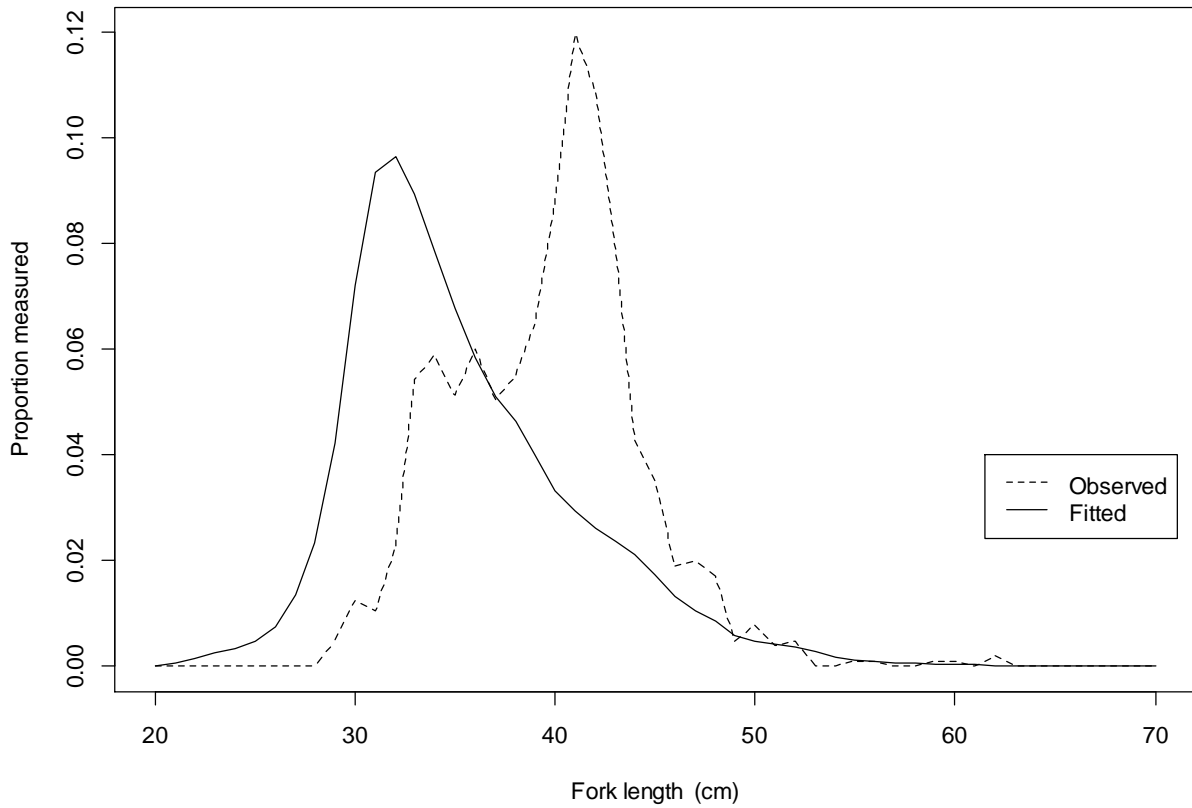
**Queensland recreational, 1978, ESS = 22.2**



Queensland recreational, 1979, ESS = 78.3

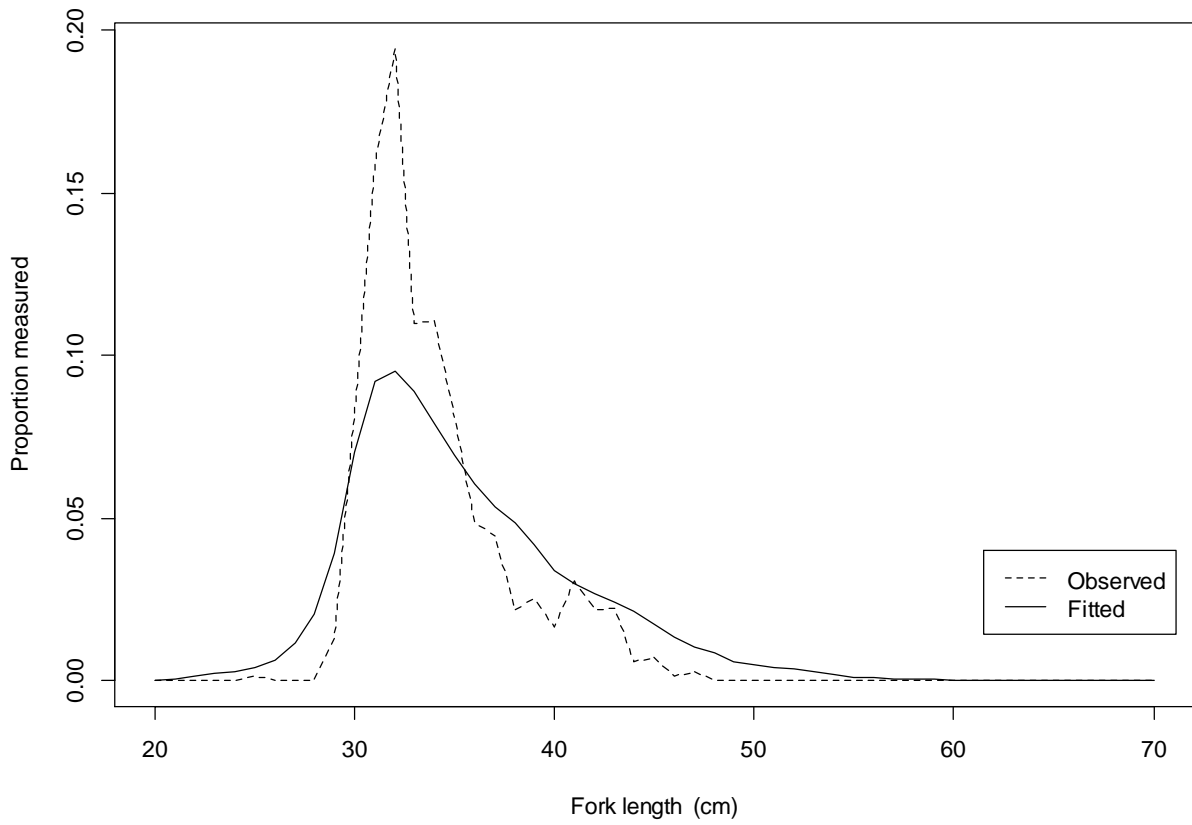


Queensland recreational, 1980, ESS = 28.7

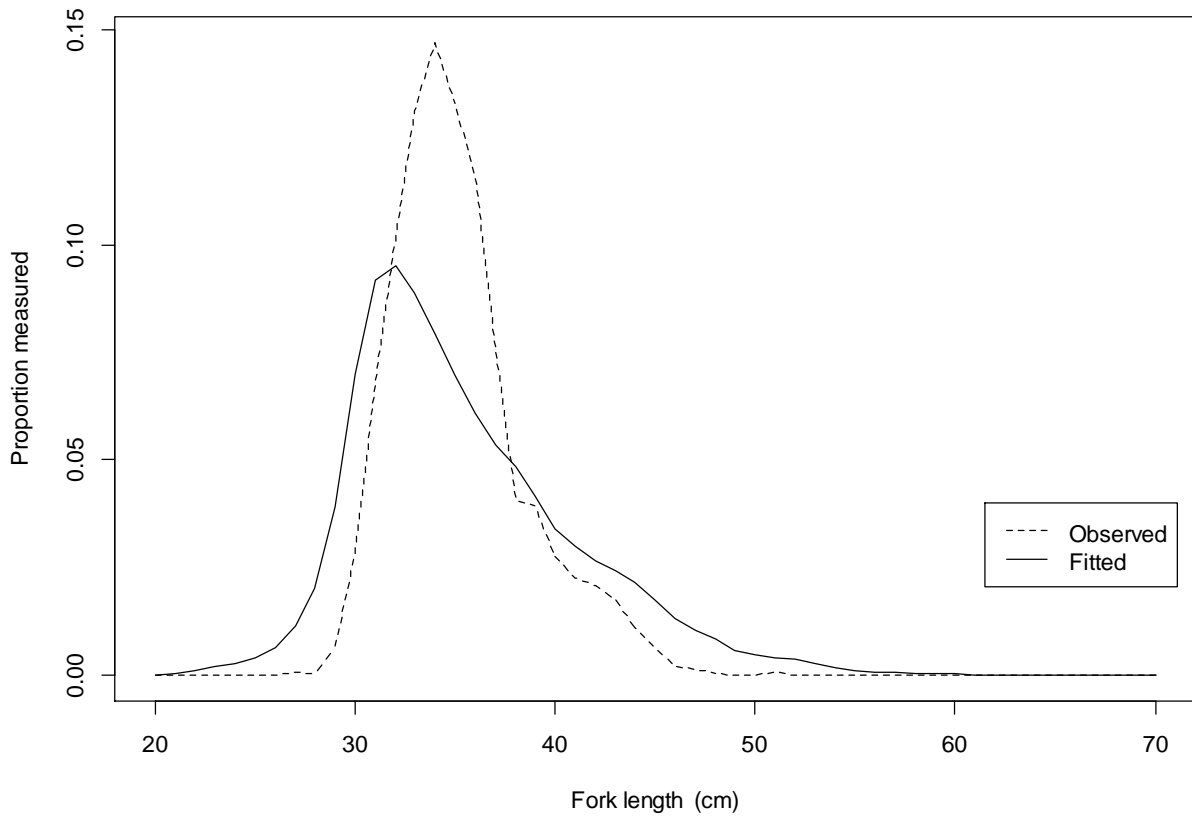




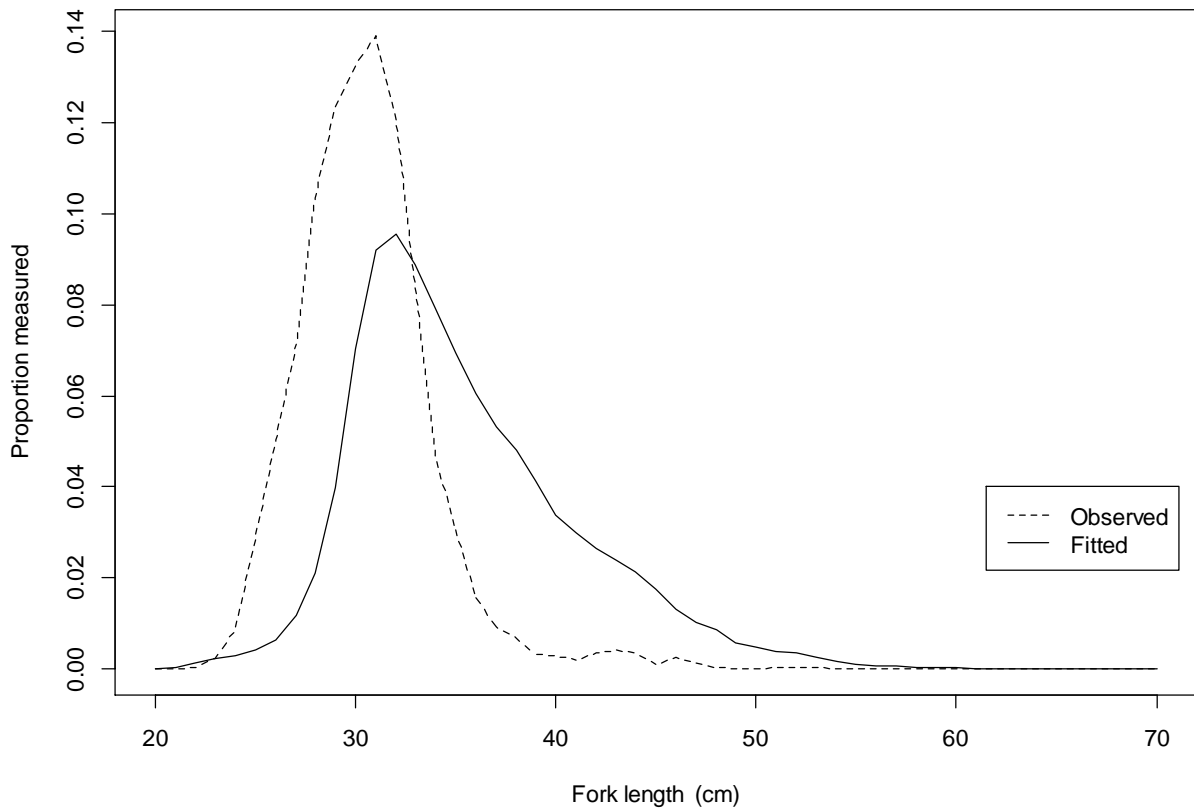
Queensland recreational, 1987, ESS = 48.1



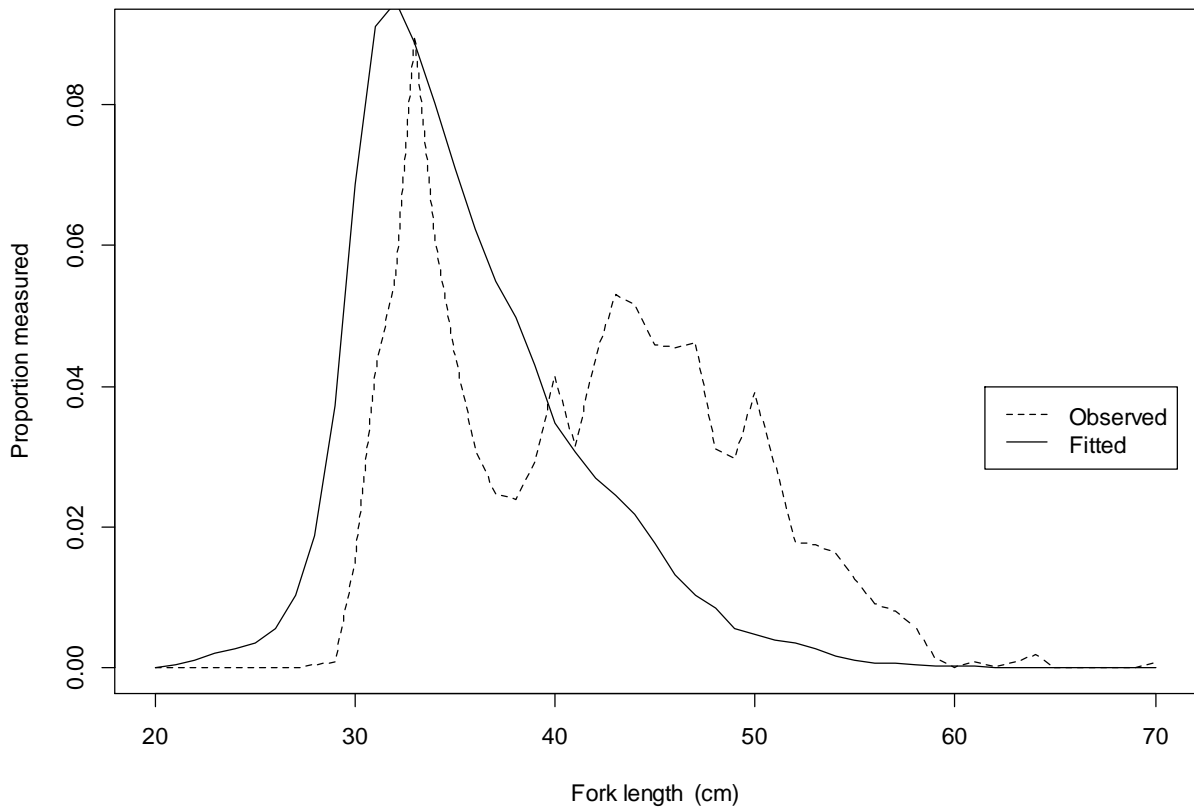
Queensland recreational, 1988, ESS = 52.2



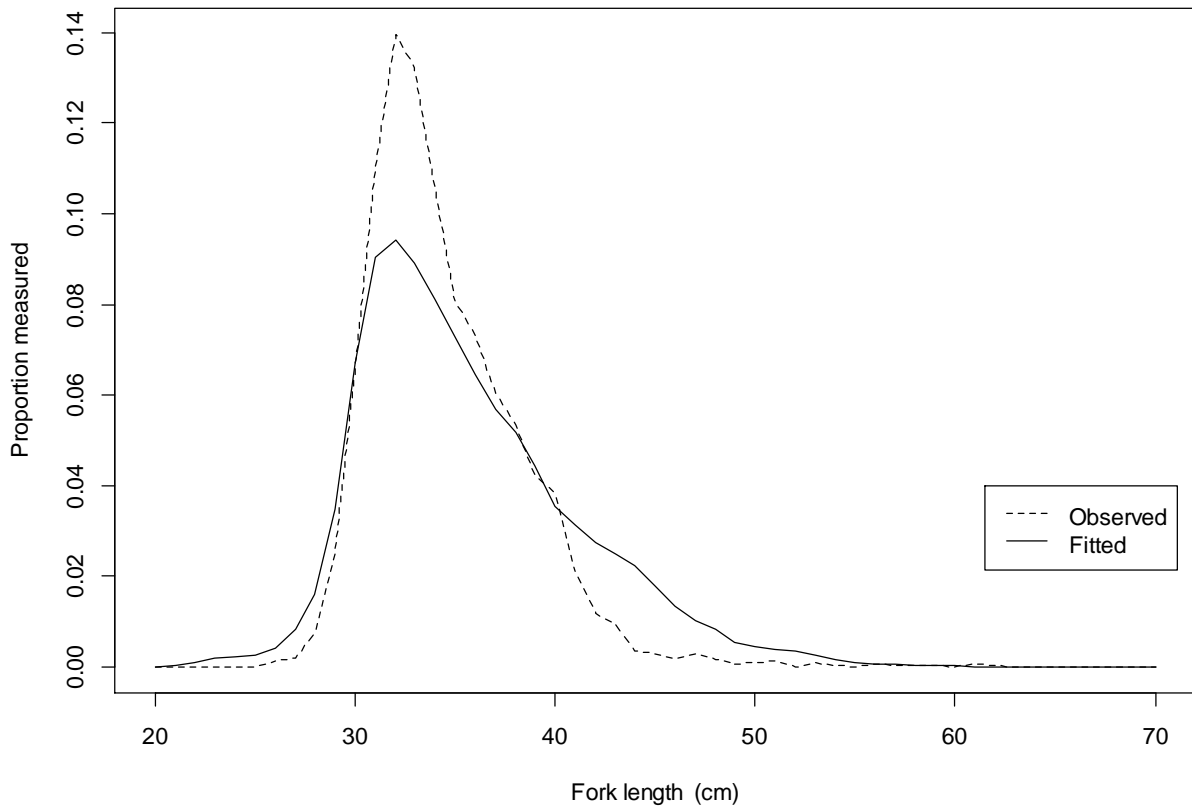
Queensland recreational, 1989, ESS = 23.6



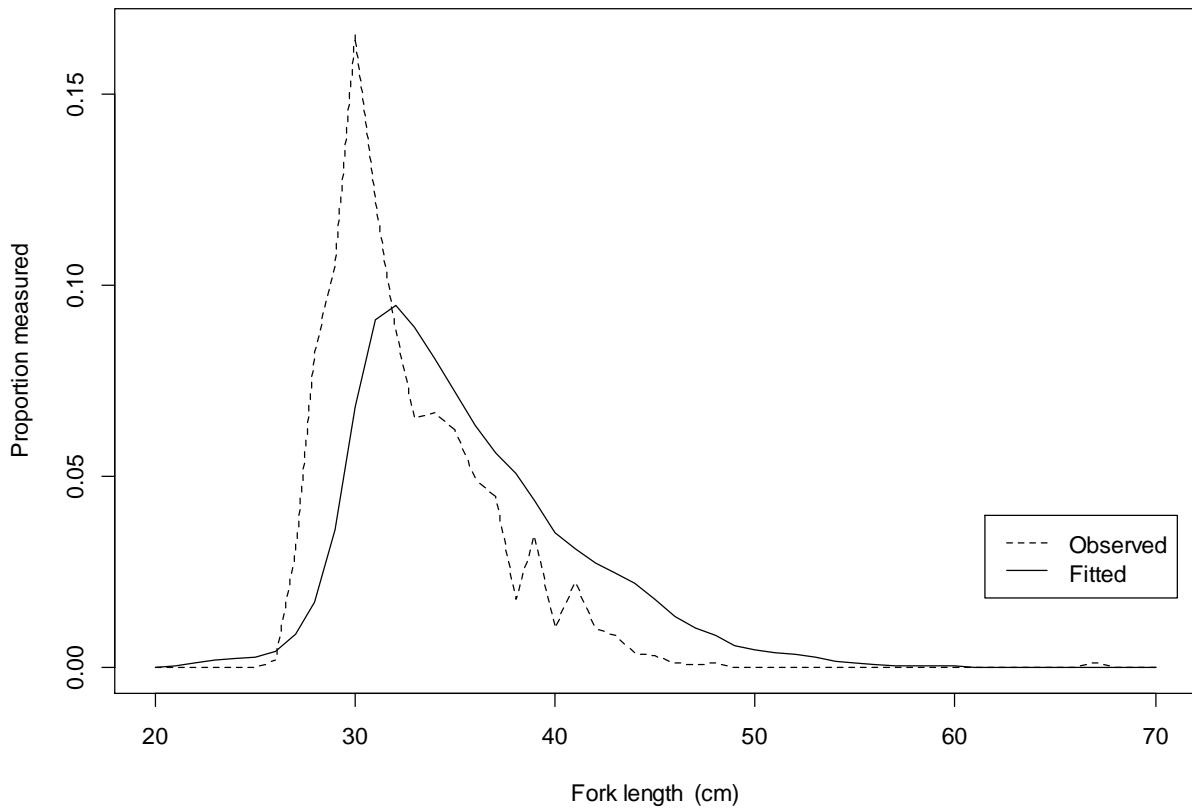
Queensland recreational, 1990, ESS = 32.5



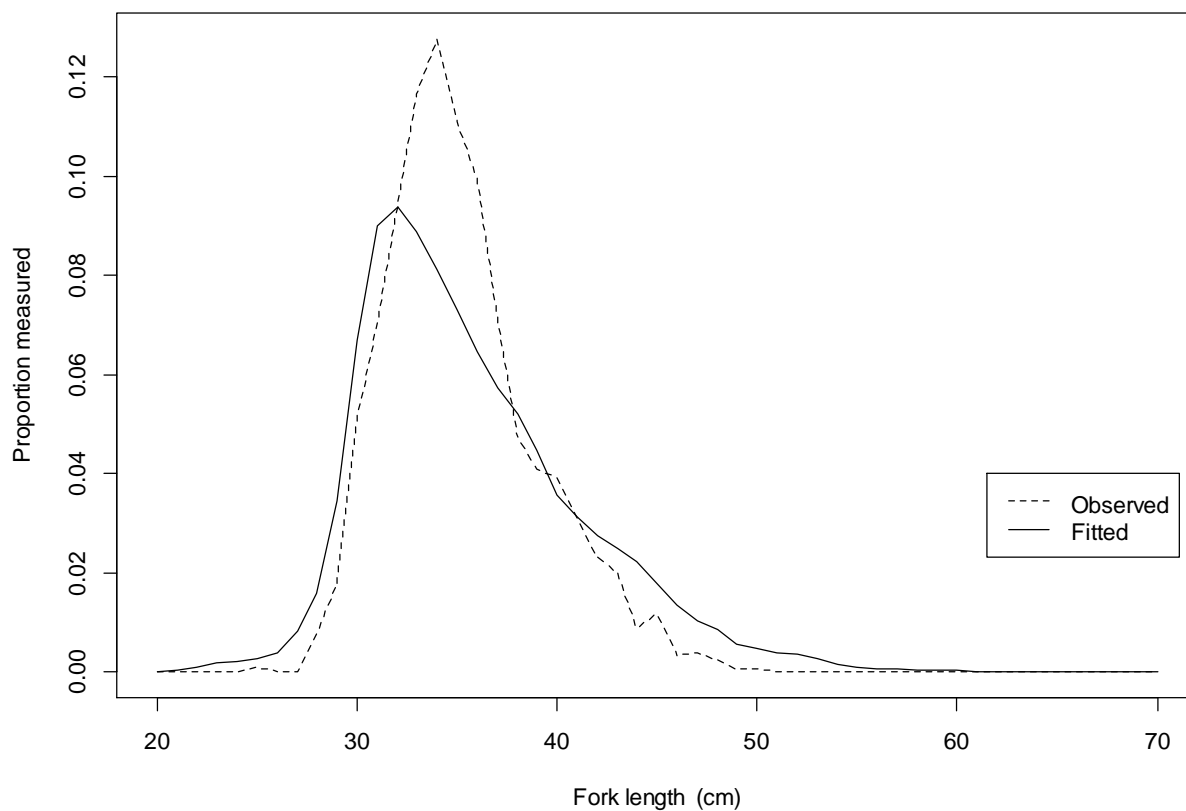
Queensland recreational, 1995, ESS = 159.1



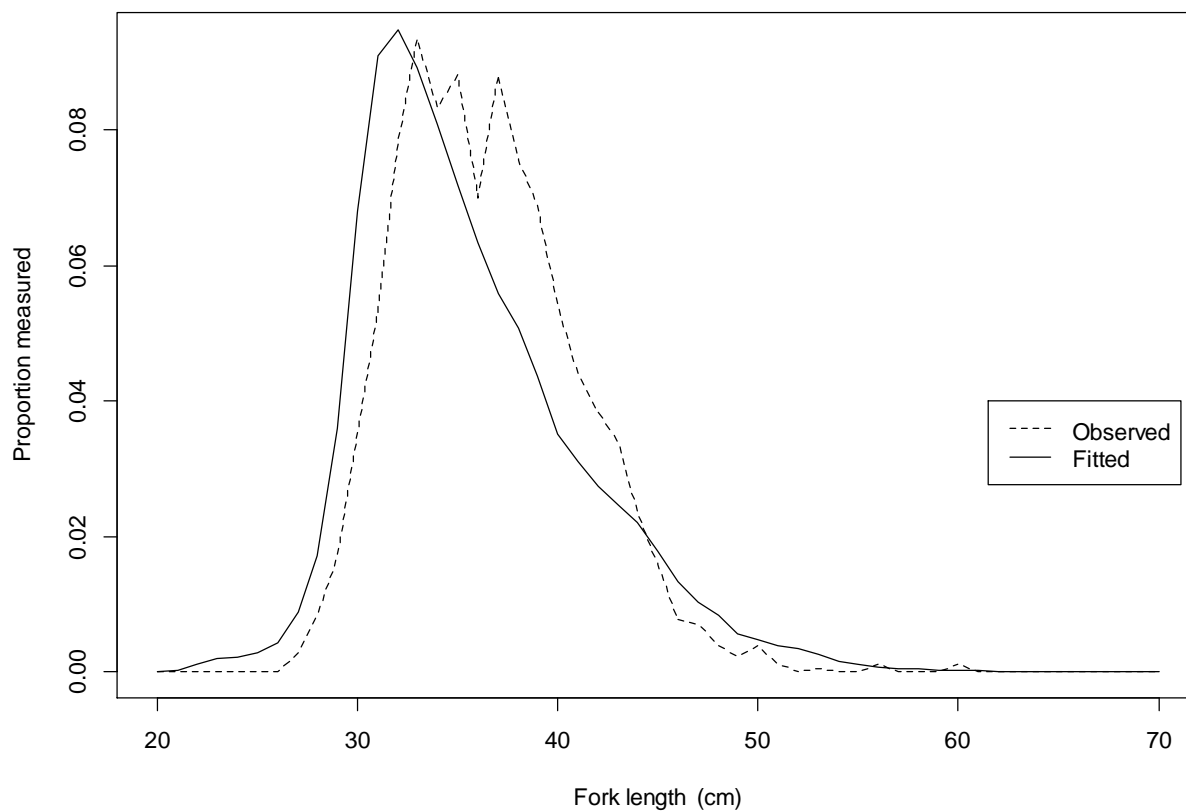
Queensland recreational, 1996, ESS = 38



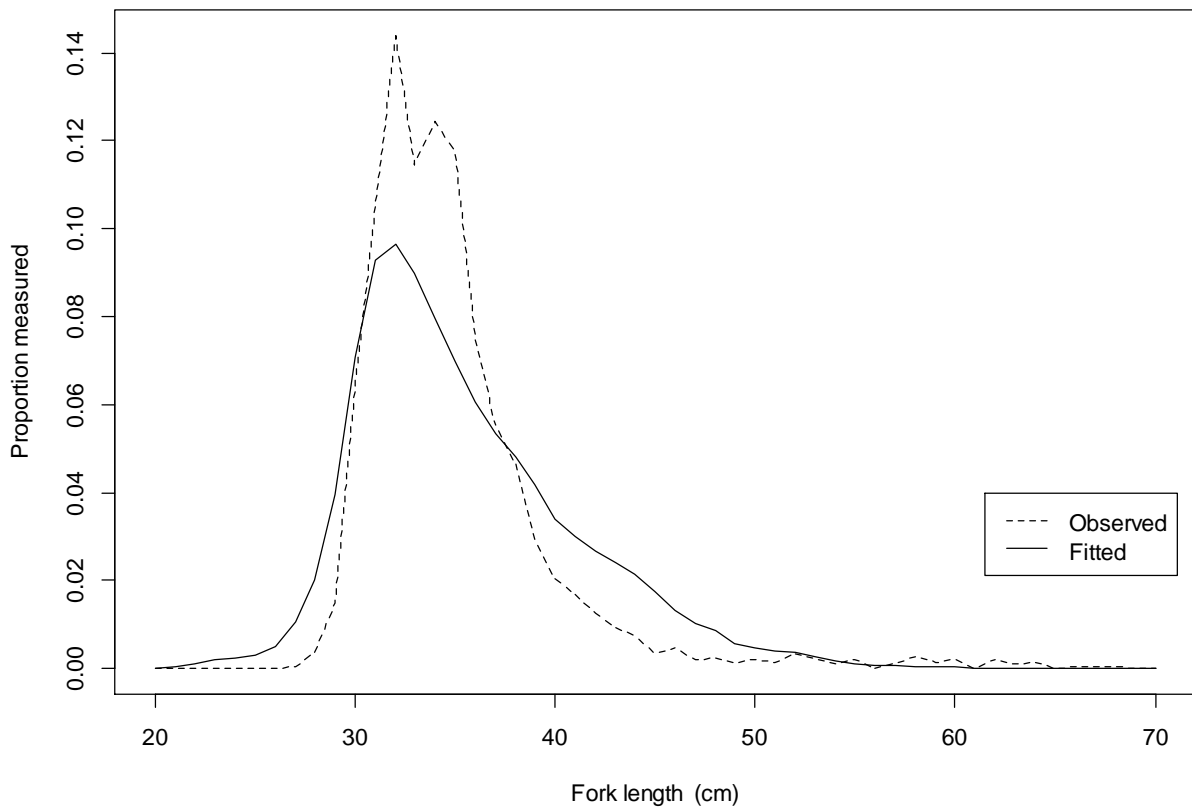
Queensland recreational, 1997, ESS = 117.2



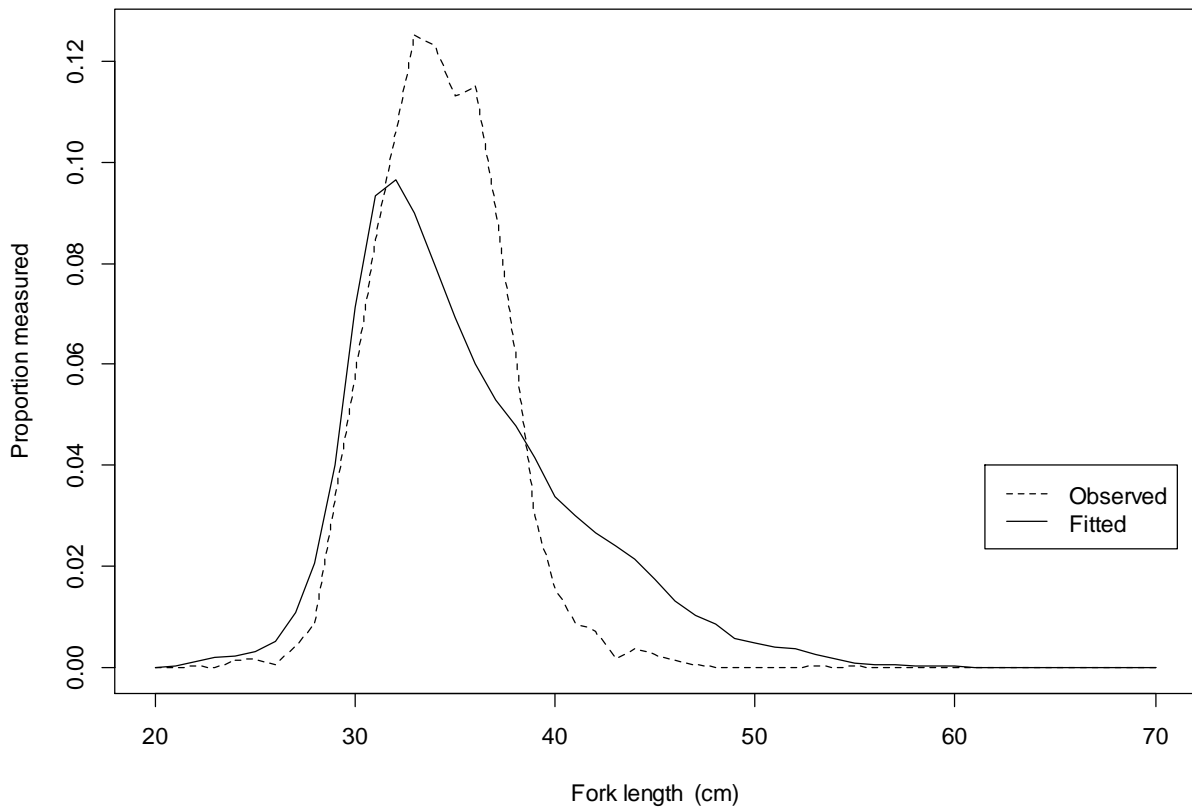
Queensland recreational, 1999, ESS = 152.5



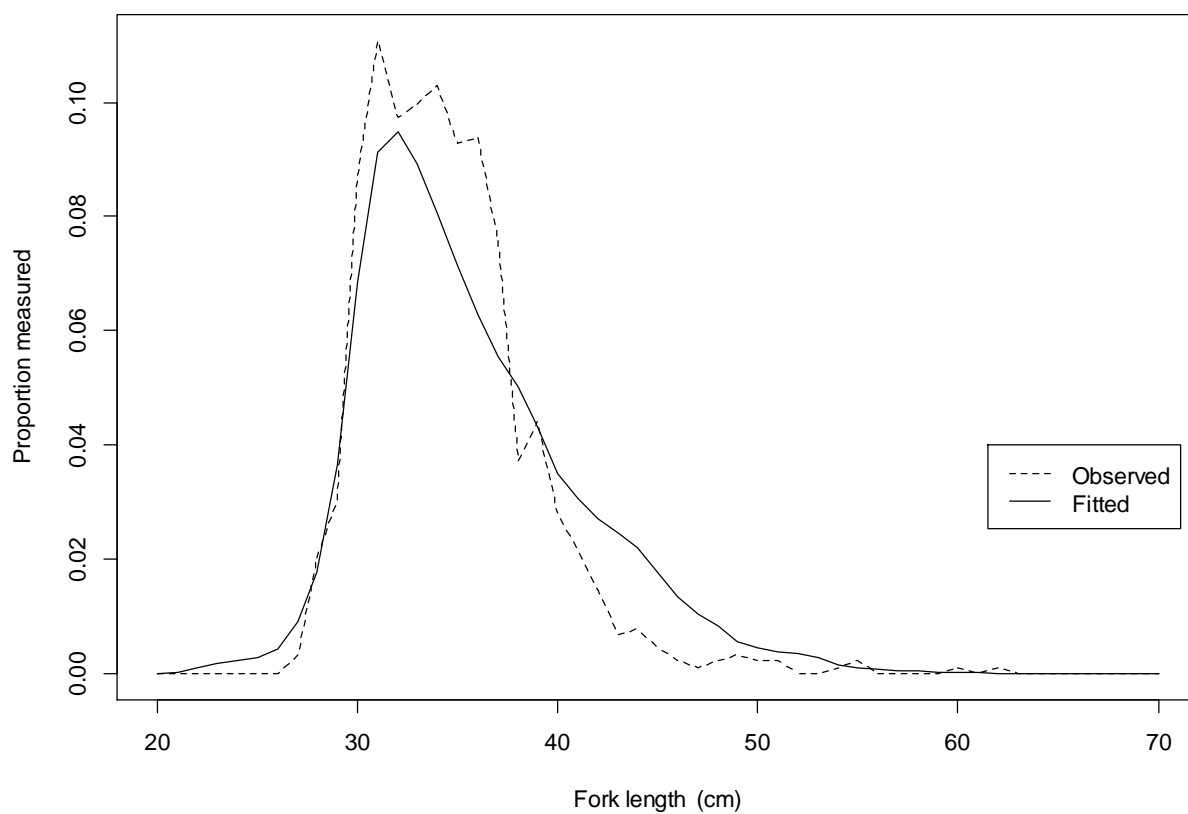
**Queensland recreational, 2000, ESS = 127.9**



