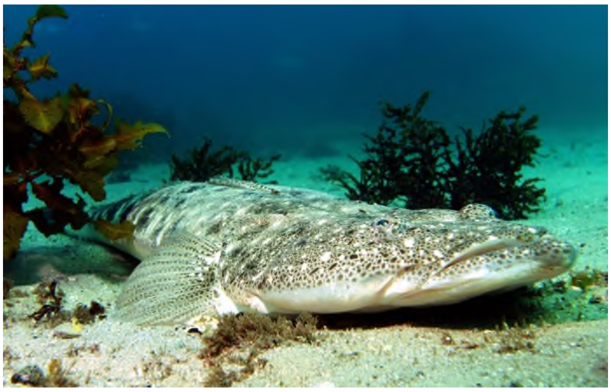


Stock assessments of bream, whiting and flathead *(Acanthopagrus australis, Sillago ciliata* and *Platycephalus fuscus)* in South East Queensland

April 2019

This publication has been compiled by George M. Leigh[1], Wen-Hsi Yang[2], Michael F. O'Neill[3], Jason G. McGilvray[4] and Joanne Wortmann[3] for the Department of Agriculture and Fisheries. It provides assessments of the status of south east Queensland's populations of yellowfin bream, sand whiting and dusky flathead, three of Australia's most commonly fished species.

[1]Agri-Science Queensland, Floor 5, 41 George Street, Brisbane, Queensland 4000, Australia

[2]Centre for Applications in Natural Resource Mathematics (CARM), School of Mathematics and Physics, The University of Queensland, St Lucia, Queensland 4072, Australia

[3]Agri-Science Queensland, Maroochy Research Facility, 47 Mayers Road, Nambour, Queensland 4560, Australia

[4]Fisheries Queensland, Department of Agriculture and Fisheries, Level 1A East, Ecosciences Precinct, 41 Boggo Rd, Dutton Park, Queensland 4102, Australia

Cover photos: Yellowfin bream *Acanthopagrus australis*, sand whiting *Sillago ciliata* and dusky flathead *Platycephalus fuscus* (source: John Turnbull, Creative Commons by Attribution, Non-commercial, Share-alike licence).

Executive summary

Yellowfin bream, sand whiting and dusky flathead are major target species for both commercial and recreational fishers in South East Queensland. Their fishery and regional social and economic importance prompted stock assessments to inform on the sustainability of fishing. The assessments covered both estuarine and ocean-beach waters between Baffle Creek north of Bundaberg and Coolangatta on the Gold Coast.

All three of these species are common in Queensland, New South Wales and Victorian waters and may constitute single genetic stocks across these three jurisdictions. There is, however, only a very small amount of genetic exchange and interbreeding in bream, whiting and flathead between jurisdictions, implying that Queensland populations can be managed separately from the others.

Over the last five years (2013 to 2017), the South East Queensland total harvest for yellowfin bream, sand whiting and dusky flathead averaged 242, 272 and 121 tonnes per year respectively.

The catches split for bream was 54 per cent commercial versus 46 per cent recreational, 77 per cent commercial versus 23 per cent recreational for whiting and 36 per cent commercial versus 64 per cent recreational for flathead.

An annual fish population model structured by age and length for bream and whiting, and age, length and sex for flathead, assessed each of the three species separately. Separate Fraser and Moreton regions north and south of Double Island Point were considered, under a reasonable assumption of low fish exchange between these regions. Modelling the Fraser region separately was difficult for bream and whiting, and was pursued only for flathead.

The stock assessment used commercial, recreational, charter and indigenous catch, and research data. Inputs to the model included fish harvest sizes (1945 to present), standardised catch rates from commercial net logbook data (1988 to present), and fish age–length data collected from the fishery (2007 to present).

Assessment results include target reference points for the *Queensland Government's Sustainable Fisheries Strategy 2017–2027*. These reference points provide options to build the fished biomass or spawning biomass to around 60 per cent of unfished. The 60 per cent target aims to improve the future quality of fishing, both in number of fish caught per day fishing and size of fish caught. A spawning biomass target, instead of fished biomass, is recommended for dusky flathead, as female flathead may mature at a length well above the 40 cm minimum legal size.

All three assessments were challenging due to lack of contrast in the data since the commercial logbook system began in 1988. All three species had been subject to high harvests prior to that year, and commercial catch rates had not varied much since then. In addition, the only available catch rates came from net fishing, which can target whole schools of fish. Hence, net catch rates may be 'hyperstable' and not sensitive to trends in fish population size; this can occur if the average school size of fish remains constant, or if fishing effort information used to calculate catch rates is insufficient.

Bream was estimated to be at 33.8 per cent of unfished fished biomass, which compares to 50.1 per cent required for maximum sustainable yield and 60 per cent for the Sustainable Fisheries Strategy. The equilibrium maximum sustainable yield (MSY) was estimated as 420 t per year (commercial and recreational sectors combined, and Moreton and Fraser regions combined). The model indicated that maintenance of a harvest size of 220 t per year will recover the biomass to 60 per cent of unfished in about 25 years. A lower harvest of 150 t per year would recover to 60 per cent in about 12 years.

Whiting fished biomass in 2017 was estimated as 28.7 per cent of unfished, which is approximately the biomass corresponding to MSY (denoted B_{MSY}). The model's estimate of equilibrium MSY was 452 t per year. Current combined harvest size is approximately equal to the equilibrium harvest at 60 per cent unfished (B_{60}). Responsible rebuilding of the stock from its current level to B_{60} , however, would require the harvest to be reduced, ideally to about 150 t (commercial and recreational sectors combined, and Moreton and Fraser regions combined) to rebuild within about five years. Yearly harvests between 150 and 270 t per year would recover the stock more slowly; the midpoint 210 t per year would reach B_{60} in about seven years.

The status of flathead is more uncertain than bream and whiting, due to lack of contrast in the data. Model estimates of biomass appeared unrealistically high. More precautionary conclusions are based on fixing some model parameters (recruitment compensation ratio and natural mortality rate) to lower levels than estimated in the full model.

Precautionary estimates of dusky flathead status in the Moreton region were spawning biomass in 2017 of 36 to 39 per cent of unfished, approximately equal to or slightly below B_{MSY} , and MSY of 104 t per year to 112 t per year, approximately equal to current harvests. Unlike bream and whiting, the harvest of flathead in the Moreton region has not fallen substantially from its peak levels over the period 1990–2010. In particular, recreational fishing effort on flathead in the Moreton region is still very high. Recovery of the spawning stock to the 60 per cent level in the Moreton region would require the harvest to be reduced, ideally to 63 t per year (commercial and recreational sectors combined, Moreton region only) which would recover to B_{60} within eight years. After recovery, the equilibrium harvest for 60 per cent spawning biomass is estimated at 83 to 96 t per year. As for whiting, an intermediate harvest level between 63 and 83 t per year would recover the stock more slowly. The midpoint 73 t per year would reach B_{60} within 16 years.

The combined harvest of flathead in the Moreton region was not reduced by the increase in minimum legal size from 30 cm to 40 cm in December 2002 or the imposition of a maximum legal size (70 cm in December 2002, increased to 75 cm in May 2009). Although these measures undoubtedly assist flathead to reach spawning size and protect large individual spawners, measures that directly affect harvest size are required to recover the stock to the 60 per cent spawning biomass target.

In the Fraser region, estimated fishing pressure on flathead was lower than in the Moreton region, and 2017 estimated spawning biomass was 70 per cent of unfished. Peak harvests occurred in the 1950s in this region, with an average of about 40 t over this decade (predominantly commercial). Harvests in recent years (commercial and recreational combined) have been about 22 t per year. Estimated equilibrium MSY was at 35 t per year, although this quantity was difficult to estimate due to lack of contrast in the data. The equilibrium harvest for 60 per cent spawning biomass was 33 t per year and again was difficult to estimate.

Although the above results for flathead in the Moreton region are already precautionary, additional caution may be needed in view of fishing-club catch rates which date back to the 1950s. Flathead catch rates by fishing-club members fell greatly relative to other species in the 1950s, 1960s and 1970s, indicating that flathead were already heavily fished by the time the commercial logbook database (and model-input catch rates) began in 1988. Fishing-club catch rates were certainly affected by changes in clubs' local regulations (e.g., progressively setting a minimum size greater than the minimum legal size) and competition scoring systems, and probably also by localised depletion in locations commonly fished by clubs, but it is doubtful that these factors can fully explain the falls in club catch rates prior to 2000.

Summary table: Bream and whiting estimates are for combined Moreton and Fraser regions. Flathead estimates in this table are precautionary and for Moreton region only. Current harvest is the average over the period 2013–2017.

	Yellowfin bream	**Sand whiting**	**Dusky flathead**
MSY biomass ⁄ unfished	50.1% exploitable	33.5% exploitable	34.6% spawning
Current biomass ⁄ unfished	33.8% exploitable	28.7% exploitable	35.8% spawning
MSY (tonnes ⁄ year)	420	452	104
Current harvest (t per year)	242	272	99
Harvest proportions	54% comm., 46% rec.	77% comm., 23% rec.	64% rec., 36% comm.
Equilibrium B_{60} harvest	380	300	83
Harvest to build to B_{60}	220	150	63
Time to build to B_{60}	25 yr	5 yr	8 yr

Flathead in Fraser region:

	Dusky flathead (Fraser)
MSY biomass ⁄ unfished	50.0% spawning
Current biomass ⁄ unfished	69.5% spawning
MSY (tonnes ⁄ year)	35
Current harvest (t per year)	22
Harvest proportions	63% rec., 37% comm.
Equilibrium B_{60} harvest	33
Harvest to build to B_{60}	NA
Time to build to B_{60}	NA

Contents

Tables

Figures

Acknowledgements

Many people have contributed to the data and background knowledge used in this report. We are grateful to a multitude of past researchers and to fishers who have contributed their specialised knowledge.

The following members of the assessment's Project Team helped with the assessment process and contributed wide-ranging knowledge and experience (in alphabetical order):

- Tony Ham (Fisheries Queensland fishery management)
- Malcolm Keag (Fisheries Queensland)
- Ashley Lawson (Fisheries Queensland data specialist)
- Jason McGilvray (Fisheries Queensland Fishery Monitoring team)
- Dr Genevieve Phillips (Fisheries Queensland data coordinator)
- Anthony Roelofs (Fisheries Queensland)
- Prasadini Salgado (Fisheries Queensland data specialist)
- Dr James Webley (Fisheries Queensland recreational fishing specialist)

The role of the Project Team was collaborative to share interpretation and decision making on information and results. We are especially grateful to Ashley Lawson from the data team for providing an updated version of the fishing-club database at short notice.

We would also like to thank Eddie Jebreen (Fisheries Queensland Director), Claire Andersen (Fisheries Queensland Executive Director), Paul Palmer (group leader, Fisheries and Aquaculture, Agri-Science Queensland) and the Project Team for reviewing and providing comment on parts of the draft report.

The assessment was funded by the Queensland Department of Agriculture and Fisheries.

1. Introduction

1.1 Background

Bream, whiting and flathead are highly desired fish for both recreational and commercial fishers in South East Queensland, the most popular species being yellowfin bream *Acanthopagrus australis*, sand whiting *Sillago ciliata* and dusky flathead *Platycephalus fuscus* (Figures 1.1–1.3).

Recreational fishing of bream, whiting and flathead is by hook and line, both from boats and from the shore. Commercial fishing is predominantly by nets, mainly gillnets which mesh fish around the body and tunnel nets which are set to capture fish as the tide recedes from suitable beach, sandbank and mud-bank locations. Small harvests are also taken by beach seine netting which hauls schools of fish from both estuarine and ocean beach gutters and banks.

In eastern Australia, aboriginal artisanal fishing for bream, whiting and flathead using spears, nets and hooks dates back many thousands of years (Williams, 1982, p. 14; Wallace-Carter, 1987, pp. 2–4; Pepperell, 2009). All three species were popularly fished by net and hook-and-line from the beginning of white settlement. Each species probably produced an annual harvest of hundreds of tonnes per year in New South Wales (NSW) from at least the late 19th century onwards (Stead, 1908; Pepperell, 2009). The three species were popular with Queensland commercial fishers from at least the early 20th century (Darcey, 1990, pp. 12–39, 91–112, 154–165). Official records related to harvest size begin from about the 1940s in both Queensland and NSW.

Figure 1.1: Yellowfin bream, Acanthopagrus australis. Source: John Turnbull, Creative Commons by Attribution, Non-commercial, Share-alike licence.

Figure 1.2: Sand whiting, Sillago ciliata. Source: Richard Ling, Creative Commons by Attribution, Non-commercial, No-derivatives licence.

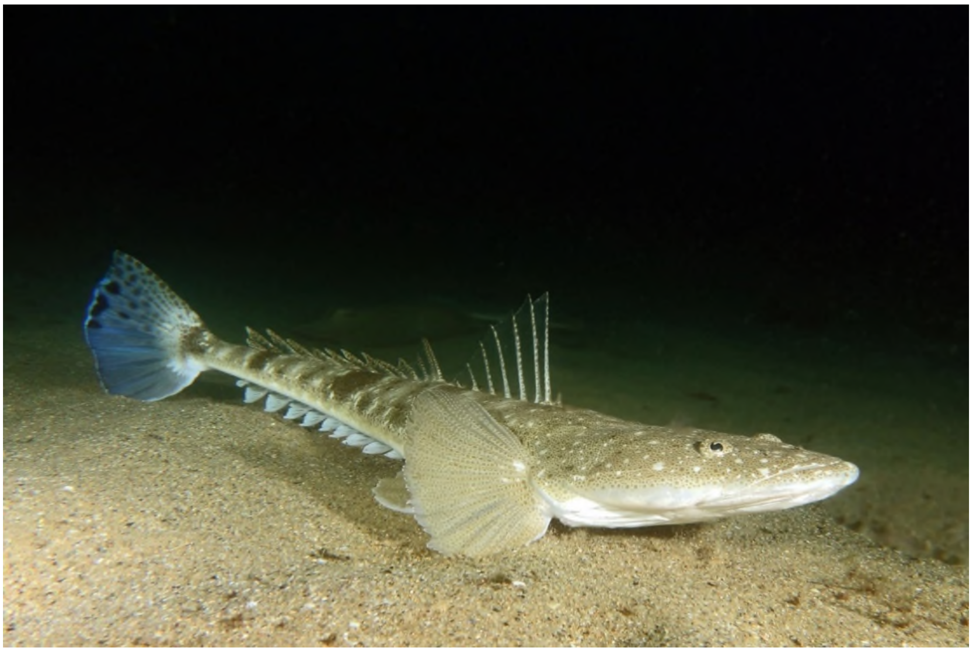


Figure 1.3: Dusky flathead, Platycephalus fuscus. Source: John Turnbull, Creative Commons by Attribution, Non-commercial, Share-alike licence.

The recreational line fishery benefited from technological developments generally introduced from the 1950s onwards. These include improved access to fishing locations and improved day–night fishing methods through nylon fishing lines which are less visible to fish, waders which allow shore fishers to venture into deeper water, traces and baits (Claydon, 1996, p. 11–15). In more recent years, many recreational fishers have acquired devices such as GPS locators and plotters to find boat-fishing locations more quickly. For South East Queensland beach-based fishing, Leigh et al. (2017) inferred a technological or 'fishing power' increase for recreational fishing of 4.6 per cent per year from 1954 (the first year for which fishing-club data were available) to 1974, 2.3 per cent per year from 1974 to 1997 and no further increase after 1997.

This stock assessments of the three important species were motivated in part by the potential fishing pressure on them arising from the presence of major human population centres in South East Queensland. The State's largest city and capital, Brisbane, is located very close to the fishing grounds, as are the densely populated regions of the Gold Coast (south) and Sunshine Coast (north), and the cities of Hervey Bay and Bundaberg further north (see Figure 1.4).

This stock assessment covers only South East Queensland, specifically from Baffle Creek (24.5 °S) to the NSW border (about 28.2 °S). It is the first full stock assessment that has been carried out on any of these species in Queensland.

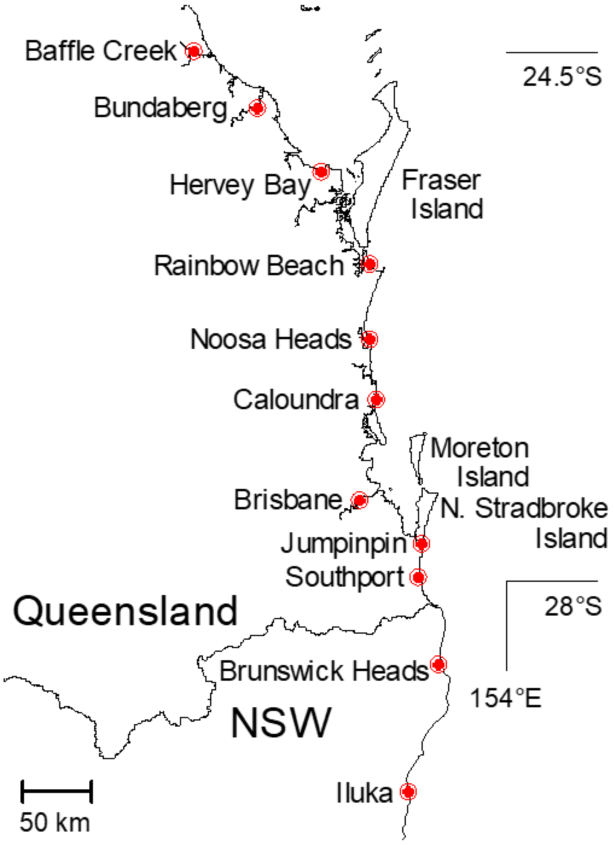


Figure 1.4: Map of the South East Queensland fishery for bream, whiting and flathead, showing some popular fishing locations, major towns and the state border with New South Wales (NSW).

1.2 Biology of bream, whiting and flathead

1.2.1 Age and length measurement

Yellowfin bream, sand whiting and dusky flathead can all be aged reliably by counting annual rings in their sagittal otoliths (ear bones). Scientific validation of ageing from otolith ring counts has been undertaken by Gray et al. (2000) for yellowfin bream and sand whiting using tag recaptures with chemical staining of the otoliths, Ochwada-Doyle et al. (2014) for sand whiting using the same technique, and Gray et al. (2002) for dusky flathead using marginal increment analysis. All of these studies helped to establish that rings are formed annually but did not establish the age at which the first ring is laid down. More thorough validation using daily rings on otoliths has been undertaken by Krusic-Golub et al. (2012) for deep-water flathead *Neoplatycephalus conatus* which comes from the same family as dusky flathead (Platycephalidae).

The ageing studies discussed below, other than Pollock (1982b, 1985), use the otolith annual-ring technique. For yellowfin bream, Pollock (1982b, 1985) used length-frequency modes to distinguish age classes up to age 4+ yr (age group 5). He combined all age classes from 5+ yr upwards (age group ≥ 6).

Fishery management is usually based on the total length (TL) of a fish to the tip of its tail whereas scientific measurement uses fork length (FL, measured only to the fork of the tail). This assessment uses published formulae to convert between the two. Unlike bream and whiting, dusky flathead has no fork in its tail (see Figure 1.3): for it, total length and fork length are the same and no conversion is necessary.

1.2.2 Descriptions of biology

All three of these species are common in Queensland, New South Wales and Victorian waters and may constitute single genetic stocks across these three jurisdictions. Available data from tagging experiments indicates that there is only a very small amount of genetic exchange and interbreeding in bream, whiting and flathead between jurisdictions, implying that Queensland populations can be managed separately from the others.

Yellowfin bream *Acanthopagrus australis* inhabits shallow coastal and estuarine waters and occupies a wide range of habitat types (Kerby and Brown, 1994, p. 1; Curley et al., 2013). It is a generalist, predominantly benthic feeder and often forms large schools (Curley et al., 2013) (see Figure 1.6).

Bream is a protandrous hermaphrodite in which fish are male when they mature and can later change sex to female, although some may bypass the male stage and become females immediately they mature (Pollock, 1985). Bream can spawn throughout the year in the southern states of Australia but in South East Queensland there is a pronounced spawning peak in the winter (Pollock, 1982b).

Individual bream migrate over distances of up to tens of kilometres but generally do not leave their ‘home’ estuaries (Thomson, 1959; Pollock, 1982a).

Pollock (1985) found that few yellowfin bream were mature at age 0+ (age group 1), about 65 per cent were mature at age 1+ (age group 2), split about 60 per cent male to five per cent female, and nearly all were mature by age 2+ (age group 3). The sex ratio steadily declined to a split of about 25 per cent male and 75 per cent female for bream aged 5+ or more (age group ≥ 6).

Gray et al. (2000, p. 65) found that yellowfin bream ranged in size up to about 40 cm FL but few were greater than 30 cm FL. The size at recruitment to the fishery in NSW was about 22 cm FL. The corresponding ages at recruitment varied from 2+ yr (age group 3) to 10+ yr (age group 11). The oldest fish that they aged was 22+ yr (age group 23).

The oldest bream aged by the Fisheries Queensland Monitoring team was 20+ yr (age group 21). Only ten fish were older than 15+ yr (age group > 16) and 20 were older than 14+ yr (age group > 15). Fork lengths ranged from 15 cm to 44 cm. The overall age–length structure is plotted in Figure 1.5.

The following relationships between length and weight of yellowfin bream come from regressions fitted by O'Neill (2000), where lengths are measured in cm and weight (W) in kg:

$$W = 2.77 \times 10^{-5}\ \mathrm{TL}^{2.8385}$$

$$\mathrm{TL} = 0.4201 + 1.10874\ \mathrm{FL}.$$

We used these relationships to fit a linear regression to log W to convert the length–weight relationship to fork length (L), concentrating on the length range 20 cm to 30 cm FL:

$$W = 4.456 \times 10^{-5}\ L^{2.7952}.$$

The population dynamic model primarily used length but required weight to take account of commercial fishery catches which are usually measured in weight.

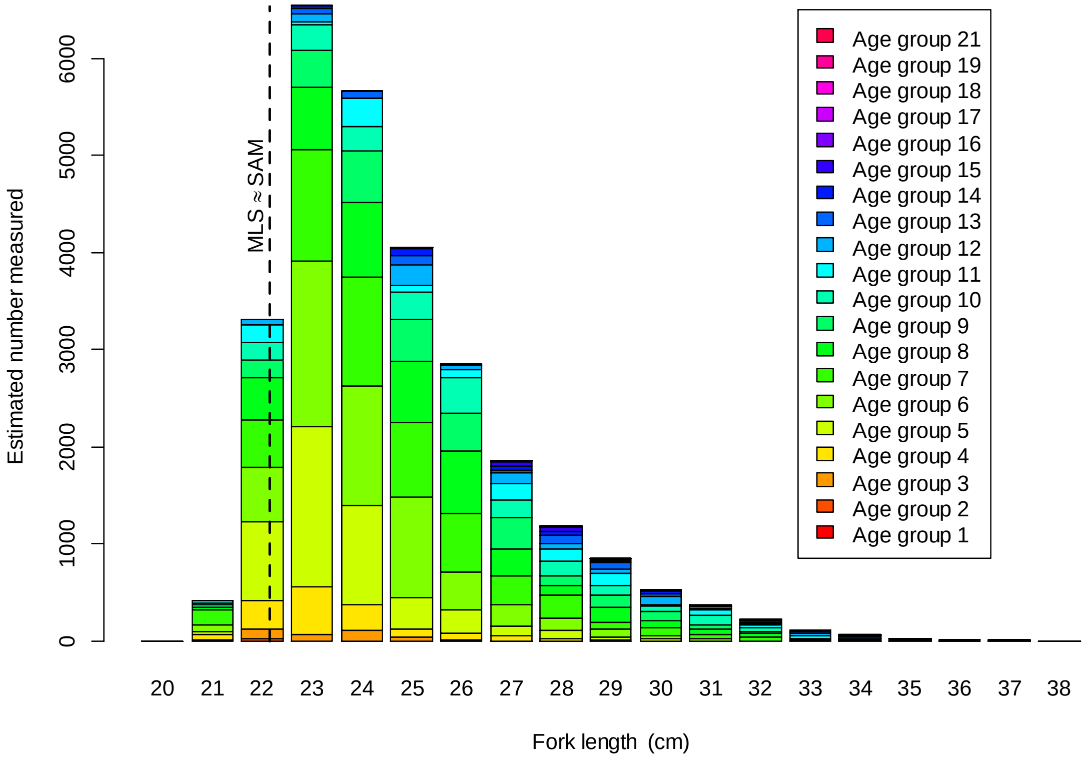


Figure 1.5: Age–length structure of bream from Fisheries Queensland monitoring 2010–2016, length classes with any fish aged. MLS = minimum legal size (2010 to present); SAM = size at maturity.

Figure 1.6: School of yellowfin bream Acanthopagrus australis. Source: John Turnbull, Creative Commons by Attribution, Non-commercial, Share-alike licence.

Sand whiting *Sillago ciliata* are found in shallow inshore waters, mostly 0–5 m deep, prefers sandy substrates and often forms large schools (Kerby and Brown, 1994, p.9) (see Figure 1.8). It is a benthic feeder, consuming mainly polychaete worms and crustaceans (Burchmore et al., 1988). It is caught by fishers all year round. The Queensland commercial logbook database shows that the commercial catch peaks in the month of August.

The majority of literature states that sand whiting has an extended spawning season over the summer, from about September to March in Queensland (Morton, 1985a; Ochwada-Doyle et al., 2014) and possibly a month or two later in NSW (Burchmore et al., 1988). Cleland (1947), on the other hand, estimated that the mid-spawning time in Queensland is in September but admitted that very few running ripe individuals were available to study.

Morton (1985b) found that sand whiting move only locally (e.g., less than 15 km), although the times at liberty in that experiment were short (most less than two months and 50 per cent two weeks or less). There appears to be a paucity of data on migration of sand whiting.

For sand whiting in NSW, Gray et al. (2000, p. 72–86) state a length range of 24–42 cm FL for their sampled fish, with most retained fish in haul nets being 25–30 cm FL and in gillnets 30–35 cm FL. Females tend to grow faster and attain a higher maximum length; Burchmore et al. (1988) found a maximum of 40 cm FL for females and 31 cm FL for males. The oldest fish aged by Gray et al. (2000) was 16+ years old (age group 17). They found that the relationship between length and age was weak. The maximum age recorded by Ochwada-Doyle et al. (2014) (judging from their Figure 2) was 10+ yr (age group 11) for both females and males. The average length at age 0+ (judging from their Figure 7) was about 10 cm FL and at age 1+ about 18 cm FL. Stocks et al. (2011) recorded one fish of age 12+ (age group 13) but all other fish they sampled were 10+ (age group 11) or less.

Burchmore et al. (1988) found that sand whiting matures at about 24 cm fork length. Ochwada-Doyle et al. (2014) found that females mature between 15 cm and 25 cm FL and males between 10 cm and 21 cm FL, and estimated the age and fork length at 50 per cent maturity as 1.63+ yr (average age group 2.63) and 19.13 cm for females, and 1.10+ yr (average age group 2.10) and 17.07 cm for males. They found that females reached a mean size of 17.25 cm FL at 1 yr, 28.36 cm at 3 yr and 31.81 cm at 6 yr. For males the figures were 15.75 cm at 1 yr, 24.99 cm at 3 yr and 28.83 cm FL at 6 yr.

The oldest fish aged by the Fisheries Queensland monitoring team was 10+ yr (age group 11). Fork lengths ranged from 14 cm to 46 cm. Because the sampling in this program was fishery-dependent, it did not include whiting as small as those sampled by Ochwada-Doyle et al. (2014). Of the fish whose lengths were measured, 77 per cent had unknown sex. Of the fish whose sex was known, the largest male was 37 cm and the largest female was 41 cm fork length. Modal lengths were 24 cm for both sexes. Average lengths were 24.4 cm for males and 25.8 cm for females. The overall age–length structure is plotted in Figure 1.7.

Cleland (1947, p. 219) provides the following length–weight relationship for sand whiting; we have converted it so that L is fork length in cm and W is weight in kg:

$$W = 1.004 \times 10^{-5} L^3 .$$

Cleland states that the length–weight relationships for Queensland and NSW “approached” a significant difference but fewer fish were measured in Queensland; therefore we have used the estimate for NSW which appears to be what Cleland recommends.

We fitted the following equation by linear regression to data from Cleland (1947, p. 215) to convert FL to TL (both measured in cm) for sand whiting:

$$\mathrm{TL} = 1.0661 \times \mathrm{FL} - 0.016.$$

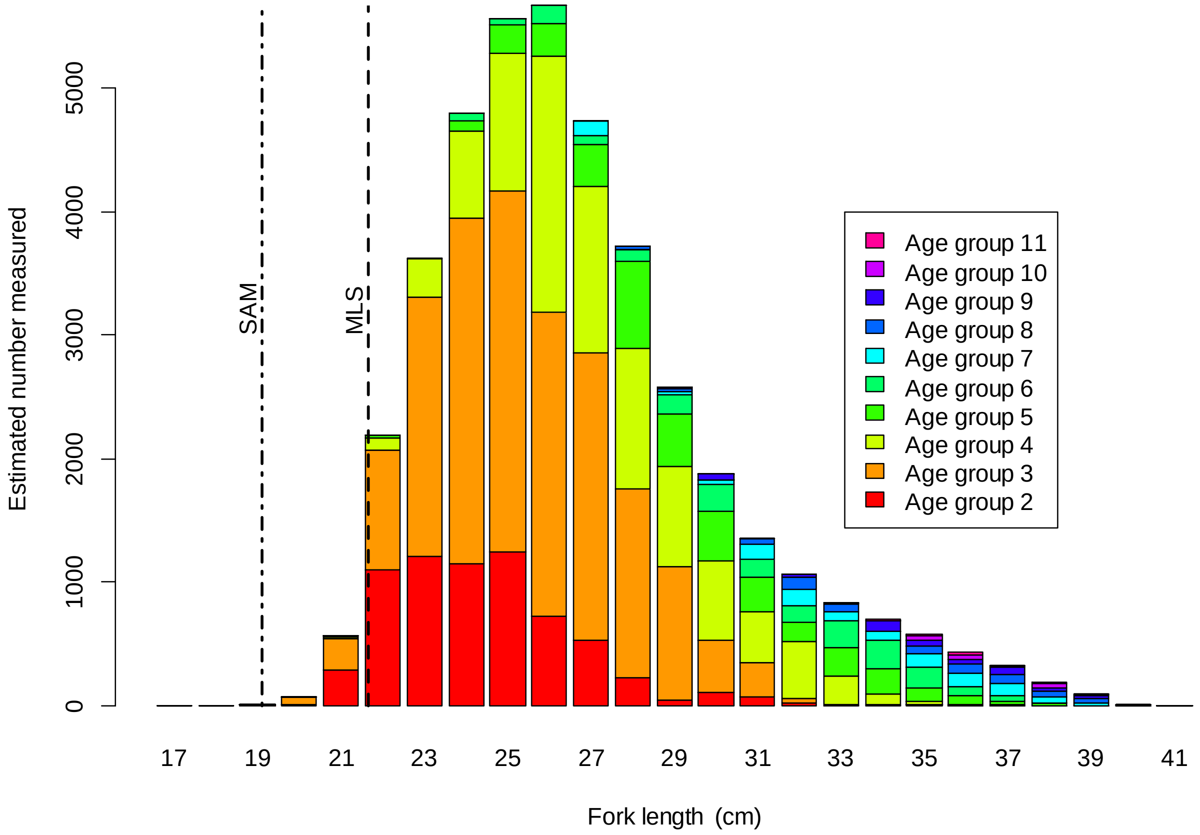


Figure 1.7: Age–length structure of whiting from Fisheries Queensland monitoring 2007–2016, length classes with any fish aged. MLS = minimum legal size (1976 to present); SAM = size at maturity.

Figure 1.8: Part of a school of sand whiting Sillago ciliata. Source: John Turnbull, Creative Commons by Attribution, Non-commercial, Share-alike licence.

Flatheads (family Platycephalidae) are bottom-dwellers that often partially bury themselves in the substrate and feed mainly on crabs and prawns with a lesser quantity of fish (Randall et al., 1997, p. 86) (see Figure 1.10). Dusky flathead *Platycephalus fuscus* is found in shallow bays and inlets up to 10 m deep with particulate substrates (mud, silt, gravel, sand, seagrass) (Kerby and Brown, 1994, p. 19). Queensland commercial fishery logbook records show that dusky flathead are caught all year round in Queensland but with a commercial peak in the winter months.

Biology of dusky flathead in NSW has been studied by Gray and Barnes (2015). They state that it is almost certainly a gonochore (retains the same sex for life and does not change sex). In this assessment we assume that it is a gonochore. We know of no observation of the presence of both male and female reproductive tissue on one fish, which would be expected to occur occasionally if the species can change sex. Gray and Barnes found evidence of spawning of dusky flathead from September through to May, with a peak from December to March.

Dusky flathead have been observed to move over distances up to 280 km (Gray et al., 2000, p. 109; Gray and Barnes, 2015). Most tagged animals, however, stay in the same river system.

Female dusky flathead grow much larger than males (see Figure 1.11). Gray and Barnes (2015) observed length ranges of generally about 0–20 cm TL for juveniles, 20–50 cm for males and 20–70 cm for females. The largest female fish that they measured was 98.5 cm TL (aged 12+ yr, age group 13) and the largest male was 61.5 cm TL (11+ yr, age group 12). The oldest female fish that they aged was 16+ yr (age group 17, 88.5 cm TL); the oldest male was the largest one. They aged only five males older than 4+ yr (age group > 5) of 1421 males in total, only nine females older than 9+ yr (age group > 10) and one female older than 12+ yr (age group > 13) of 4333 females in total.

Gray and Barnes (2015) found the length at 50 per cent maturity (which we denote L_{50}) to be 31.72 ± 1.08 cm TL for males and 56.75 ± 0.60 cm TL for females, and we used their estimates in the assessment. The corresponding ages were 1.22 ± 0.44 yr (average age group 2.22) for males and

4.55 ± 0.13 yr (average age group 5.55) for females. Hicks et al. (2015) estimated the length at 50 per cent maturity of female dusky flathead in Victoria to be 32.8 cm ± 2.4 cm standard error. This is very different from the NSW study of Gray and Barnes (2015). Gray and Barnes state that their estimate is consistent with an earlier one for Queensland by Russell (1988). An unpublished and unavailable study by the Queensland Department of Primary Industries from the early 1990s found that the age at maturity of female flathead was about 45 cm (Kerby and Brown, 1994, p. 21).

The oldest fish aged by the Fisheries Queensland monitoring team was 10+ yr (age group 11) and was a female. The oldest male was 6+ yr (age group 7). Only six fish in total were older than 7+ yr (age group > 8). Only five males were older than 4+ yr (age group > 5). Lengths ranged from 18 cm to 86 cm. Of the fish sampled in a representative manner whose lengths were measured, 87.0 per cent had unknown sex, 11.6 per cent were female and only 1.4 per cent (350 fish) were male. The largest male was 56 cm TL. Modal lengths were 42 cm for males and 44 cm for females. The fish that were aged included some non-representative samples; e.g., samples that may have been kept by fishers for some time before being collected by the monitoring team. The ageing samples included 458 males, 2498 females and 70 fish of unknown sex. The largest male in this data set was 62 cm TL. The overall age–length structure is plotted in Figure 1.9.

We note that many males do not reach the minimum legal size of 40 cm, so the sampling is skewed towards females. Also a maximum legal size of 75 cm currently applies in Queensland (see Table 1.1). Females that grow larger than this size are not allowed to be retained by fishers and so will generally not be measured by the monitoring team. Gray and Barnes (2015) conducted scientific sampling over the whole length range of dusky flathead. Queensland monitoring is fishery-dependent and restricted to legal-sized fish. It lacks some of the old fish that Gray and Barnes were able to sample in NSW (known from seizures of oversize flathead in Queensland, and data provided by catch-and-release recreational fishers).

Hicks et al. (2015) studied fecundity of female dusky flathead and found no statistically significant deviation from the hypotheses that egg production is proportional to body mass and that egg quality does not depend on body size.

Length–weight relationships come from Gray and Barnes (2015). For male dusky flathead

$$W = 2.76 \times 10^{-6} L^{3.223}$$

and for females

$$W = 2.09 \times 10^{-6} L^{3.282}$$

where total length L is measured in cm and weight W in kg.

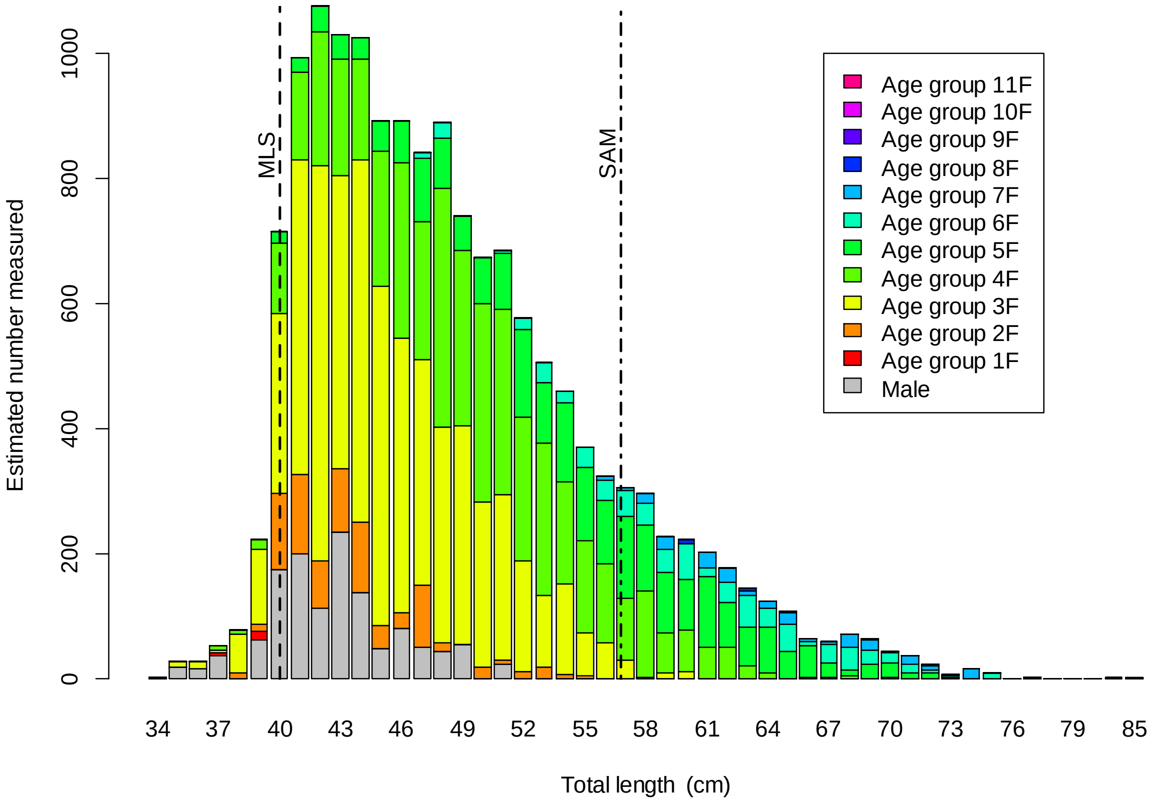


Figure 1.9: Age–length structure of flathead from Fisheries Queensland monitoring 2007–2016, length classes with any fish aged. MLS = minimum legal size (2003 to present); SAM = size at maturity.

Figure 1.10: Dusky flathead Platycephalus fuscus camouflaged against the substrate. Source: Richard Ling, Creative Commons by Attribution, Non-commercial, No-derivatives licence.

Figure 1.11: Presumed male (in front) and female (behind) dusky flathead Platycephalus fuscus, showing the difference in size. Source: John Turnbull, Creative Commons by Attribution, Non-commercial, Share-alike licence.

1.2.3 Closely related species

All three species assessed here have close relatives, and fishery data often do not distinguish the related species from the primary species. The assessments focus on the primary species although to a small extent they relate to species complexes.

The biggest related-species problem to these assessments is posed by trumpeter whiting (also known as winter whiting or diver whiting) *Sillago maculata* (Figure 1.15). By recreational fishers, trumpeter whiting appear to be caught in similar numbers to sand whiting although trumpeter whiting are smaller in size. We expect this to be less of a problem for the commercial fishery, as market demand favours bigger fish.

In South East Queensland, with the exception of trumpeter whiting, the primary species for assessment are much more common than the related species. For example, Kerby and Brown (1994, p. 22) noted that dusky flathead made up about 94 per cent of the commercial catch. This may not be true in northern Queensland or NSW: if a future stock assessment wishes to cover those areas it might have to account for other species. Pikey bream, the major species that can be confused with yellowfin bream, generally inhabits waters north of Baffle Creek, outside the spatial range of the stock assessment.

The following species commonly confused with the species assessed here are encountered in South East Queensland. Additional species to those listed below occur in NSW.

- Bream:
  - Pikey bream *Acanthopagrus pacificus* (formerly classified as *Acanthopagrus berda*) (Figure 1.12)
  - Tarwhine *Rhabdosargus sarba* (Figure 1.13).
  - Silver javelin *Pomadasys argenteus* (Figure 1.14).

We note that luderick, which is also known as black bream, *Girella tricuspidata* is generally not reported as bream by fishers.

- Whiting:
  - Trumpeter whiting *Sillago maculata* (Figure 1.15)
  - Goldenline whiting *Sillago analis* (Figure 1.16)
  - Northern whiting *Sillago sihama* (Figure 1.17)
  - Stout whiting *Sillago robusta* (Figure 1.18)
- Flathead:
  - Northern sand flathead *Platycephalus endrachtensis* (previously classified as *Platycephalus arenarius*) (see Imamura, 2008)
  - Yellowtail flathead *Platycephalus westraliae* (previously classified as *Platycephalus endrachtensis*) (see Imamura, 2008) (Figure 1.19)
  - Australian bartail flathead *Platycephalus australis* (previously classified as *Platycephalus indicus*) (see Imamura, 2015)

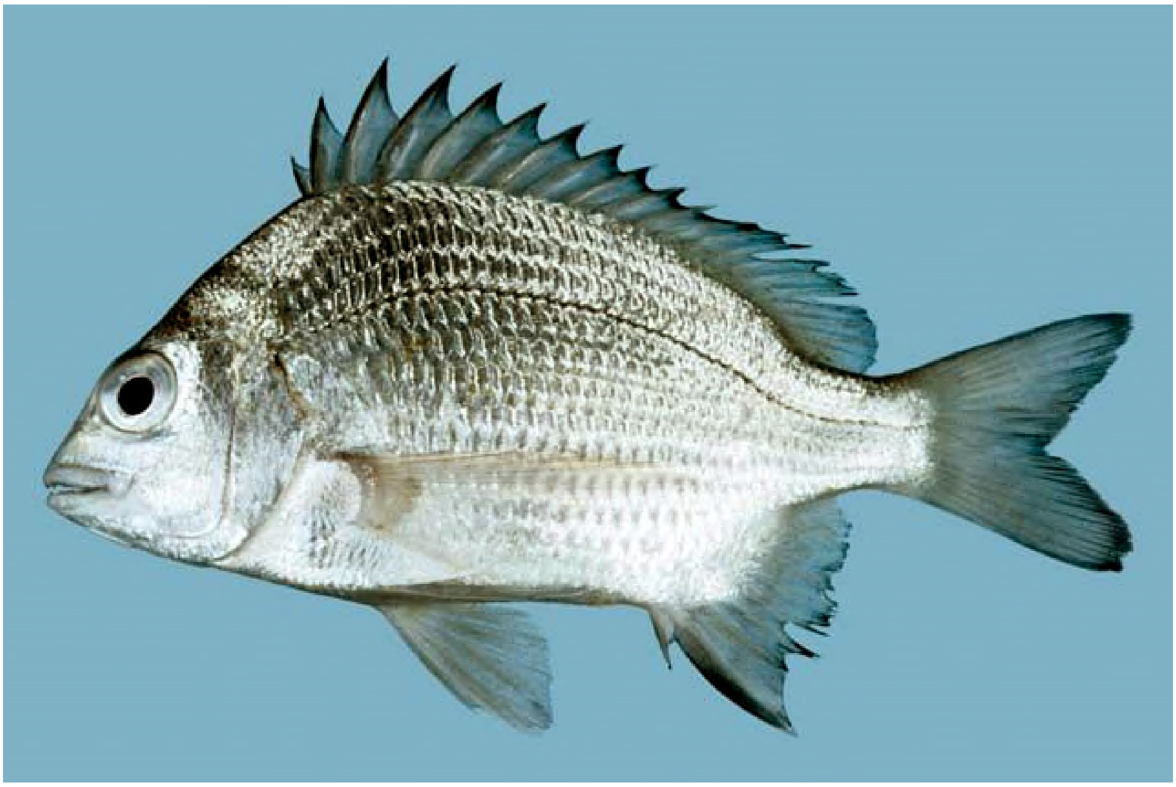


Figure 1.12: Pikey bream, Acanthopagrus pacificus. Source: Rick Winterbottom, Creative Commons by Attribution, Non-commercial, Share-alike licence.

Figure 1.13: Tarwhine, Rhabdosargus sarba. Source: John Turnbull, Creative Commons by Attribution, Non-commercial, Share-alike licence.

Figure 1.14: Silver javelin, Pomadasys argenteus. Source: Barry Pollock, Queensland recreational fisher.

Figure 1.15: Trumpeter whiting, Sillago maculata. Source: DAF archive.

Figure 1.16: Goldenline whiting, Sillago analis. Source: Lek via BowerBird.org.au (cropped), Creative Commons by Attribution, Non-*commercial*, Share-alike licence.

Figure 1.17: Northern whiting, Sillago sihama. Source: Jeffrey T. Williams, US National Museum of Natural History (cropped), Creative Commons by Attribution, Non-commercial, Share-alike licence.

Figure 1.18: Stout whiting, Sillago robusta. Source: DAF archive.

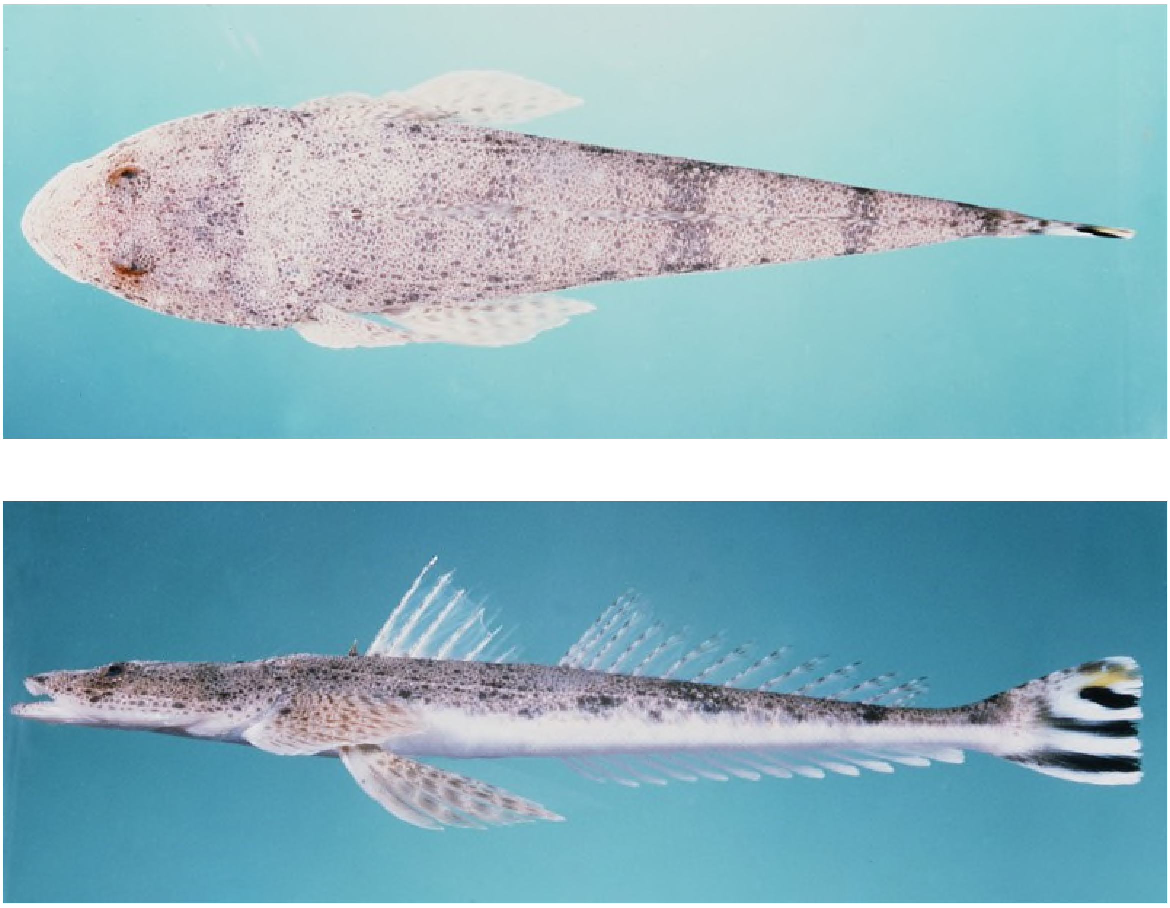


Figure 1.19: Flathead believed to be yellowtail flathead Platycephalus westraliae from its small isolated anterior dorsal spine and single yellow blotch on the upper lobe of the tail, although identified as Platycephalus indicus by Fishbase. Source: John E. Randall via Fishbase.org, from Northern Territory, Australia; Creative Commons by Attribution, Non-commercial licence.

1.2.4 Discard mortality

When line-caught fish are returned to the sea by fishers, not all of them survive. We assume discard mortality rates of 0.30 for bream and whiting, and 0.20 for flathead which are larger and therefore may be less likely to die after being discarded. These figures were used for all fishery sectors, including net fishing. The feature of allowing discard mortality to depend on fishing method has not yet been added to the population model, but would be straightforward to do.

1.3 Management of the fishery

Various management measures have been applied to the bream, whiting and flathead fisheries in both Queensland and NSW since the late 19th century. Key management measures in Queensland and NSW are summarised in Table 1.1. The NSW summary does not relate to this assessment but is included for comparison and future assessments of these species.

Table 1.1: Management measures applied to bream, whiting and flathead in Queensland and NSW waters. Source: Queensland (Qld) and NSW state government legislation. *This table includes only fisheries legislation that is available online: Qld Acts from 1914, NSW Acts from 1935, NSW Regulations from 1990, Qld Regulations from 1991.*

Date	State	Measure
1877–1974	Qld	Numerous measures relating to fishing gear and practices; e.g., mesh size, net length, allowed species, closed seasons, powers of inspectors
1902–1994	NSW	Numerous measures relating to fishing gear and practices; e.g., mesh size, net length, closed seasons, prohibition of explosives and poisons
3 Dec 1914	Qld	Minimum legal sizes: bream 8 inches (20.3 cm) total length, whiting (all species) 8 in. TL, flathead 12 in. (30.5 cm) TL (*The Fish and Oyster Act of 1914*)
1926–1933	Qld	Minimum legal sizes: bream 9 in. (22.9 cm) TL, whiting (all species) 9 in. TL, flathead 13 in. (33.0 cm) TL (Amendments 1926, 1929 and 1933 by Order in Council to *The Fish and Oyster Act of 1914*)
18 Apr 1957	Qld	Minimum legal sizes: bream 9 in. (22.9 cm) TL, whiting (sand and goldenline) 9.5 in. (24.1 cm) TL, whiting (trumpeter, northern, stout and southern school *Sillago bassensis*) 8 in. (20.3 cm) TL, flathead 13 in. (33.0 cm) TL (*Fisheries Act 1957*)
16 Dec 1976	Qld	Minimum legal sizes (TL, cm): bream and tarwhine 23, whiting (sand and goldenline) 23 (other species no limit), flathead 30 (*Fisheries Act 1976*)
10 Mar 1990	Qld	Confirm minimum legal sizes from 1976 (*Fisheries Organization and Marketing Regulations, 1990*)
1 Jul 1990	NSW	Minimum legal sizes: bream 25 cm TL, sand whiting 27 cm TL (no limit for other whiting species), flathead 33 cm TL; in-possession limit: bream and tarwhine species combined 20 (*Fisheries and Oyster Farms Act 1935—Regulation no. 357, 1990*) [A NSW Government brochure states 9 in prior to 1950s, 25 cm since 1960s. We have not found the source of this.]
11 Jun 1993	NSW	Minimum legal sizes: bream 25 cm TL, sand whiting 21 cm TL, flathead 33 cm TL; in-possession limits: bream 20 (*Acanthopagrus* species combined), whiting 20 (all *Sillago* species combined); daily bag limits: dusky flathead 10 (*Fisheries and Oyster Farms Act 1935—Regulation no. 199, 1993*)
1 Jul 1993	Qld	Confirm minimum legal sizes from 1976 (*Fishing Industry Organization and Marketing Amendment Regulation No. 3, Subordinate Legislation 1993 No. 235)*
13 Jan 1995	NSW	Minimum legal sizes: bream 25 cm TL, sand whiting 27 cm TL, flathead 33 cm TL; in-possession limits bream 20 (*Acanthopagrus* species combined), whiting 20 (all *Sillago* species combined); daily bag limits: dusky flathead 10 (*Fisheries Management (General) Regulation, 1995—No. 11*)
1 Dec 1995	Qld	Closure to commercial net fishing of most of Moreton Bay foreshore and waterways in the City of Brisbane (Manly to Brighton); Great Sandy Strait, all foreshore south of Double Island Point and all of Moreton Bay at weekends; and the eastern (ocean beach) shore of Fraser Island from 1 September to 1 April (*Fisheries Regulation, 1995 No. 325*) No change to minimum legal sizes (bream, whiting and flathead) set 1976
1 Sep 2002	NSW	Minimum legal sizes (TL) bream 25 cm, sand whiting 27 cm, flathead (dusky) 36 cm, flathead (other species) 33 cm; in-possession limits: bream 20 (*Acanthopagrus* species combined), whiting 20 (*Sillago* species combined); daily bag limits: dusky flathead 10 (no more than one > 70 cm) (*Fisheries Management (General) Regulation, 2002 No. 626)*
9 Dec 2002	Qld	Legal sizes (TL) dusky flathead minimum 40 cm, maximum 70 cm; other flathead species remain at 30 cm minimum, no maximum (*Fisheries Amendment Regulation (No. 4), Subordinate Legislation 2002 No. 339*)
1 Apr 2008	Qld	In-possession limit 5 dusky flathead; no change to legal sizes for bream, whiting or flathead set 1993–2002 (*Fisheries Regulation, 2008 No. 83*)
1 Mar 2009	Qld	*Marine Parks (Moreton Bay) Zoning Plan 2008* closed 16 per cent of the area of Moreton Bay Marine Park to all fishing and a further eight per cent to net fishing. This Marine Park is not confined to Moreton Bay itself and includes ocean beaches.
22 May 2009	Qld	Maximum legal size: dusky flathead 75 cm; no change to minimum legal sizes for bream, whiting or flathead from 1976–2002

Date	State	Measure
		In-possession limits: bream 30 (bream and tarwhine species combined), whiting (sand, goldenline and northern combined) 30, trumpeter whiting 50, dusky flathead 5, other flatheads combined 5 (*Fisheries Legislation Amendment Regulation (No. 2), 2009 No. 61*)
1 Mar 2010	Qld	Minimum legal size: bream 25 cm TL; (*Fisheries Legislation Amendment Regulation (No. 2), 2009 No. 61*)
1 Sep 2010	NSW	Minimum legal sizes (TL) bream 25 cm, sand whiting 27 cm, dusky flathead 36 cm; in-possession limits: bream and tarwhine species combined 20, whiting 20 (all *Sillago* species combined); daily bag limits: dusky flathead 10 (no more than one > 70 cm) (*Fisheries Management (General) Regulation, 2010 No. 475)*

Minimum legal sizes (MLSs) of 9 inches (about 23 cm) TL for bream and whiting, and 13 inches TL (about 33 cm) for flathead were imposed early in the fishery's history in Queensland. The MLS for sand and goldenline whiting was raised to 9.5 inches (about 24 cm) in 1957. Metric measurements from December 1976 were 23 cm for bream and whiting and 30 cm for flathead. In December 2002, the MLS for dusky flathead was increased to 40 cm and a maximum legal size of 70 cm was imposed. The maximum legal size for dusky flathead was increased to 75 cm in 2009 and the MLS for bream was increased to 25 cm in 2010.

In NSW MLSs appear to have been first imposed in 1990, with initial values of 25 cm TL for bream, 27 cm TL for sand whiting and 33 cm TL for flathead. The MLS for sand whiting was reduced to 21 cm in 1993 but increased back to 27 cm in 1995. The MLS for dusky flathead was increased to 36 cm in September 2002.

Recreational in-possession limits were first imposed in NSW in 1990 (20 fish per person in possession, bream and tarwhine combined). The NSW rules were extended to whiting (20 fish, all *Sillago* species combined) and dusky flathead (10 fish) in 1993. In September 2002 an additional NSW restriction of only one dusky flathead over 70 cm was imposed.

In Queensland, dusky flathead first received an in-possession limit of 5 fish in 2008. Queensland bream and whiting received in-possession limits in 2009 of 30 bream and tarwhine species combined and 30 whiting (sand, goldenline and northern combined).

The total amount of fishing effort on bream, whiting and flathead in Queensland is not currently limited. Recreational fishers must adhere to in-possession limits but there is no effective limit to the total number of fishers or the number of days they may fish. The numbers of commercial fishers are limited by the number of licences available and there are various spatial and temporal closures but currently there is no total allowable commercial catch (TACC).

Commercial net fishing has been gradually restricted since 1995 in both Queensland and NSW. Although there are various spatial and temporal closures, the total potential commercial fishing effort is still limited only by the number of licences and there are no limits on the total commercial catch.

1.4 Scientific data

1.4.1 Age–length data

Age and length data for bream, whiting and flathead were collected by Fisheries Queensland's Fishery Monitoring team from 2007 onwards. The data used in this assessment were from 2007 to 2016 in South East Queensland. These data were fishery-dependent with samples taken from recreational and commercial harvests and measured by scientific staff.

Important earlier sources of data were also available. Time limitations did not allow their inclusion in this assessment. Although some pre-processing was undertaken during this assessment, more is needed before these data can be used for assessment purposes. The earlier data were

- Coastal Streams project: Caloundra and Jumpinpin (Gold Coast), 1993; Burnett River, Maroochy River and Pumicestone Passage, 1997 and 1998 (O'Neill, 2000)
- Integrated Stock Assessment and Monitoring Program (ISAMP) in Queensland, 1995, 1996 and 1997 (Hoyle et al., 2000).

1.4.2 Recreational fishing surveys

Statewide recreational catches of fish in Queensland have been quantified 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, 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 (Taylor et al., 2012) and 2013 (Webley et al., 2015).

All of these surveys used two-stage sampling methodology: 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, as the RFISH surveys had less regular prompting of participants (Lawson, 2015). They were included in the assessment but were adjusted to match the NRIFS and SWRFS catch levels (see Section 2.1).

These surveys provided only harvest size estimates, not catch rates.

1.4.3 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 formally estimated.

The Queensland state-wide human population was used as a recreational fishing effort proxy up to 1997. State population records were available from the Australian Bureau of Statistics (ABS, 2014) (ABS), record number 3105.0.65.001.

Alternative proxies that might have been used were numbers of motor vehicle registrations, on the premise that fishers needed transport to fishing locations, and numbers of motor boat registrations, on the premise that these species are often caught by boat. The Project Team believed that historically fishers managed to get to fishing locations without needing their own motor vehicles or boats.

1.5 Fishery data

1.5.1 Commercial data

The major source of fishery data was the commercial logbook database maintained by Fisheries Queensland, which allowed estimation of harvest sizes and standardised catch rates from 1988 to present (final year 2017). 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), 1945–1980
- Queensland daily harvest records by fisher from compulsory commercial logbooks, 1988–2017.

Commercial harvests between 1981 and 1988 had to be interpolated as no data were available. The interpolation was done linearly on the log scale (see Section 2.2 below).

Ranges of daily catches of bream, whiting and flathead are presented as histograms in Appendix 1 (page 97). They are highly skewed, having 'long tails': there are many small catches which would make little money, and few large catches up to several tonnes. Modelling these 'catch per operation day' data to obtain meaningful catch rates is problematic (see Section 0 below).

The commercial logbook database also included data from the charter fishery in recent years. These data were not used in the assessment. Reported charter harvests of bream, whiting and flathead were infrequent and were assumed to be already recorded in the recreational harvest estimates. We note also that charter logbooks are not compulsory for charter fishing in inshore waters of depth five metres or less, which could complicate the analysis of charter data.

1.5.2 Fishing club data

Fisheries Queensland holds a database of South East Queensland fishing club trips covering the years 1951–2003. This data source was valuable because it went back decades before commercial catch rates were available. It contained about 194,000 records from 47 clubs and provided catch sizes of bream, whiting and flathead by fisher–trip.

Standardised catch-rate time series from the fishing-club data are provided in this report but were not input to the stock-assessment population model. This exclusion was directed by some Project Team members, as more time was required to demonstrate data consistency and standardise fishing and targeting practices between clubs, fishers and seasons. Concerns that were expressed included the following:

- Increasing accessibility of various fishing locations due to rising individual ownership of boats and four-wheel drive vehicles
- Changes in targeting of different species due to changes in club scoring methods and the relative importance ascribed to weight versus total number of fish
- Self-imposed regulations such as the imposition of higher minimum sizes than the legal minimum.
- Grading of competitors for club competitions, and possible changes over time in the representation of the different grades in the club database.

The fishing-club data are analysed in Section 3.1 (page 34). Importantly, the analysis used only the *ratio* of the catch rate of the individual species being assessed (bream, whiting or flathead) to the catch rate of other species. It was not necessary to model the very steep increase in recreational fishing power that obviously took place from the 1950s to the 1970s, which would have been a more difficult task.

1.6 Data carried forward to the stock assessment

The stock assessment used the following data:

- Length-frequencies, 2007–2016
- Age-at-length, 2007–2016
- Recreational survey harvest (kept fish) estimates, 1997, 1999, 2000, 2002, 2005, 2011, 2014
- Queensland human population statistics, 1945–1997, used to infer recreational fish harvests
- Queensland Fish Board commercial harvest size estimates, 1945–1980
- Queensland commercial logbook data, 1988–2017, used for both harvest size and standardised catch rates

The stock assessment used an annual population model over the calendar years 1945–2017.

2. Historical harvest sizes

2.1 Recreational harvest

Recreational harvest estimates of bream, whiting and flathead came from the following time periods:

- National Recreational and Indigenous Fishing Survey: diary period 1 May 2000 to 30 April 2001; assumed to come from calendar year 2000 in the population model
- State-Wide Recreational Fishing Surveys: diary periods 1 October 2010 to 30 September 2011 and 1 November 2013 to 31 October 2014; model years 2011 and 2014
- RFISH surveys: calendar years 1997, 1999, 2002 and 2005
- Queensland population statistics: 1945–1997 from the Australian Bureau of Statistics, record number 3105.0.65.001 (ABS, 2014).

The following tasks converted the data into an annual time series of recreational harvest (kept fish) by weight:

1. Estimate species splits in order to exclude related species (see Section 1.2.3) and estimate harvests only of the species assessed.
2. Convert recreational harvests from numbers to weights.
3. Adjust the RFISH recreational harvest estimates to match the methodology used by NRIFS and SWRFS.
4. Interpolate recreational harvests in years between 1997 and 2017 in which surveys were not undertaken.
5. Extrapolate recreational harvests backward in time from 1997 back to 1945.

Task 1 was long and complex. The quality of data on species split in the recreational surveys improved over time, and we could use the final survey (2014) as the best estimate of species splits in previous surveys. The most important part of the species split analysis was to separate out the catches of trumpeter whiting which is a smaller fish than sand whiting but very numerous.

For task 2 we multiplied catch numbers by average weights of recreationally caught fish which were calculated by averaging the weight of fish measured by the Fisheries Queensland Fishery Monitoring team, using the length–weight relationships from Section 1.2.2:

- 0.355 kg for yellowfin bream
- 0.176 kg for sand whiting
- 0.571 kg for dusky flathead up to 2002
- 0.825 kg for dusky flathead from 2003 onwards, taking account of the increase in minimum legal size in December 2002.

For task 3, the RFISH estimates from all years (1997, 1999, 2002 and 2005) were all multiplied by the factor

$$C_{2000} \Big/ \left(C_{1999}^{2/3} C_{2002}^{1/3} \right)$$

which is the ratio of the NRIFS harvest estimate (denoted C_{2000}) 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 (⅔) than the 2002 survey (⅓) because it was one year from the target year, as opposed to two years.

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 (James Webley, SWRFS coordinator, personal communication).

For task 4, estimates of recreational harvest were available for the years 1997, 1999, 2000, 2002, 2005, 2011 and 2014. In other years between 1997 and 2017, estimates 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 matched 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 for task 3, 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

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

For Task 5, the human population of Queensland, adjusted for a fishing power increase of three per cent, per year from 1945 to 1980, was used as a proxy for recreational harvest size from 1945 to 1997. This figure is consistent with the fishing club data analysed in Section 3.1. The final year of fishing-power increase, 1980, was chosen as a year beyond which involvement of recreational fishers in fishing clubs declined and the major technological innovations of nylon fishing line, waders and modern fishing rods had all been introduced.

A potentially important additional source of recreational fishing power, especially for flathead, was the rise in use of soft plastic lures. We believe that this took place mainly after 1997. Hence any increase in harvest size promoted by soft plastic lures would be included in the recreational diary surveys.

Only the trend in the recreational harvest proxy was important to the reconstruction of historical harvests, not the absolute level of the values. The recreational harvest proxy was scaled to match the recorded harvests from the diary survey in 1997.

In principle it would be more accurate to make fishing effort, rather than harvest, proportional to the effort proxy. This has been undertaken by, e.g., O'Neill et al. (2018) and Wortmann et al. (2018) but a complete treatment would require splicing a catch-driven recreational harvest formulation from 1997 onwards onto an effort-driven one prior to 1997, in order to prevent the population model from interpreting post-1997 variation in harvest as variation in abundance.

2.2 Commercial harvest

Commercial harvests were estimated from the following sources:

- Commercial logbook data: 1988–2017
- Queensland Fish Board records: 1945–1980 (Halliday and Robins, 2007).

Tasks to convert these data to an annual time series 1945–2017 were the following:

6. Convert Queensland Fish Board harvests from financial years (July to June) to calendar years (January to December).
7. Interpolate Queensland commercial harvests between 1978 and 1988.

Task 6 was accomplished by assuming that the harvest was taken in the months July to December. This assumption was not perfect but fitted the majority of seasonal patterns of the commercial catch in

Queensland, which generally peaked in July or August. For example, data for the 1955–56 financial year were assigned to the 1955 calendar year.

For task 7, we interpolated harvests in the years 1979–1987 by fitting a straight line to the logs of the commercial harvests in 1978 and 1988. Fish Board records contained harvest sizes for 1979 and 1980 but these were much lower than preceding years. They were not used, due to assumed changes in marketing of bream, whiting and flathead outside of the Fish Board. 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.

2.3 Complete time series of estimated harvest sizes

The estimated time series of harvest tonnages are plotted in Figure 2.1, using the regions mapped in Figure 1.4 (page 9). The highest harvests generally occurred in the period 1975–2005 for bream and whiting, and 1990 to present for flathead. Recreational harvests of bream and whiting have declined greatly since 2005, while those of flathead have remained fairly constant.

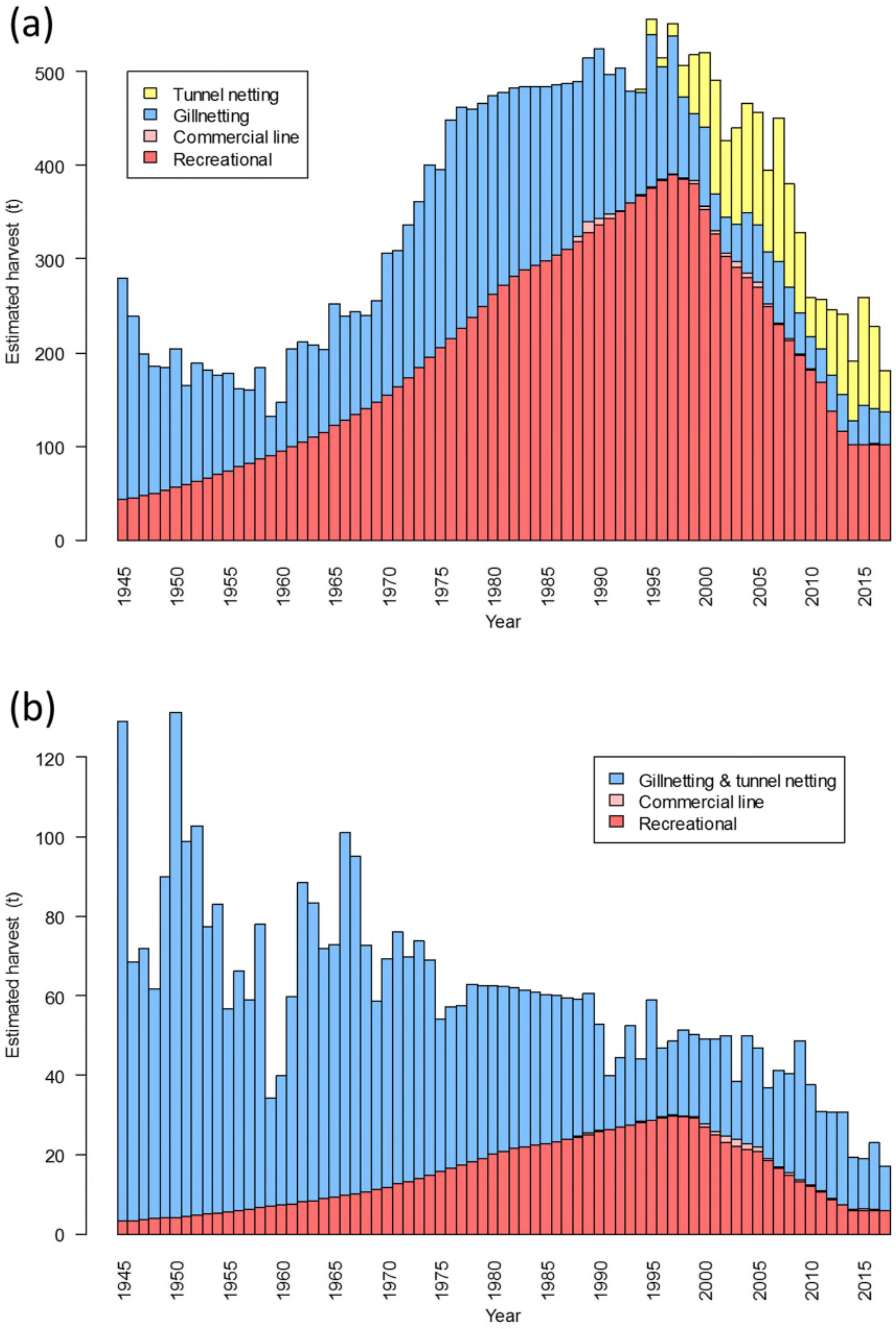


Figure 2.1: Estimated harvest sizes, 1945–2017 by region: (a) bream Moreton, (b) bream Fraser. Note that most commercial fishing was recorded as gillnetting prior to about 2000, so the apparent increase in tunnel netting activity at this time is not real. Regions are mapped in Figure 1.4, page 9. Continued on following three pages.