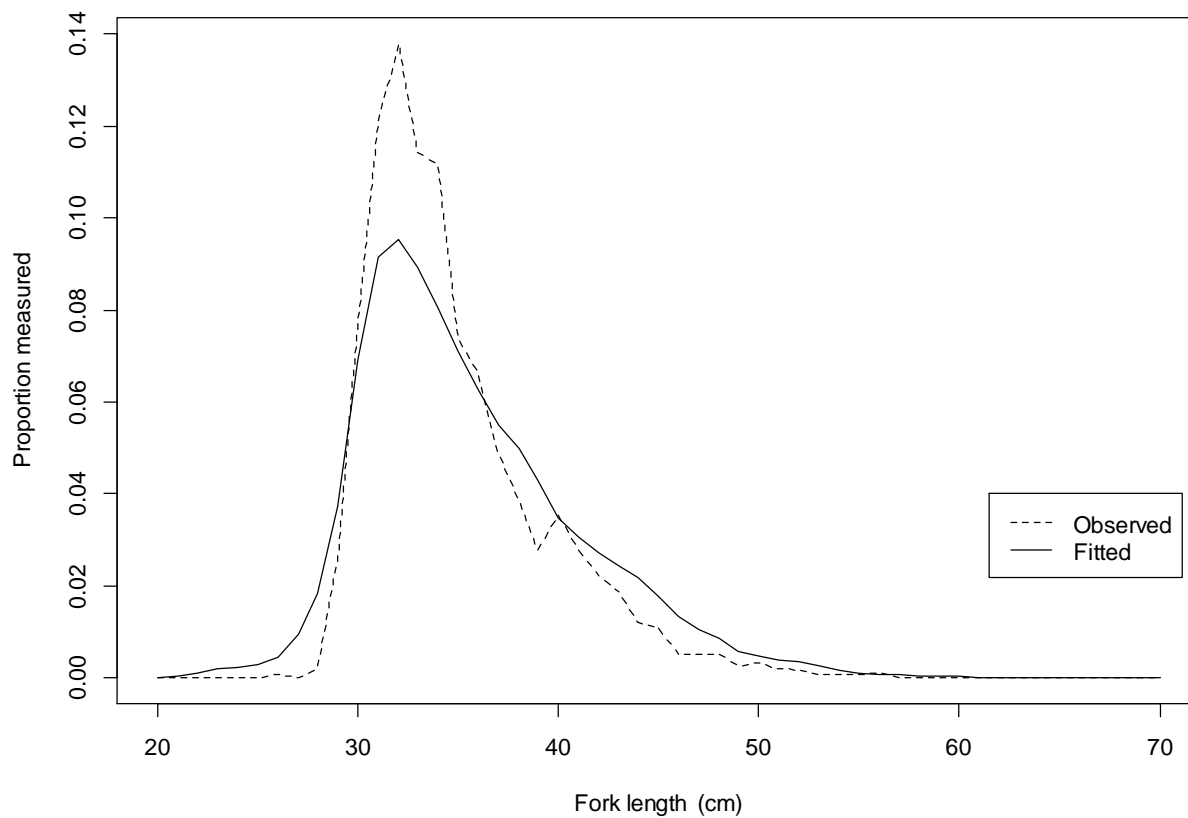
**Queensland recreational, 2001, ESS = 69.6**



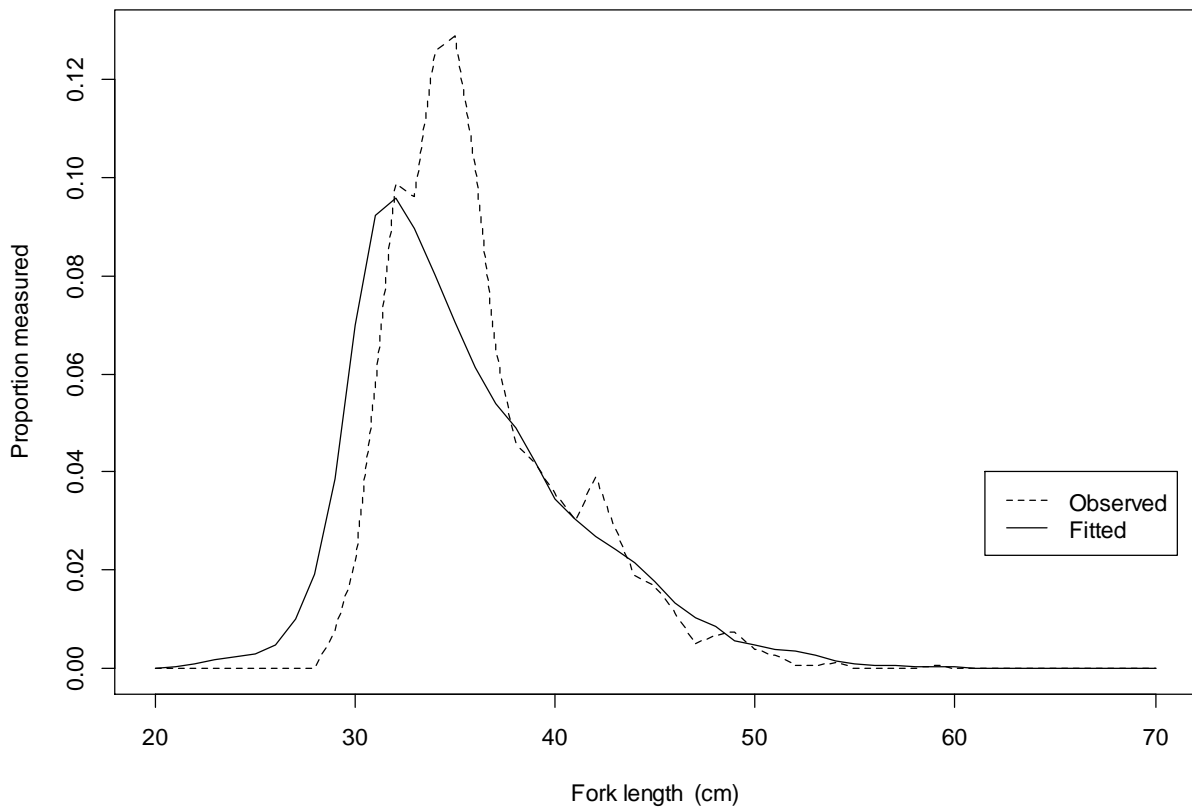
**Queensland recreational, 2002, ESS = 144.3**



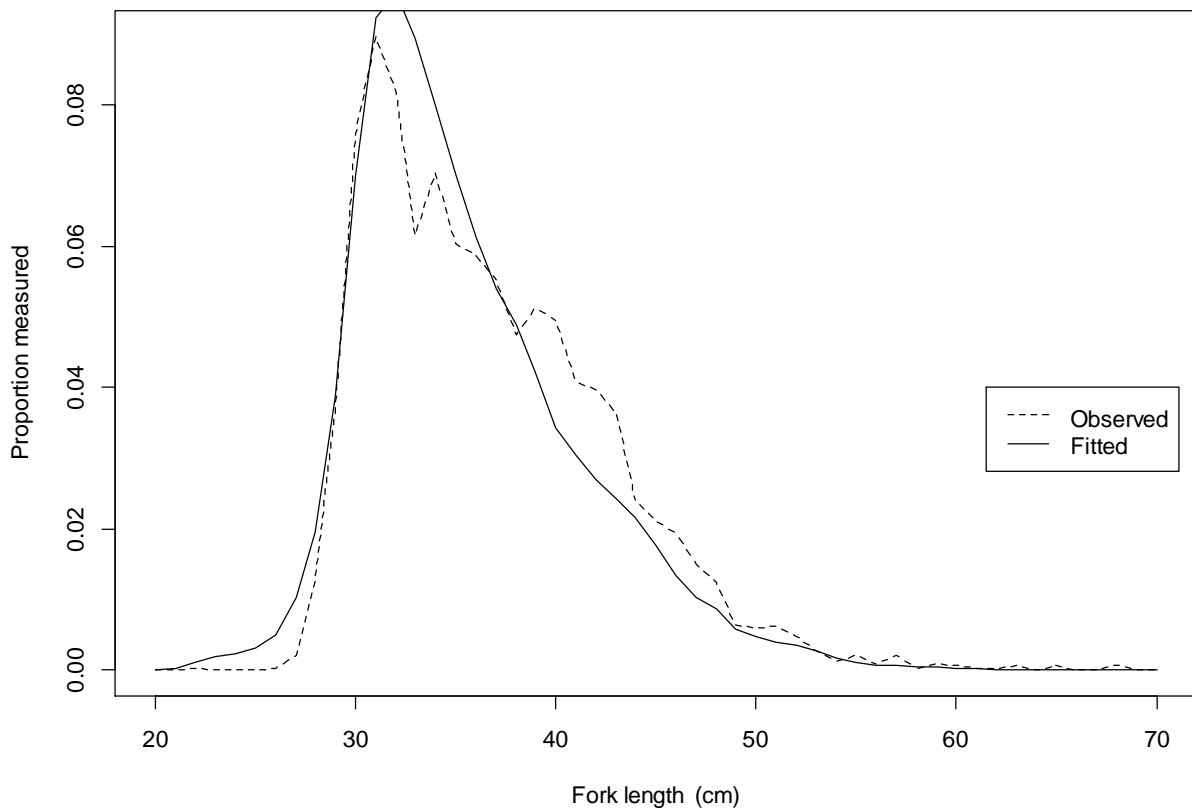
**Queensland recreational, 2003, ESS = 185.7**



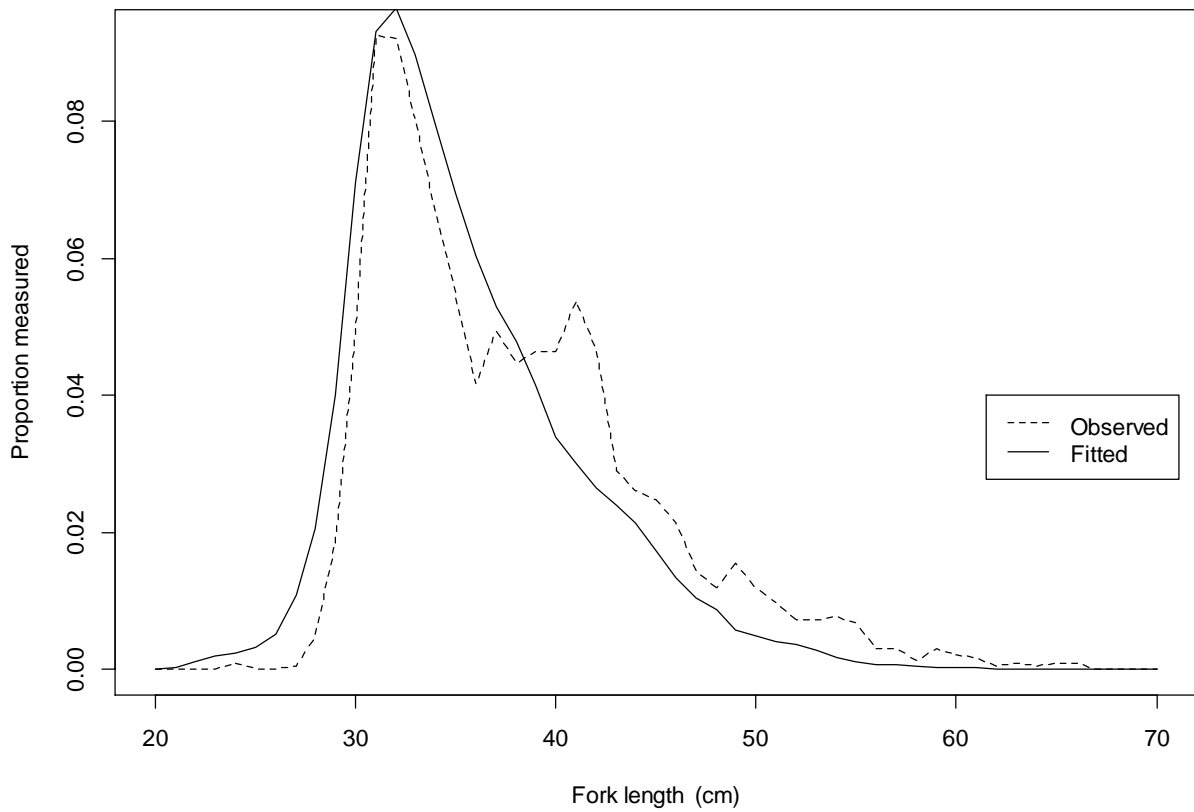
**Queensland recreational, 2004, ESS = 92.2**



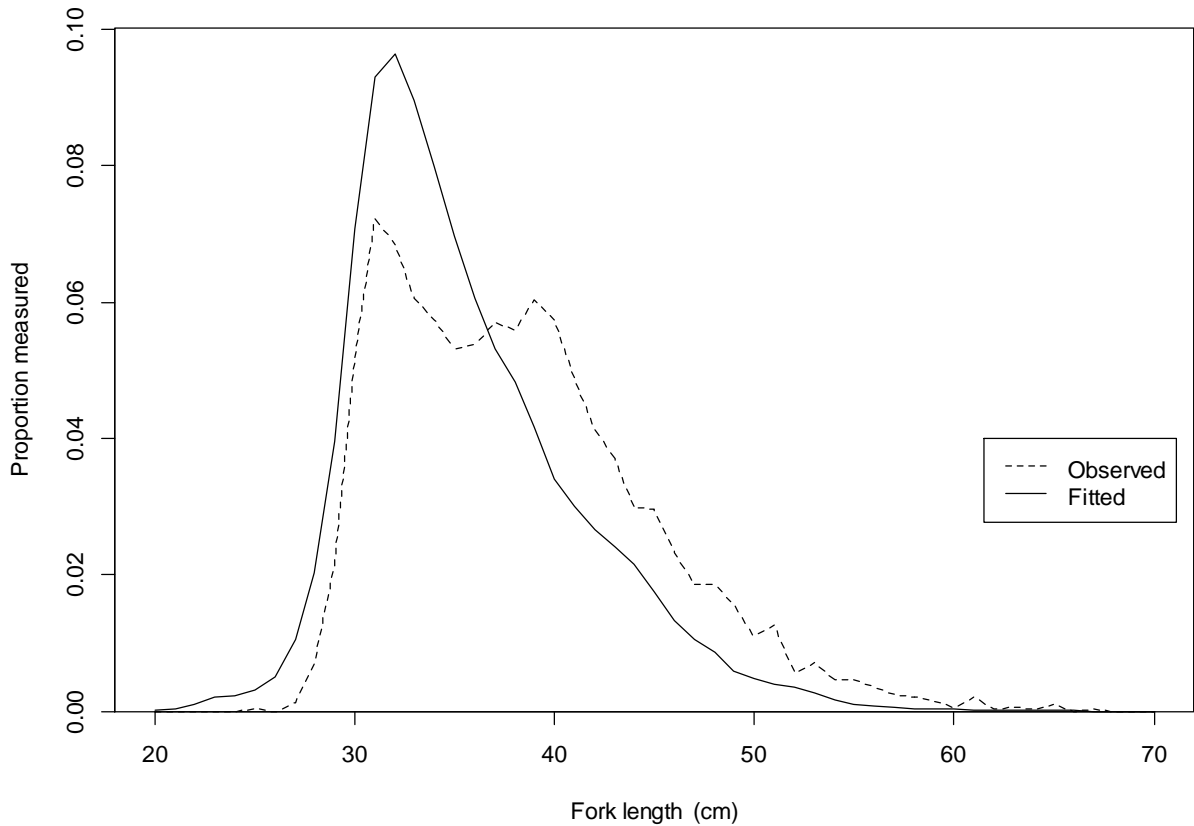
**Queensland recreational, 2005, ESS = 443.6**



**Queensland recreational, 2006, ESS = 173.3**

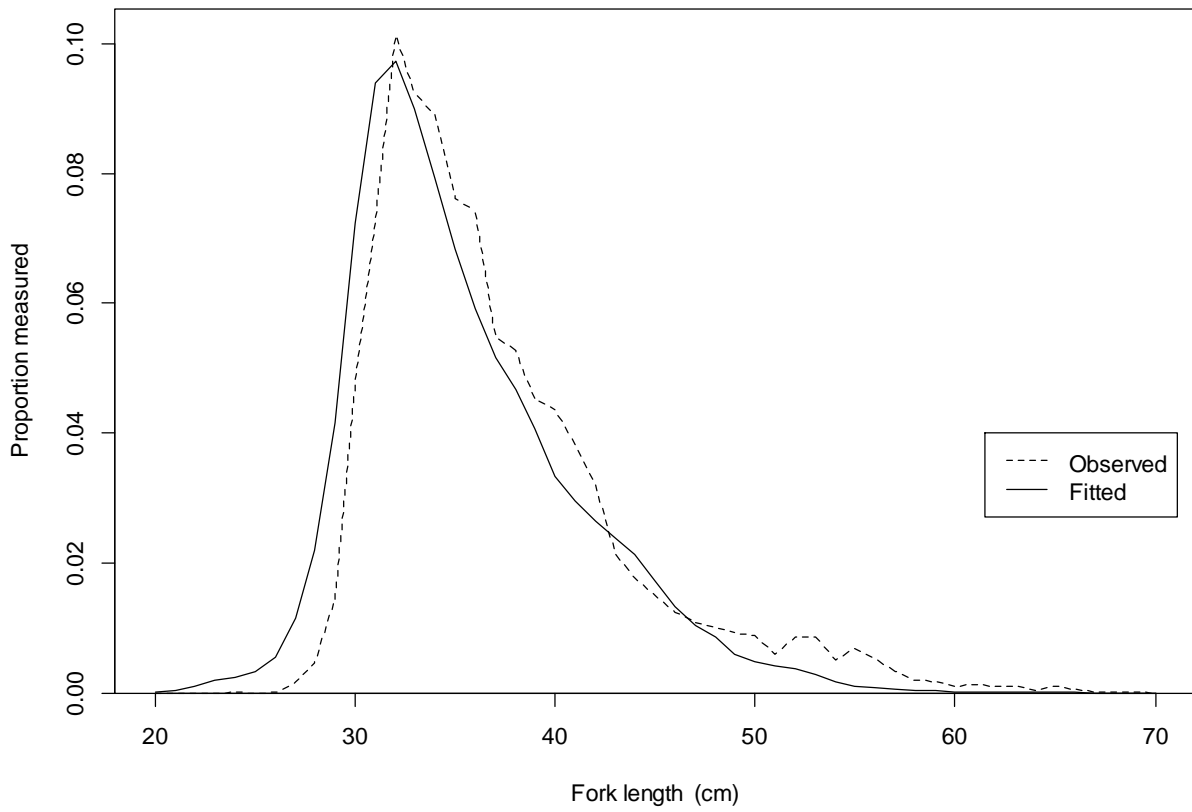


**Queensland recreational, 2007, ESS = 166.3**

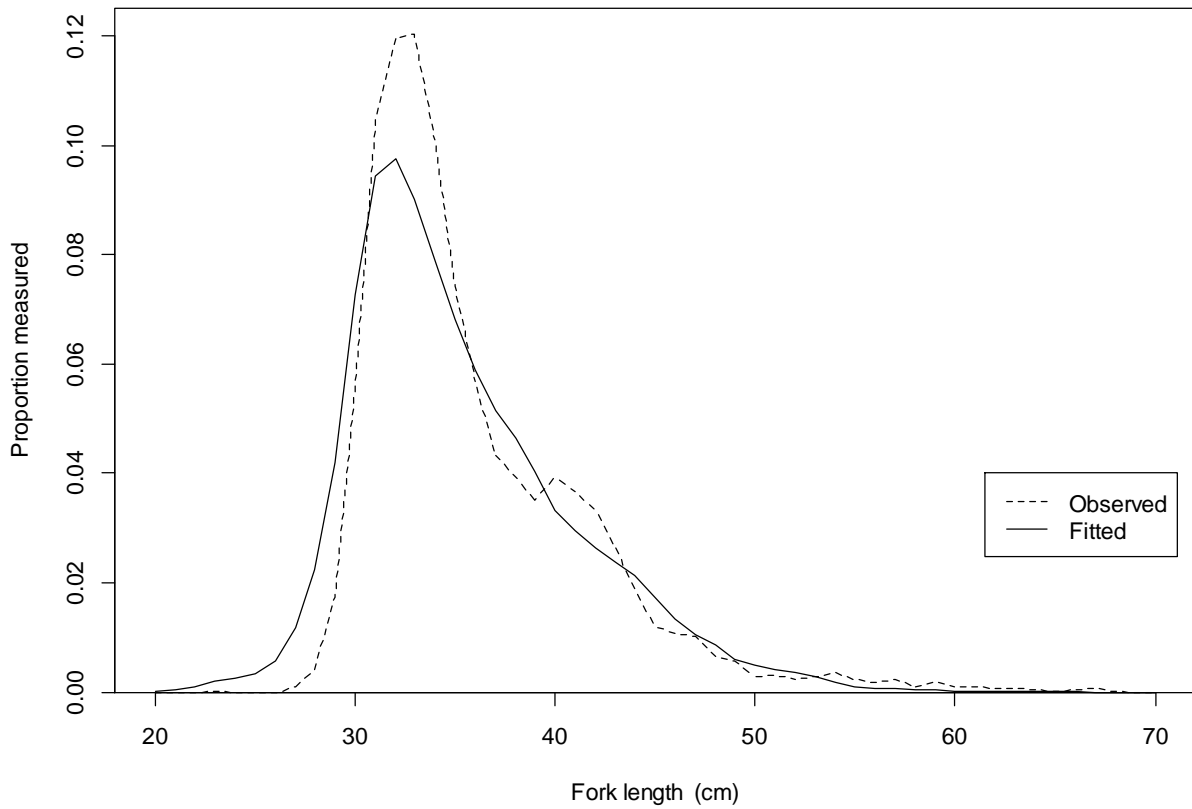




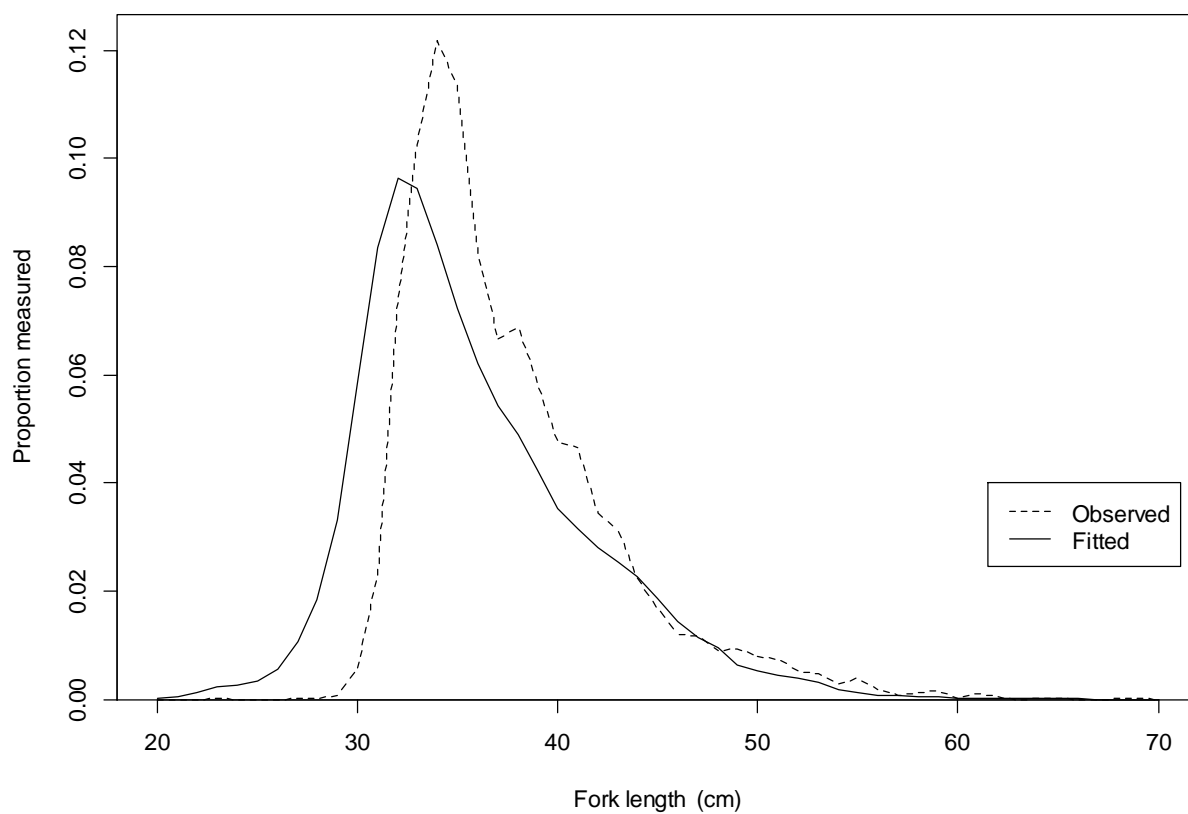
**Queensland recreational, 2008, ESS = 234**



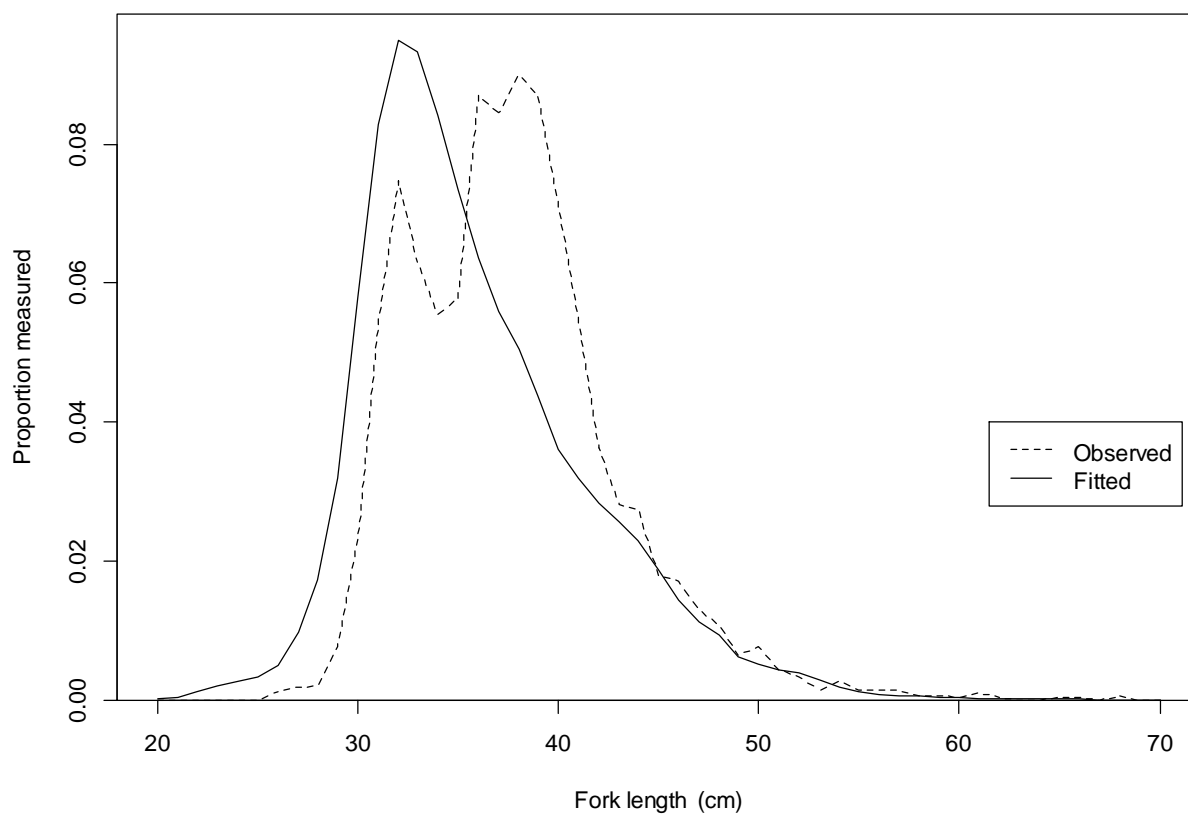
**Queensland recreational, 2009, ESS = 289.8**



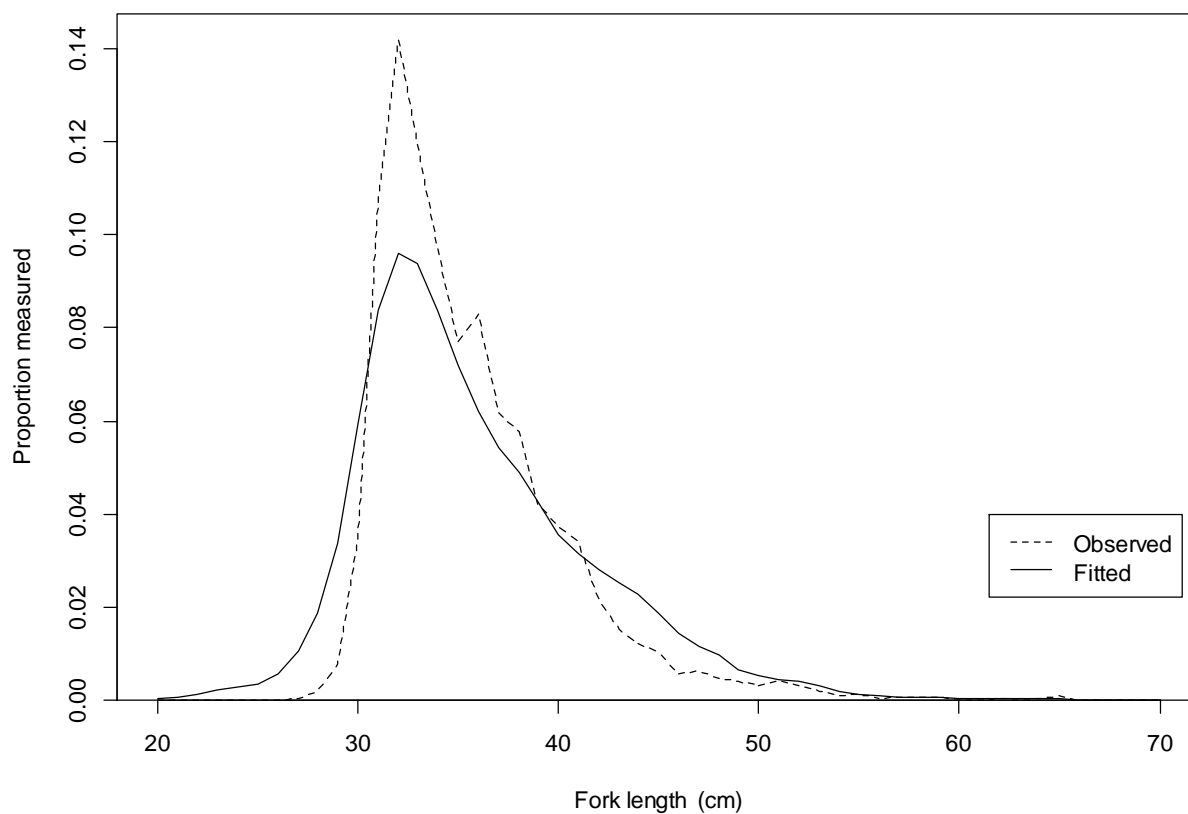
**Queensland recreational, 2010, ESS = 108.4**



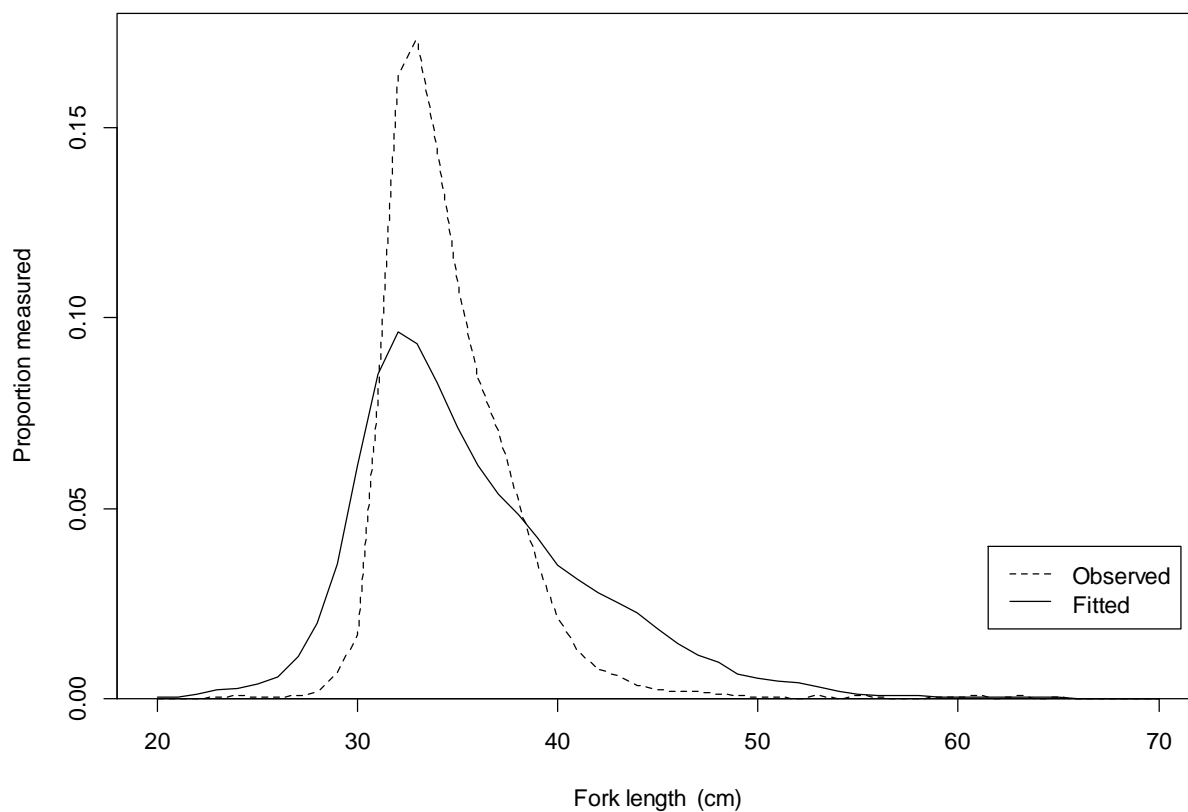
**Queensland recreational, 2011, ESS = 141.6**



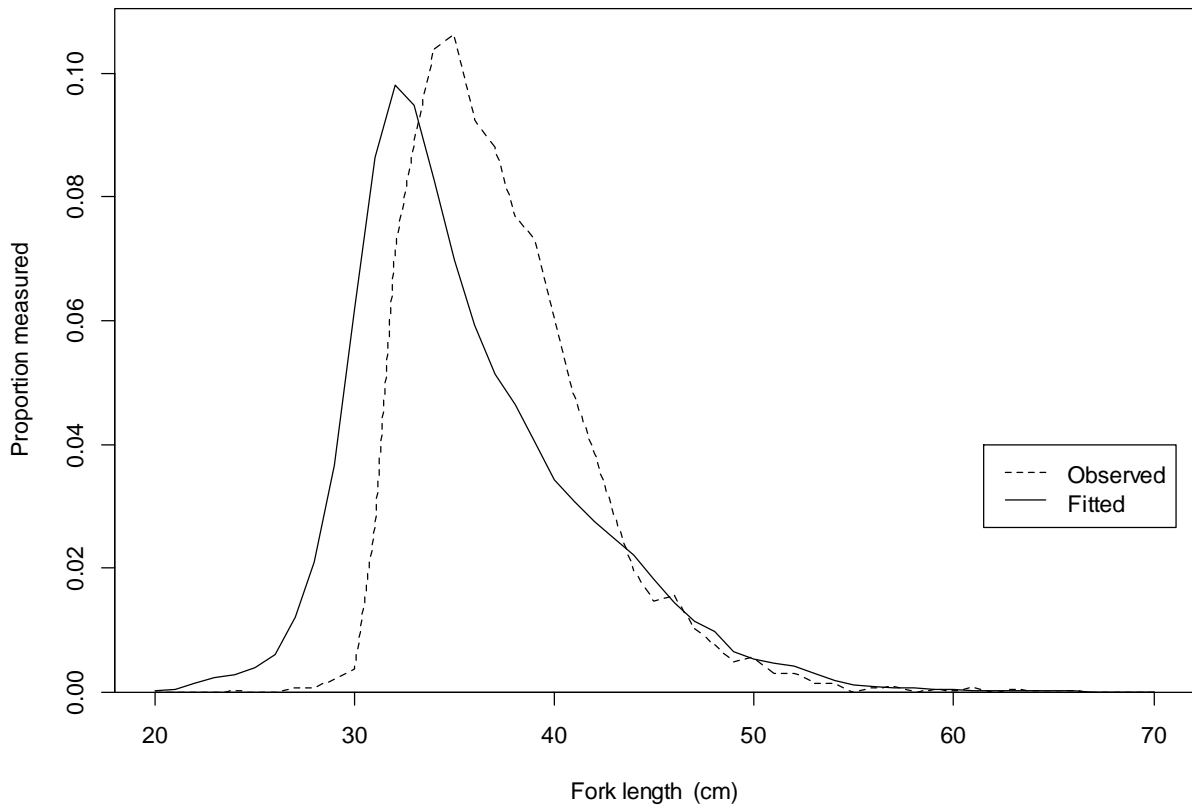
Queensland recreational, 2012, ESS = 183.8



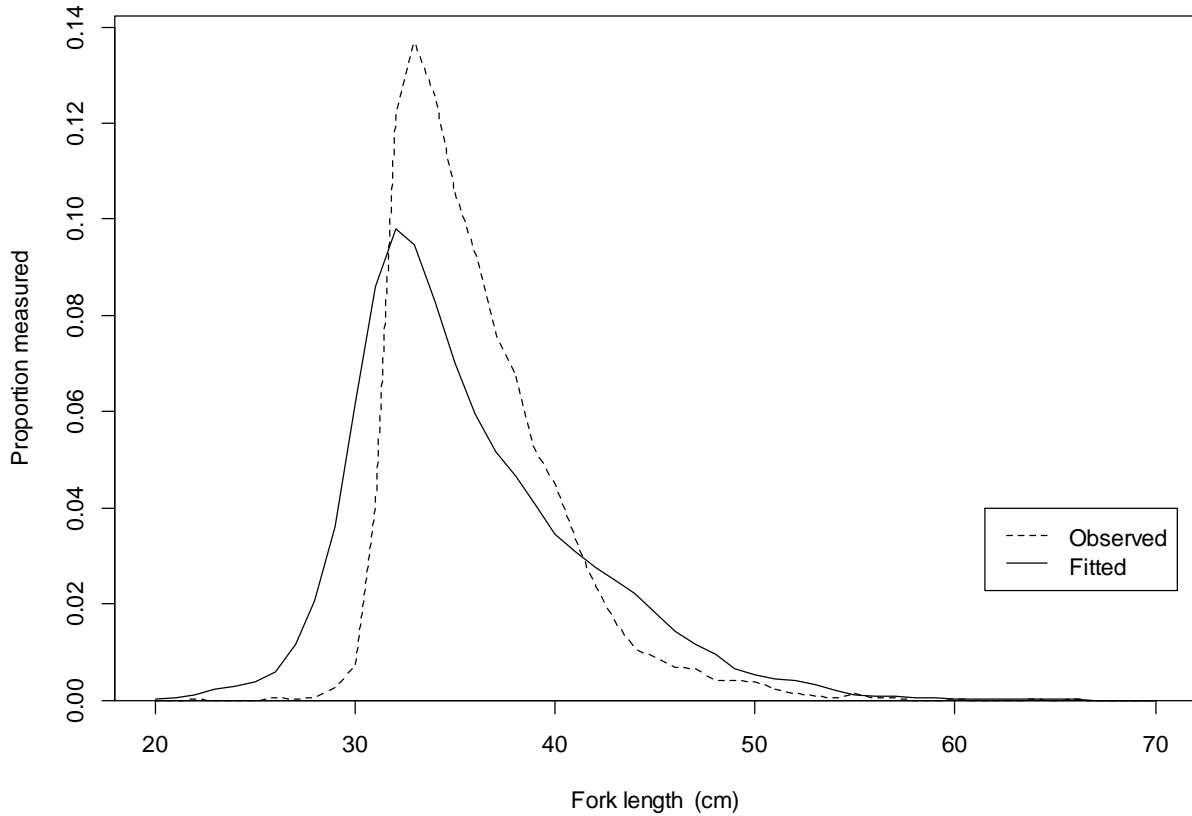
Queensland recreational, 2013, ESS = 71.8



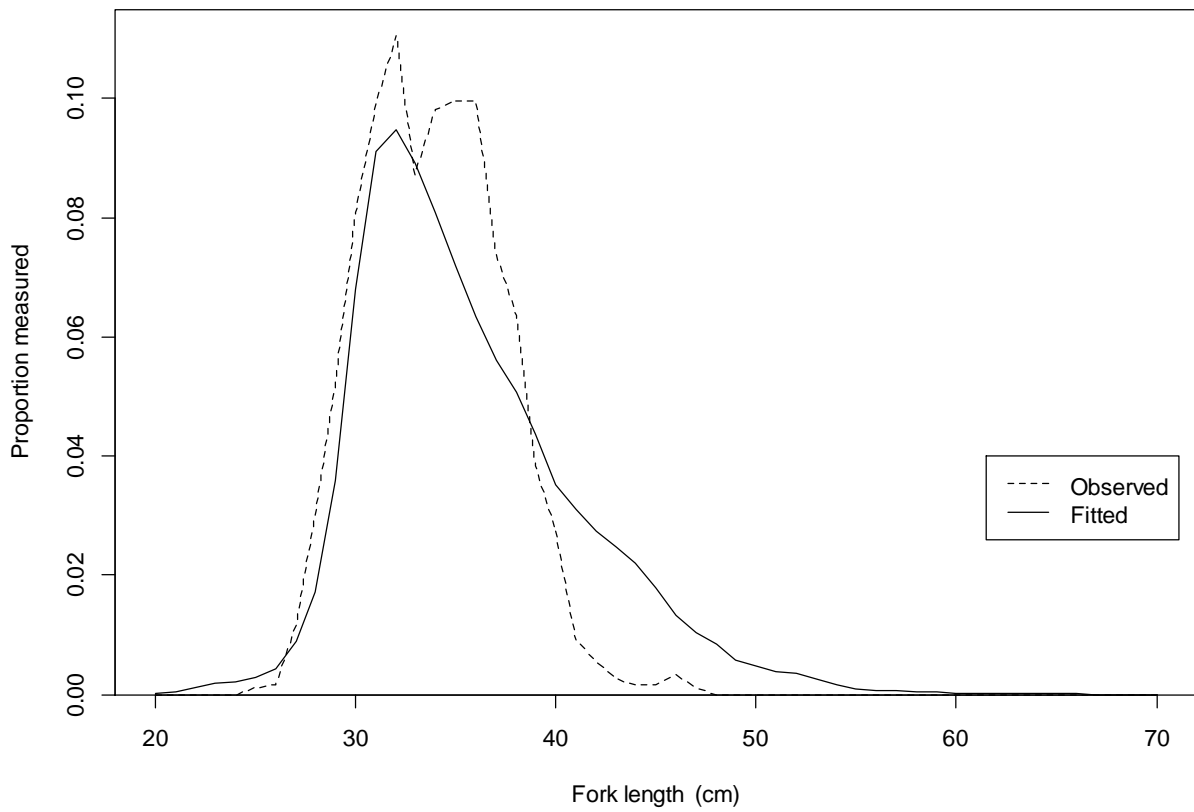
**Queensland recreational, 2014, ESS = 83.5**



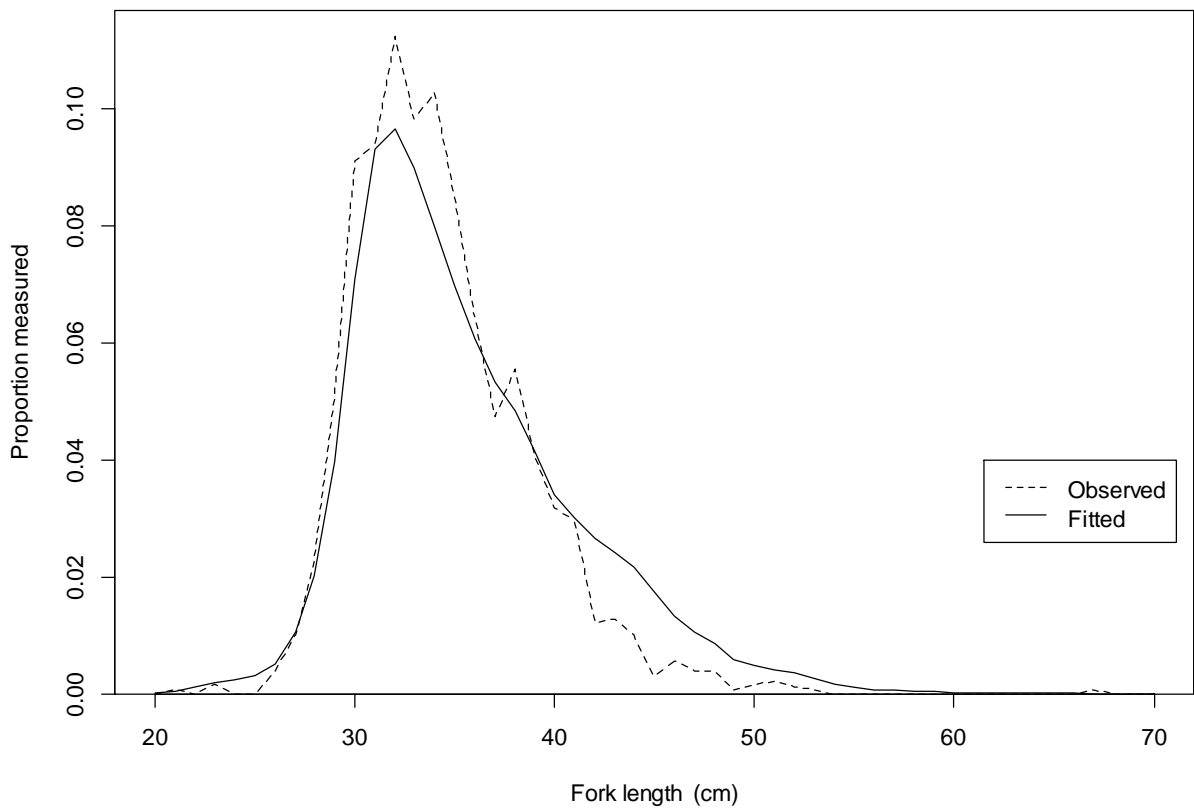
**Queensland recreational, 2015, ESS = 92.5**



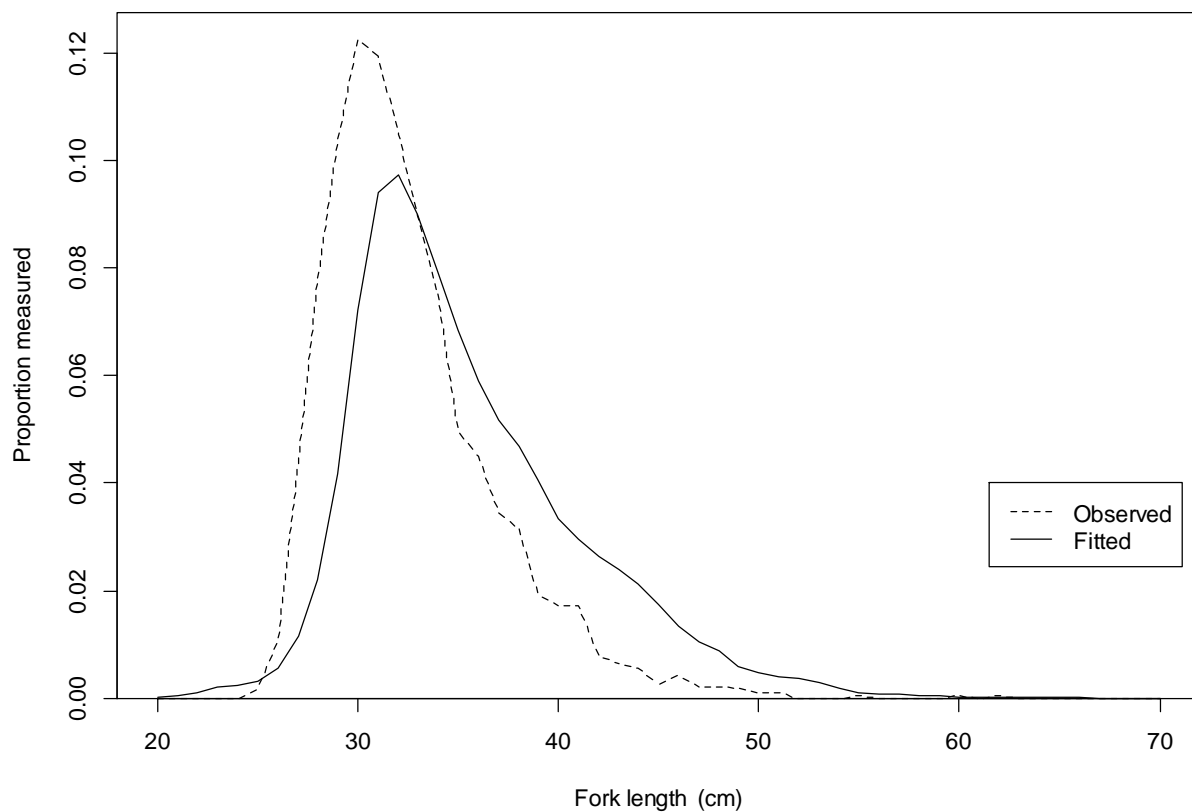
**Queensland gillnet, 1996, ESS = 76**



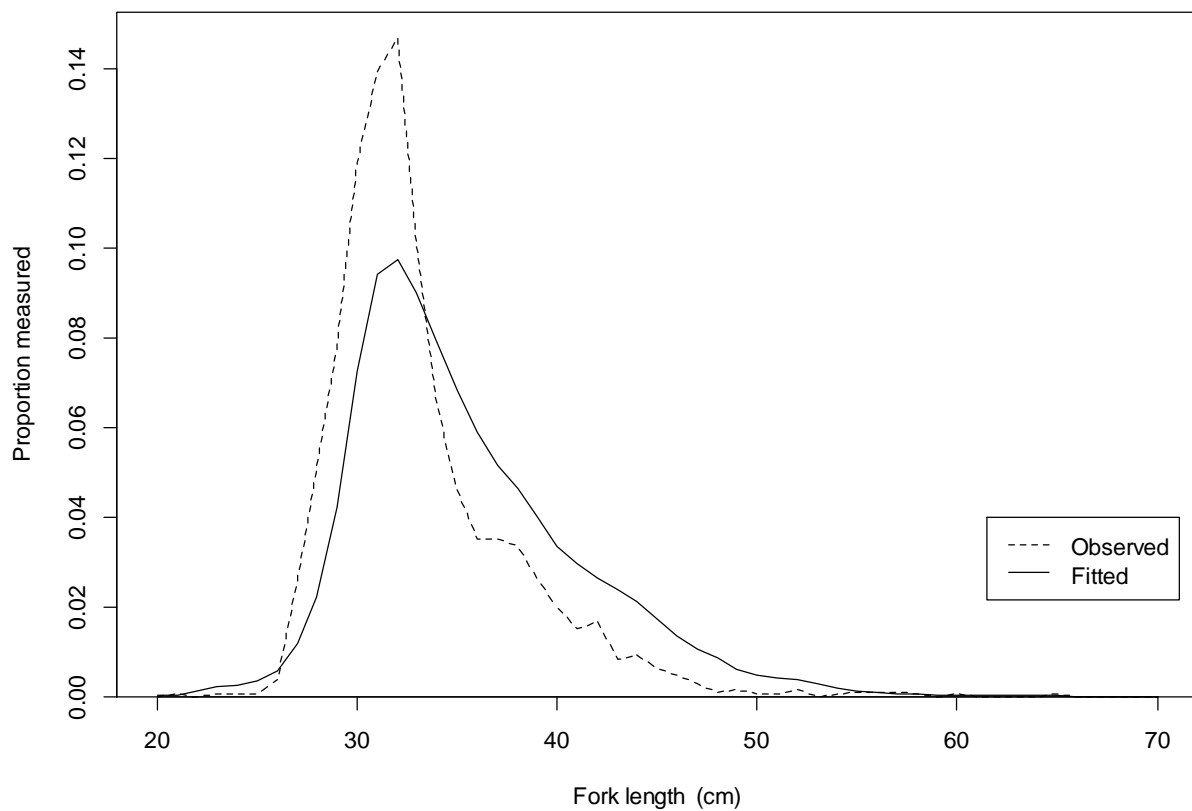
**Queensland gillnet, 2007, ESS = 252.8**



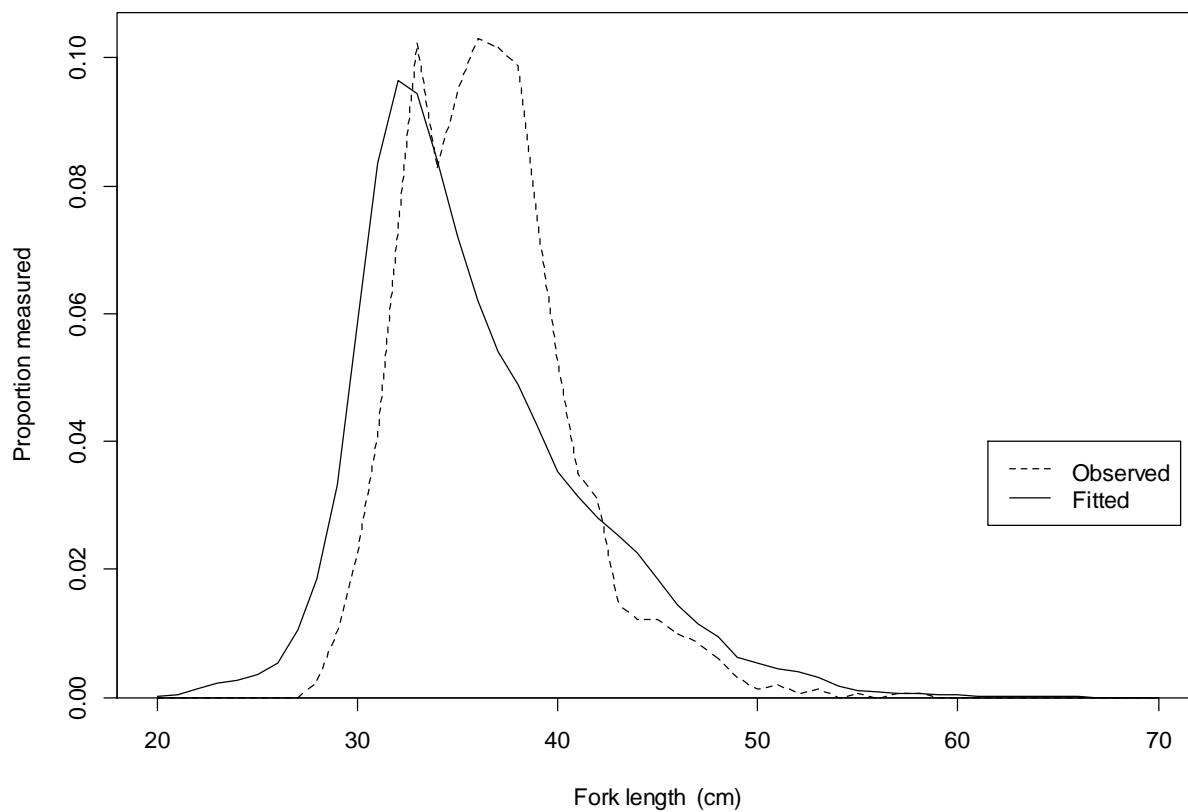
Queensland gillnet, 2008, ESS = 68.3



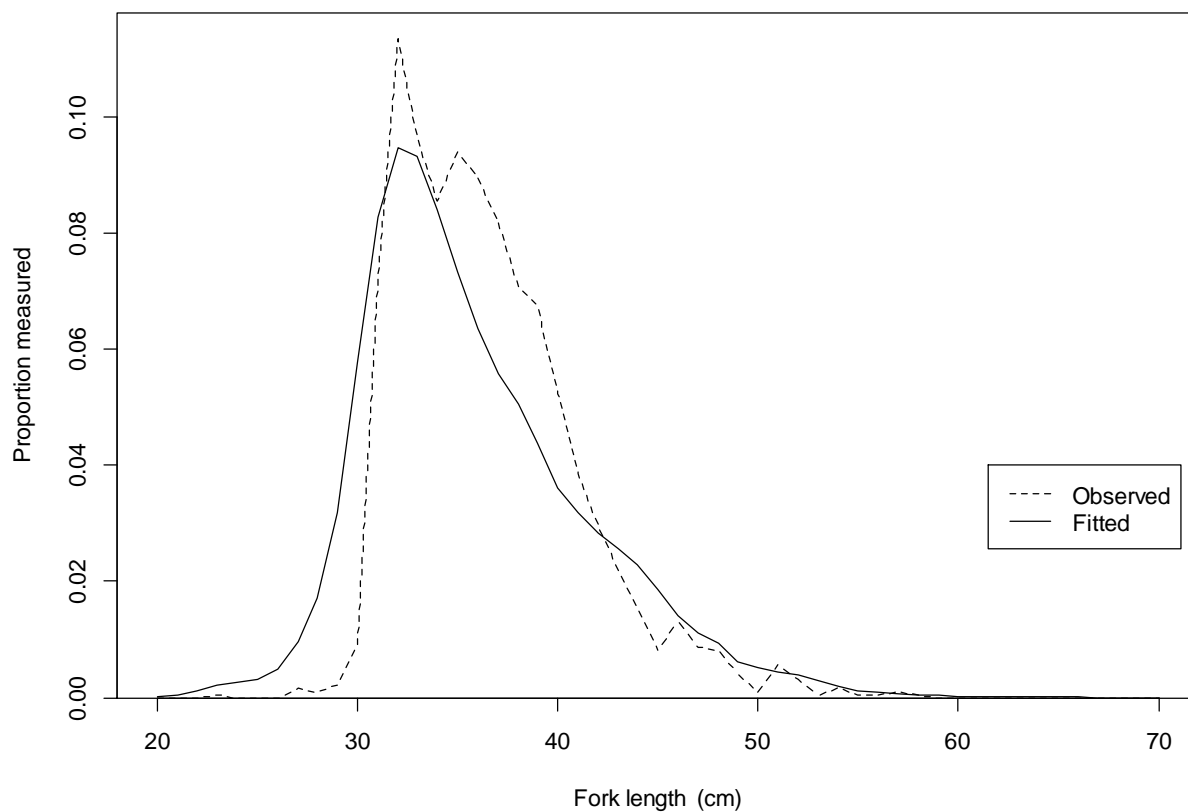
Queensland gillnet, 2009, ESS = 134.5



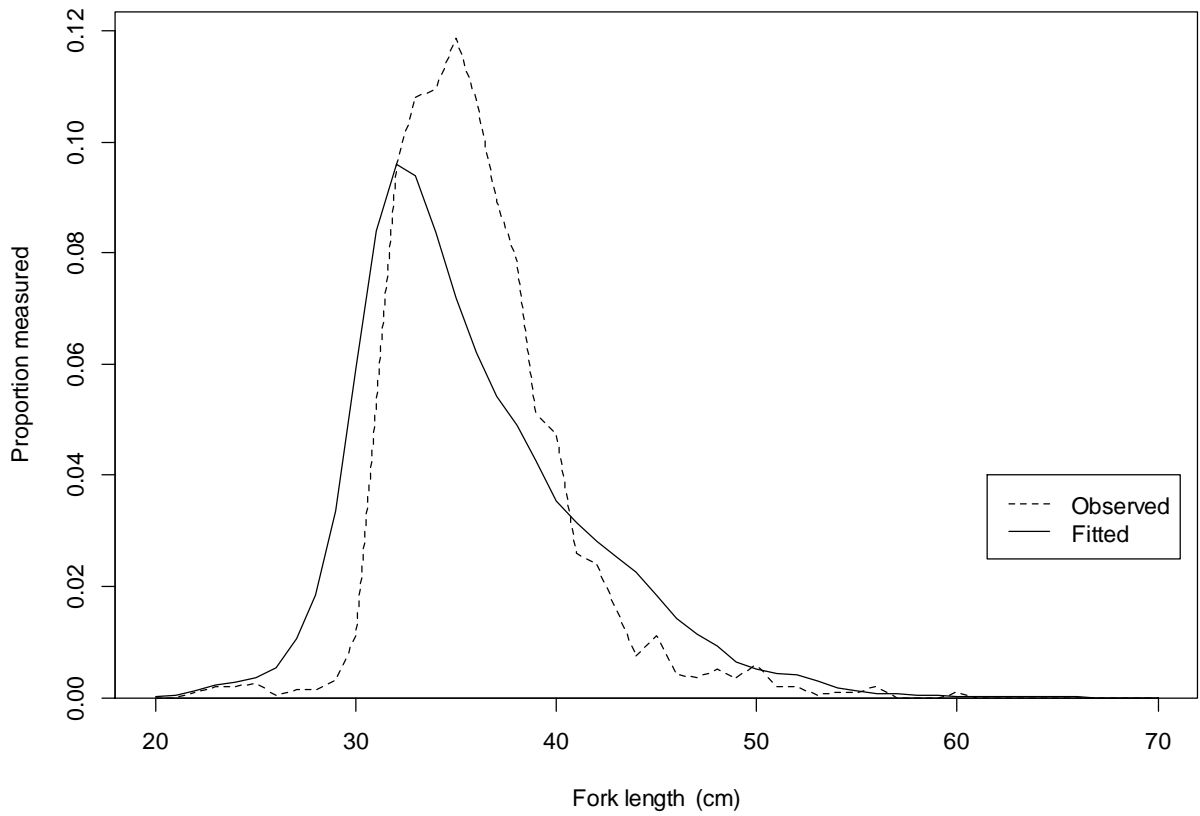
**Queensland gillnet, 2010, ESS = 89.6**



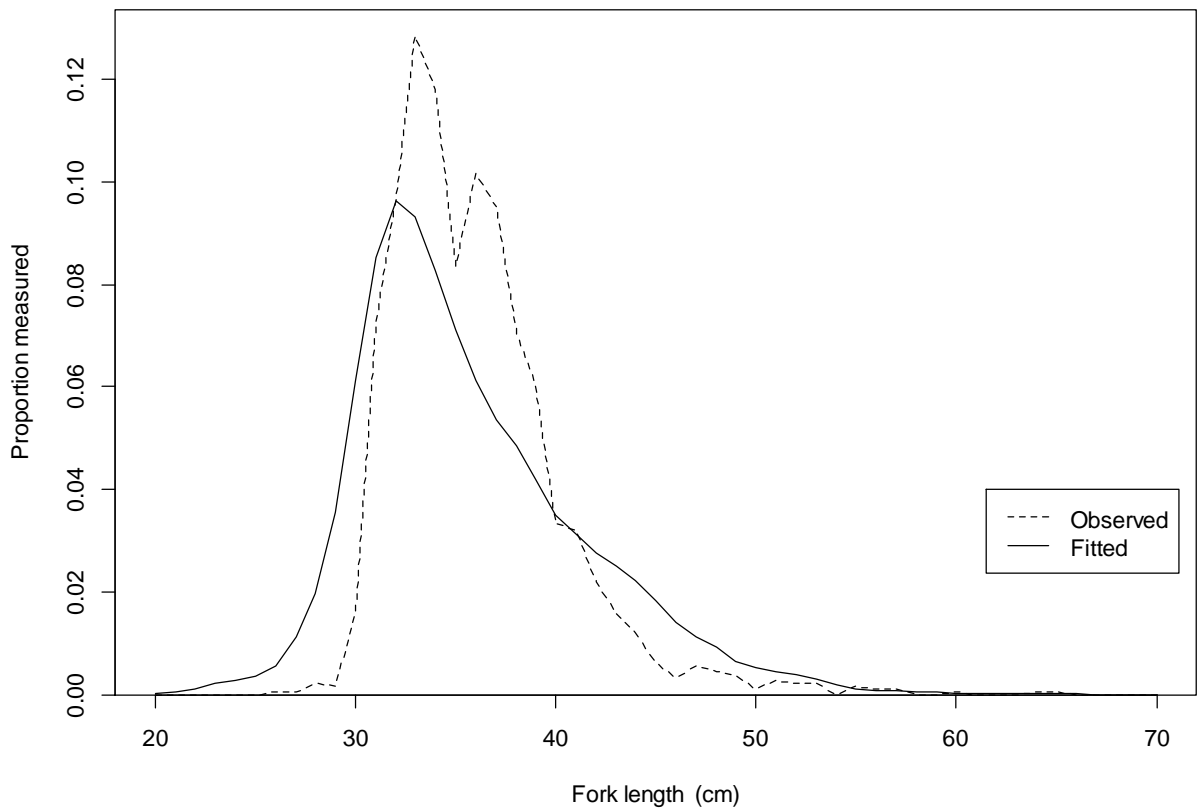
**Queensland gillnet, 2011, ESS = 129.6**



**Queensland gillnet, 2012, ESS = 110.7**

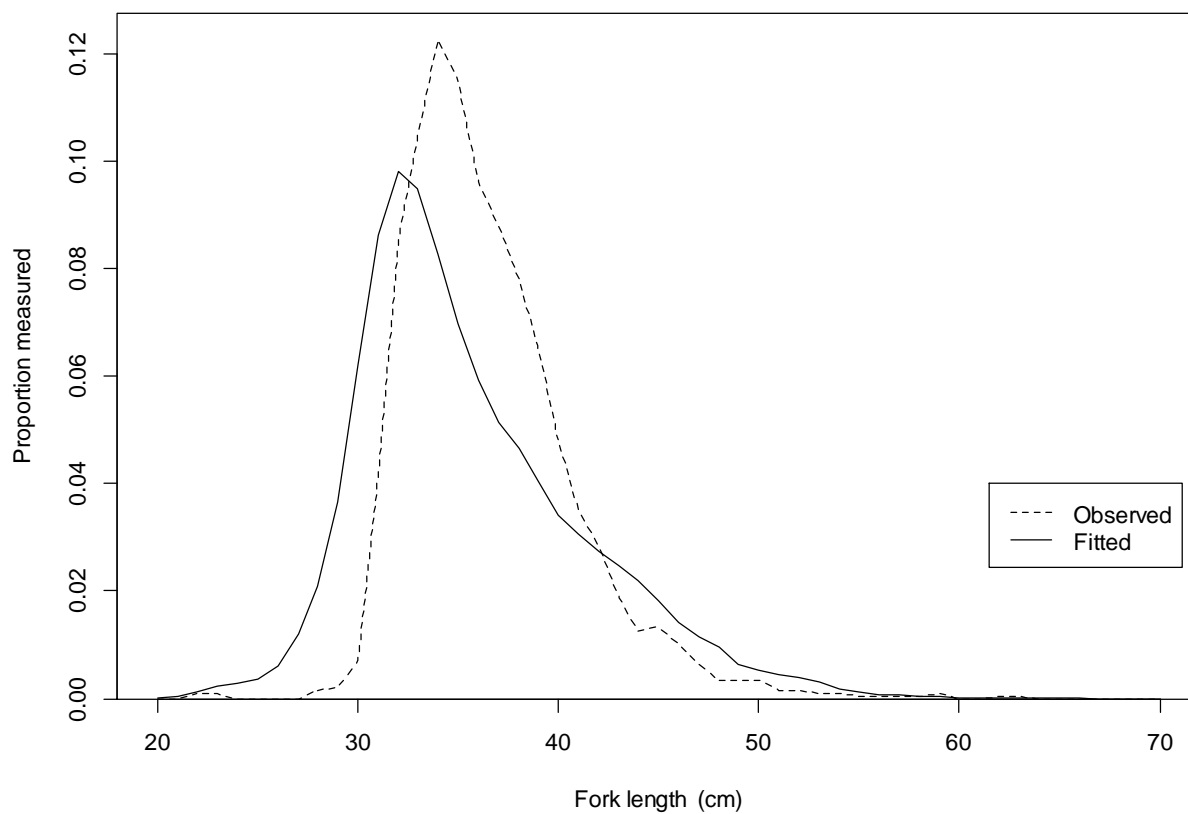


**Queensland gillnet, 2013, ESS = 103.6**

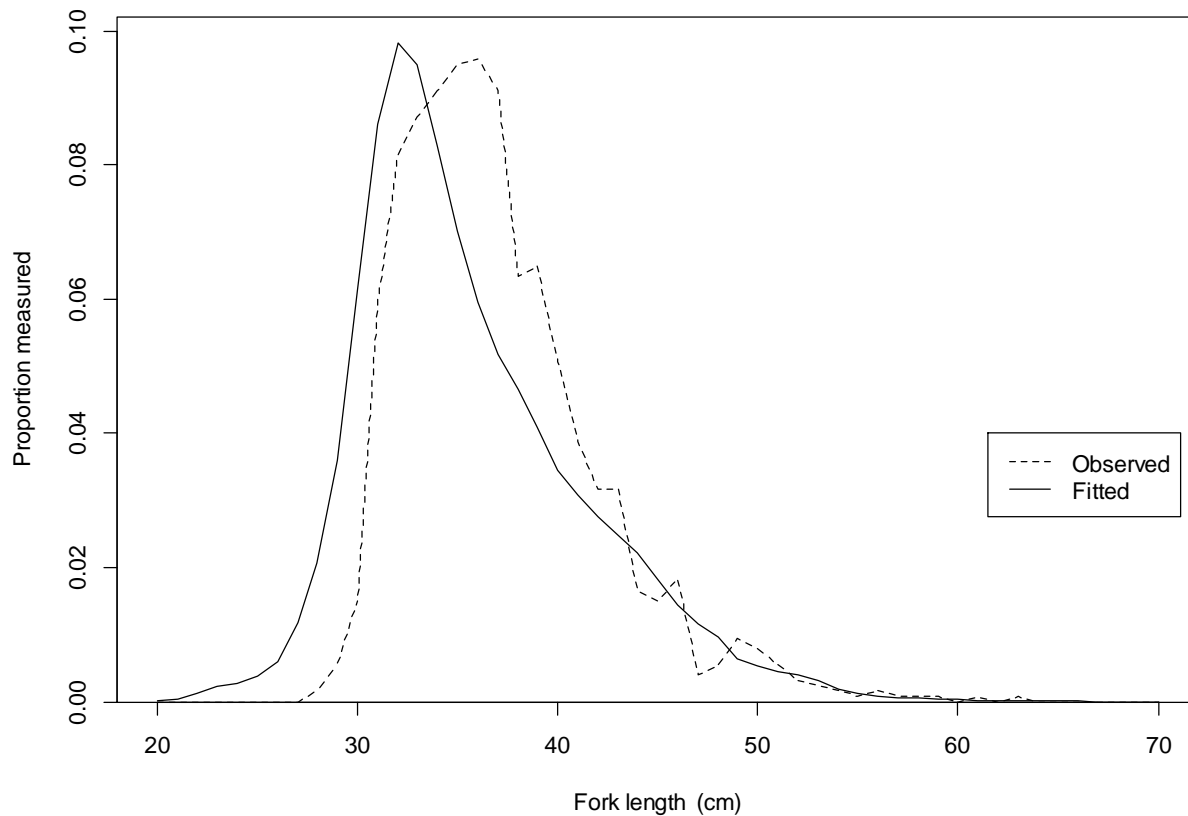




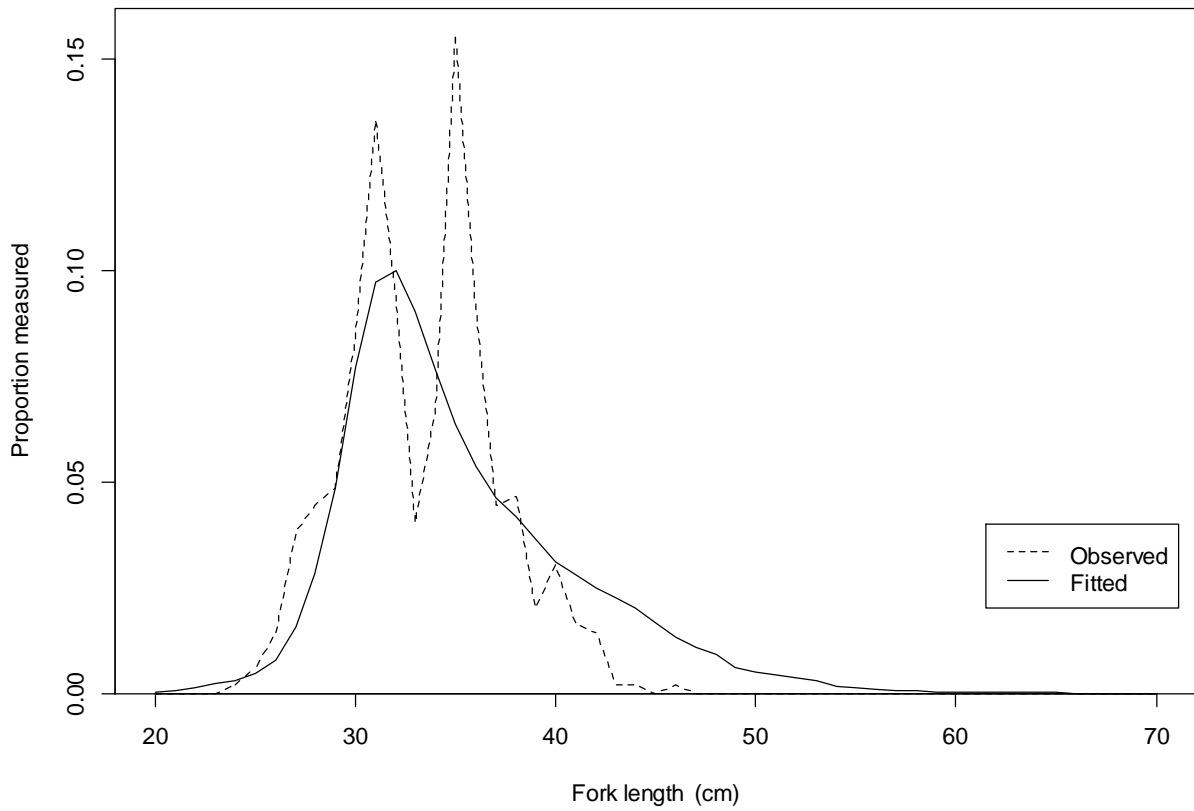
**Queensland gillnet, 2014, ESS = 89.7**