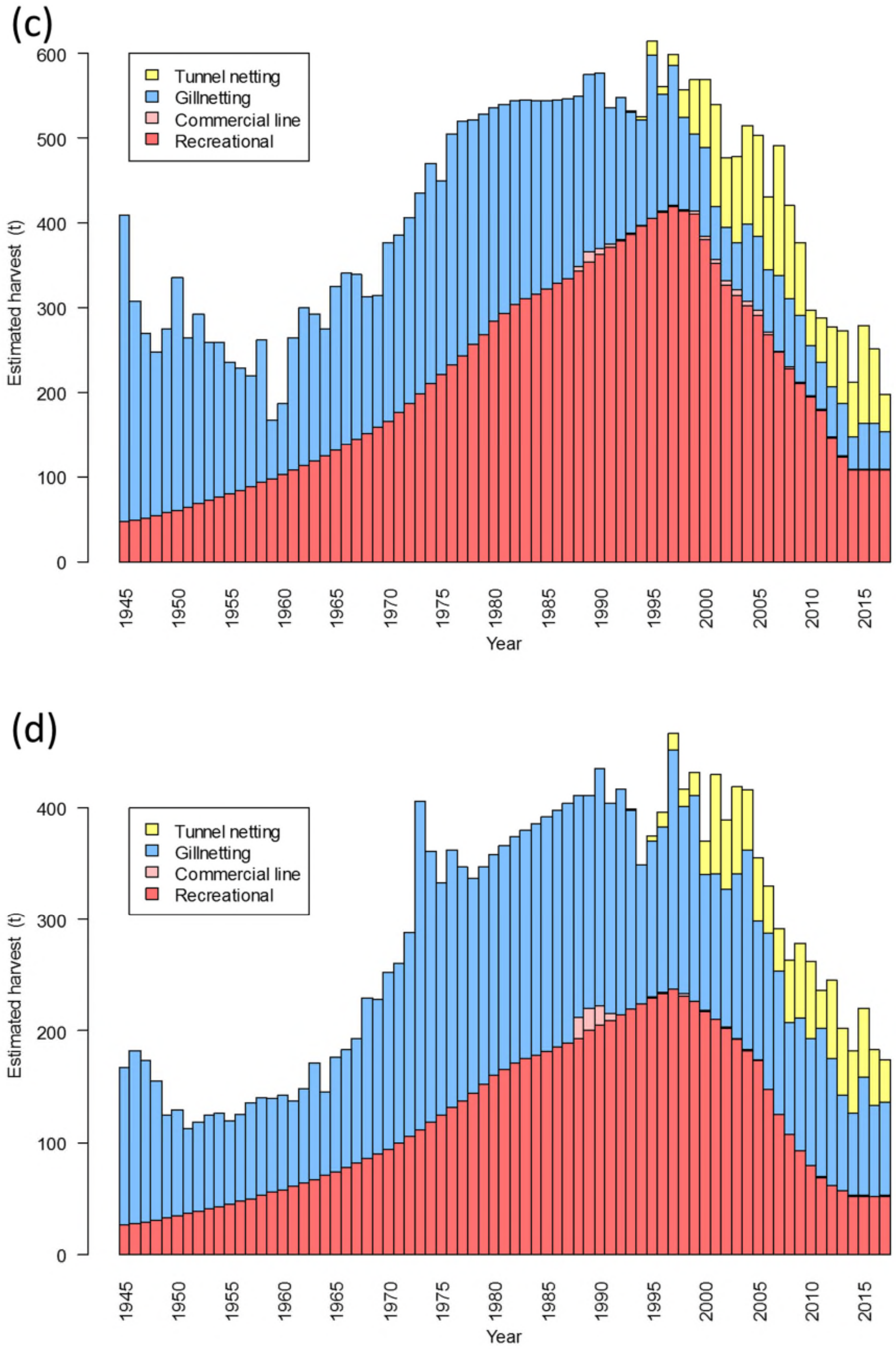


Figure 2.1, continued: (c) bream combined Moreton–Fraser regions, (d) whiting Moreton.

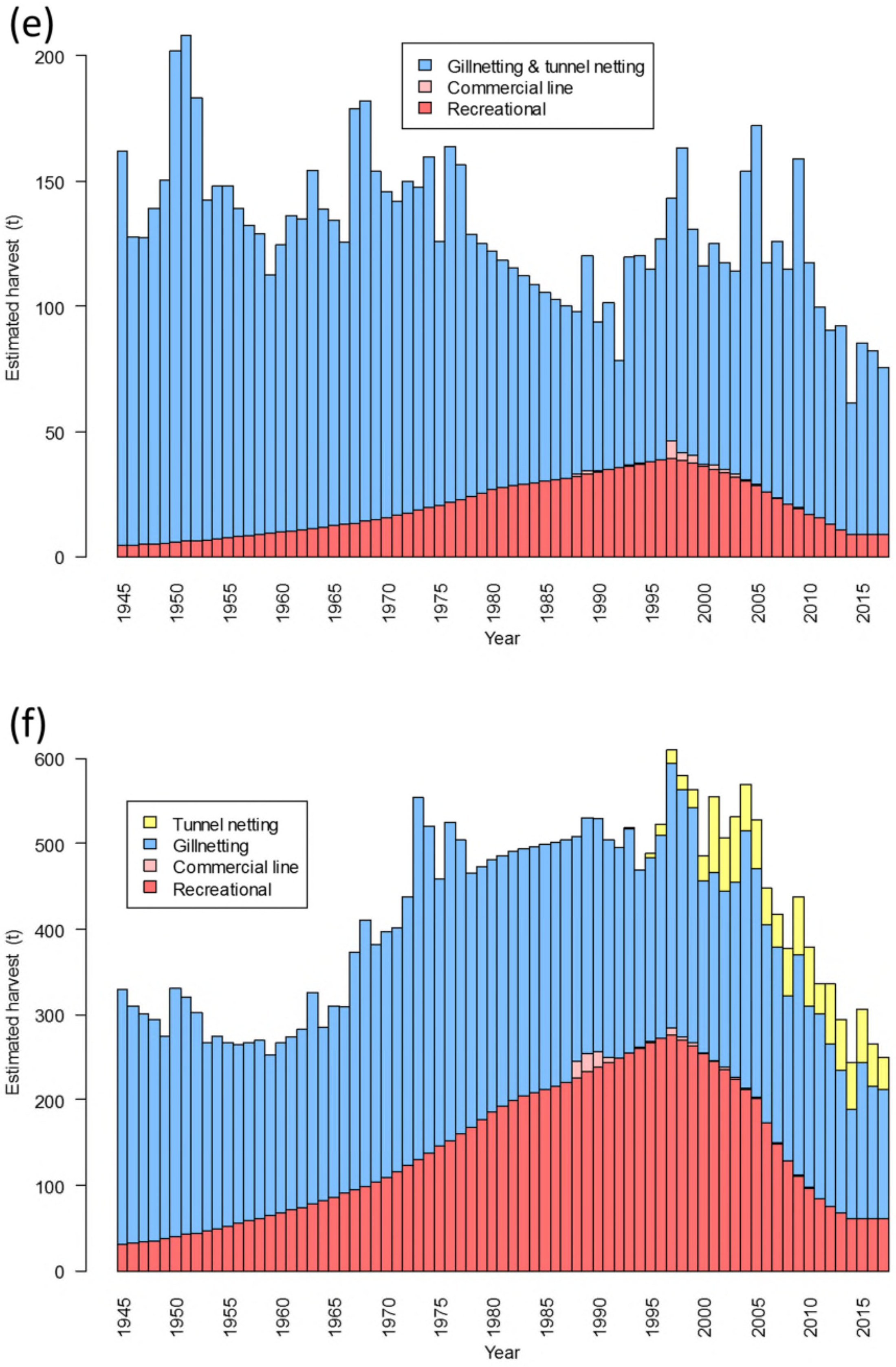
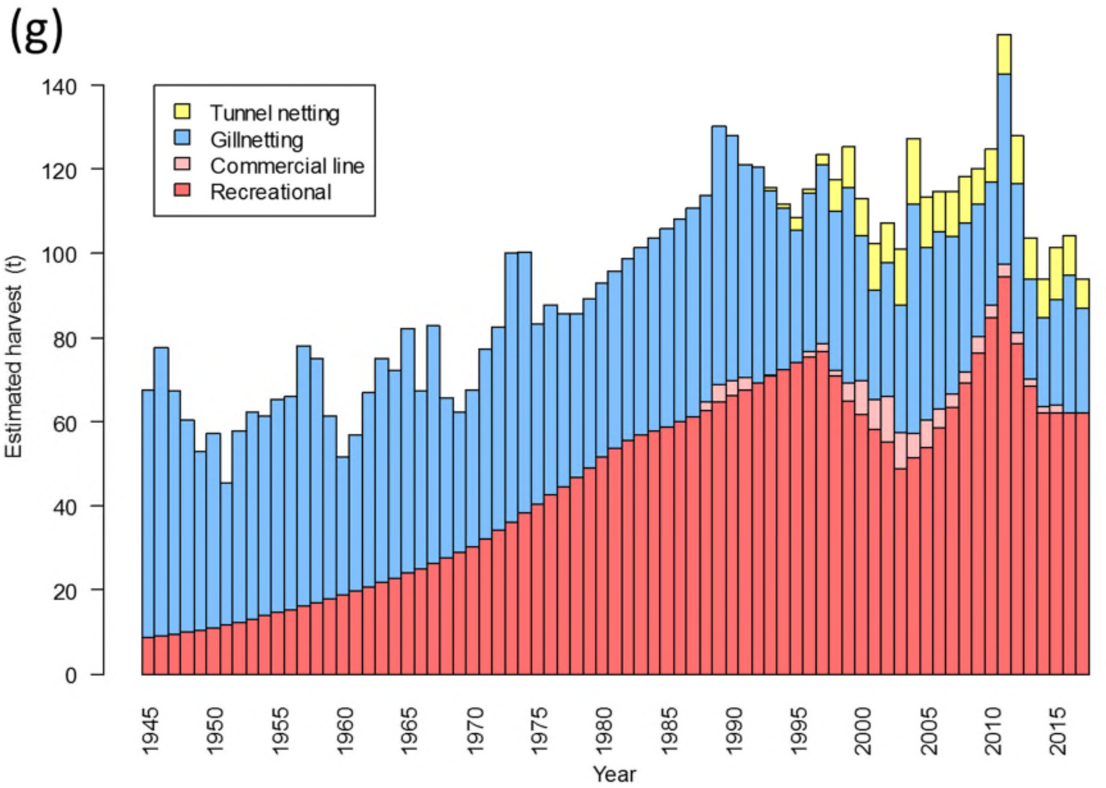


Figure 2.1, continued: (e) whiting Fraser region, (f) whiting combined Moreton–Fraser.



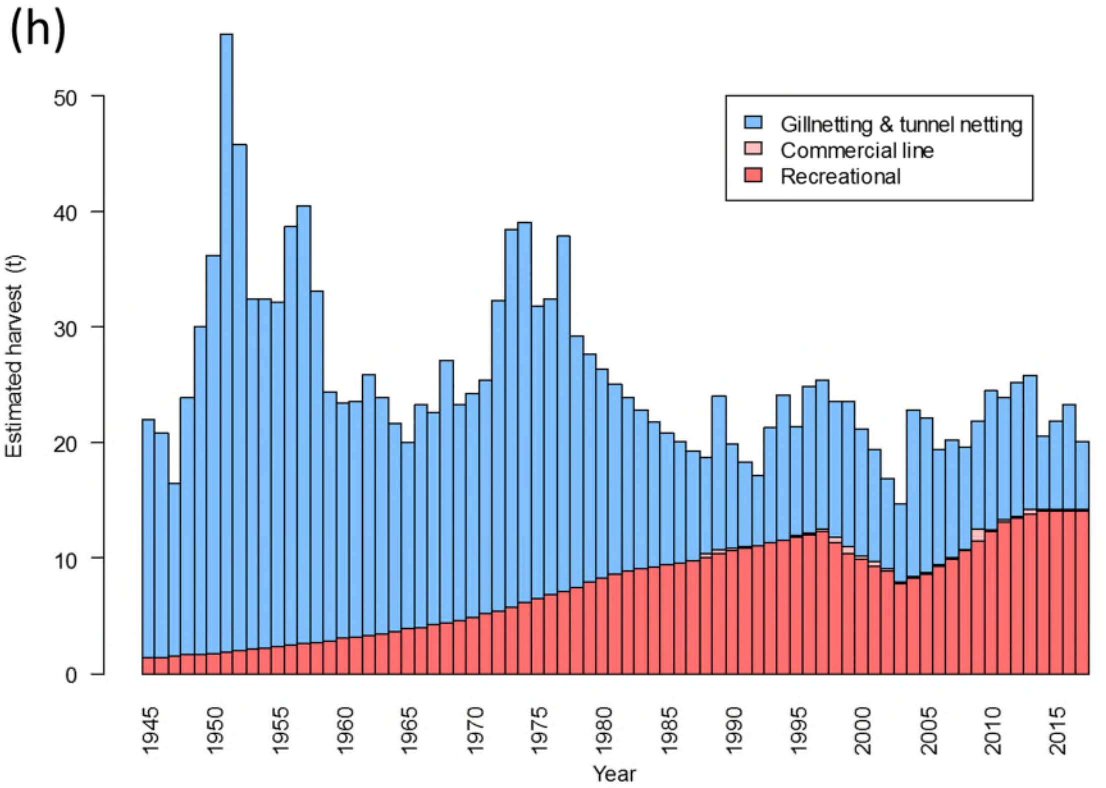


Figure 2.1, continued: (g) flathead Moreton region, (h) flathead Fraser.

3. Catch-rate analysis

3.1 Fishing club catch rates

Queensland fishing club data were available for the period 1951–2003. This important period covered the rise in harvest sizes of bream, whiting and flathead prior to the beginning of the commercial logbook database in 1988. There was little contrast in catch rates from 1988 onwards.

Some members of the assessment's Project Team were cautious about the use of fishing club catch rates in stock assessment. Fishing clubs changed their practices over time: for example, changes in scoring systems changed fishers' preferred species, and clubs introduced their own minimum size limits which were larger than those set by Government. Also the data indicated big increases in recreational fishing power; the alternative explanation of greatly increased abundance of many different species of fish was not considered possible. Another concern was the potential increase in the number of accessible fishing locations over the years, related to the rise in individual ownership of motor boats and four-wheel drive vehicles, and developments such as vehicular ferries to islands and the opening of the Bribie Island Bridge in October 1963. Until the 1970s fishing clubs tended to go to a very limited number of fishing locations.

We believe that extra documentation of the data and appropriate standardisation can overcome the above perceived problems.

The analysis here is mainly for the purpose of background information to document fishing-club catch rates and trends, not as input to the population model. In addition, it uses only catch rates of the species of interest relative to other species. Adjustment for specific changes in fishing power was too difficult.

Catch rates were analysed by a Poisson generalised linear model (GLM) with log link (i.e., multiplicative effects). The terms fitted were year (as a factor, i.e., one model coefficient for each calendar year), month of the year (also a factor, 12 levels), trip duration, location and fishing club name. The estimated dispersion parameter provided standard errors on the parameter estimates. The analysis was carried out in the software R (R Core Team, 2019).

Three GLM analyses were undertaken for each species:

- one for the species of interest
- one for the total of all other species caught
- one for the species of interest with an 'offset' fishing power calculated from the abundance of all other species.

Two time series of relative abundance estimates of the species of interest were calculated:

- the ratio of the two 'year' effects from the first two GLM analyses, and
- the year effect from the third GLM analysis.

The offset fishing power for the second time series was calculated for the period 1953–1975, chosen to be the shortest period over which a steep increase in fishing power could be inferred. The resulting catch rates, if based on plausible methodology in the view of the reader, may therefore err on the side of optimism if fishing power increases continued at some level after 1975.

Results are shown in Figure 3.1. They show a slight fall in apparent abundance of whiting relative to other species (Figure 3.1(d)), a big fall in apparent abundance of bream (especially Figure 3.1(b)) and a very big fall in apparent abundance of flathead (Figure 3.1(e) and (f)).

Fishing clubs concentrated on the Moreton region. Not enough data were available from the Fraser region to draw any meaningful conclusions.

Also few data were available from the early years of the fishing club database (1950s and into the 1960s).

Despite the limitations in the data, the fishing-club catch-rate analysis shows that all three species, and especially bream and flathead, have been heavily fished since at least the 1970s.

We note an interesting finding that catch rates of bream were very low around 1960 (Figure 3.1), which appears to be due to low abundance. This hypothesis is supported by low commercial harvests at this time (see Figure 2.1(a)–(c), page 30). Commercial catch rates are not available for this period.

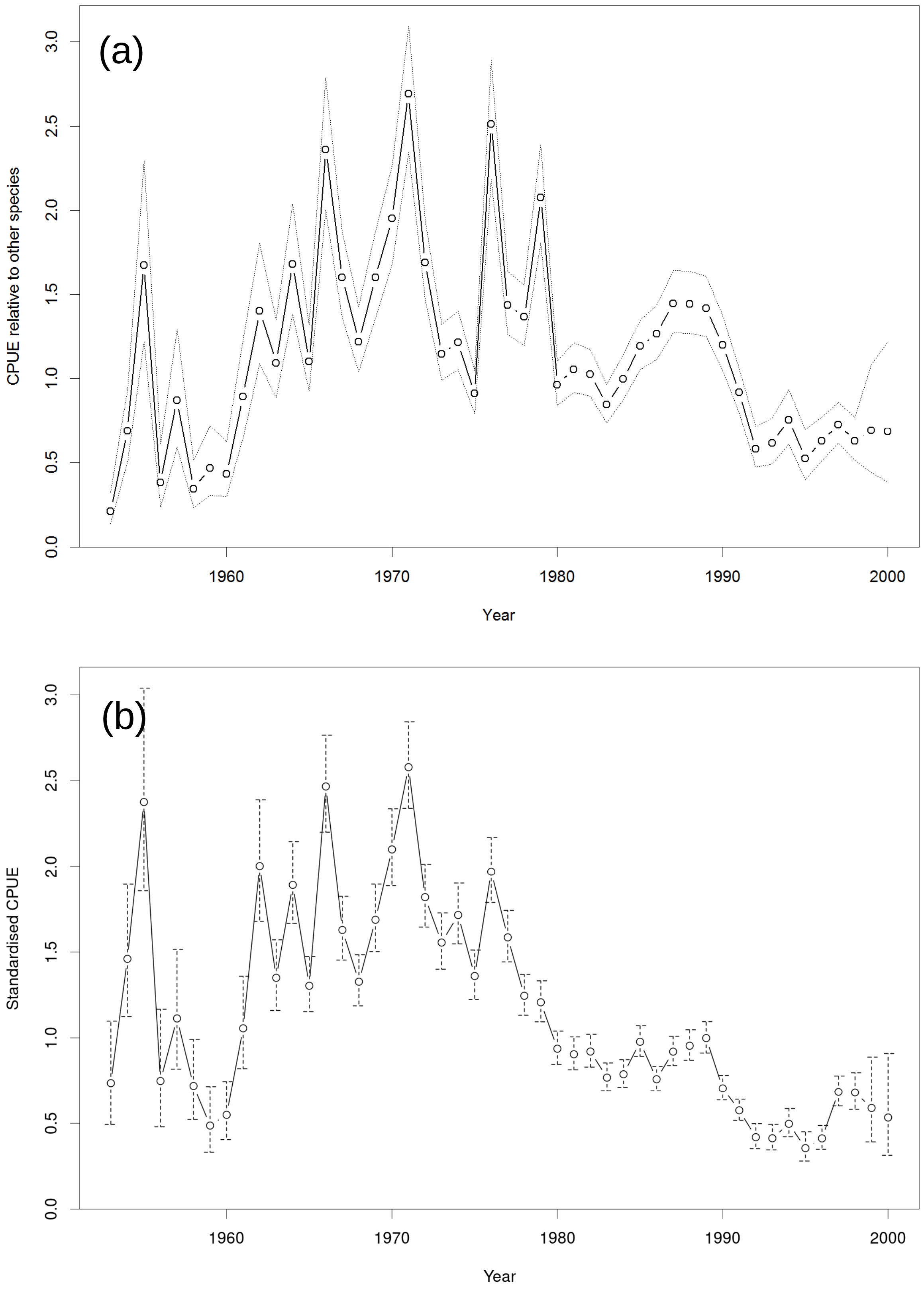
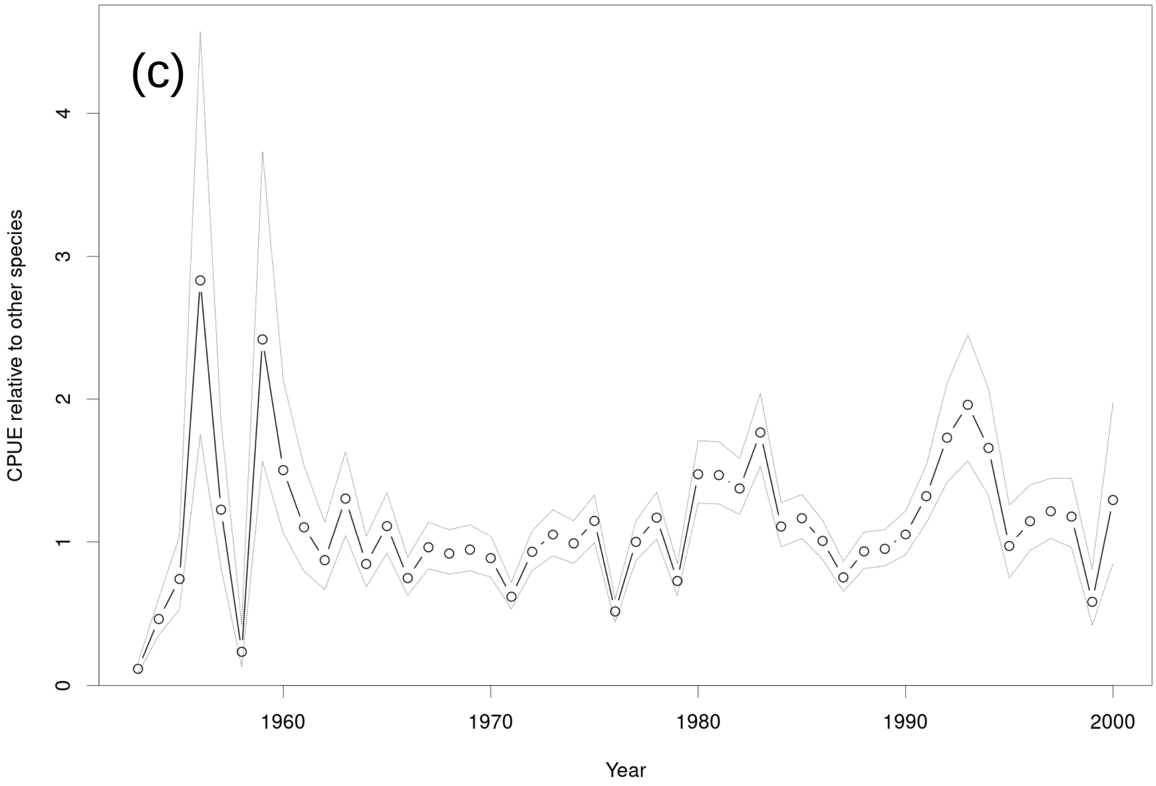


Figure 3.1: Fishing-club catch rates: (a) bream relative to non-bream, (b) bream relative to fishing power calculated from non-bream catches, with 95 per cent confidence limits. Catch rates have been scaled to average to 1. Continued on next two pages.



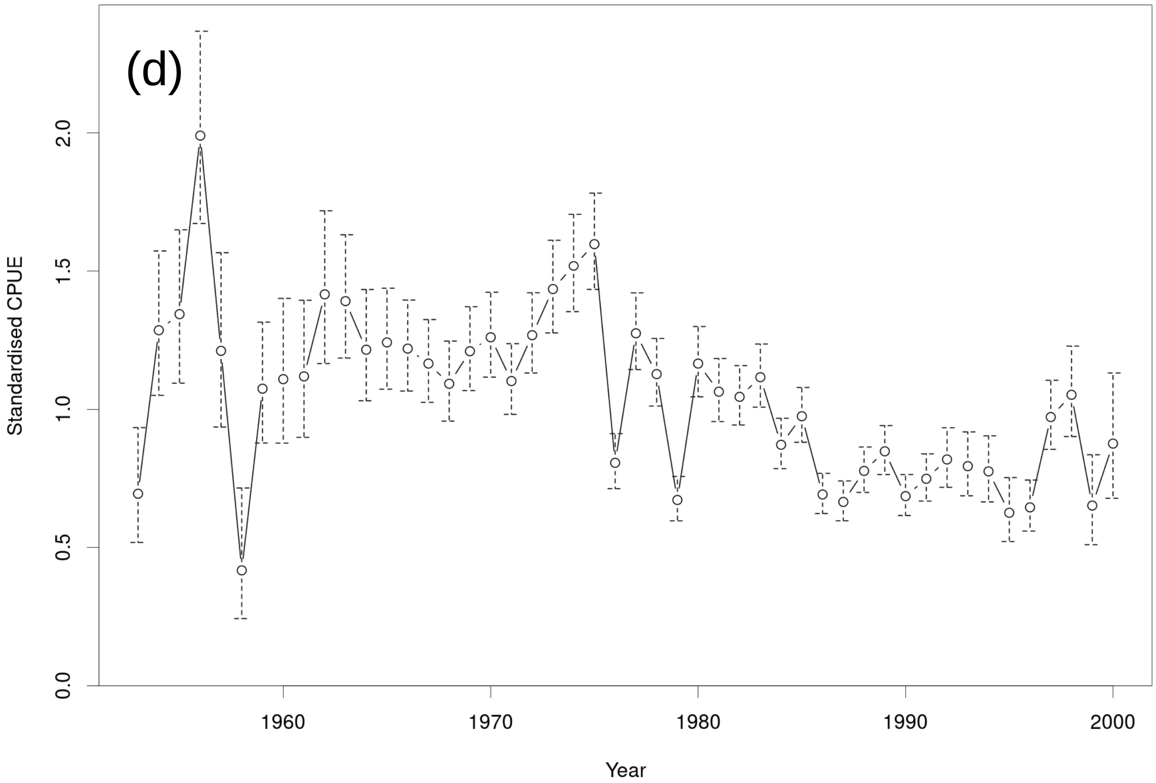
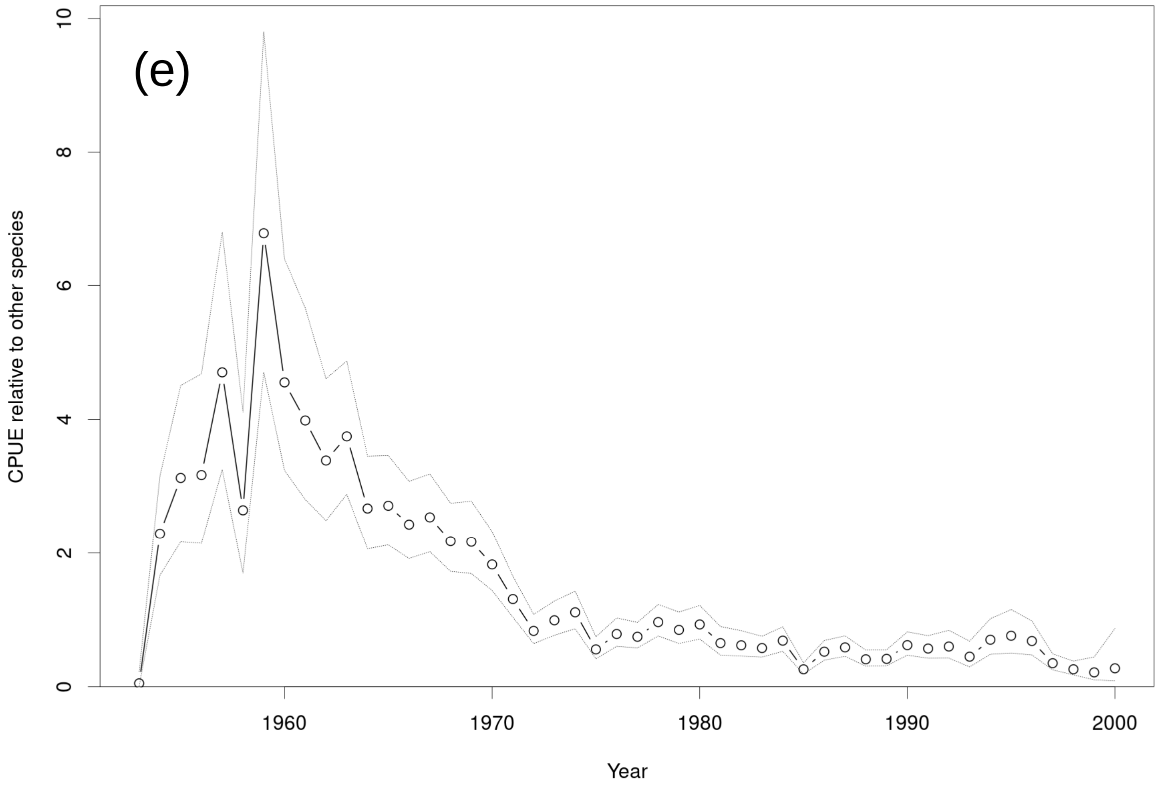


Figure 3.1, continued: (c) whiting relative to non-whiting, (d) whiting relative to fishing power calculated from non-whiting catches.



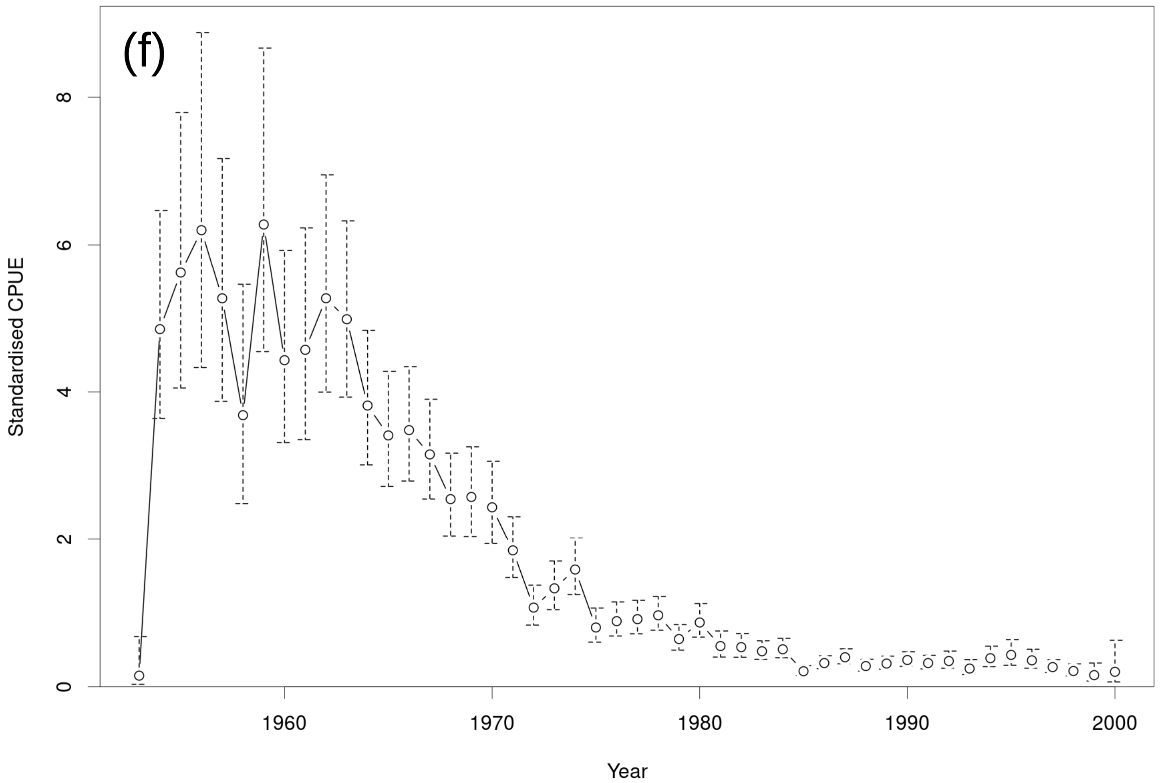


Figure 3.1, continued: (e) flathead relative to non-flathead, (f) flathead relative to fishing power calculated from non-flathead catches.

3.2 Queensland commercial data

Commercial logbook data were available for the period 1988–2017. Catch-rate analysis was conducted only for net fishing because there was very little catch from line fishing. Sufficient data were available for both gillnetting and tunnel netting in the Moreton region, and only for gillnetting in the Fraser region. Tunnel-net catch rates were identifiable in the database only from the late 1990s and were lumped in with gillnetting before then.

The method of catch rate analysis was almost identical to that used for the 2017 assessment of tailor (Leigh et al., 2017) and it is described in detail in that report. The data were collated into one record per fisher-day and analysed by a Poisson GLM with log link in which the dispersion parameter was estimated.

For some of the analyses the residuals from the Poisson GLM still showed an unacceptable amount of heteroscedasticity (higher variance of residuals for higher fitted catch rates). In these cases we applied a square-root or (where necessary) cube-root transformation to the data before entering it into the Poisson GLM. Where these transformations were necessary, the resulting parameter estimates were back-transformed to the original scale; no change to the link function was needed. The analysis was conducted in the software R (R Core Team, 2019).

A more consistent way to handle heteroscedasticity in the Poisson GLM would be to use a negative binomial GLM in which both the dispersion parameter and the shape parameter are estimated. Work on such a model is in progress but it was not ready in time for this assessment. When completed, the new GLM structure will provide an objective method to estimate the shape parameter by maximum likelihood and will no longer rely wholly on achieving visually acceptable residual plots.

The following associated species groups were used in the analysis, based on the average catches of bream, whiting or flathead that they gave rise to:

- Bream gillnetting: rabbitfish and luderick
- Bream tunnel netting: trevally, javelin fish, luderick, tailor, jewfish and garfish.
- Whiting and flathead: no associated species, so no zero catches in the analysis.

Catch records of the associated species were included in the bream analysis even when they included no bream. These records were considered genuine zero catches, where fishers could reasonably have been expected to catch bream but didn't actually catch any.

The GLMs included effects for fisher, year, month, location, net mesh size (for gillnetting only) and net length. All terms in the GLM were treated as factors, i.e., variables with discrete levels. Location was grouped into the small regions used by the Fisheries Queensland Fishery Monitoring team for their sampling. Mesh size and net length were not analysed as continuous variables because their relationships to catch size are often complex. Each factor level comprised an interval around a very frequent value; e.g., 50 mm or 75 mm mesh size, or 400 m or 600 m net length.

The year coefficients from the GLMs were used as indices of abundance. These are plotted in Figure 3.2. They are most notable for not showing much contrast over the period of the commercial logbook database. An exception is Figure 3.2(a) where the catch rates of bream decrease.

The catch rates from gillnetting were based on greater volumes of data and a much greater range of fishing locations than tunnel netting. Hence the gillnetting catch rates were preferred in the population model.

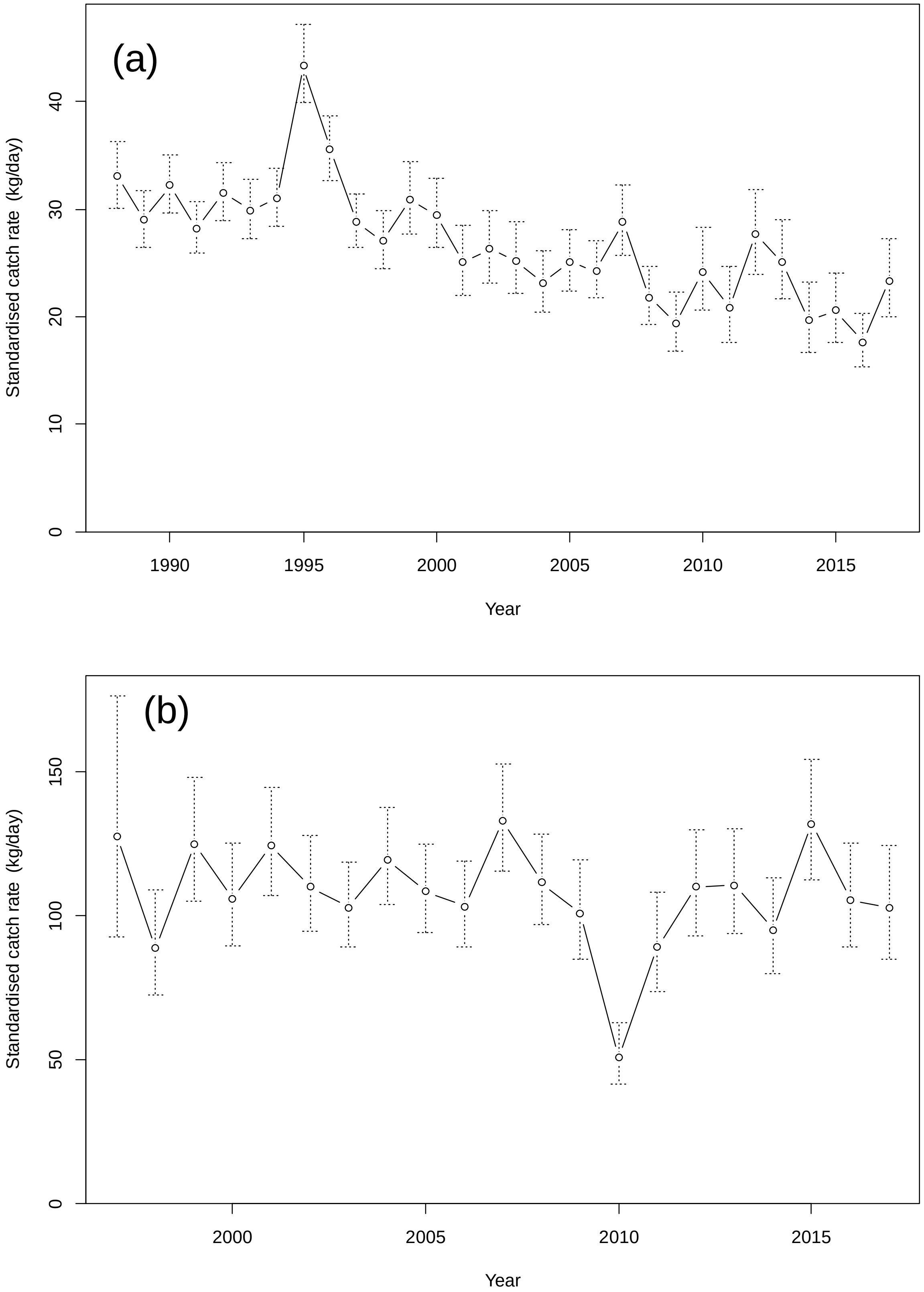
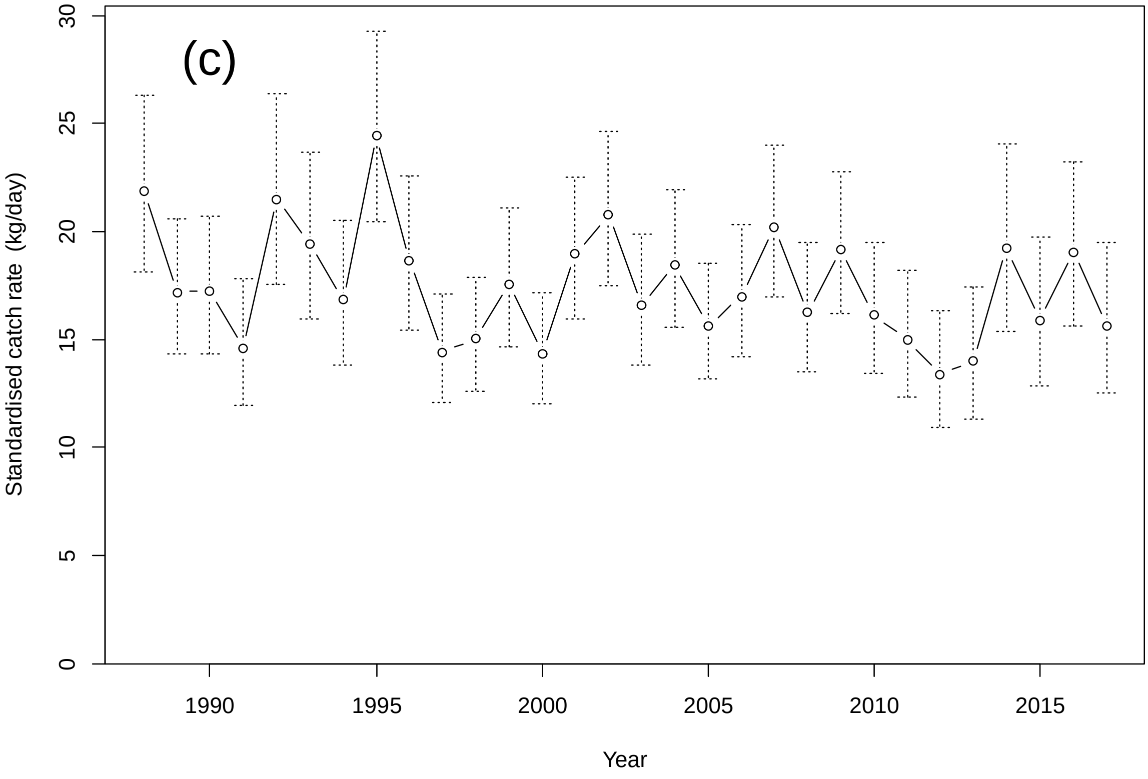


Figure 3.2: Standardised catch rates (CPUE) as measures of abundance: (a) bream Moreton gillnetting, Poisson GLM with square-root transformation (b) bream Moreton tunnel netting, Poisson GLM with square-root transformation. Continued next four pages.



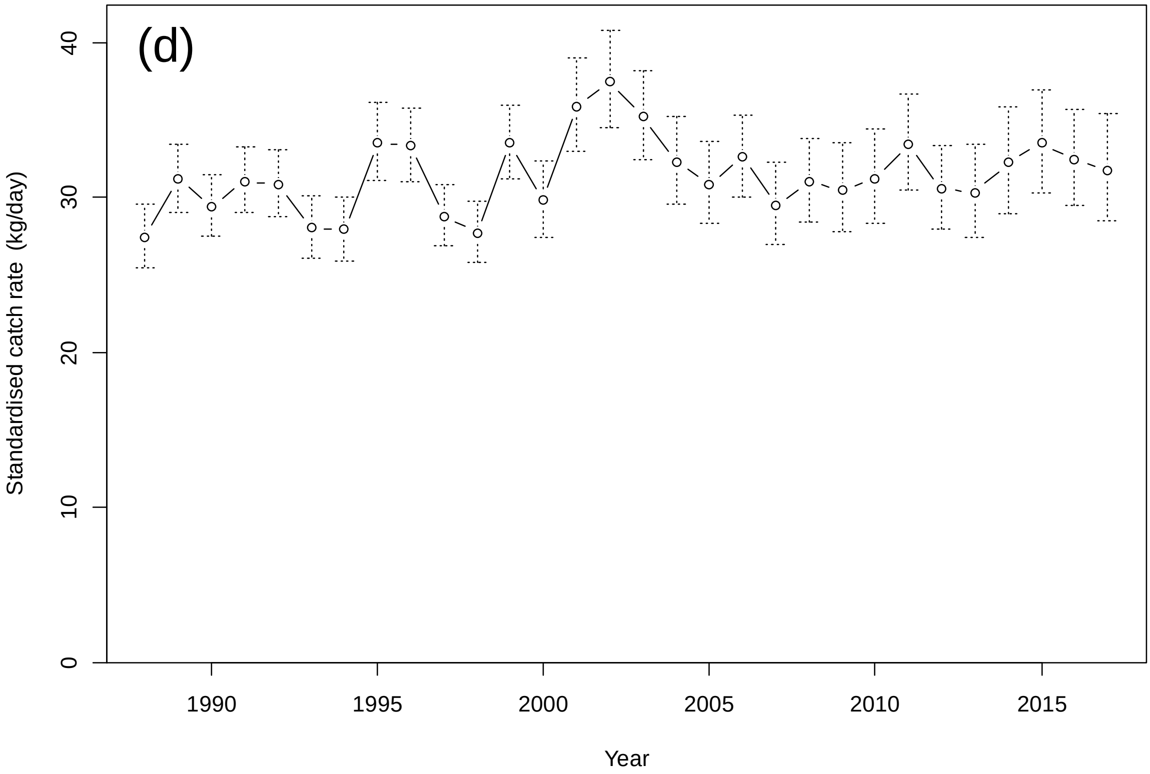
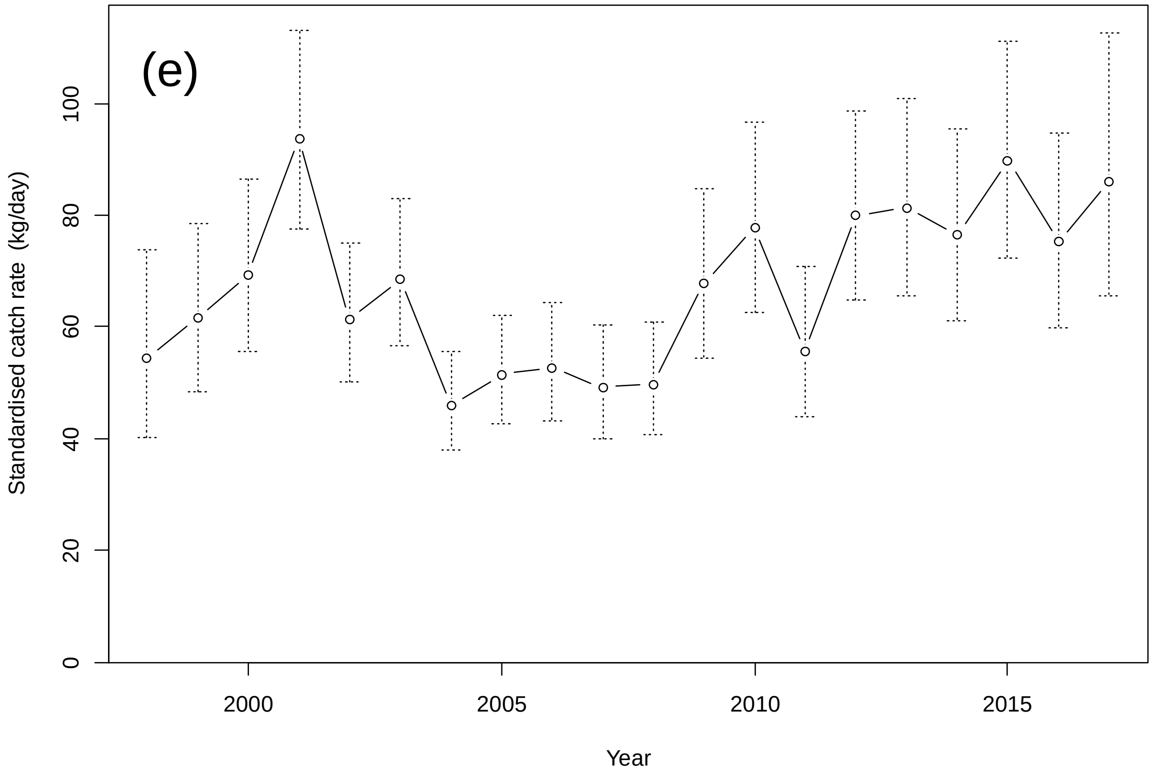


Figure 3.2 (continued): (c) bream Fraser gillnetting, Poisson GLM with square-root transform, (d) whiting Moreton gillnetting, Poisson GLM with cube-root transform.



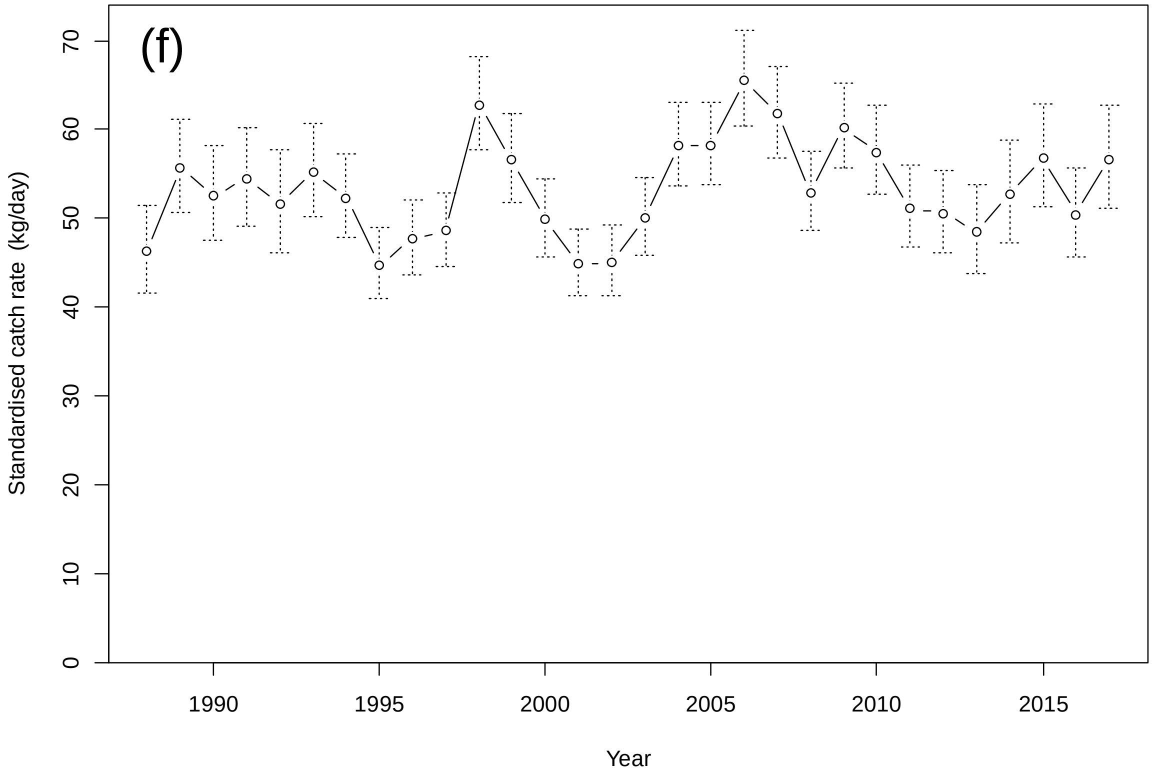
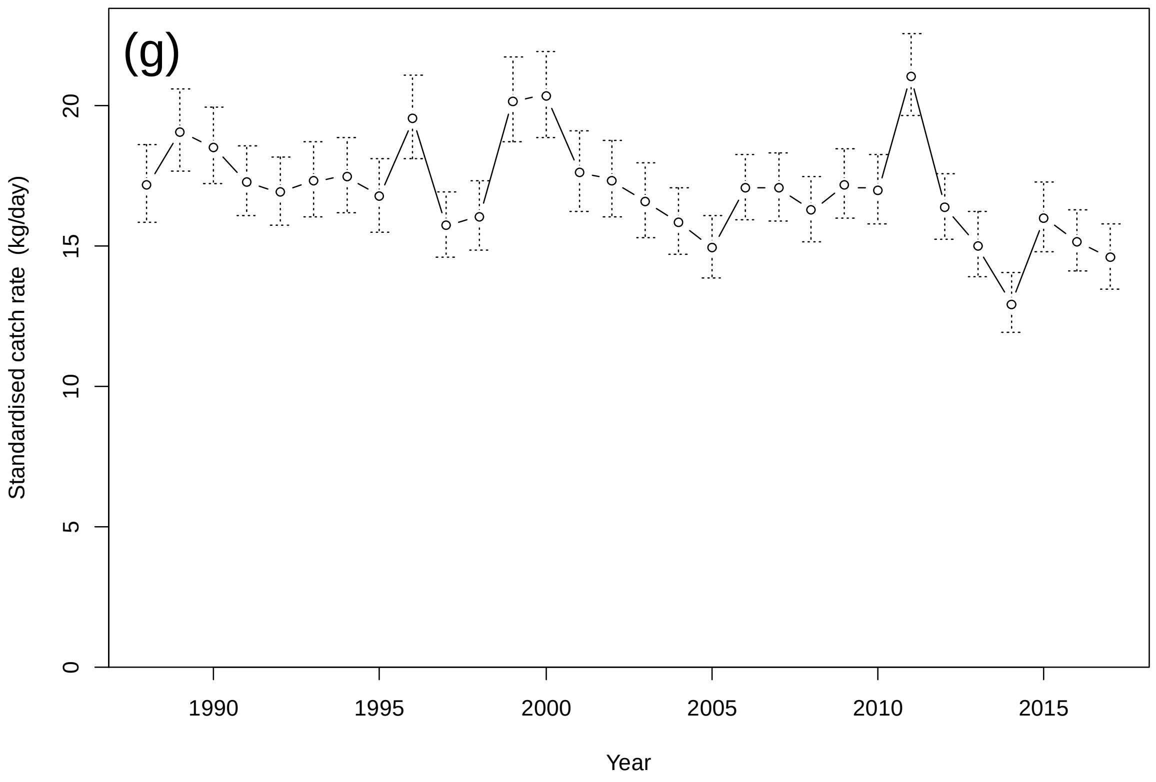


Figure 3.2 (continued): (e) whiting Moreton tunnel netting, Poisson GLM with cube-root transformation, (f) whiting Fraser gillnetting, Poisson GLM with cube-root transformation.



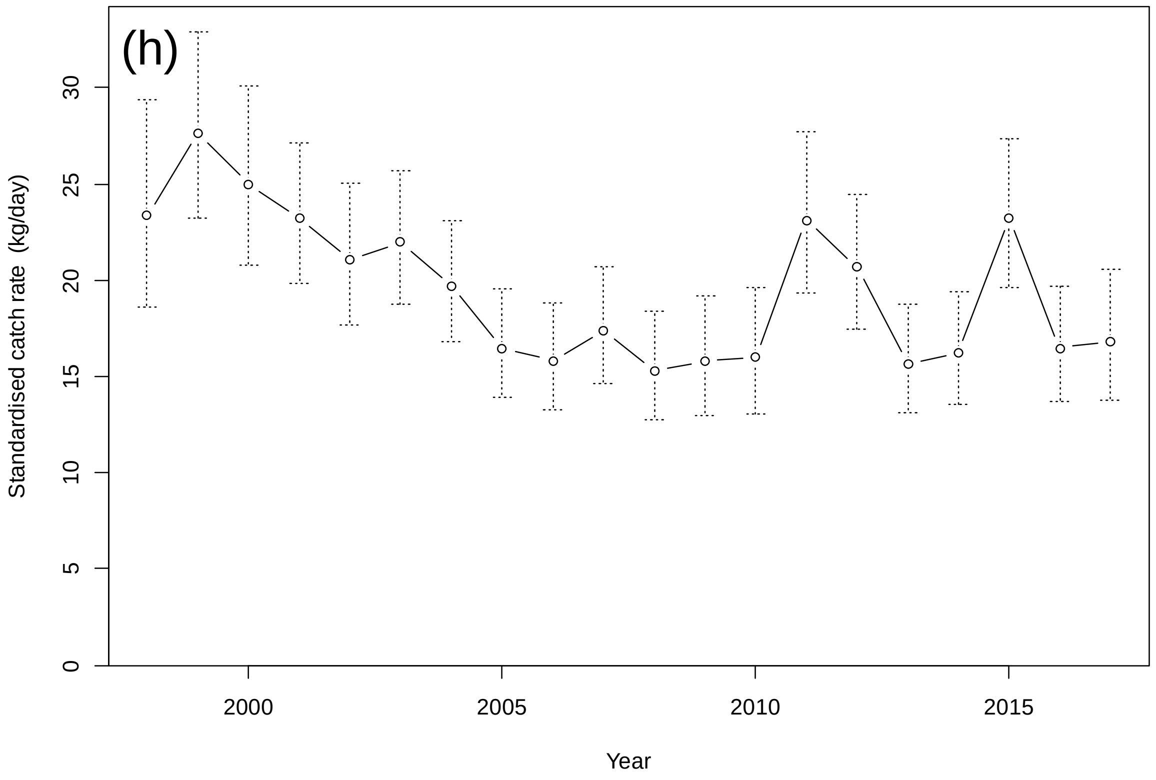


Figure 3.2 (continued): (g) flathead Moreton gillnetting, Poisson GLM with square-root transformation, (h) flathead Moreton tunnel netting, Poisson GLM untransformed.

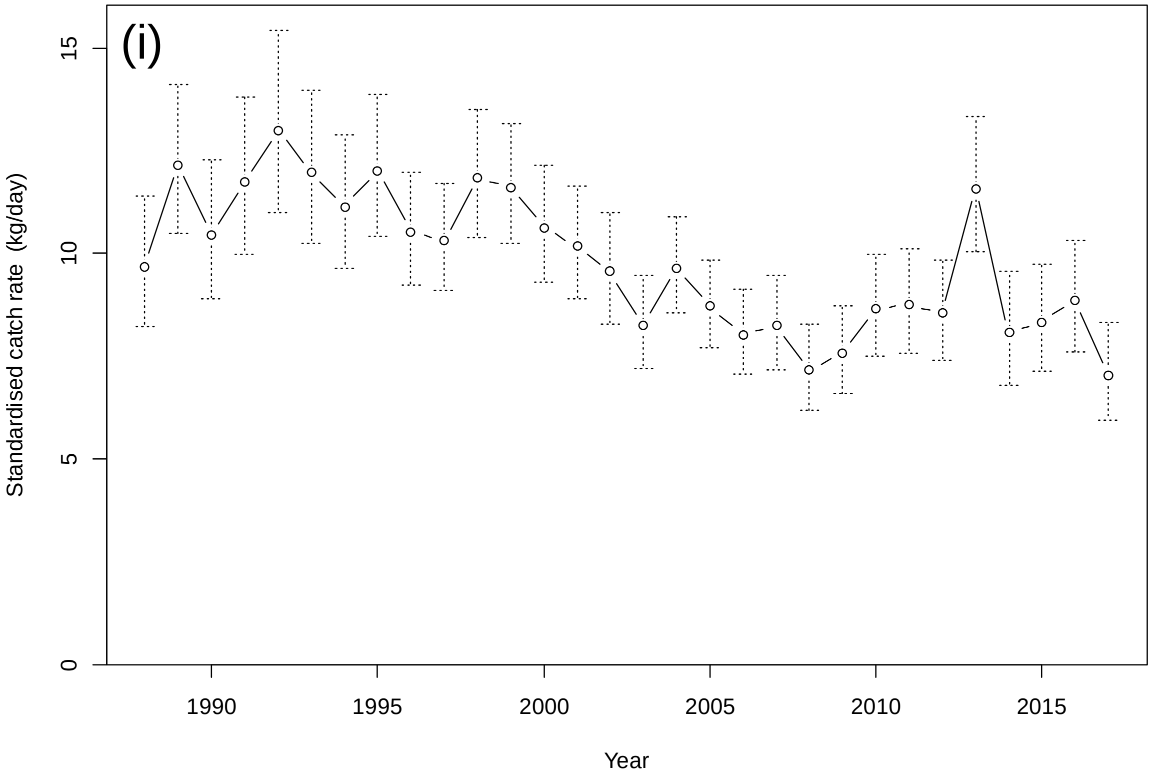


Figure 3.2 (continued): (i) flathead Fraser gillnetting, Poisson GLM untransformed.

4. Population model

4.1 Model overview

The population model was structured by age, length and (in the case of flathead) sex, and was given the name SAIGE, standing for Stock Assessment with Individual Growth Equations. It is similar to the model used for the 2017 tailor stock assessment (Leigh et al., 2017) but has some important improvements, including the ability to handle dome-shaped vulnerability to fishing, whereby vulnerability decreases above some length. In programming, the major difference from the tailor model is that growth of fish is projected backward in time instead of forward: for each possible length of a fish in year t, its possible lengths in years $t - 1$, $t - 2$, etc. are considered in reconstructing its length history and hence its history of vulnerability to fishing.

Structuring by length in addition to age for bream, whiting and flathead allowed the model to take detailed account of the minimum legal sizes for these species, and the changes in minimum legal sizes over time. This model also includes individual variability in growth, equivalent to growth-type groups (Punt et al., 2001) but modelled continuously so as not to require arbitrarily selected discrete values for the asymptotic length L_∞.

A feature of the SAIGE model is the decoupling of its reference lengths, used in the population dynamics, from the lengths used in length-frequency and age-at-length data. This allows growth to be modelled smoothly and the precision of the model to be chosen independently of the length data.

The types of possible growth of individual fish in the SAIGE model are illustrated in Figure 4.1. The most general model is that the individual length at age zero, denoted L_0, and old-age asymptotic length L_∞ follow independent normal distributions; lengths at intermediate ages follow an individual von Bertalanffy growth curve (the equation for which is given in the model description below).

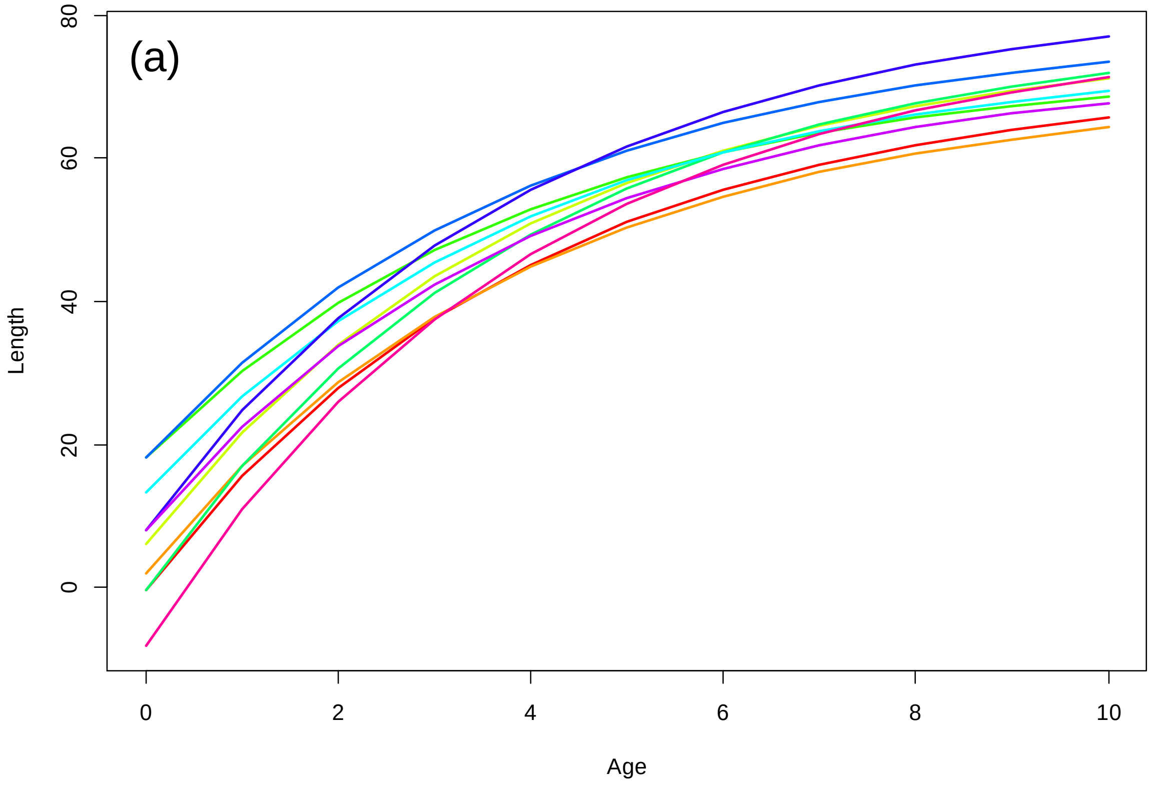
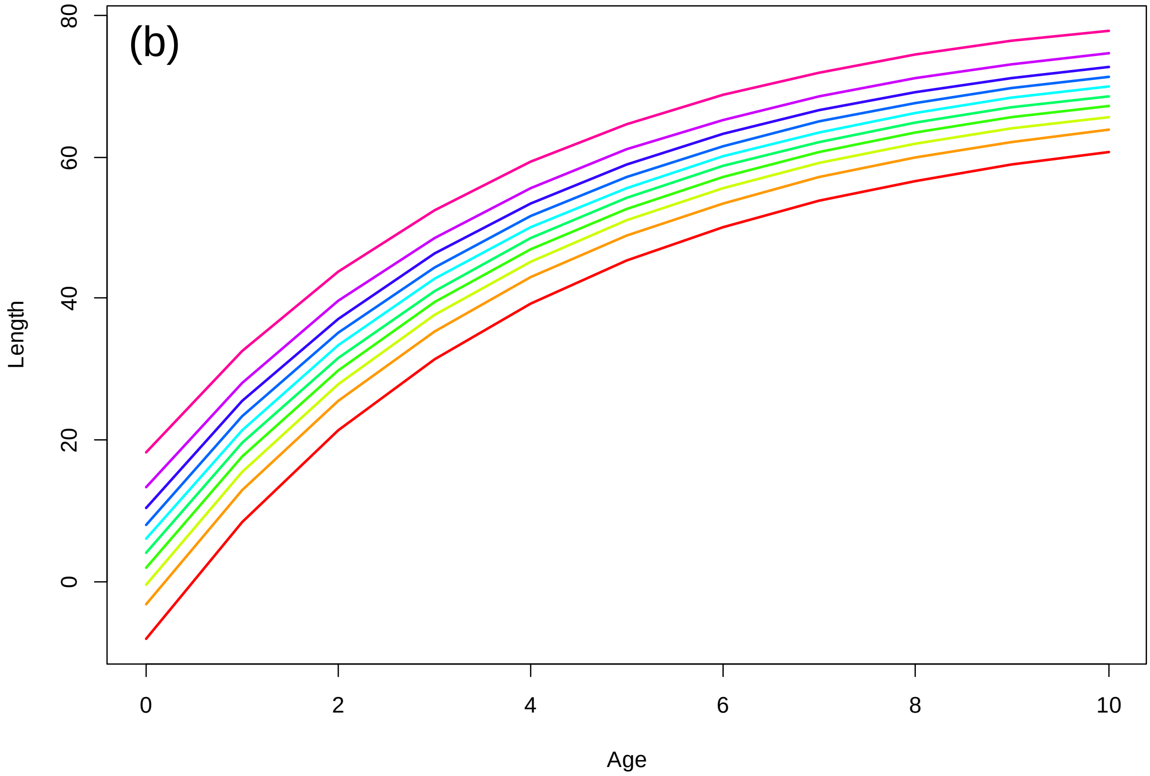


Figure 4.1: Types of growth handled by the SAIGE model. In (a), growth is random at all ages: the length L_0 at age 0 and the old-age asymptotic length L_∞ follow independent normal distributions and length follows an individual von Bertalanffy growth curve. In (b), growth is deterministic from one reference length (quantile of a normal distribution) to the corresponding reference length at the next age. In (c), growth is random up to some age (here age 5) and deterministic thereafter; vulnerability to fishing is allowed to decrease (i.e., become dome-shaped) beyond that age. Fish with negative lengths at a particular age have not yet been born by the time fishing takes place and do not yet contribute to the population. (Continued on next page)



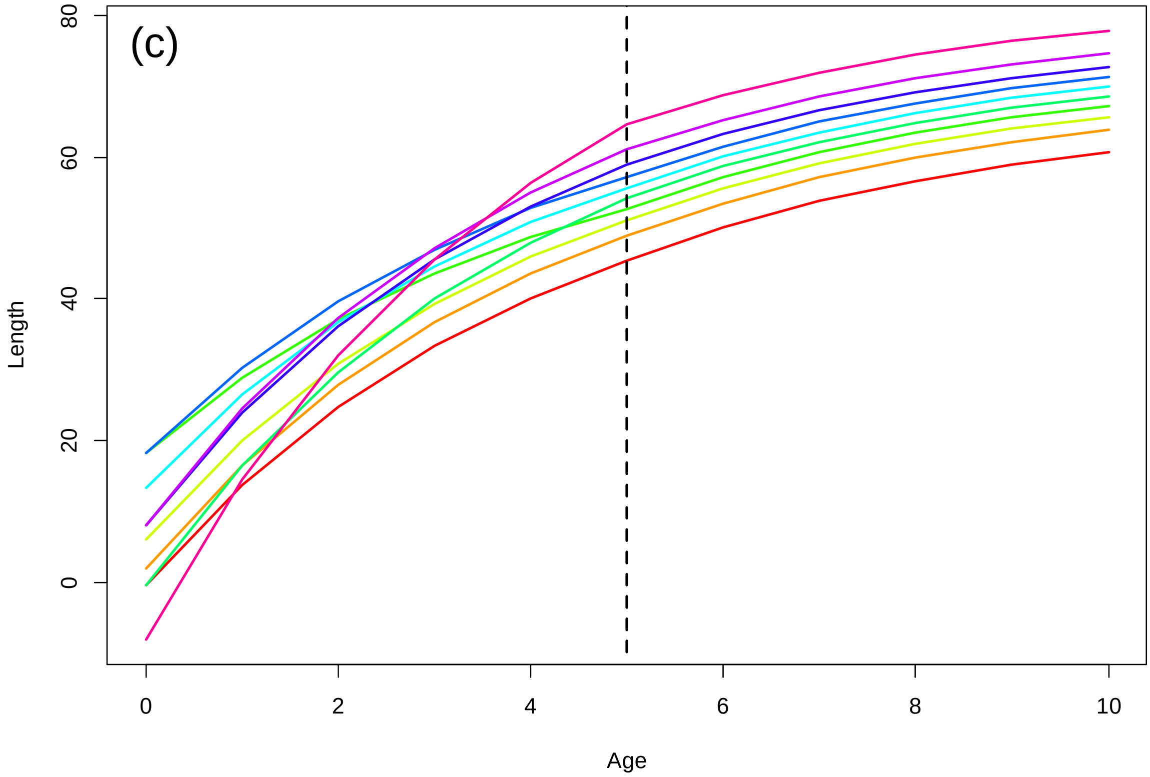


Figure 4.1, continued from previous page.

The simplest growth model is that fish grow deterministically from one reference length (percentile of a normal distribution) to the corresponding reference length at the next age (Figure 4.1(b)). This provides rapid computation and allows arbitrary fishing vulnerability functions.

An intermediate or 'hybrid' growth model is that fish grow randomly up to some threshold age and grow deterministically after that (Figure 4.1(c)). Beyond the threshold age, vulnerability to fishing is allowed to decrease (i.e., become 'dome-shaped') with increasing length. The threshold age can vary with individual fish to allow decreasing vulnerability at an earlier age for fish that happen to reach the maximum-vulnerability length quickly.

We note that none of these growth models requires any adjustment to stop animals from growing backwards, which is a common problem in matrix population models (Punt et al., 2016).

For each length in each year, for each age up to the threshold age (which may itself depend on length and year if dome-shaped vulnerability is present), the number of fish present is determined by considering possible lengths at earlier ages in, which provide the history of vulnerability to fishing. An example is the highest trajectory for age 4–10 in Figure 4.1(c). Normally we would expect such a large fish to have also been relatively large in previous years, hence more exposed to fishing and have had less chance of surviving to age 4. In this case, however, the fish was by chance born late in the year, was in fact smaller than the majority of its contemporaries until age 2, so could have had substantially less exposure to fishing and had a greater chance of survival.

The model was coded in both ADMB (Fournier et al., 2011) and R (R Core Team, 2019). ADMB was used to do the optimisation to produce maximum-likelihood estimates, and Markov chain Monte Carlo (MCMC). The R version provided extra detail, reference points and plots.