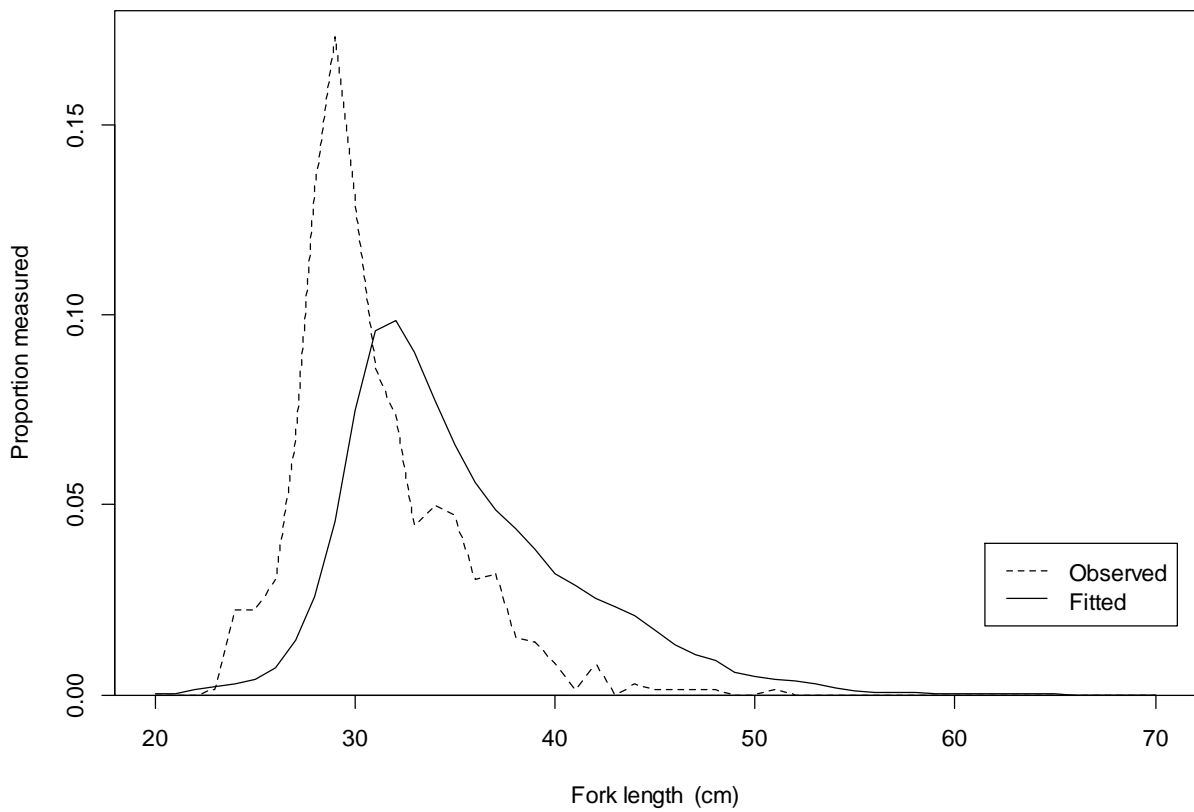
**Queensland gillnet, 2015, ESS = 117.6**



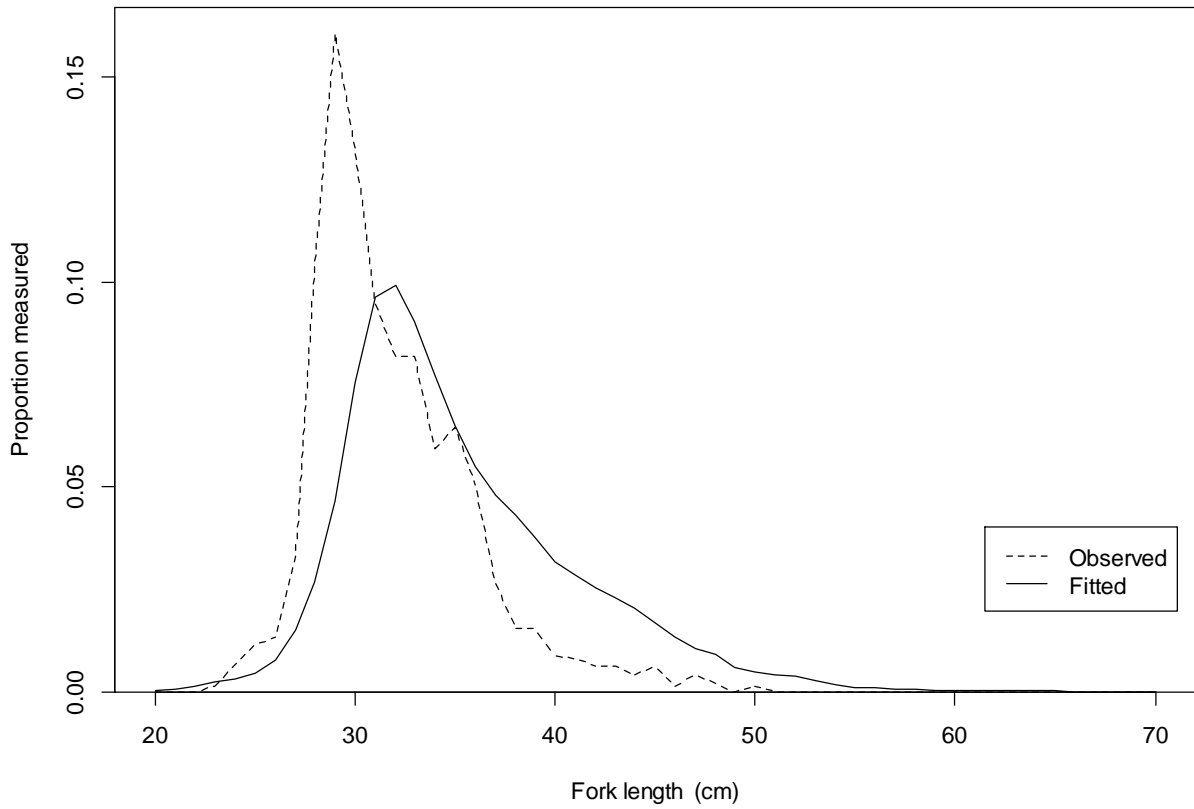
**NSW gillnet, 1971, ESS = 51.7**



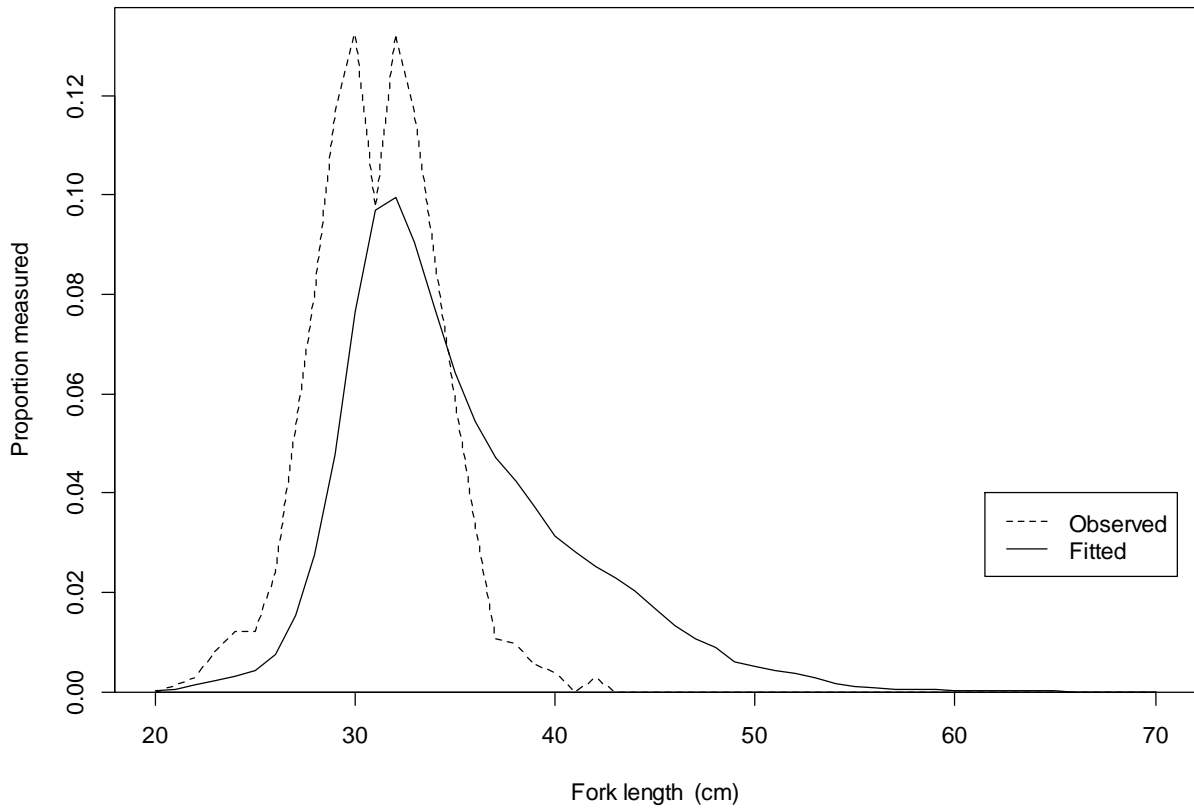
**NSW gillnet, 1972, ESS = 22.8**



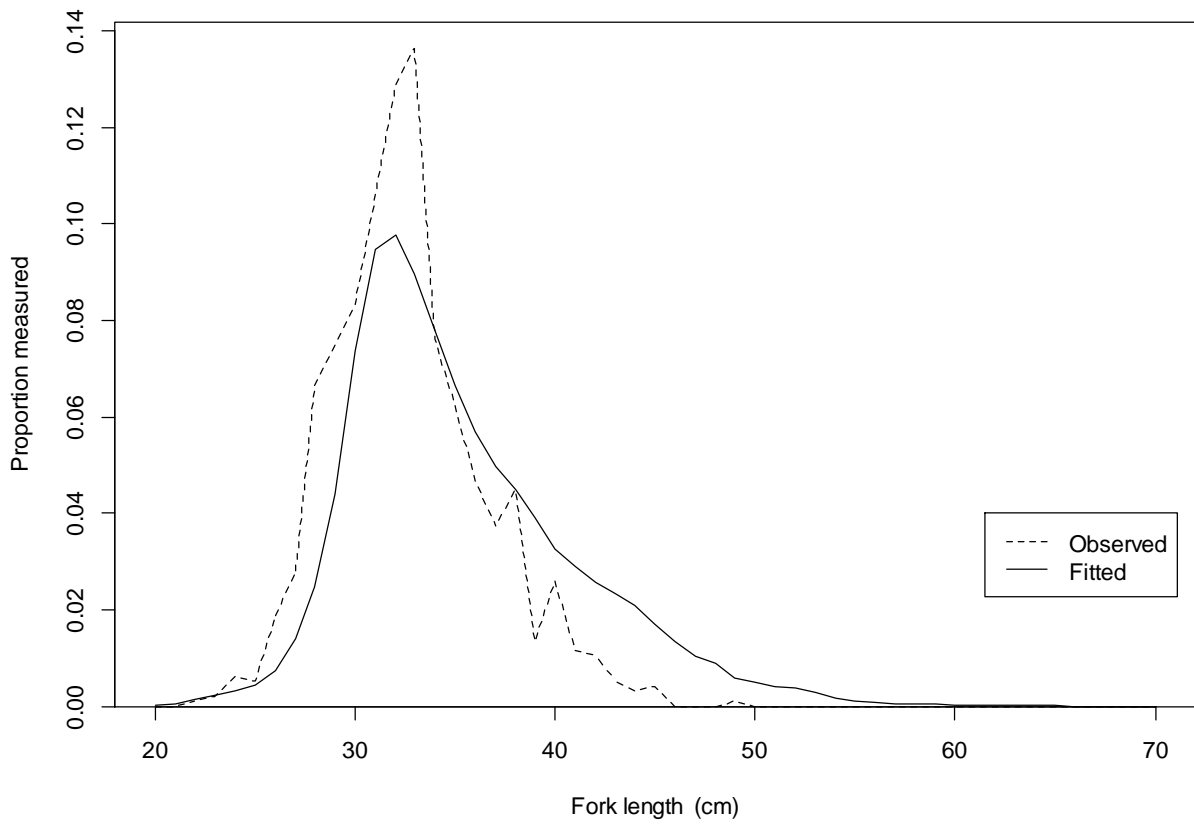
**NSW gillnet, 1973, ESS = 42.6**



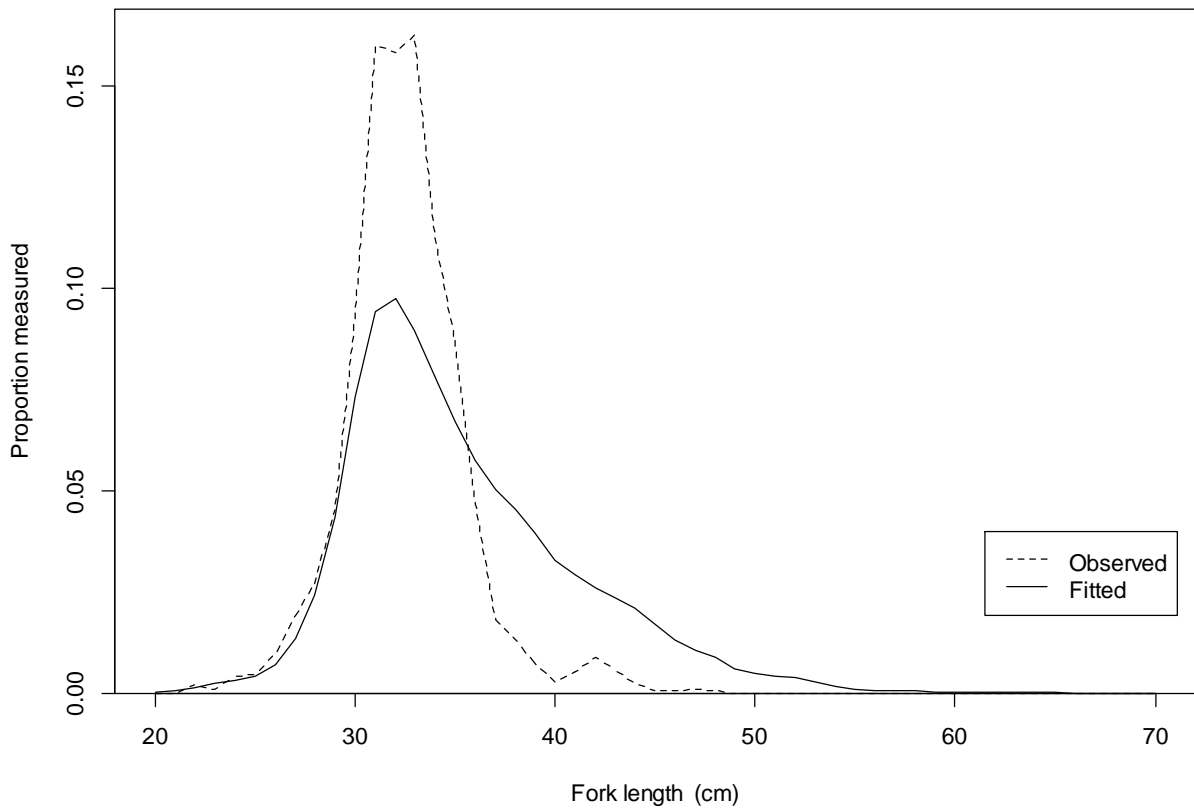
**NSW gillnet, 1974, ESS = 25.5**



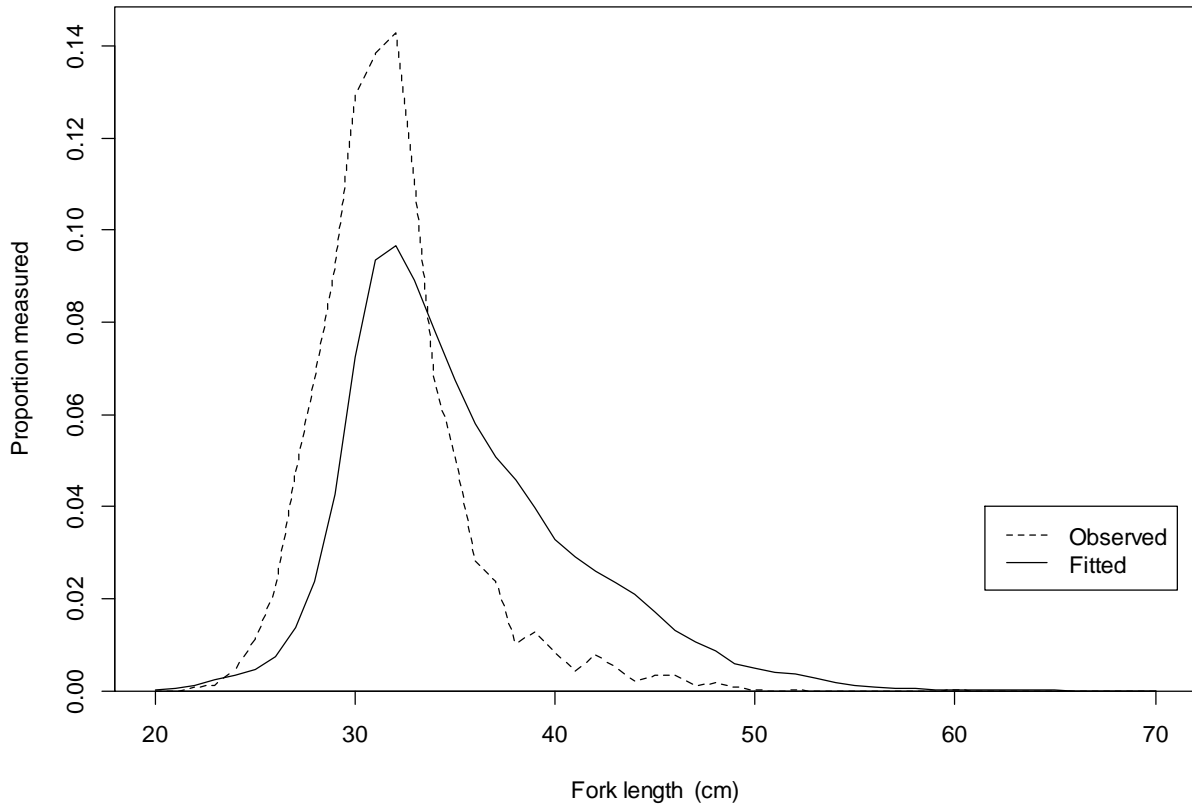
**NSW gillnet, 1975, ESS = 71.3**



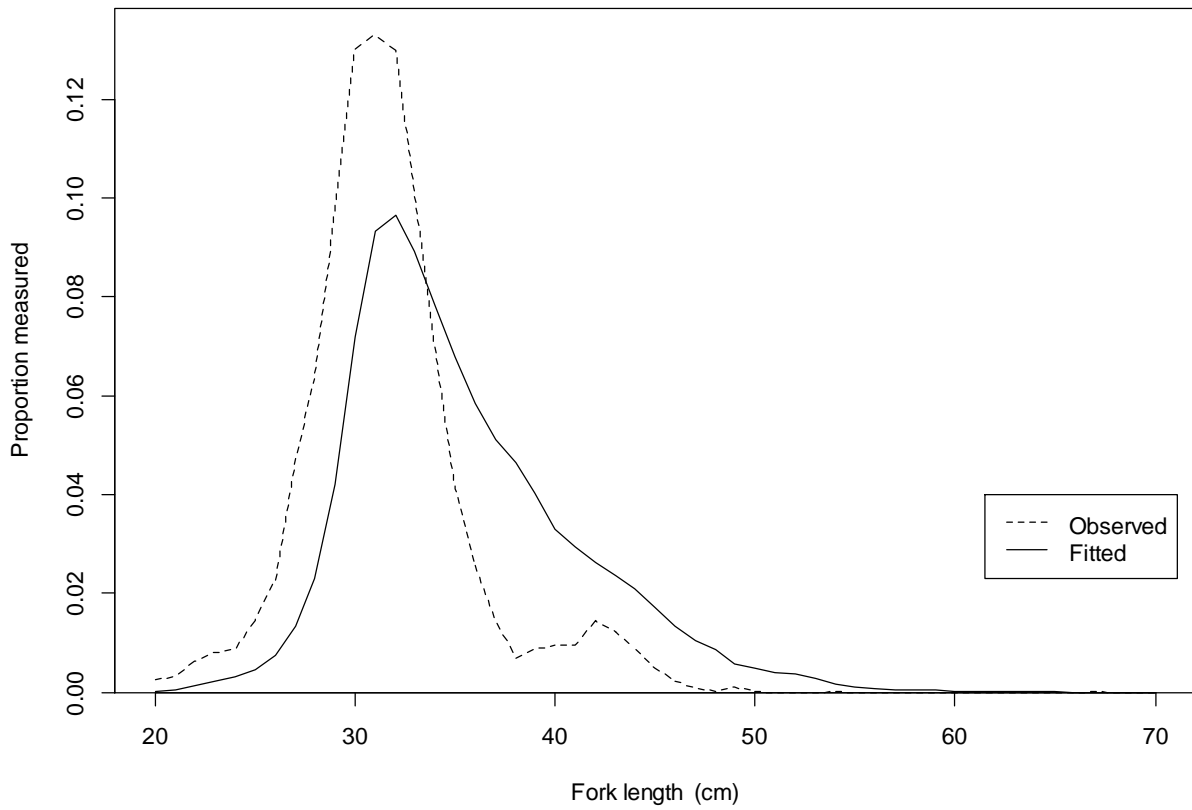
**NSW gillnet, 1976, ESS = 51.2**



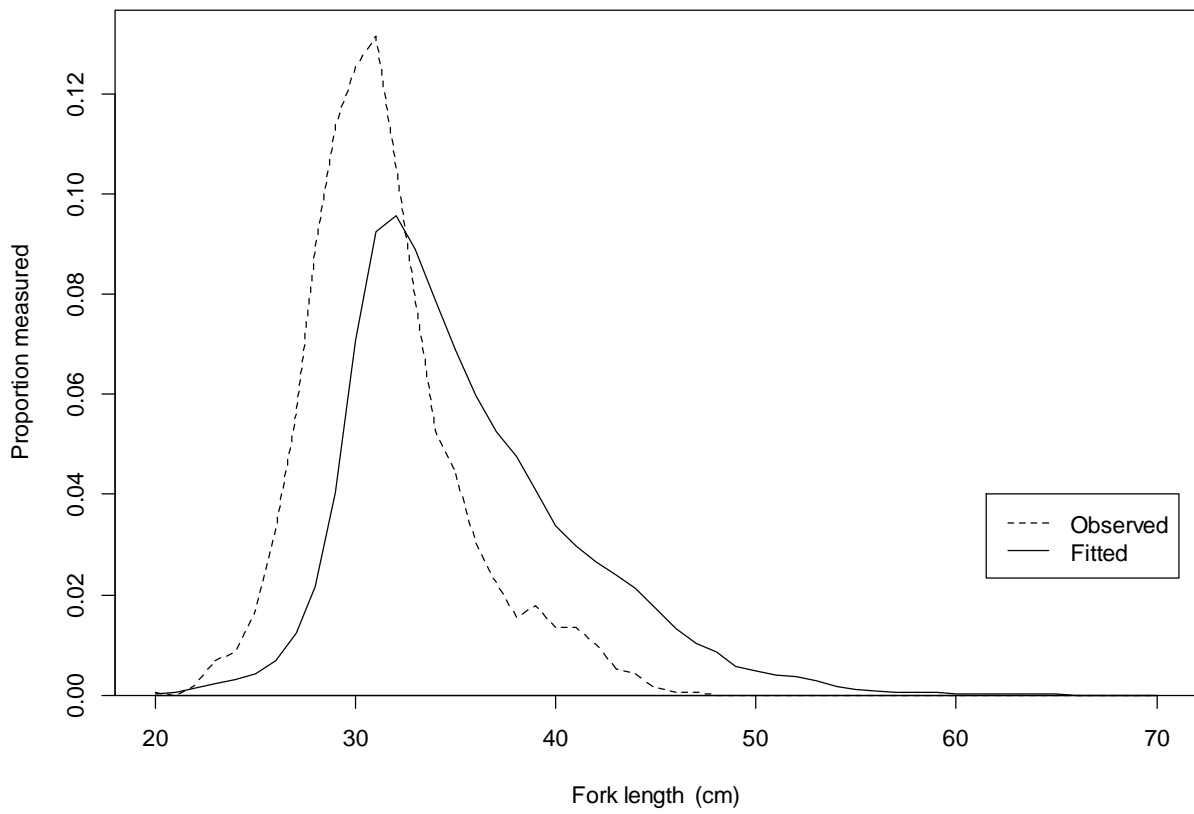
**NSW gillnet, 1977, ESS = 55.1**



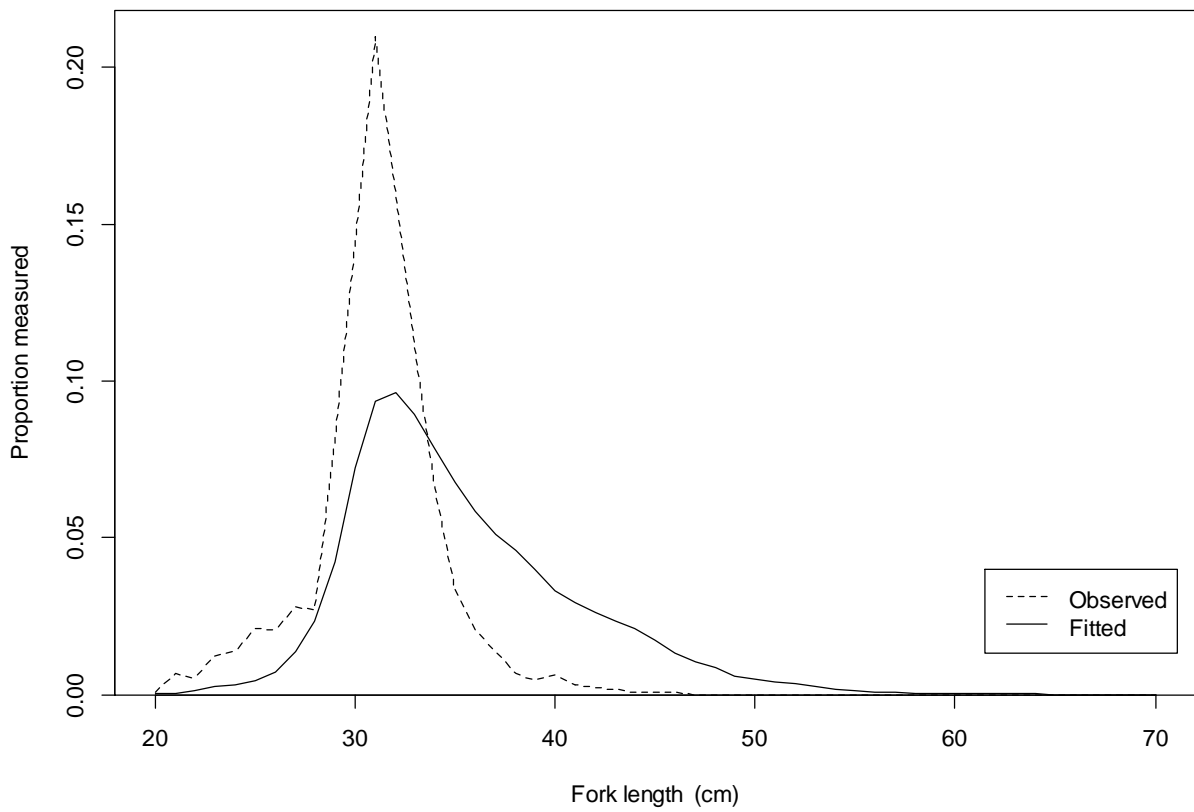
**NSW gillnet, 1978, ESS = 53.3**



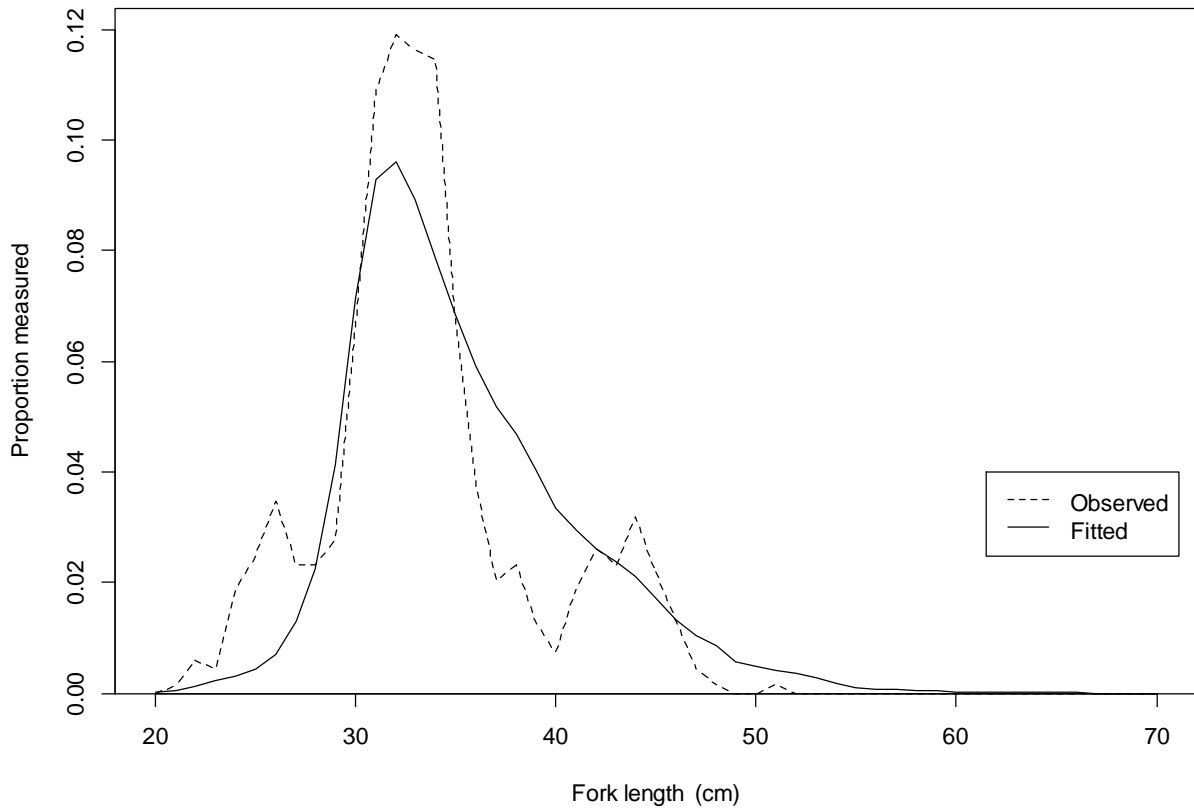
**NSW gillnet, 1979, ESS = 34.6**



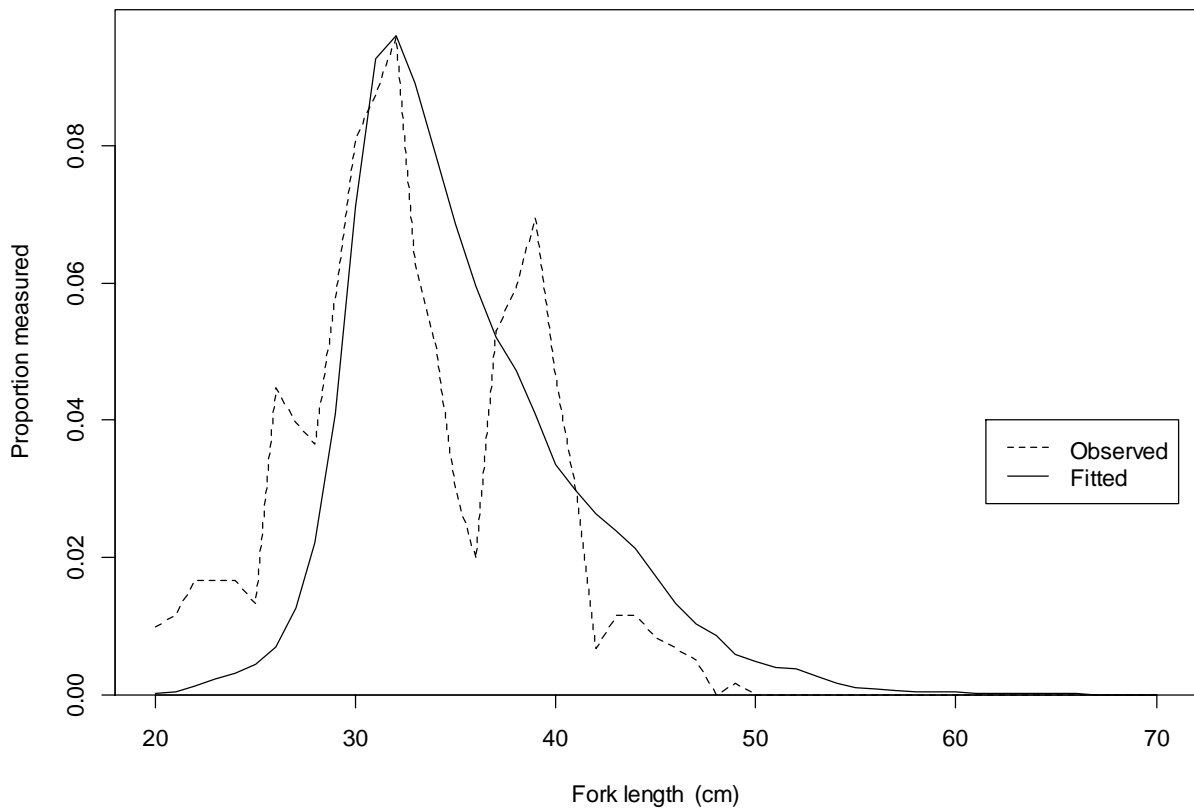
**NSW gillnet, 1980, ESS = 29.3**



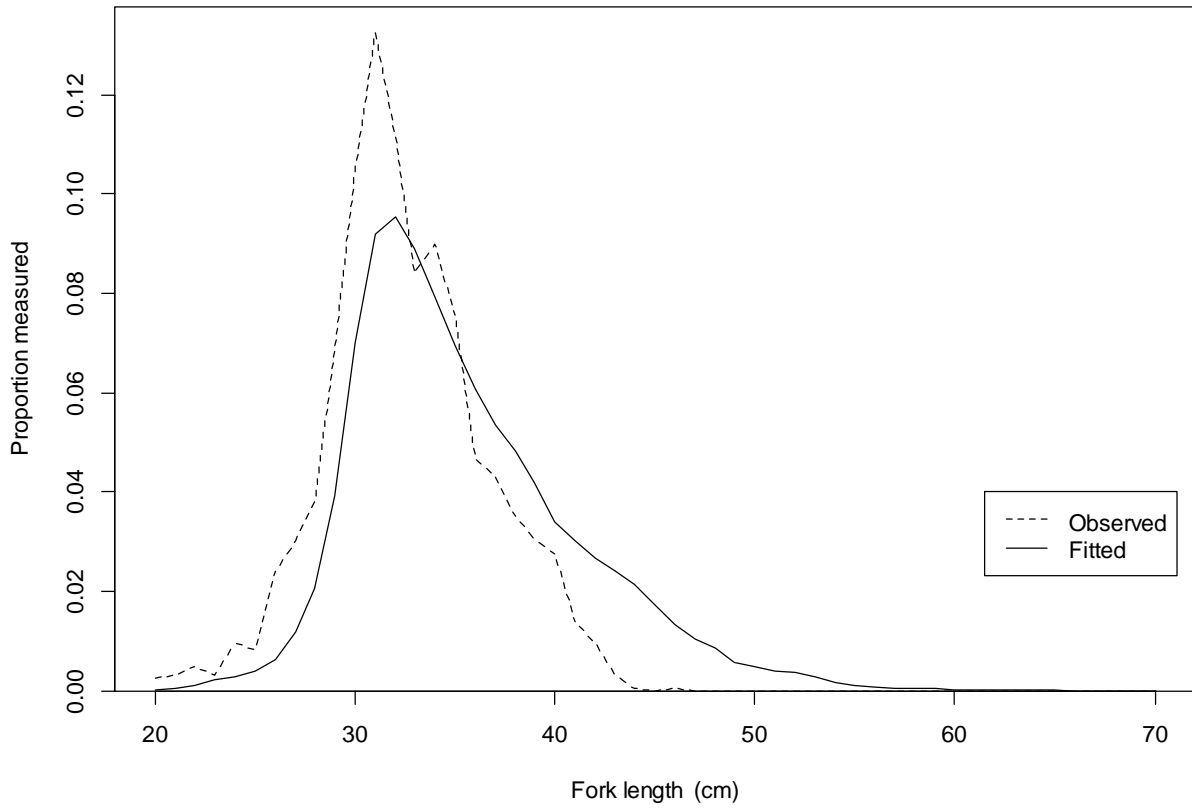
**NSW gillnet, 1981, ESS = 80.4**



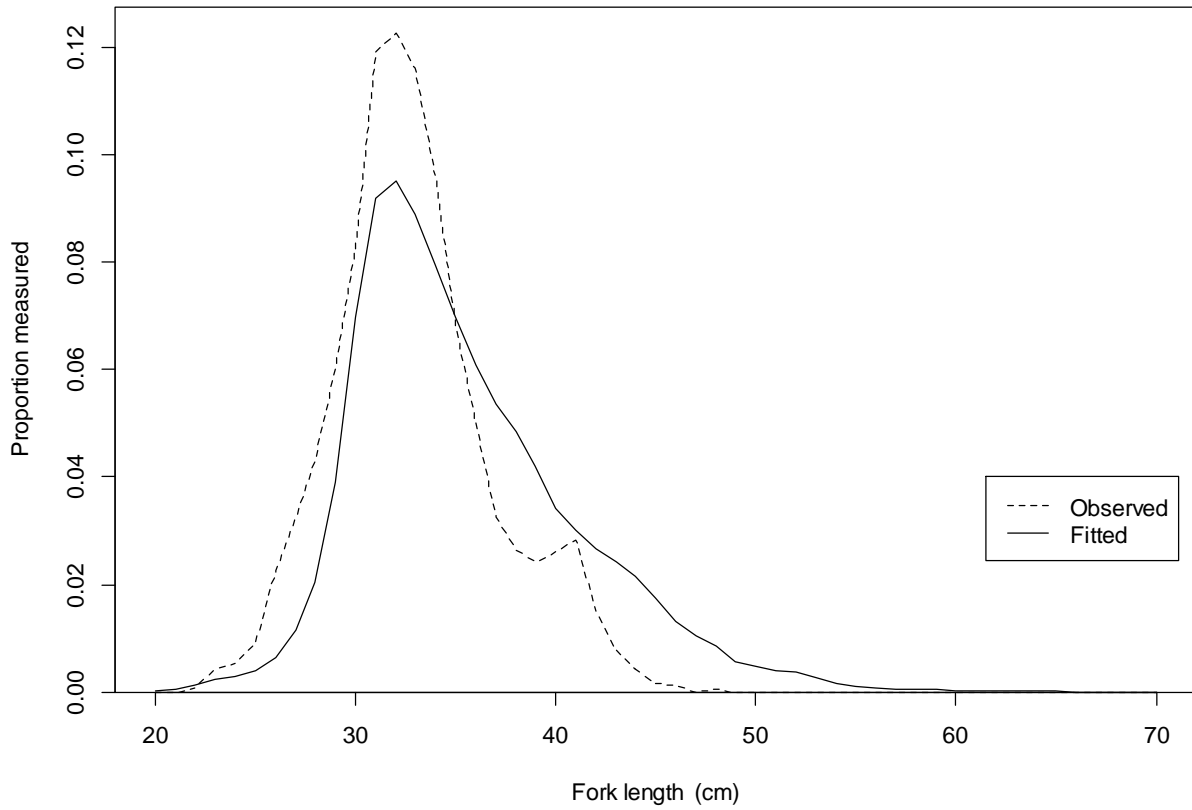
**NSW gillnet, 1982, ESS = 47**



**NSW gillnet, 1987, ESS = 63.9**

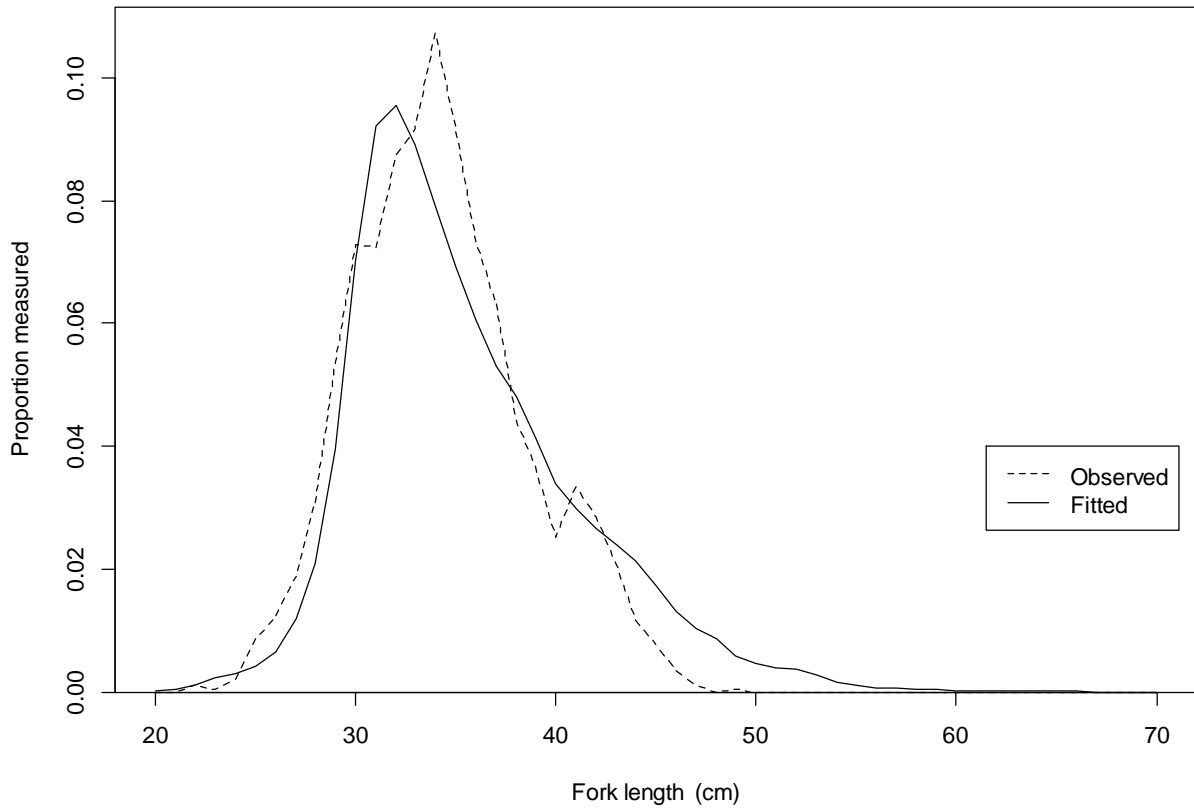


**NSW gillnet, 1988, ESS = 80.8**

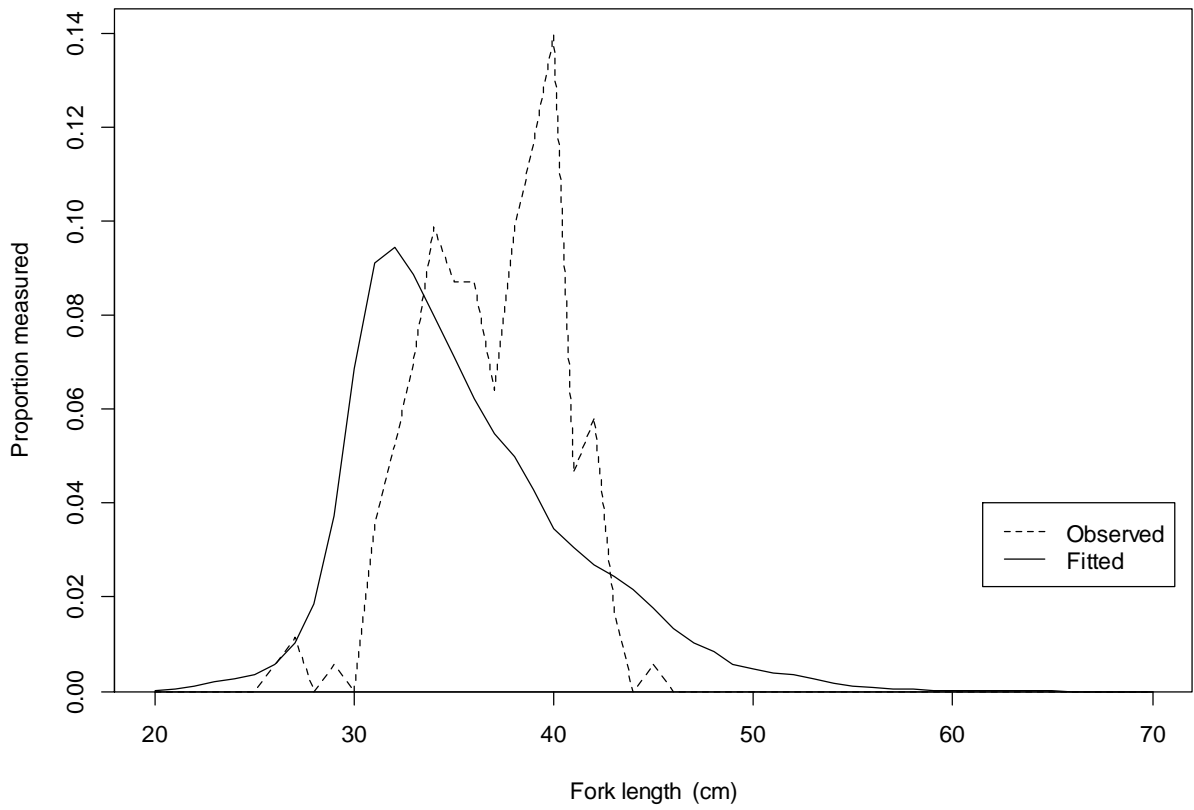




**NSW gillnet, 1989, ESS = 177.1**

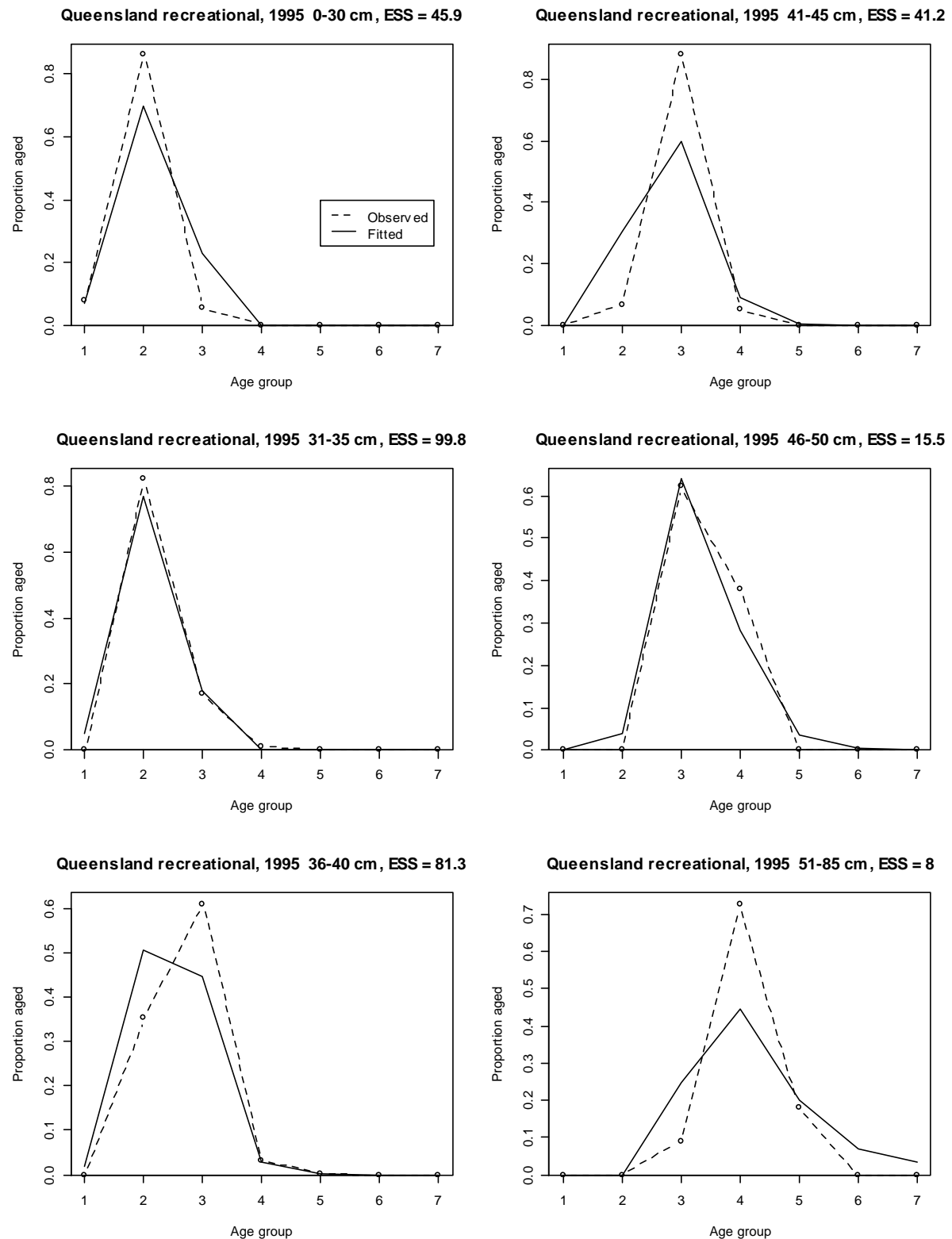


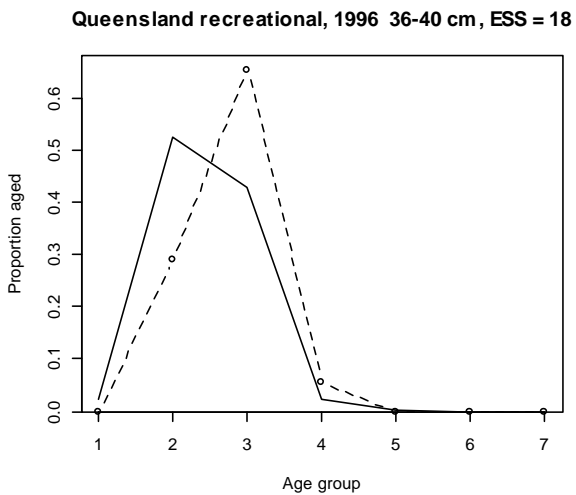
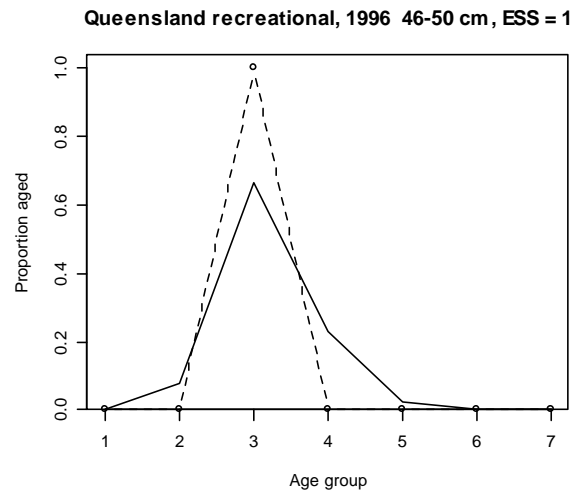
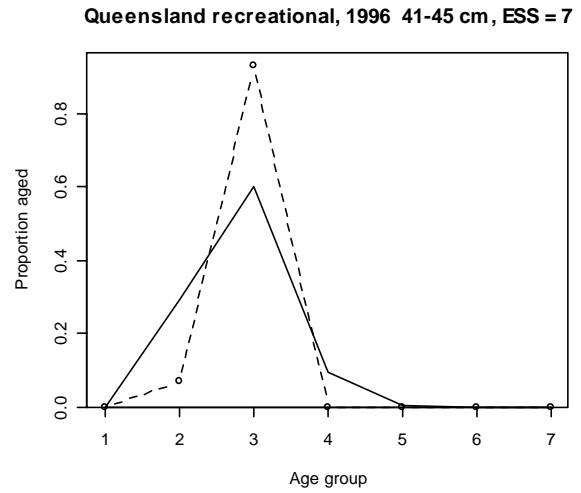
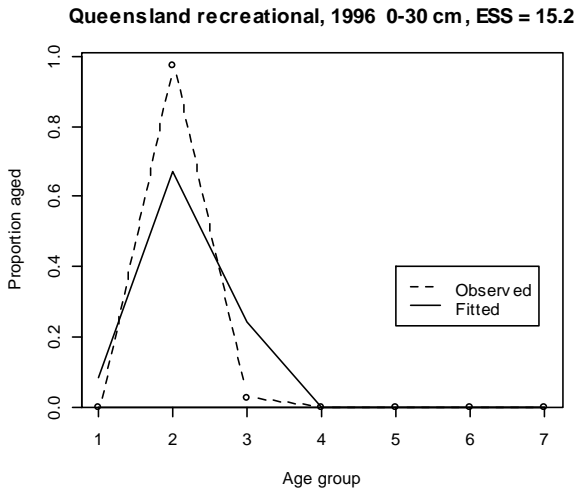
**NSW gillnet, 1990, ESS = 21.1**



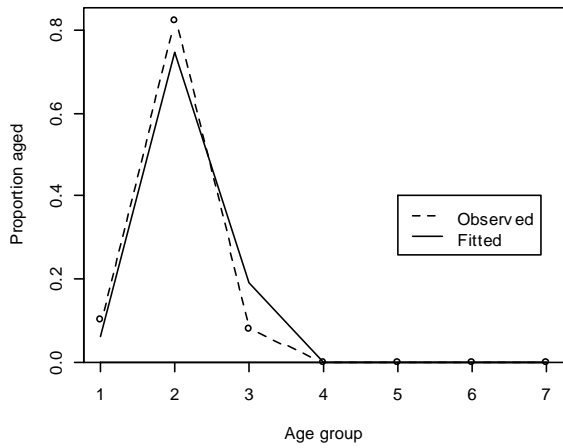
## A4.4 Age-at-length data

This section shows model fits to age-at-length data using the coarse, 5-cm length intervals as described in section 4.5.3. Again the model's estimated effective sample sizes (ESSs) are noted on the titles of the plots, for each length interval in each sample. Many of the samples had low numbers of fish in the larger length intervals. Intervals with no fish are not plotted. As stated in section 4.5.3, the ESS was restricted to lie between half the actual sample size and the full sample size.

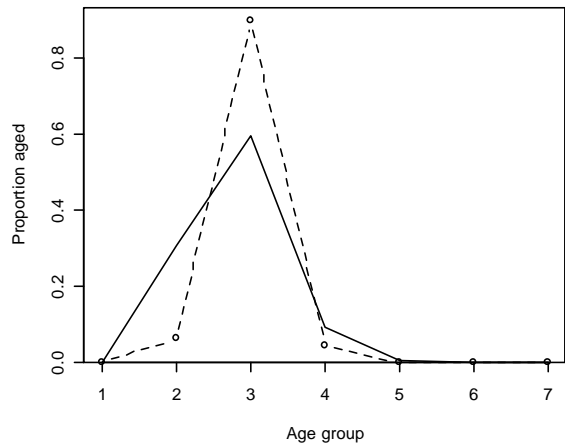




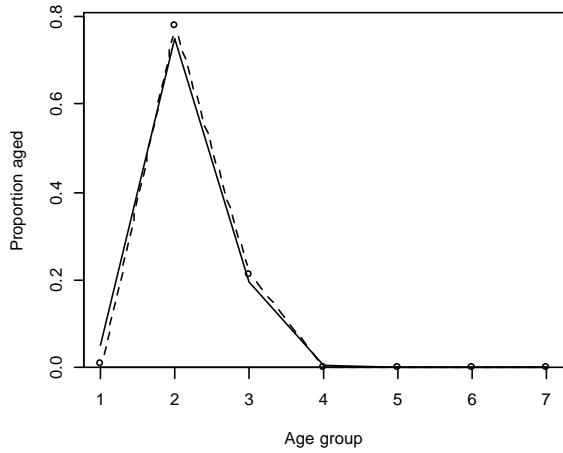
Queensland recreational, 1997 0-30 cm, ESS = 40



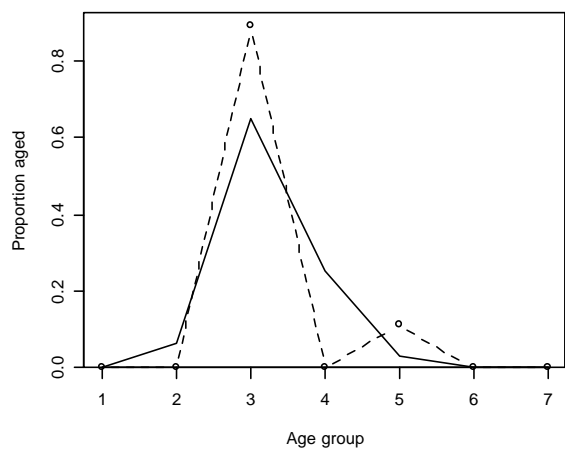
Queensland recreational, 1997 41-45 cm, ESS = 44.6



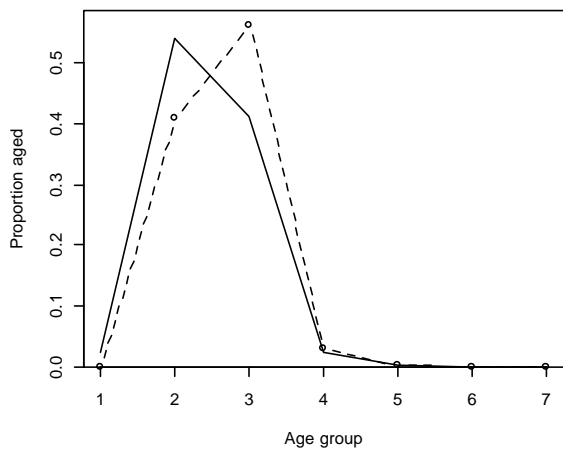
Queensland recreational, 1997 31-35 cm, ESS = 100.1



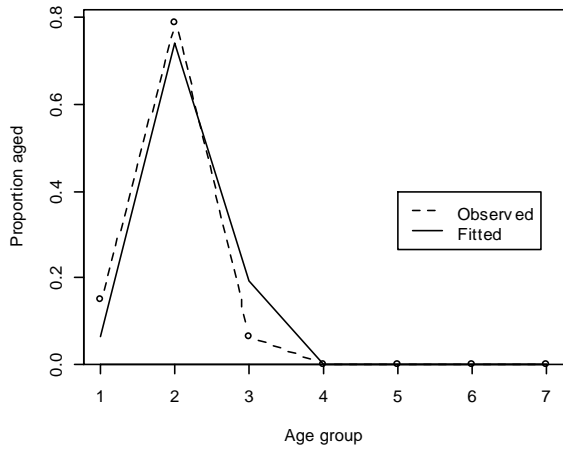
Queensland recreational, 1997 46-50 cm, ESS = 4.5



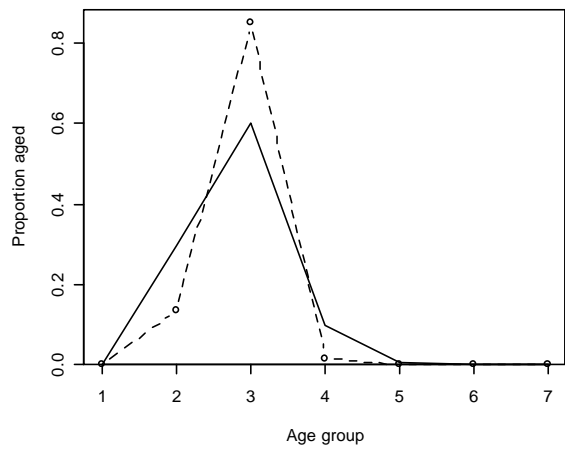
Queensland recreational, 1997 36-40 cm, ESS = 99.6



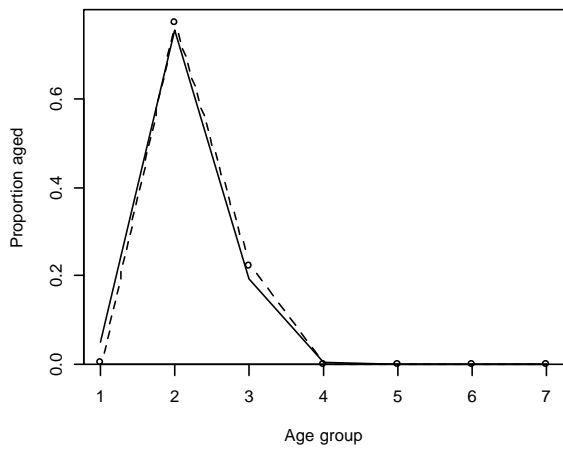
Queensland recreational, 1999 0-30 cm, ESS = 23.7



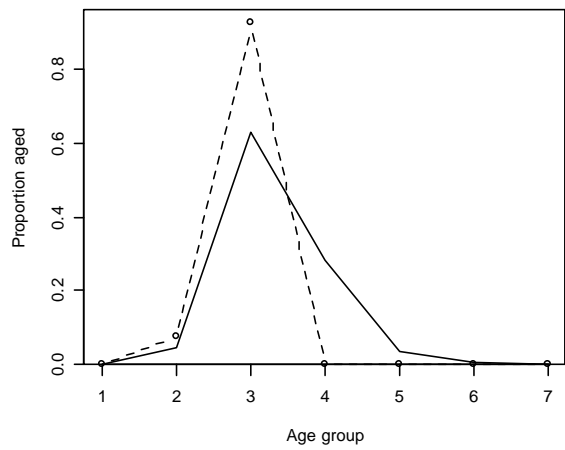
Queensland recreational, 1999 41-45 cm, ESS = 63.3



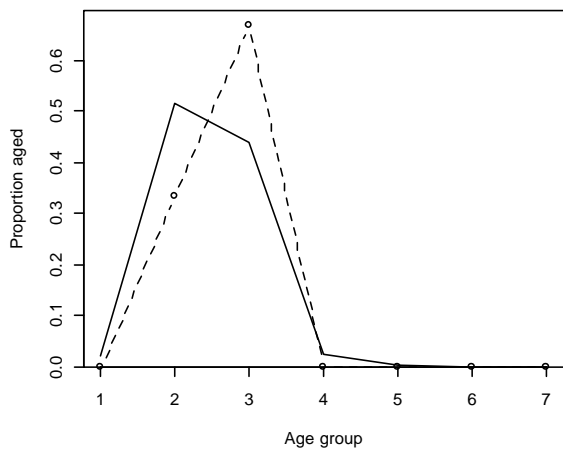
Queensland recreational, 1999 31-35 cm, ESS = 100



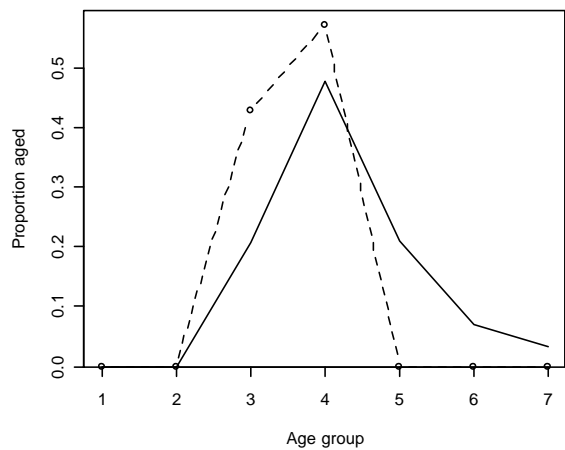
Queensland recreational, 1999 46-50 cm, ESS = 13



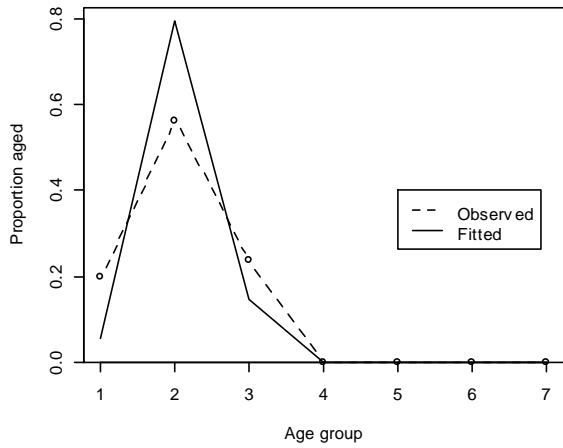
Queensland recreational, 1999 36-40 cm, ESS = 99.6



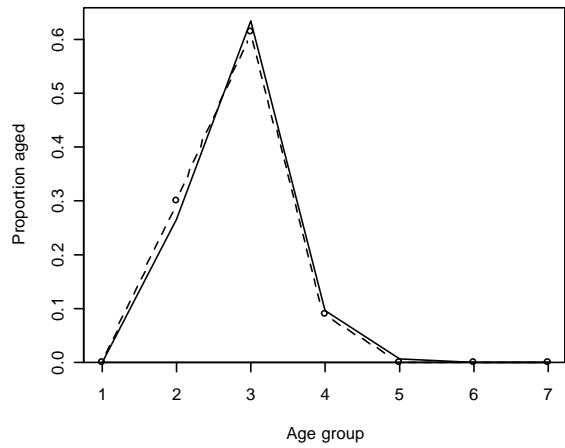
Queensland recreational, 1999 51-85 cm, ESS = 3.7



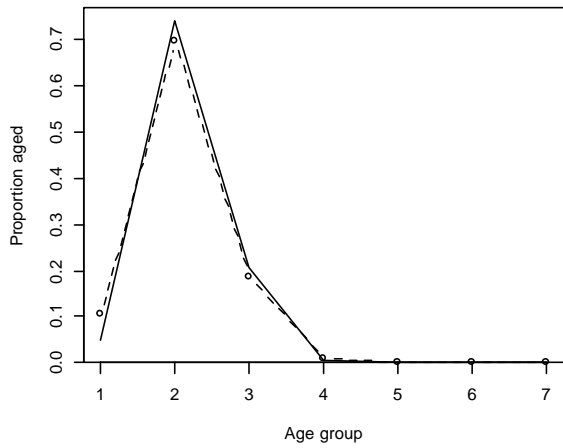
Queensland recreational, 2000 0-30 cm, ESS = 27.4



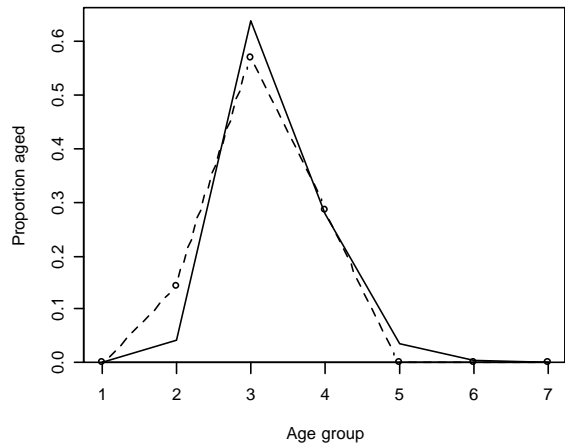
Queensland recreational, 2000 41-45 cm, ESS = 66.9