4.2 Assumptions and terminology

The model is based on the following assumptions:

1. The size (or length) 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 μ and variance σ^2.
2. Each animal grows according to an individual von Bertalanffy growth function. The growth rate K is constant and asymptotic size L_∞ is normally distributed, independently of L_0, with some mean λ and variance ρ^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, but this is not a requirement of the model. Fecundity can also depend on age.
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 fishing, it remains vulnerable up to a threshold age which is either pre-set or the age at which it reach maximum vulnerability to fishing. More simply expressed, the animals exposed to fishing this year are those that were already exposed last year, with the addition of some more that have grown big enough to be newly exposed to fishing. Above the threshold age this assumption does not apply.

8. Above its threshold age, an animal grows deterministically to the corresponding quantile of length at the next age. The threshold age is conceived as an age at which the animal is already highly vulnerable to fishing, so for vulnerability calculations its exact growth trajectory beyond that age is irrelevant.
9. 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 9 simplifies the model's equations but has little impact on the results for fish with life spans of more than a few years. The major alternative assumption would be a Ricker Type 2 fishery in which fishing effort is assumed constant right through the year: compared to a Type 1 fishery, a Type 2 fishery leads to more complex but still tractable equations. For animals with short life spans, greater flexibility would be provided by a monthly model instead of an annual one.

The standard size-based vulnerability function *V*(*L*) for use in assumption 6 is the logistic function which is a monotonic increasing function of size:

$$V(L) = 1 \big/ \left[1 + \exp\left\{-(\log 19)\,(L - L_{50}) \big/ (L_{95} - L_{50})\right\}\right], \tag{4.1}$$

where L_{50} is the size at 50 per cent vulnerability and L_{95} is the size at 95 per cent vulnerability (see, e.g., Haddon, 2001, p. 353).

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 μ, σ, λ and ρ 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, for example, a monthly time step may be used. Then the stock–recruitment relationship (see Section 4.7 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 Individual growth equations

The equations here are the same as those for the tailor model (Leigh et al., 2017, ch. 4), except that the ages *v* and *a* in equations (4.4) and (4.7) have been swapped to highlight that projection of lengths is now done backwards in time instead of forwards. All the equations are reproduced here for convenience.

Growth of an animal follows an individual-specific von Bertalanffy growth function: its size at age *a* is

$$L_a = L_\infty \left\{1 - e^{-K(a - a_0)}\right\} \tag{4.2}$$

where the individual-specific parameter a_0 is the theoretical age at size zero; parameters L_∞ (individual-specific) and *K* (the same for all animals) 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 (4.2),

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

from which

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

Substituting this expression for a_0 into (4.2) provides the von Bertalanffy growth function in terms of the parameters (L_0, L_∞, K) as

$$L_a = \gamma^a L_0 + (1 - \gamma^a) L_\infty \tag{4.3}$$

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

$$L_v = \gamma^{v-a} L_a + (1 - \gamma^{v-a}) L_\infty , \tag{4.4}$$

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

We define the variable

$$X_a = -(1 - \gamma^a)\rho^2 L_0 + \gamma^a \sigma^2 L_\infty \tag{4.5}$$

so that it is uncorrelated with L_a, as can be seen from taking the covariance with equation (4.3). Because L_a and X_a follow a bivariate normal distribution, being uncorrelated also means that they are independent. Solving the 2×2 linear system given by equations (4.3) and (4.5) yields L_∞ in terms of L_a and X_a:

$$L_\infty = \{(1 - \gamma^a)\rho^2 L_a + \gamma^a X_a\} / \{(1 - \gamma^a)^2 \rho^2 + \gamma^{2a}\sigma^2\}. \tag{4.6}$$

Substituting this expression for L_∞ into the right-hand side of (4.4), L_v can be written in terms of L_a and X_a. After some manipulation,

$$L_v = \frac{\{(1-\gamma^a)(1-\gamma^v)\rho^2 + \gamma^{a+v}\sigma^2\} L_a + (\gamma^a - \gamma^v) X_a}{(1-\gamma^a)^2 \rho^2 + \gamma^{2a}\sigma^2} = p_{va}\, L_a + q_{va}\, X_a \tag{4.7}$$

where $p_{a\,v}$ and $q_{a\,v}$ are defined for convenience to be the coefficients of L_v and X_v in the middle expression in (4.7).

The variables L_a and X_a are normally distributed and independent. From (4.3), the mean and variance of L_a are, respectively,

$$\mu_a = \gamma^a \mu + (1 - \gamma^a)\lambda \tag{4.8}$$

and

$$\sigma_a^2 = \gamma^{2a}\sigma^2 + (1 - \gamma^a)^2 \rho^2 , \tag{4.9}$$

while from (4.5) those of X_a are

$$\mu_{X\,a} = -(1 - \gamma^a)\rho^2 \mu + \gamma^a \sigma^2 \lambda \tag{4.10}$$

and

$$\sigma_{X\,a}^2 = (1 - \gamma^a)^2 \rho^4 \sigma^2 + \gamma^{2a} \sigma^4 \rho^2 . \tag{4.11}$$

4.4 Exploitable biomass, harvest rates and multiple fishing fleets

The model handles multiple fishing fleets $f = 1, \ldots, f_{\max}$ with separate size-dependent vulnerability functions $V_f(L)$. A commonly used vulnerability function is the logistic one (4.1) which we make fleet-specific:

$$V_f(L) = 1\Big/\left[1 + \exp\left\{-(\log 19)\,(L - L_{50\,f})\big/(L_{95\,f} - L_{50\,f})\right\}\right]. \tag{4.12}$$

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

A typical dome-shaped vulnerability function is a 'double logistic' which consists of an increasing and a decreasing logistic function multiplied together. In its full parameterisation this function contains four parameters, an L_{50} and an L_{diff} parameter for each logistic function, but a two-parameter version is to keep these parameters common between the two logistic functions:

$$V_f(L) = 4\Big/\left[\left(1 + \exp\left\{-(\log 19)\,(L - L_{50\,f})\big/L_{\mathrm{diff}\,f}\right\}\right)\left(1 + \exp\left\{(\log 19)\,(L - L_{50\,f})\big/L_{\mathrm{diff}\,f}\right\}\right)\right]. \tag{4.13}$$

The parameter $L_{50\,f}$ is now the size at 100 per cent vulnerability and $L_{50\,f} \pm L_{\mathrm{diff}\,f}$ are the sizes at 19 per cent vulnerability. This function approaches zero at both very small and very large sizes.

The model records the start-of-fishing-season number of animals in the population in each year t, age class a and length class ℓ in an array $N_{t\,a\,\ell}$. The model's reference length for age-class a and length-class ℓ is denoted $L_{a\,\ell}$. This reference length is a quantile of the normal distribution with mean μ_a and from equation (4.8) above and variance σ_a^2 from equation (4.9). The number of such reference lengths at each age is fixed, e.g., to 51 or 101 (an odd number allows the mean length μ_a to be included as one of the reference lengths, with equal numbers of other reference lengths on either side of it). For a fishing fleet f, the corresponding vulnerability to fishing at length $L_{a\,\ell}$ is $V_f(L_{a\,\ell})$ which we denote $V_{f\,a\,\ell}$ (with three subscripts).

For a sex-structured model, which is required for flathead where the females grow much bigger than the males, there are separate male and female versions of the population array and most of the other variables. Exploitable biomass is summed over both male and female animals. Spawning biomass consists of female animals only.

The individual weight at length is given by an allometric relationship

$$W = \alpha L^{\beta} \tag{4.14}$$

which is pre-determined from biological data outside the model. The weight of an animal in age-class a and length-class ℓ is

$$W_{a\,\ell} = \alpha L_{a\,\ell}^{\beta}. \tag{4.15}$$

The exploitable (or vulnerable) biomass in year t for fleet f is

$$B_{t\,f} = \sum_a \sum_\ell N_{t\,a\,\ell} W_{a\,\ell} V_{f\,a\,\ell}. \tag{4.16}$$

The corresponding harvest is denoted $C_{t\,f}$. Using the Type 1 fishery assumption (assumption 9 above), natural mortality is negligible within the fishing season and end-of-fishing-season population numbers are

$$N_{t\,a\,\ell}^{(\text{end})} = N_{t\,a\,\ell} \left\{ 1 - \sum_{f} \left(C_{t\,f} \big/ B_{t\,f} \right) V_{f\,a\,\ell} \right\}. \tag{4.17}$$

Mid-season numbers are

$$N_{t\,a\,\ell}^{(\text{mid})} = \sqrt{N_{t\,a\,\ell}\, N_{t\,a\,\ell}^{(\text{end})}} \tag{4.18}$$

and are used for calculating spawning biomass and matching abundance indices and age and length data. The formula for $N_{t\,a\,\ell}^{(\text{mid})}$ is an approximation that avoids having to loop over fleets and should be accurate for practical purposes. An alternative would be to use the numbers after half the harvest has been taken, which would give

$$N_{t\,a\,\ell}^{(\text{mid})} = \tfrac{1}{2} \left(N_{t\,a\,\ell} + N_{t\,a\,\ell}^{(\text{end})} \right)$$

and doesn't require looping over fleets, but this formula is inaccurate when the level of fishing is very high, because the time at which half the harvest has been taken can be early in the season and not correspond well to the time at which abundance estimates are measured or length and age samples are taken.

The mid-season and end-of-season biomasses for fleet *f* are

$$B_{t\,f}^{(\text{mid})} = \sum_{a} \sum_{\ell} N_{t\,a\,\ell}^{(\text{mid})}\, W_{a\,\ell}\, V_{f\,a\,\ell} \tag{4.19}$$

and

$$B_{t\,f}^{(\text{end})} = \sum_{a} \sum_{\ell} N_{t\,a\,\ell}^{(\text{end})}\, W_{a\,\ell}\, V_{f\,a\,\ell} \tag{4.20}$$

and the harvest of the fleet-*f* exploitable biomass by all fleets combined is

$$C_{t\,f}^{(\text{all})} = B_{t\,f} - B_{t\,f}^{(\text{end})}\,. \tag{4.21}$$

The proportion of this harvest taken by fleet *f* is

$$C_{t\,f} \big/ C_{t\,f}^{(\text{all})}.$$

Let $F_{t\,f}$ be the fishing mortality rate applied in year *t* by fleet *f*, expressed as an equivalent whole-year instantaneous rate: if there were no competing fleets, $F_{t\,f}$ would be defined as the negative log of the probability of surviving fishing:

$$F_{t\,f} = -\log\left\{ \left(B_{t\,f} - C_{t\,f} \right) \big/ B_{t\,f} \right\}.$$

In the presence of competing fleets this is no longer true for an individual fleet, as the biomass will be depleted by the other fleets during the season and fleet *f* would have to fish harder to take the same harvest. The equation is, however, still true for the combination of all fleets, and we can define

$$F_{t\,f}^{(\text{all})} = -\log\left(B_{t\,f}^{(\text{end})} \big/ B_{t\,f} \right). \tag{4.22}$$

Then we use the result that the ratio of instantaneous fishing mortality rates for the different fleets is the same as the ratio of harvests, which comes from the well-known Baranov catch equation and provides the equation

$$F_{t\,f} \big/ F_{t\,f}^{(\mathrm{all})} = C_{t\,f} \big/ C_{t\,f}^{(\mathrm{all})}$$

and hence

$$F_{t\,f} = \left(C_{t\,f} \big/ C_{t\,f}^{(\mathrm{all})} \right) F_{t\,f}^{(\mathrm{all})} = -\left(C_{t\,f} \big/ C_{t\,f}^{(\mathrm{all})} \right) \log\left(B_{t\,f}^{(\mathrm{end})} \big/ B_{t\,f} \right). \tag{4.23}$$

This equation still involves an approximation whereby, within the fleet-*f* exploitable biomass, all the other fleets target the different length classes in the same proportions as fleet *f* does. We believe that this approximation is sufficiently accurate for practical cases.

We define the harvest rate for fleet *f* as

$$U_{t\,f} = 1 - \exp(-F_{t\,f}) = 1 - \left(B_{t\,f}^{(\mathrm{end})} \big/ B_{t\,f} \right)^{C_{t\,f} / C_{t\,f}^{(\mathrm{all})}} . \tag{4.24}$$

This harvest rate is applied to the animals that, in year *t*, are vulnerable to fleet *f*. Then the model's equation for projecting population numbers to the end of the season is transformed from the summation formulation (4.17) to a product formulation representing fishing fleets that act as independent, competing hazards on the population:

$$N_{t\,a\,\ell}^{(\mathrm{end})} = N_{t\,a\,\ell} \prod_{f} \left(1 - U_{t\,f} V_{f\,a\,\ell} \right). \tag{4.25}$$

4.5 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 $L_{t\,f}^{\mathrm{MLS}}$. 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 (4.12) with parameters $L_{t\,f}^{\mathrm{MLS}}$ and $L_{\mathrm{diff}}^{\mathrm{MLS}}$. We denote the resulting logistic function $V_{t\,f}^{\mathrm{MLS}}(L)$.

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

$$V_{t\,f}^{(K)}(L) = V_{t\,f}^{\mathrm{MLS}}(L)\, V_{f}(L) \tag{4.26}$$

$$V_{t\,f}^{(D)}(L) = D V_{f}(L) + (1 - D)\, V_{t\,f}^{(K)}(L). \tag{4.27}$$

Equations (4.16), (4.17), (4.19), (4.20) and (4.25) are converted to

$$B_{t\,f} = \sum_{a} \sum_{\ell} N_{t\,a\,\ell} W_{a\,\ell} V_{t\,f\,a\,\ell}^{(K)} . \tag{4.28}$$

$$N_{t\,a\,\ell}^{(\mathrm{end})} = N_{t\,a\,\ell} \left\{ 1 - \sum_{f} \left(C_{t\,f} \big/ B_{t\,f} \right) V_{t\,f\,a\,\ell}^{(D)} \right\}. \tag{4.29}$$

$$B_{t\,f}^{(\text{mid})} = \sum_a \sum_\ell N_{t\,a\,\ell}^{(\text{mid})} W_{a\,\ell} V_{t\,f\,a\,\ell}^{(K)} \tag{4.30}$$

$$B_{t\,f}^{(\text{end})} = \sum_a \sum_\ell N_{t\,a\,\ell}^{(\text{end})} W_{a\,\ell} V_{t\,f\,a\,\ell}^{(K)} \tag{4.31}$$

and

$$N_{t\,a\,\ell}^{(\text{end})} = N_{t\,a\,\ell} \prod_f \left(1 - U_{t\,f} V_{t\,f\,a\,\ell}^{(D)}\right), \tag{4.32}$$

where the subscript *t* has been inserted to clarify that the vulnerability functions may now vary with year according to changes in the MLS.

Very similar adjustments work for maximum legal sizes when they are applied; the only difference is that, similarly to the right-hand logistic function in the double logistic vulnerability function (see equation (4.13) above), the logistic function is monotonic decreasing instead of monotonic increasing. A maximum legal size implies dome-shaped vulnerability, the handling of which is described in Section 4.1 above.

4.6 Projection of population numbers

Let $v_{\min}$ be the minimum age at first vulnerability to fishing. For ages less than or equal to $v_{\min}$ the population numbers are the same as the unfished population numbers, which we denote $N_{0\,a\,\ell}$.

For ages above the age threshold described in Sections 4.1 and 4.2, projection of population numbers is simple, based on ‘quantile to quantile’ growth: an animal simply grows from reference length $L_{a-1\,\ell}$ at age *a* – 1 in year *t* – 1, to reference length $L_{a\,\ell}$ at age *a* in year *t*, and the number of animals in that age–size class is multiplied by e^{-M}:

$$N_{t\,a\,\ell} = e^{-M} N_{t-1,\,a-1,\,\ell}^{(\text{end})}\,. \tag{4.33}$$

For ages greater than $v_{\min}$ but below the threshold age, we cast an animal’s length backwards in time to take account of its history of vulnerability to fishing. Conditional on an animal’s size at age *a* in year *t*, its size at some previous age *v* at which the animal may have been vulnerable to fishing is normal according to equation (4.7). We discretise this distribution using the model’s reference lengths $L_{v\,\ell}$ and find the expected vulnerability to fleet *f* at age *v* as

$$w_{t\,f\,a\,v\,\ell} = E\left(V_{t-v+a,\,f\,v\,\ell'}^{(D)} \,\middle|\, a, \ell\right) \tag{4.34}$$

where the expectation is over the length class ℓ' at the earlier age *v*, and is conditional on the age *a* and the length class ℓ at age *a*.

Let t_0 be the year in which fishing began. Then the probability that an animal of age *a* in length class ℓ in year *t first became* vulnerable to fleet *f* at age *v* is given by

$$w_{t\,f\,a\,v\,\ell}^{(\text{first})} = \begin{cases} 0 & \text{if } v < v_{\min} \text{ or } t - a + v < t_0 \\ w_{t\,f\,a\,v\,\ell} & \text{if } v = v_{\min} \text{ and } t - a + v \ge t_0 \\ w_{t\,f\,a\,v\,\ell} - w_{t\,f\,a,\,v-1,\,\ell} & \text{if } v > v_{\min} \text{ and } t - a + v \ge t_0\,. \end{cases} \tag{4.35}$$

Finally, the equation for the number of animals of age *a* in length class ℓ in year *t* is

$$N_{t\,a\,\ell} = N_{0\,a\,\ell} \prod_{f} \left[\left(1 - \sum_{v=v_{\min}}^{a-1} w_{t\,f\,a\,v\,\ell}^{(\text{first})} \right) + \sum_{v=v_{\min}}^{a-1} \left\{ w_{t\,f\,a\,v\,\ell}^{(\text{first})} \prod_{t'=t-a+v}^{t-1} \left(1 - U_{t'\,f} \right) \right\} \right]. \tag{4.36}$$

The first expression in round brackets represents the animals that were not vulnerable to fishing by fleet *f* in previous years, and hence are not multiplied by any fishing-related depletion factor. The second sum is for animals that previously became vulnerable at an earlier age *v* and whose numbers have therefore been depleted by fishing in every year since then. This formulation uses assumption 7 in Section 4.2 above, whereby animals that became vulnerable to fleet *f* in a previous year (*t* – *a* + *v*) have remained vulnerable in every year t' since then.

4.7 Spawning biomass and recruitment

The total spawning biomass in year *t* is

$$S_t = \sum_a \sum_\ell N_{t\,a\,\ell}^{(\text{mid})} \, m_a \, \text{fec}_{a\,\ell} \, W_{a\,\ell} \,,$$

where $N_{t\,a\,\ell}^{(\text{mid})}$ is defined by equation (4.18), m_a is the proportion of individuals mature at age *a* (see assumption 4 in Section 4.2 above), $\text{fec}_{a\,\ell}$ is an optional fecundity factor in case fecundity of an animal is not proportional to its weight, and $W_{a\,\ell}$ is the animal's weight given by equation (4.15).

Recruitment of new individuals to the population is assumed to take place almost one year later: any larval or juvenile natural mortality in the first year of life forms part of the stock–recruitment relationship. We assume a Beverton–Holt (1957) stock recruitment relationship, parameterised as

$$R_{t+1}/R_0 = \frac{r\, S_t/S_0}{1 + (r-1)\, S_t/S_0} \exp(d_{t+1}) \tag{4.37}$$

where R_t is the recruitment at age zero in year *t*, R_0 is the unfished recruitment, S_0 is the unfished 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 and normally distributed with mean zero; their standard deviation is a model parameter. To enter the recruits into the population matrix, for $v = v_{\min}, \ldots, v_{\max}$,

$$N_{t+1,\,0,\,\ell} = R_{t+1} \, \text{rp}_\ell$$

where rp_ℓ denotes the recruitment proportion of animals of age zero into length class ℓ in an unfished population, which is normally distributed according to assumption 1 in Section 4.2 above.

The model also takes account of recruitment deviations in calculating the population numbers in Section 4.6: the right-hand side of equation (4.36) is in fact multiplied by $\exp(d_{t-a})$ if the model contains a recruitment deviation in year *t* – *a*. For ease of readability, equation (4.36) does not show this factor.

4.8 Predictions for matching to data

4.8.1 Catch rates

Fishery catch rates (see chapter 3) are fleet-specific and assumed to be proportional to mid-season exploitable biomass, which is given by equation (4.19) or (4.30).

4.8.2 Size frequency and age-at-length

Predicted age–size frequencies are found using mid-season population numbers (equation (4.18)) and, for fishery-dependent sampling, multiplying by the appropriate vulnerability function for the fleet that does the sampling. An extra step in this model is that the sizes (lengths) have to be converted from the model's reference lengths to the size intervals used in the input data which are typically one centimetre in width. This conversion is accomplished by a matrix multiplication.

The predicted age–size frequency is summed over ages to make the predicted size frequency. Then, if age data are present for that sample, the conditional age distribution at each size is used to match the observed size-at-age data.

No assumptions are made about the size distribution of animals that are chosen for ageing. The Fisheries Queensland Fishery Monitoring program has two common protocols for selection of fish for ageing: 'direct ageing', in which a random sample of the fish whose lengths have been measured is taken for ageing; and the 'age–length key' protocol, which attempts to select a pre-set number of fish from each length class, but often there are not enough fish available to fill all the length classes of big fish. The age–length key protocol can also accept fish (typically, large 'trophy' fish) that have not been sampled in a representative manner and hence do not appear in the length-frequency data.

The model assumes that there is no *age* bias in the selection of animals to age, but it allows arbitrary *size* biases in the selection.

By using only the *conditional* distributions of age at length, the model can handle the above protocols and many other potential protocols. It does not need to multiply the length frequency by an age–length key (Friðriksson, 1934) to come up with an estimated age frequency that may have been achieved if every fish had been aged, which could imply spuriously high precision in the age frequencies.

4.9 Matching predictions to data

4.9.1 Catch rates

Elements $Y_{s\,t}$ 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 $\mu_s^{(\mathrm{CR})}$ and $\sigma_{st}^{(\mathrm{CR})}$ respectively be the mean and standard deviation of $\log Y_{s\,t} - B_{t\,f}^{(K,\,\mathrm{mid})}$, where $B_{t\,f}^{(K,\,\mathrm{mid})}$ is given by (4.19). If $\mu_s^{(\mathrm{CR})}$ and $\sigma_{st}^{(\mathrm{CR})}$ are specified, the likelihood of series *s* is

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

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

$$\ell_{Ys} = \sum_t \left\{ \log \sigma_{st}^{(\mathrm{CR})} + \tfrac{1}{2} \left(\log Y_{st} - \log B_{t\,f}^{(K,\,\mathrm{mid})} - \mu_s^{(\mathrm{CR})} \right)^2 \Big/ \sigma_{st}^{(\mathrm{CR})\,2} \right\}. \tag{4.38}$$

We set the standard deviation $\sigma_{st}^{(\mathrm{CR})}$ to the product of a scale factor $\sigma_{s\,*}^{(\mathrm{CR})} \geq 1$ 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 $\mathrm{CVY}_{s\,t}$. The scale factor $\sigma_{s\,*}^{(\mathrm{CR})}$ accounts for experimental error in the model, additional to experimental error due to finite sample sizes in the GLM which is already captured in $\mathrm{CVY}_{s\,t}$. Such additional experimental error may come from changes in environmental conditions or fish behaviour from year to year. The NLL, omitting constant terms, is

$$\ell_{Ys} = \sum_t \left\{ \log\sigma_{s*}^{(\mathrm{CR})} - \tfrac{1}{2}\log w_{st} + \tfrac{1}{2} w_{st}\left(\log Y_{st} - \log B_{tf}^{(K,\,\mathrm{mid})} - \mu_s^{(\mathrm{CR})}\right)^2 \Big/ \sigma_{s*}^{(\mathrm{CR})\,2} \right\}, \tag{4.39}$$

where $w_{st} = 1\big/\mathrm{CVY}_{st}^2$.

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

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

and

$$\hat{\sigma}_{s*}^{(\mathrm{CR})\,2} = \sum_t \left\{ w_{st}\left(\log Y_{st} - \log B_{tf}^{(K,\,\mathrm{mid})} - \hat{\mu}_{Ys}\right)^2 \right\} \Big/ (n_{Ys} - 1)\,, \tag{4.40}$$

where $n_{Y\,s}$ is the number of years of catch-rate data in series *s*. Substituting these expressions into (4.39) provides a likelihood that depends only on data ($Y_{s\,t}$ and $w_{s\,t}$) and model predictions ($B_{tf}^{(K,\,\mathrm{mid})}$):

$$\ell_Y = \sum_s (n_{Ys} - 1)\left(\log\tilde{\sigma}_{s*}^{(\mathrm{CR})} + \tfrac{1}{2}\hat{\sigma}_{s*}^{(\mathrm{CR})\,2} \Big/ \tilde{\sigma}_{s*}^{(\mathrm{CR})\,2}\right), \tag{4.41}$$

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

$$\tilde{\sigma}_{s*}^{(\mathrm{CR})} = \max\left(\hat{\sigma}_{s*}^{(\mathrm{CR})}, \sigma_{\min}^{(\mathrm{CR})}\right). \tag{4.42}$$

The factor applied to $\log\,\tilde{\sigma}_{Y\,s}$ in (4.41) is $n_{Y\,s} - 1$ instead of $n_{Y\,s}$ as a correction for the need to estimate $\mu_s^{(\mathrm{CR})}$ by $\hat{\mu}_s^{(\mathrm{CR})}$. Formula (4.41) is similar to the negative log-likelihood derived by Haddon (2001, p. 89) but includes the adjustment term for the lower bound on $\sigma_{s*}^{(\mathrm{CR})}$.

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 $\hat{\sigma}_Y$ either, but to use $\hat{\sigma}_Y^2$ directly from (4.40), because $\hat{\sigma}_Y$ involves a square root which causes trouble if $\hat{\sigma}_Y^2 = 0$. Therefore we used the following expression for $\tilde{\sigma}_Y$:

$$\tilde{\sigma}_{s*}^{(\mathrm{CR})} = \sqrt{\tfrac{1}{2}\left(\hat{\sigma}_{s*}^{(\mathrm{CR})\,2} + \sigma_{\min}^{(\mathrm{CR})\,2}\right) + \sqrt{\tfrac{1}{4}\left(\hat{\sigma}_{s*}^{(\mathrm{CR})\,2} - \sigma_{\min}^{(\mathrm{CR})\,2}\right)^2 + 4\delta^2\sigma_{\min}^{(\mathrm{CR})\,4}}}\;, \tag{4.43}$$

where $\delta > 0$ is a smoothness parameter that took the value 0.1. The value $\delta = 0$ makes (4.43) the same as (4.42), which is the formula that has to be avoided. The smoothing has the side effect of shifting the value of $\tilde{\sigma}_{s*}^{(\mathrm{CR})\,2}$ at $\sigma_{\min}^{(\mathrm{CR})}$ up to approximately $(1 + \delta)\,\sigma_{\min}^{(\mathrm{CR})\,2}$ instead of the desired value of $\sigma_{\min}^{(\mathrm{CR})\,2}$. The value $\delta = 0.1$ shifts $\tilde{\sigma}_{s*}^{(\mathrm{CR})\,2}$ up about 10% and $\tilde{\sigma}_{s*}^{(\mathrm{CR})}$ up about 5%, which we believed was a reasonable compromise.

The overall negative log-likelihood for catch rates is the sum of (4.41) over *s*, i.e., over all the catch rate series that are available.

4.9.2 Size frequency

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

$$\binom{y_{t\ f\ \mathrm{tot}}}{y_{t\,f\,1},\ldots,y_{t\ f\ n^{(LF)}}}\prod_{k=1}^{n^{(LF)}} p_{t\,f\,k}{}^{y_{t\,f\,k}}, \tag{4.44}$$

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

$$\binom{y_{t\ f\ \mathrm{tot}}}{y_{t\,f\,1},\ldots,y_{t\ f\ n^{(LF)}}} = y_{t\ f\ \mathrm{tot}}!\bigg/\prod_{k=1}^{n^{(LF)}} y_{t\,f\,k}!,$$

and the factorial function is defined as

$$y! = \prod_{j=1}^{y} j.$$

In practice, animals sampled from fishery populations are not independent, and instead of the total number $y_{t\ f\ \mathrm{tot}}$ 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 $y_{t\ f\ \mathrm{tot}}$.

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 $y_{t\ f\ \mathrm{tot}}$ in (4.44) 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 (4.44) becomes

$$\left\{ y_{t\ f\ \mathrm{tot}}!\bigg/\prod_{k\in Q_{t\,f}} y_{t\,f\,k}! \right\} \prod_{k\in Q_{t\,f}} p_{t\,f\,k}{}^{y_{t\,f\,k}}. \tag{4.45}$$

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 $y_{t\ f\ \mathrm{tot}}$ is transformed to an effective observation of $\left(T_{t\,f}/y_{t\,f\ \mathrm{tot}}\right)y_{t\ f\ a}$ animals from a sample of size $T_{t\,f}$. We also treat the likelihood (4.45) 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 $y_{t\ f\ \mathrm{tot}}$. The transformed likelihood has to remain a p.d.f. of $y_{t\,f\,k}$, not of $\left(T_{t\,f}/y_{t\ f\ \mathrm{tot}}\right)y_{t\ f\ k}$, which necessitates multiplying by the factor $\left(T_{t\,f}/y_{t\ f\ \mathrm{tot}}\right)^{q-1}$. Therefore the likelihood (4.45) is transformed to

$$\left(T_{t\,f}/y_{t\,f\,\text{tot}}\right)^{q-1}\left\{T_{t\,f}!\Big/\prod_{k\in Q_{t\,f}}\left(T_{t\,f}\;y_{t\,f\,k}/y_{t\,f\,\text{tot}}\right)!\right\}\prod_{k\in Q_{t\,f}} p_{t\,f\,k}{}^{T_{t\,f}\;y_{t\,f\,k}/y_{t\,f\,\text{tot}}}\,. \tag{4.46}$$

When $T_{t\,f}\;y_a/y_{t\,f\,\text{tot}}$ 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 $x \to \infty$, 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 (4.46) becomes

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

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

$$\ell_{t\,f}^{(\text{LF})}=-\tfrac{1}{2}(q_{t\,f}-1)\log T+T\sum_{k\in Q_{t\,f}}\hat{p}_{t\,f\,k}\log\!\left(\hat{p}_{t\,f\,k}/p_{t\,f\,k}\right). \tag{4.47}$$

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 (4.47):

$$\hat{T}=\tfrac{1}{2}(q_{t\,f}-1)\Big/\sum_{k\in Q_{t\,f}}\hat{p}_{t\,f\,k}\log\!\left(\hat{p}_{t\,f\,k}/p_{t\,f\,k}\right). \tag{4.48}$$

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, $2T\sum\hat{p}_{t\,f\,k}\log\!\left(\hat{p}_{t\,f\,k}/p_{t\,f\,k}\right)$ to its asymptotic, large-sample expectation $q_{t\,f}-1$. Substituting the estimate (4.48) into the negative log-likelihood (4.47) and ignoring the resulting constant term yields the final negative log-likelihood for the size-frequency sample:

$$\ell_{t\,f}^{(\text{LF})}=-\tfrac{1}{2}(q_{t\,f}-1)\log\hat{T}_{t\,f}\,. \tag{4.49}$$

For every available size-frequency sample, the negative log-likelihood given by (4.49) and (4.48) 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

$$-\tfrac{1}{2}(q_{t\,f}-1)\log\tilde{T}_{t\,f}+\tfrac{1}{2}(q_{t\,f}-1)\tilde{T}_{t\,f}\big/\hat{T}_{t\,f}\,, \tag{4.50}$$

where $\tilde{T}_{t\,f} = \min(\max(\hat{T}_{t\,f}\,, T_{\min}), T_{\max})$. For size-frequencies we impose upper bounds equal to the actual sample sizes, with a maximum of 1000, which corresponds to an extremely informative sample. We did not consider it necessary to apply any lower bounds on the effective sample size.

4.9.3 Age at size

An age-at-size frequency in size class *k* from fleet *f* in year *t* consists of a number of animals $y_{t\,f\,k\,a}$ measured in each age class *a*. When each animal is considered to be independent of all other animals, the likelihood of an age-at-size frequency is multinomial, identically to the likelihood of size-frequency data :

$$\binom{y_{t\,f\,k\,\mathrm{tot}}}{y_{t\,f\,k1}, \ldots, y_{t\,f\,k\,n^{(AF)}}} \prod_{a=1}^{n^{(AF)}} p_{t\,f\,k\,a}^{\;y_{t\,f\,k\,a}}, \tag{4.51}$$

where $y_{t\,f\,k\mathrm{tot}}$ is the total number of animals measured in sample (*t*, *f*, *k*) (sum of the $y_{t\,f\,k\,a}$ over *a*), and $p_{t\,f\,k\,a}$ is the model's predicted proportion of animals from age class *a*.

The treatment of effective sample size for age-at-size data is the same as for size-frequency data as described above, except that the ratio of effective sample size to true sample size is forced to be the same for all length classes *k* in a sample (*t*, *f*) from year *t* and fleet *f*. The ratio

$$\theta_{t\,f} = T_{t\,f\,k} \big/ y_{t\,f\,k\mathrm{tot}} \tag{4.52}$$

is the same over all length classes and does not depend on *k*. This modification prevents the effective sample size from varying wildly between individual age-at-size samples for different fish sizes, each of which may contain only a few fish.

With the inclusion of the parameter $\theta_{t\,f}$, the negative log-likelihood for the sample in year *t* from fleet *f* becomes

$$\ell_{t\,f}^{(\mathrm{AF})} = -\tfrac{1}{2}\left(\log\theta_{t\,f}\right) \sum_{k\in Q_{t\,f}} (q_{t\,f\,k} - 1) + \theta_{t\,f} \sum_{k\in Q_{t\,f}} \left\{ y_{t\,f\,k\,\mathrm{tot}} \sum_{a\in Q_{t\,f\,k}} \hat{p}_{t\,f\,k\,a} \log\left(\hat{p}_{t\,f\,k\,a} \big/ p_{t\,f\,k\,a}\right) \right\}. \tag{4.53}$$

The parameter $\theta_{t\,f}$ is estimated by maximum likelihood, by minimising the negative log-likelihood (4.53):

$$\hat{\theta}_{t\,f} = \tfrac{1}{2} \sum_{k\in Q_{t\,f}} (q_{t\,f\,k} - 1) \Bigg/ \sum_{k\in Q_{t\,f}} \left\{ y_{t\,f\,k\,\mathrm{tot}} \sum_{a\in Q_{t\,f\,k}} \hat{p}_{t\,f\,k\,a} \log\left(\hat{p}_{t\,f\,k\,a} \big/ p_{t\,f\,k\,a}\right) \right\}. \tag{4.54}$$

Substituting the estimate (4.54) into the negative log-likelihood (4.53) and ignoring the resulting constant term yields the final negative log-likelihood for the age-at-size sample:

$$\ell_{t\,f}^{(\mathrm{AF})} = -\tfrac{1}{2}\left(\log\hat{\theta}_{t\,f}\right) \sum_{k\in Q_{t\,f}} (q_{t\,f\,k} - 1). \tag{4.55}$$

For every available age-at-length sample, the negative log-likelihood given by (4.55) and (4.54) is added into the overall negative log-likelihood for the model. Using this formulation it would be easy to impose lower and upper bounds $\theta_{\min}$ and $\theta_{\max}$ on the scale factor $\theta_{t\,f}$. The negative log-likelihood for such a case is

$$\tfrac{1}{2}\left(-\log\tilde{\theta}_{t\,f} + \tilde{\theta}_{t\,f} \big/ \hat{\theta}_{t\,f}\right) \sum_{k\in Q_{t\,f}} (q_{t\,f\,k} - 1), \tag{4.56}$$

where $\tilde{\theta}_{tf} = \min(\max(\hat{\theta}_{tf}, \theta_{\min}), \theta_{\max})$. We imposed upper bounds equal to 1, corresponding to effective sample sizes equal to actual sample sizes.

4.9.4 Recruitment deviations

The log-recruitment deviations d_t (see equation (4.37) above) were assumed to follow a normal distribution with mean zero and standard deviation $\sigma^{(\mathrm{RD})}$, although they were constrained to sum to zero. They were treated similarly to the relative abundance indices in Section 4.9.1 and produced a single term to add into the overall negative log-likelihood.

When applied to recruitment deviations the negative log-likelihood (4.38) becomes

$$\ell^{(\mathrm{RD})} = \sum_t \left\{ \log \sigma^{(\mathrm{RD})} + \tfrac{1}{2} d_t^2 \big/ \sigma^{(\mathrm{RD})\,2} \right\}. \tag{4.57}$$

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

$$\hat{\sigma}^{(\mathrm{RD})\,2} = \sum_t d_t^2 \Big/ \left(n^{(\mathrm{RD})} - 1 \right),$$

where $n^{(\mathrm{RD})}$ 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 (4.57) provides a data-only version and analogue to (4.41):

$$\ell^{(\mathrm{RD})} = (n^{(\mathrm{RD})} - 1) \left\{ \log \tilde{\sigma}^{(\mathrm{RD})} + \tfrac{1}{2} \hat{\sigma}^{(\mathrm{RD})\,2} \big/ \tilde{\sigma}^{(\mathrm{RD})\,2} \right\}, \tag{4.58}$$

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

$$\tilde{\sigma}^{(\mathrm{RD})} = \min(\max(\hat{\sigma}^{(\mathrm{RD})}, \sigma_{\min}^{(\mathrm{RD})}), \sigma_{\max}^{(\mathrm{RD})}). \tag{4.59}$$

Analogous to (4.43), a derivative-friendly formula for $\tilde{\sigma}^{(\mathrm{RD})}$ is

$$\begin{aligned} 2\tilde{\sigma}^{(\mathrm{RD})\,2} = {} & \sigma_{\min}^{(\mathrm{RD})\,2} + \sigma_{\max}^{(\mathrm{RD})\,2} + \sqrt{\left(\hat{\sigma}^{(\mathrm{RD})\,2} - \sigma_{\min}^{(\mathrm{RD})\,2} \right)^2 + 4\delta^2 \sigma_{\min}^{(\mathrm{RD})\,4}} \\ & - \sqrt{\left(\sigma_{\max}^{(\mathrm{RD})\,2} - \hat{\sigma}^{(\mathrm{RD})\,2} \right)^2 + 4\delta^2 \sigma_{\min}^{(\mathrm{RD})\,4}}. \end{aligned} \tag{4.60}$$

We used bounds of $\sigma_{\min}^{(\mathrm{RD})}$ = 0.1 and $\sigma_{\max}^{(\mathrm{RD})}$ = 0.25.

4.10 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 μ and λ 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.

Symbol	**Description**	**Estimated?**
α, β	Parameters in size–weight relationship; see equation (4.15) and sec. 1.2.2.	No
m_a	Maturity at age (proportion of female fish mature); see sec. 1.2.2 and 4.2.	No
μ	Mean size at age zero, L_0; see Section 4.3	Yes
σ	Standard deviation of size at age zero, L_0; see Section 4.3.	Yes
λ	Mean asymptotic size, L_∞; see Section 4.3; actually parameterised as the mean size at the highest age in the model, for ease of guessing initial values.	Yes
ρ	Standard deviation of asymptotic size, L_∞; see Section 4.3.	Yes
K	Growth rate parameter in von Bertalanffy growth function; see Section 4.3.	Yes
R_0	Unfished recruitment; see equation (4.37); actually parameterised as log(R_0).	Yes
P_{female}	Proportion of recruits that are female, in sex-structured model	Yes
r	Recruitment compensation ratio; see equation (4.37); actually parameterised as log(r – 1) to give it a distribution closer to normal.	Yes
d_t	Log-recruitment deviations; see equation (4.37).	Yes
M	Instantaneous natural mortality rate	Yes
$L_{50}^{(\text{line})}$	Length at 50% vulnerability to line fishing; see Section 4.4.	Yes
$L_{\text{diff}}^{(\text{line})}$	Difference between lengths at 95% and 50% vulnerability; see Section 4.4.	Yes
$L_{50}^{(\text{gillnet})}$	Length at 50% vulnerability to gillnet fishing; see Section 4.4.	Yes
$L_{\text{diff}}^{(\text{gillnet})}$	Difference between lengths at 95% and 50% vulnerability; see Section 4.4.	Yes
$L_{50}^{(\text{MLS})}$	Lengths at 50% discarding from minimum legal size (MLS); see sec. 4.5.	No
$L_{\text{diff}}^{(\text{MLS})}$	Difference between lengths at 95% and 50% MLS discarding; see sec. 4.5.	No
$V^{(\text{age})}$	Additional age-based multipliers of vulnerability of young fish, to facilitate model fit to age data	Yes

5. Results and discussion

5.1 Preliminary comments

Modelling the Fraser region separately was difficult for bream and whiting, and was pursued only for flathead. Bream and whiting were modelled as combined stocks over the Moreton and Fraser regions. For bream, the age and length data suggested that bream may migrate from the Fraser region to the Moreton region, as there were fewer old fish in the Fraser region.

All three assessments suffered from lack of contrast in the data since the commercial logbook system began in 1988. All three species had been subject to high harvests prior to that year, and commercial catch rates had not varied much since then (see Chapters 2 and 3 above).

The lack of contrast in the catch rates may have been exacerbated by the fact that the only available catch rates came from net fishing, which can target whole schools of fish. As a result of this form of targeting, catch rates from net fishing may be inclined towards being ‘hyperstable’, whereby they are not changed much by trends in population size if the average school size remains large.

Flathead was particularly difficult to assess. When all parameters were estimated, the model converged to unrealistically high estimates of both population size and productivity (‘recruitment compensation’, see equation (4.37), page 55) in the Moreton region.

In the reported results for the Moreton region, therefore, we fixed both the recruitment compensation ratio, r, and the natural mortality rate, M, to somewhat lower values than estimated in the model. Flathead is known to be extensively targeted by both commercial and recreational fishers, and harvest rates of less than 0.1 per year (i.e., less than 10 per cent of available fish actually being caught in each year) were not considered realistic.

Model estimates for flathead in the Fraser region were also high but in this region such estimates were considered realistic, due to the much lower levels of both commercial and recreational fishing for flathead in this region.

Flathead was the species that showed the greatest conflict between optimistic model results and steeply falling fishing-club catch rates (see Section 3.1 and Figure 3.1, page 36). This conflict supports a precautionary approach to model outputs.

Interpretation of biomass targets for the different species was also difficult. For bream and whiting (which were run prior to flathead), the biomass target was interpreted as exploitable biomass, which related to catch rates that fishers could expect.

For flathead, recent literature indicated that the length at maturity for female fish was much higher than the minimum legal size (Gray and Barnes, 2015). Hence, high exploitable biomass could still result in low spawning stock. Therefore, for flathead, the biomass target was interpreted as spawning biomass, in order to ensure that the flathead stock will be able to replenish itself in future.

The vulnerability parameters for flathead were impossible to estimate, due to the high minimum legal size which appears to be much greater than the length at 50 per cent vulnerability to fishing. They were fixed at L_{50} = 30 cm and L_{diff} = 5 cm for all fishing sectors (see Table 4.1 above for definitions of these parameters).

Estimates quoted in the next section are maximum likelihood estimates from the population model. For the sex-structured model (flathead), little importance should be given to the estimate P_{female} of the proportion of female recruits, because it is confounded with the difference in natural mortality rates between M_{female} and M_{male}. The parameter P_{female} is a 'nuisance parameter' whose inclusion is necessary when sex-specific natural mortality rates are estimated; it is unlikely to reflect the true value of the proportion of female recruits.

5.2 Overview of results

The three species differed markedly in their estimates of recruitment compensation ratio, r (the productivity parameter in the population dynamics). Bream had a low estimate of r (2.53), which resulted in a relatively high estimate (50.1 per cent of unfished) of the exploitable biomass B_{MSY} that corresponds to maximum sustainable yield (MSY). Whiting had a moderately high estimate of r (9.52) which made it more resilient to fishing and resulted in a B_{MSY} estimate of 33.5 per cent of unfished. For flathead in Moreton region the model hit the upper bound of $r = 20$ (practically equivalent to infinity, indicating that the model could not find any relationship between spawning-stock size and recruitment): we considered it prudent to report results for $r = 8$ and $r = 4$.

Bream was estimated to be at 33.8 per cent of unfished exploitable biomass in 2017, which compares to 50.1 per cent required for maximum sustainable yield and 60 per cent for the Sustainable Fisheries Strategy. The maximum sustainable yield (MSY) was estimated as 420 t per year (commercial and recreational sectors combined, and Moreton and Fraser regions combined). The model indicated that maintenance of a harvest size of about 220 t per year would recover the biomass to 60 per cent of unfished in about 25 years. A lower harvest of 150 t per year would recover to 60 per cent in about 12 years.

Whiting exploitable biomass in 2017 was estimated as 28.7 per cent of unfished, which is slightly less than B_{MSY}. The model's estimate of MSY was 452 t per year. Current combined harvest size is about 300 t per year, approximately equal to the equilibrium harvest at 60 per cent unfished (B_{60}). Rebuilding the stock from its current level to B_{60}, however, would require the harvest to be reduced, ideally to about 150 t (commercial and recreational sectors combined, and Moreton and Fraser regions combined) to rebuild within about five years. Yearly harvests between 150 and 270 t would recover the stock more slowly; the midpoint 210 t per year would reach B_{60} in about seven years.

The status of flathead is more uncertain than bream and whiting, due to lack of contrast in the data. As described above, in the Moreton region, model estimates of biomass appeared unrealistically high and corresponded to harvest rates that we regarded as unrealistically low.

Precautionary conclusions for the Moreton region are based on fixing the recruitment compensation ratio r and the natural mortality rate M to lower levels than estimated in the full model. We derived detailed results for the combinations $r = 8$ and $M = 0.7\ \text{yr}^{-1}$, and $r = 4$ and $M = 0.75\ \text{yr}^{-1}$. For both of these cases the maximum harvest rate occurred in 2011 and took the values 0.276 and 0.216 respectively, which we regard as realistic.

The negative log-likelihood (NLL) values for these two precautionary cases were about 10 units higher than the NLL value from unconstrained estimation. Statistically, this difference corresponds to a χ^2 value of about 20 on two degrees of freedom, and a probability (P-value) less than 10^{-4} (0.01 per cent). The model therefore indicates that these cases can be viewed as highly precautionary.

Precautionary estimates of dusky flathead status in the Moreton region were spawning biomass in 2017 of 36 to 39 per cent of unfished, approximately equal to or slightly below B_{MSY}, and MSY of 104 t per year to 112 t per year, approximately equal to current harvests. Unlike bream and whiting, the harvest of flathead in the Moreton region has not fallen substantially from its peak levels over the period 1990 to 2010. In particular, recreational fishing effort on flathead in the Moreton region is still very high. Recovery of the spawning stock to 60 per cent of unfished in the Moreton region would require the harvest to be reduced, ideally to 63 t per year (commercial and recreational sectors combined, Moreton region only) which would recover to B_{60} within eight years. After recovery, the equilibrium harvest for 60 per cent spawning biomass is estimated at 83 to 96 t per year. A harvest level between 63 and 83 t per year would recover the stock more slowly. The midpoint 73 t per year would reach B_{60} within 16 years.

The combined harvest of flathead in the Moreton region has not been reduced by the increase in minimum legal size from 30 to 40 cm in December 2002 or the imposition of a maximum legal size (70 cm in December 2002, increased to 75 cm in May 2009). Although these measures undoubtedly assist flathead to reach spawning size and protect large individual spawners, measures that directly affect harvest size are required to recover the stock to the 60 per cent spawning biomass target.

Calculations of the above recommended harvests to build to B_{60} assumed constant fishing effort throughout the recovery period. The longer rebuild options for whiting and flathead would still reach B_{60} but would require fishing effort to be progressively reduced, in order to maintain the harvest size as stocks increase. This would result in some ongoing disruption to both the commercial and recreational sectors during the rebuilding period.

In the Fraser region, fishing pressure on flathead was estimated to be lower than in the Moreton region and 2017 spawning biomass was estimated at 70 per cent of unfished. We considered the unconstrained maximum likelihood estimates to be realistic for this region and did not consider it necessary to apply precautionary settings of r and M. Peak harvests occurred in the 1950s in this region, with an average of about 40 t per year over this decade (predominantly commercial). Harvests in recent years (commercial and recreational combined) have been about 22 t per year.

Although the results for flathead in Moreton region are already precautionary, additional caution may be needed in view of fishing-club catch rates which show very big falls since the 1950s in locations commonly fished by clubs. Flathead catch rates by fishing-club members fell greatly relative to other species in the 1950s, 1960s and 1970s, indicating that flathead were already heavily fished by the time the commercial logbook database (and model-input catch rates) began in 1988.

It is true that fishing-club catch rates were affected by changes in clubs’ local regulations (e.g., progressively setting a minimum size greater than the minimum legal size) and competition scoring systems, and that any depletion in flathead stocks that these catch rates show could be only local to the locations commonly visited by clubs. Nevertheless, it is doubtful that these factors can explain all of the falls in club catch rates of flathead.

Parameter estimates from the model are listed in Tables 5.1 (bream and whiting), 5.2 (flathead, Moreton region) and 5.3 (flathead, Fraser region). Plots of model fit are provided in Appendix 2.

Table 5.1: Parameter estimates for bream and whiting, Moreton and Fraser regions combined. Lengths are fork lengths. Minimum legal sizes varied with time and are listed in Table 1.1. The 'F/e' columns record whether a parameter was fixed outside the model (F) or estimated within it (e).

Symbol	**Bream**		**Whiting**	
	Value	**F/e**	**Value**	**F/e**
α	4.456×10^{-5} (cm, kg)	F	1.004×10^{-5} (cm, kg)	F
β	2.7952	F	3.0000	F
m_a	0, 0.65, 1, 1, …	F	0, 0.2, 0.65, 0.95, 1, …	F
μ	7.5 cm	F	13.38 cm	e
σ	5.65 cm	e	5.42 cm	e
λ	33.63 cm	e	37.65 cm	e
ρ	5.72 cm	e	3.49 cm	e
K	0.0824 yr^{-1}	e	0.2310 yr^{-1}	e
$\log R_0$	16.735	e	17.416	e
r	2.53	e	9.52	e
M_{young}	–	–	0.8740 yr^{-1} (age ≤ 4+)	e
M	0.2950 yr^{-1}	e	0.2004 yr^{-1} (age ≥ 5+)	e
$L_{50}^{(\text{line})}$	20.89 cm	e	20.38 cm	e
$L_{\text{diff}}^{(\text{line})}$	1.93 cm	e	8.00 cm	F
$L_{50}^{(\text{gillnet})}$	19.21 cm	e	23.41 cm	e
$L_{\text{diff}}^{(\text{gillnet})}$	1 cm	F	3.33 cm	e
$L_{50}^{(\text{tunnel})}$	19.14 cm	e	20.13 cm	e
$L_{\text{diff}}^{(\text{tunnel})}$	1 cm	F	4.26 cm	e
$L_{\text{diff}}^{(\text{MLS})}$	1.5 cm	F	1.5 cm	F
$V^{(\text{age})}$	0, 0, 0.2587, 0.6599, 1, …	e	0, 0.4006, 1, …	e

Table 5.2: Parameter estimates for flathead in Moreton region for the two precautionary cases.

Symbol	**Flathead Moreton, *r* = 8, *M* = 0.70**		**Flathead Moreton, *r* = 4, *M* = 0.75**	
	Value	**F/e**	**Value**	**F/e**
α	2.09×10^{-6} (cm, kg)	F	2.09×10^{-6} (cm, kg)	F
β	3.282	F	3.282	F
m_a	0, 0, 0, 0.05, 0.35, 0.65, 1, …	F	0, 0, 0, 0.05, 0.35, 0.65, 1, …	F
μ_{female}	19.35 cm	e	19.44 cm	e
σ_{female}	8.85 cm	e	8.82 cm	e
λ_{female}	77.92 cm	e	77.90 cm	e
ρ_{female}	2.00 cm	e	2.00 cm	e
K_{female}	0.0545 yr^{-1}	e	0.0532 yr^{-1}	e
μ_{male}	14.36 cm	e	14.29 cm	e
σ_{male}	12.52 cm	e	12.57 cm	e
λ_{male}	36.02 cm	e	36.00 cm	e
ρ_{male}	9.48 cm	e	9.45 cm	e
K_{male}	0.4864 yr^{-1}	e	0.4907 yr^{-1}	e
$\log R_0$	16.296	e	16.719	e
P_{female}	0.1981	e	0.2030	e
r	8.00	e	4.00	e
M_{female}	0.7000 yr^{-1}	F	0.7500 yr^{-1}	F
M_{male}	1.4831 yr^{-1}	e	1.5169 yr^{-1}	e
$L_{50}^{(\text{line})}$	30.00 cm	F	30.00 cm	F
$L_{\text{diff}}^{(\text{line})}$	5.00 cm	F	5.00 cm	F
$L_{50}^{(\text{gillnet})}$	30.00 cm	F	30.00 cm	F
$L_{\text{diff}}^{(\text{gillnet})}$	5.00 cm	F	5.00 cm	F
$L_{50}^{(\text{tunnel})}$	30.00 cm	F	30.00 cm	F
$L_{\text{diff}}^{(\text{tunnel})}$	5.00 cm	F	5.00 cm	F
$L_{\text{diff}}^{(\text{MLS})}$	1.5 cm	F	1.5 cm	F
$V_{\text{female}}^{(\text{age})}$	0, 0.2668, 1, …	e	0, 0.2705, 1, …	e
$V_{\text{male}}^{(\text{age})}$	0, 0.0894, 1, …	e	0, 0.0904, 1, …	e

Table 5.3: Parameter estimates for flathead in Fraser region. The parameter μ_{male} had to be fixed, as it converged to an unrealistically high value (greater than 20 cm).

Symbol	Flathead Fraser	
	Value	**F/e**
α	2.09×10^{-6} (cm, kg)	F
β	3.282	F
m_a	0, 0, 0, 0.05, 0.35, 0.65, 1, …	F
μ_{female}	10.80 cm	e
σ_{female}	11.53 cm	e
λ_{female}	80.34 cm	e
ρ_{female}	9.44 cm	e
K_{female}	0.1463 yr^{-1}	e
μ_{male}	15.00 cm	F
σ_{male}	11.34 cm	e
λ_{male}	38.84 cm	e
ρ_{male}	6.67 cm	e
K_{male}	0.7894 yr^{-1}	e
$\log R_0$	15.818	e
P_{female}	0.3000	e
r	3.85	e
M_{female}	0.9847 yr^{-1}	F
M_{male}	2.1195 yr^{-1}	e
$L_{50}^{(\text{line})}$	30.00 cm	F
$L_{\text{diff}}^{(\text{line})}$	5.00 cm	F
$L_{50}^{(\text{gillnet})}$	30.00 cm	F
$L_{\text{diff}}^{(\text{gillnet})}$	5.00 cm	F
$L_{50}^{(\text{tunnel})}$	30.00 cm	F
$L_{\text{diff}}^{(\text{tunnel})}$	5.00 cm	F
$L_{\text{diff}}^{(\text{MLS})}$	1.5 cm	F
$V_{\text{female}}^{(\text{age})}$	0, 0.3237, 1, …	e
$V_{\text{male}}^{(\text{age})}$	0, 0.0807, 1, …	e

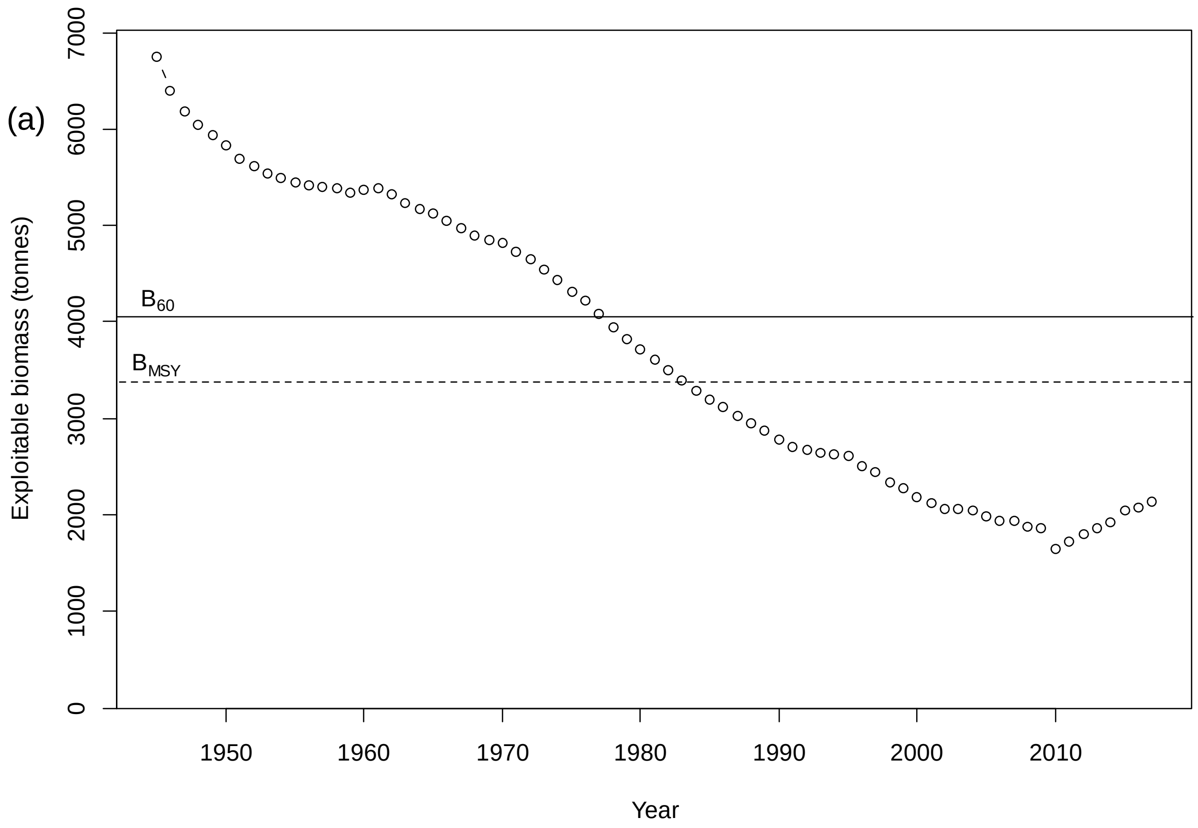
5.3 Biomass and recruitment trajectories

Estimated trajectories of exploitable biomass, spawning biomass and recruitment are plotted in Figures Figure 5.1: Estimated trajectories for bream: (a) exploitable biomass, (b) spawning biomass, (c) recruitment. (bream), Figure 5.2 (whiting), Figure 5.3 (flathead Moreton region, case $r = 8$, $M = 0.7\ \text{yr}^{-1}$), Figure 5.4 (flathead Moreton region, case $r = 4$, $M = 0.75\ \text{yr}^{-1}$) and Figure 5.5 (flathead Fraser region).

Bream and whiting show smooth declines in estimated biomasses with little recovery. As noted above, bream is expected to recover if the current harvest size is maintained. Whiting probably requires management intervention to reduce the harvest.

Bream also shows a smooth pattern of recruitment, indicating that variation in year-class strength is low for this species. Whiting and flathead both show substantial variation in year-to-year recruitment due to variation in year-class strength (the recruitment deviation parameters d_t in the model; see Table 4.1).

Flathead estimated biomass bottomed in the late 1990s and has shown a moderate recovery since then, mainly due to the higher minimum legal sizes and the imposition of a maximum legal size. The plotted flathead exploitable biomasses have been adjusted to equivalent biomasses with the minimum and maximum legal sizes from the final year of the model, to show like-for-like biomass over the years, because the changes in size limits made a big different to the available biomass.



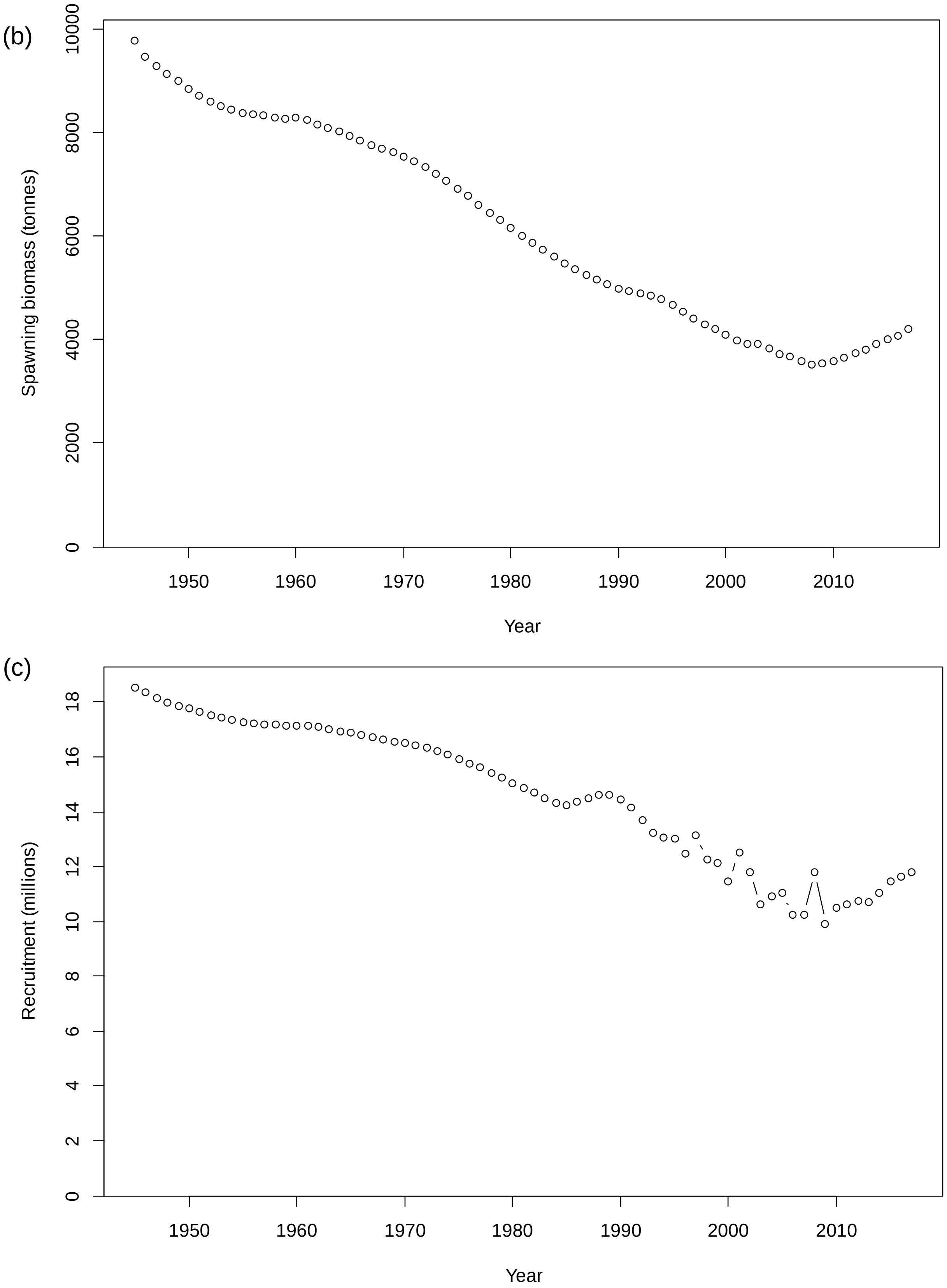
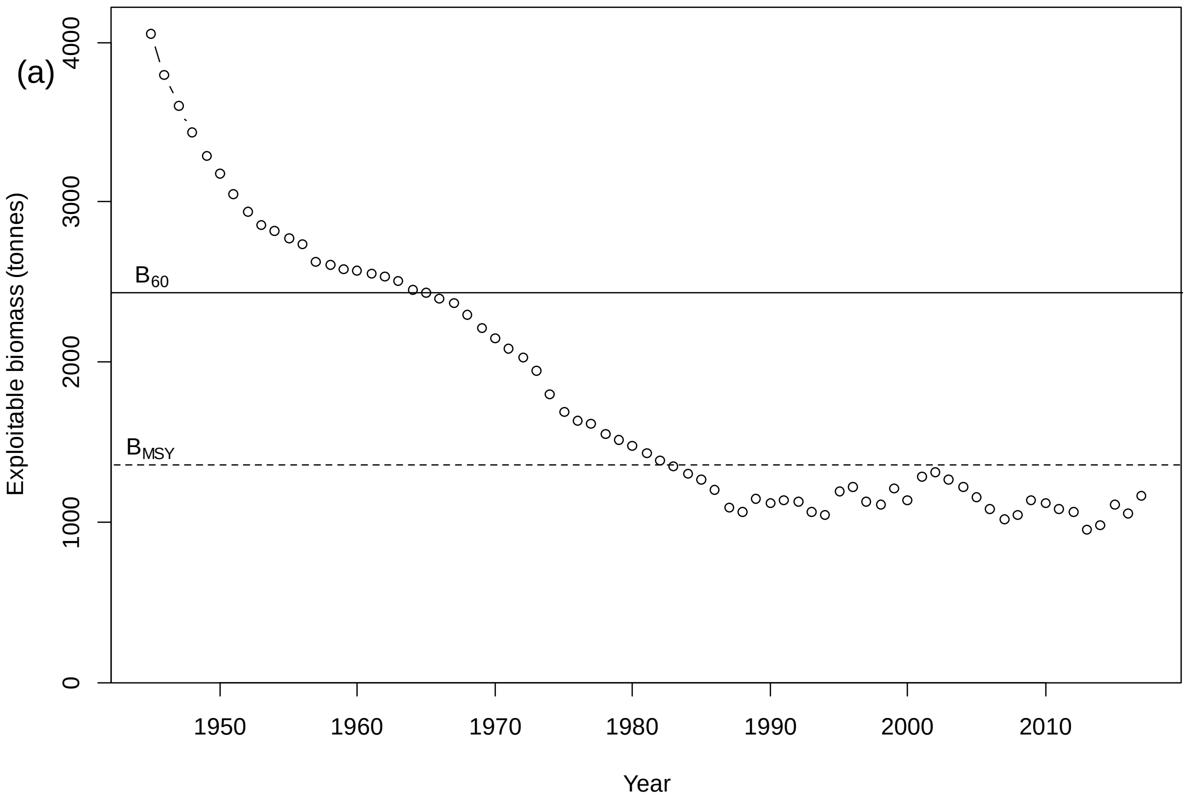
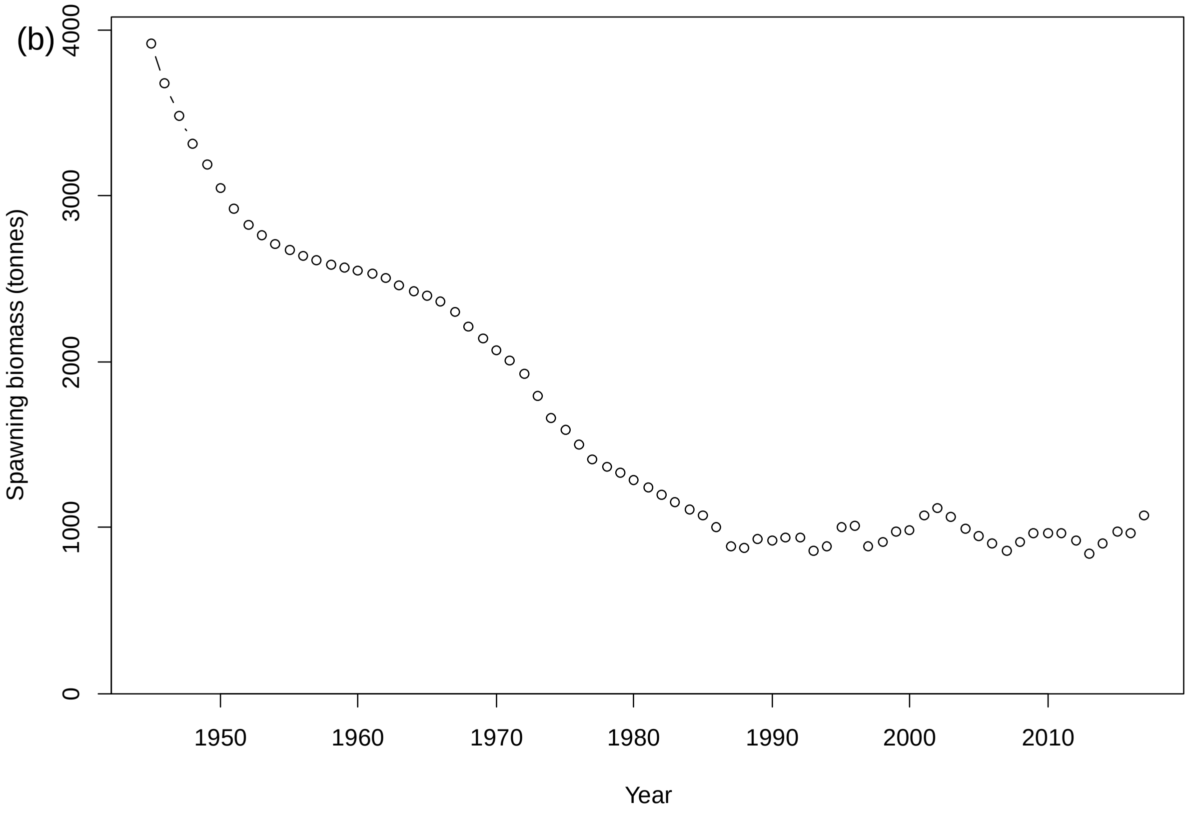


Figure 5.1: Estimated trajectories for bream: (a) exploitable biomass, (b) spawning biomass, (c) recruitment.