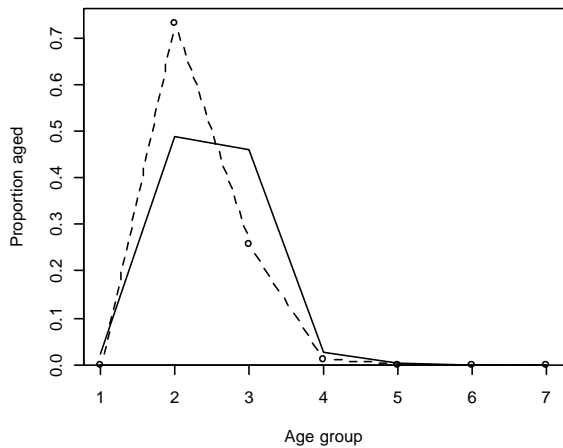
Queensland recreational, 2000 31-35 cm, ESS = 100.3



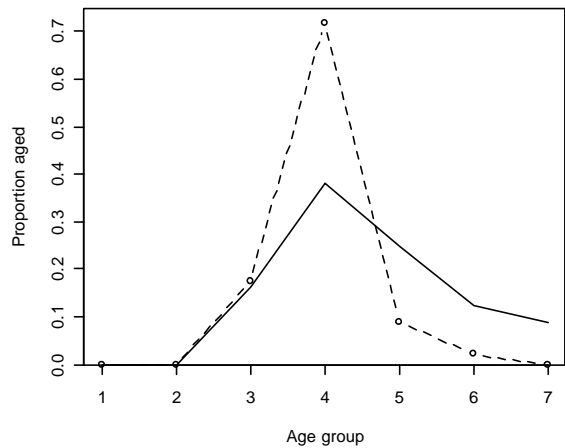
Queensland recreational, 2000 46-50 cm, ESS = 17.3



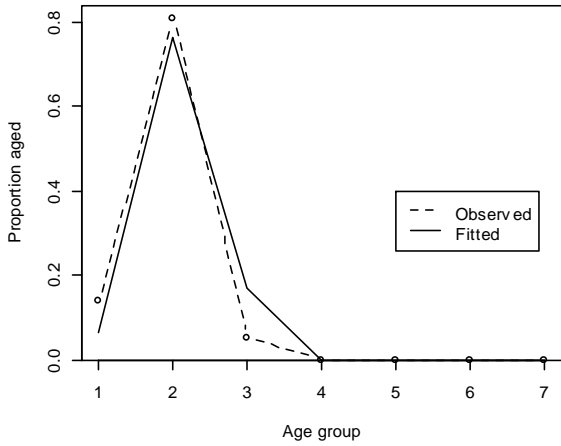
Queensland recreational, 2000 36-40 cm, ESS = 99.6



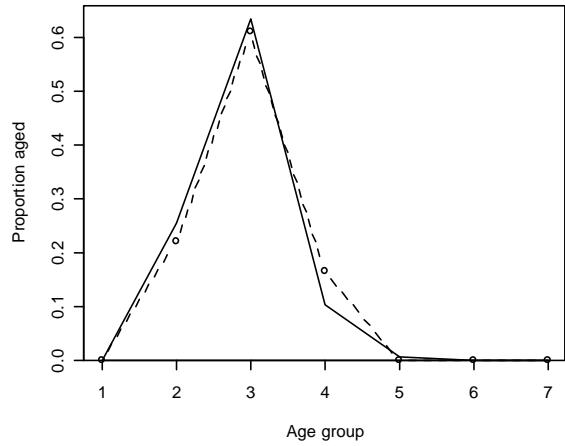
Queensland recreational, 2000 51-85 cm, ESS = 22.9



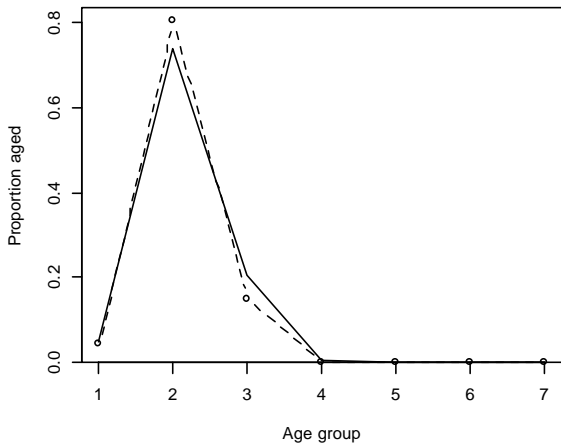
Queensland recreational, 2001 0-30 cm, ESS = 46.4



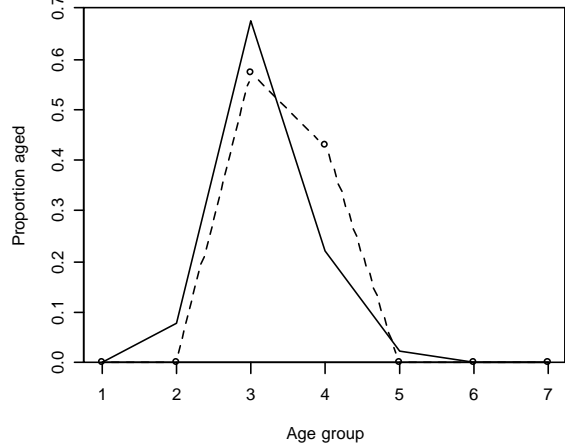
Queensland recreational, 2001 41-45 cm, ESS = 53.7



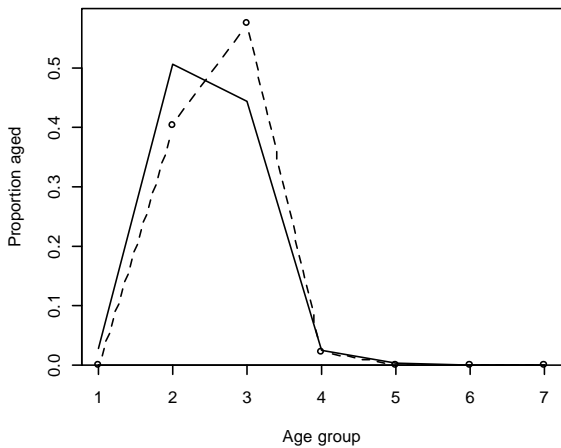
Queensland recreational, 2001 31-35 cm, ESS = 229.2



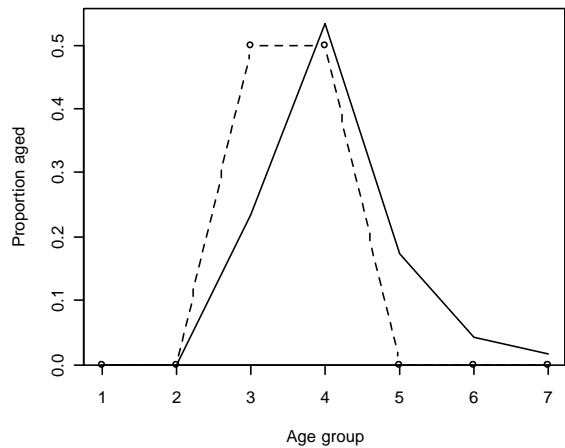
Queensland recreational, 2001 46-50 cm, ESS = 6.9

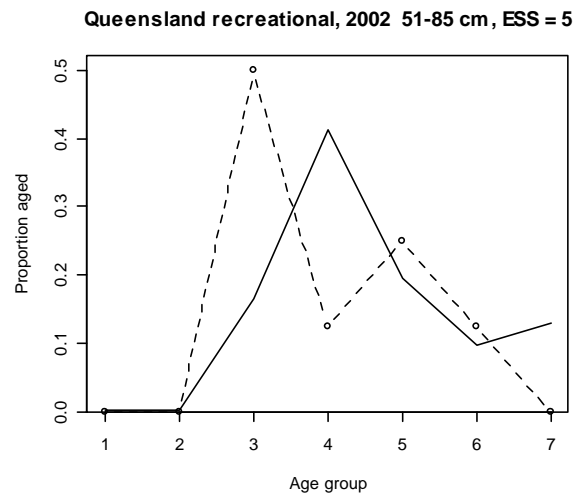
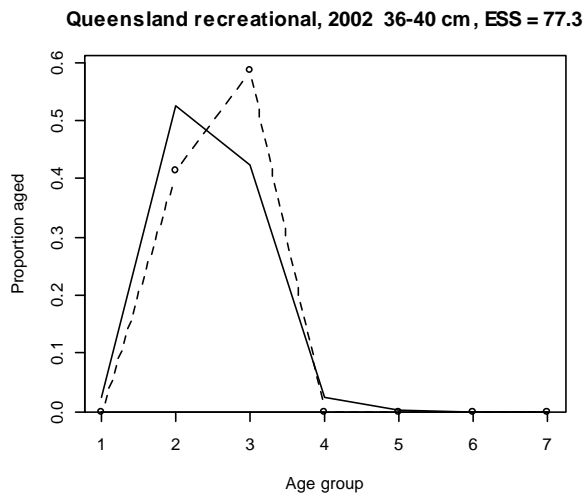
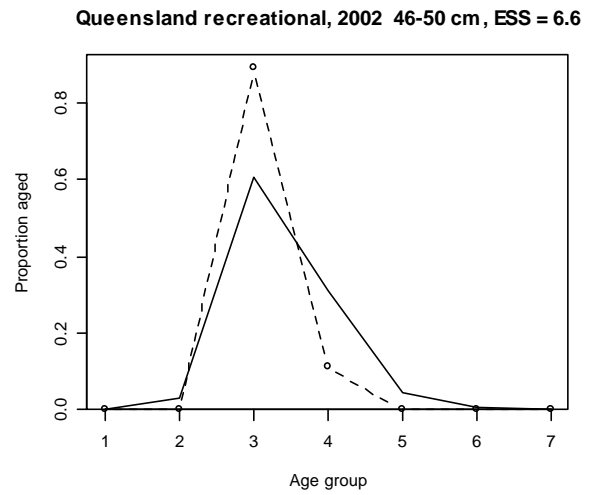
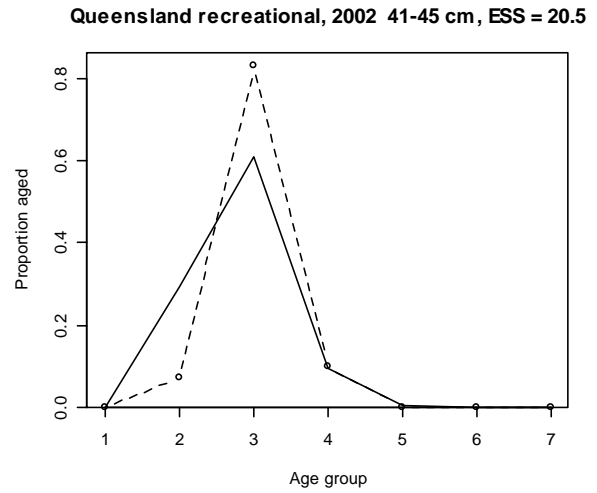


Queensland recreational, 2001 36-40 cm, ESS = 99.3



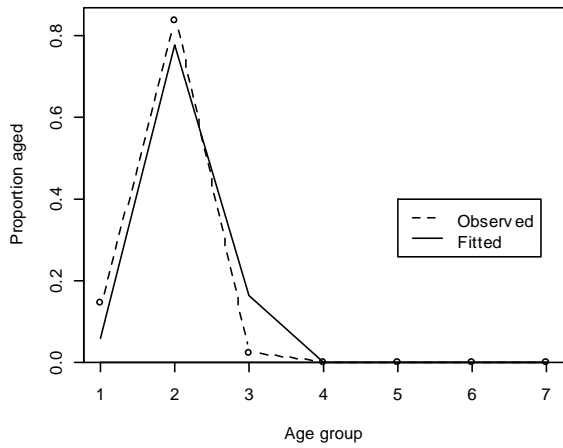
Queensland recreational, 2001 51-85 cm, ESS = 2



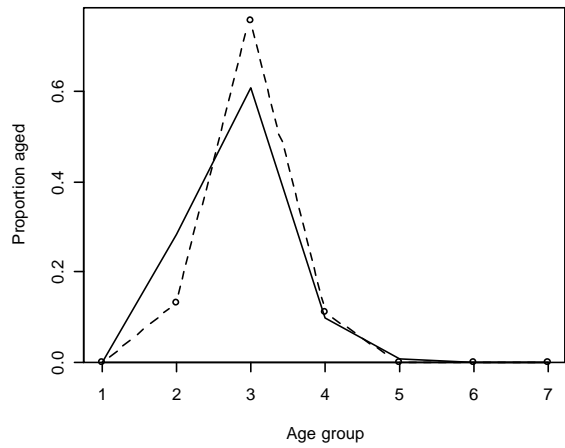




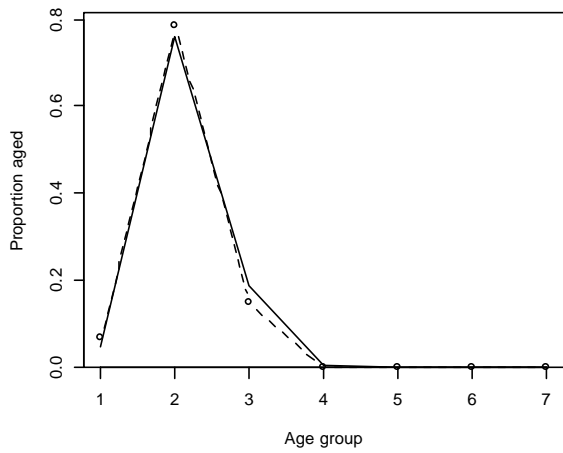
Queensland recreational, 2003 0-30 cm, ESS = 41.9



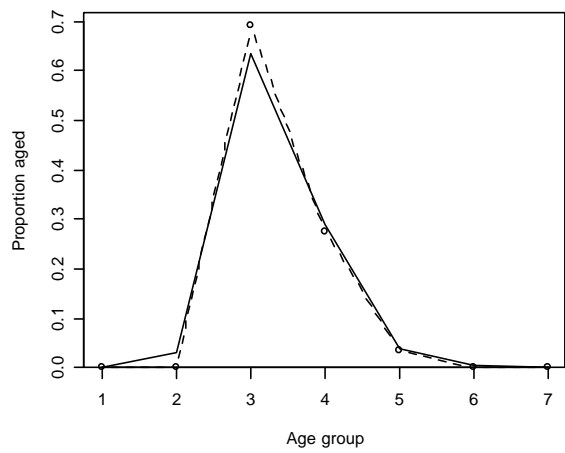
Queensland recreational, 2003 41-45 cm, ESS = 49.4



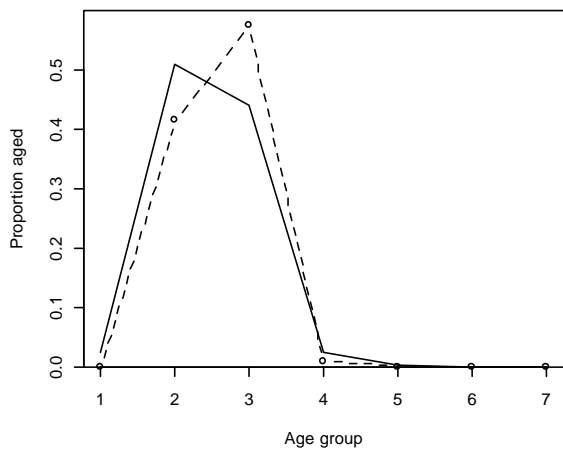
Queensland recreational, 2003 31-35 cm, ESS = 164.5



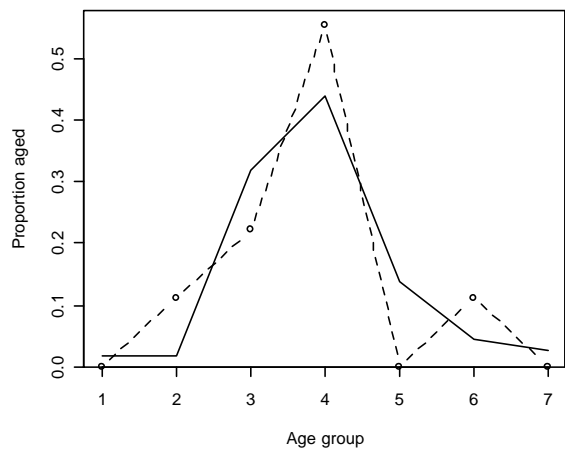
Queensland recreational, 2003 46-50 cm, ESS = 28.9



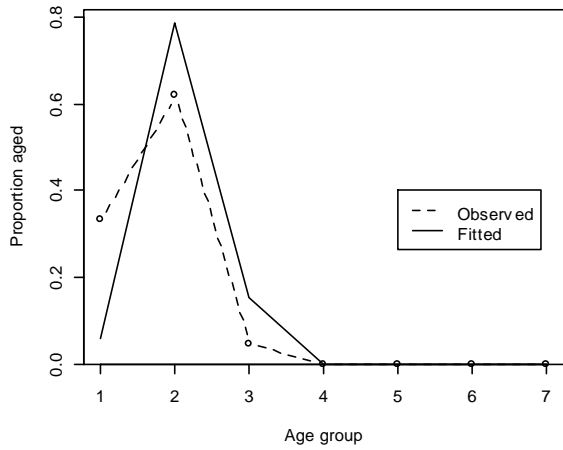
Queensland recreational, 2003 36-40 cm, ESS = 99.7



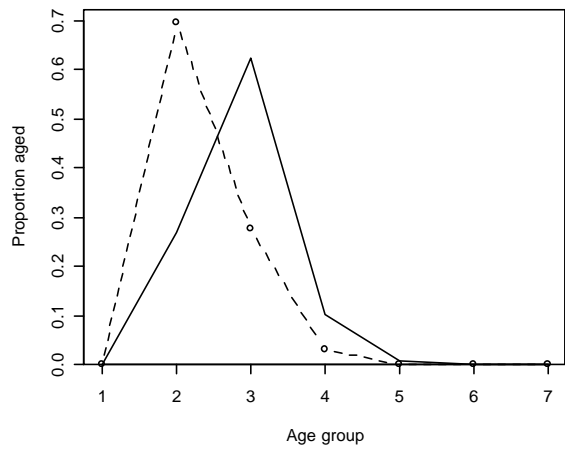
Queensland recreational, 2003 51-85 cm, ESS = 6.7



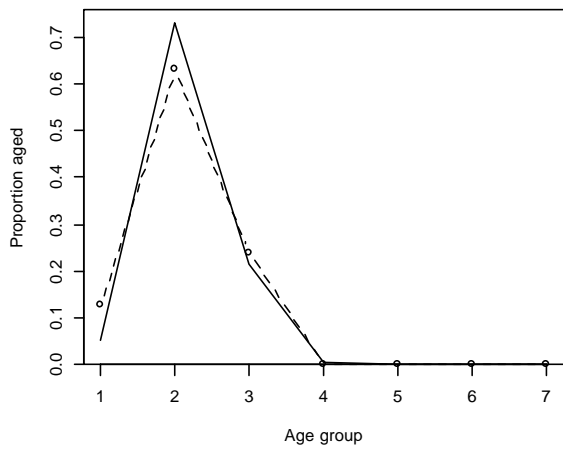
Queensland recreational, 2004 0-30 cm, ESS = 10.5



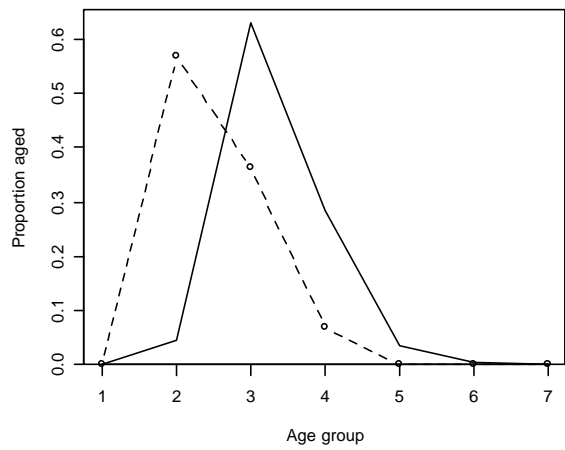
Queensland recreational, 2004 41-45 cm, ESS = 86.8



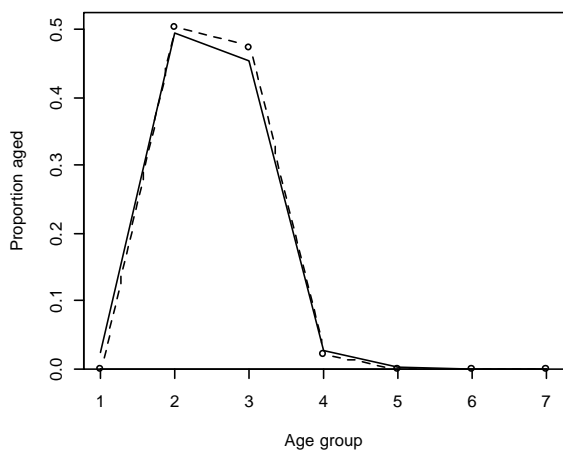
Queensland recreational, 2004 31-35 cm, ESS = 99.2



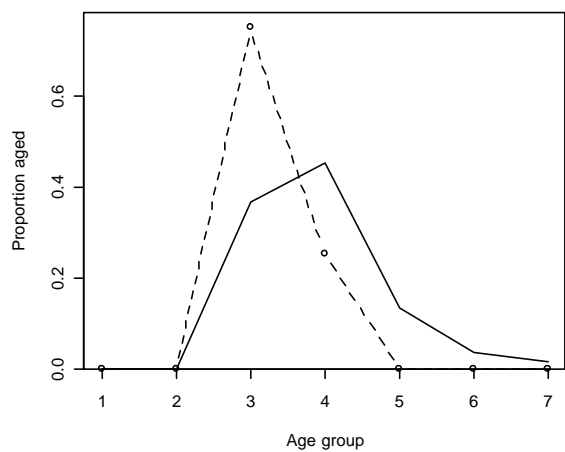
Queensland recreational, 2004 46-50 cm, ESS = 21.9



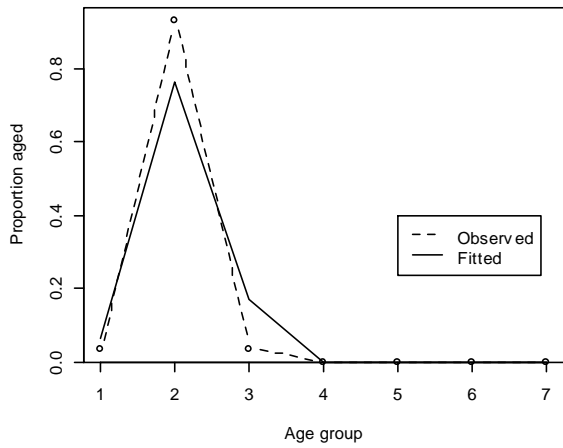
Queensland recreational, 2004 36-40 cm, ESS = 100



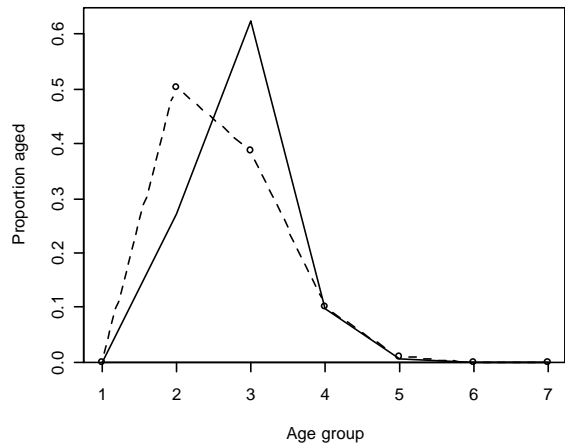
Queensland recreational, 2004 51-85 cm, ESS = 4.1



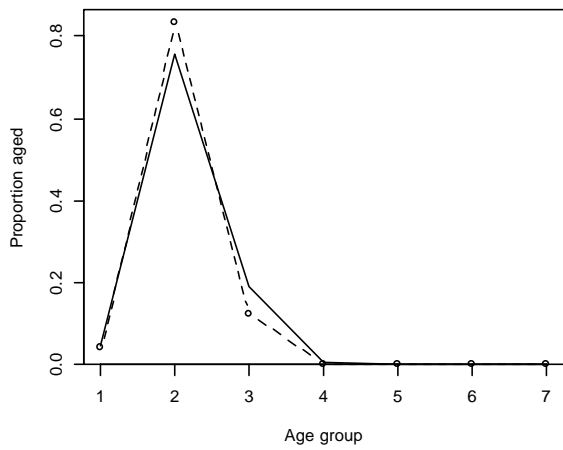
Queensland recreational, 2005 0-30 cm, ESS = 99.7



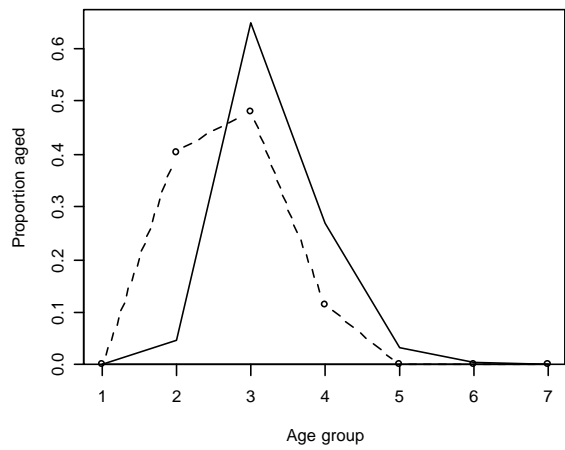
Queensland recreational, 2005 41-45 cm, ESS = 98.3



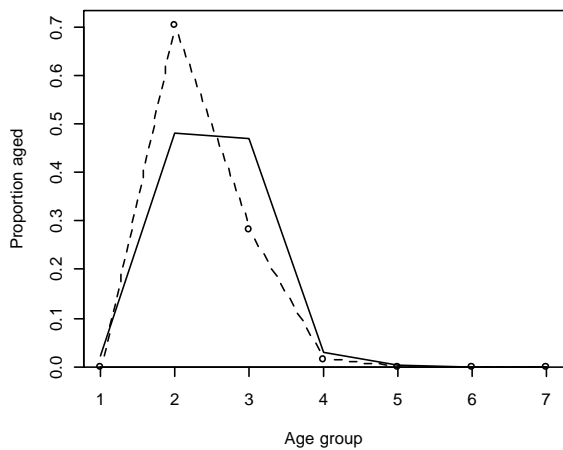
Queensland recreational, 2005 31-35 cm, ESS = 137.6



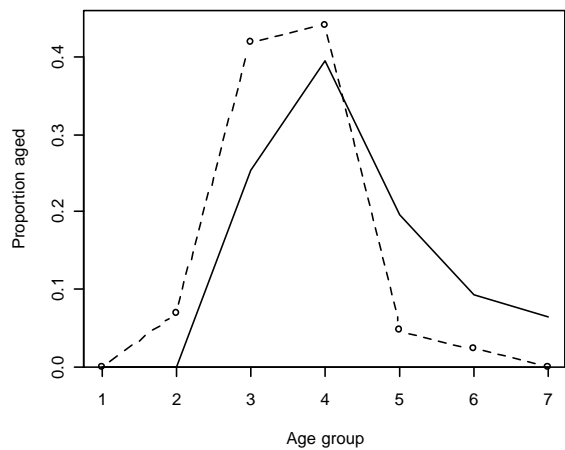
Queensland recreational, 2005 46-50 cm, ESS = 25.9



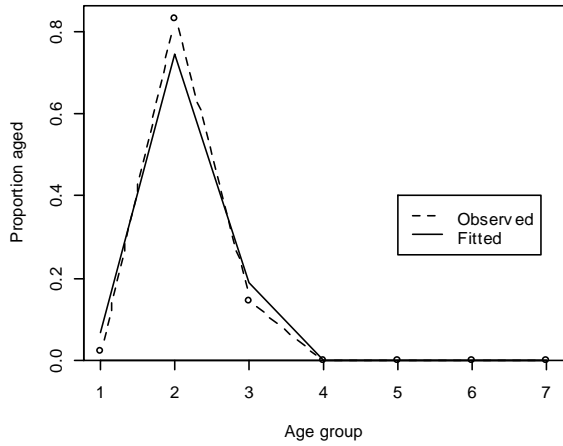
Queensland recreational, 2005 36-40 cm, ESS = 99.4



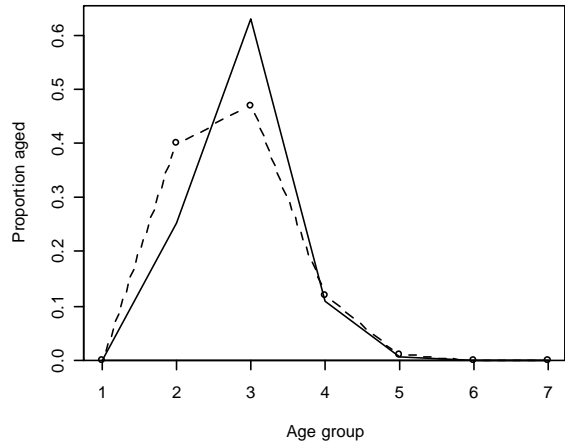
Queensland recreational, 2005 51-85 cm, ESS = 21.4



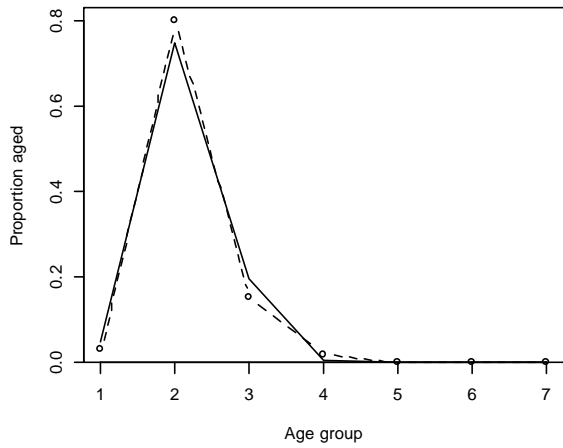
Queensland recreational, 2006 0-30 cm, ESS = 40.9



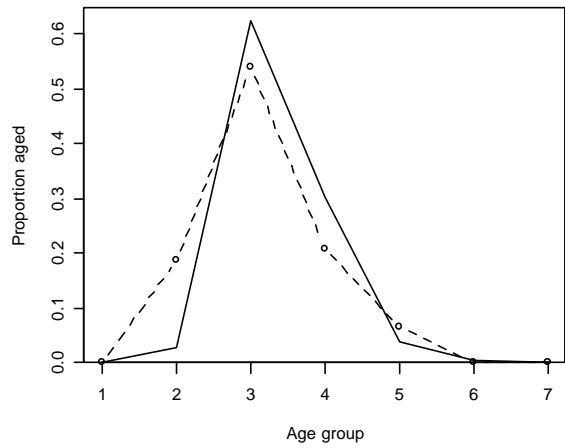
Queensland recreational, 2006 41-45 cm, ESS = 50.3



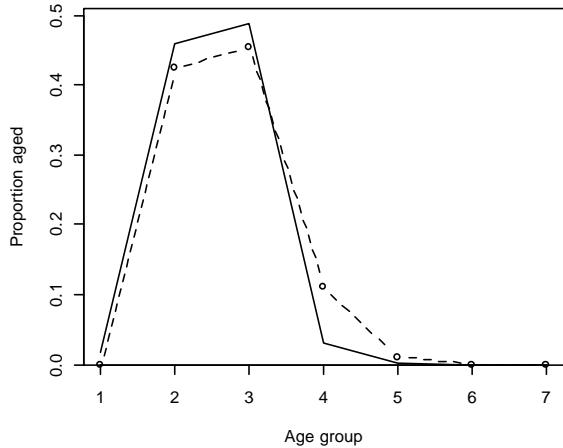
Queensland recreational, 2006 31-35 cm, ESS = 87.3



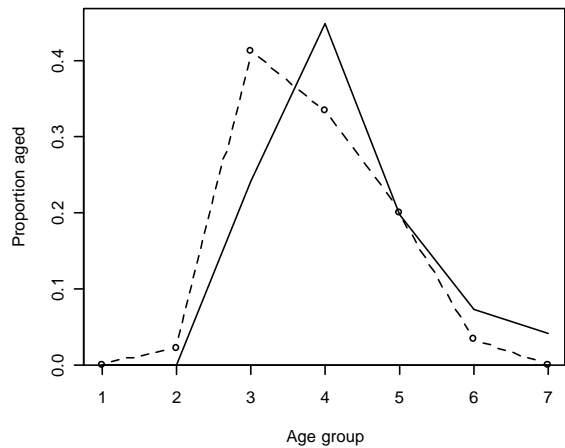
Queensland recreational, 2006 46-50 cm, ESS = 45.4



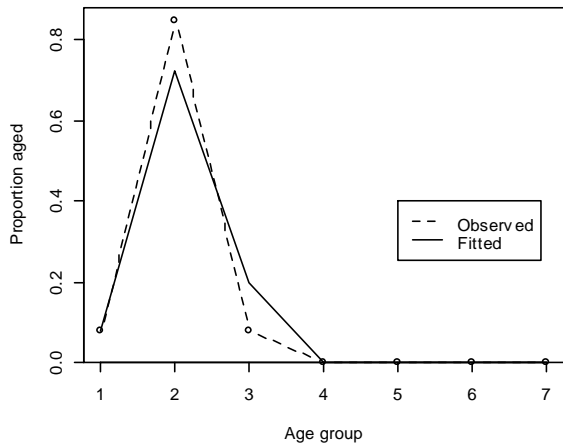
Queensland recreational, 2006 36-40 cm, ESS = 49.4



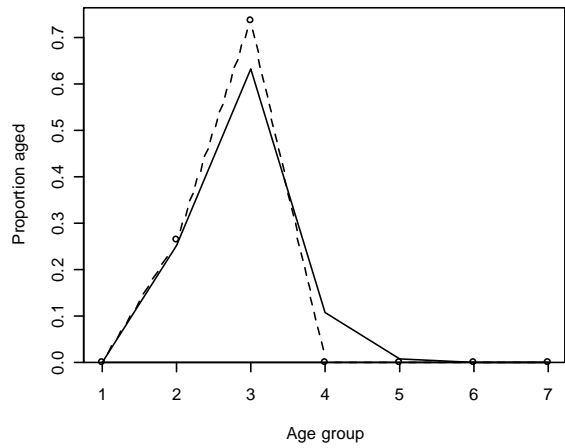
Queensland recreational, 2006 51-85 cm, ESS = 44.9



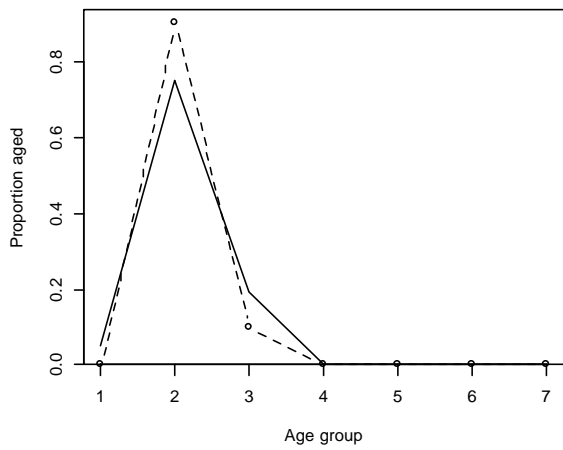
Queensland recreational, 2007 0-30 cm, ESS = 25.8



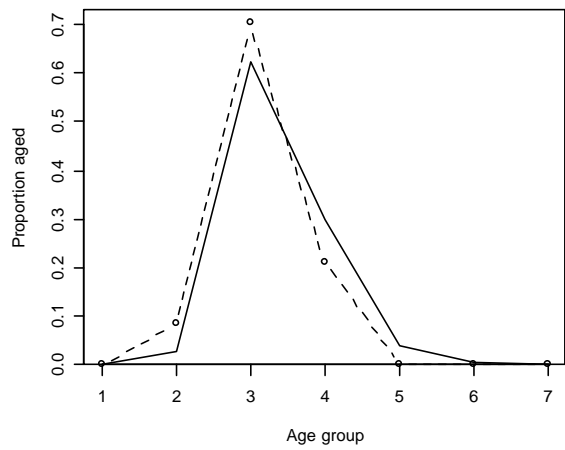
Queensland recreational, 2007 41-45 cm, ESS = 26.4