(a)
Exploitable biomass (tonnes)
0
1000
2000
3000
4000
B_{60}
B_{MSY}
1950
1960
1970
1980
1990
2000
2010
Year


(b)
Spawning biomass (tonnes)
0
1000
2000
3000
4000
1950
1960
1970
1980
1990
2000
2010
Year

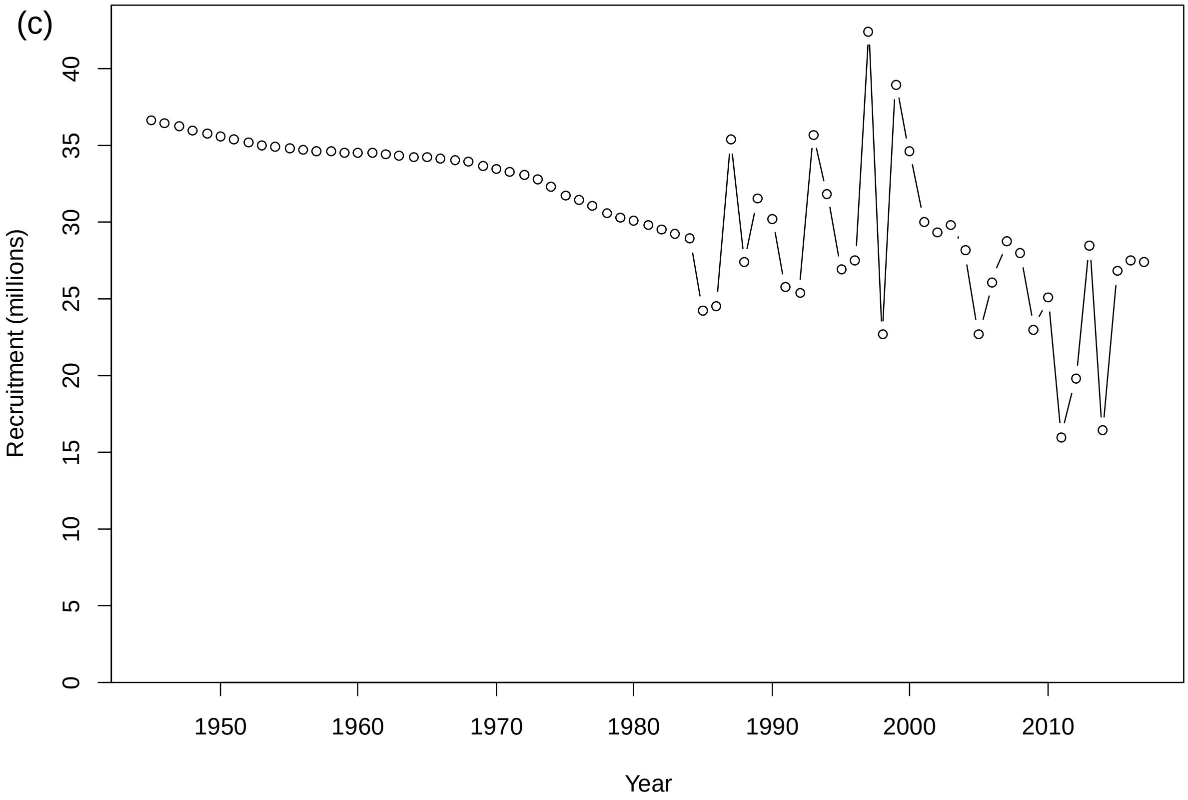
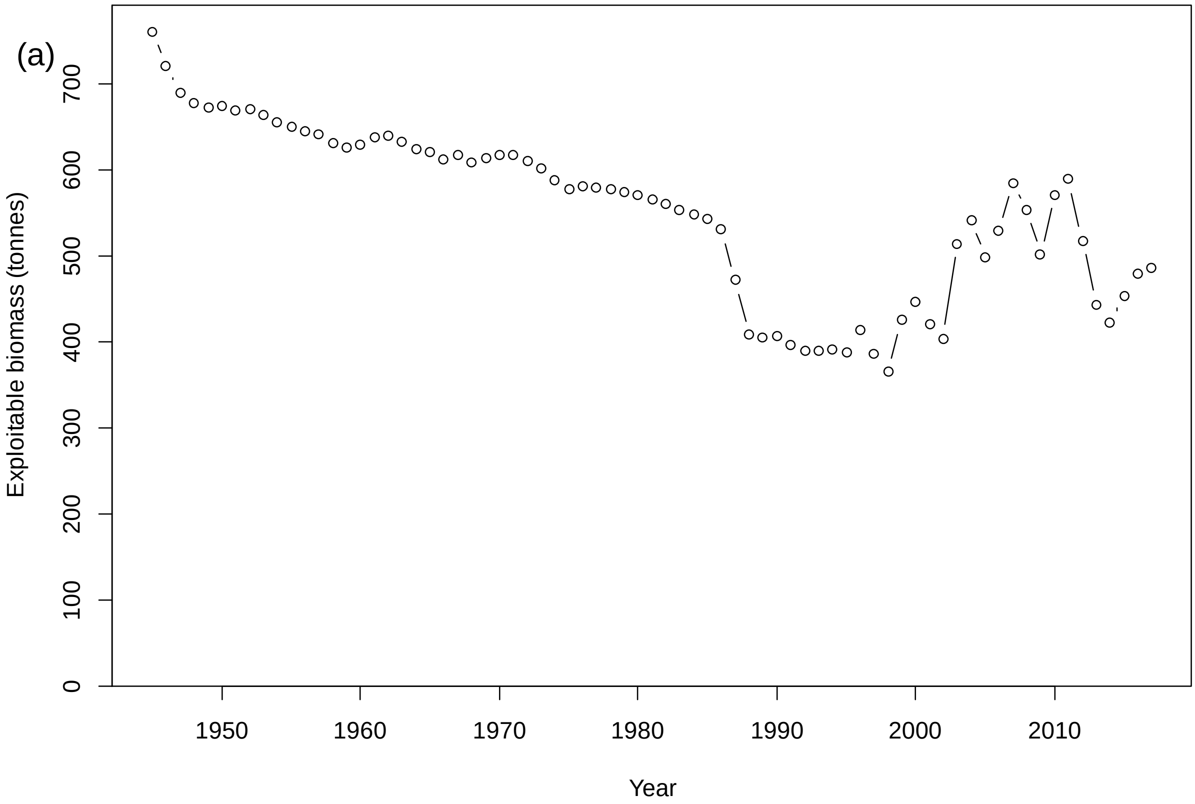


Figure 5.2: Estimated trajectories for whiting: (a) exploitable biomass, (b) spawning biomass, (c) recruitment.



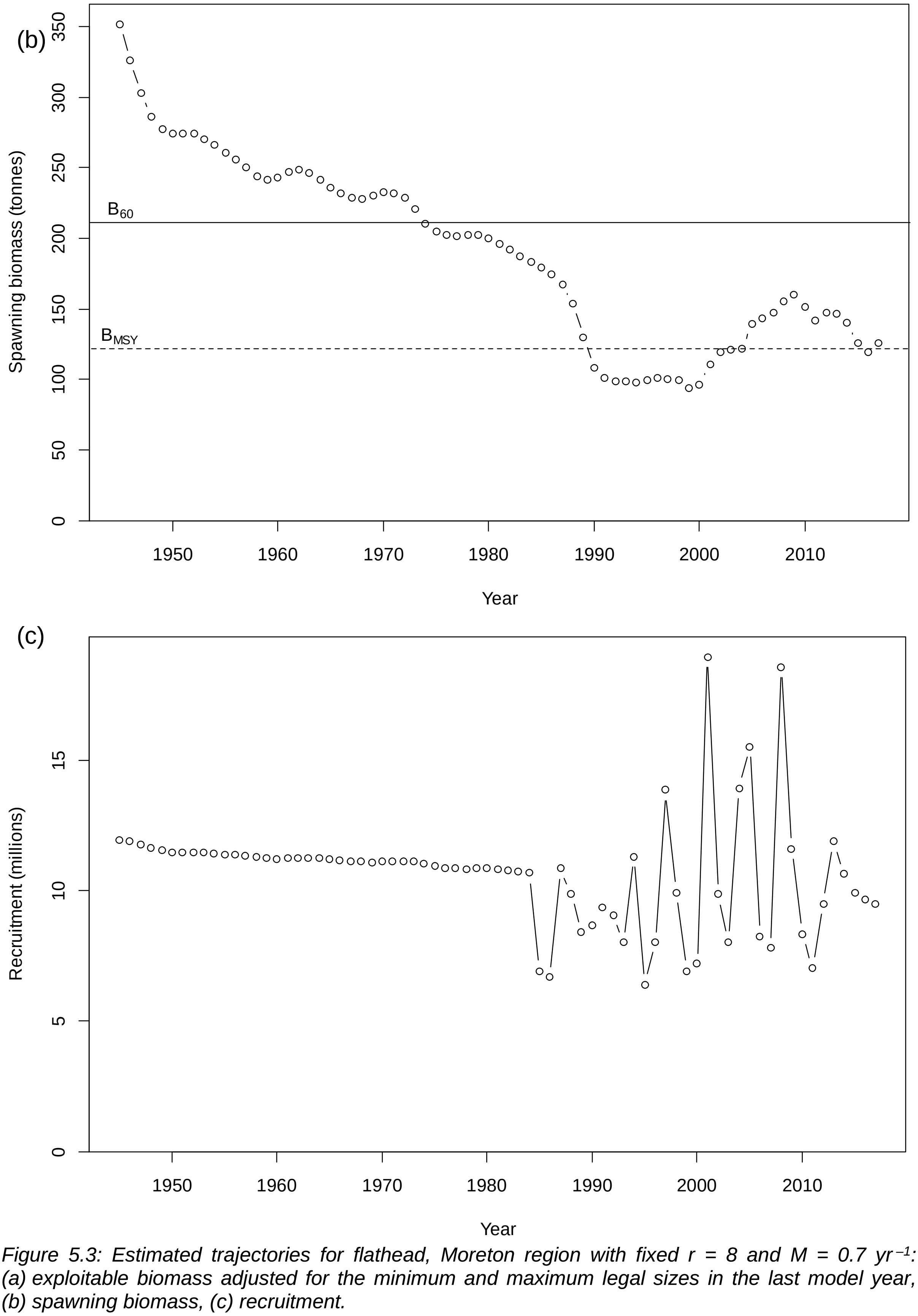
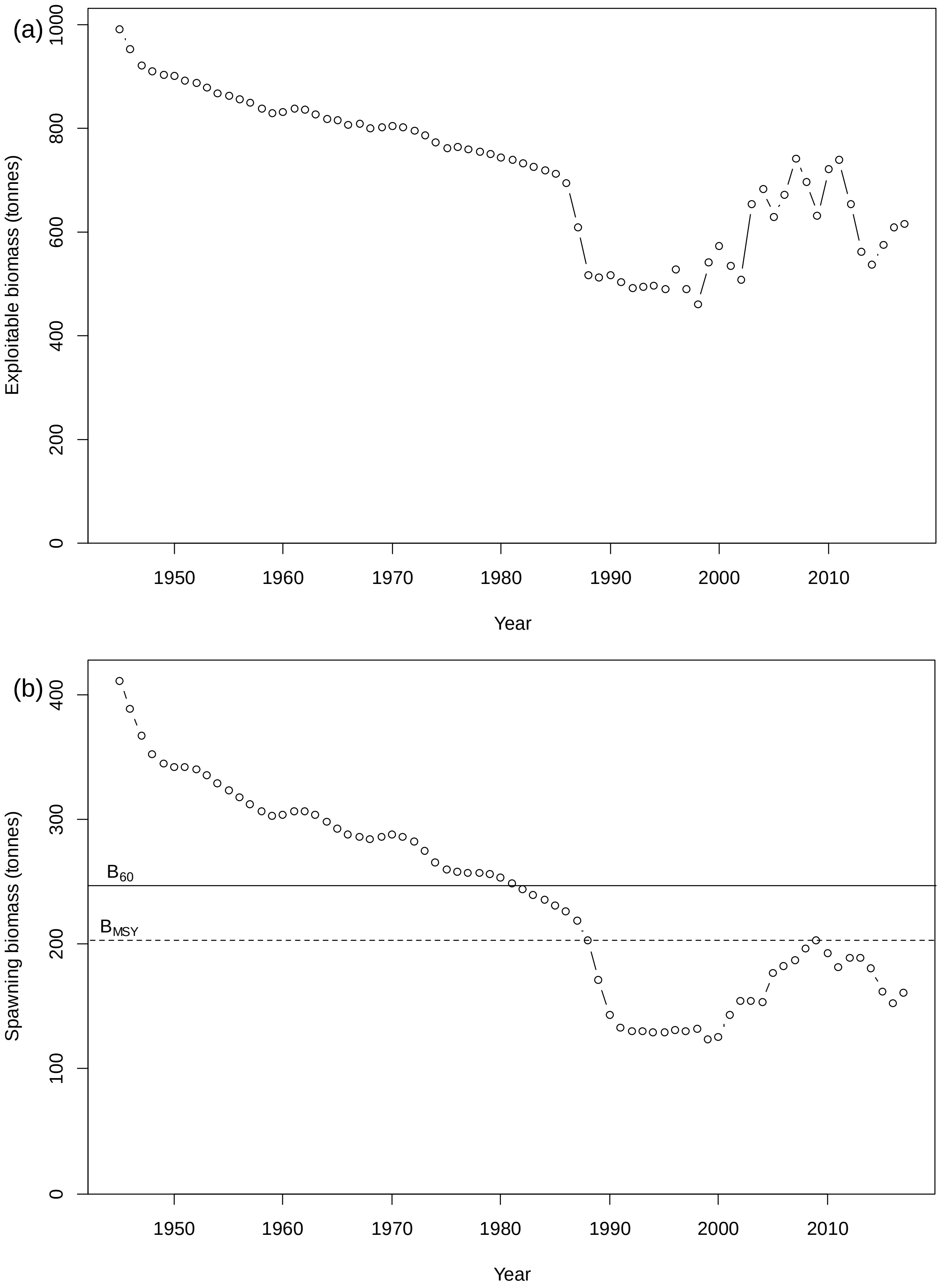


Figure 5.3: Estimated trajectories for flathead, Moreton region with fixed r = 8 and M = 0.7 yr⁻¹: (a) exploitable biomass adjusted for the minimum and maximum legal sizes in the last model year, (b) spawning biomass, (c) recruitment.


(a)
Exploitable biomass (tonnes)
0
200
400
600
800
1000
1950
1960
1970
1980
1990
2000
2010
Year
(b)
Spawning biomass (tonnes)
0
100
200
300
400
B_{60}
B_{MSY}
1950
1960
1970
1980
1990
2000
2010
Year

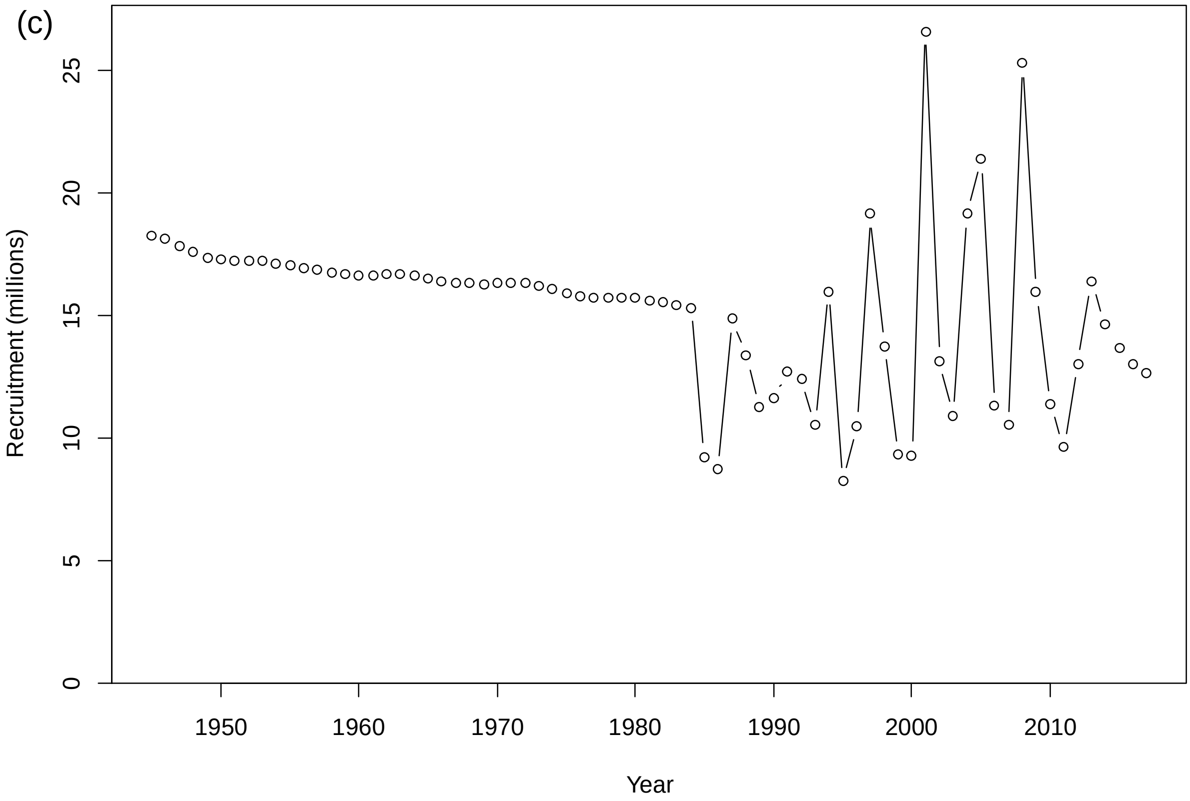
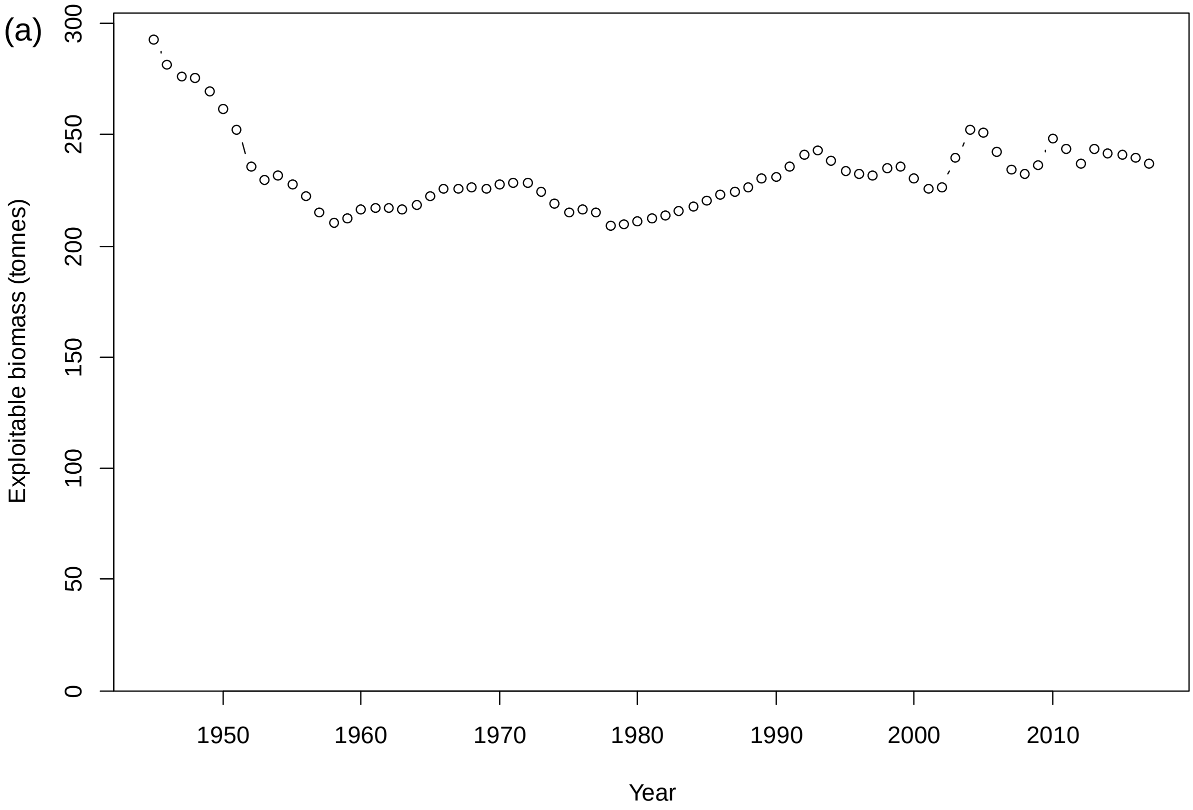


Figure 5.4: Estimated trajectories for flathead, Moreton region with fixed r = 4 and M = 0.75 yr^{-1}: (a) exploitable biomass adjusted for the minimum and maximum legal sizes in the last model year, (b) spawning biomass, (c) recruitment.



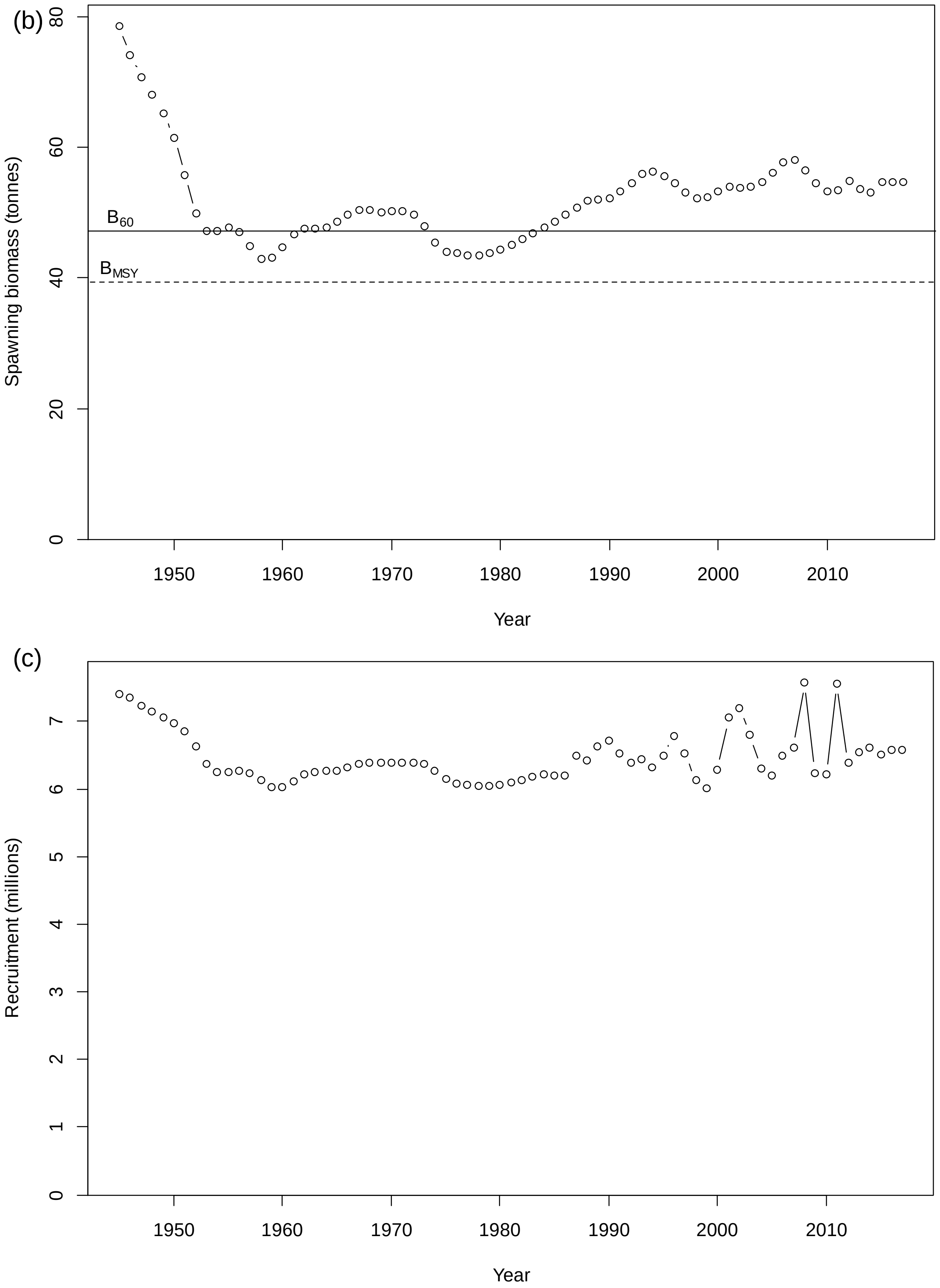


Figure 5.5: Estimated trajectories for flathead, Fraser region: (a) exploitable biomass adjusted for the minimum and maximum legal sizes in the last model year, (b) spawning biomass, (c) recruitment.

5.4 Uncertainty from Markov chain Monte Carlo

Markov chain Monte Carlo (MCMC) simulations were run for the model estimates reported above, using ADMB's inbuilt MCMC capability which begins the simulations from the maximum likelihood point. Each case included 1.05 million simulations, of which the first 50,000 were discarded as 'burn-in' and of the remaining one million, every 100th simulation was saved, resulting in 10,000 values that could be plotted and analysed.

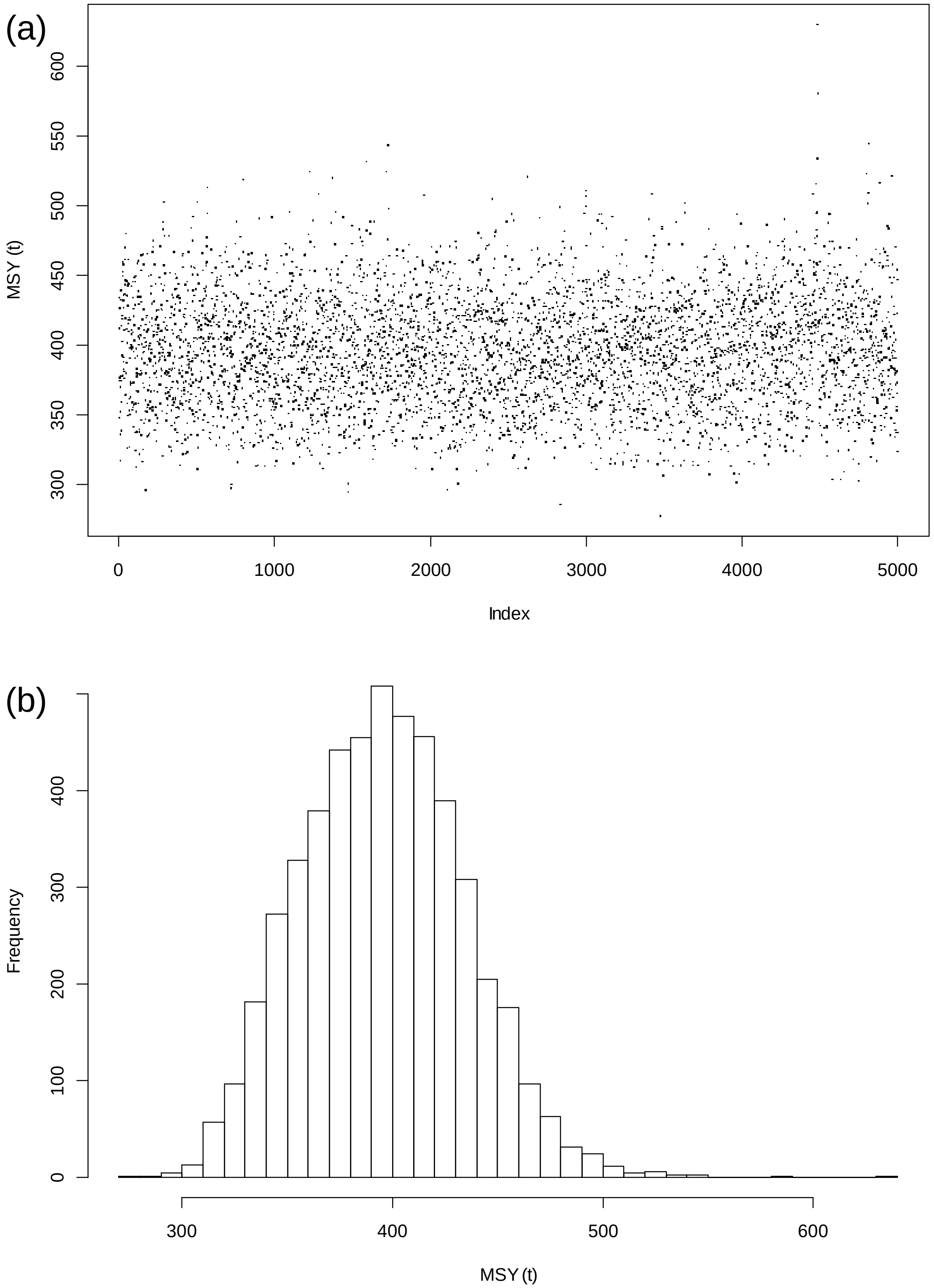
MCMC results for bream are plotted in Figure 5.6, whiting in Figure 5.7, and flathead Moreton region in Figure 5.8 and Figure 5.9. It was not considered worthwhile to conduct MCMC for flathead in the Fraser region, due to lack of meaningful data on the size of harvest that is sustainable.

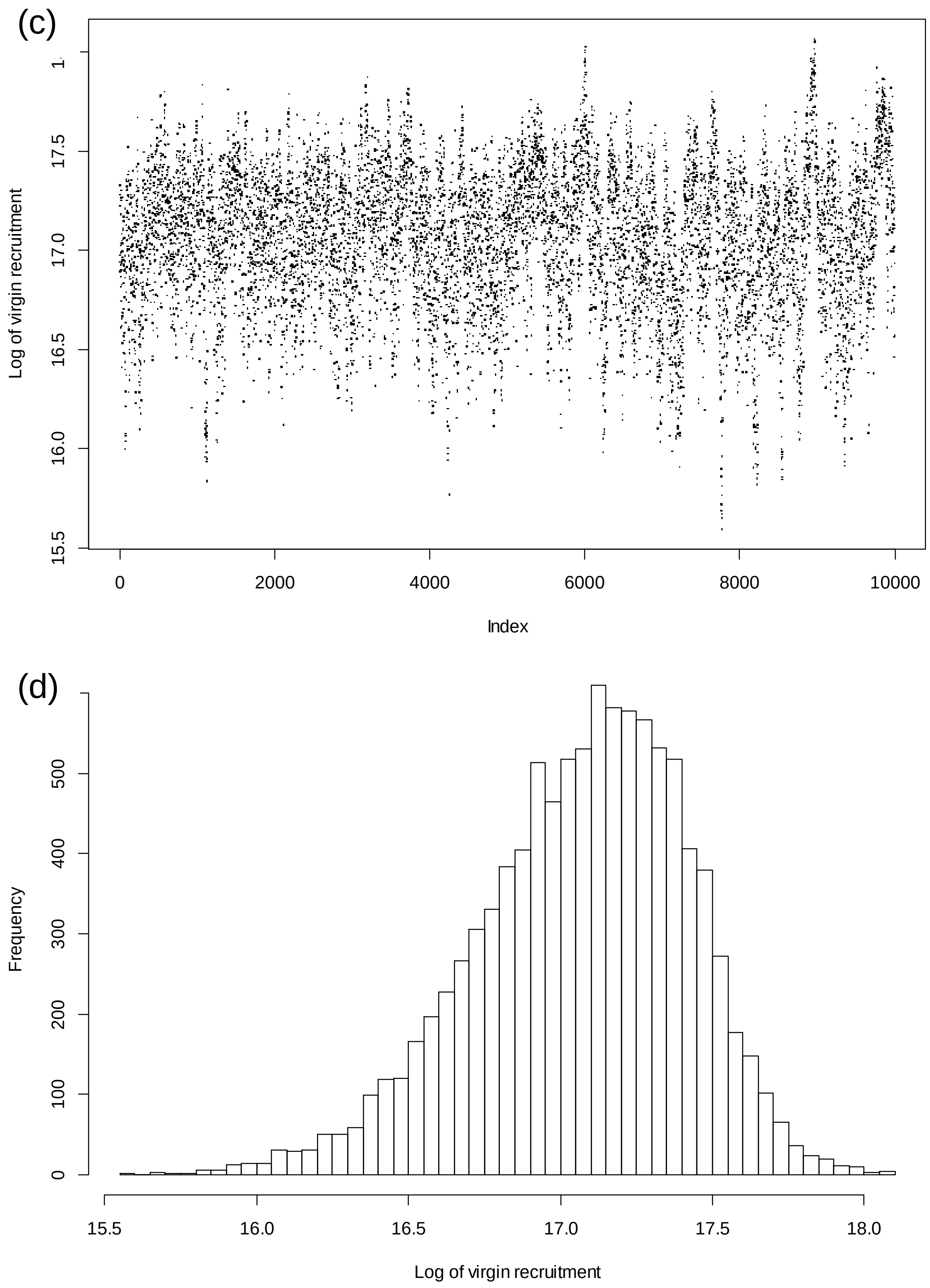
For bream the MCMC results are well behaved and give MSY values between 300 and 500 t ⁄ yr, with both mean and mode at about 400 t ⁄ yr. We put a lower bound of 1.5 on the recruitment compensation ratio r, and the MCMC process often ran into this bound, although there is a clear mode slightly above that value.

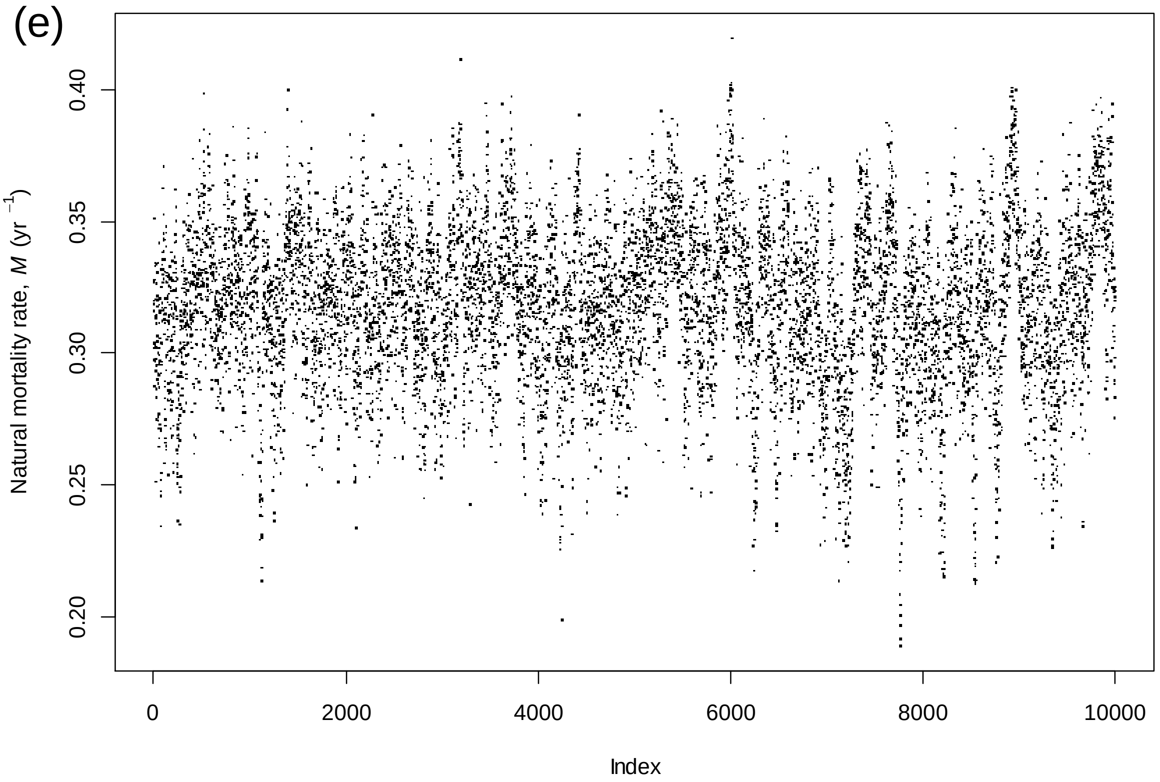
Whiting results are also well behaved except for showing bimodality (simulations clustered around two different solutions), especially in the natural mortality value for young fish, M_{young} . MSY values range between 400 and 600 t ⁄ yr with a long tail on the right-hand side and mode (most frequent value) around 450 t ⁄ yr.

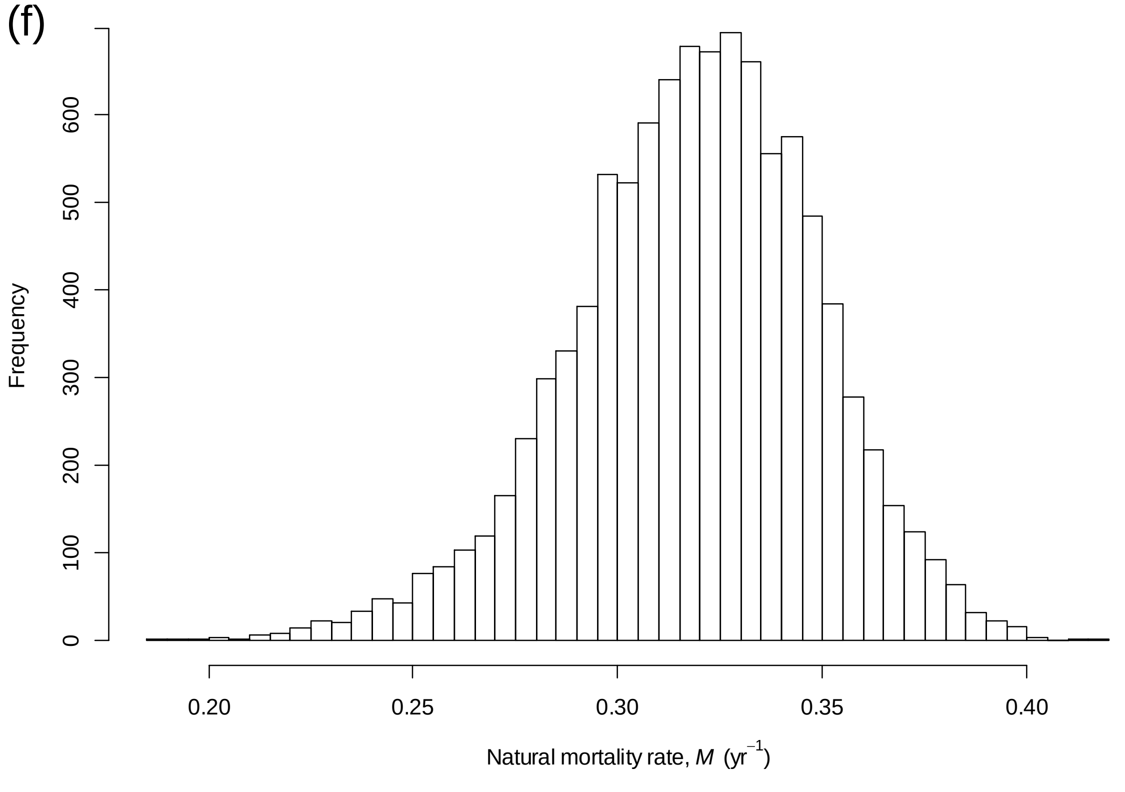
Flathead results are less well behaved. We had to impose lower bounds of 15.5 and 15.9 on the recruitment parameter $\log(R_0)$ in the two scenarios (Figures Figure 5.8 and Figure 5.9 respectively) to prevent the MCMC process becoming 'stuck' at a low level of this parameter, which would have been delicately balanced with the recruitment deviations d_t and therefore not realistic.

The MSY values for flathead have tight ranges, indicating that much of the variation in them is due to variation in the parameters r and M_{female} which were fixed in these simulations.


(a)
MSY (t)
300
350
400
450
500
550
600
0
1000
2000
3000
4000
5000
Index
(b)
Frequency
0
100
200
300
400
300
400
500
600
MSY (t)


(c)
Log of virgin recruitment
15.5
16.0
16.5
17.0
17.5
1
0
2000
4000
6000
8000
10000
Index
(d)
Frequency
0
100
200
300
400
500
15.5
16.0
16.5
17.0
17.5
18.0
Log of virgin recruitment


(e)
0.20
0.25
0.30
0.35
0.40
Natural mortality rate, M (yr⁻¹)
0
2000
4000
6000
8000
10000
Index


(f)
0
100
200
300
400
500
600
Frequency
0.20
0.25
0.30
0.35
0.40
Natural mortality rate, M (yr⁻¹)

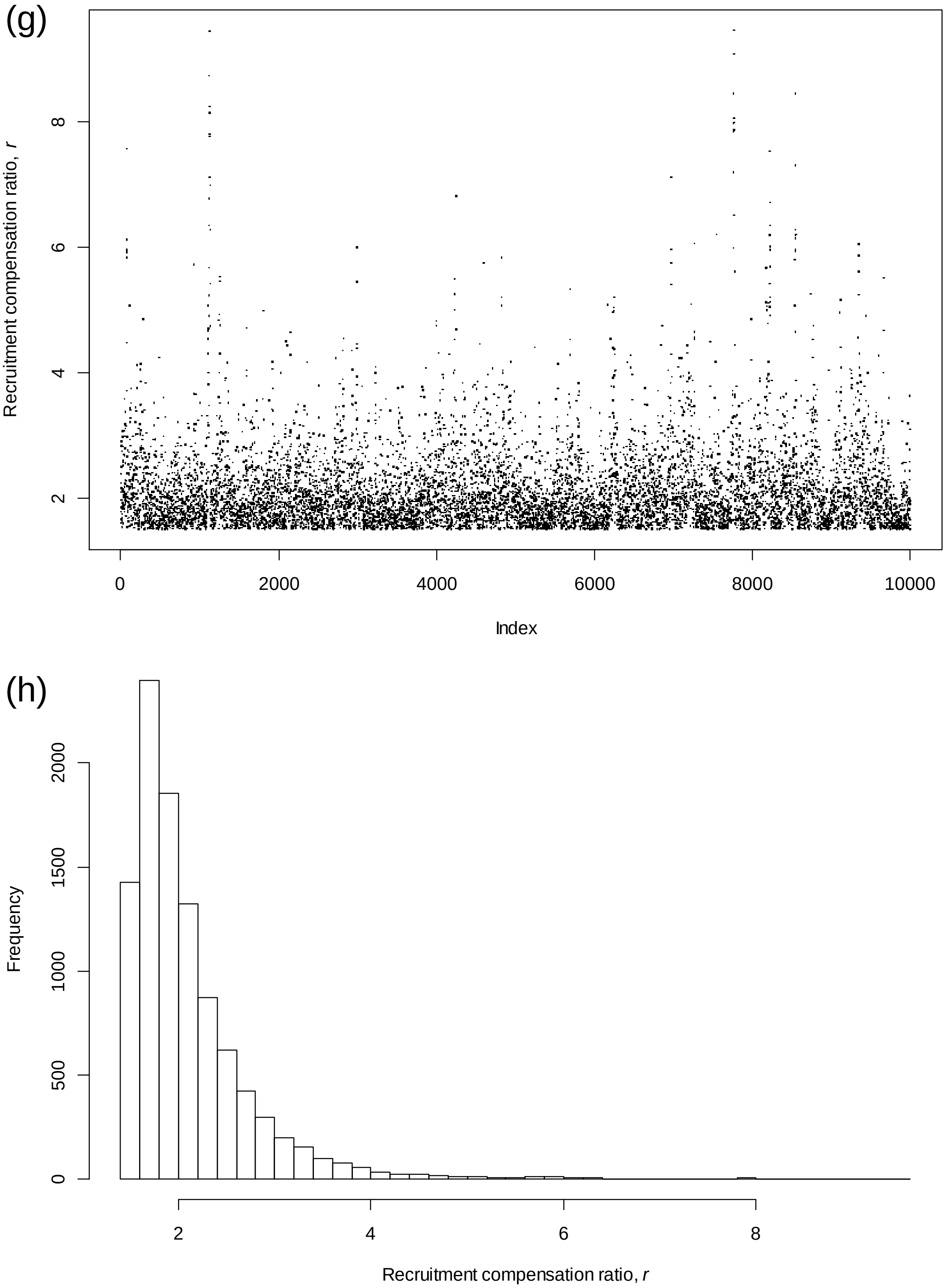
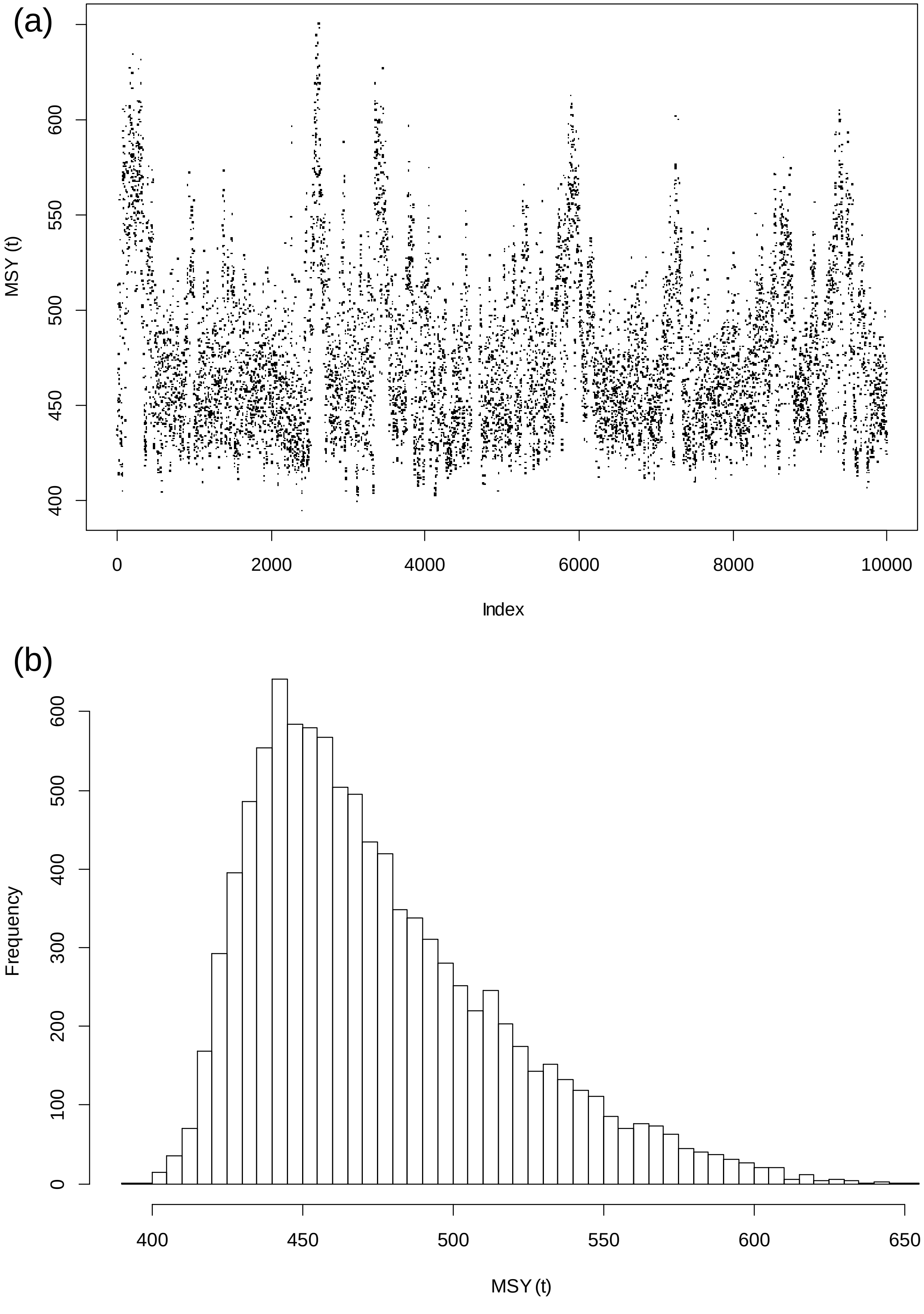
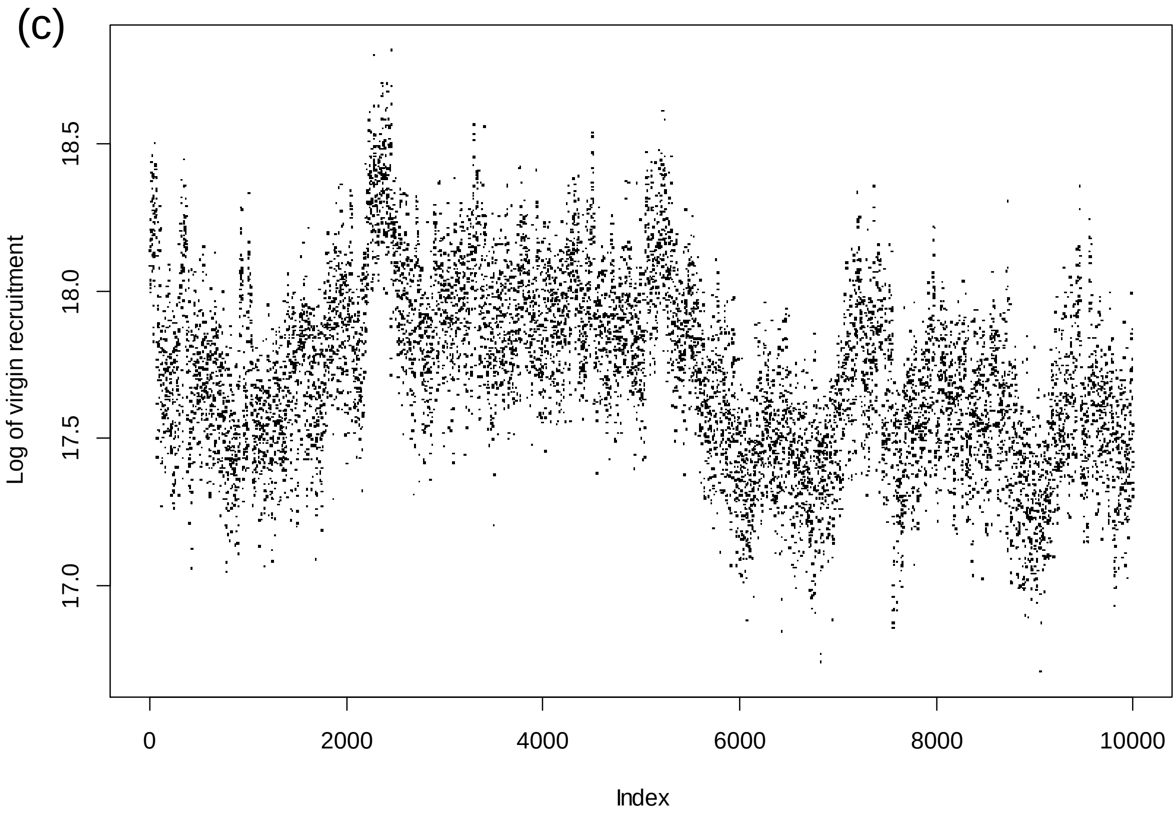
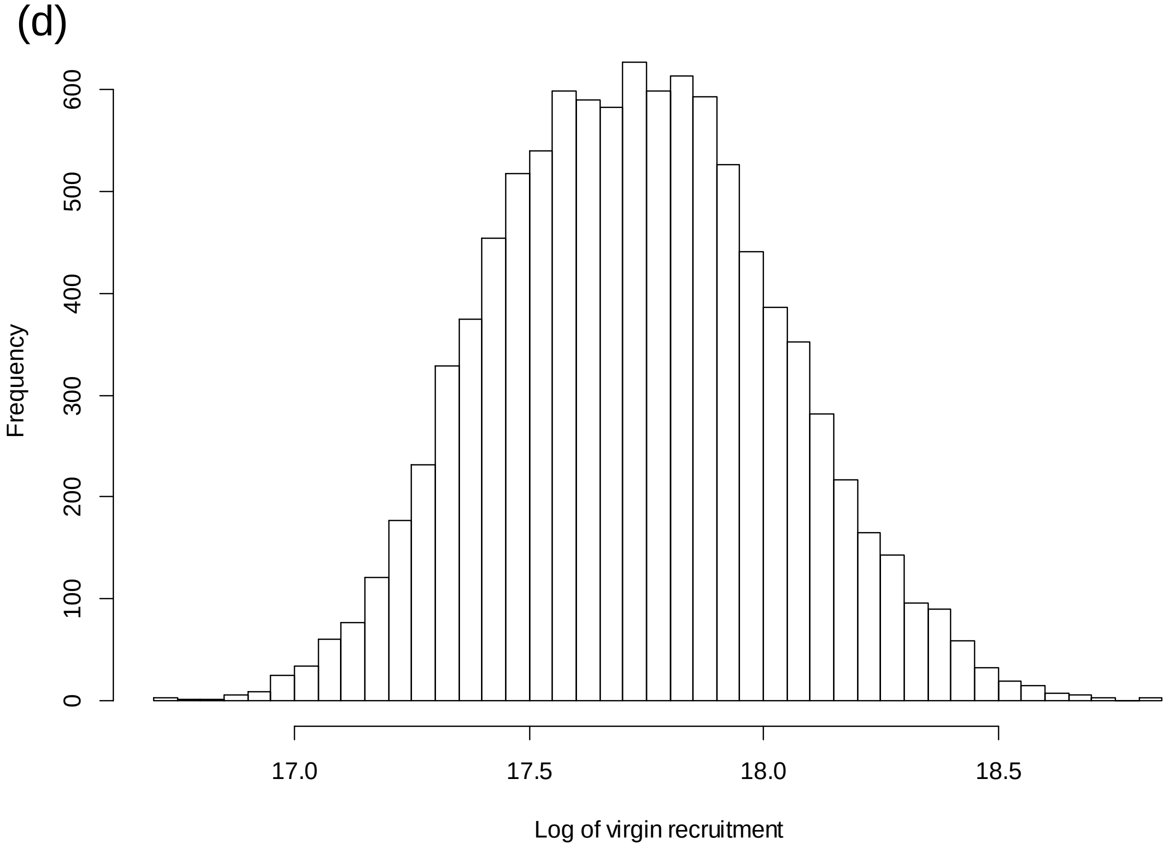


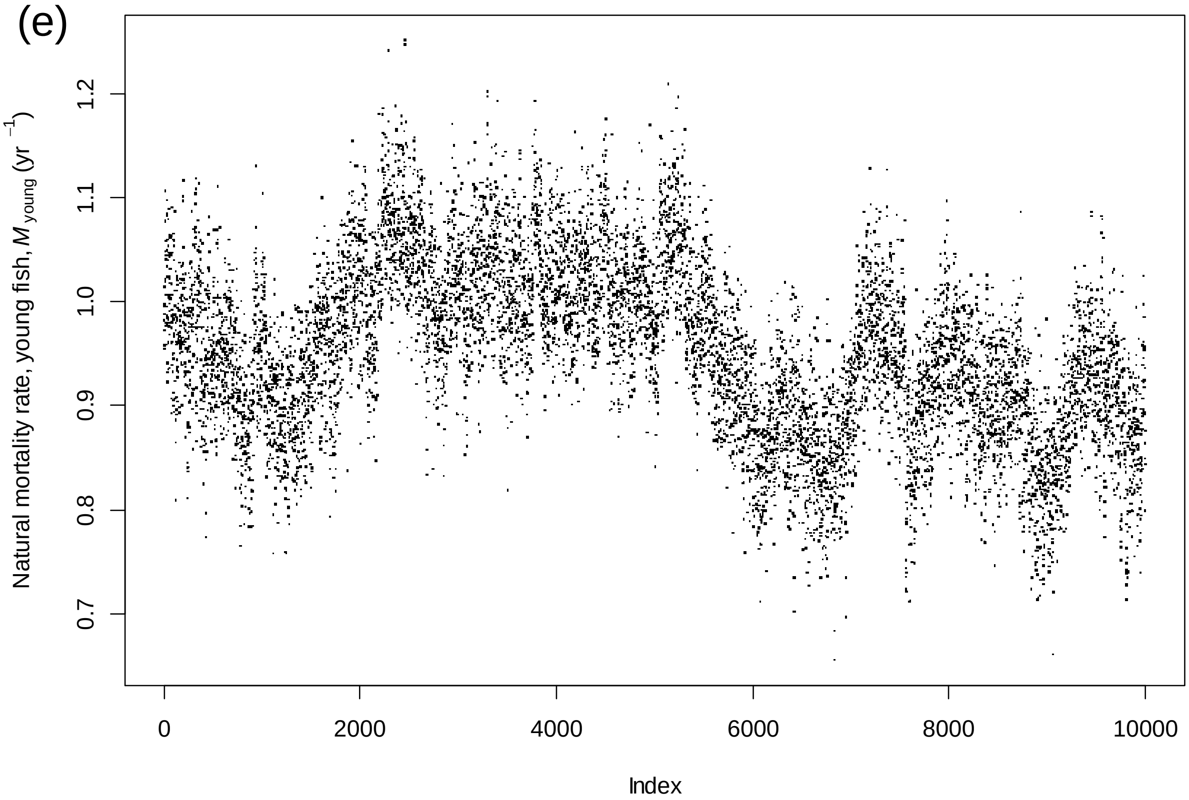
Figure 5.6: MCMC results for bream: (a)–(b) MSY estimates; (c)–(d) log of unfished recruitment log R_0*; (e)–(f) instantaneous natural mortality rate, M; (g)–(h) recruitment compensation ratio, r.*


(a)
MSY (t)
400
450
500
550
600
0
2000
4000
6000
8000
10000
Index
(b)
Frequency
0
100
200
300
400
500
600
400
450
500
550
600
650
MSY (t)

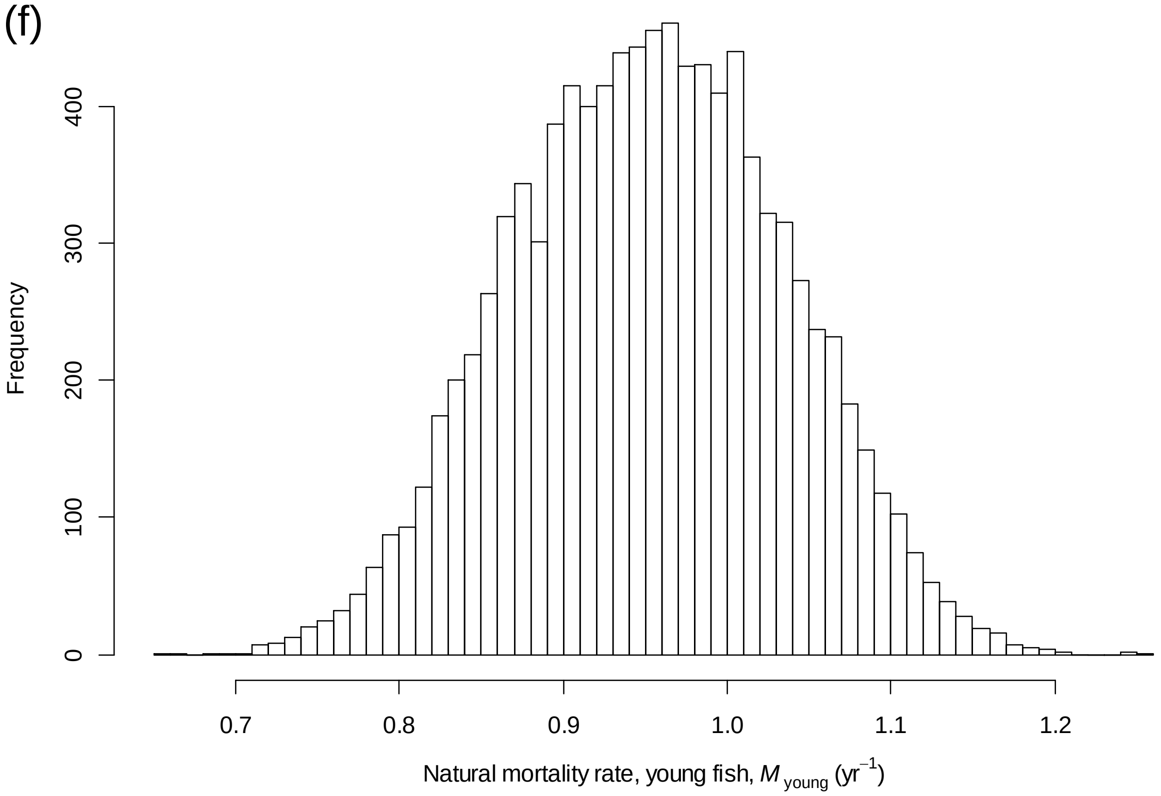

(c)
Log of virgin recruitment
17.0
17.5
18.0
18.5
0
2000
4000
6000
8000
10000
Index

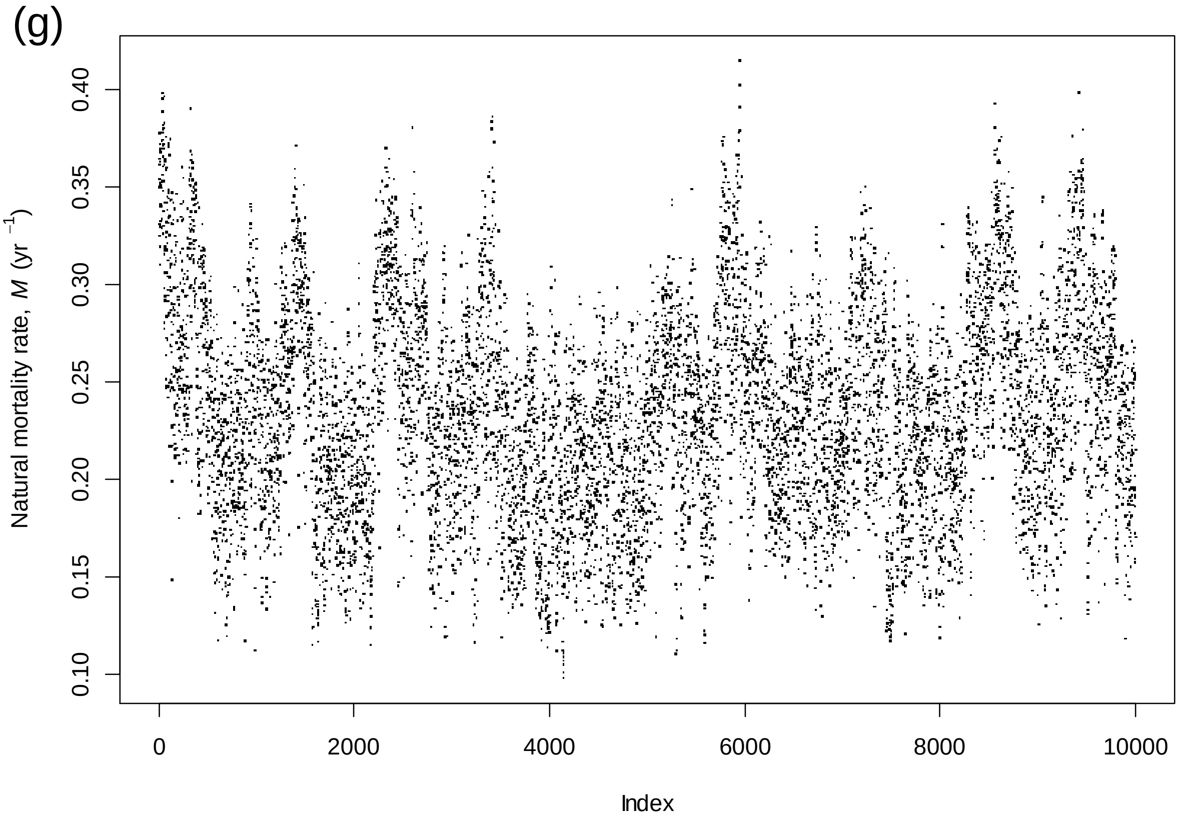

(d)
Frequency
0
100
200
300
400
500
600
17.0
17.5
18.0
18.5
Log of virgin recruitment

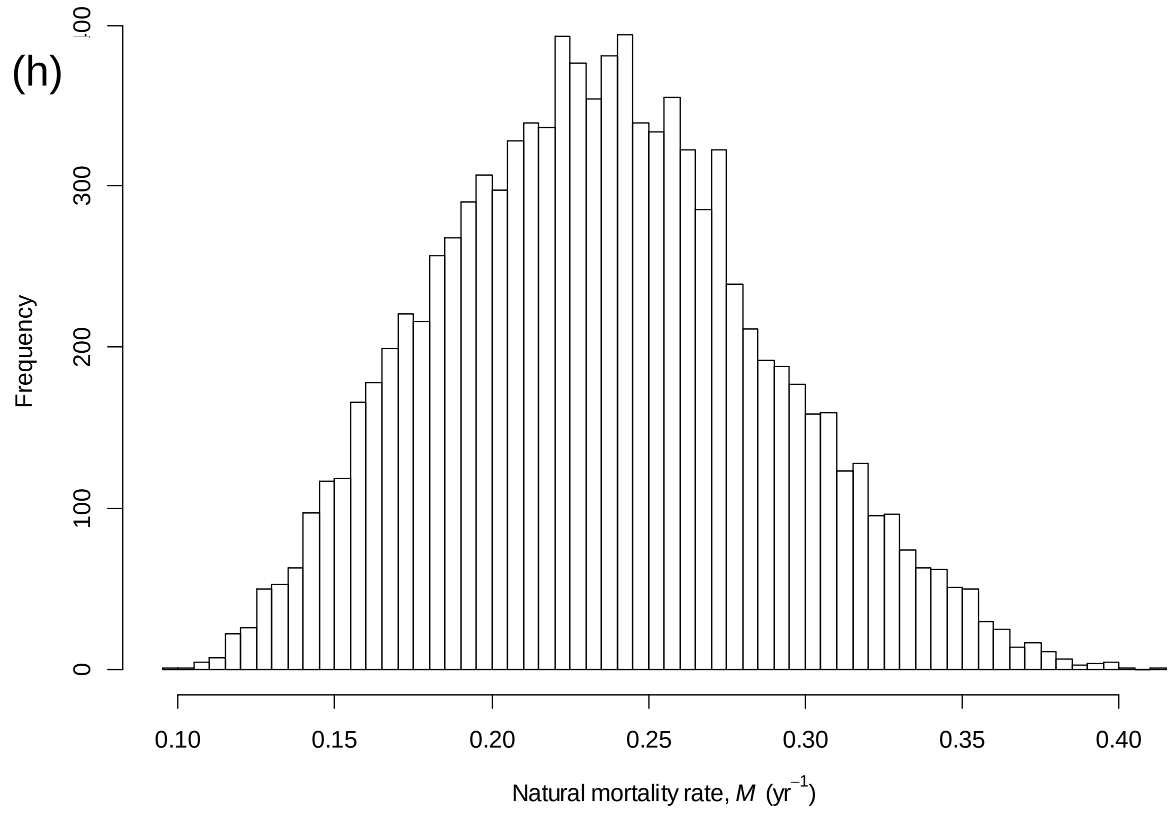
(e)


Natural mortality rate, young fish, M_{young} (yr^{-1})
0.7
0.8
0.9
1.0
1.1
1.2
0
2000
4000
6000
8000
10000
Index

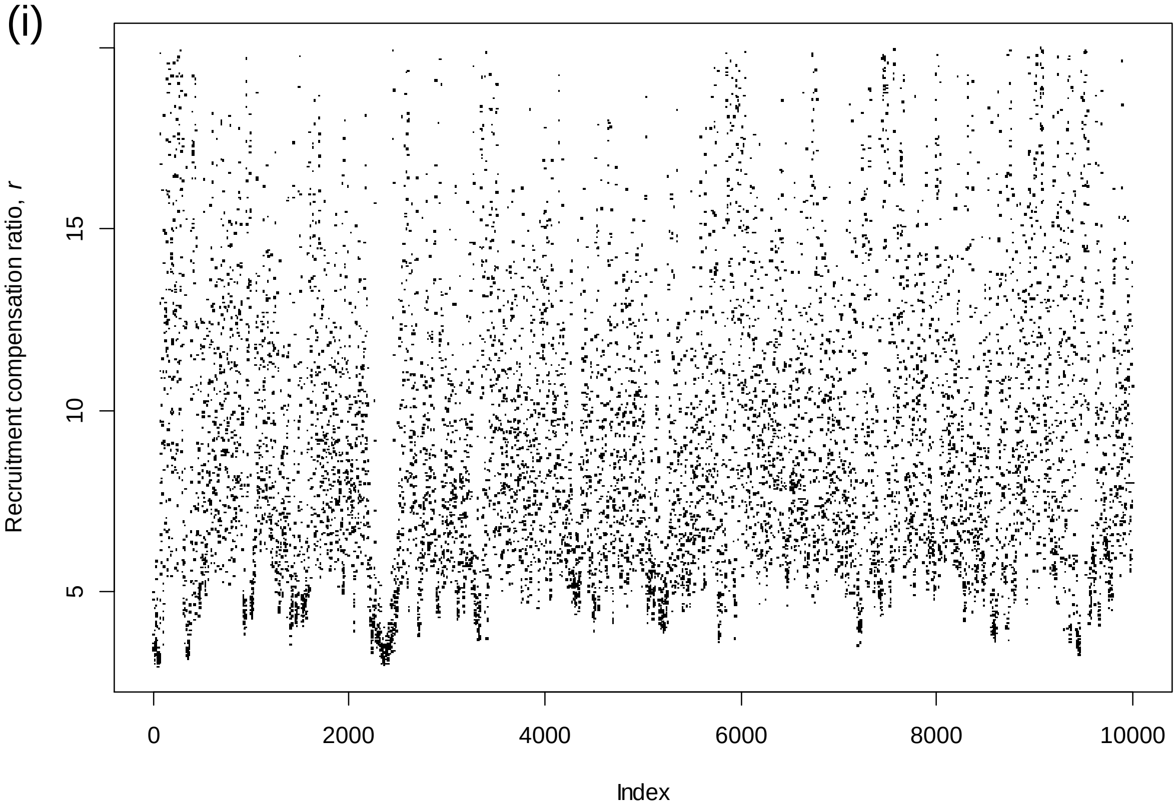
(f)


Frequency
0
100
200
300
400
0.7
0.8
0.9
1.0
1.1
1.2
Natural mortality rate, young fish, M_{young} (yr^{-1})


(g)
Natural mortality rate, M (yr −1)
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0
2000
4000
6000
8000
10000
Index


(h)
Frequency
0
100
200
300
00
0.10
0.15
0.20
0.25
0.30
0.35
0.40
Natural mortality rate, M (yr−1)

(i)



(j)

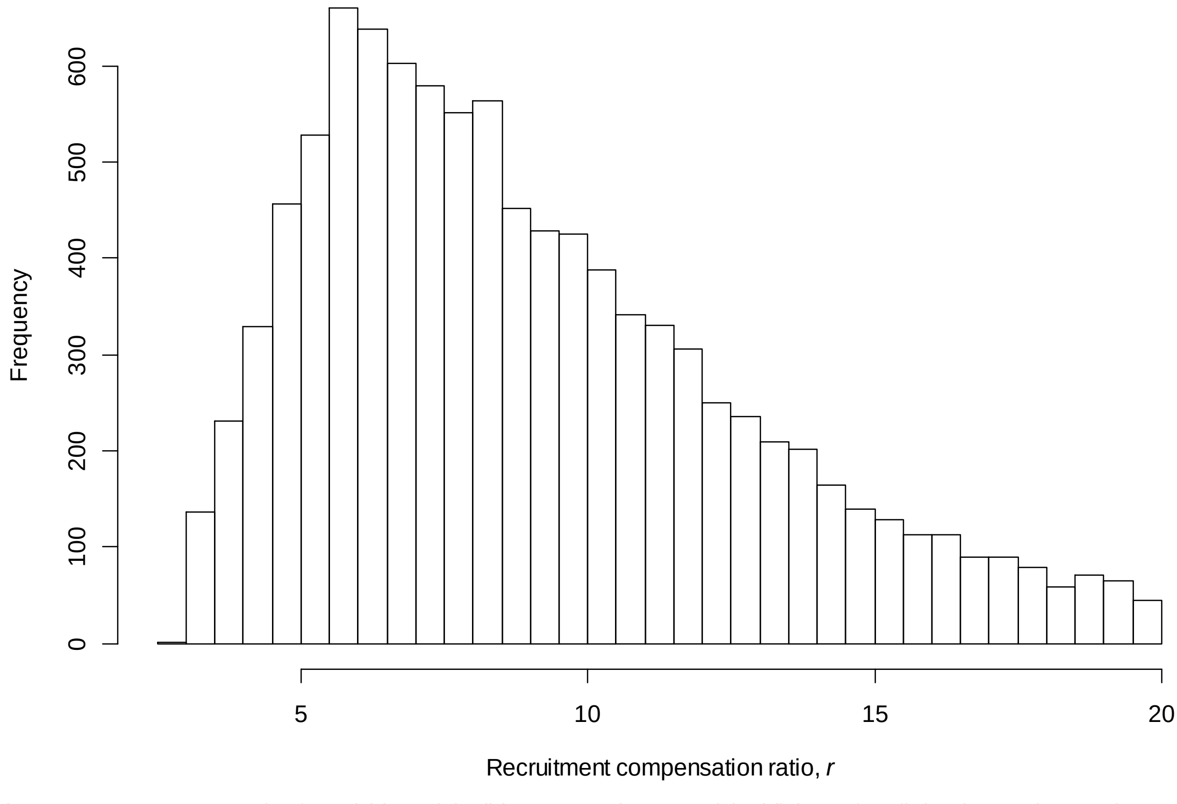
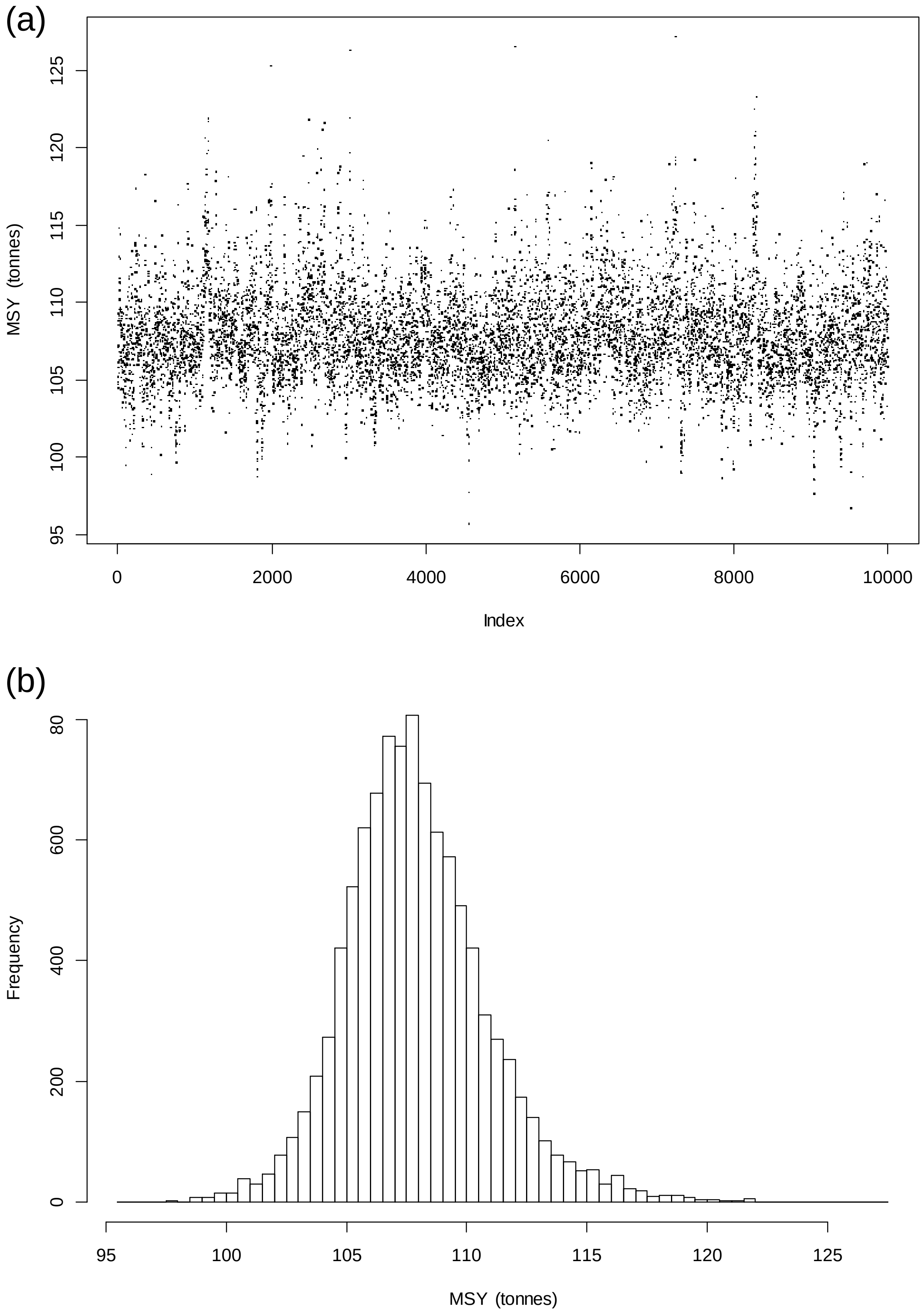
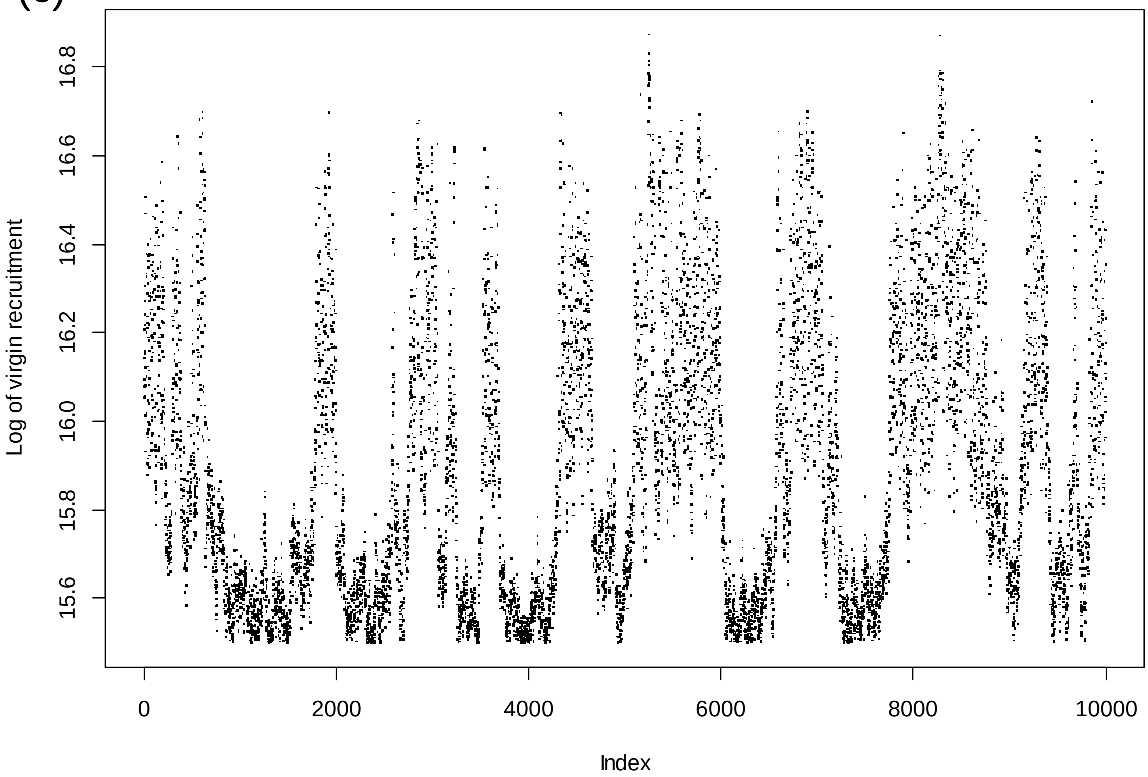


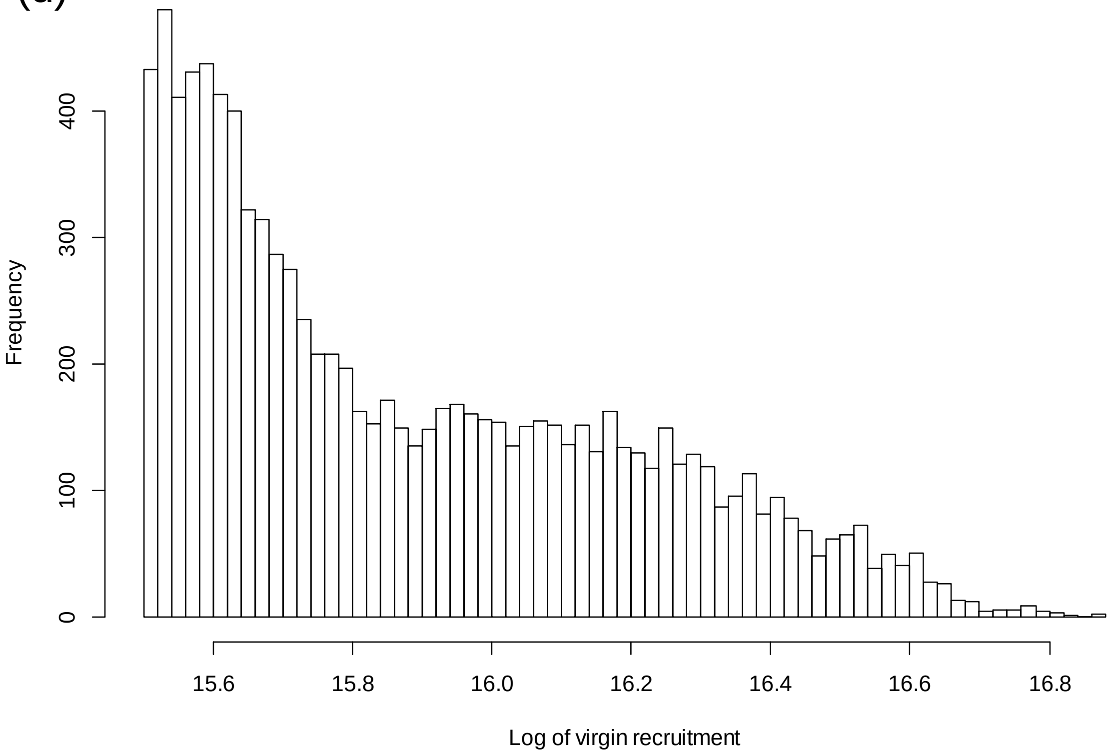
Figure 5.7: MCMC results for whiting: (a)–(b) MSY estimates; (c)–(d) log of unfished recruitment log R_0*; (e)–(f) instantaneous natural mortality rate, M for young fish (age ≤ 4+ yr, age group 5); (g)–(h) instantaneous natural mortality rate, M for older fish (age ≥ 5+ yr, age group 6); (i)–(j) recruitment compensation ratio, r.*

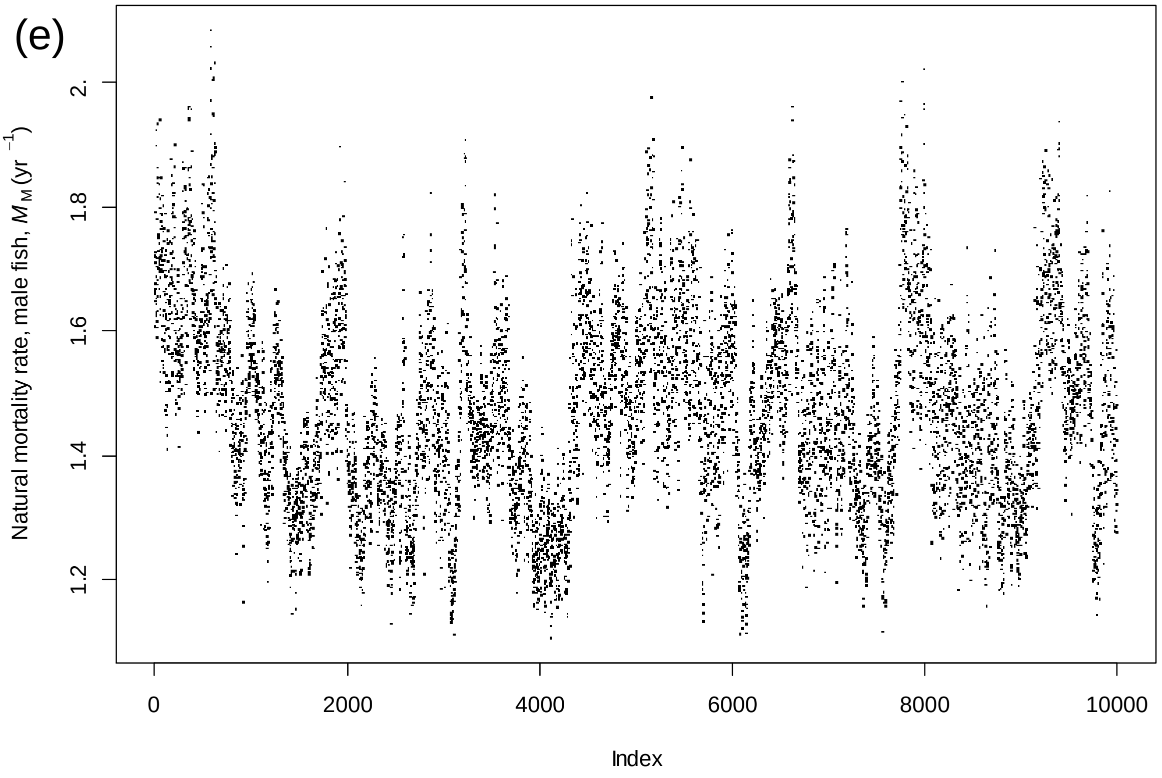

(a)
MSY (tonnes)
95
100
105
110
115
120
125
0
2000
4000
6000
8000
10000
Index
(b)
Frequency
0
200
400
600
800
95
100
105
110
115
120
125
MSY (tonnes)

(c)


Log of virgin recruitment
15.6
15.8
16.0
16.2
16.4
16.6
16.8
0
2000
4000
6000
8000
10000
Index

(d)


Frequency
0
100
200
300
400
15.6
15.8
16.0
16.2
16.4
16.6
16.8
Log of virgin recruitment



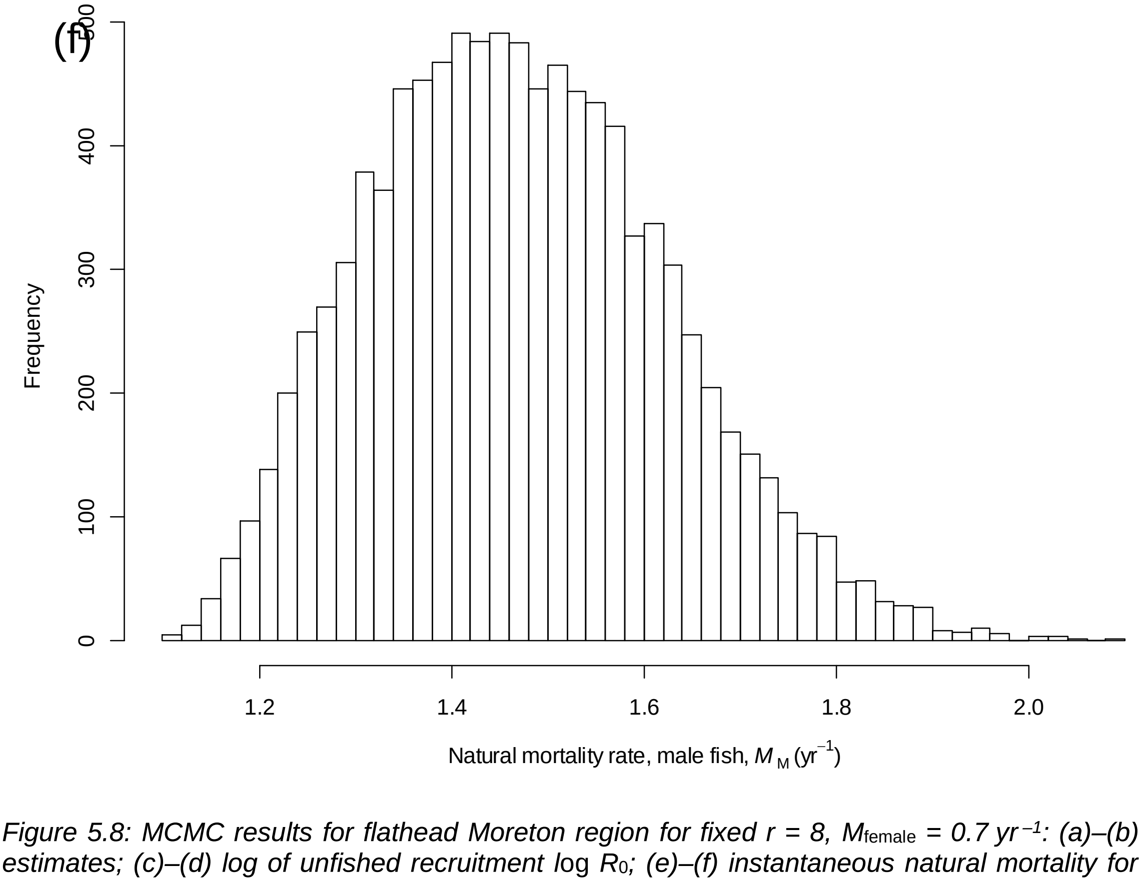
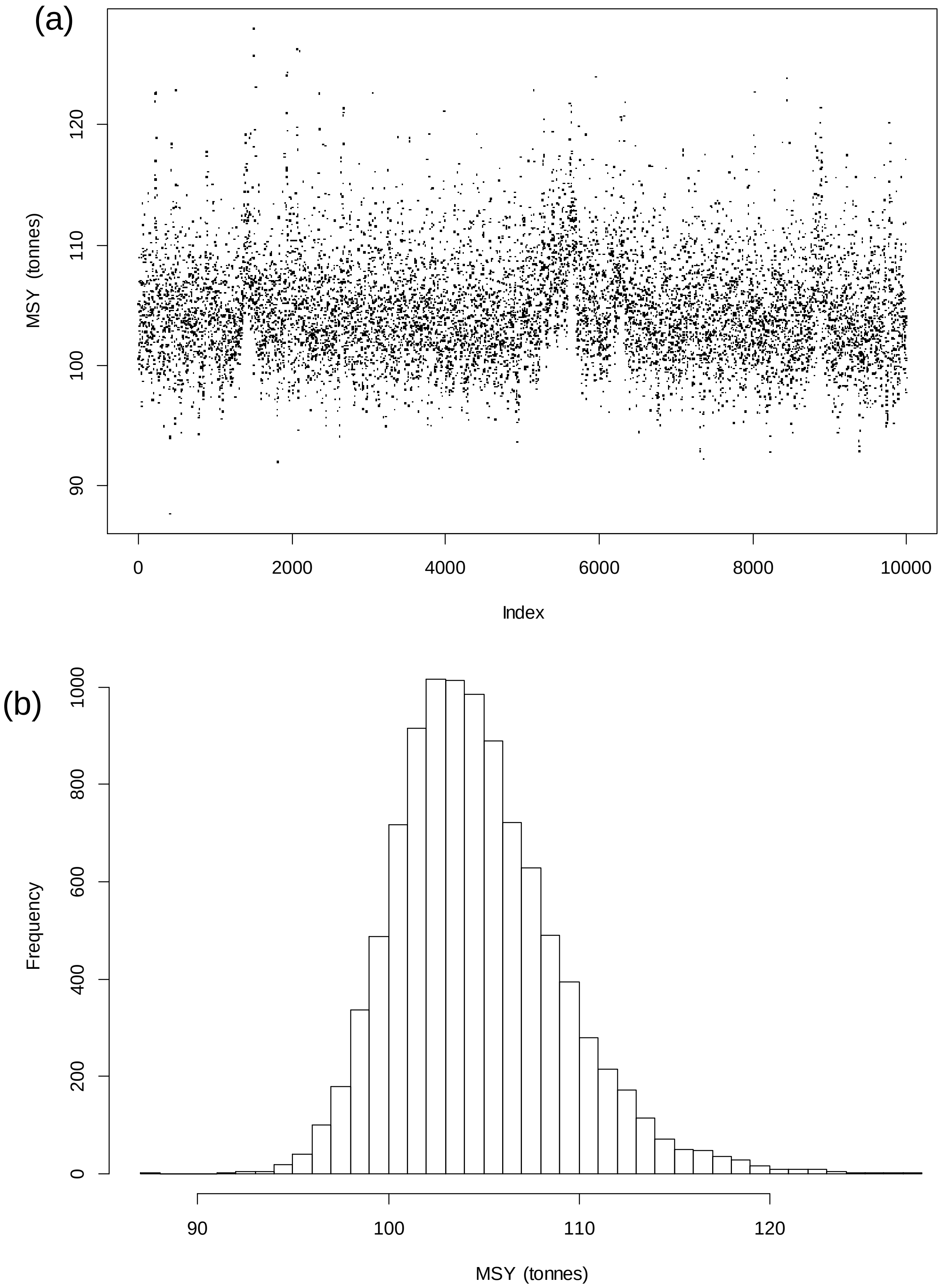
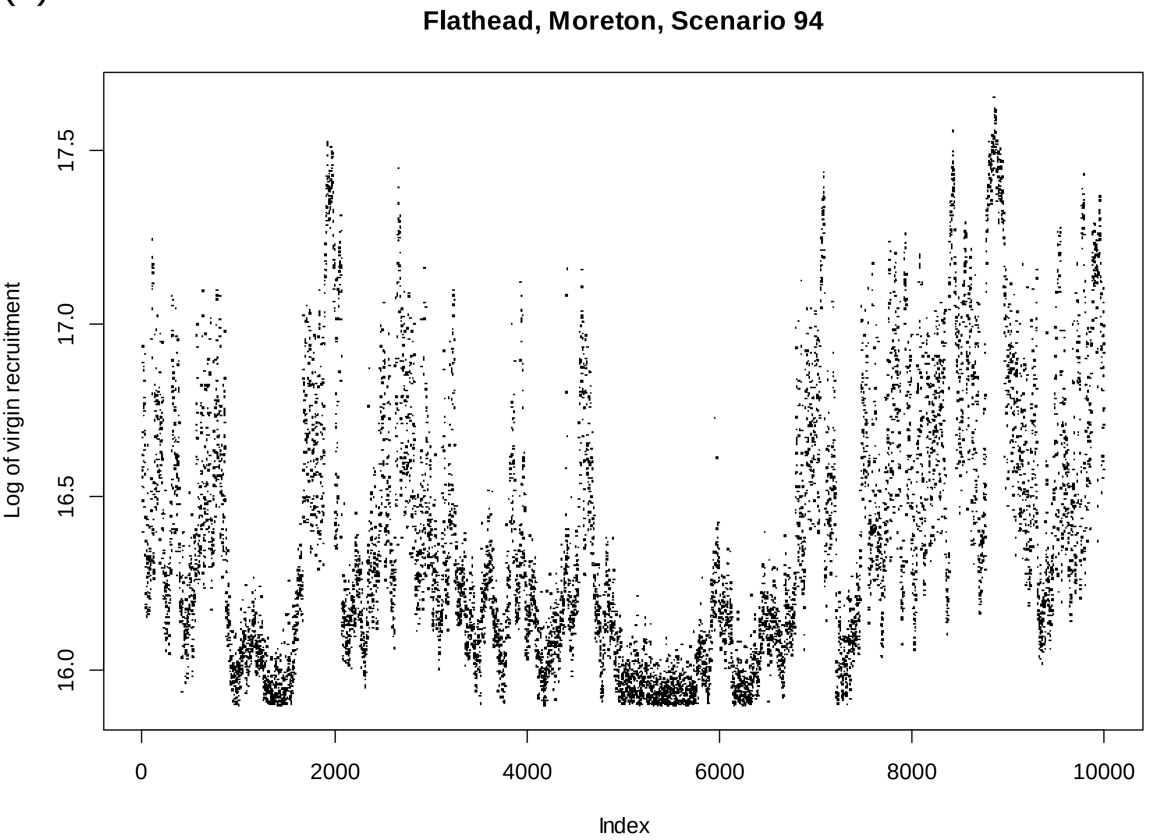


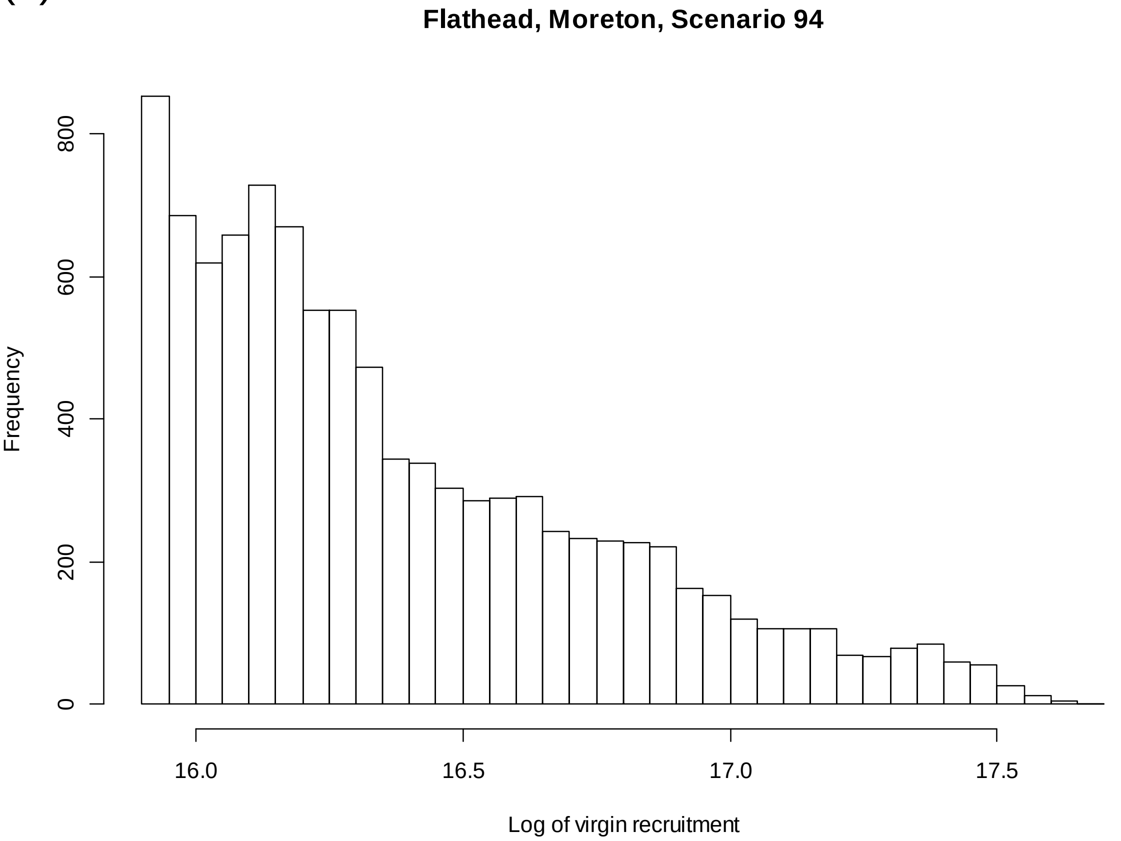
Figure 5.8: MCMC results for flathead Moreton region for fixed r = 8, $M_{\text{female}} = 0.7$ *yr*$^{-1}$*: (a)–(b) MSY estimates; (c)–(d) log of unfished recruitment* log R_0*; (e)–(f) instantaneous natural mortality for male fish,* M_{male}.


(a)
MSY (tonnes)
90
100
110
120
0
2000
4000
6000
8000
10000
Index
(b)
Frequency
0
200
400
600
800
1000
90
100
110
120
MSY (tonnes)

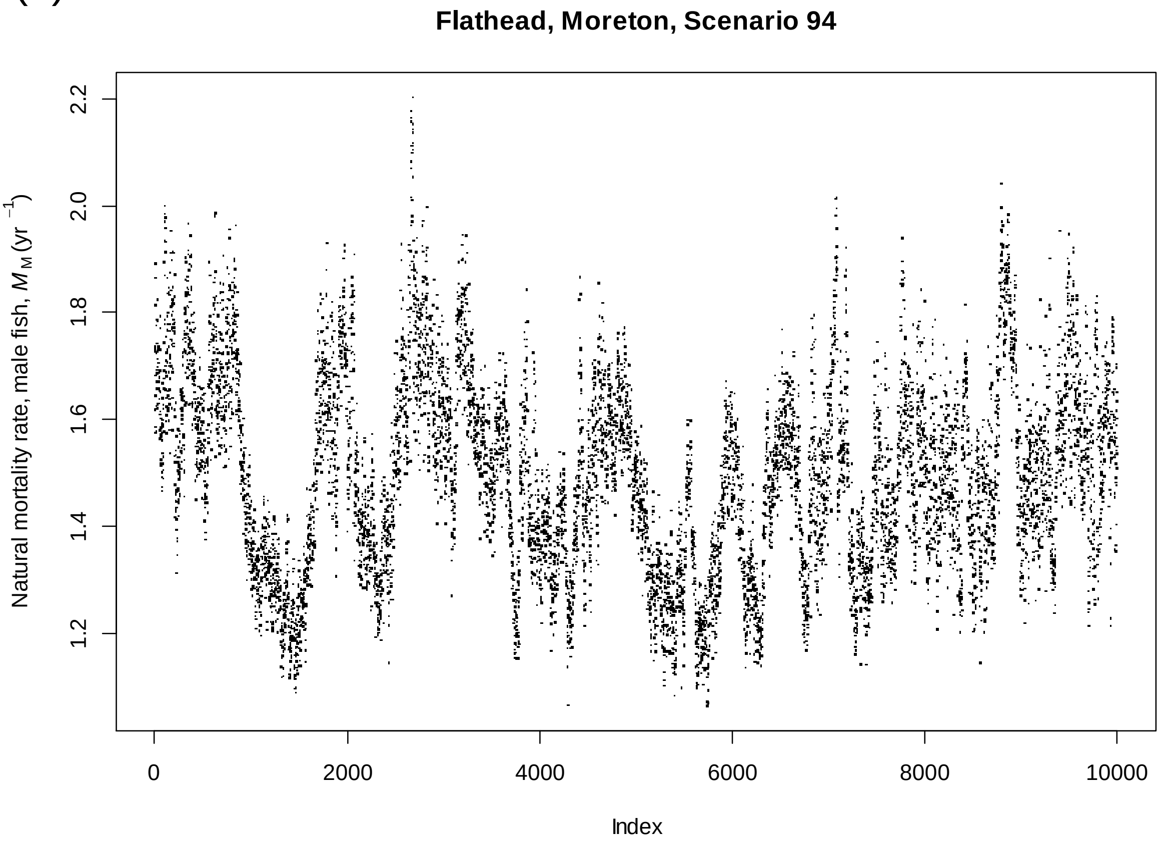
(c)


Flathead, Moreton, Scenario 94
Log of virgin recruitment
16.0
16.5
17.0
17.5
0
2000
4000
6000
8000
10000
Index

(d)


Flathead, Moreton, Scenario 94
Frequency
0
200
400
600
800
16.0
16.5
17.0
17.5
Log of virgin recruitment

(e)



(f)

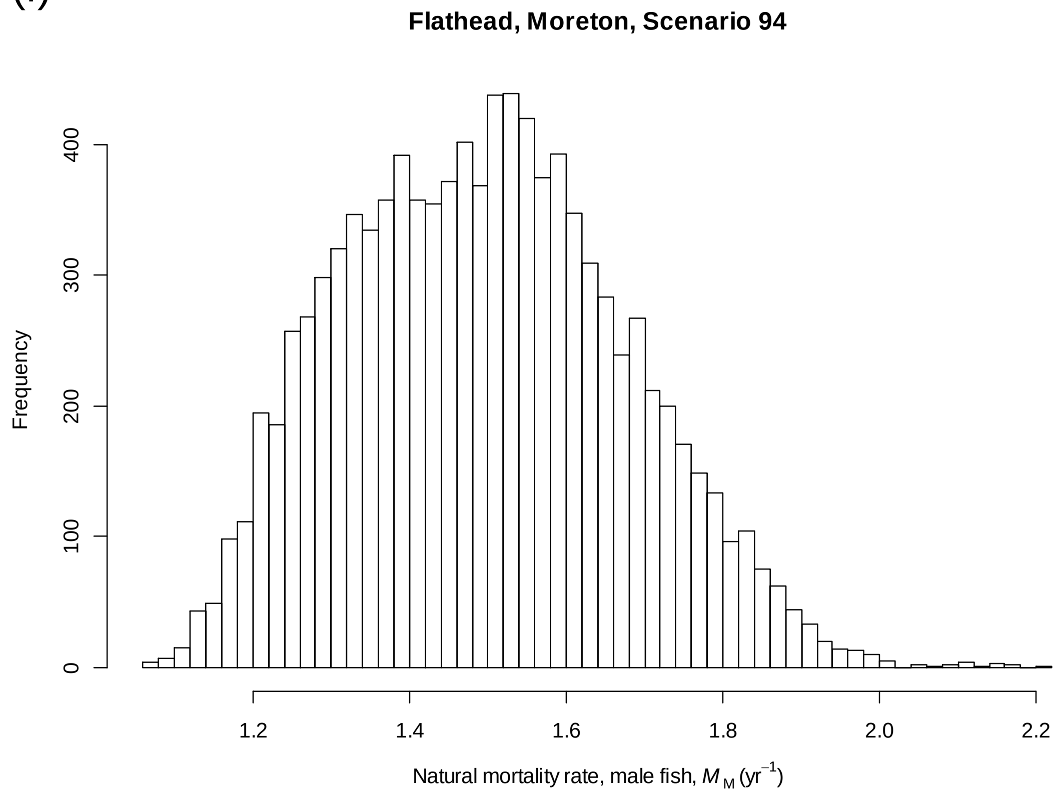


Figure 5.9: MCMC results for flathead Moreton region for fixed r = 4, $M_{\text{female}} = 0.75\ \text{yr}^{-1}$*: (a)–(b) MSY estimates; (c)–(d) log of unfished recruitment* log R_0*; (e)–(f) instantaneous natural mortality for male fish,* M_{male}.

6. Recommendations

6.1 Fishery management

Some management actions are needed for all three species, to restrain the total harvest of bream to current levels and reduce the total harvests of whiting and flathead to allow the populations to recover to targets set by the Queensland Sustainable Fisheries Strategy. Fishing pressure for bream and flathead in the Fraser region appears to be less than in the Moreton region.

6.2 Biological research

The most important research that could aid future assessments of these species is a study of age–length at maturity of female flathead. Available data are contradictory, with the most recent study (which comes from New South Wales) indicating that, even though the minimum legal size of dusky flathead has been raised substantially in Queensland, the median size of maturity of female flathead is still much larger than the minimum legal size. If true, this constitutes a major risk to the stock. We have used those data in this assessment, both because the data are the most recent available and because they produce precautionary outcomes, but we acknowledge that there may be scope to improve them.

The extent of migration of bream, whiting and flathead is also somewhat uncertain, and a well-designed tagging study may help to improve the precision of migration estimates. Age–length data indicate that bream may migrate out of the Fraser region into the Moreton region but no tagging data are available to support this hypothesis.

A skilfully conducted tagging experiment, if it can enlist the cooperation of commercial and recreational fishers to return tags of tagged fish that they catch, and reward them for doing so, could also greatly improve the estimates of natural mortality rates (parameter M) of these species, which are currently imprecise. All three species have been heavily fished (at least in the Moreton region) for many years; hence, available age data can only estimate the total mortality rate Z and cannot separate it into fishing mortality (F) and natural mortality (M). The latter separation has to rely on a full stock assessment and contrast in other fishery data such as catch rates and harvest sizes, which has also been difficult in the assessments reported here.

6.3 Future assessments

We provide the following suggestions for how future stock assessments of these species can be improved over this one. They are listed in decreasing order of importance:

- Make use of older sets of data which time did not permit to be included in this assessment:
    - Coastal Streams project: data from 1993, 1997 and 1998
    - Integrated Stock Assessment and Monitoring Program (ISAMP): data from 1995, 1996 and 1997
    - DAF study on fecundity from the early 1990s (cited by Kerby and Brown, 1994, but not available to the assessments reported here).

  Those data sets may also provide improved biological relationships over those used in these assessments.

- Consider including fishing-club catch rates. These are a potentially very valuable data source and the only one that can capture the increase in fishing pressure on these species from the 1950s to the 1980s.

- Use a sex-structured model for whiting. Male sand whiting grow only slightly smaller than females but available age data from Fisheries Queensland Monitoring indicate that the natural mortality rate of males may be much higher than that of females. Separate natural mortality rates could be fitted to males and females instead of to younger and older fish as the current assessment does.
- Use a separate average weight for bream caught prior to the increase in minimum legal size in March 2010.
- Use the charter logbook database and exclude catches taken from charter vessels in the recreational catch surveys.
- Consider starting the populations at something other than unfished state in 1945. For example, fishing could be made to start in 1901 and harvests could be extrapolated from 1945 back to zero in 1900.
- Consider joint assessments with New South Wales if the fish are thought to migrate further than has been assumed in this assessment. (See above recommendation to investigate migration).
- Consider extending the assessments to North Queensland. This would be complicated by the presence of other, closely related species in large numbers in waters north of Baffle Creek (see Section 1.2 above). Fishery data generally do not distinguish these species.

References

ABS (2014) Australian Historical Population Statistics. Catalogue no. 3105.0.65.001. Australian Bureau of Statistics, Canberra. http://www.abs.gov.au/ausstats/abs@.nsf/cat/3105.0.65.001 [Accessed 10 November 2016].

Beverton, R.J.H. and Holt, S.J. (1957) *On the Dynamics of Exploited Fish Populations*. Chapman and Hall, London.

Burchmore, J.J., Pollard, D.A., Middleton, M.J., Bell, J.D. and Pease, B.C. (1988) Biology of four species of whiting (Pisces: Sillaginidae) in Botany Bay, NSW. *Marine and Freshwater Research* **39**, 709–727.

Claydon, W.C. (1996) *Remembering Len Thompson, the Legend of Bait Spinning*. Queensland Department of Primary Industries, Brisbane.

Cleland, K.W. (1947) Studies on the economic biology of the sand whiting (*Sillago ciliata* C. & V.). *Proceedings of the Linnean Society of New South Wales* **72**, 215–228.

Curley, B.G., Jordan, A.R., Figueira, W.F. and Valenzuela, V.C. (2013) A review of the biology and ecology of key fishes targeted by coastal fisheries in south-east Australia: Identifying critical knowledge gaps required to improve spatial management. *Reviews in Fish Biology and Fisheries* **23**, 435–458.

Darcey, J. (1990) An oral history of the Australian fishing industry. Final report, FRDC project number 1987-021.090. Fisheries Research and Development Corporation, Canberra. http://frdc.com.au/research/final-reports/Pages/1987-021.90-DLD.aspx [Accessed 23 March 2017].

Encyclopedia of Mathematics (2012) Linear interpolation. *Encyclopedia of Mathematics*. Springer. http://www.encyclopediaofmath.org/index.php?title=Linear_interpolation&oldid=27068 [Accessed 23 March 2017].

Encyclopedia of Mathematics (2015) Stirling formula. *Encyclopedia of Mathematics*. http://www.encyclopediaofmath.org/index.php?title=Stirling_formula&oldid=36832 [Accessed 23 March 2017].

Fournier, D.A., Skaug, H.J., Ancheta, J., et al. (2011) AD Model Builder: Using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. *Optimization Methods and Software* **27**, DOI: 10.1080/10556788.2011.597854.

Francis, R.I.C.C. (2011) Data weighting in statistical fisheries stock assessment models. *Canadian Journal of Fisheries and Aquatic Sciences* **68**, 1124–1138.

Friðriksson, Á. (1934) On the calculation of age-distribution within a stock of cod by means of relatively few age determinations as a key to measurements on a large scale. *Rapports et Procès-verbaux des Réunions du Conseil Permanent International pour l'Exploration de la Mer* **86 (VI)**, 1–5.

Goodyear, C.P. (1977) Assessing the impact of power plant mortality on the compensatory reserve of fish populations. In: *Conference on Assessing the Effects of Power Plant Induced Mortality on Fish Populations*. (ed W. van Winkle). Pergamon Press, New York, pp 186–195.

Gray, C.A. and Barnes, L.M. (2015) Spawning, maturity, growth and movement of *Platycephalus fuscus* (Cuvier, 1829) (Platycephalidae): Fishery management considerations. *Journal of Applied Ichthyology* **31**, 442–450.

Gray, C.A., Gale, V.J., Stringfellow, S.L. and Raines, L.P. (2002) Variations in sex, length and age compositions of commercial catches of *Platycephalus fuscus* (Pisces : Platycephalidae) in New South Wales, Australia. *Marine and Freshwater Research* **53**, 1091–1100.

Gray, C.A., Pease, B.C., Stringfellow, S.L., et al. (2000) Sampling estuarine fish species for stock assessment. NSW Fisheries Final Report Series No. 18, FRDC Project no. 94/042. NSW Fisheries Research Institute, Sydney. http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0020/545600/FFRS-18_Gray-2000.pdf [Accessed 19 April 2017].

Haddon, M. (2001) *Modelling and Quantitative Methods in Fisheries*. CRC Press, Boca Raton, FL.

Halliday, I. and Robins, J. (2007) Environmental Flows for Sub-tropical Estuaries: Understanding the Freshwater Needs of Estuaries for Sustainable Fisheries Production and Assessing the Impacts of Water Regulation. Department of Primary Industries and Fisheries, Brisbane. http://frdc.com.au/research/Documents/Final_reports/2001-022-DLD.PDF [Accessed 10 November 2016].

Henry, G.W. and Lyle, J.M. (2003) The National Recreational and Indigenous Fishing Survey. Australian Government Department of Agriculture, Fisheries and Forestry, Canberra. http://eprints.utas.edu.au/2526/1/Henry_Lyle_Nationalsurvey.pdf [Accessed 10 November 2016].

Hicks, T., Kopf, R.K. and Humphries, P. (2015) Fecundity and egg quality of dusky flathead (*Platycephalus fuscus*) in East Gippsland, Victoria. Report no. 94. Charles Sturt University, Institute for Land, Water and Society. https://www.csu.edu.au/research/ilws/publications/ilws-reports/2015/Hicks-et-al-Fecundity-and-egg-quality-of-dusky-flathead.pdf [Accessed 9 March 2016].

Higgs, J. (2001) Recreational Catch Estimates for Queensland Residents. RFISH Technical Report No. 3. Queensland Department of Primary Industries, Brisbane.

Higgs, J. (1999) RFISH Technical Report No. 2: Results from the 1997 Diary Round. Queensland Department of Primary Industries, Brisbane.

Higgs, J., Olyott, L. and McInnes, K. (2007) Experimental Results from the Third Statewide Recreational Fishing Information System Diary Program (2002). Queensland Department of Primary Industries and Fisheries, Brisbane.

Hoyle, S.D., Brown, I.W., Dichmont, C.M., Sellin, M.J., Cosgrove, M. and McLennan, M.F. (2000) Integrated Fish Stock Assessment and Monitoring Program. QO99011, FRDC Project 1994/161. Department of Primary Industries, Brisbane. http://frdc.com.au/research/Documents/Final_reports/1994-161-DLD.pdf [Accessed 3 August 2016].

Imamura, H. (2008) Synonymy of two species of the genus *Platycephalus* and validity of *Platycephalus westraliae* (Teleostei: Platycephalidae). *Ichthyological Research* **55**, 399–406.

Imamura, H. (2015) Taxonomic revision of the flathead fish genus *Platycephalus* Bloch, 1785 (Teleostei: Platycephalidae) from Australia, with description of a new species. *Zootaxa* **3904**, 151–207.

Kerby, B.M. and Brown, I.W. (1994) Bream, Whiting and Flathead in south-east Queensland: A review of the literature. Information Series QI94028. Department of Primary Industries, Brisbane.

Krusic-Golub, K., Gunthorpe, L. and Robertson, S. (2012) Age Validation of Deepwater Flathead from the Great Australian Bight Trawl Fishery. Fisheries Victoria, Queenscliff, Australia. http://frdc.com.au/research/final-reports/Pages/2005-008-DLD.aspx.

Lawson, A. (2015) An Investigative Analysis of Queensland's Statewide Recreational Fishing Surveys: Identifying Bias in Self-reported Catch and Effort Data. Department of Agriculture and Fisheries, Brisbane.

Leigh, G.M., O'Neill, M.F. and Stewart, J. (2017) Stock assessment of the Australian east coast tailor (*Pomatomus saltatrix*) fishery. Department of Agriculture and Fisheries, Brisbane. era.daf.qld.gov.au/5689/ [Accessed 28 May 2018].

McAllister, M.K. and Ianelli, J.N. (1997) Bayesian stock assessment using catch-age data and the sampling-importance resampling algorithm. *Canadian Journal of Fisheries and Aquatic Sciences* **54**, 284–300.

McCullagh, P. and Nelder, J.A. (1989) *Generalized Linear Models*, 2nd edn. Springer.

McInnes, K. (2008) Experimental Results from the Fourth Queensland Recreational Fishing Diary Program (2005). Department of Primary Industries and Fisheries, Brisbane.

Morton, R.M. (1985a) The reproductive biology of summer whiting *Sillago ciliata* (C. & V.) in northern Moreton Bay, Queensland. *Australian Zoologist* **21**, 491–502.

Morton, R.M. (1985b) The tagging of summer whiting, *Sillago ciliata* in northern Moreton Bay, Queensland. *Proceedings of the Royal Society of Queensland* **6**, 19–23.

Ochwada-Doyle, F.A., Stocks, J., Barnes, L. and Gray, C.A. (2014) Reproduction, growth and mortality of the exploited sillaginid, *Sillago ciliata* Cuvier, 1829. *Journal of Applied Ichthyology* **30**, 870–880.

O'Neill, M.F. (2000) Fishery assessment of the Burnett River, Maroochy River and Pumicestone Passage. QO099012. Department of Primary Industries, Brisbane.

O'Neill, M.F., Langstreth, J., Buckley, S.M. and Stewart, J. (2018) Stock assessment of Australian east coast Spanish mackerel : Predictions of stock status and reference points. http://era.daf.qld.gov.au/id/eprint/6202/ [Accessed 4 February 2019].

O'Neill, M.F., Leigh, G.M., Wang, Y.-G., Braccini, J.M. and Ives, M.C. (2014) Linking spatial stock dynamics and economics: Evaluation of indicators and fishery management for the travelling eastern king prawn (*Melicertus plebejus*). *ICES Journal of Marine Science* **71**, 1818–1834.

Parrish, B.B. (1957) Some remarks on selection processes in fishing operations. In: *The Selectivity of Fishing Gear, Being Volume 2 of Proceedings of Joint ICNAF / ICES / FAO Special Scientific Meeting, Lisbon, 1957*. International Commission for the Northwest Atlantic Fisheries, Special Publication No. 5 (1963), Lisbon, pp 166–170.

Pennington, M. and Vølstad, J.H. (1994) Assessing the effect of intra-haul correlation and variable density on estimates of population characteristics from marine surveys. *Biometrics* **50**, 725–732.

Pepperell, J.G. (2009) The Good Old Days? Historical Insights into Coastal NSW Fish Populations and Their Fisheries. 103 pp. New South Wales Department of Primary Industries, Sydney. http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0010/264475/Historic-insights-into-NSW-Fisheries.pdf.

Pollock, B.R. (1982a) Movements and migrations of yellowfin bream, *Acanthopagrus australis* (Günther), in Moreton Bay, Queensland as determined by tag recoveries. *Journal of Fish Biology* **20**, 245–252.

Pollock, B.R. (1982b) Spawning period and growth of yellowfin bream, *Acanthopagrus australis* (Günther), in Moreton Bay, Australia. *Journal of Fish Biology* **21**, 349–355.

Pollock, B.R. (1985) The reproductive cycle of yellowfin bream, *Acanthopagrus australis* (Günther), with particular reference to protandrous sex inversion. *Journal of Fish Biology* **26**, 301–311.

Punt, A.E., Campbell, R.A. and Smith, A.D.M. (2001) Evaluating empirical indicators and reference points for fisheries management: Application to the broadbill swordfish fishery off eastern Australia. *Marine and Freshwater Research* **52**, 819–832.

Punt, A.E., Haddon, M. and McGarvey, R. (2016) Estimating growth within size-structured fishery stock assessments: What is the state of the art and what does the future look like? *Fisheries Research* **180**, 147–160.

R Core Team (2019) *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna.

Randall, J.E., Allen, G.R. and Steene, R.C. (1997) *Fishes of the Great Barrier Reef and Coral Sea*. University of Hawai'i Press, Honolulu.

Ricker, W.E. (1975) *Computation and Interpretation of Biological Statistics of Fish Populations*, (Bulletin of the Fisheries Research Board of Canada, Vol. 191). Department of the Environment, Fisheries and Marine Service, Ottawa.

Russell, D.J. (1988) An assessment of the east Queensland inshore gillnet fishery. Information Series QI88024. Queensland Department of Primary Industries, Brisbane.

Stead, D.G. (1908) *The Edible Fishes of New South Wales: Their Present Importance and Their Potentialities*. New South Wales Department of Fisheries, Sydney.

Stocks, J., Stewart, J., Gray, C.A. and West, R.J. (2011) Using otolith increment widths to infer spatial, temporal and gender variation in the growth of sand whiting *Sillago ciliata*. *Fisheries Management and Ecology* **18**, 121–131.

Taylor, S., Webley, J. and McInnes, K. (2012) 2010 Statewide Recreational Fishing Survey. Department of Agriculture, Fisheries and Forestry, Brisbane. http://www.daff.qld.gov.au/fisheries/monitoring-our-fisheries/statewide-and-regional-recreational-fishing-survey/queenslands-2010-statewide-recreational-fishing-survey.

Thomson, J.M. (1959) Some aspects of the ecology of Lake Macquarie, N.S.W., with regard to an alleged depletion of fish. X. The movements of fish. *Marine and Freshwater Research* **10**, 375–387.

Wallace-Carter, E. (1987) *For They Were Fishers: The history of the fishing industry in South Australia*. Amphitrite Publishing House.

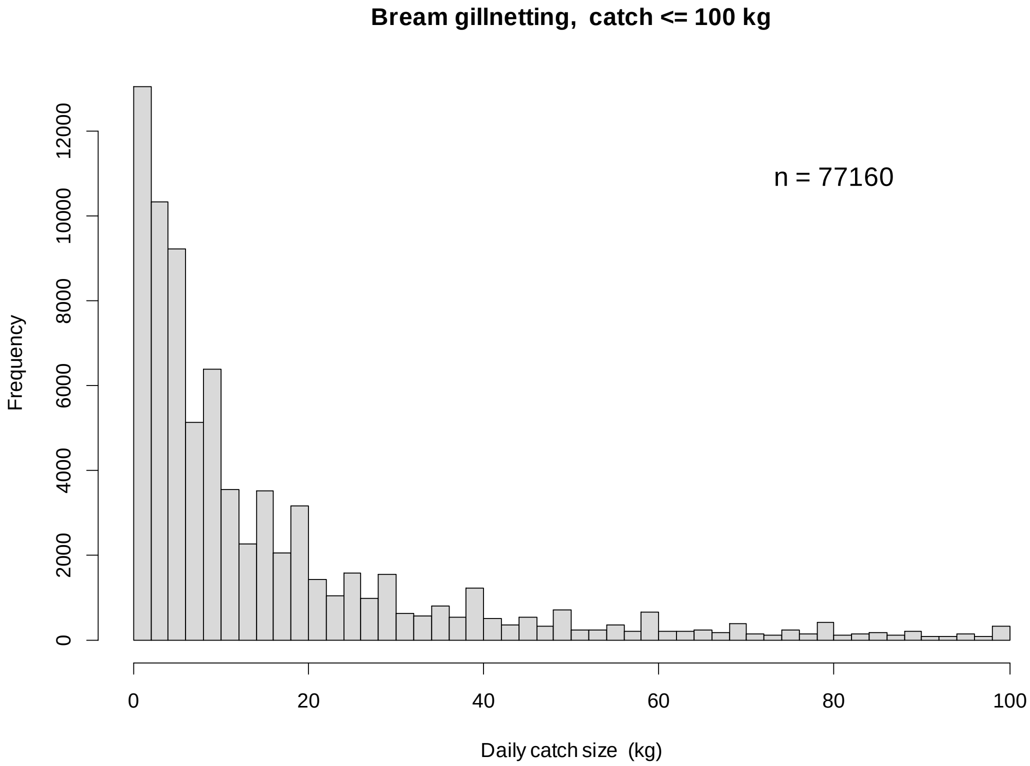
Webley, J.A.C., McInnes, K., Teixeira, D., Lawson, A. and Quinn, R. (2015) Statewide Recreational Fishing Survey 2013–14. Department of Agriculture and Fisheries, Brisbane.

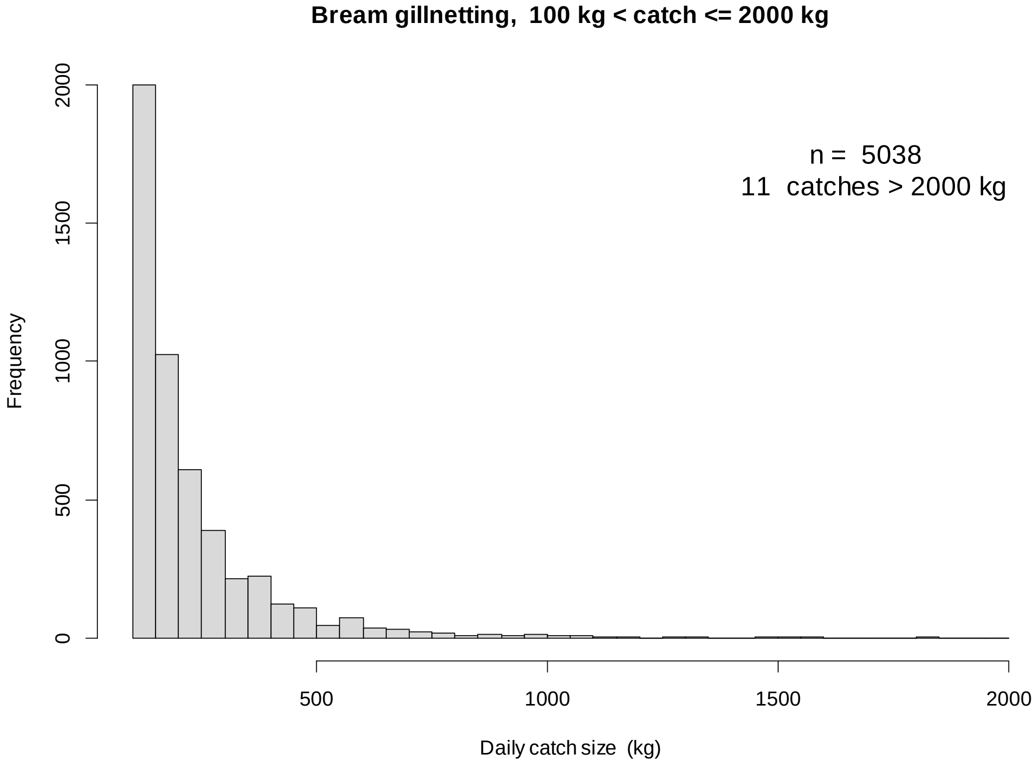
Williams, F. (1982) *A History of Fraser Island: Written in Sand*. Jacaranda Press, Brisbane.

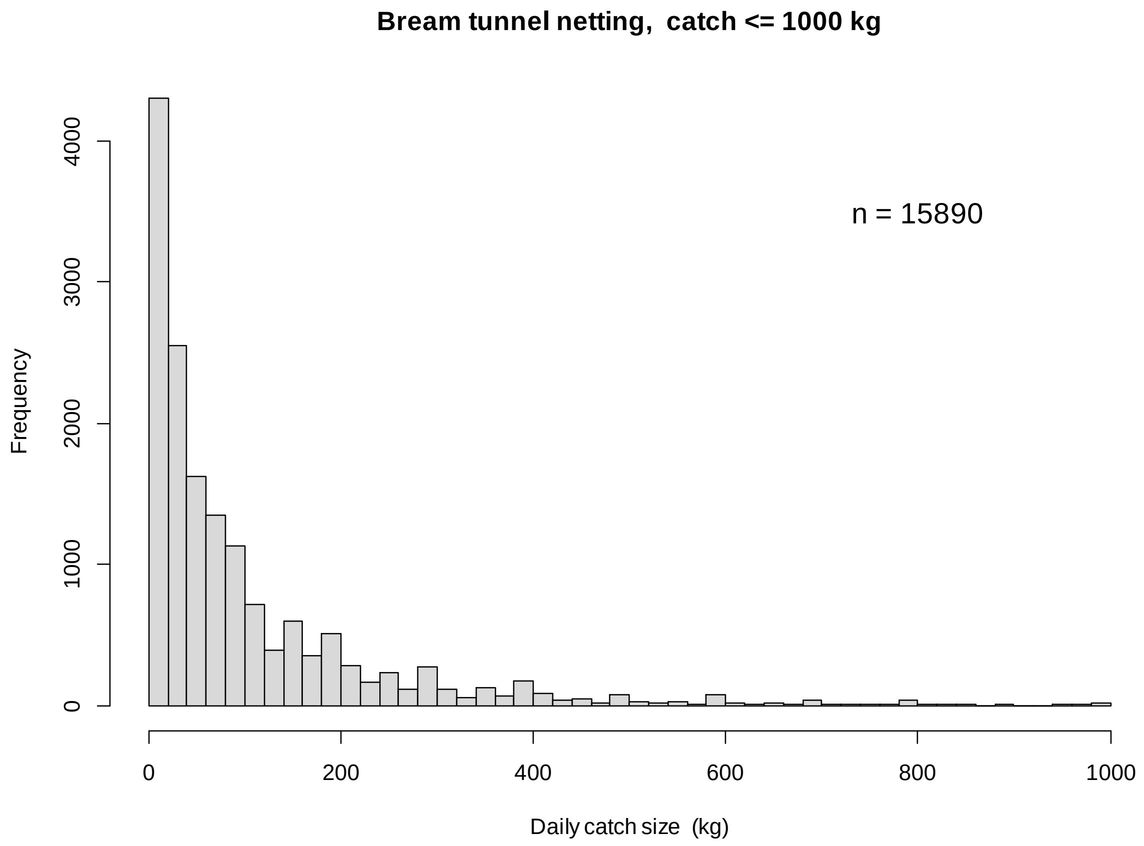
Wortmann, J., O'Neill, M.F., Sumpton, W., Campbell, M.J. and Stewart, J. (2018) Stock assessment of Australian east coast snapper, *Chrysophrys auratus*: Predictions of stock status and reference points for 2016. http://era.daf.qld.gov.au/id/eprint/6341/ [Accessed 4 February 2019].

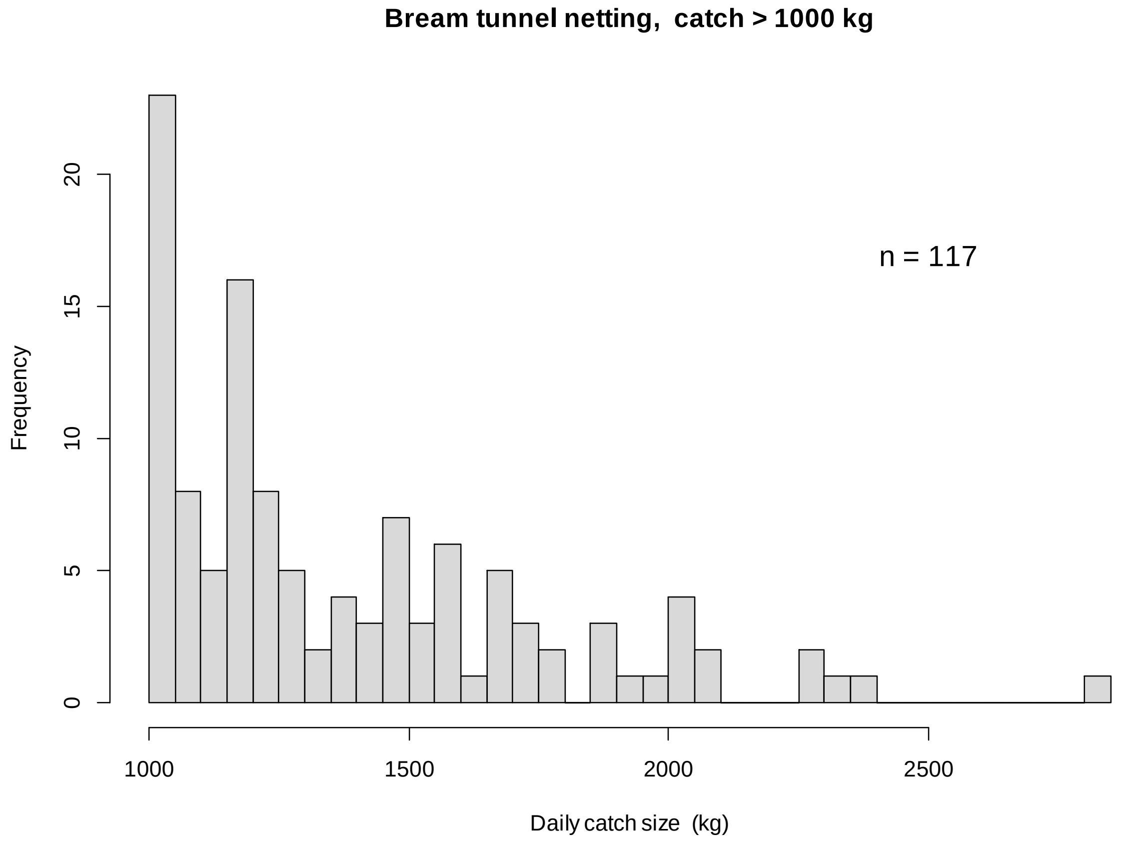
Appendix 1: Distributions of daily commercial catch

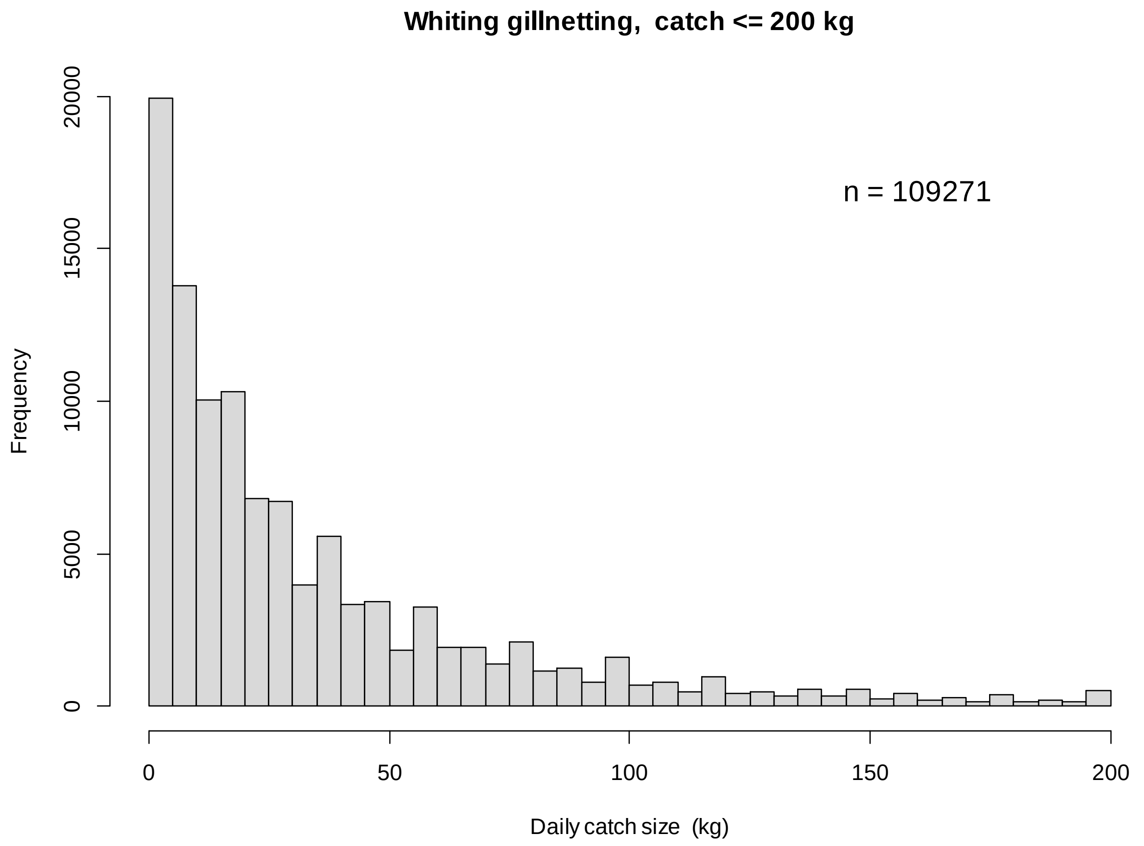
The following plots show histograms of the distributions of daily catches of bream, whiting and flathead by commercial gillnet and tunnel net fishers. Sample size 'n' is the number of fishing operation days.