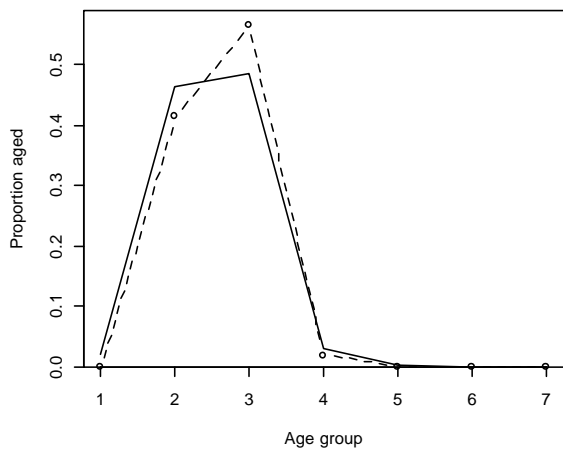
Queensland recreational, 2007 31-35 cm, ESS = 25.5



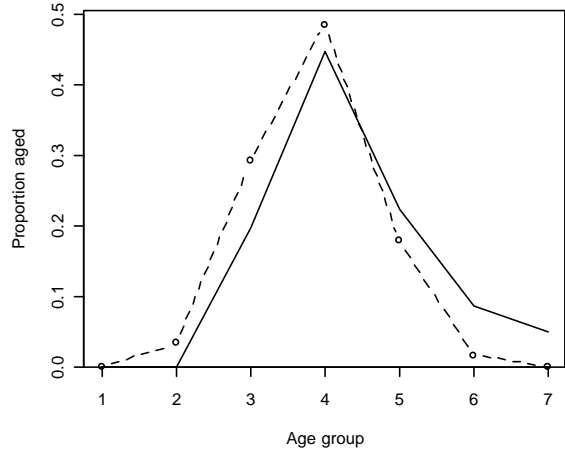
Queensland recreational, 2007 46-50 cm, ESS = 23.7



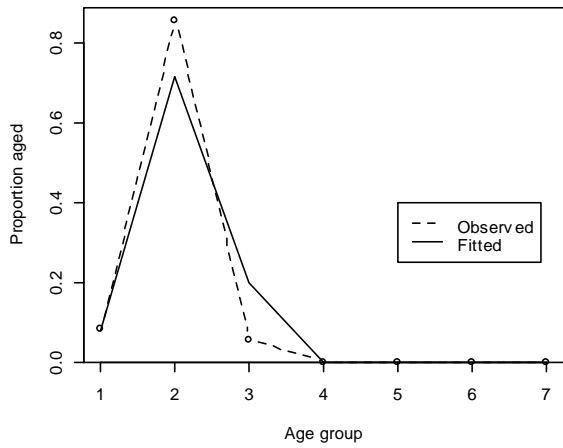
Queensland recreational, 2007 36-40 cm, ESS = 52.3



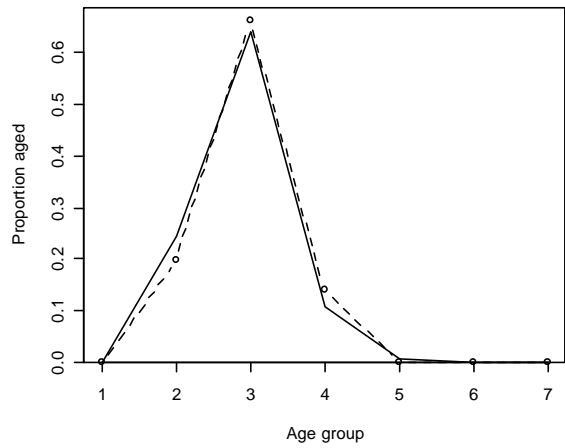
Queensland recreational, 2007 51-85 cm, ESS = 30.9



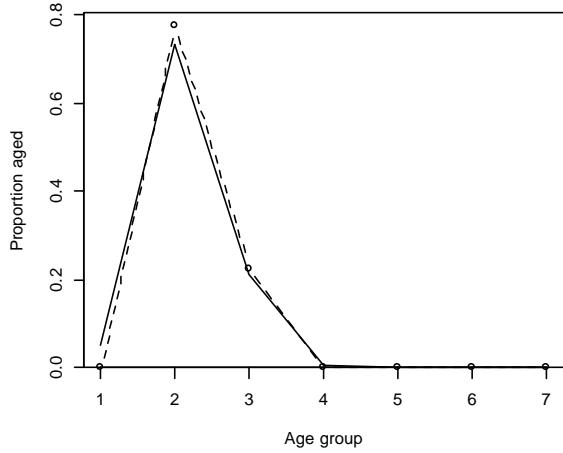
Queensland recreational, 2008 0-30 cm, ESS = 23.5



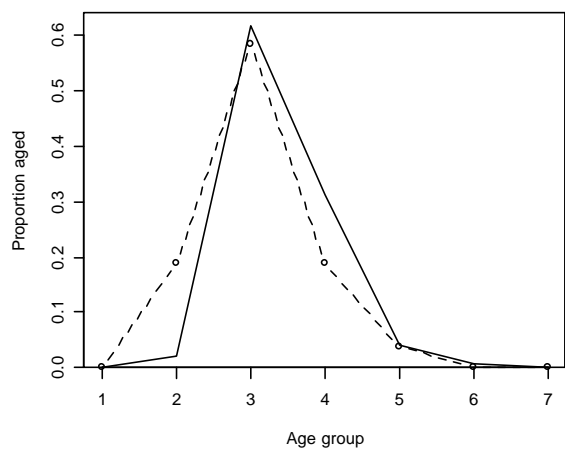
Queensland recreational, 2008 41-45 cm, ESS = 70.7



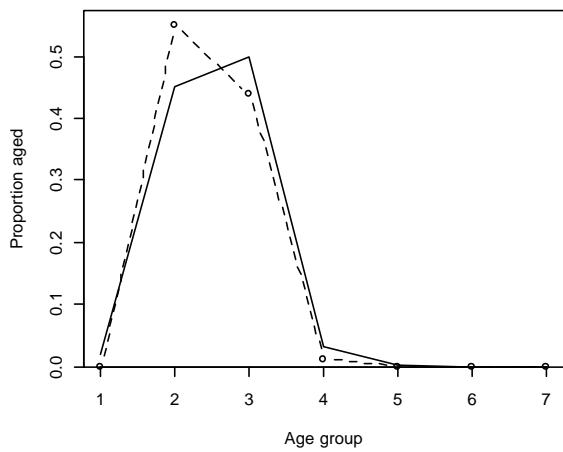
Queensland recreational, 2008 31-35 cm, ESS = 35.6



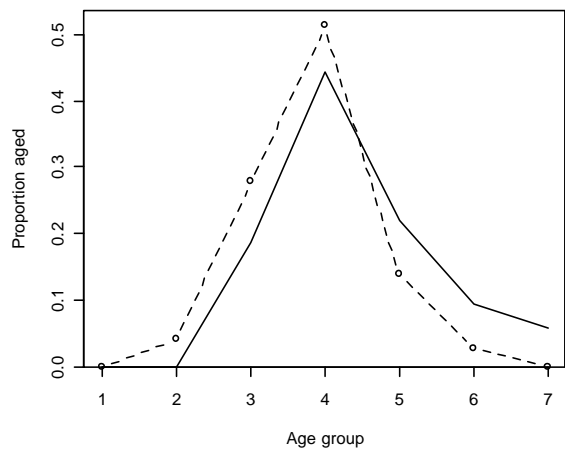
Queensland recreational, 2008 46-50 cm, ESS = 26.4



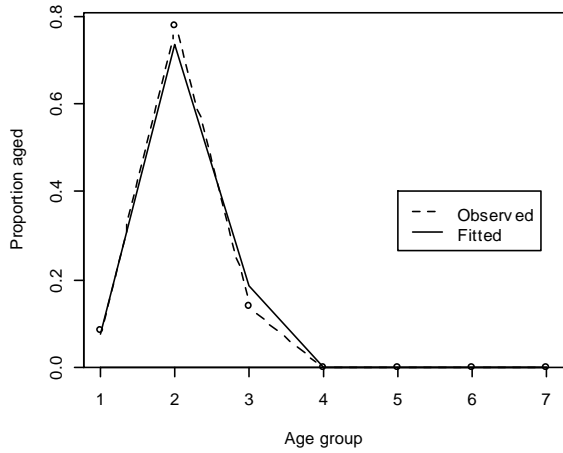
Queensland recreational, 2008 36-40 cm, ESS = 47.2



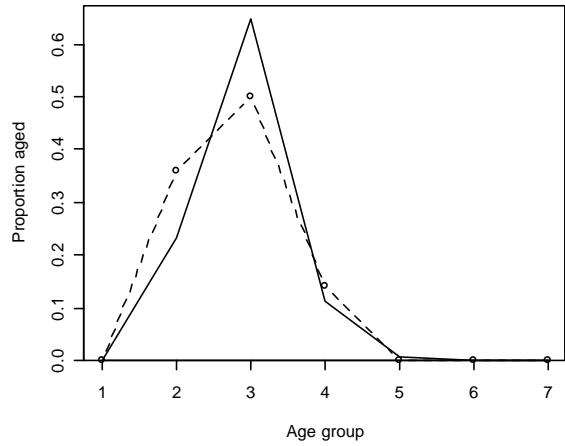
Queensland recreational, 2008 51-85 cm, ESS = 35.9



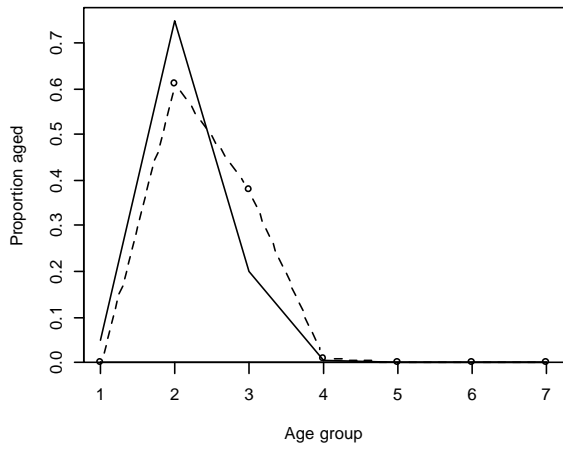
Queensland recreational, 2009 0-30 cm, ESS = 36



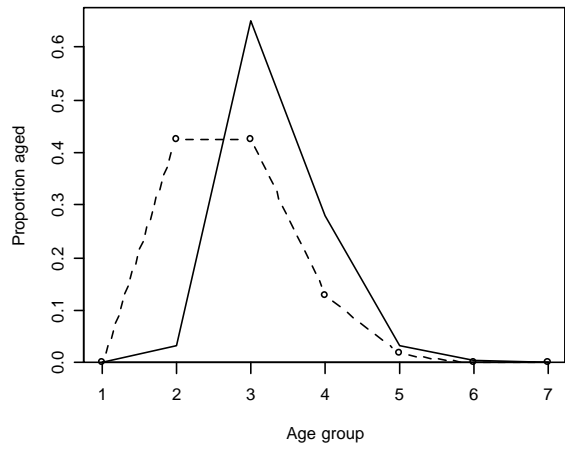
Queensland recreational, 2009 41-45 cm, ESS = 39.3



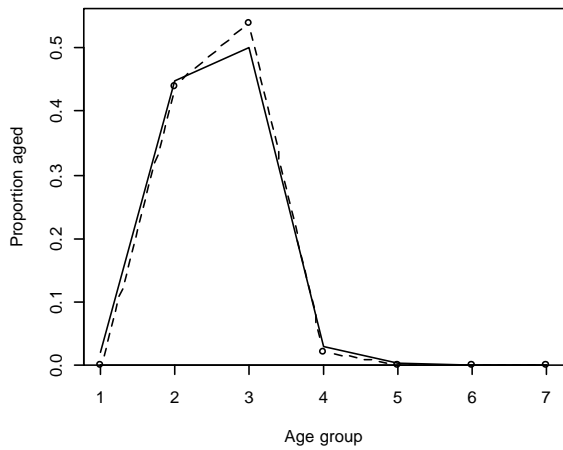
Queensland recreational, 2009 31-35 cm, ESS = 47.4



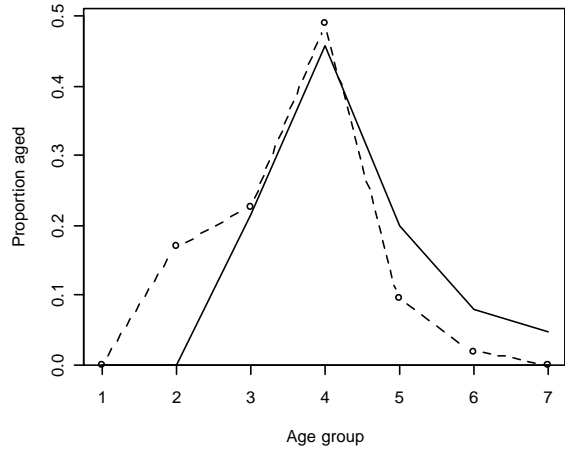
Queensland recreational, 2009 46-50 cm, ESS = 26.9



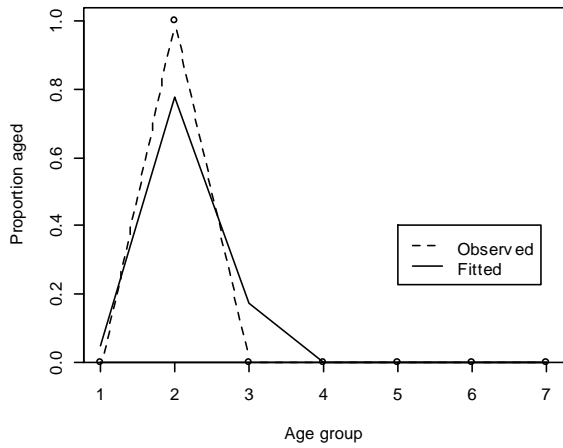
Queensland recreational, 2009 36-40 cm, ESS = 78.8



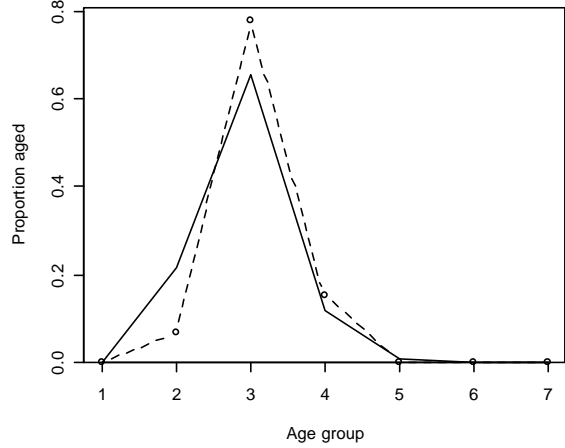
Queensland recreational, 2009 51-85 cm, ESS = 26.4



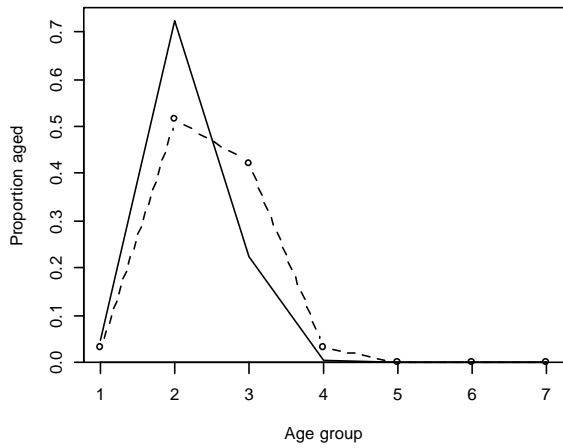
Queensland recreational, 2010 0-30 cm, ESS = 2



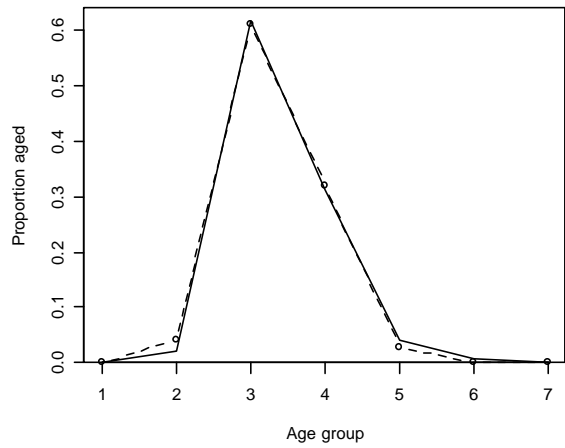
Queensland recreational, 2010 41-45 cm, ESS = 36



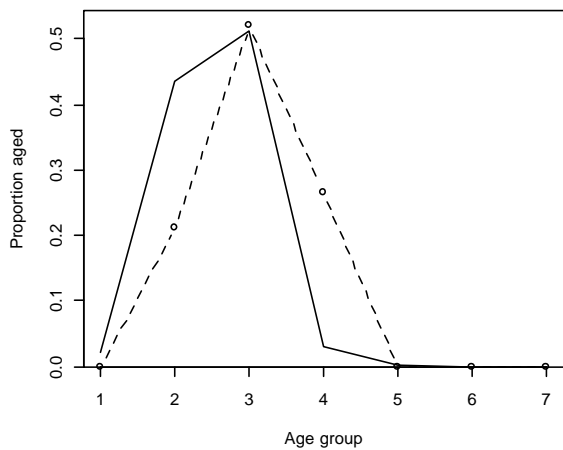
Queensland recreational, 2010 31-35 cm, ESS = 47.4



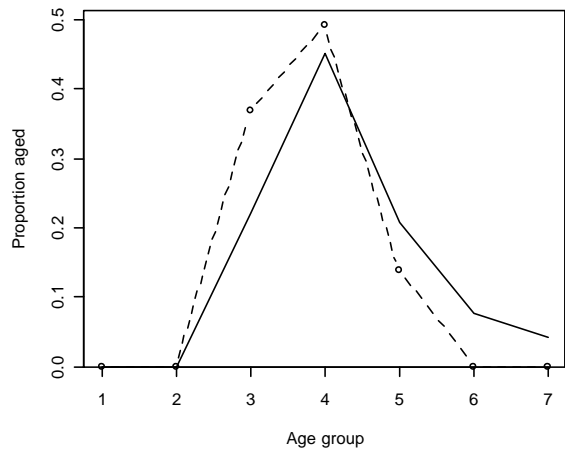
Queensland recreational, 2010 46-50 cm, ESS = 71.8



Queensland recreational, 2010 36-40 cm, ESS = 46.9

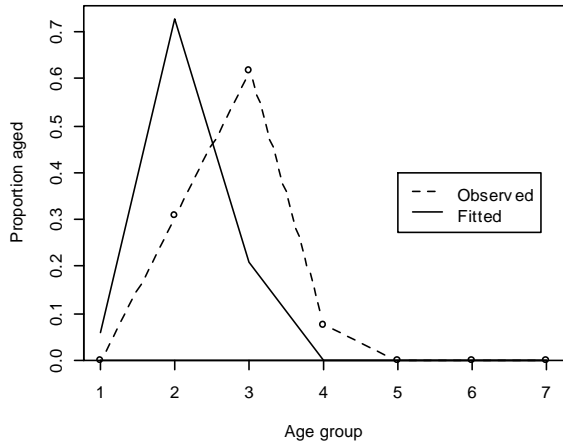


Queensland recreational, 2010 51-85 cm, ESS = 32.4

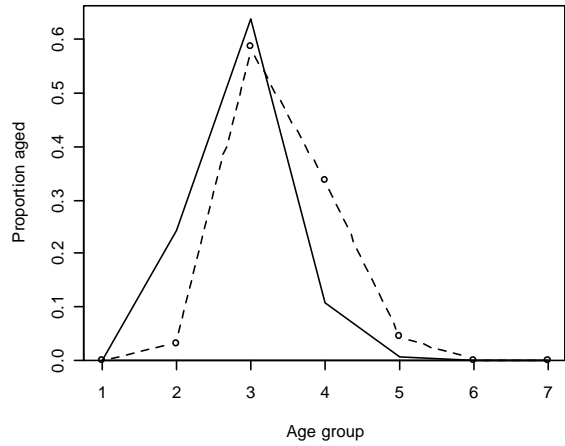




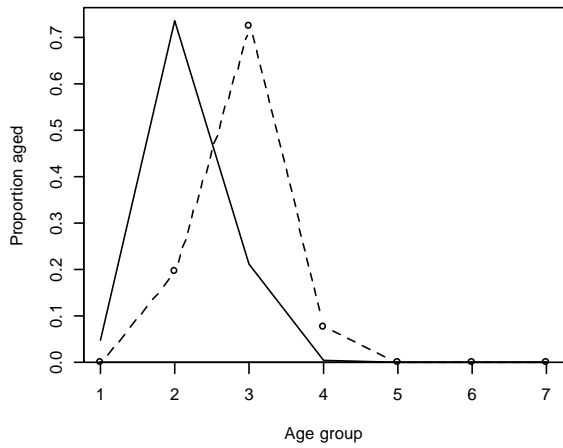
Queensland recreational, 2011 0-30 cm, ESS = 6.5



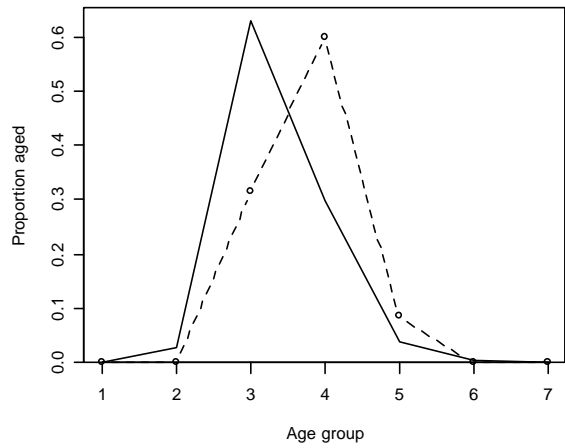
Queensland recreational, 2011 41-45 cm, ESS = 45.9



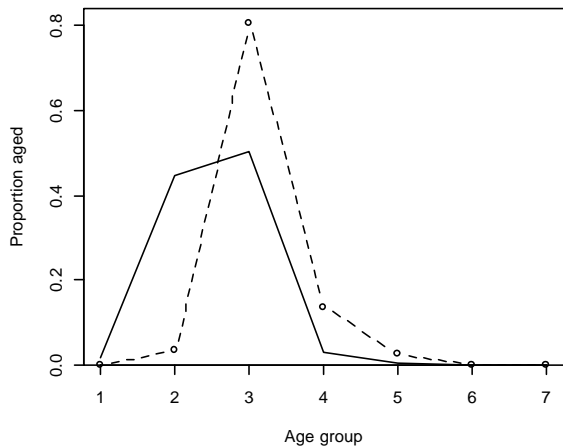
Queensland recreational, 2011 31-35 cm, ESS = 37.9



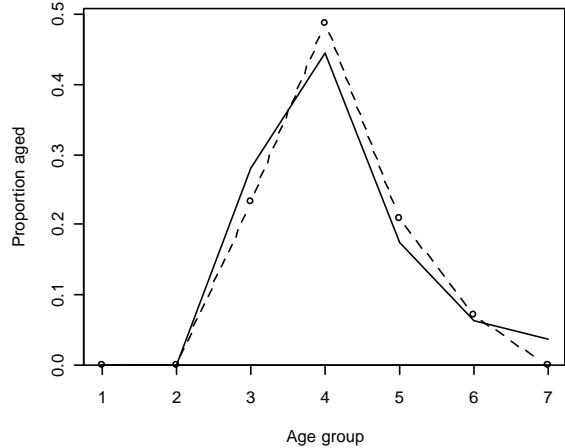
Queensland recreational, 2011 46-50 cm, ESS = 34.9



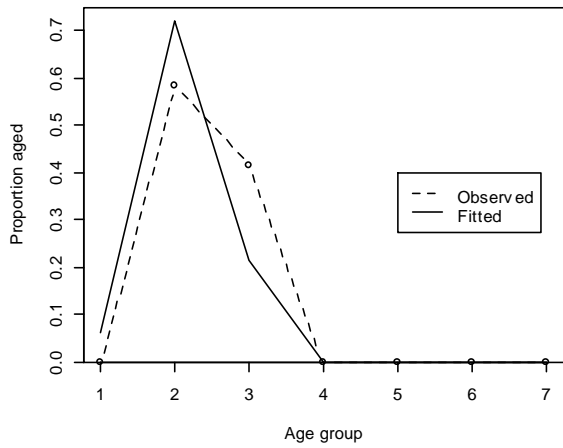
Queensland recreational, 2011 36-40 cm, ESS = 43.9



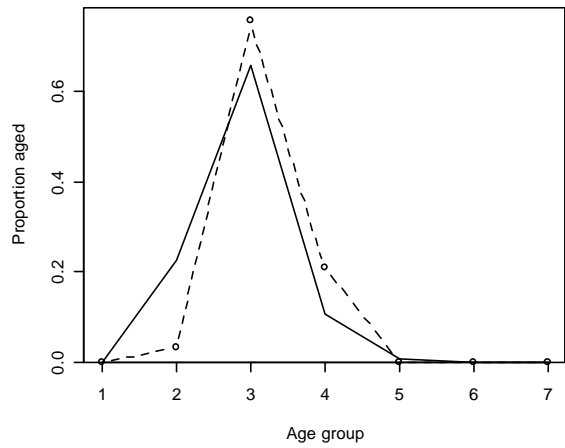
Queensland recreational, 2011 51-85 cm, ESS = 42.6



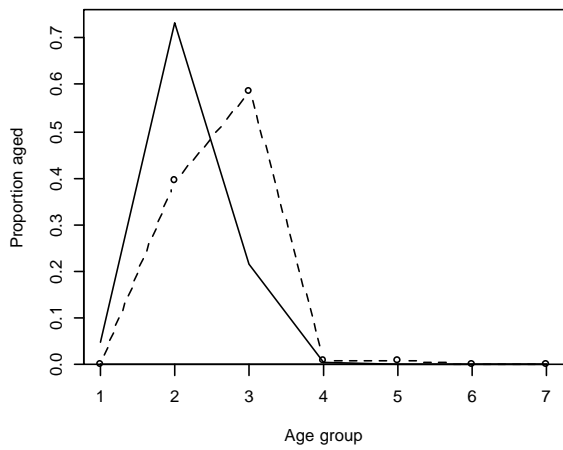
Queensland recreational, 2012 0-30 cm, ESS = 18



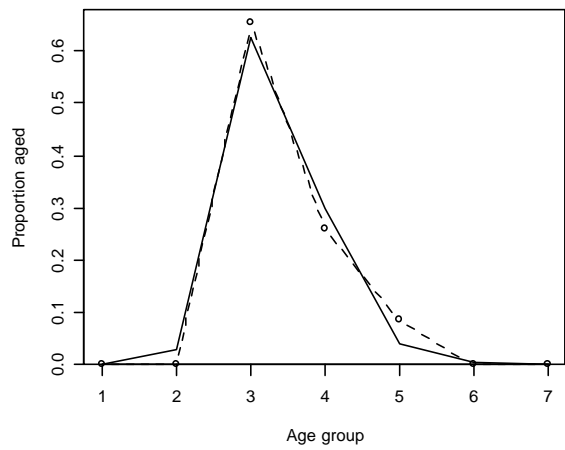
Queensland recreational, 2012 41-45 cm, ESS = 30.9



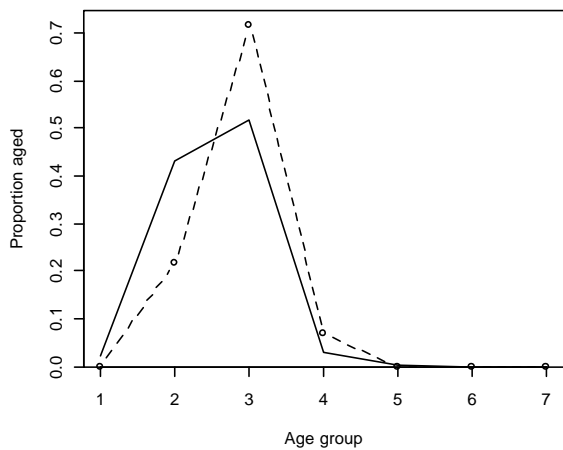
Queensland recreational, 2012 31-35 cm, ESS = 49.4



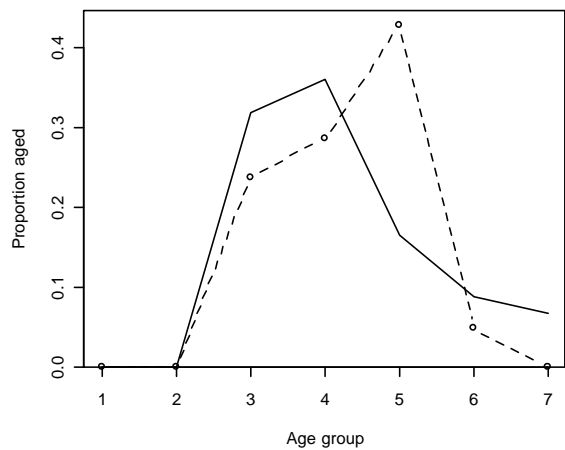
Queensland recreational, 2012 46-50 cm, ESS = 22.9



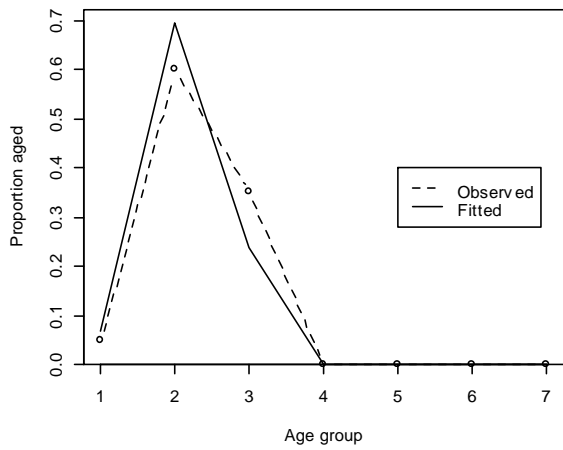
Queensland recreational, 2012 36-40 cm, ESS = 43.9



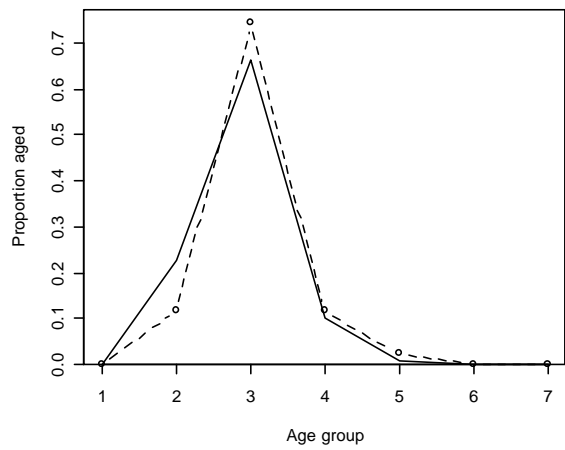
Queensland recreational, 2012 51-85 cm, ESS = 10.8



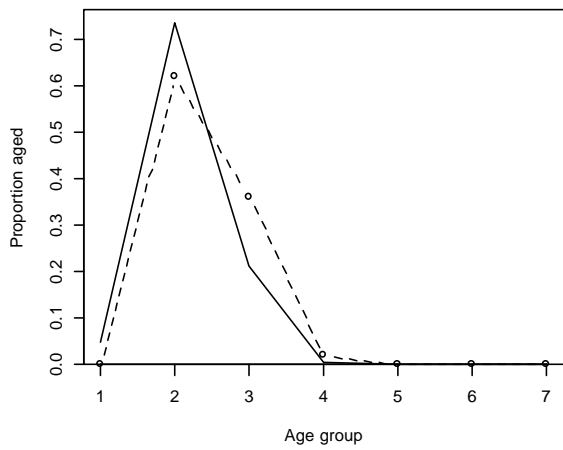
Queensland recreational, 2013 0-30 cm, ESS = 20



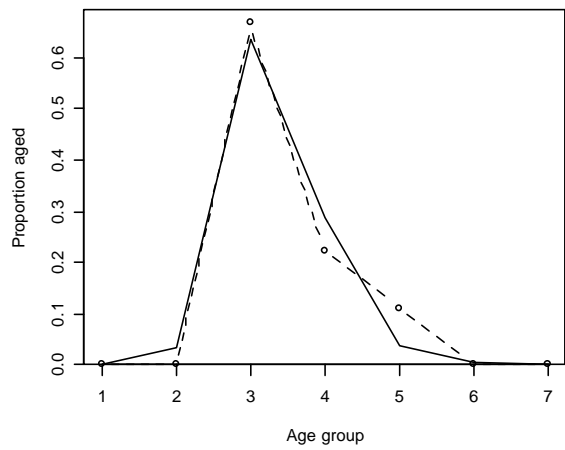
Queensland recreational, 2013 41-45 cm, ESS = 42.1



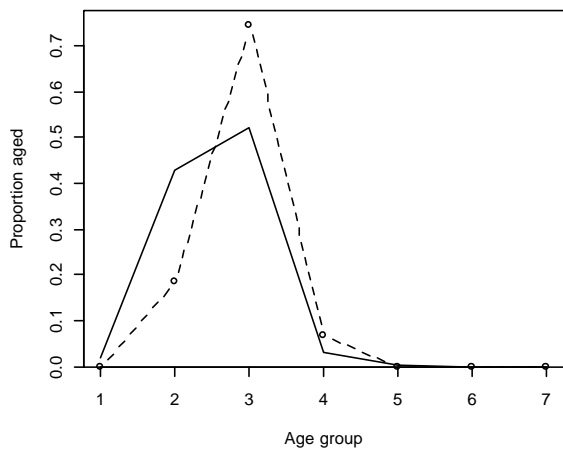
Queensland recreational, 2013 31-35 cm, ESS = 49.9



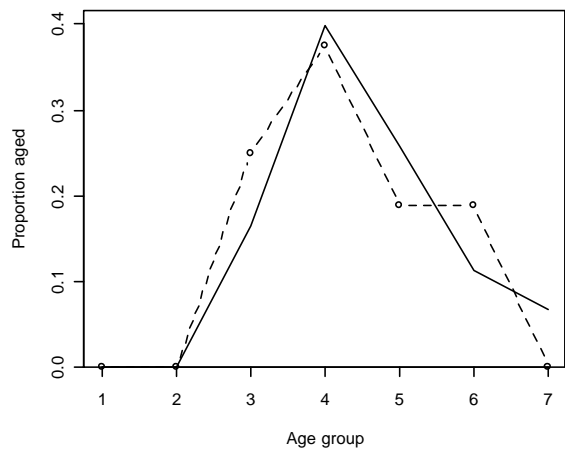
Queensland recreational, 2013 46-50 cm, ESS = 17.7



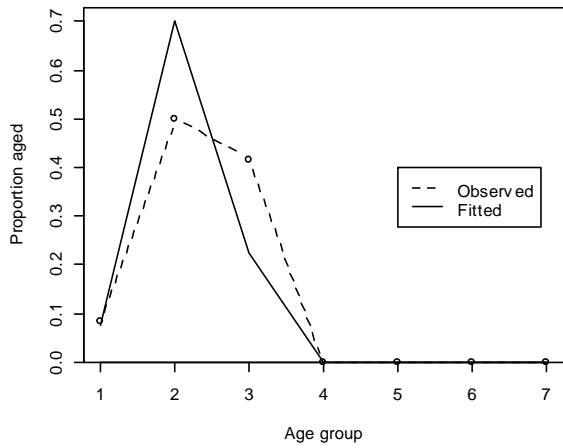
Queensland recreational, 2013 36-40 cm, ESS = 50.9



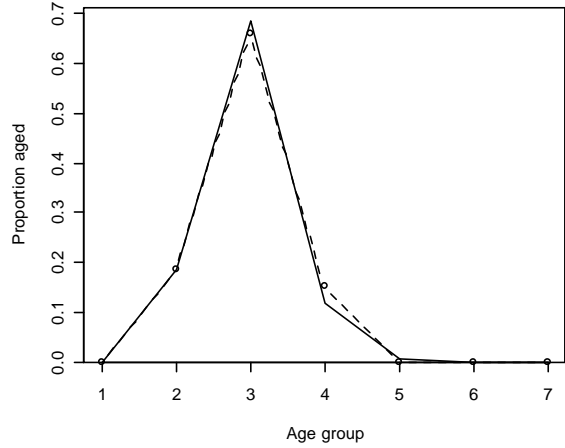
Queensland recreational, 2013 51-85 cm, ESS = 15.9



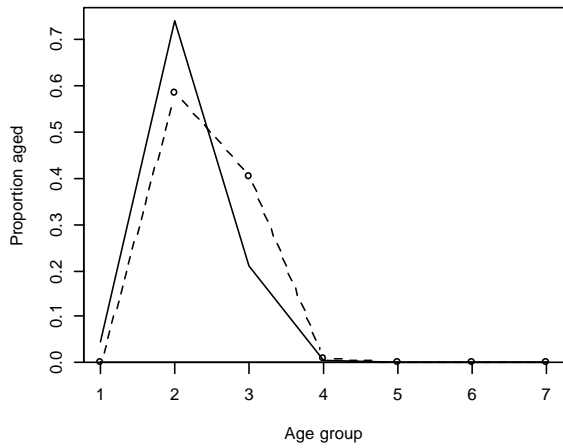
Queensland recreational, 2014 0-30 cm, ESS = 12



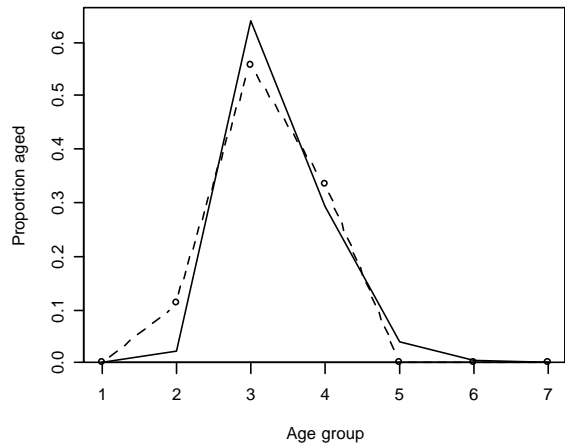
Queensland recreational, 2014 41-45 cm, ESS = 116.8



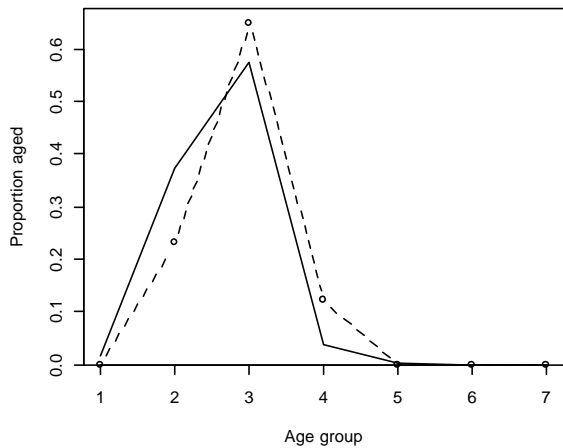
Queensland recreational, 2014 31-35 cm, ESS = 44.4



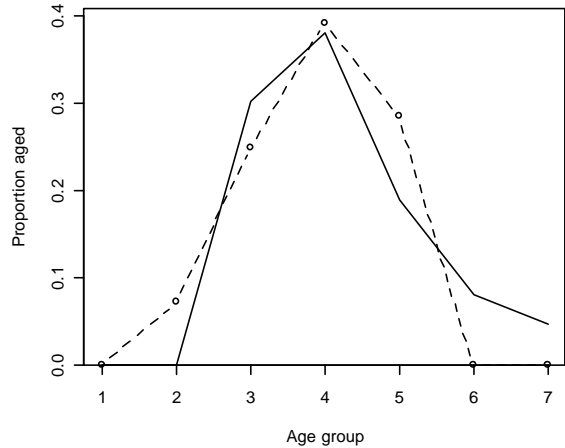
Queensland recreational, 2014 46-50 cm, ESS = 27



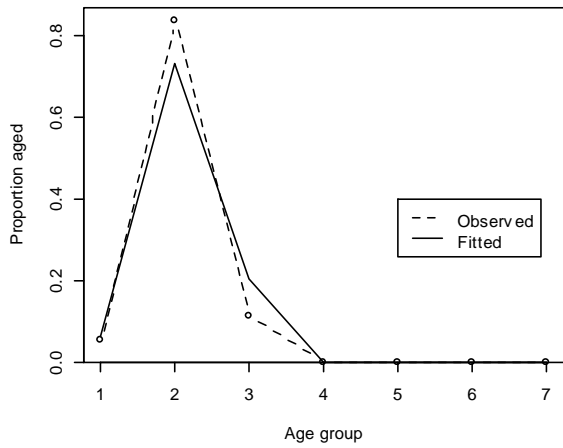
Queensland recreational, 2014 36-40 cm, ESS = 45.4



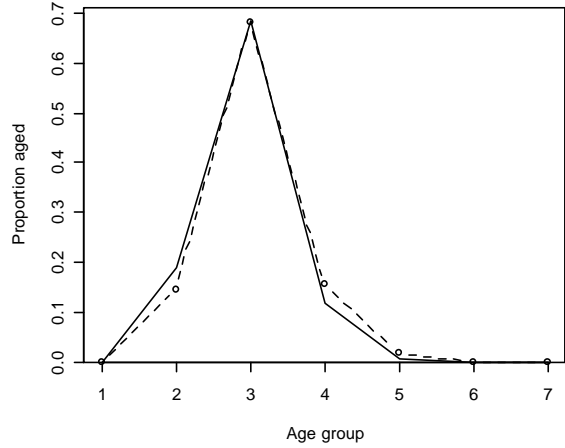
Queensland recreational, 2014 51-85 cm, ESS = 14



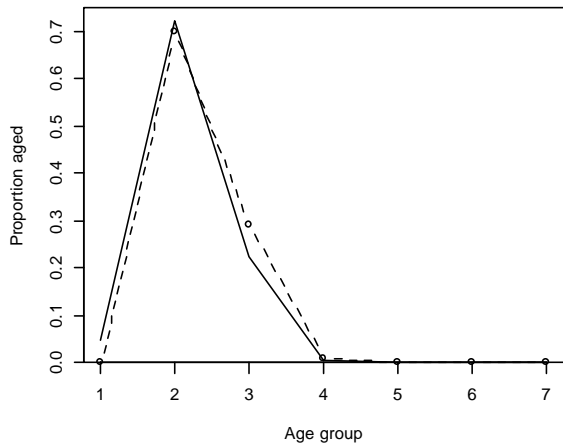
Queensland recreational, 2015 0-30 cm, ESS = 18



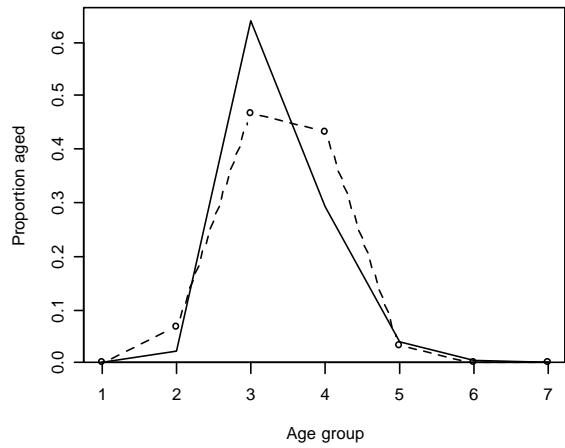
Queensland recreational, 2015 41-45 cm, ESS = 115.3



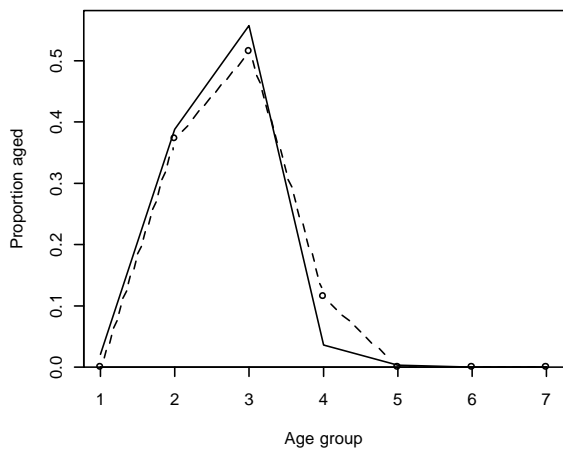
Queensland recreational, 2015 31-35 cm, ESS = 48



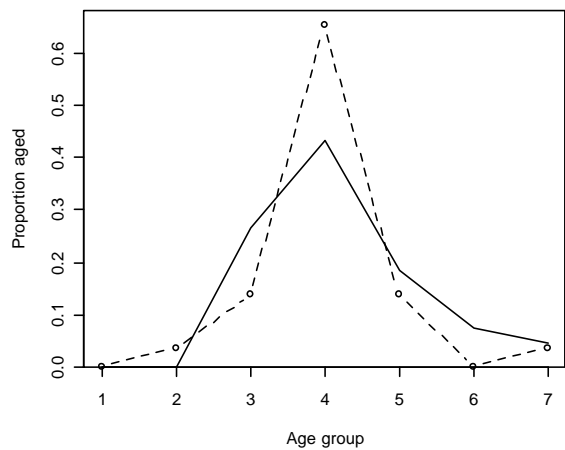
Queensland recreational, 2015 46-50 cm, ESS = 30.4



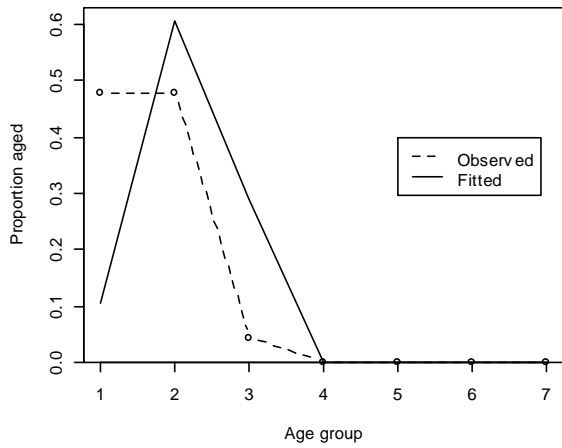
Queensland recreational, 2015 36-40 cm, ESS = 48.4



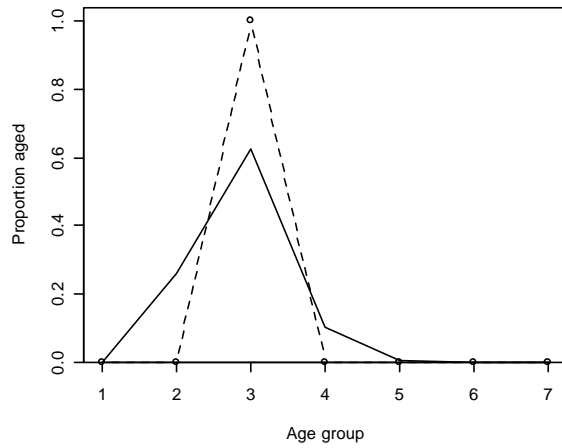
Queensland recreational, 2015 51-85 cm, ESS = 14.5



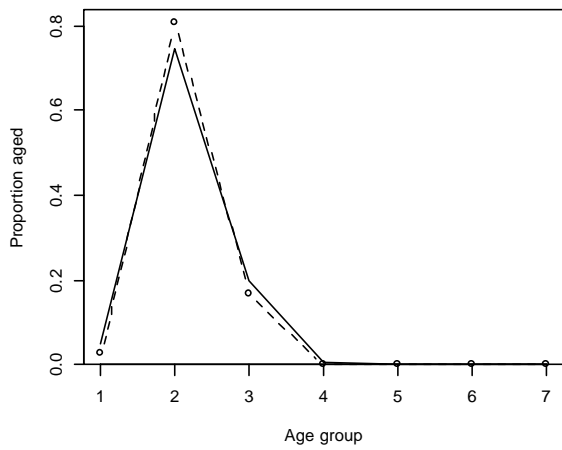
Queensland gillnet, 2007 0-30 cm, ESS = 11.5



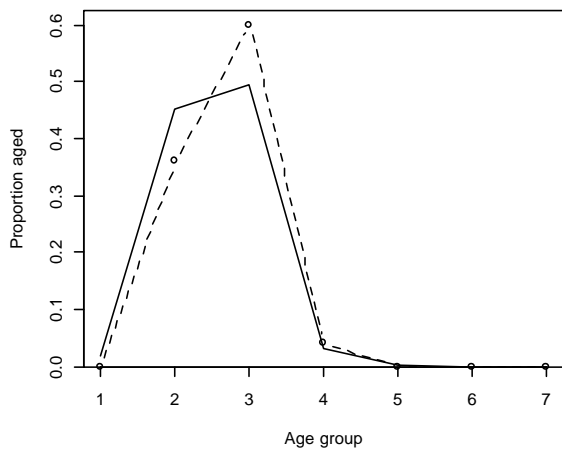
Queensland gillnet, 2007 41-45 cm, ESS = 2.2

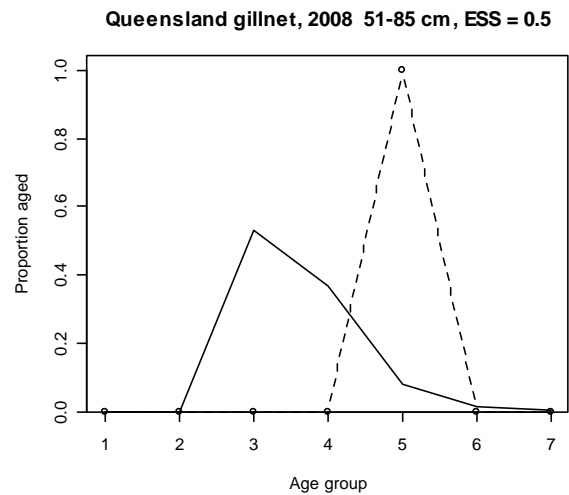
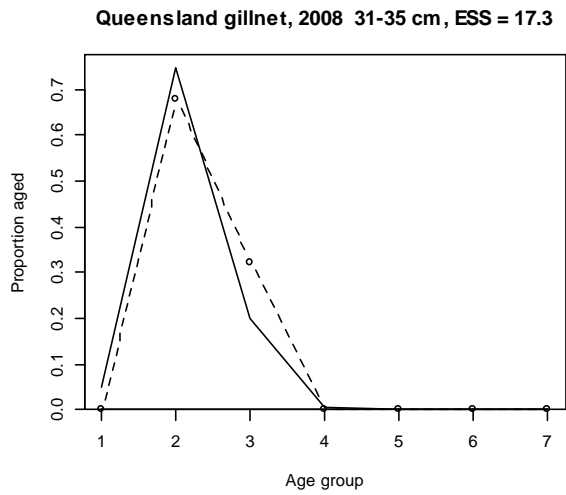
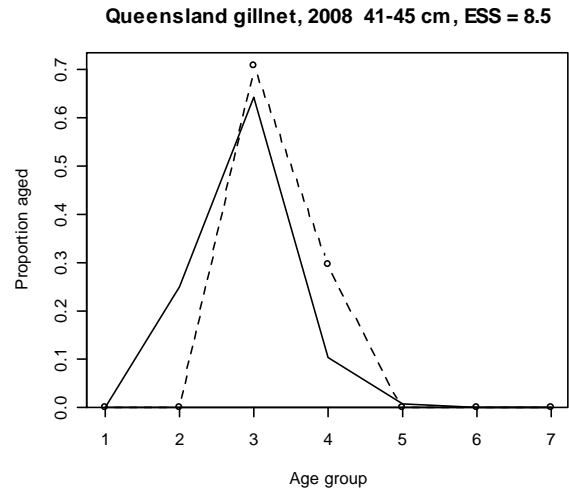
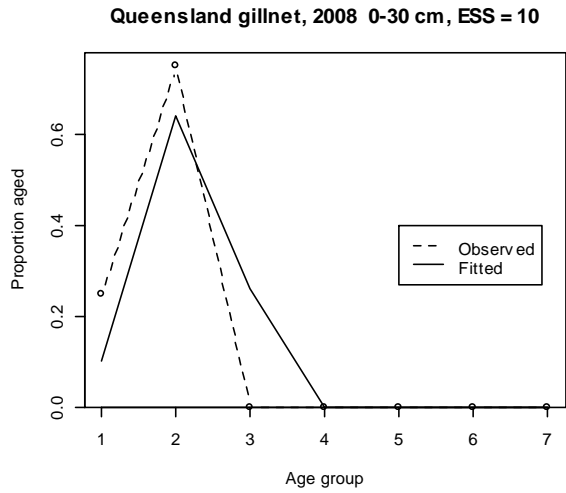


Queensland gillnet, 2007 31-35 cm, ESS = 36

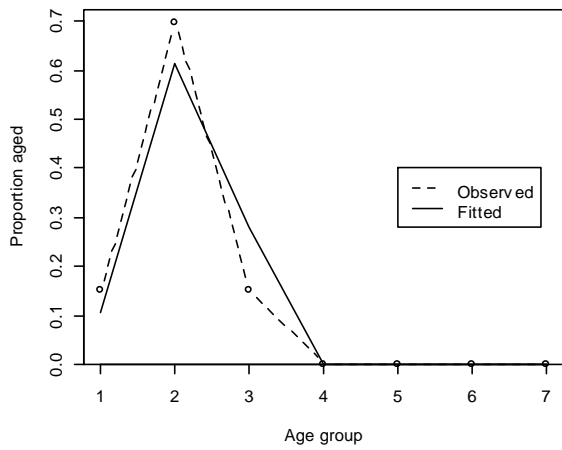


Queensland gillnet, 2007 36-40 cm, ESS = 24.9

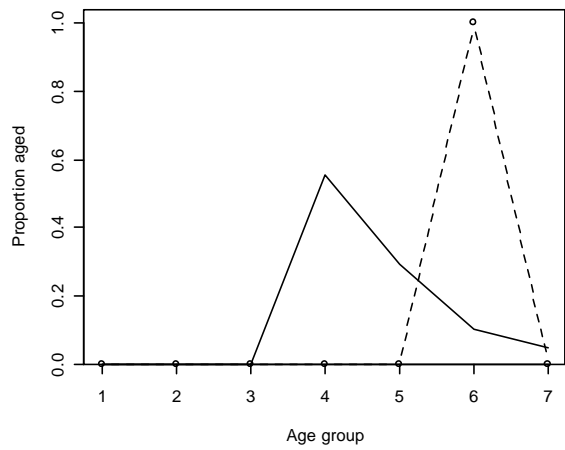




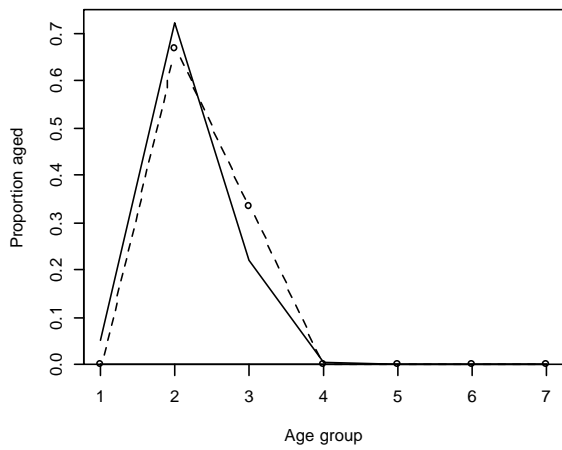
Queensland gillnet, 2009 0-30 cm, ESS = 32.7



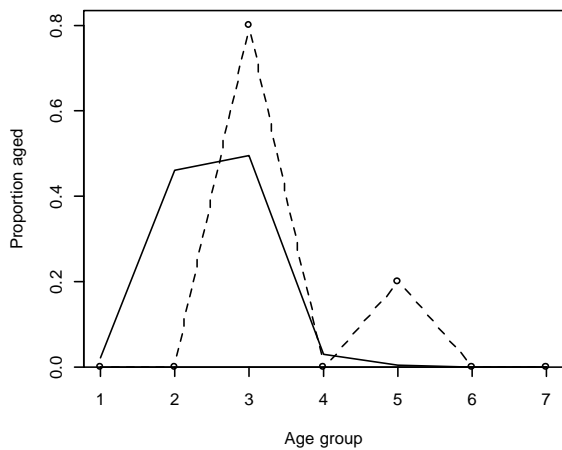
Queensland gillnet, 2009 51-85 cm, ESS = 0.5



Queensland gillnet, 2009 31-35 cm, ESS = 6

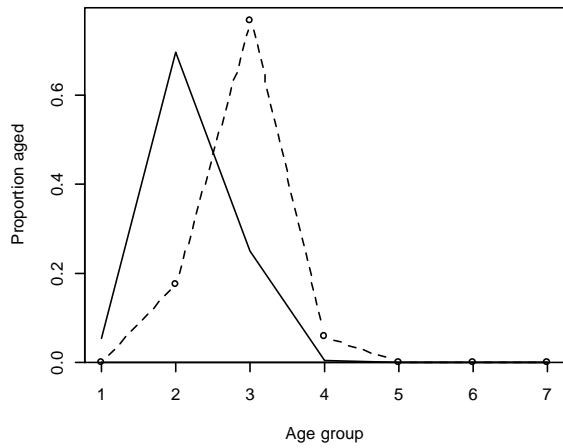


Queensland gillnet, 2009 36-40 cm, ESS = 2.5

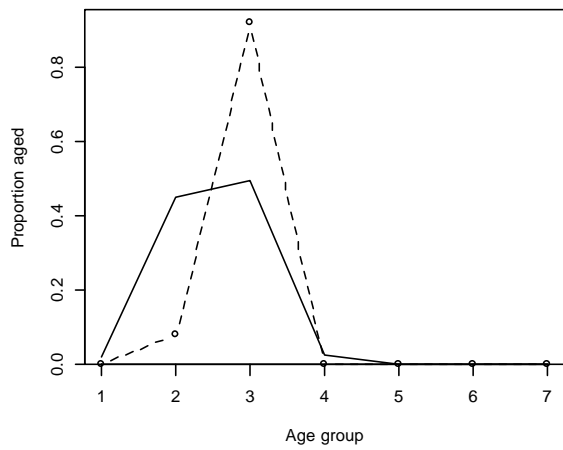




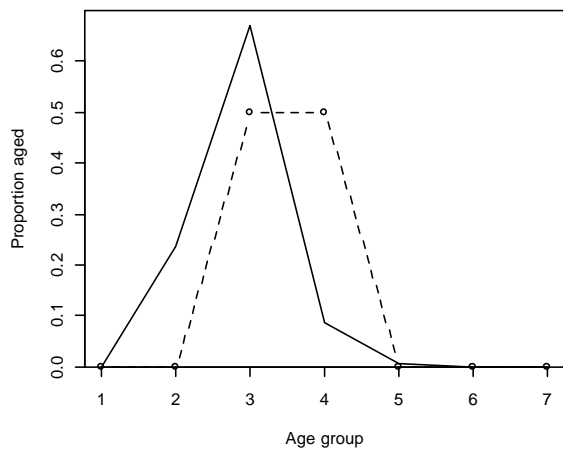
Queensland gillnet, 2010 31-35 cm, ESS = 8.5



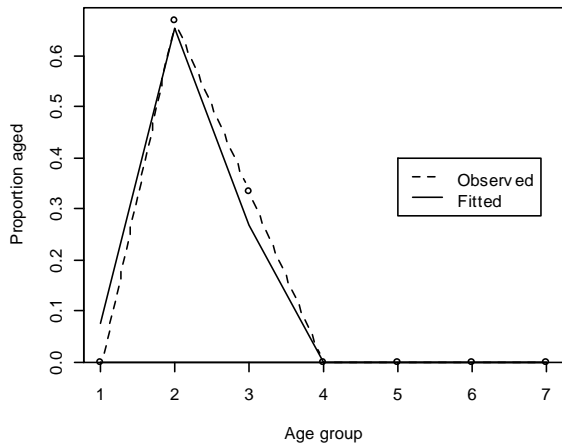
Queensland gillnet, 2010 36-40 cm, ESS = 6



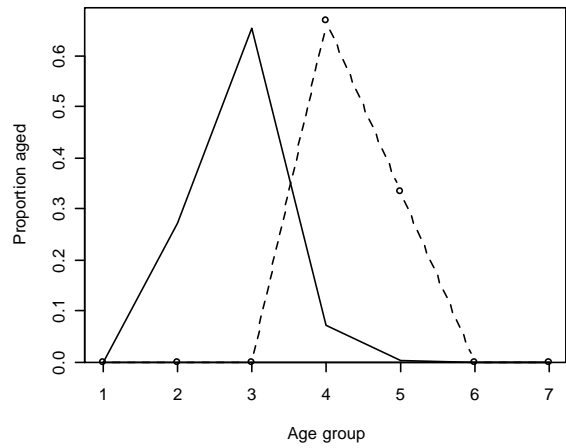
Queensland gillnet, 2010 41-45 cm, ESS = 2.1



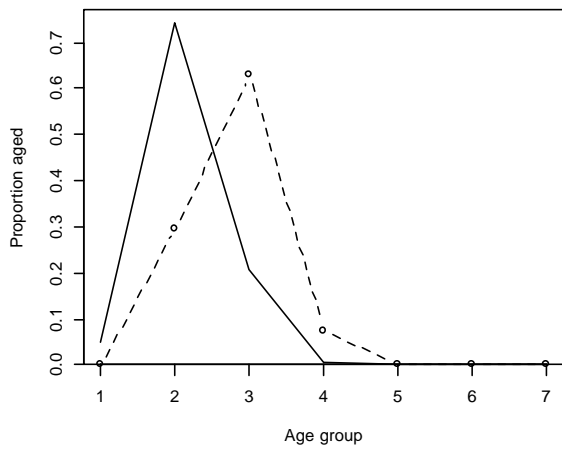
Queensland gillnet, 2011 0-30 cm, ESS = 11.9



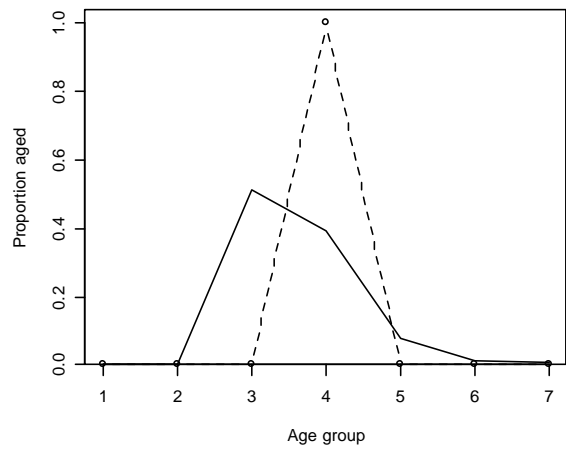
Queensland gillnet, 2011 41-45 cm, ESS = 1.5



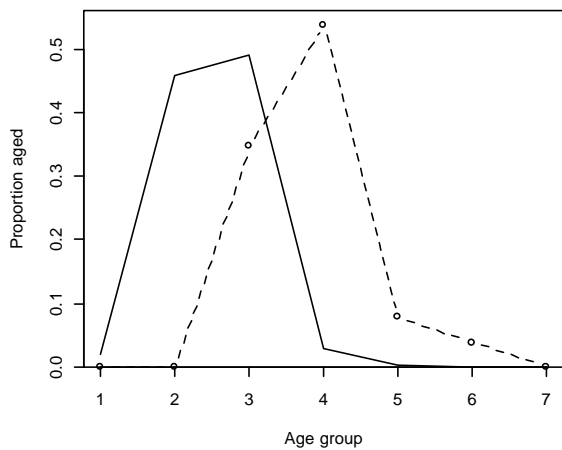
Queensland gillnet, 2011 31-35 cm, ESS = 13.5



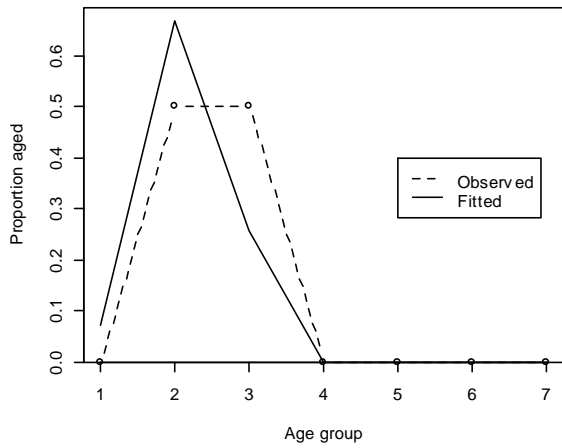
Queensland gillnet, 2011 51-85 cm, ESS = 1



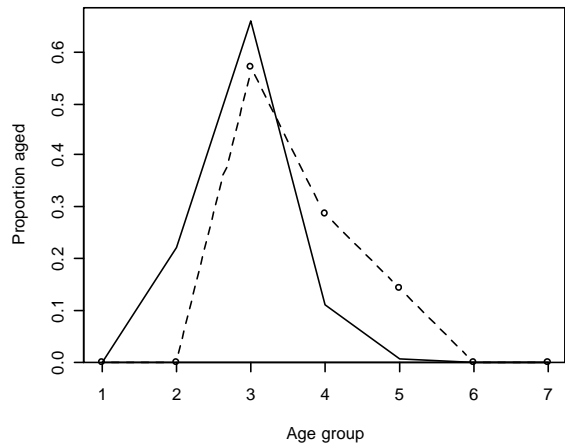
Queensland gillnet, 2011 36-40 cm, ESS = 13



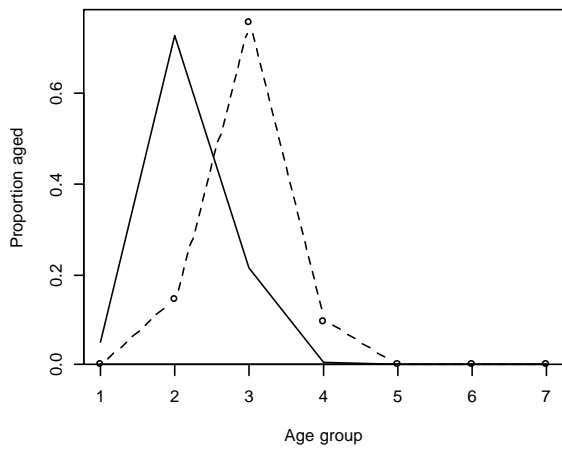
Queensland gillnet, 2012 0-30 cm, ESS = 2



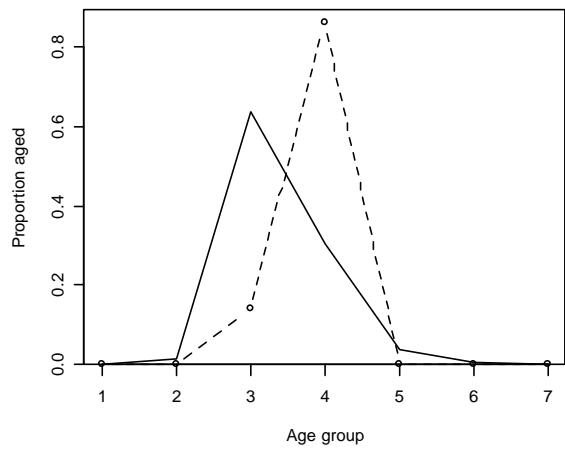
Queensland gillnet, 2012 41-45 cm, ESS = 10.5



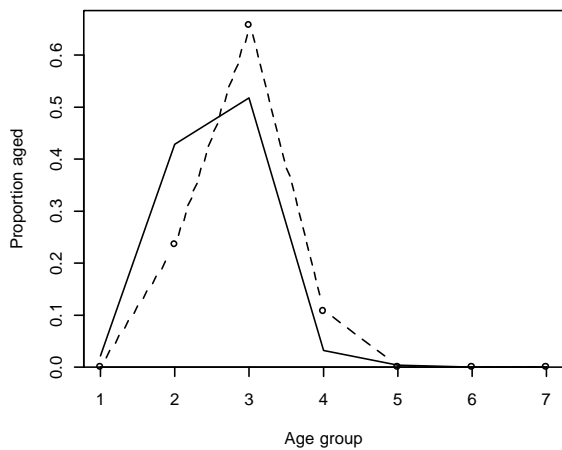
Queensland gillnet, 2012 31-35 cm, ESS = 20.4



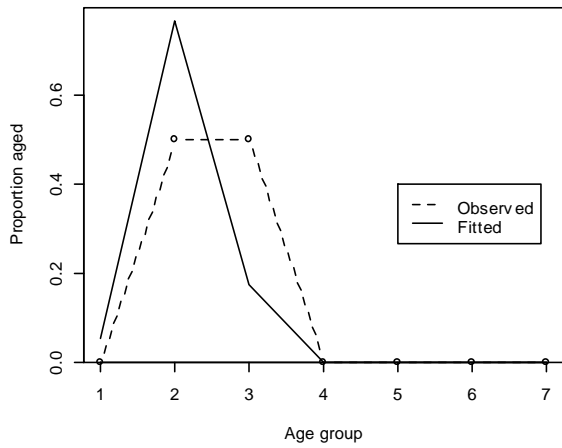
Queensland gillnet, 2012 46-50 cm, ESS = 3.5



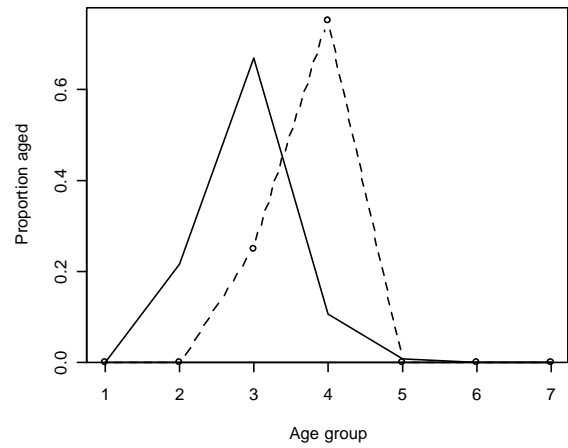
Queensland gillnet, 2012 36-40 cm, ESS = 23.5



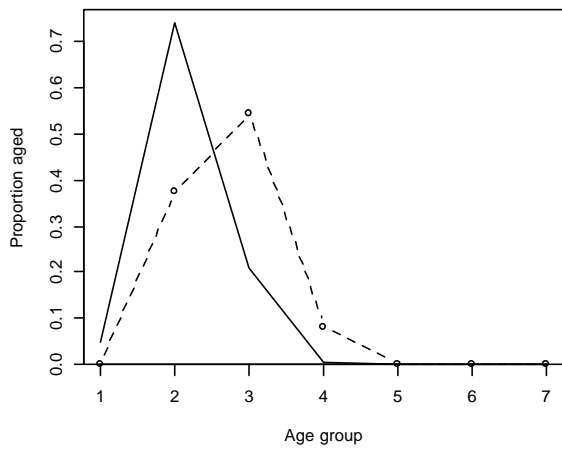
Queensland gillnet, 2013 0-30 cm, ESS = 4



Queensland gillnet, 2013 41-45 cm, ESS = 2



Queensland gillnet, 2013 31-35 cm, ESS = 12



Queensland gillnet, 2013 36-40 cm, ESS = 6.5