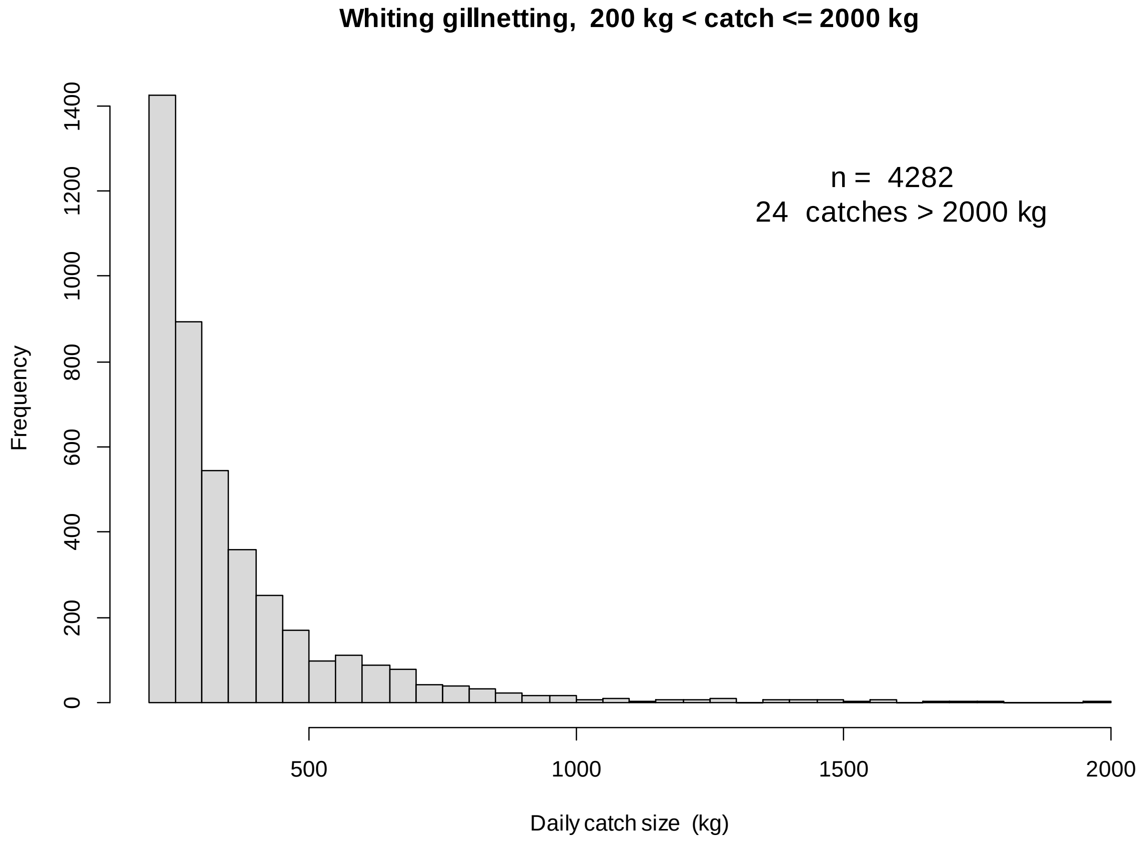


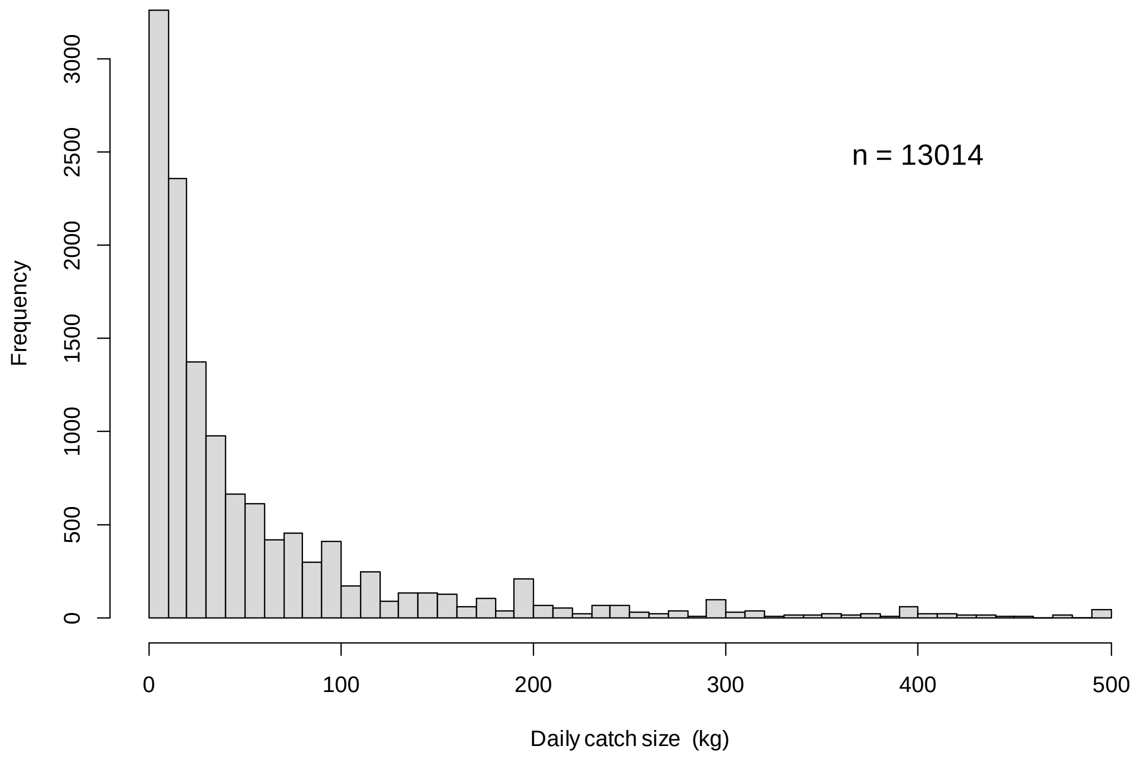



Bream tunnel netting, catch <= 1000 kg
Frequency
0
1000
2000
3000
4000
n = 15890
0
200
400
600
800
1000
Daily catch size (kg)

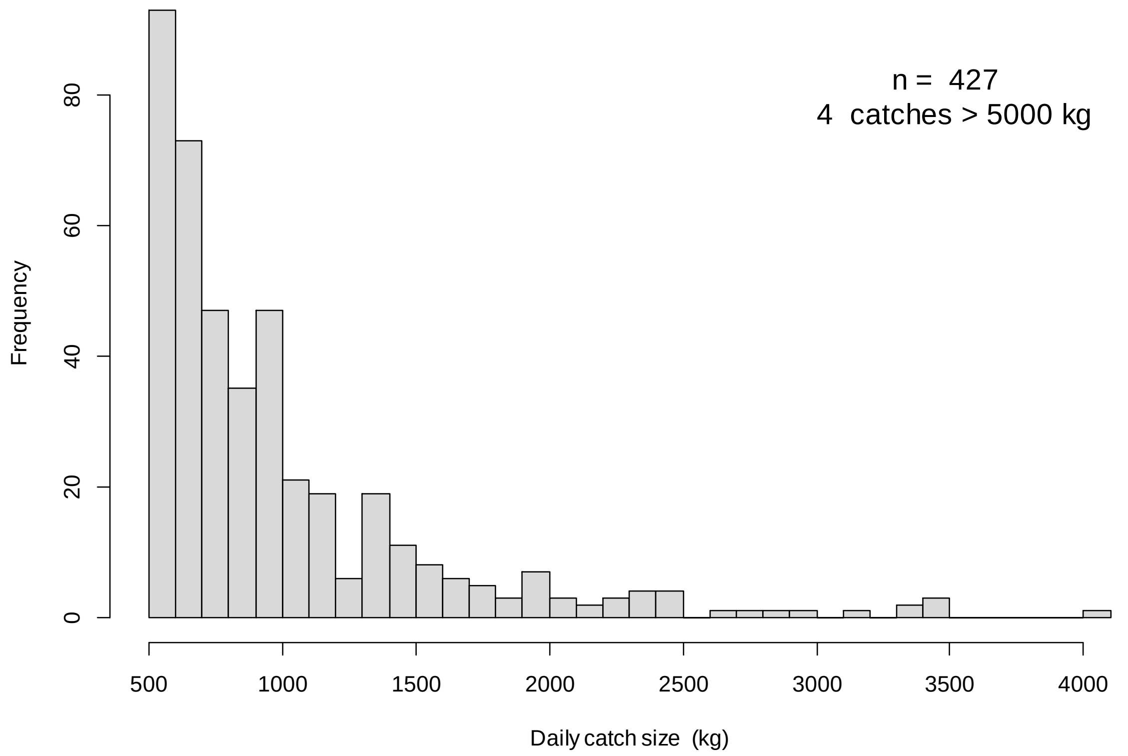

Bream tunnel netting, catch > 1000 kg
Frequency
0
5
10
15
20
n = 117
1000
1500
2000
2500
Daily catch size (kg)


Whiting gillnetting, catch <= 200 kg
n = 109271
Frequency
0
5000
10000
15000
20000
0
50
100
150
200
Daily catch size (kg)

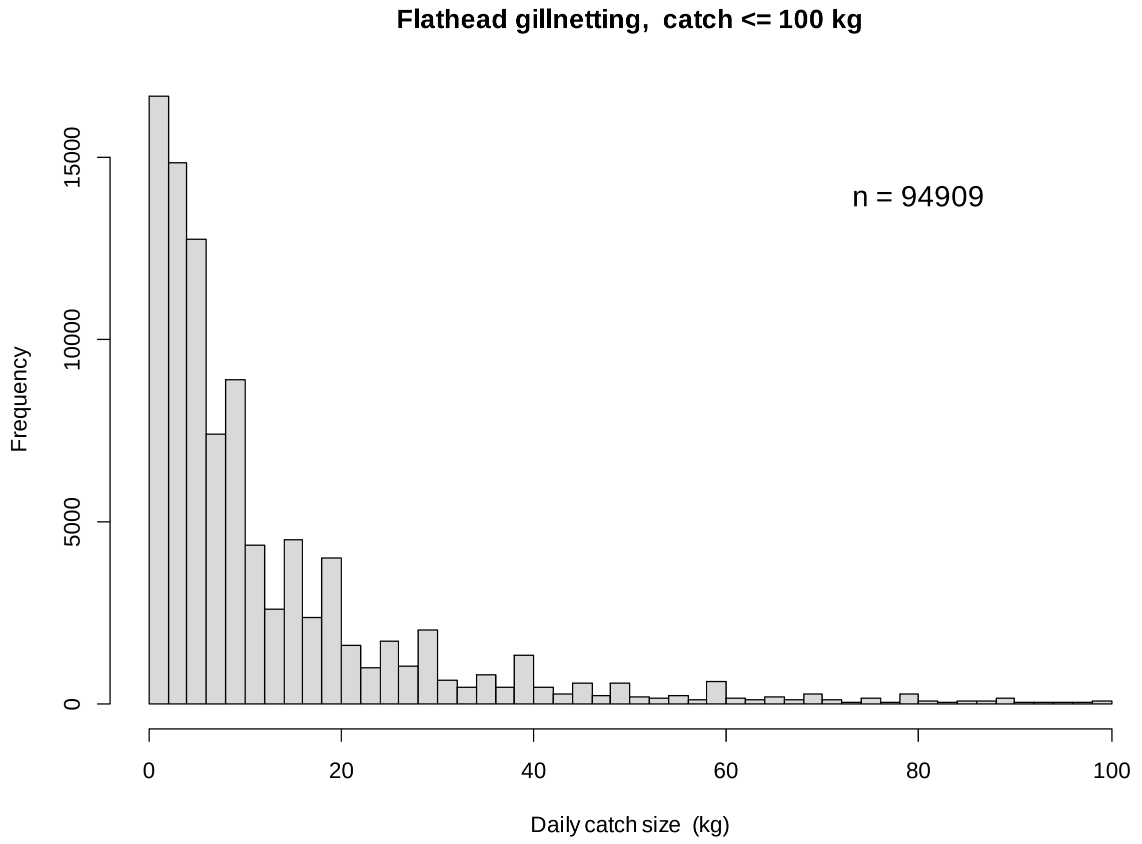

Whiting gillnetting, 200 kg < catch <= 2000 kg
n = 4282
24 catches > 2000 kg
Frequency
0
200
400
600
800
1000
1200
1400
500
1000
1500
2000
Daily catch size (kg)

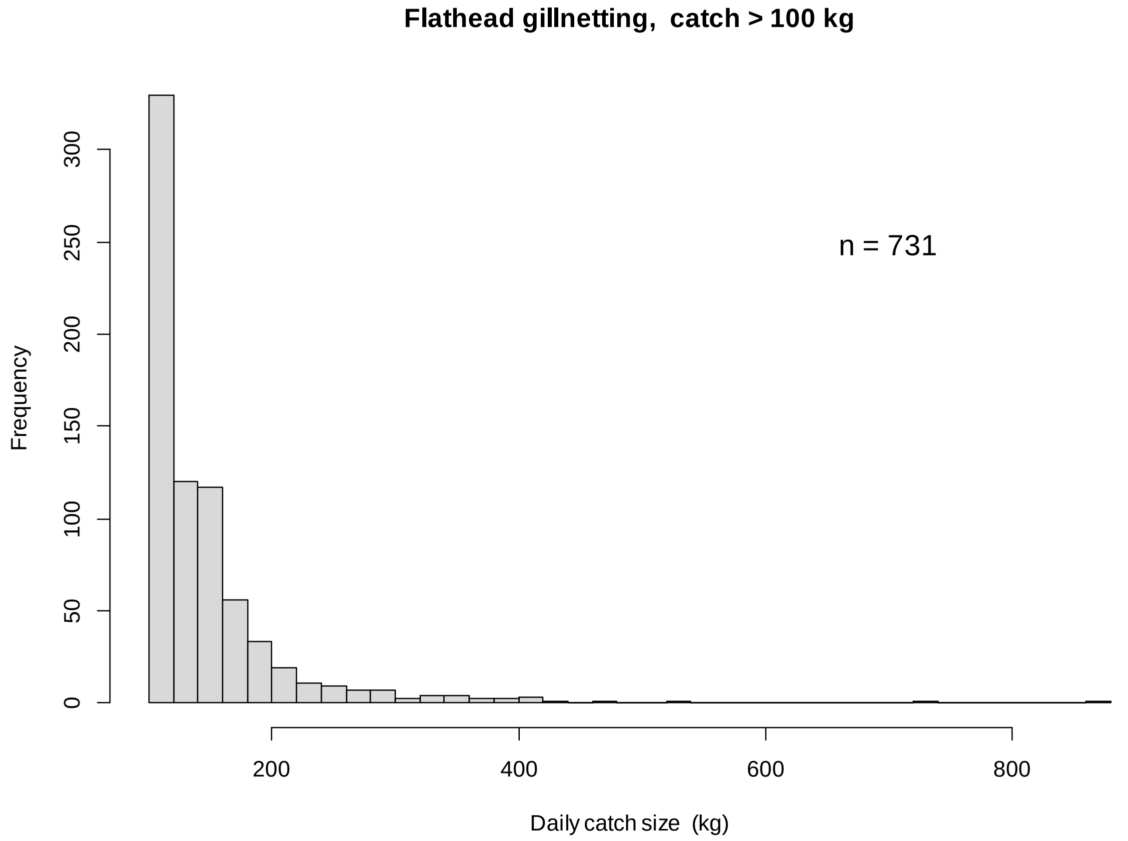


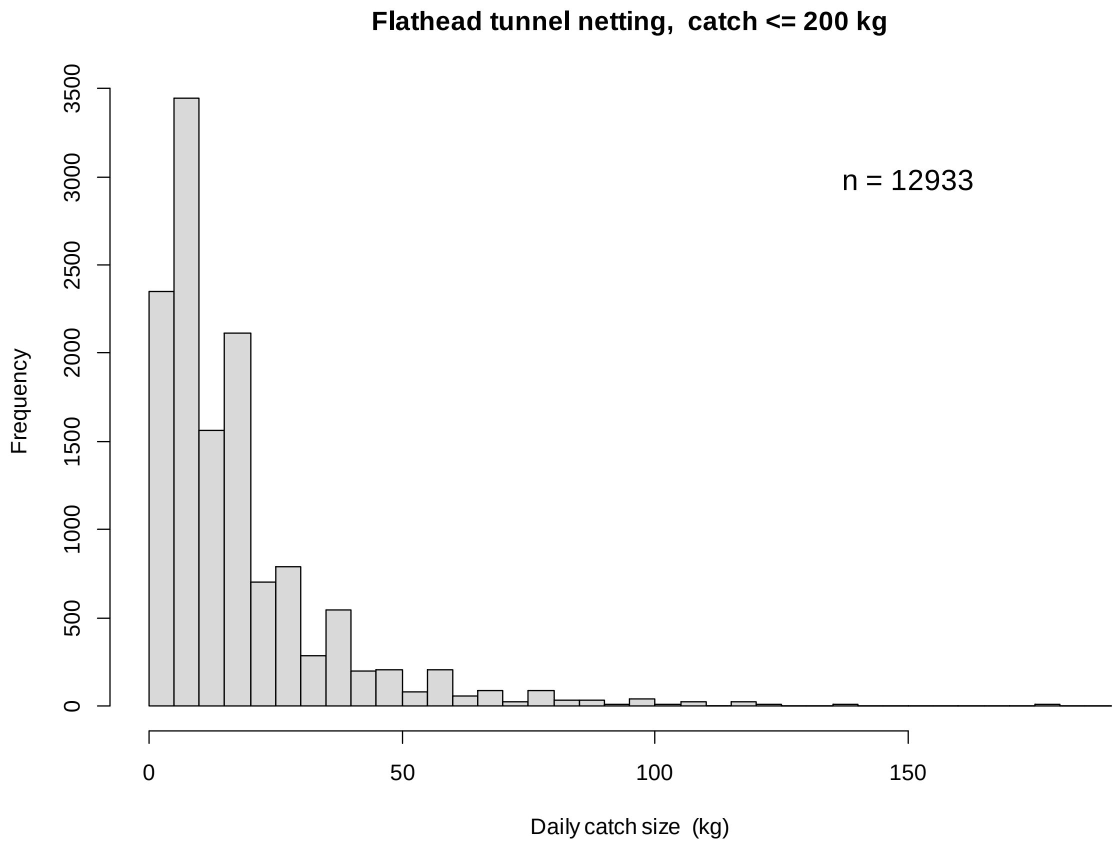
Whiting tunnel netting, catch <= 500 kg

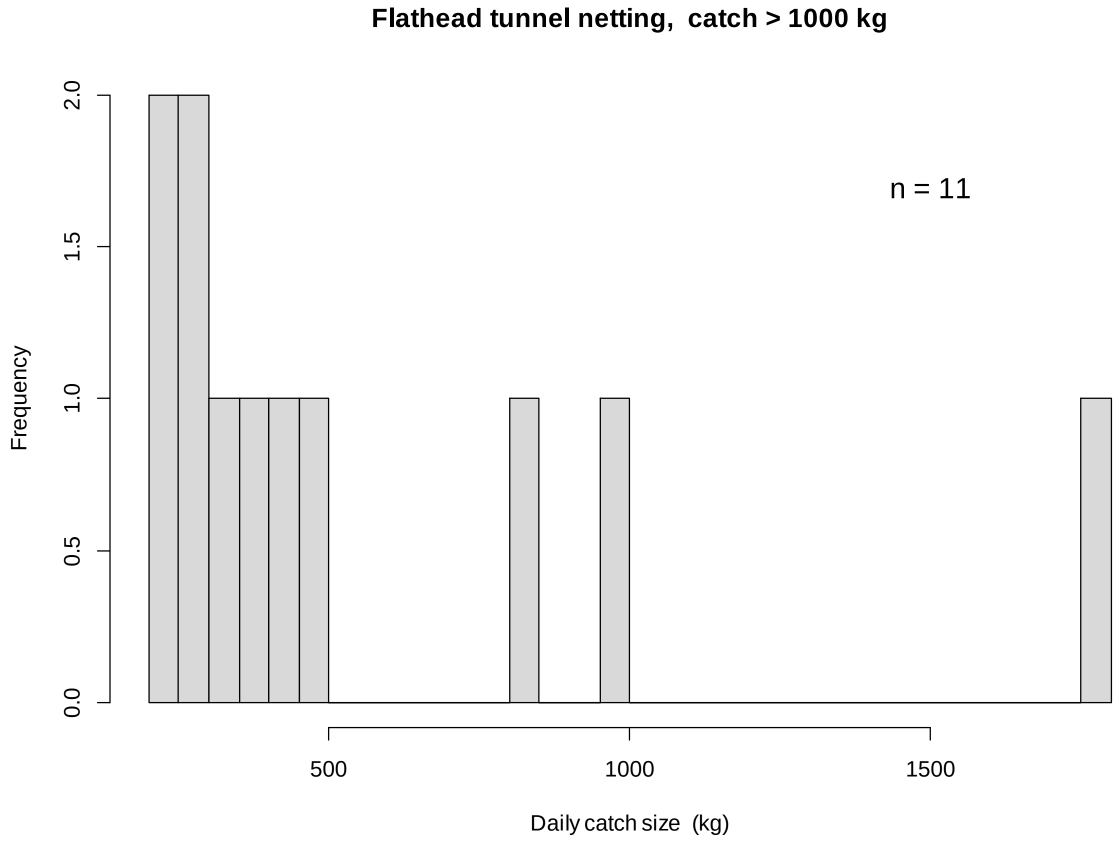


Whiting tunnel netting, 500 kg < catch <= 5000 kg


Flathead gillnetting, catch <= 100 kg
n = 94909
Frequency
0
5000
10000
15000
0
20
40
60
80
100
Daily catch size (kg)


Flathead gillnetting, catch > 100 kg
n = 731
Frequency
0
50
100
150
200
250
300
200
400
600
800
Daily catch size (kg)


Flathead tunnel netting, catch <= 200 kg
n = 12933
Frequency
0
500
1000
1500
2000
2500
3000
3500
0
50
100
150
Daily catch size (kg)

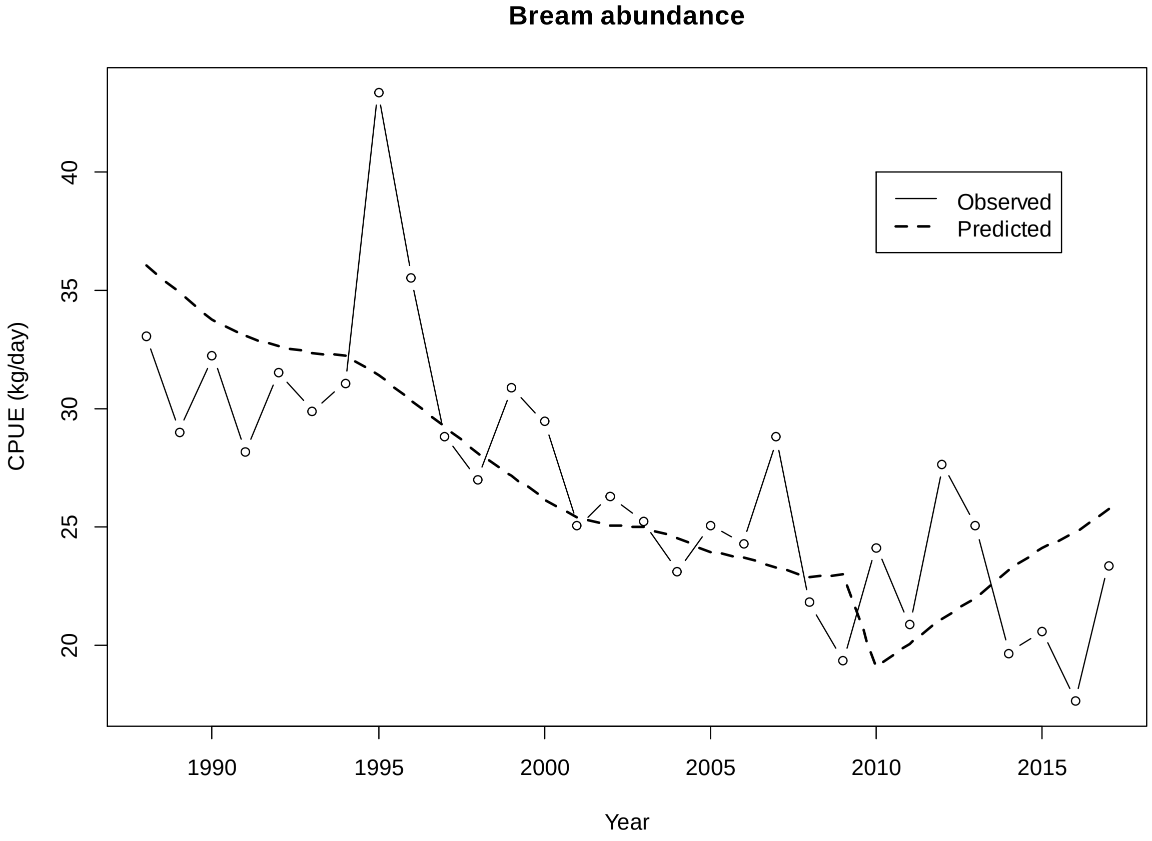

Flathead tunnel netting, catch > 1000 kg
n = 11
Frequency
0.0
0.5
1.0
1.5
2.0
500
1000
1500
Daily catch size (kg)

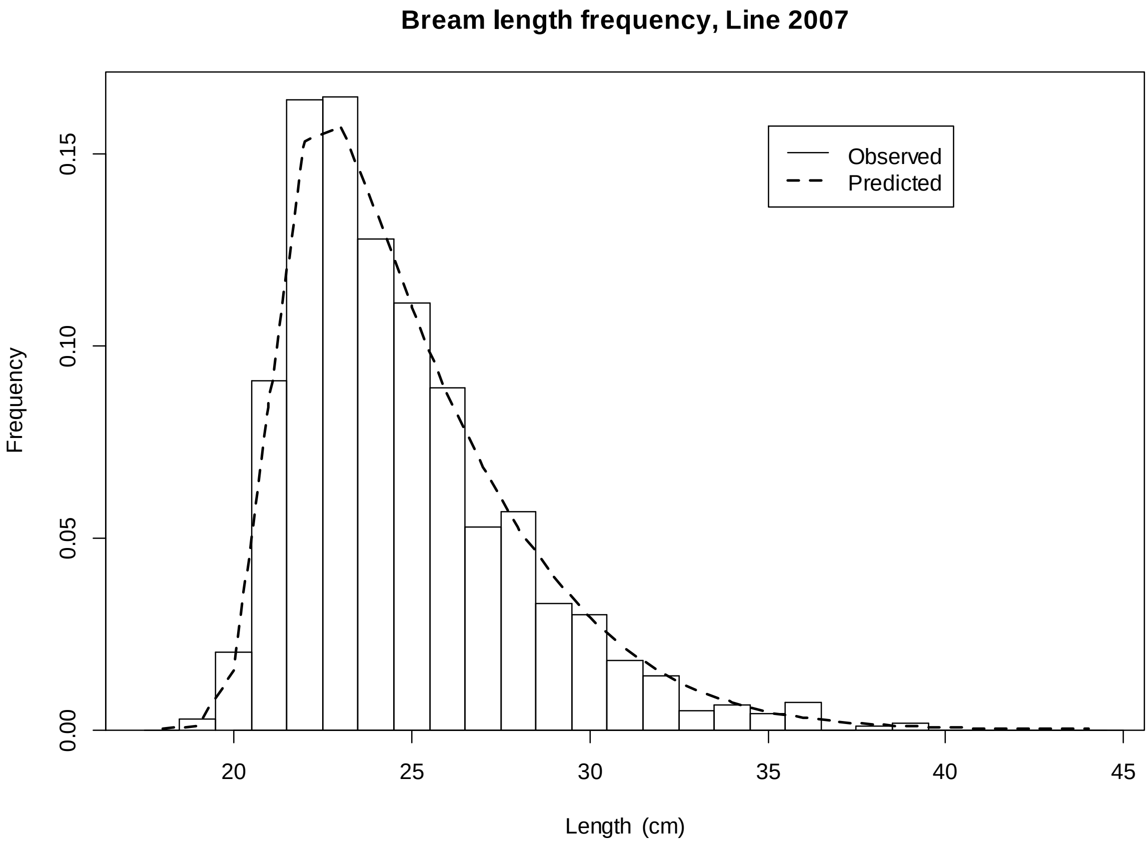
Appendix 2: Plots of model fit

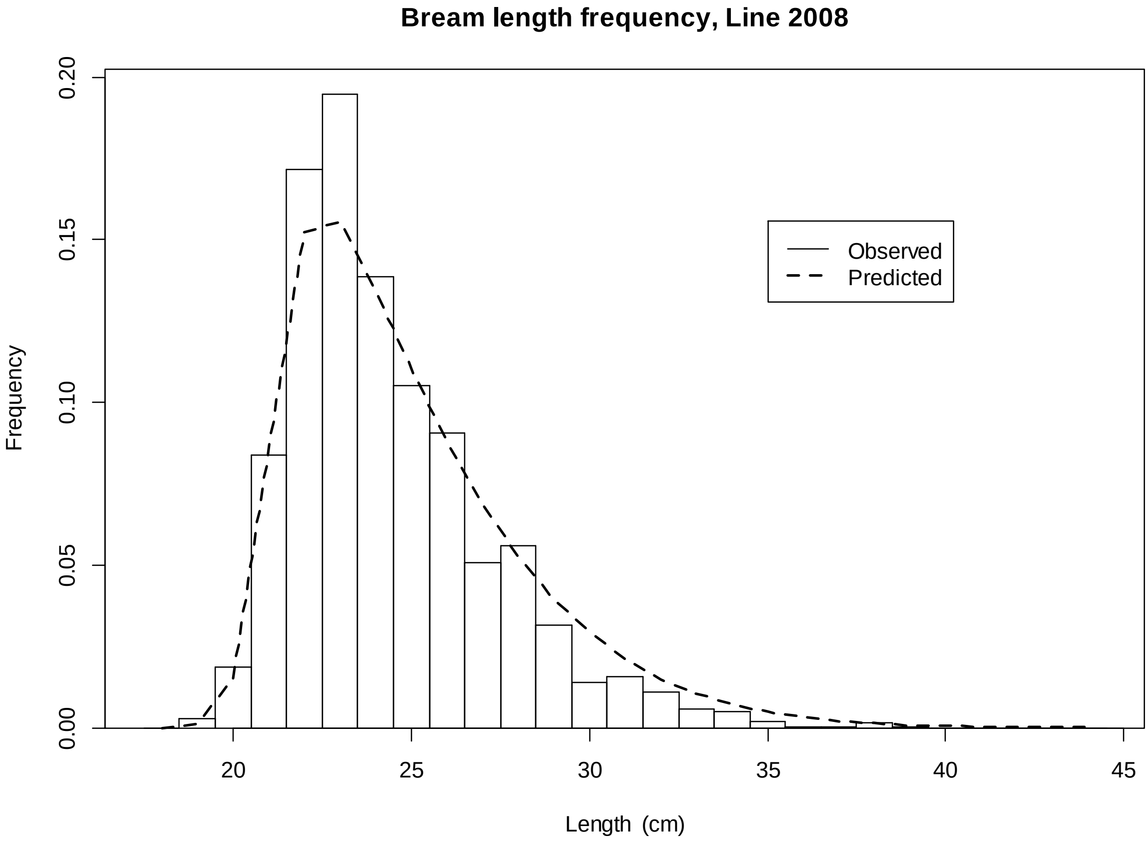
It should be noted here that the age frequencies listed as ‘Gillnet’ sector actually use age data from all sectors combined (line, gillnet and tunnel net). The qualifier ‘Gillnet’ applies only to the length frequency used to construct the plots.

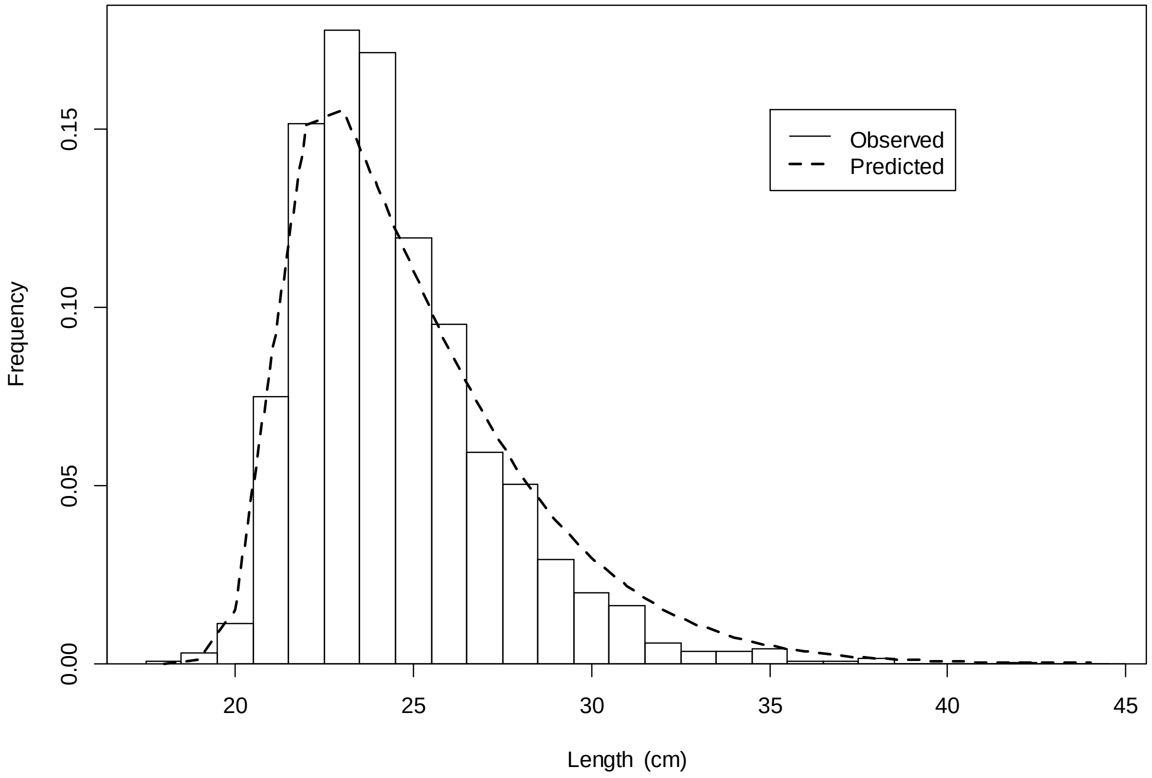
Age frequencies for flathead are plotted for females only and do not sum to 100 per cent. The sum over both males and females would be 100 per cent. Male age frequencies are not plotted because they mostly don’t grow to legal size and are only a small part of the total flathead harvest.

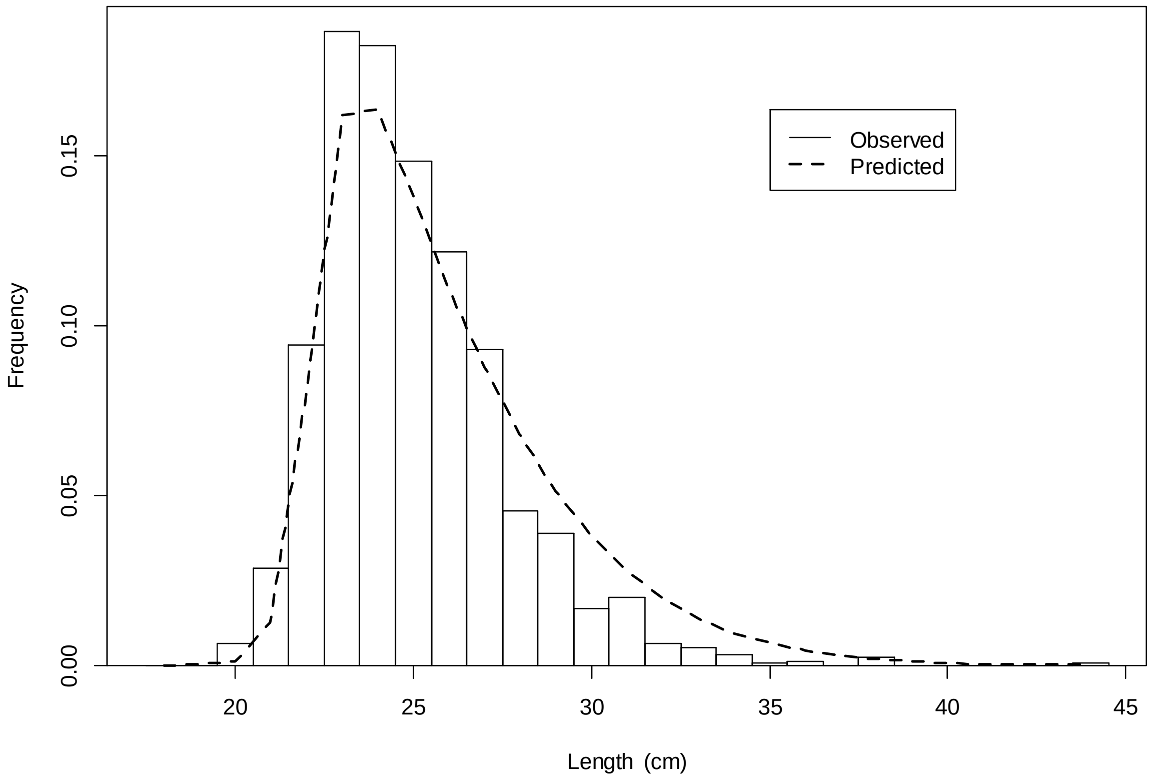
A2.1 Bream

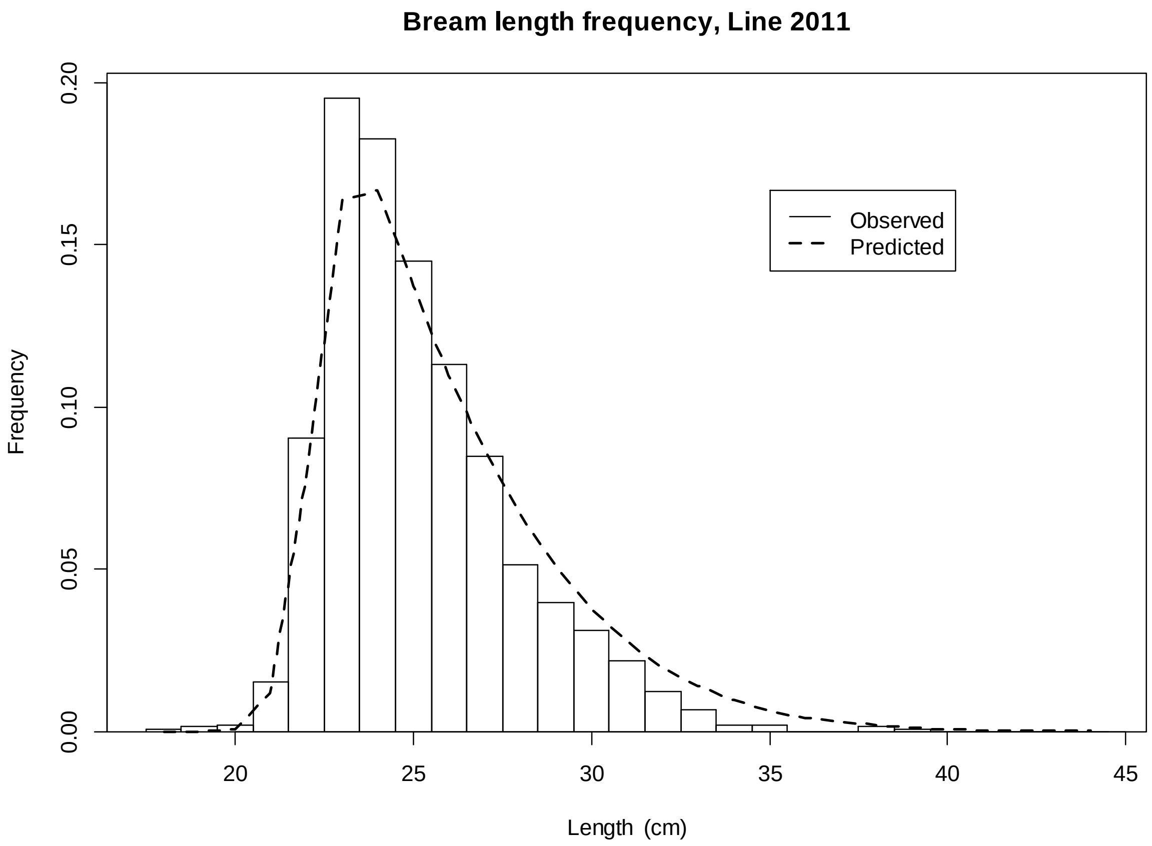


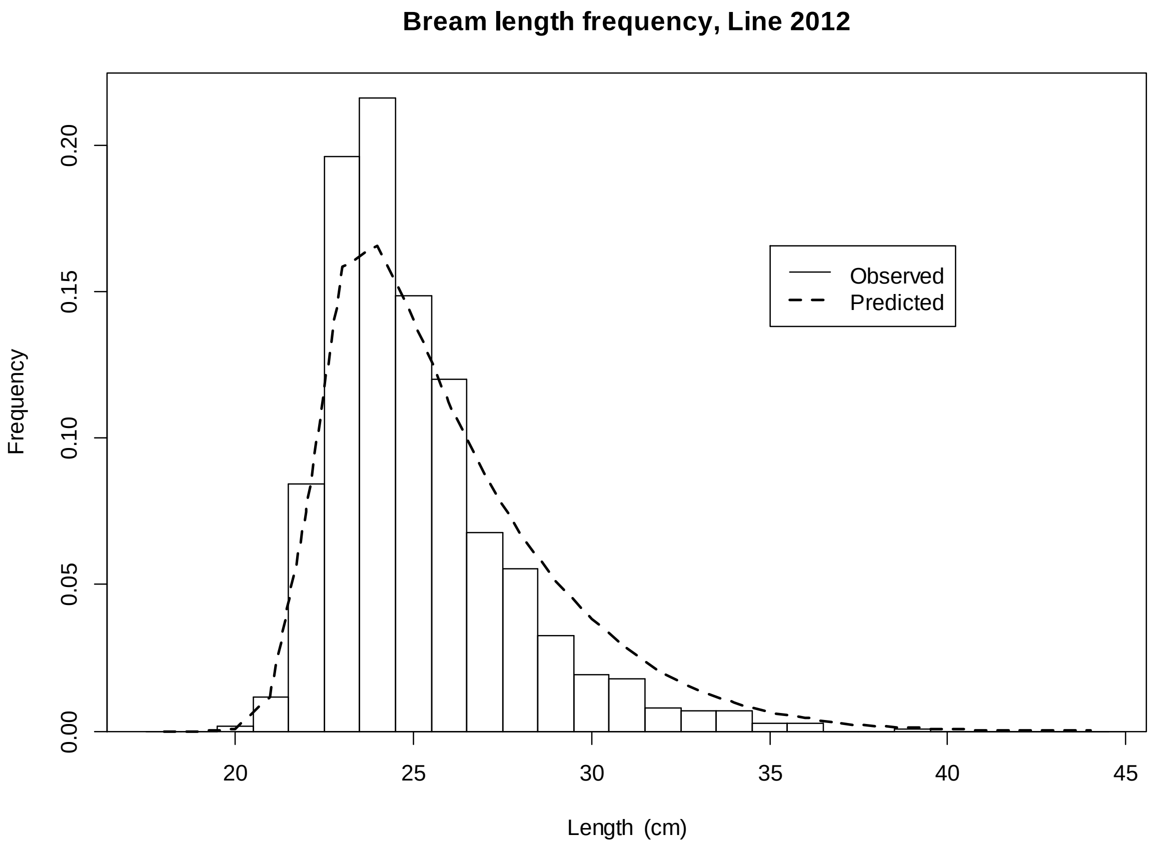

Bream length frequency, Line 2007
Observed
Predicted
Frequency
0.00
0.05
0.10
0.15
20
25
30
35
40
45
Length (cm)


Bream length frequency, Line 2008
Observed
Predicted
Frequency
0.00
0.05
0.10
0.15
0.20
20
25
30
35
40
45
Length (cm)

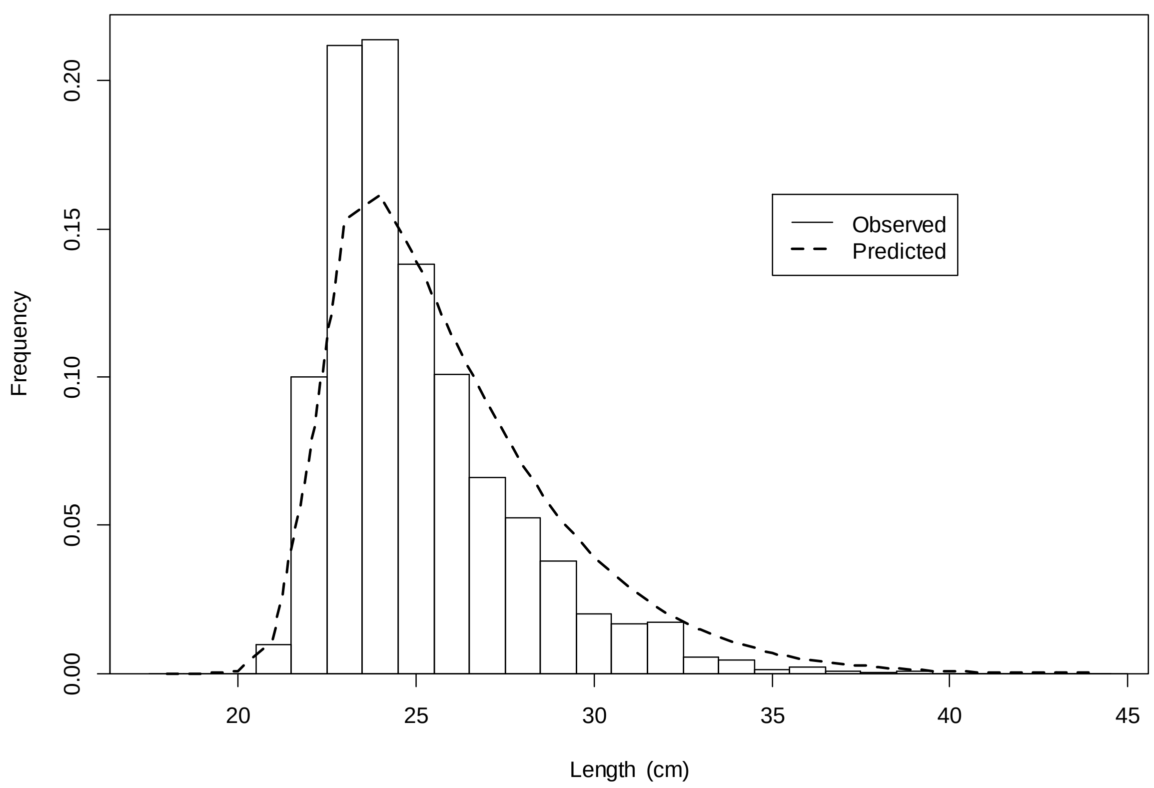

Bream length frequency, Line 2009


Bream length frequency, Line 2010

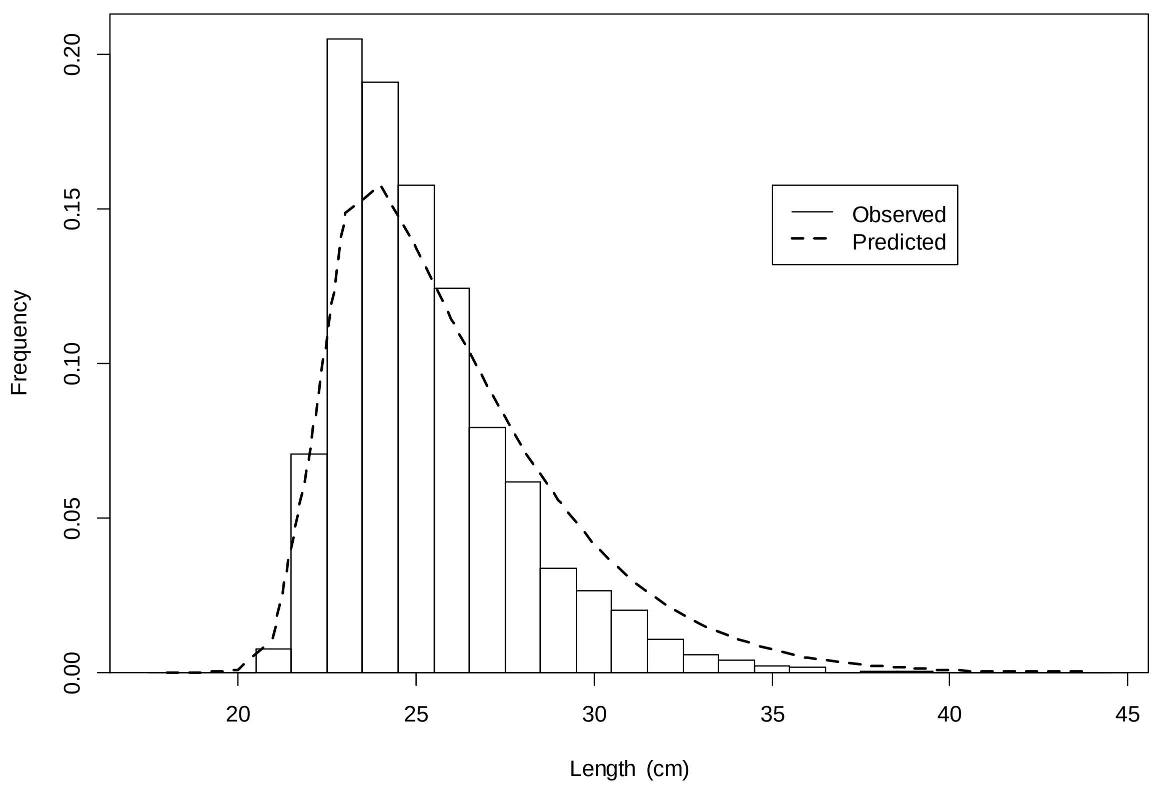

Bream length frequency, Line 2011
Frequency
0.00
0.05
0.10
0.15
0.20
20
25
30
35
40
45
Length (cm)
Observed
Predicted


Bream length frequency, Line 2012
Frequency
0.00
0.05
0.10
0.15
0.20
20
25
30
35
40
45
Length (cm)
Observed
Predicted

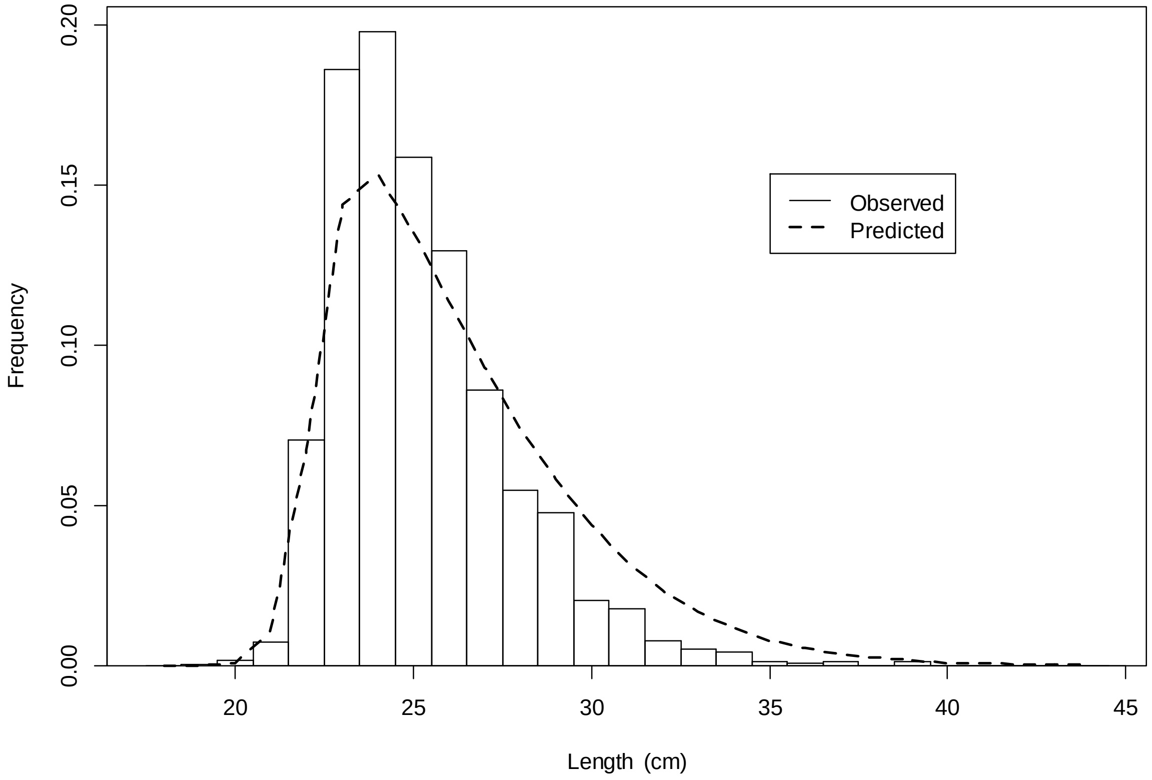
Bream length frequency, Line 2013



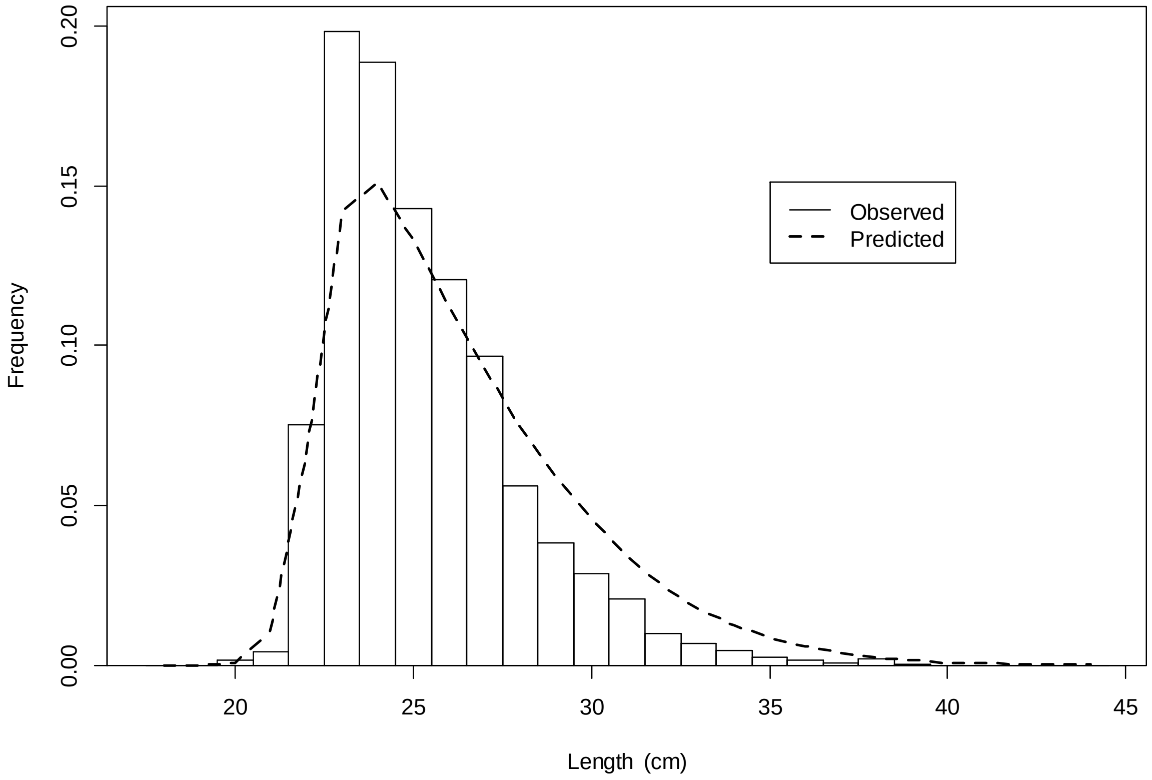
Bream length frequency, Line 2014



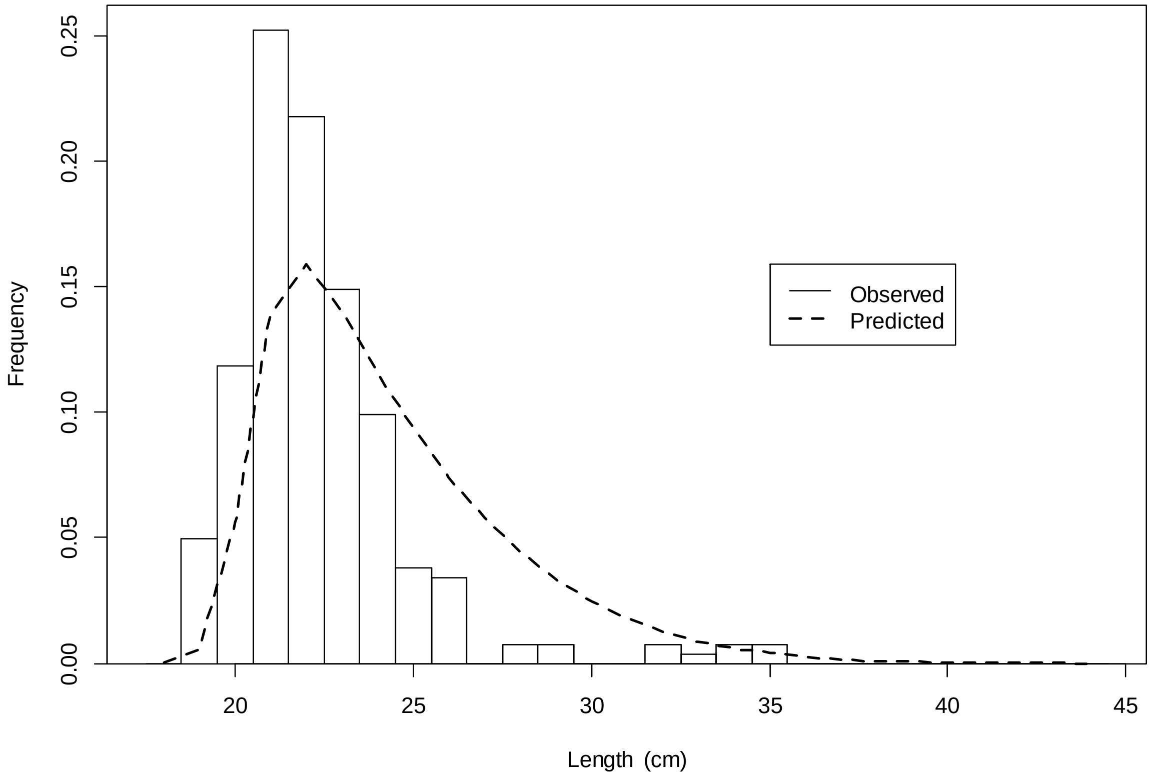
Bream length frequency, Line 2015



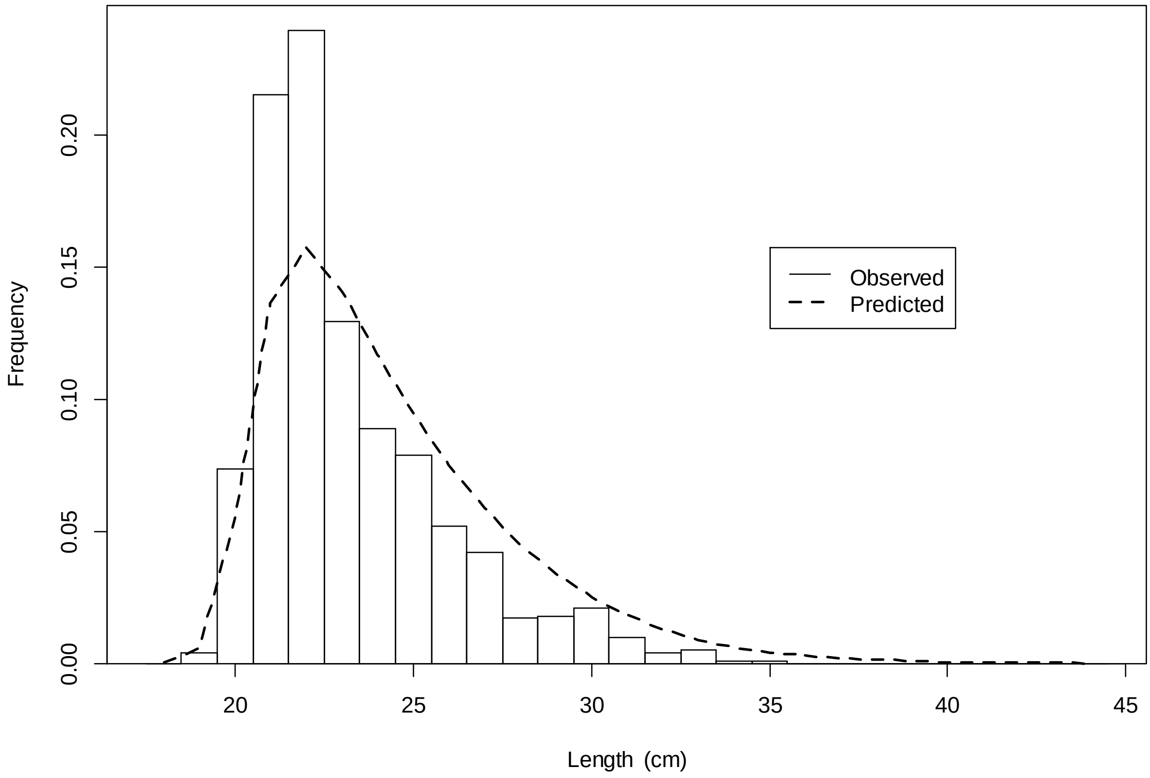
Bream length frequency, Line 2016

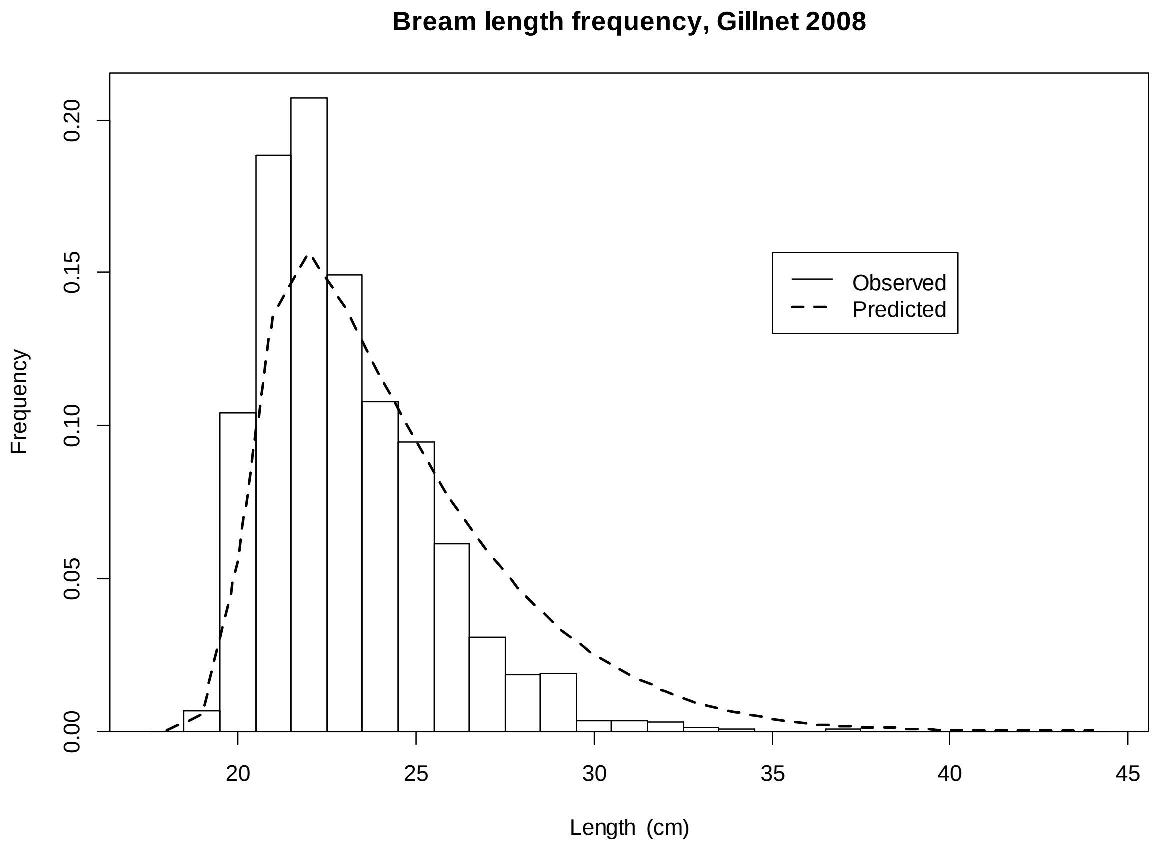


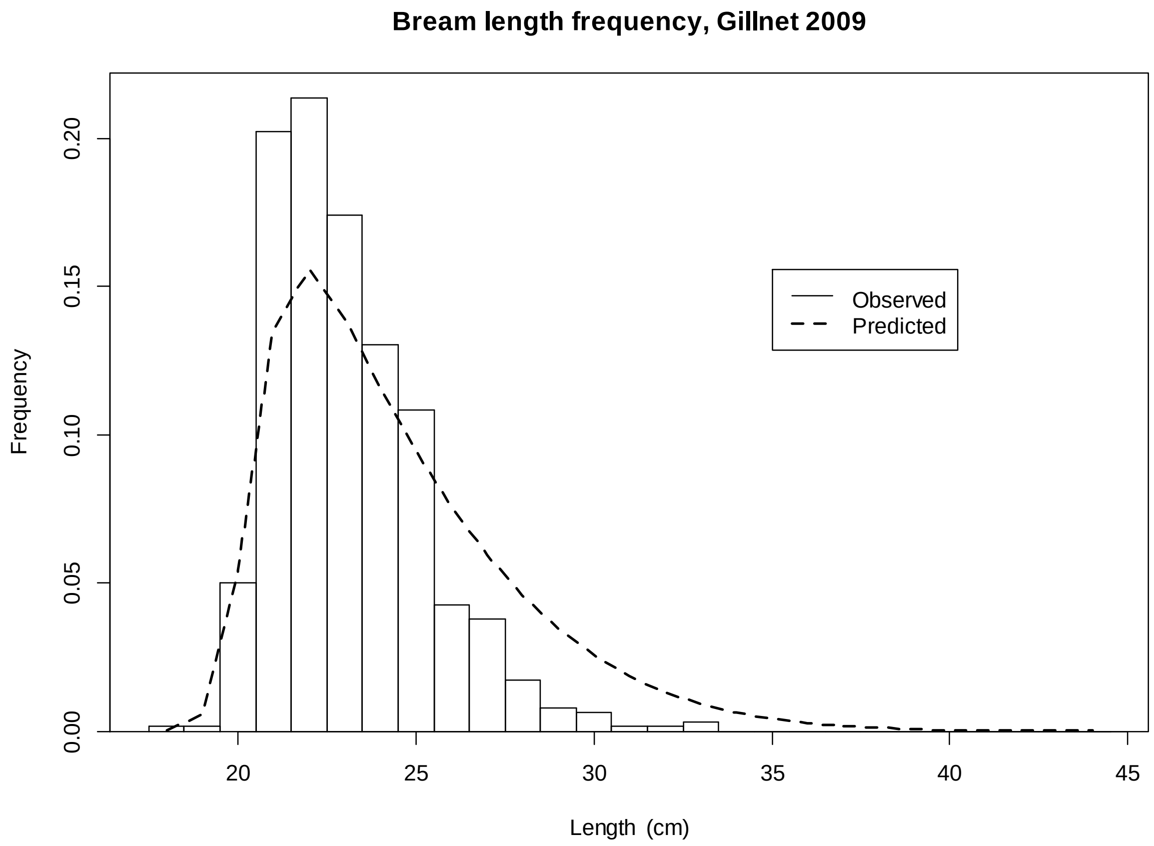
Bream length frequency, Gillnet 2006

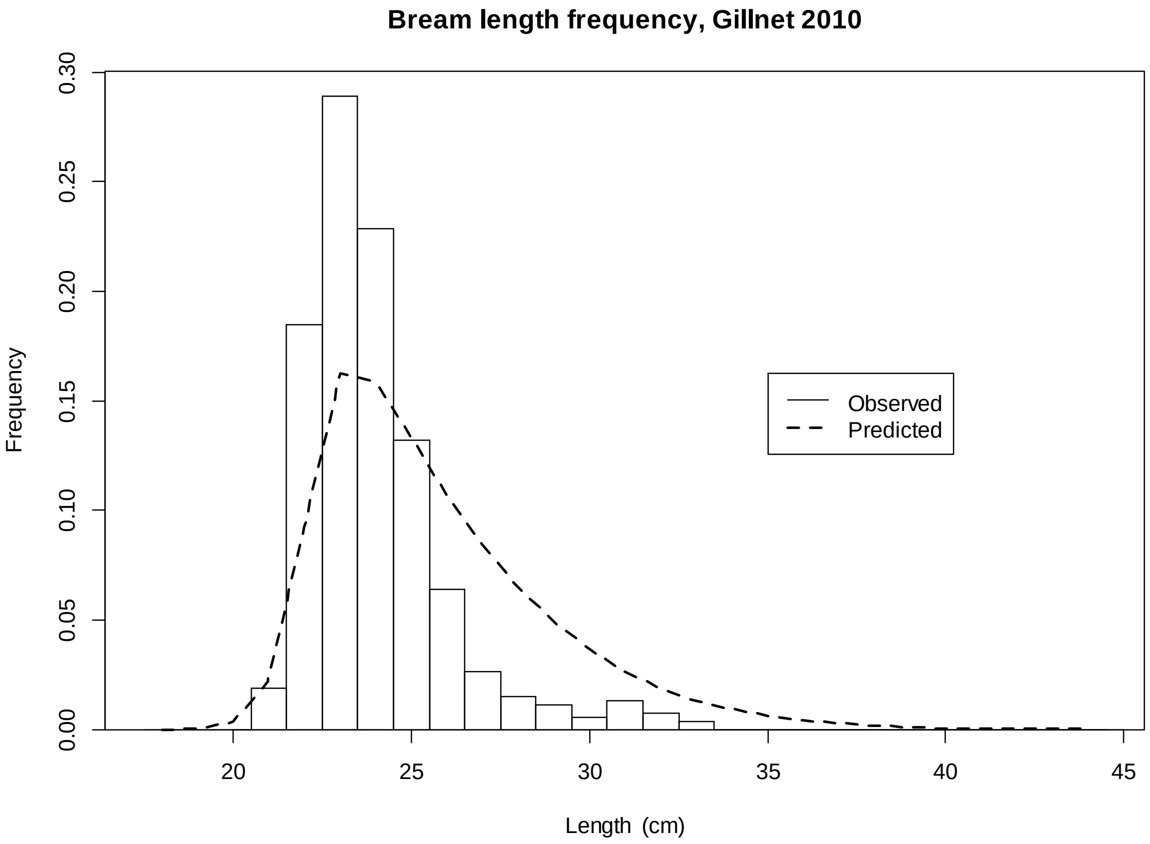


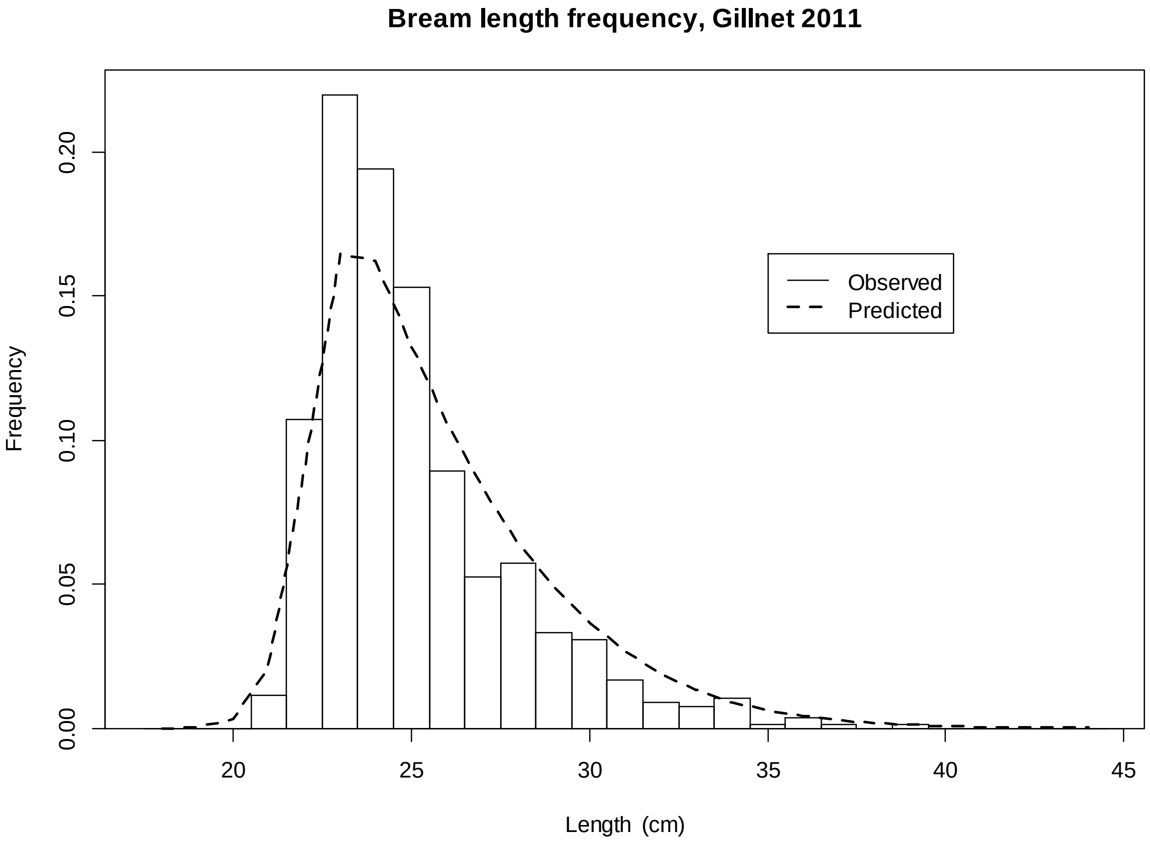
Bream length frequency, Gillnet 2007

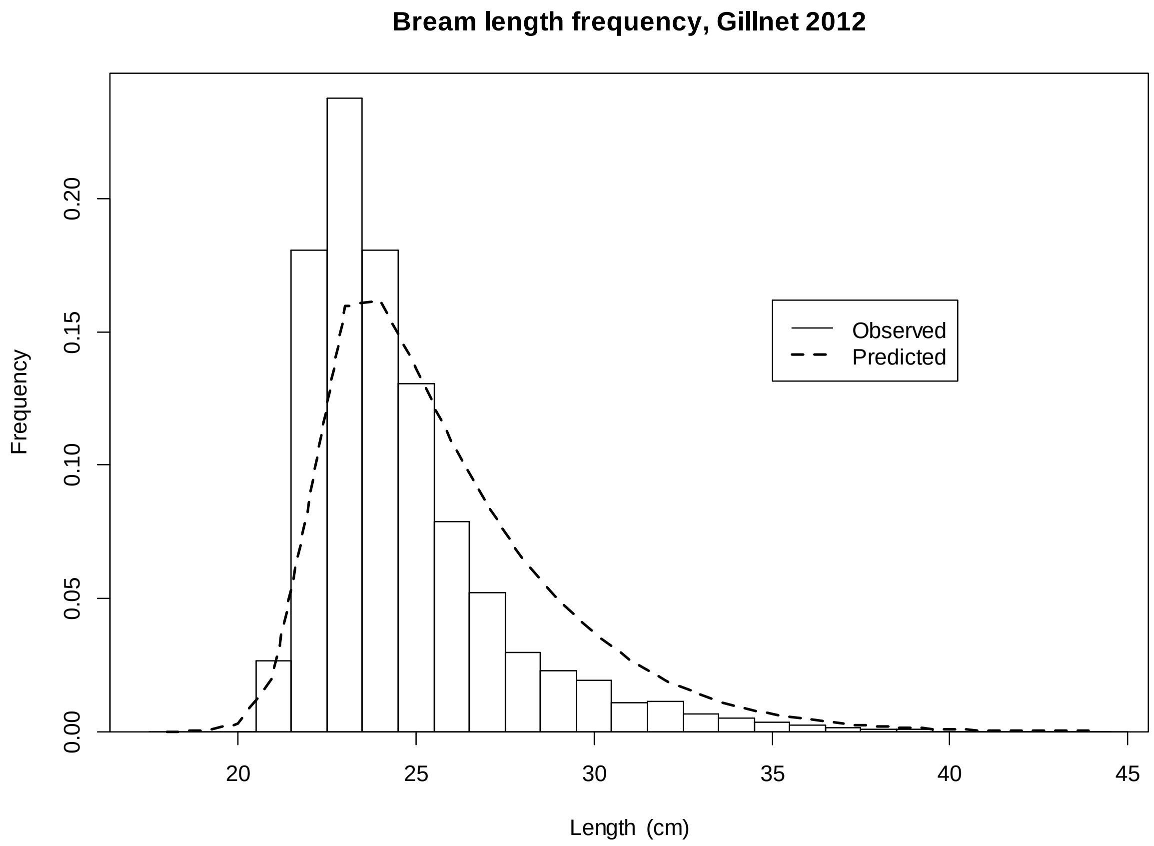


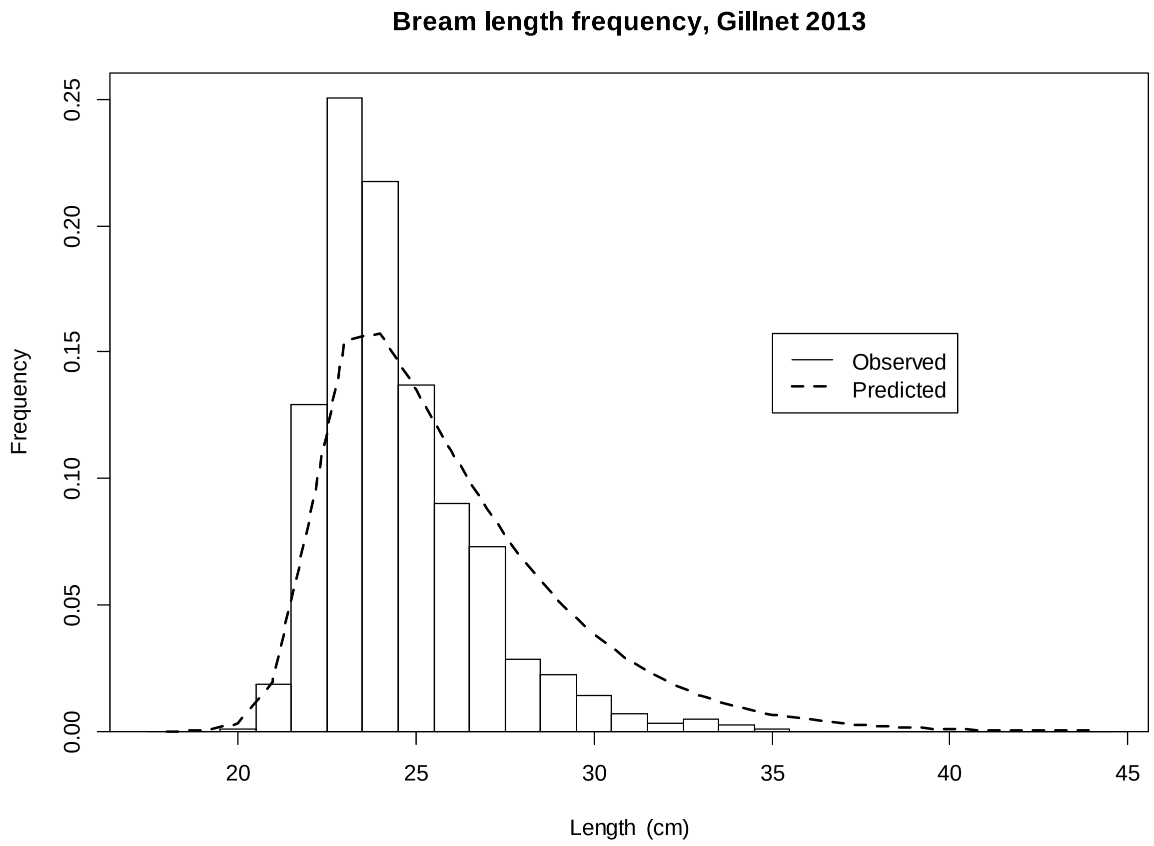

Bream length frequency, Gillnet 2008
Frequency
0.00
0.05
0.10
0.15
0.20
Length (cm)
20
25
30
35
40
45
Observed
Predicted


Bream length frequency, Gillnet 2009
Frequency
0.00
0.05
0.10
0.15
0.20
Length (cm)
20
25
30
35
40
45
Observed
Predicted

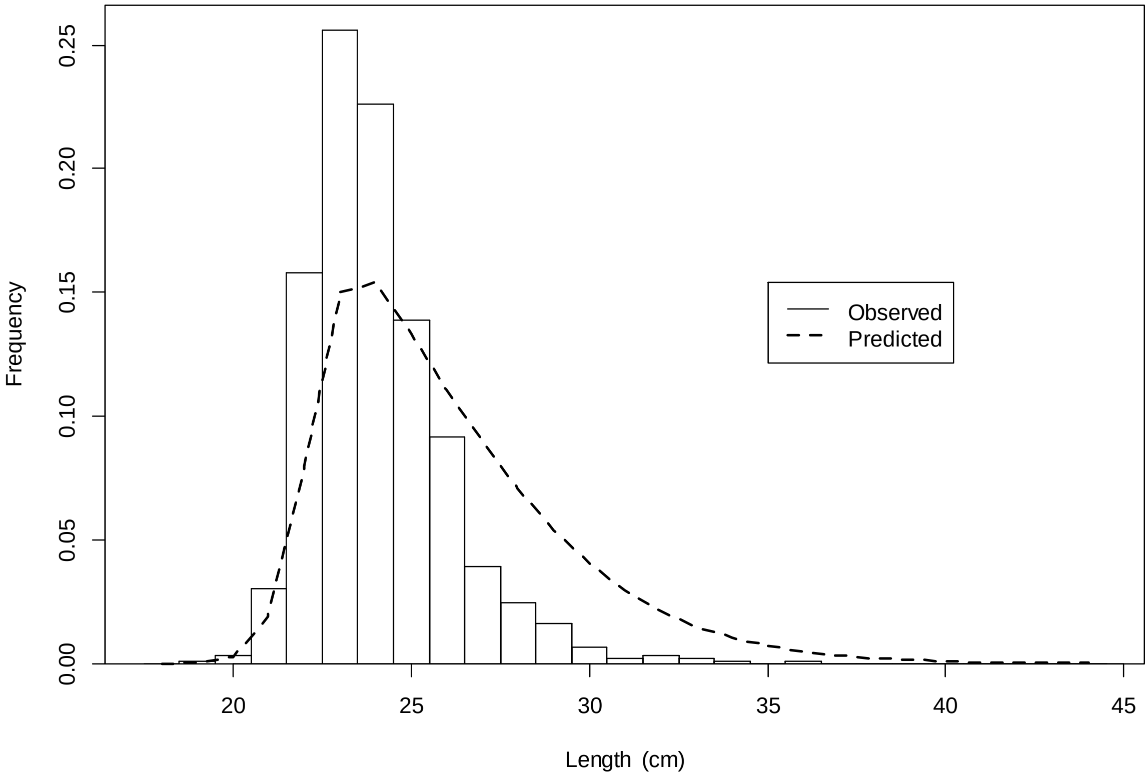

Bream length frequency, Gillnet 2010
Frequency
0.00
0.05
0.10
0.15
0.20
0.25
0.30
20
25
30
35
40
45
Length (cm)
Observed
Predicted


Bream length frequency, Gillnet 2011
Frequency
0.00
0.05
0.10
0.15
0.20
20
25
30
35
40
45
Length (cm)
Observed
Predicted

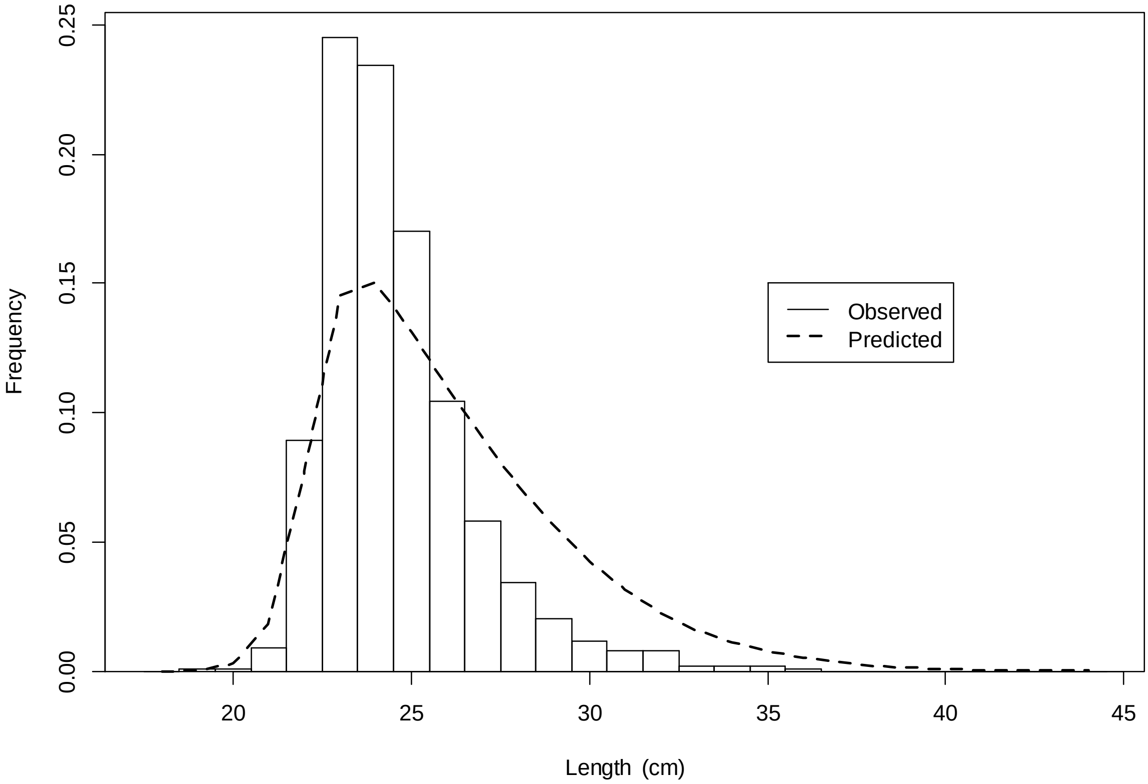

Bream length frequency, Gillnet 2012

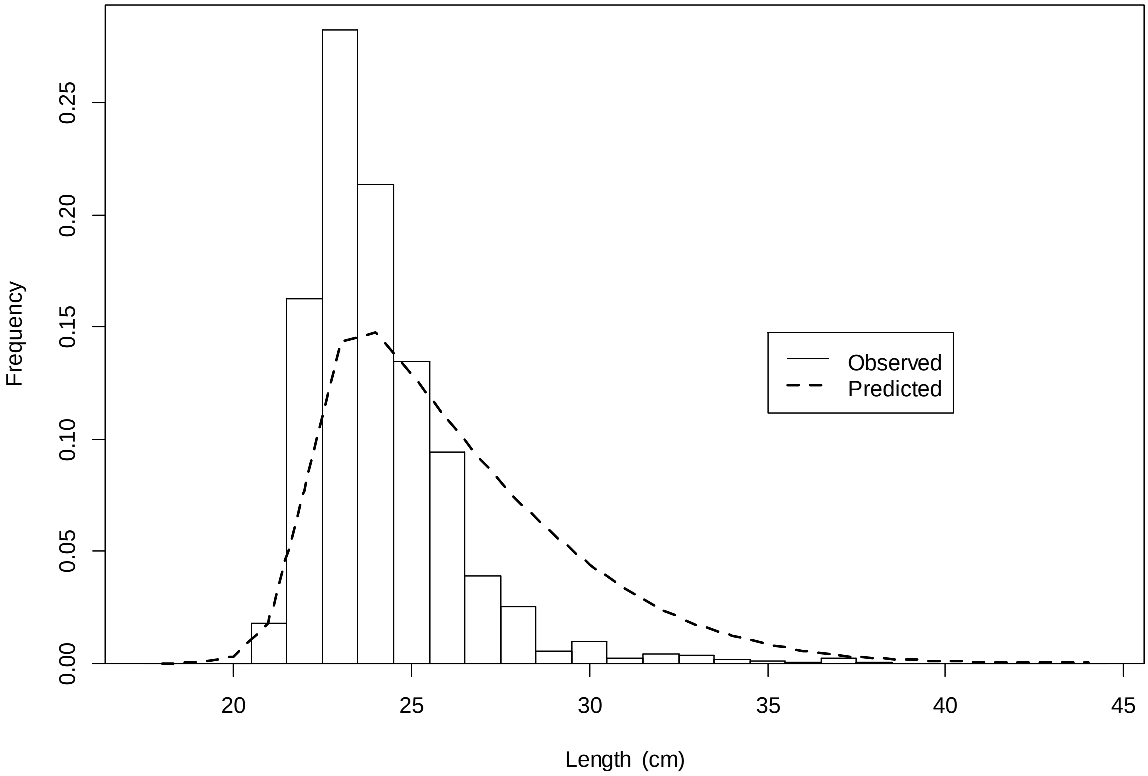

Bream length frequency, Gillnet 2013

Bream length frequency, Gillnet 2014

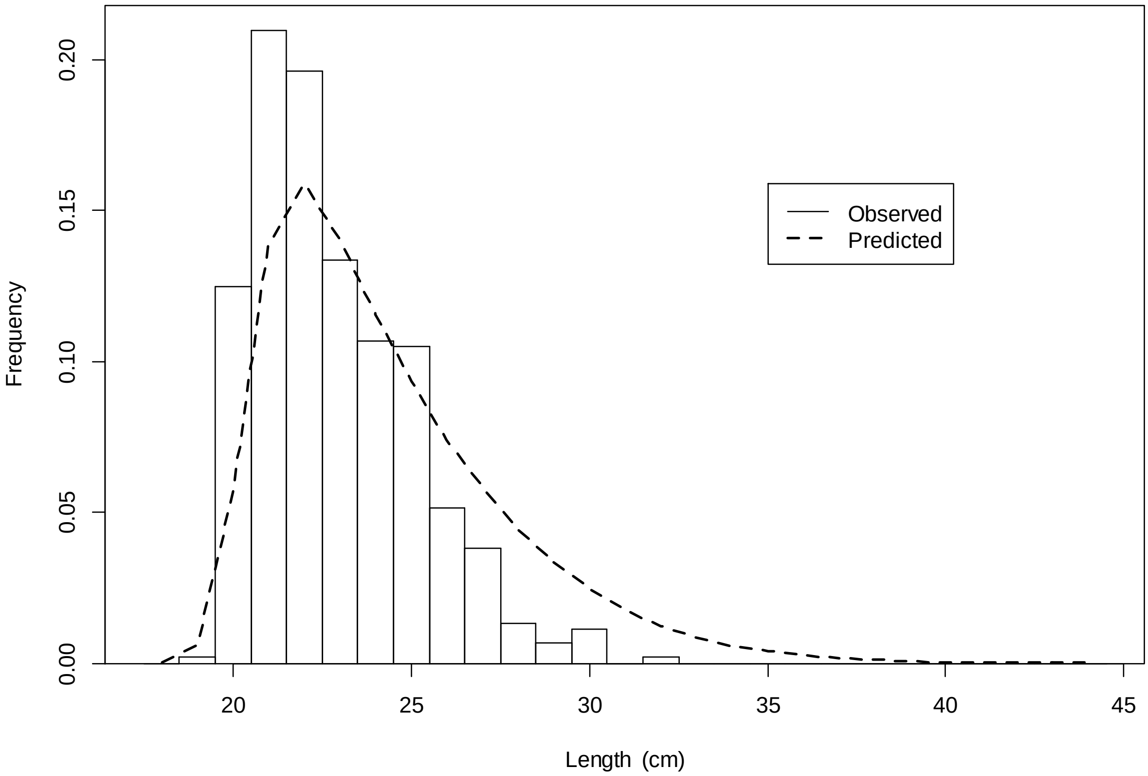


Bream length frequency, Gillnet 2015

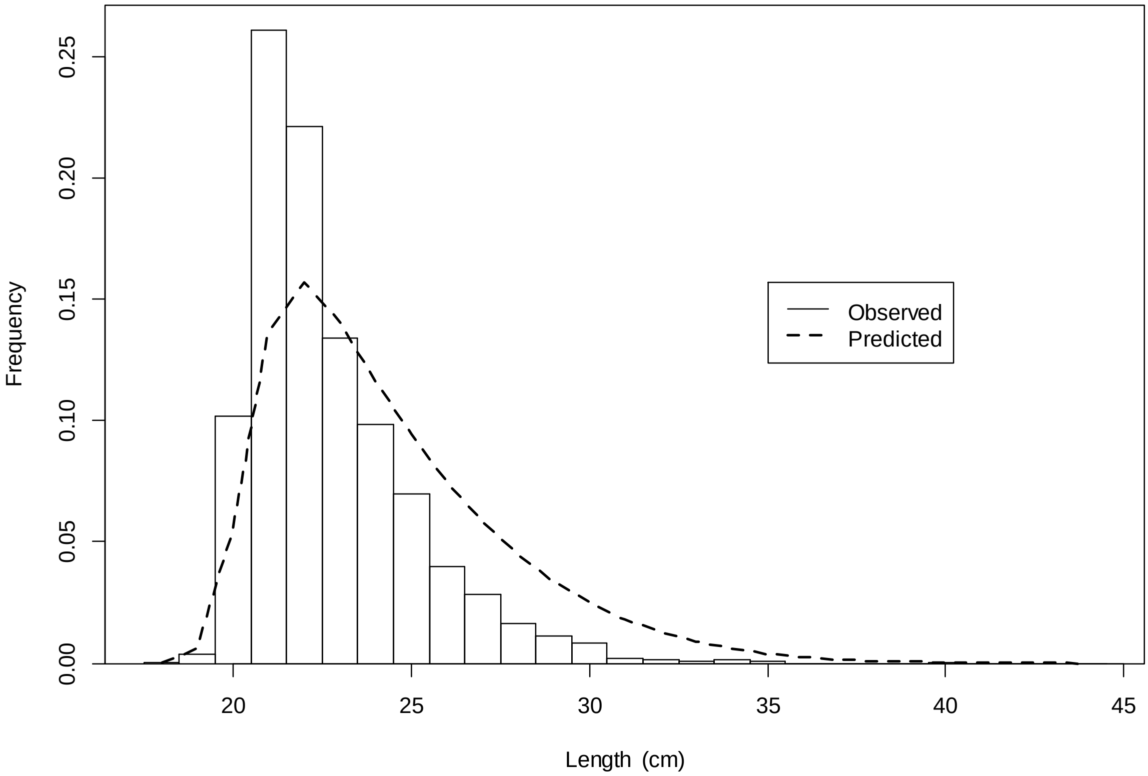


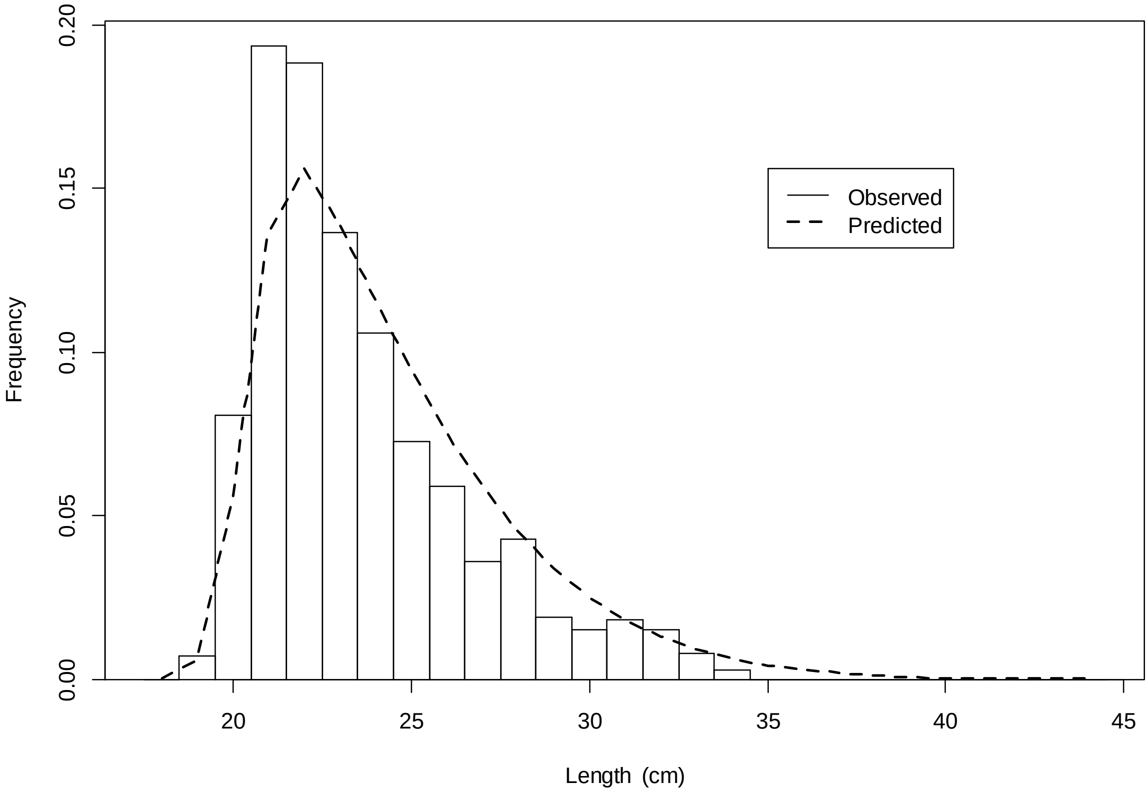


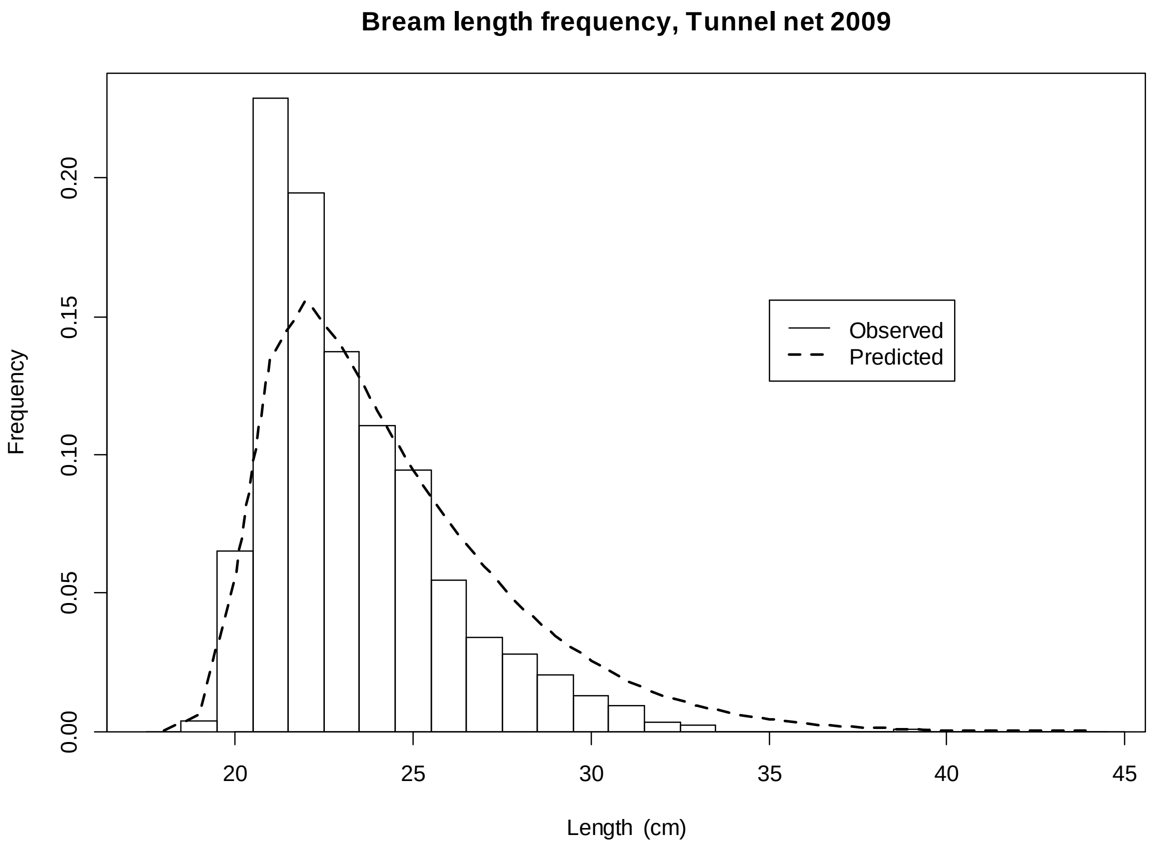
Bream length frequency, Gillnet 2016

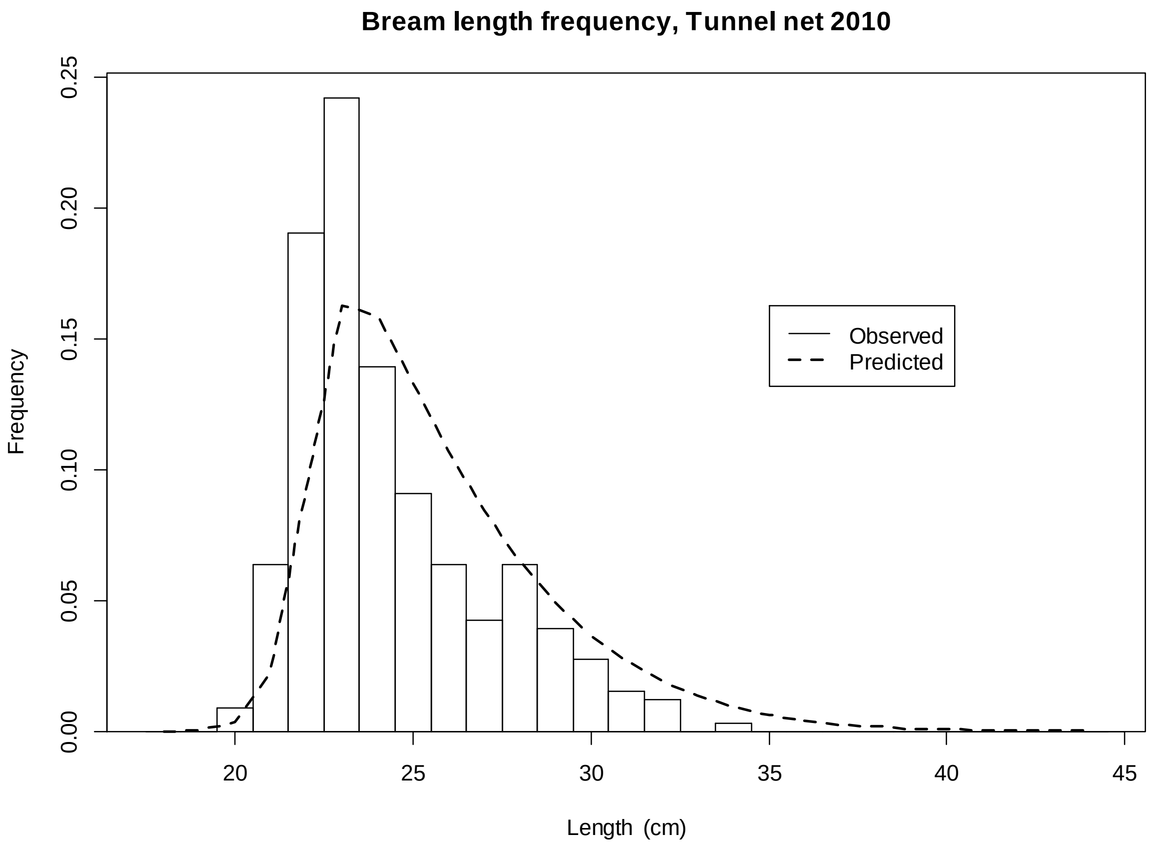


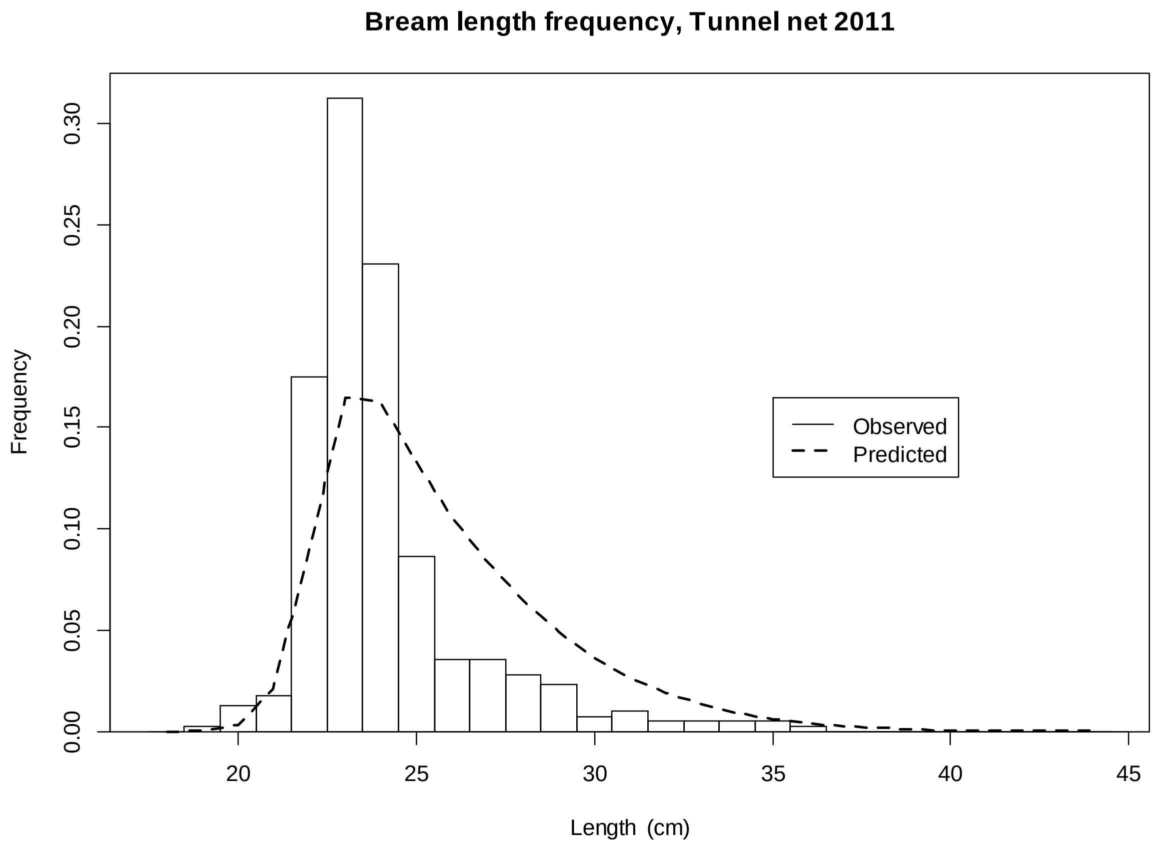
Bream length frequency, Tunnel net 2006

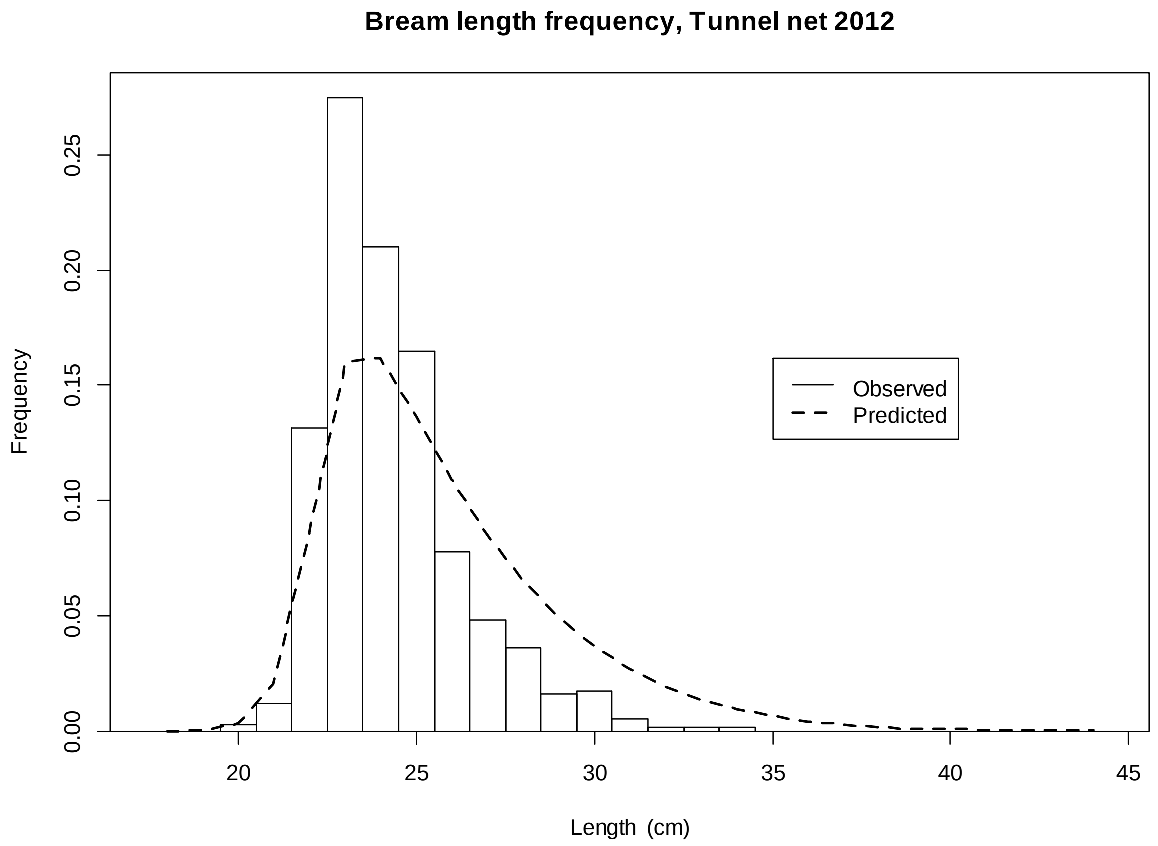

Bream length frequency, Tunnel net 2007


Bream length frequency, Tunnel net 2008

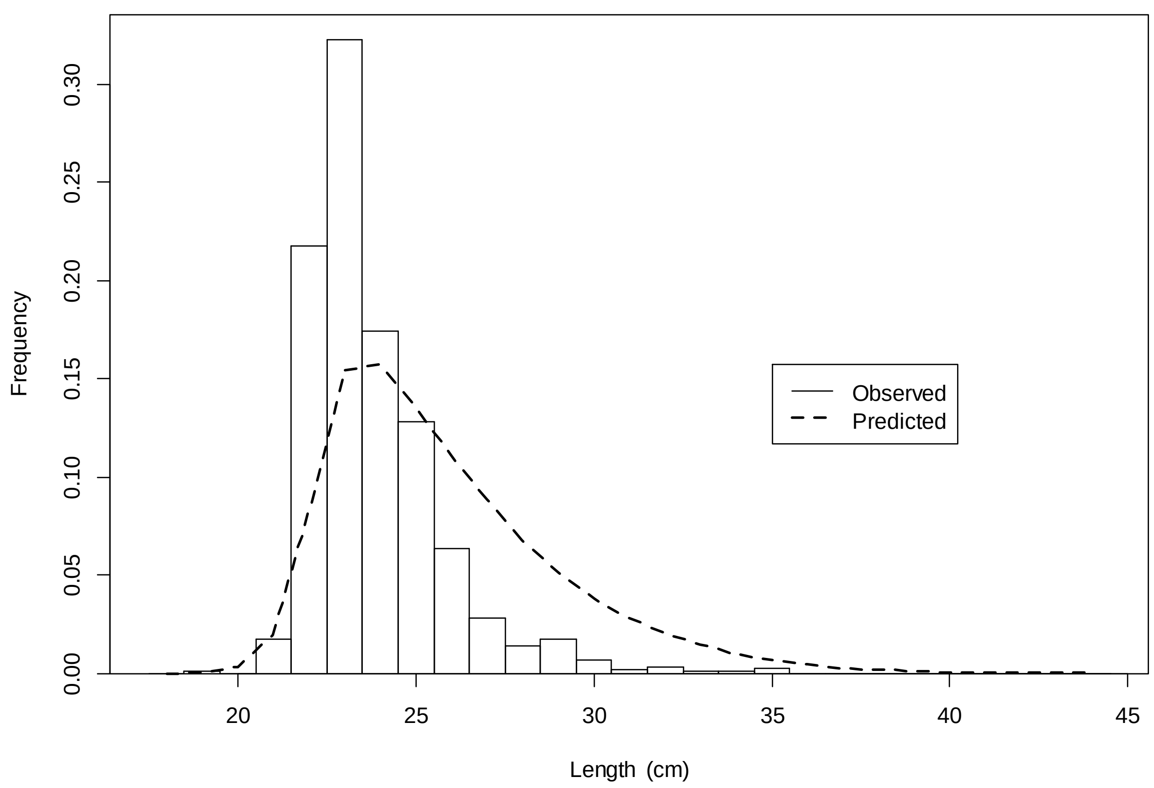

Bream length frequency, Tunnel net 2009
Frequency
0.00
0.05
0.10
0.15
0.20
20
25
30
35
40
45
Length (cm)
Observed
Predicted


Bream length frequency, Tunnel net 2010
Frequency
0.00
0.05
0.10
0.15
0.20
0.25
20
25
30
35
40
45
Length (cm)
Observed
Predicted

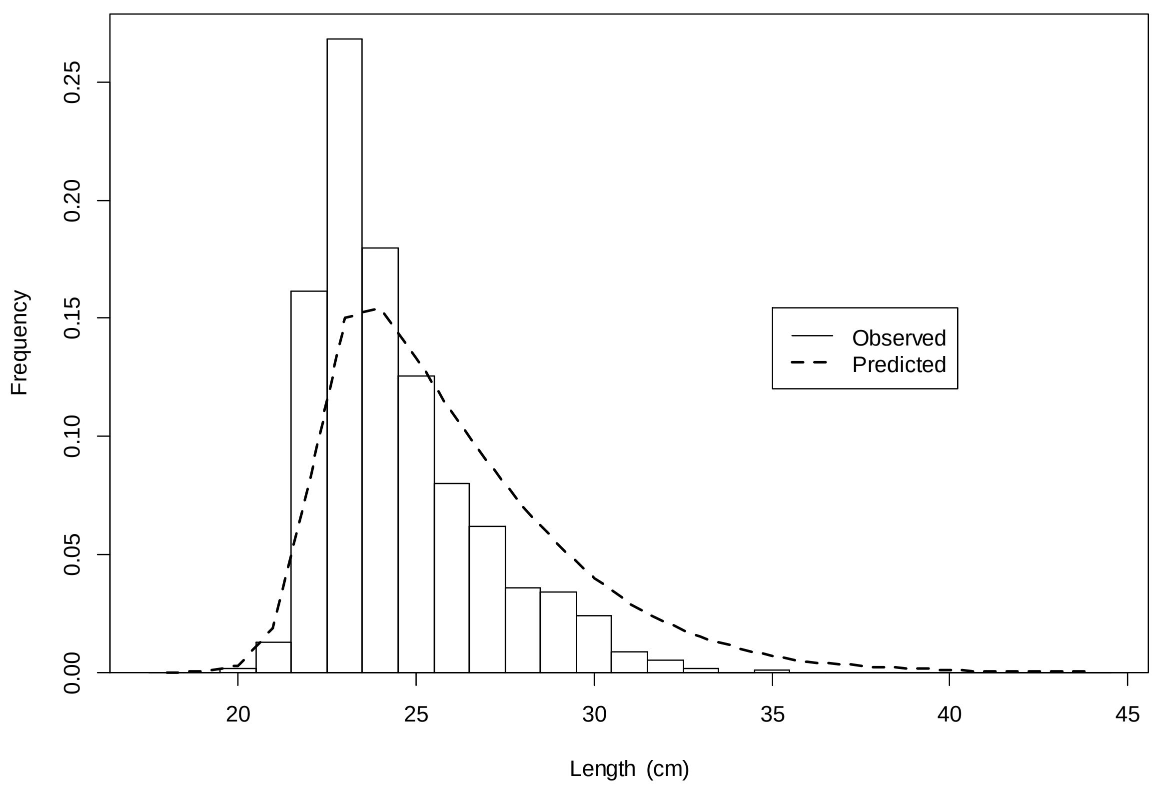

Bream length frequency, Tunnel net 2011
Frequency
0.00
0.05
0.10
0.15
0.20
0.25
0.30
Length (cm)
20
25
30
35
40
45
Observed
Predicted

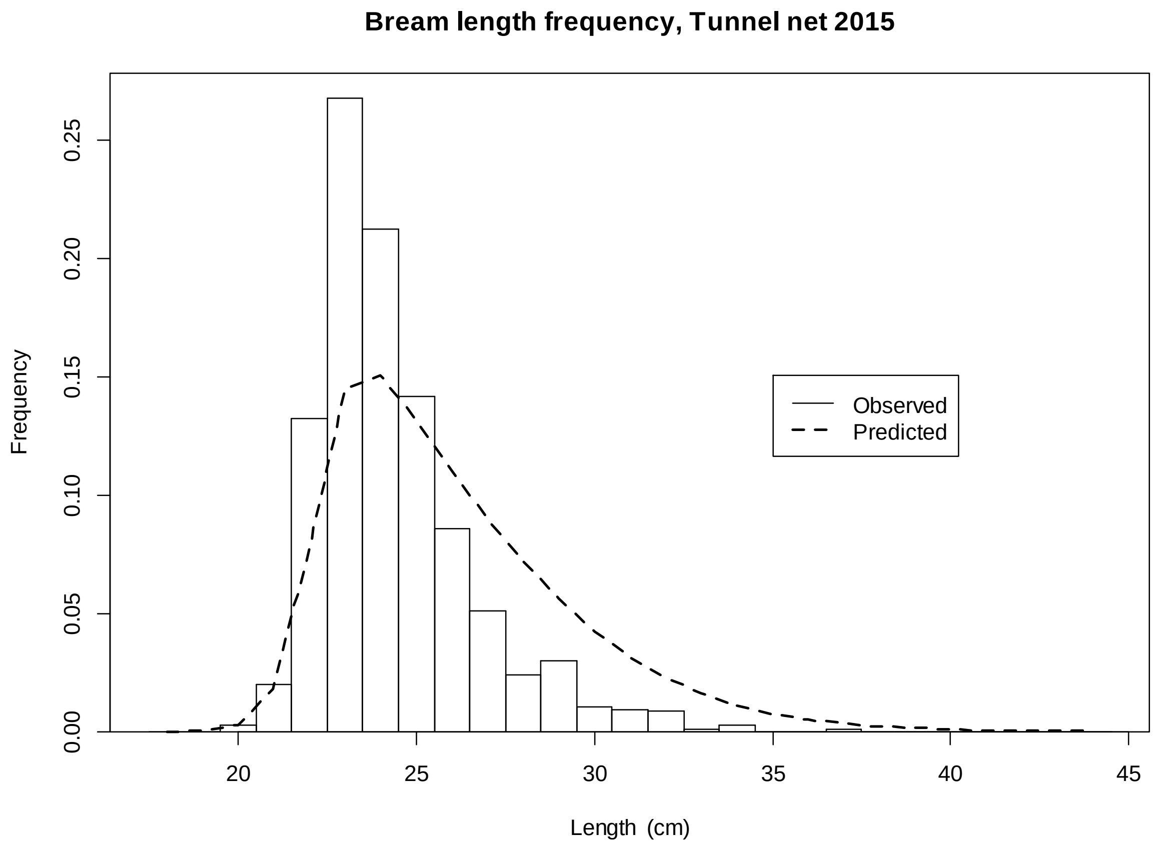

Bream length frequency, Tunnel net 2012
Frequency
0.00
0.05
0.10
0.15
0.20
0.25
Length (cm)
20
25
30
35
40
45
Observed
Predicted

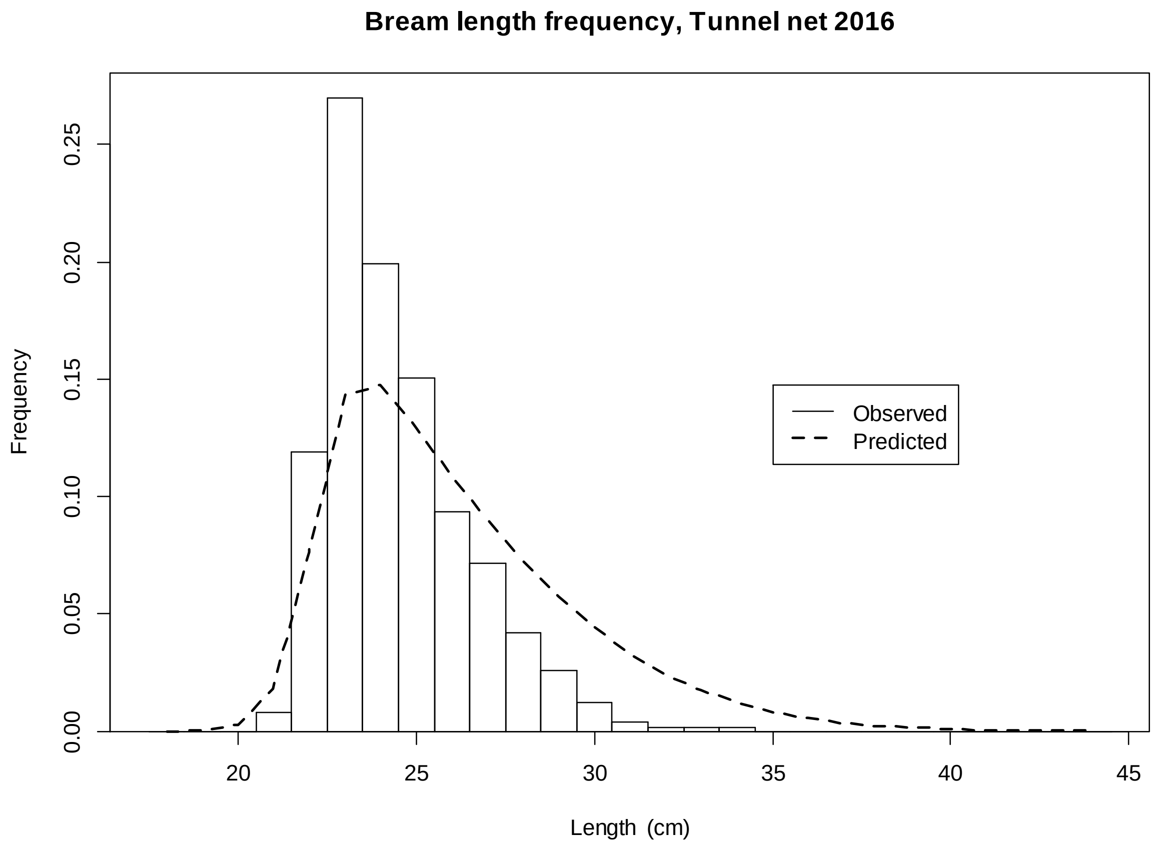
Bream length frequency, Tunnel net 2013

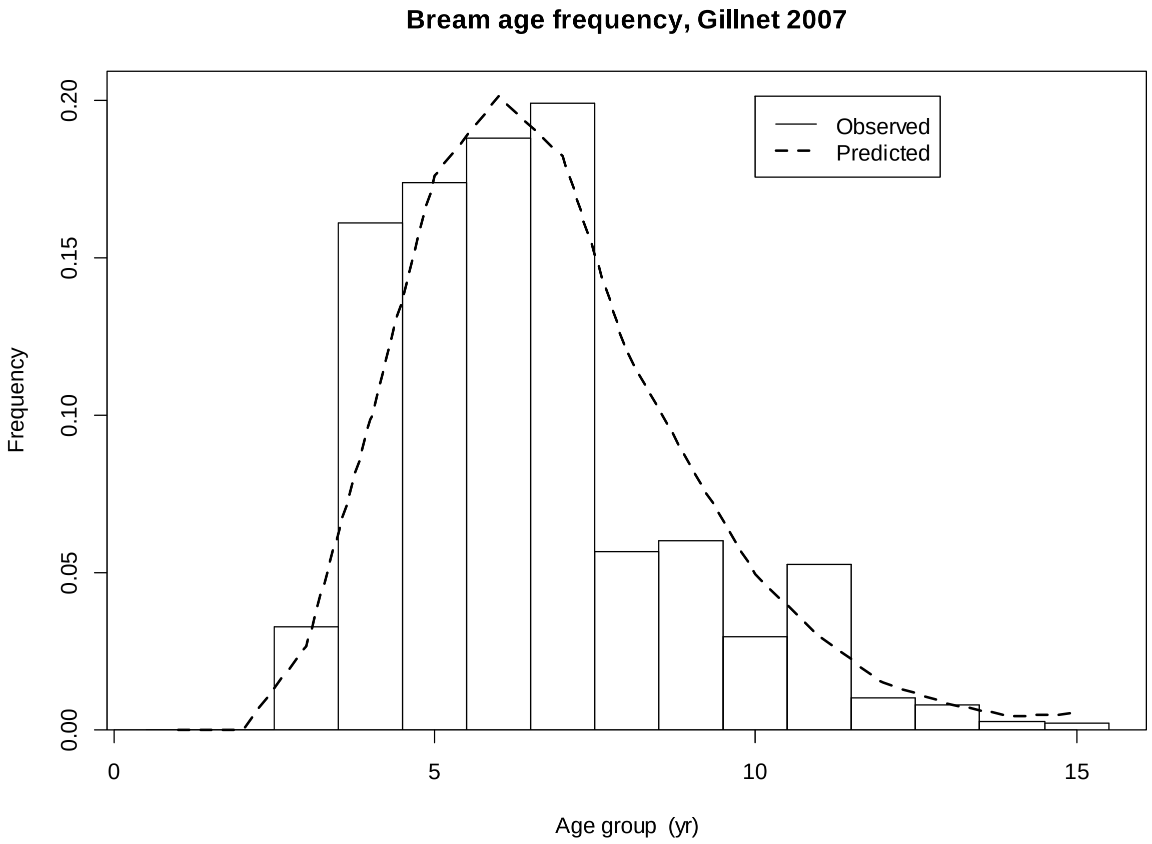


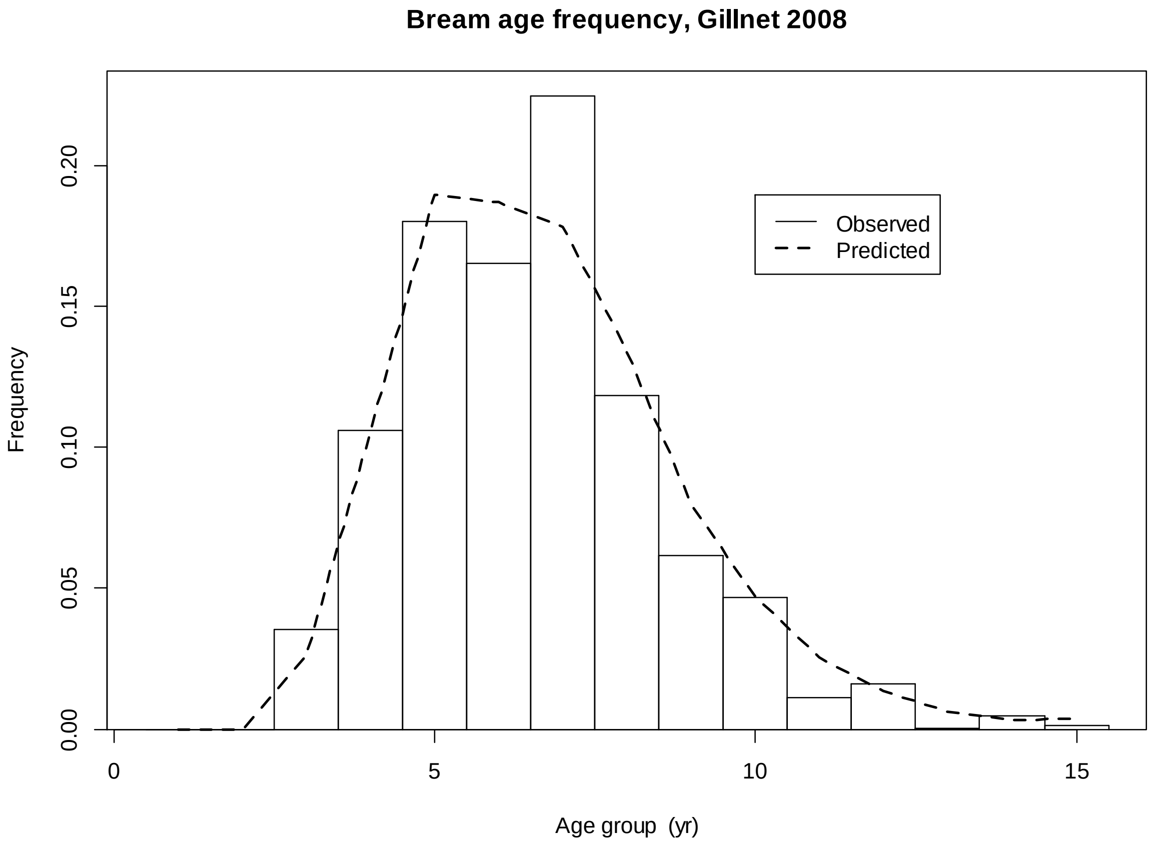
Bream length frequency, Tunnel net 2014

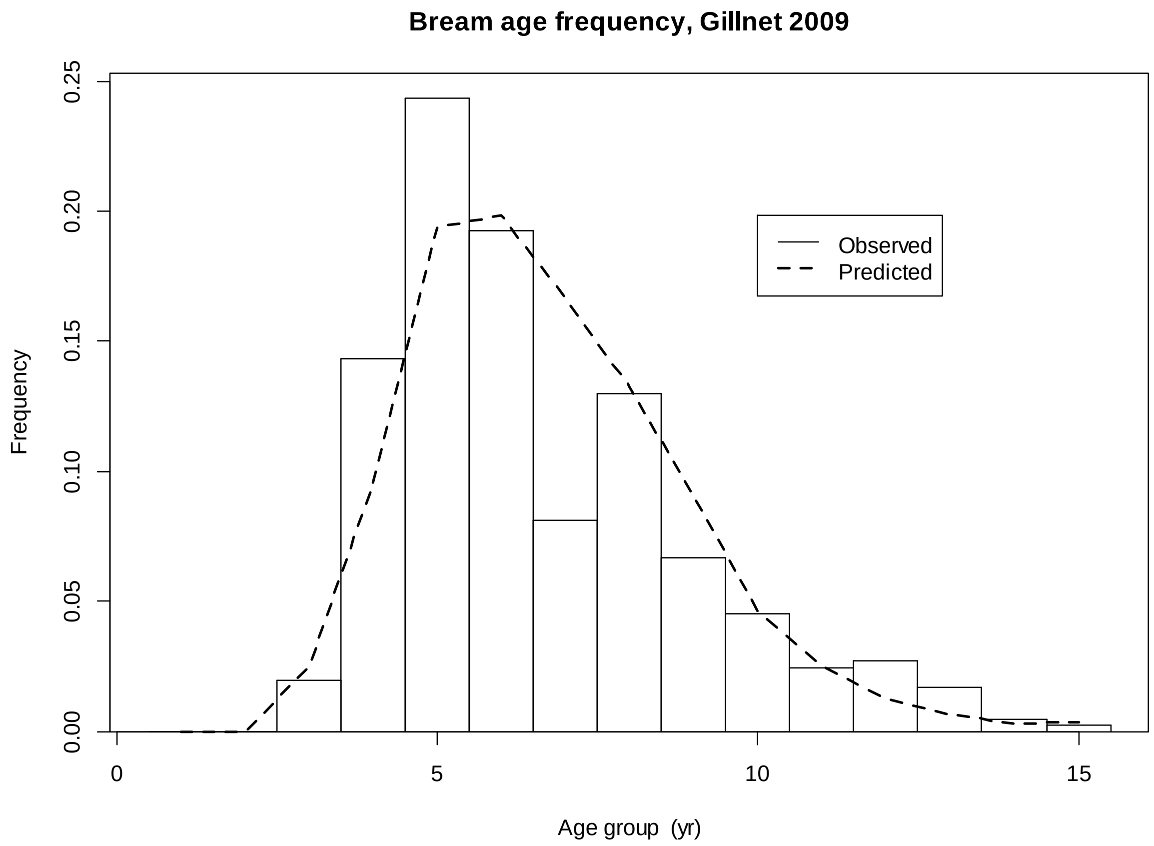


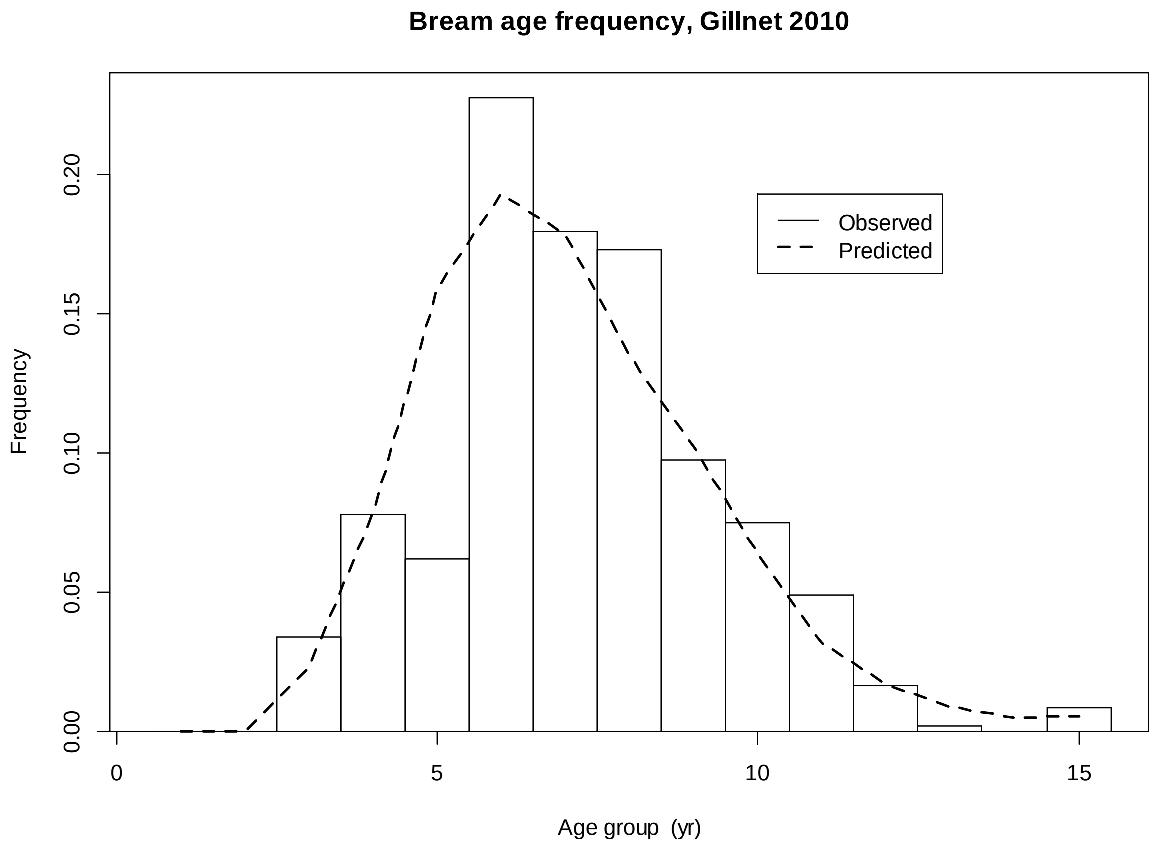

Bream length frequency, Tunnel net 2015
Frequency
0.00
0.05
0.10
0.15
0.20
0.25
20
25
30
35
40
45
Length (cm)
Observed
Predicted


Bream length frequency, Tunnel net 2016
Frequency
0.00
0.05
0.10
0.15
0.20
0.25
20
25
30
35
40
45
Length (cm)
Observed
Predicted

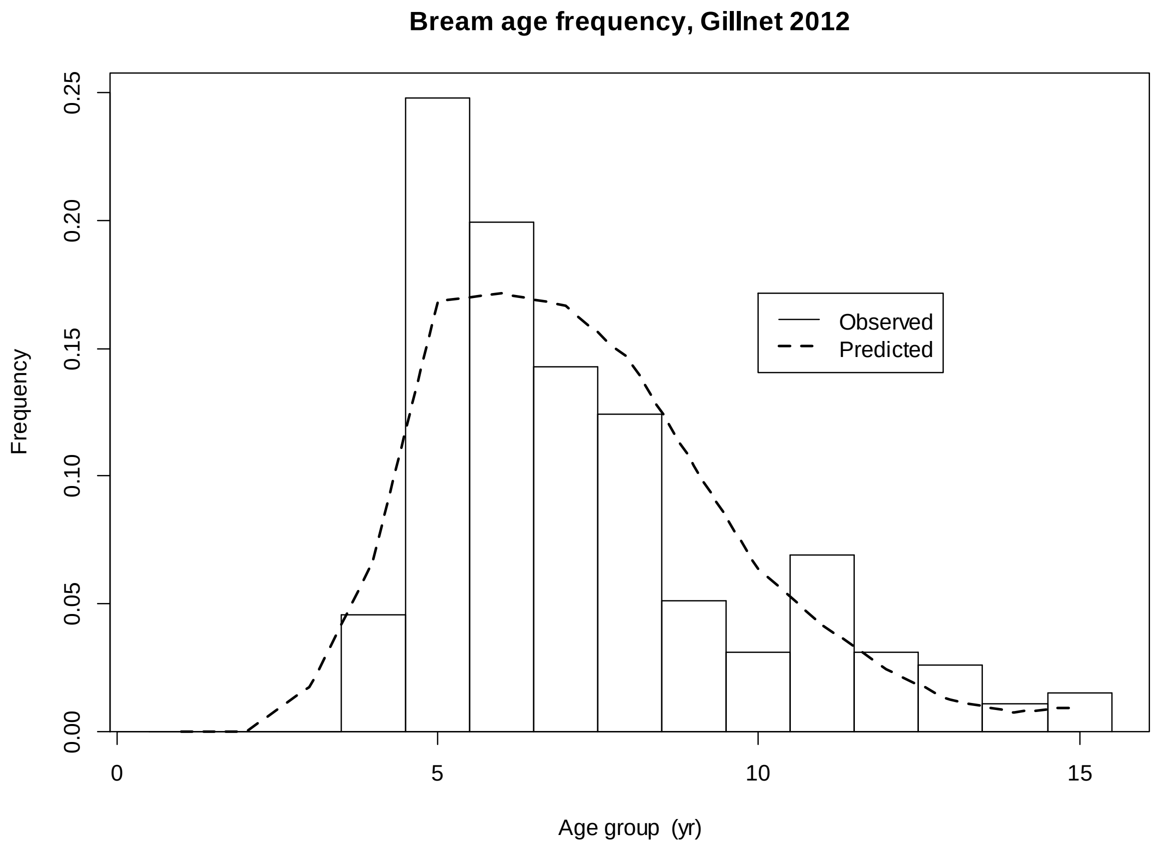

Bream age frequency, Gillnet 2007
Frequency
0.00
0.05
0.10
0.15
0.20
0
5
10
15
Age group (yr)
Observed
Predicted

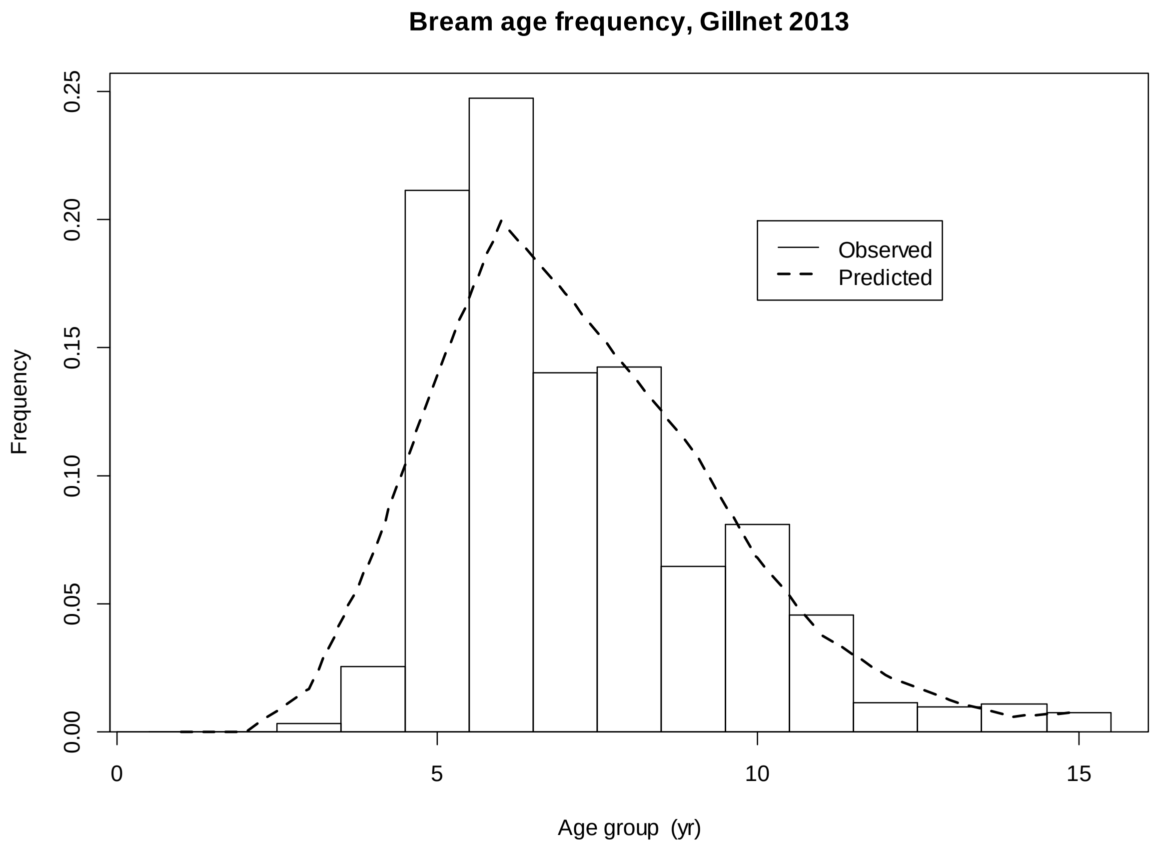

Bream age frequency, Gillnet 2008
Frequency
0.00
0.05
0.10
0.15
0.20
0
5
10
15
Age group (yr)
Observed
Predicted

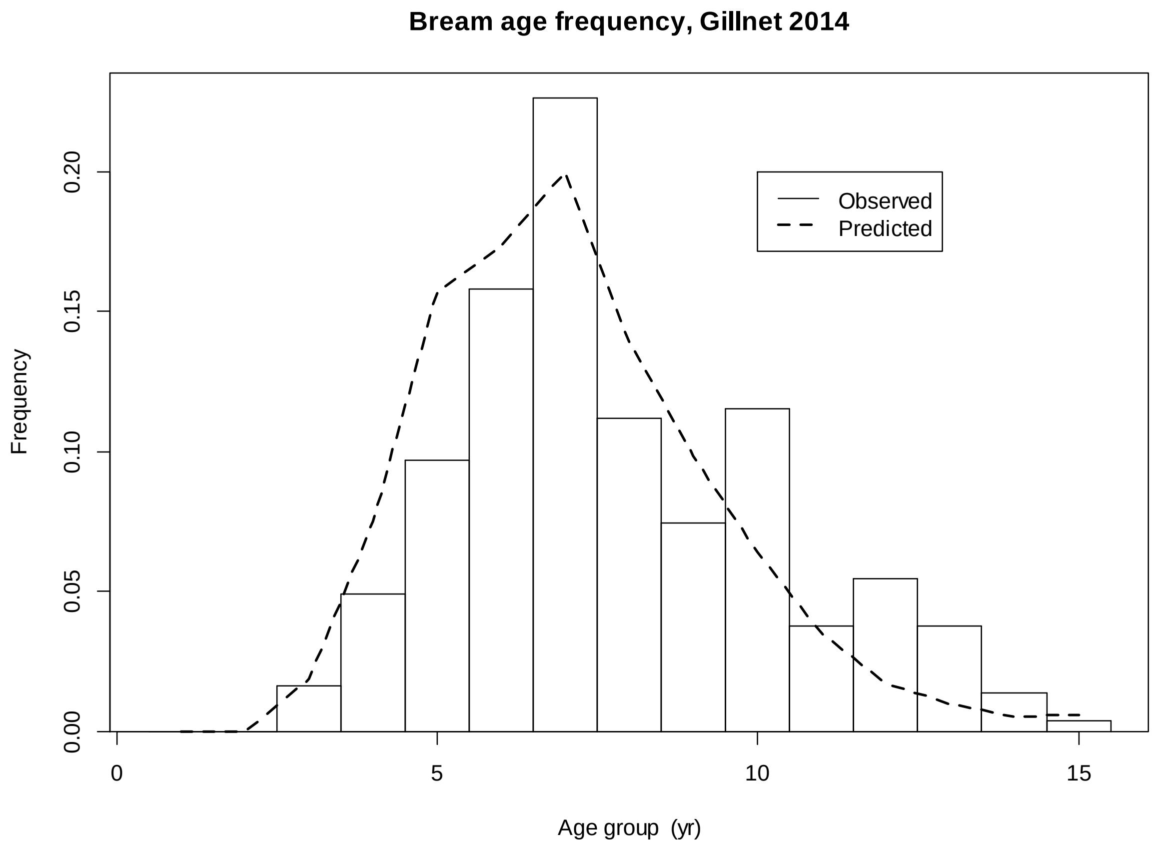

Bream age frequency, Gillnet 2009
Frequency
0.00
0.05
0.10
0.15
0.20
0.25
0
5
10
15
Age group (yr)
Observed
Predicted

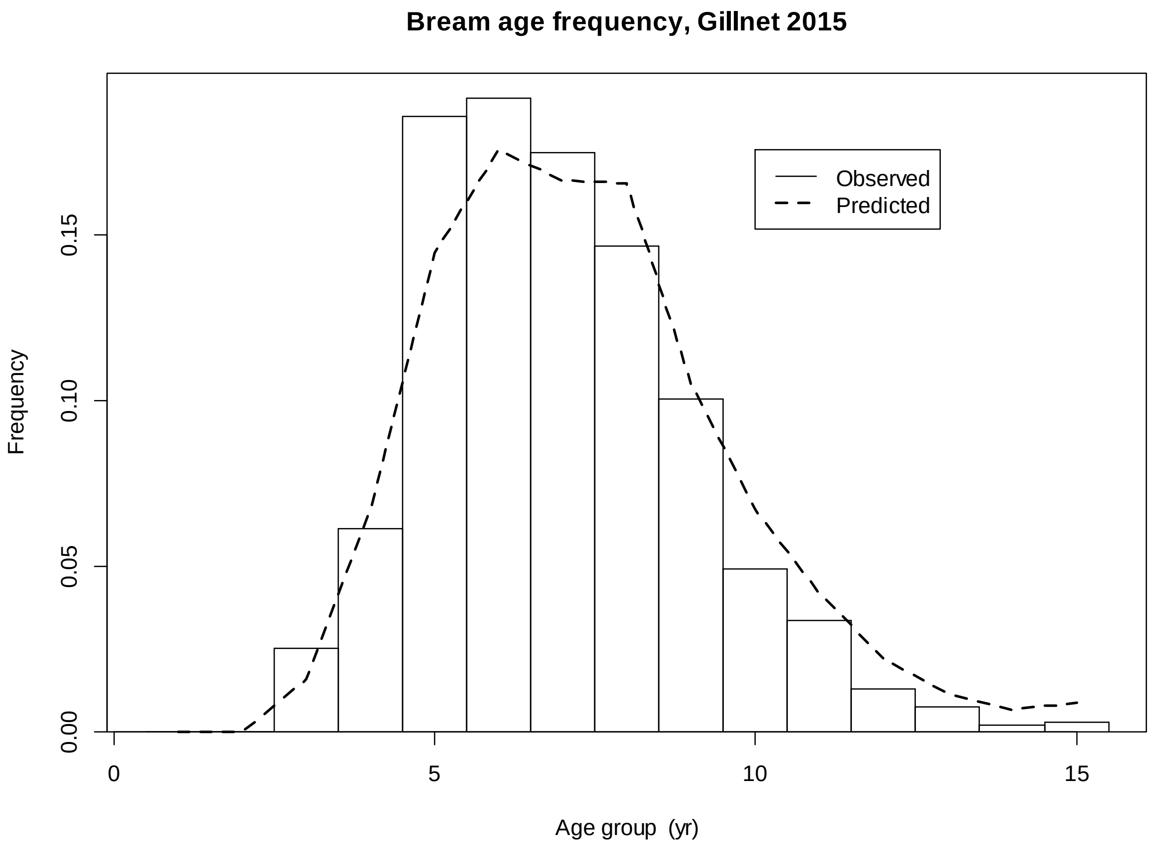

Bream age frequency, Gillnet 2010
Frequency
0.00
0.05
0.10
0.15
0.20
0
5
10
15
Age group (yr)
Observed
Predicted

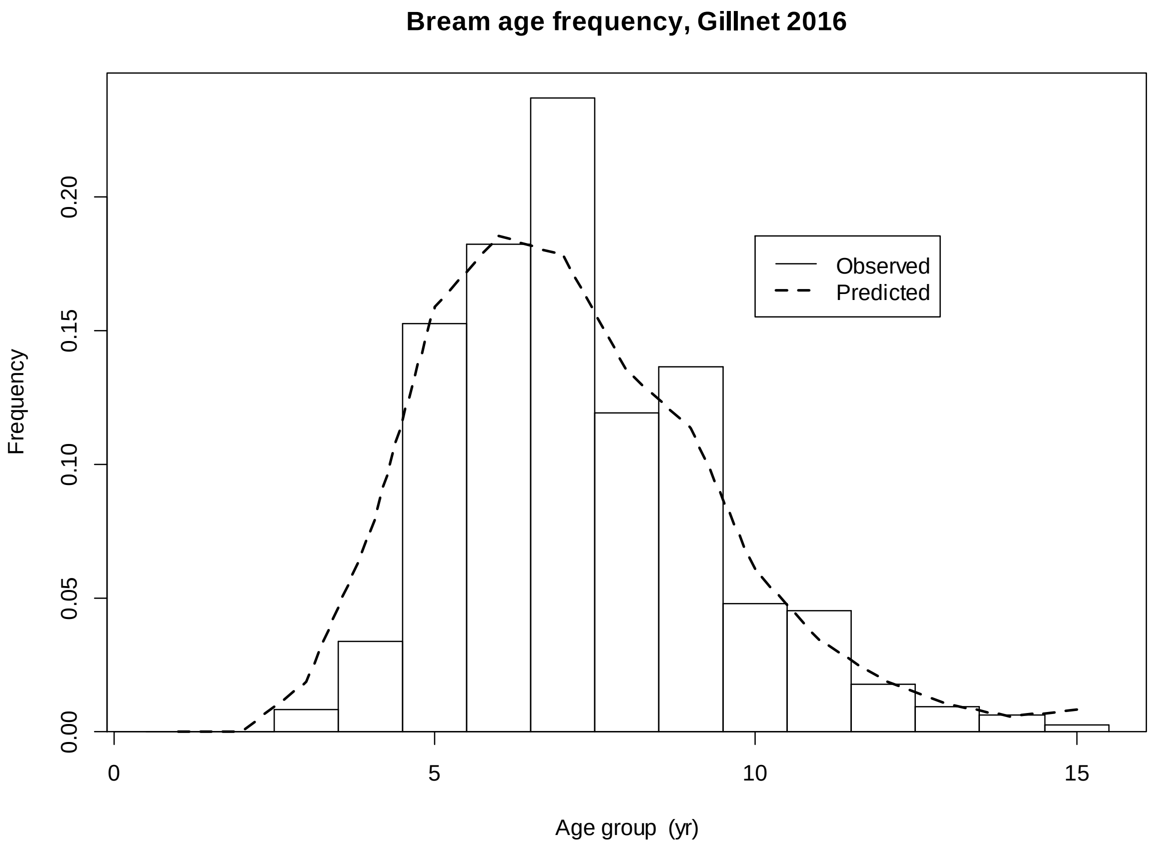

Bream age frequency, Gillnet 2011
Frequency
0.00
0.05
0.10
0.15
0.20
Observed
Predicted
0
5
10
15
Age group (yr)


Bream age frequency, Gillnet 2012
Frequency
0.00
0.05
0.10
0.15
0.20
0.25
Observed
Predicted
0
5
10
15
Age group (yr)

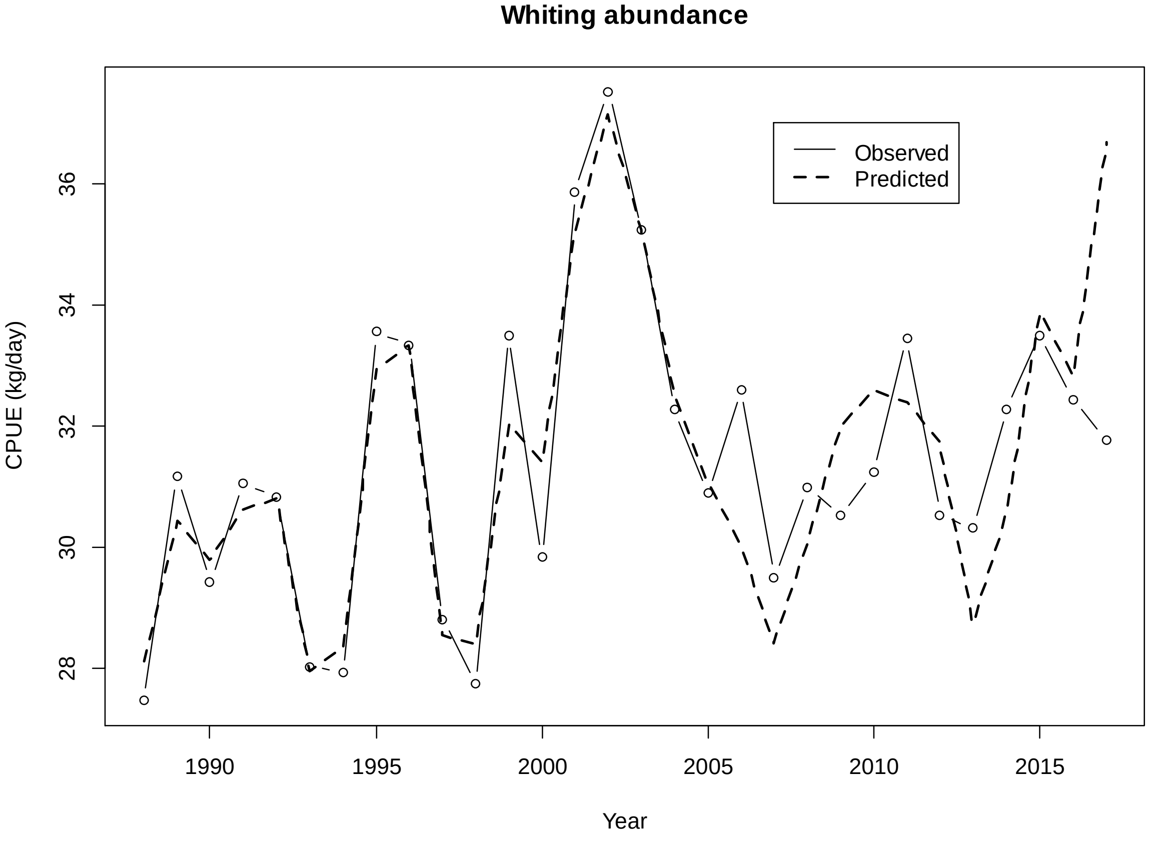

Bream age frequency, Gillnet 2013
Frequency
0.00
0.05
0.10
0.15
0.20
0.25
Age group (yr)
0
5
10
15
Observed
Predicted

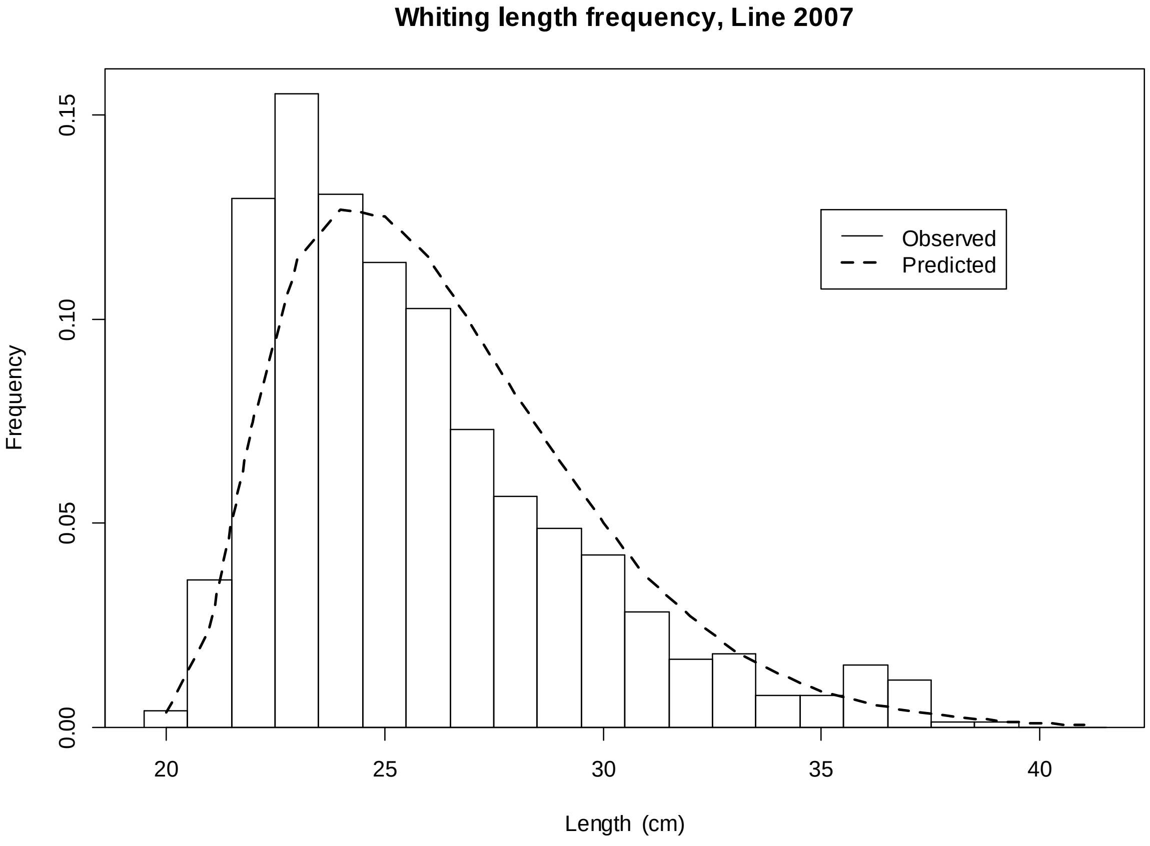

Bream age frequency, Gillnet 2014
Frequency
0.00
0.05
0.10
0.15
0.20
Age group (yr)
0
5
10
15
Observed
Predicted

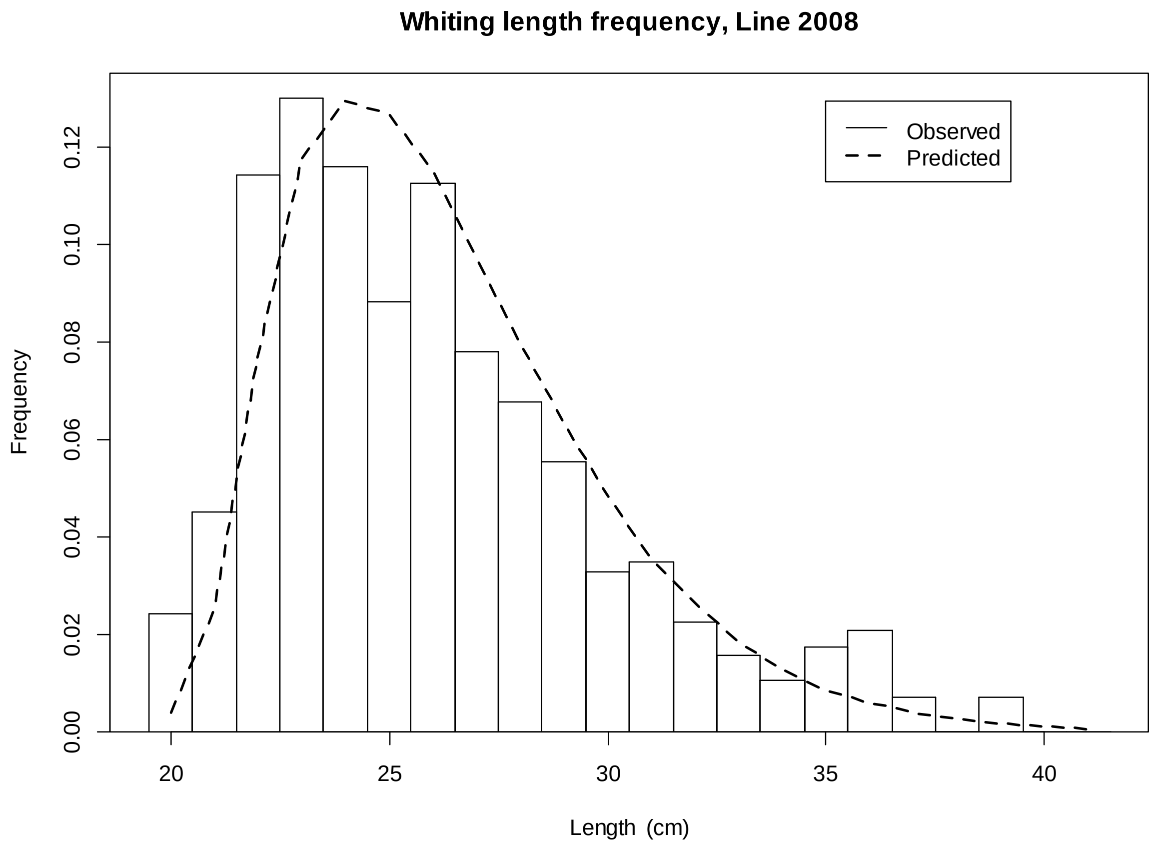

Bream age frequency, Gillnet 2015
Frequency
0.00
0.05
0.10
0.15
0
5
10
15
Age group (yr)
Observed
Predicted


Bream age frequency, Gillnet 2016
Frequency
0.00
0.05
0.10
0.15
0.20
0
5
10
15
Age group (yr)
Observed
Predicted

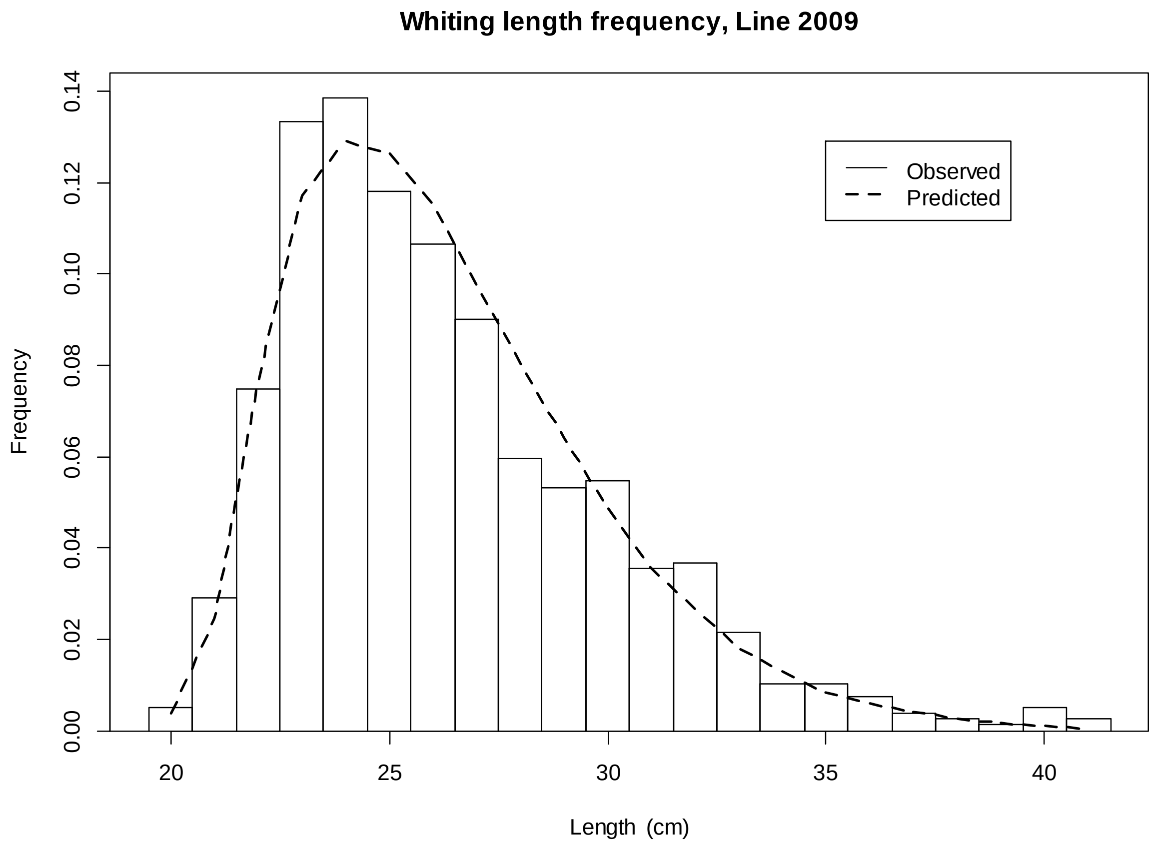
A2.2 Whiting


Whiting abundance
CPUE (kg/day)
28
30
32
34
36
1990
1995
2000
2005
2010
2015
Year
Observed
Predicted

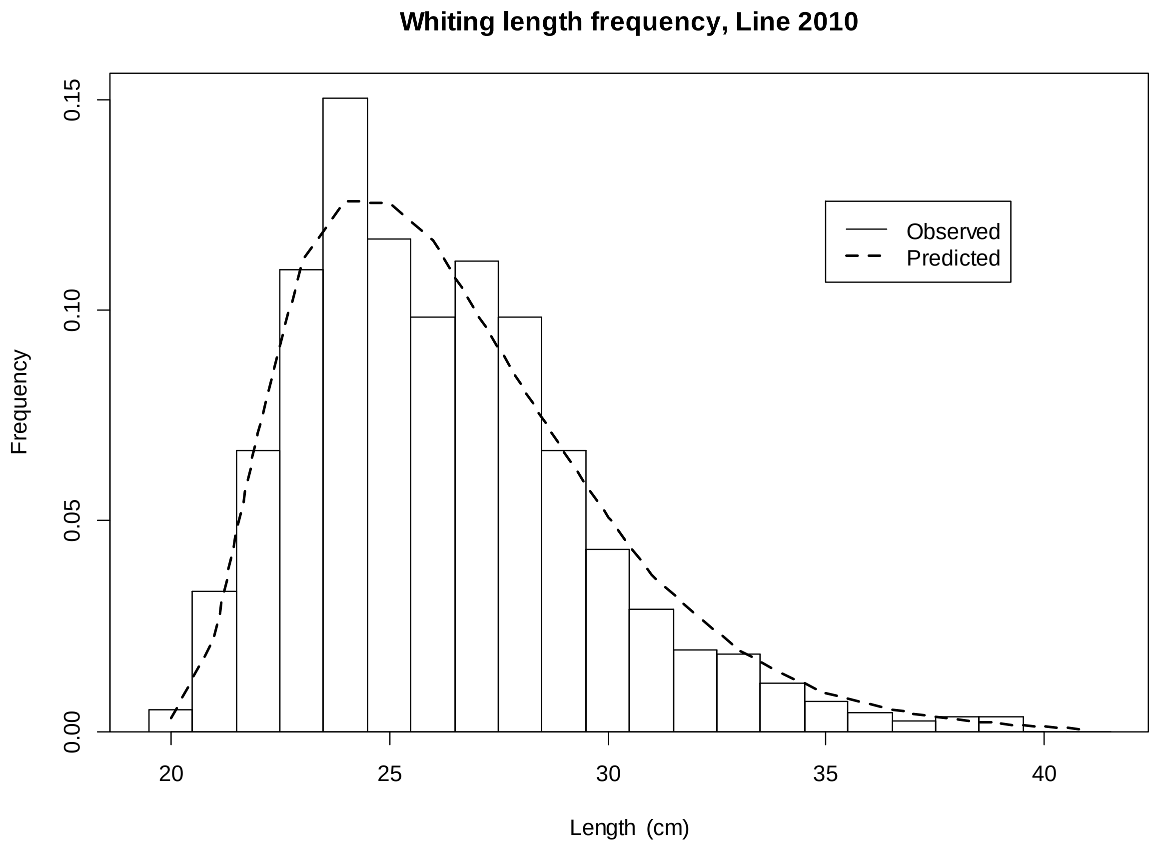

Whiting length frequency, Line 2007
Frequency
0.00
0.05
0.10
0.15
20
25
30
35
40
Length (cm)
Observed
Predicted

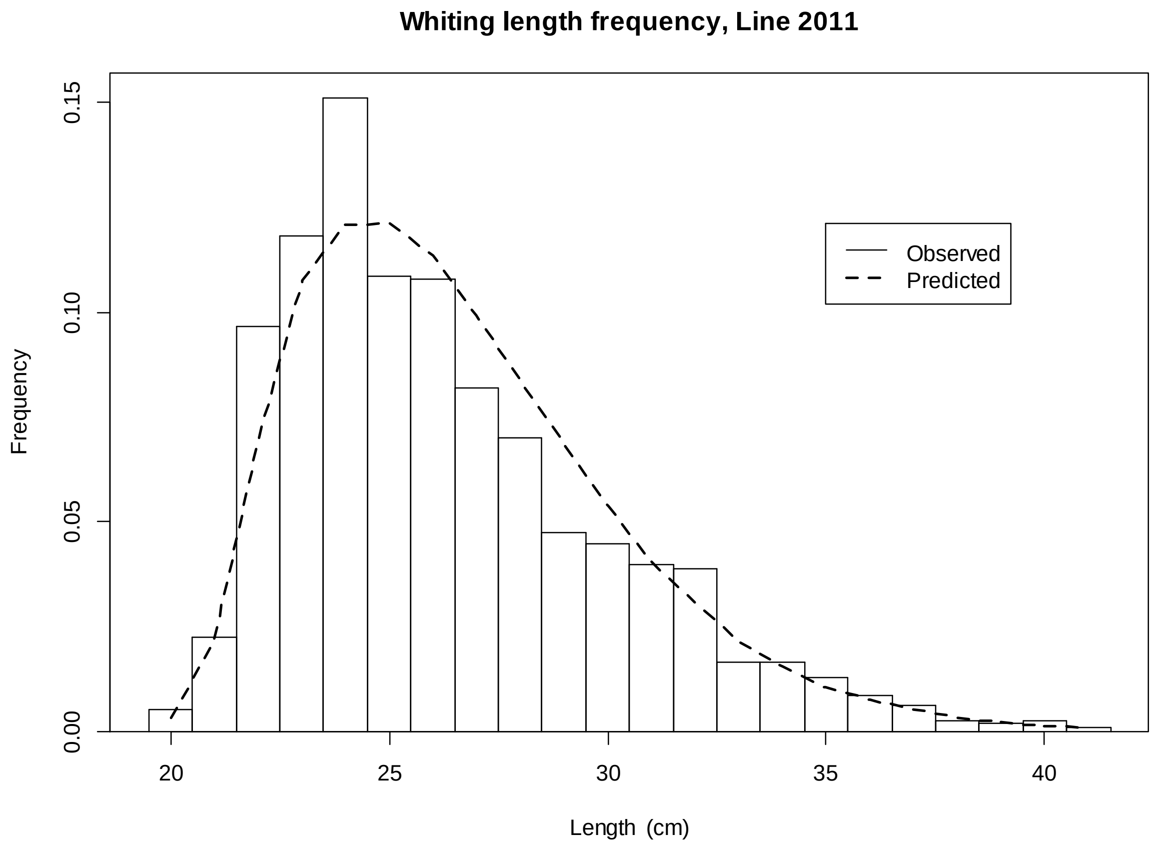


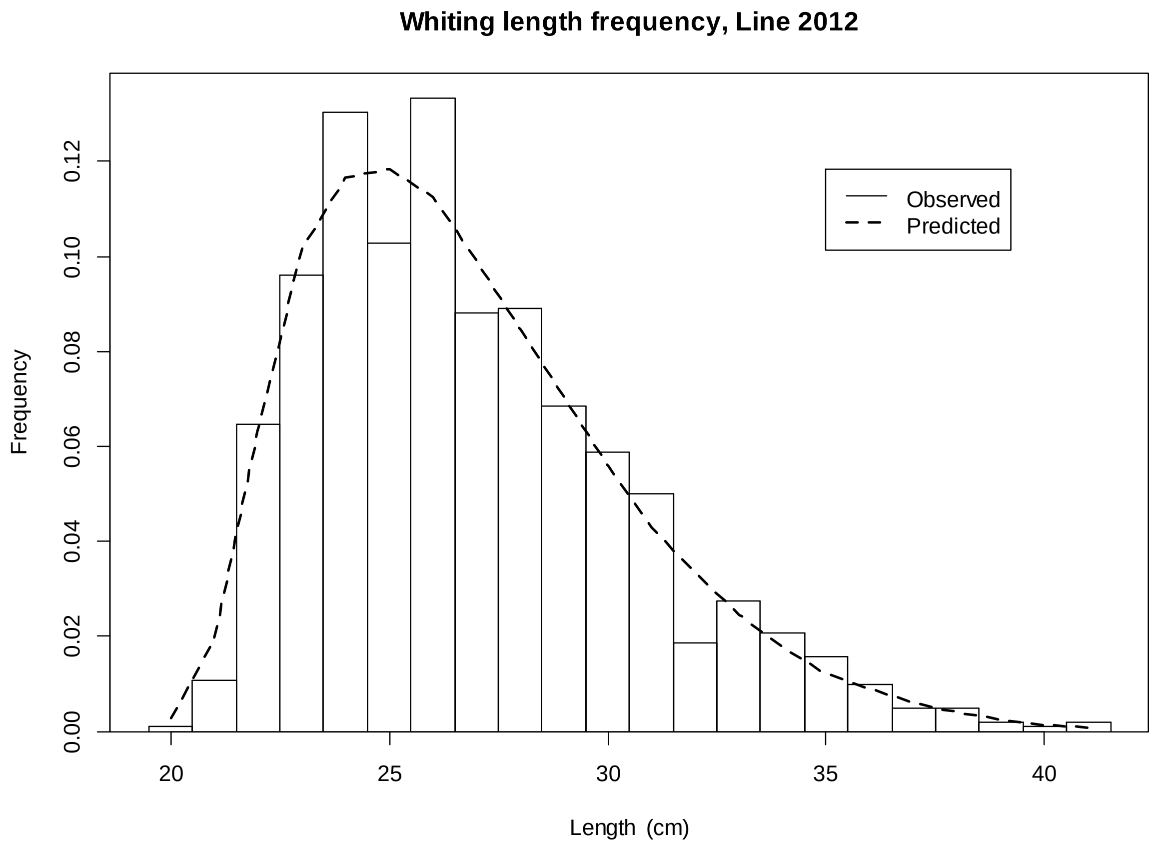
Whiting length frequency, Line 2008
Observed
Predicted
Frequency
0.00
0.02
0.04
0.06
0.08
0.10
0.12
20
25
30
35
40
Length (cm)

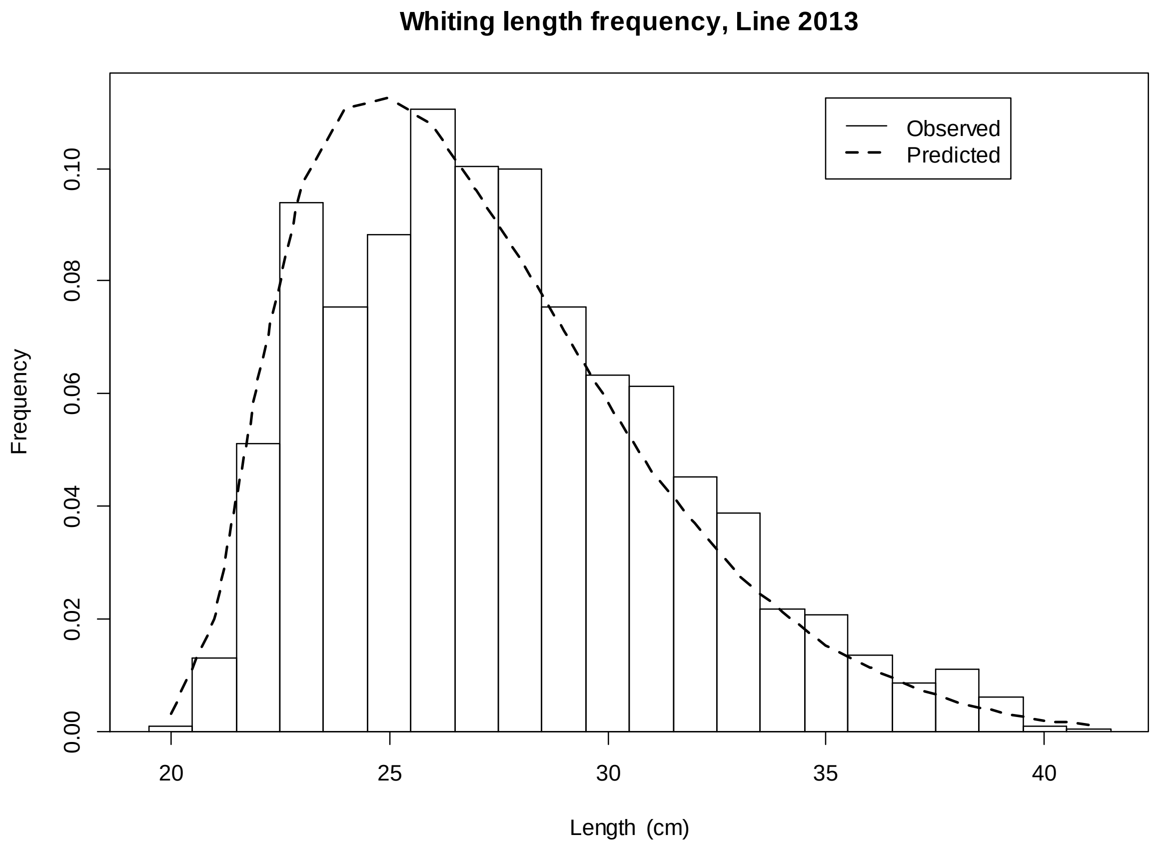


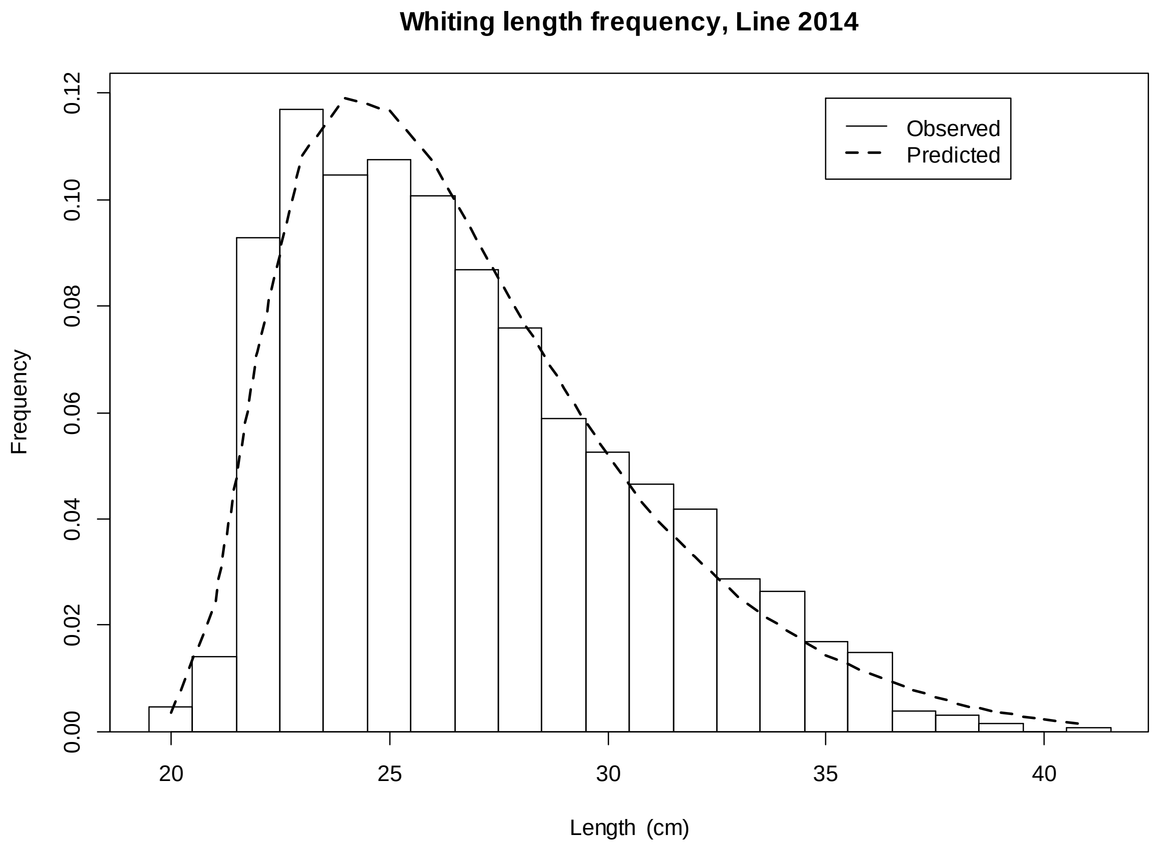
Whiting length frequency, Line 2009
Observed
Predicted
Frequency
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
20
25
30
35
40
Length (cm)

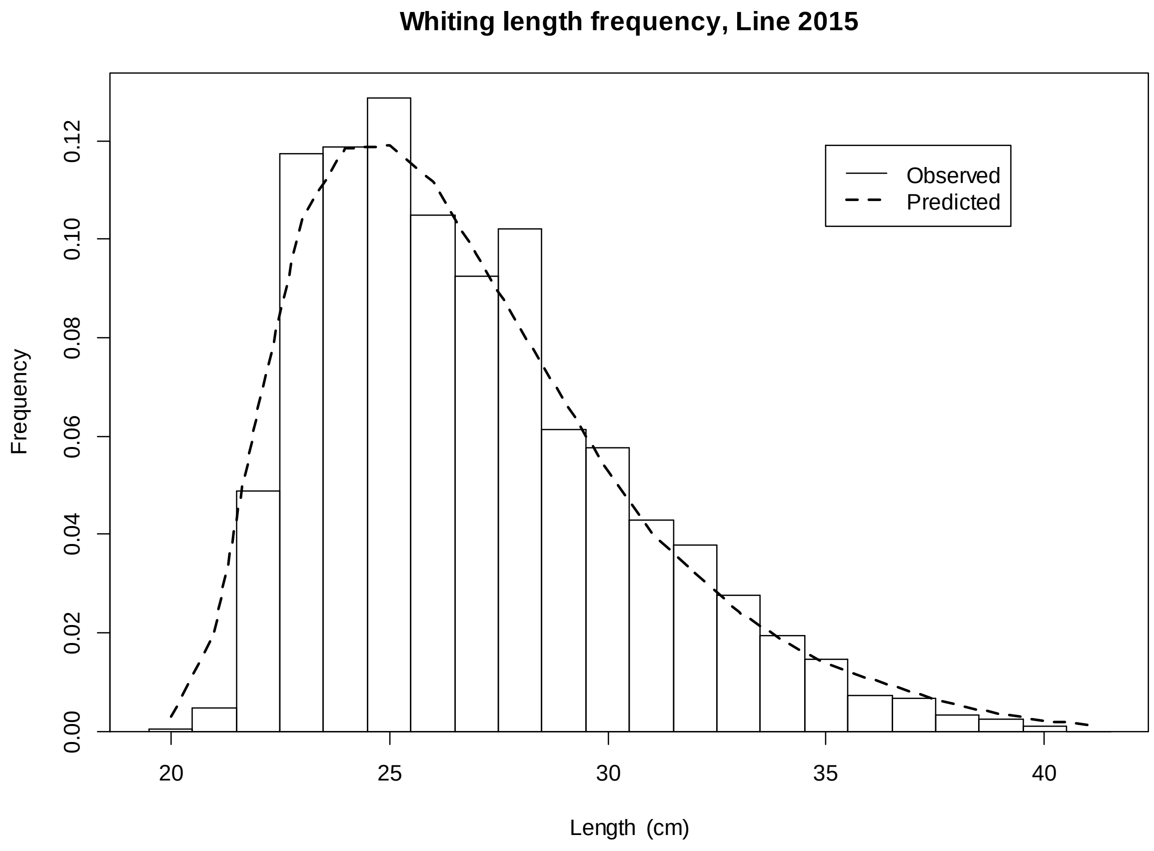

Whiting length frequency, Line 2010
Frequency
0.00
0.05
0.10
0.15
20
25
30
35
40
Length (cm)
Observed
Predicted

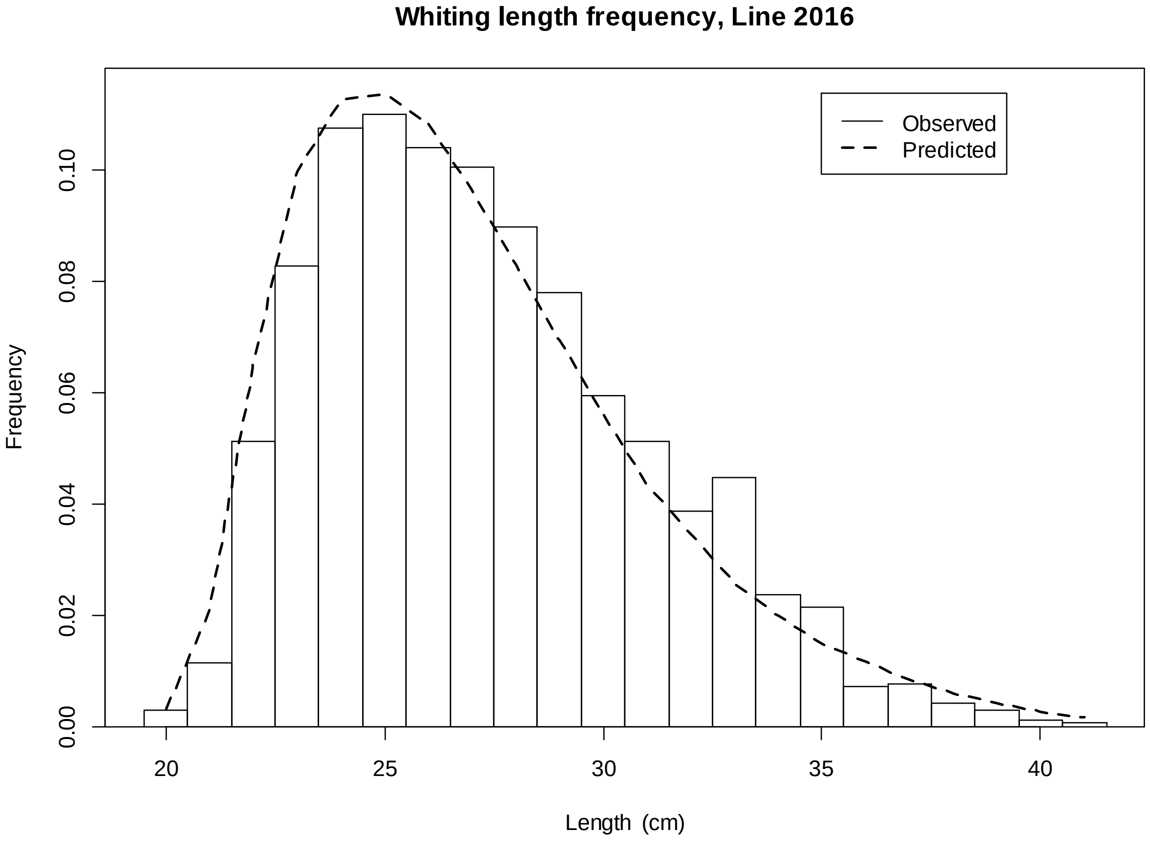

Whiting length frequency, Line 2011
Frequency
0.00
0.05
0.10
0.15
20
25
30
35
40
Length (cm)
Observed
Predicted

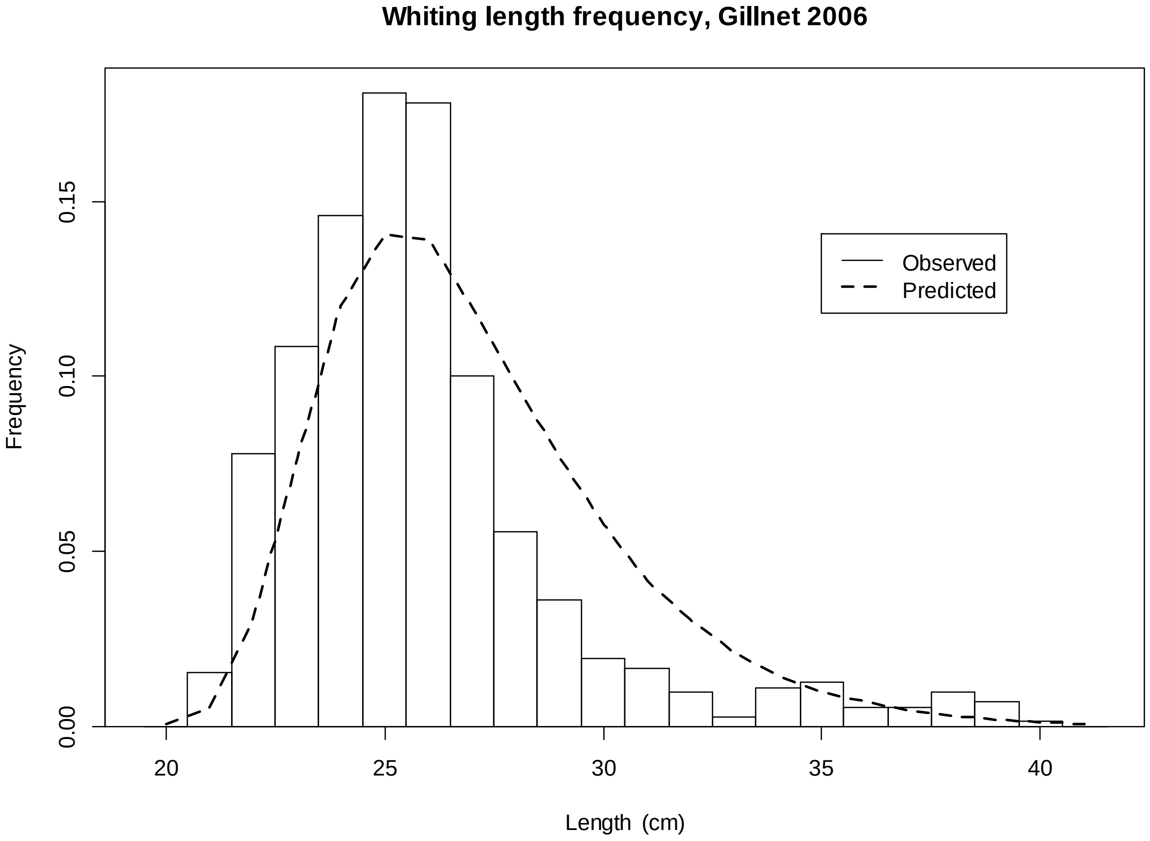

Whiting length frequency, Line 2012
Frequency
0.00
0.02
0.04
0.06
0.08
0.10
0.12
20
25
30
35
40
Length (cm)
Observed
Predicted

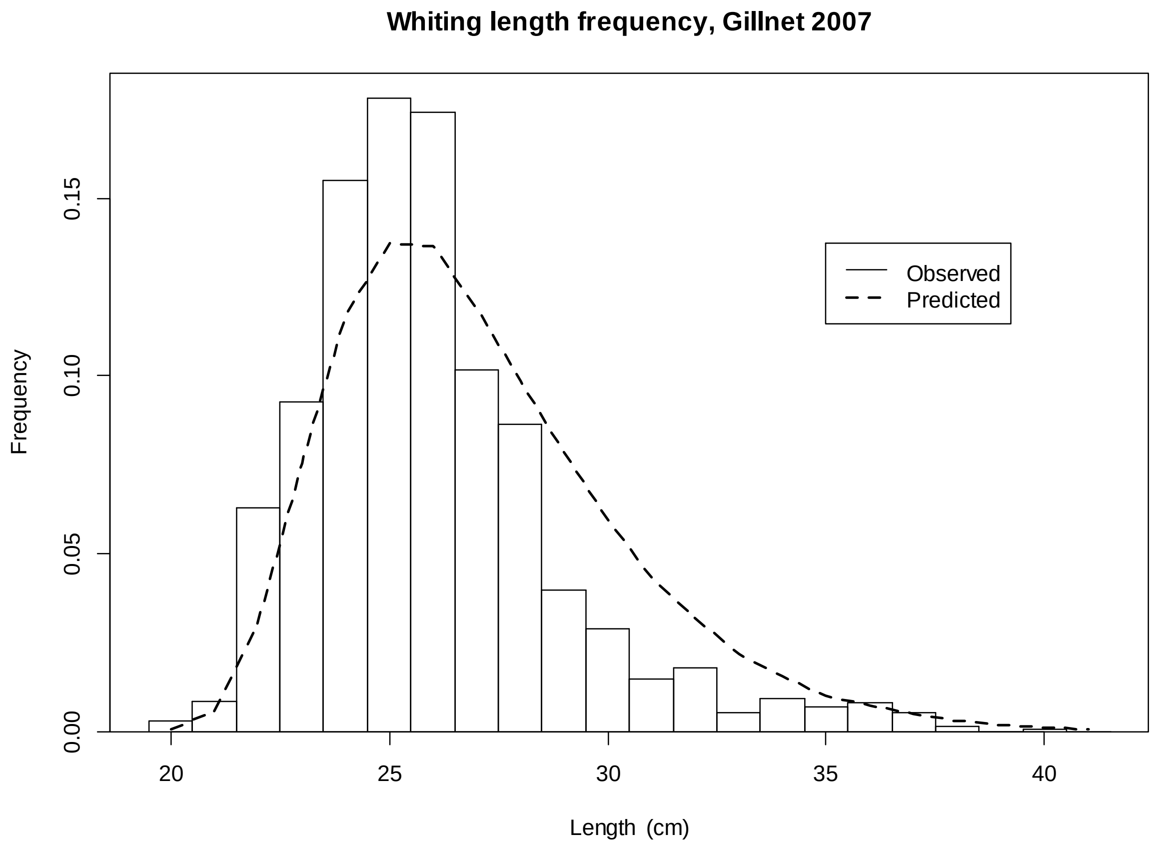

Whiting length frequency, Line 2013
Frequency
0.00
0.02
0.04
0.06
0.08
0.10
20
25
30
35
40
Length (cm)
Observed
Predicted

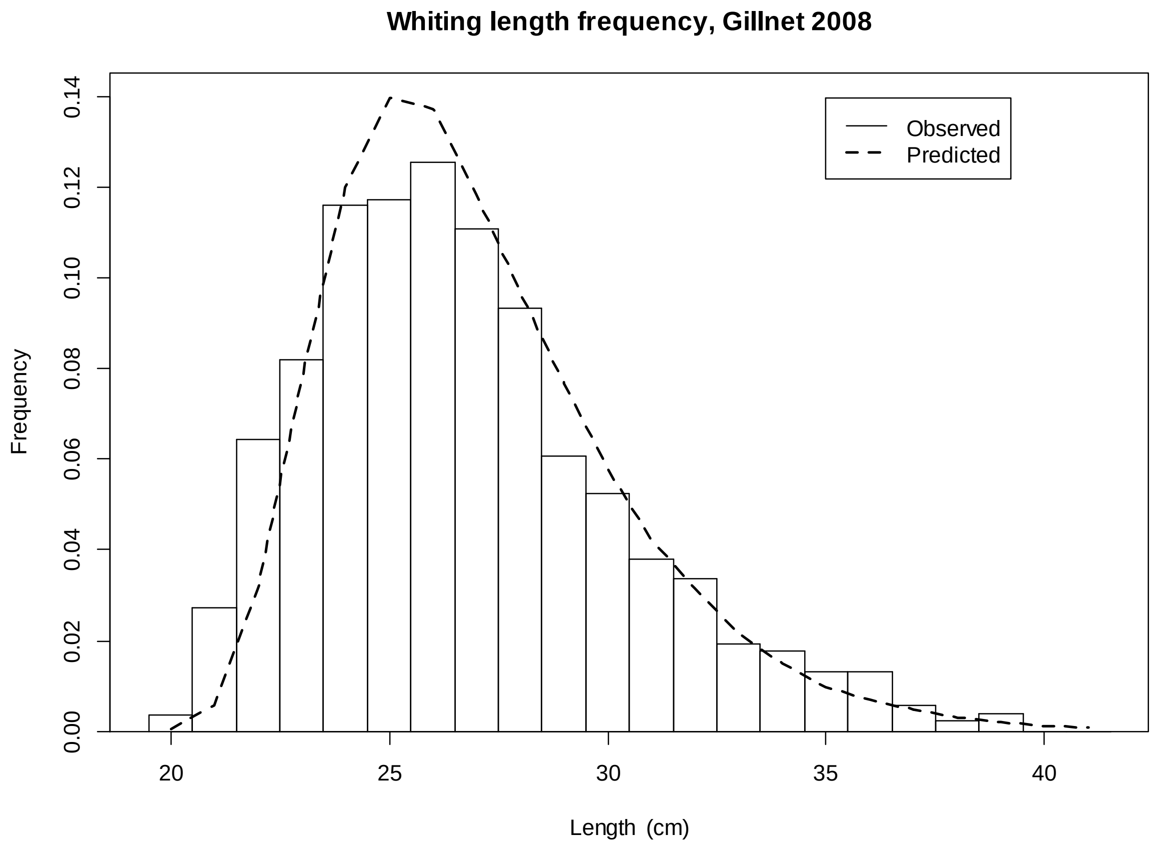

Whiting length frequency, Line 2014
Observed
Predicted
Frequency
0.00
0.02
0.04
0.06
0.08
0.10
0.12
20
25
30
35
40
Length (cm)


Whiting length frequency, Line 2015
Observed
Predicted
Frequency
0.00
0.02
0.04
0.06
0.08
0.10
0.12
20
25
30
35
40
Length (cm)

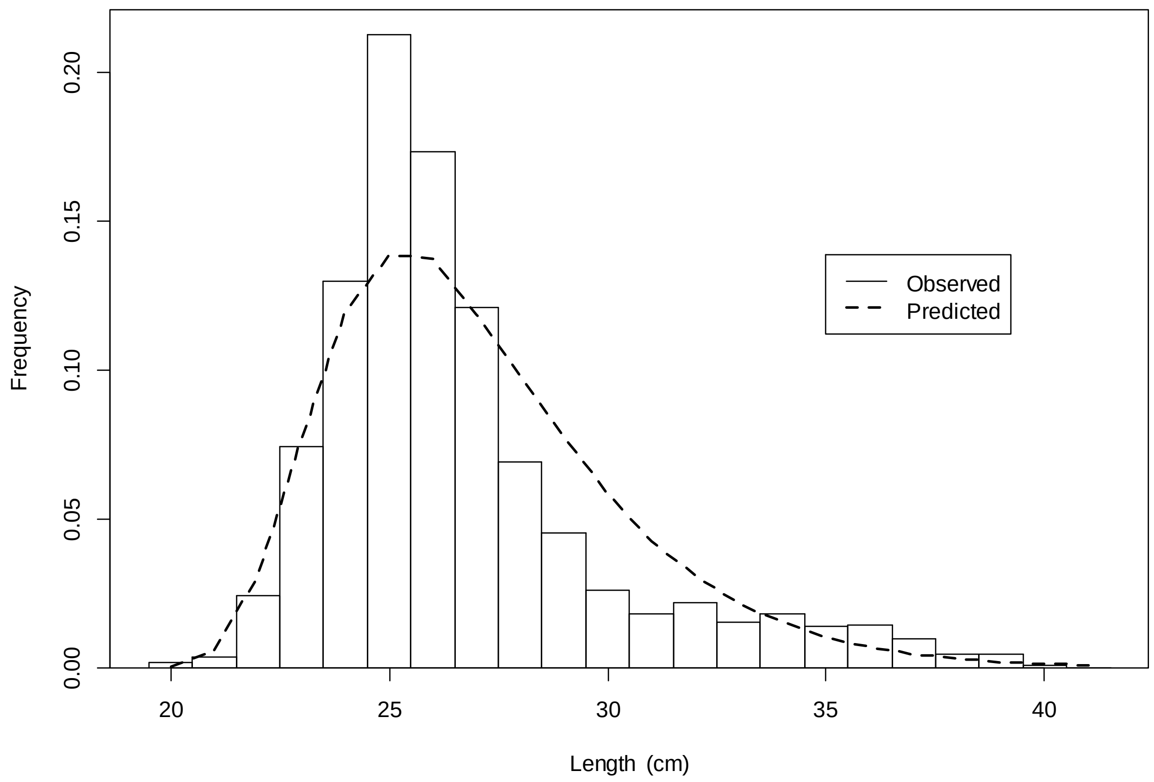

Whiting length frequency, Line 2016
Observed
Predicted
Frequency
0.00
0.02
0.04
0.06
0.08
0.10
20
25
30
35
40
Length (cm)


Whiting length frequency, Gillnet 2006
Observed
Predicted
Frequency
0.00
0.05
0.10
0.15
20
25
30
35
40
Length (cm)

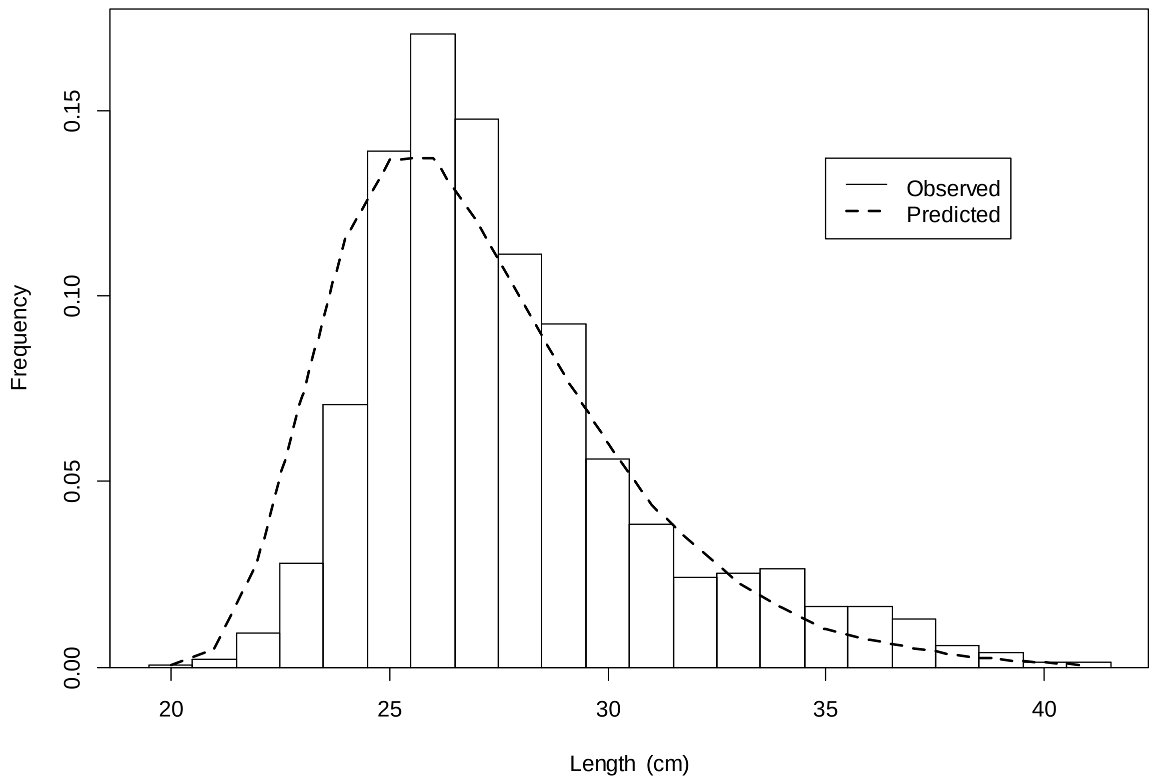

Whiting length frequency, Gillnet 2007
Frequency
0.00
0.05
0.10
0.15
20
25
30
35
40
Length (cm)
Observed
Predicted

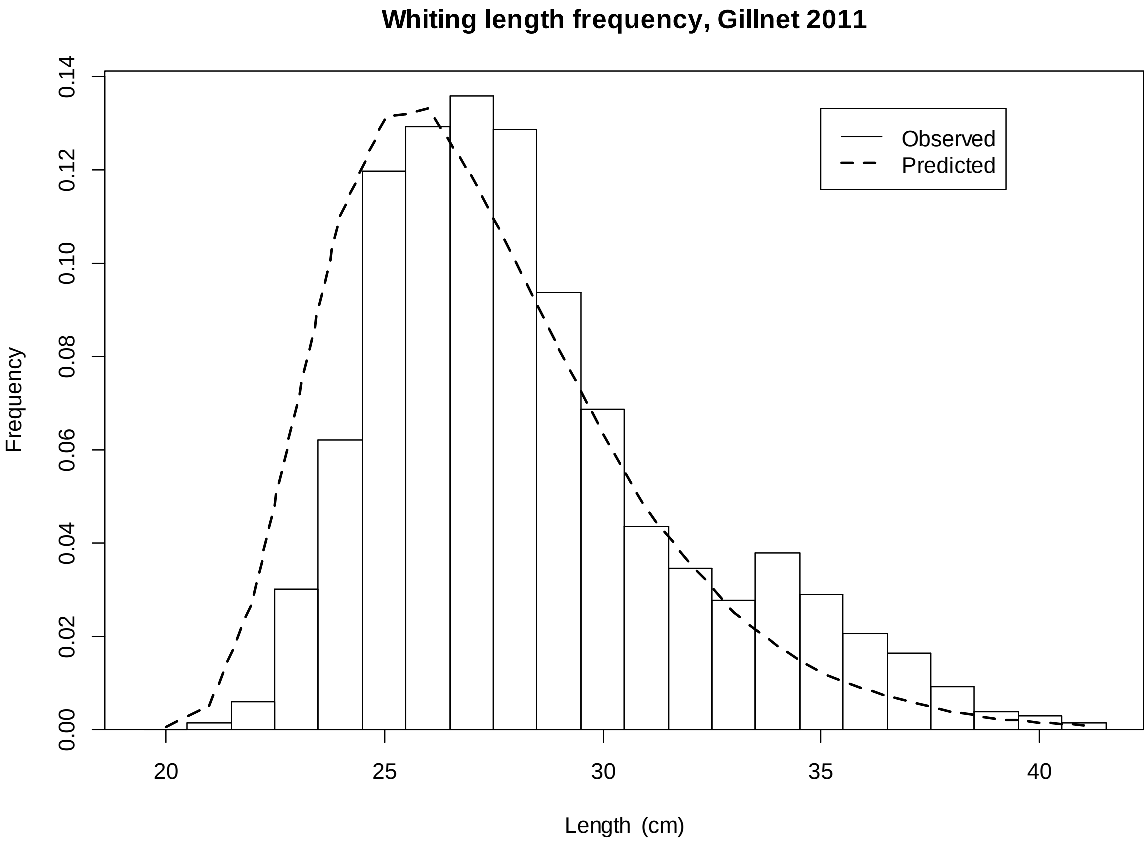

Whiting length frequency, Gillnet 2008
Frequency
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
20
25
30
35
40
Length (cm)
Observed
Predicted

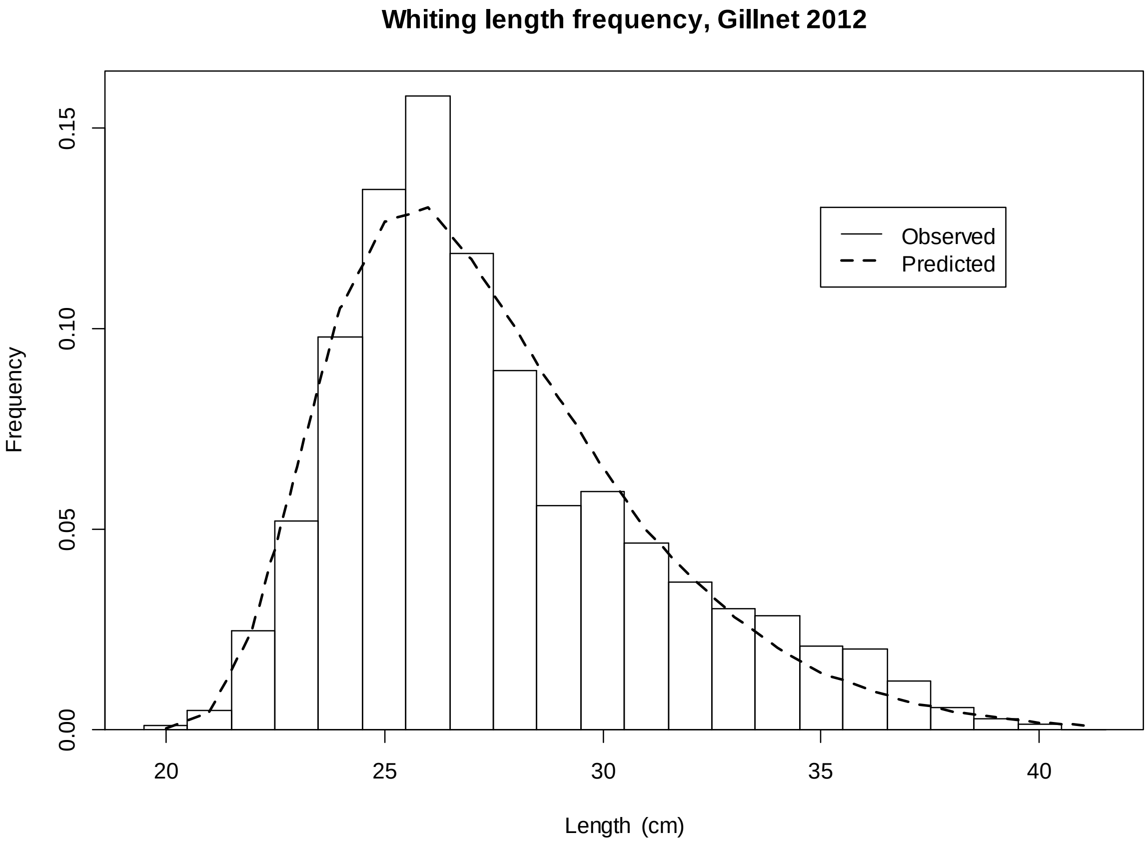
Whiting length frequency, Gillnet 2009

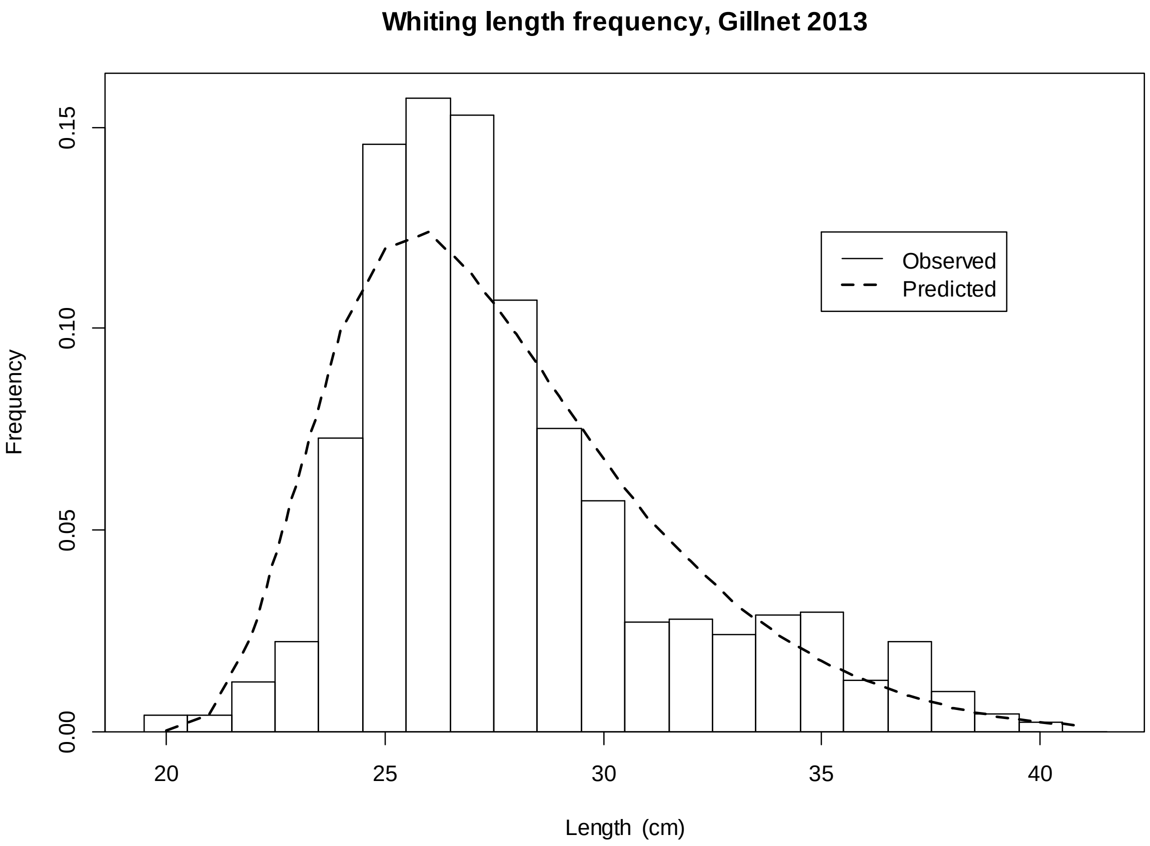


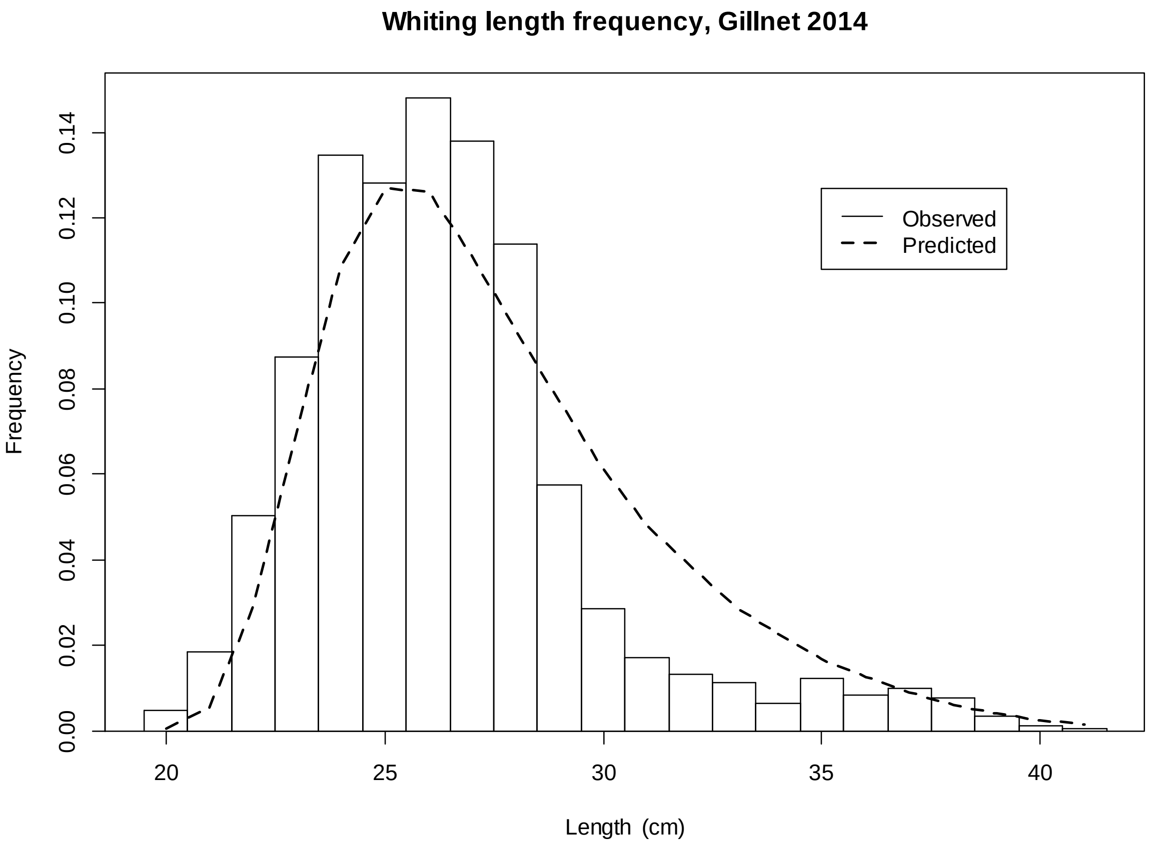
Whiting length frequency, Gillnet 2010

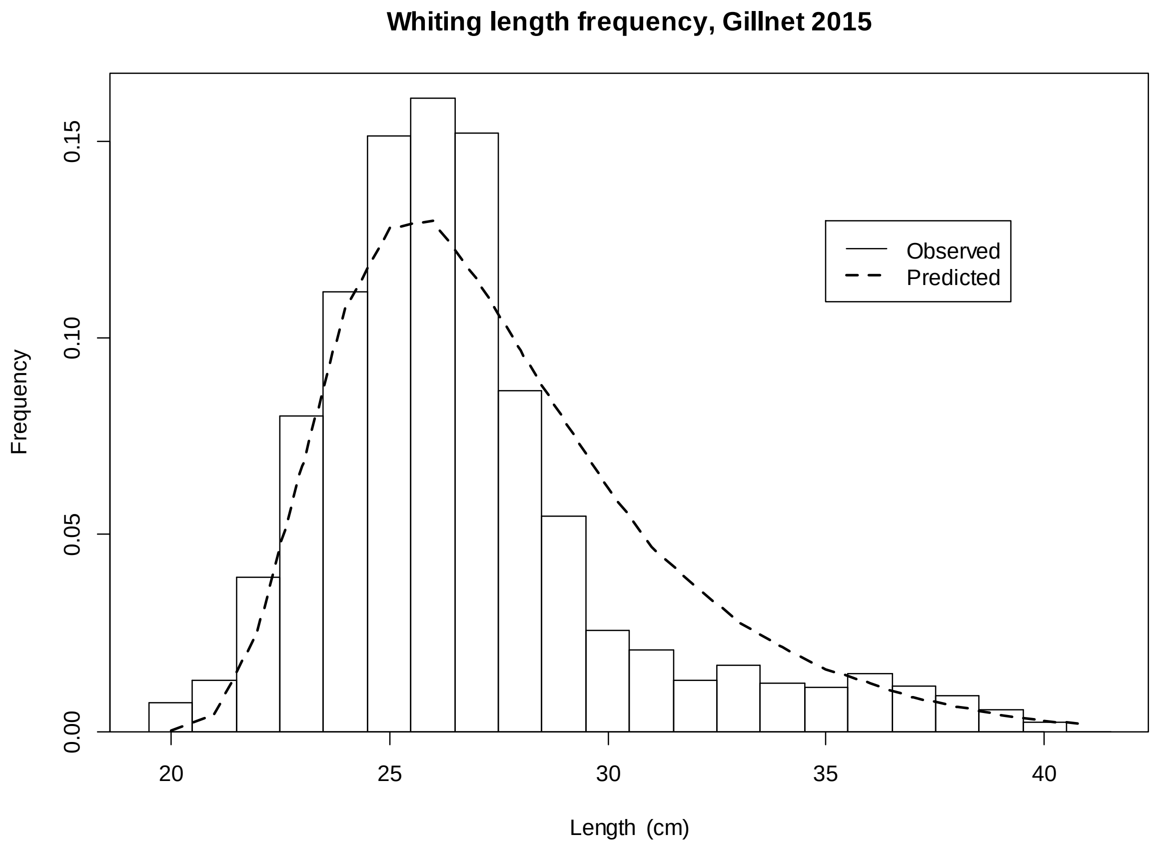


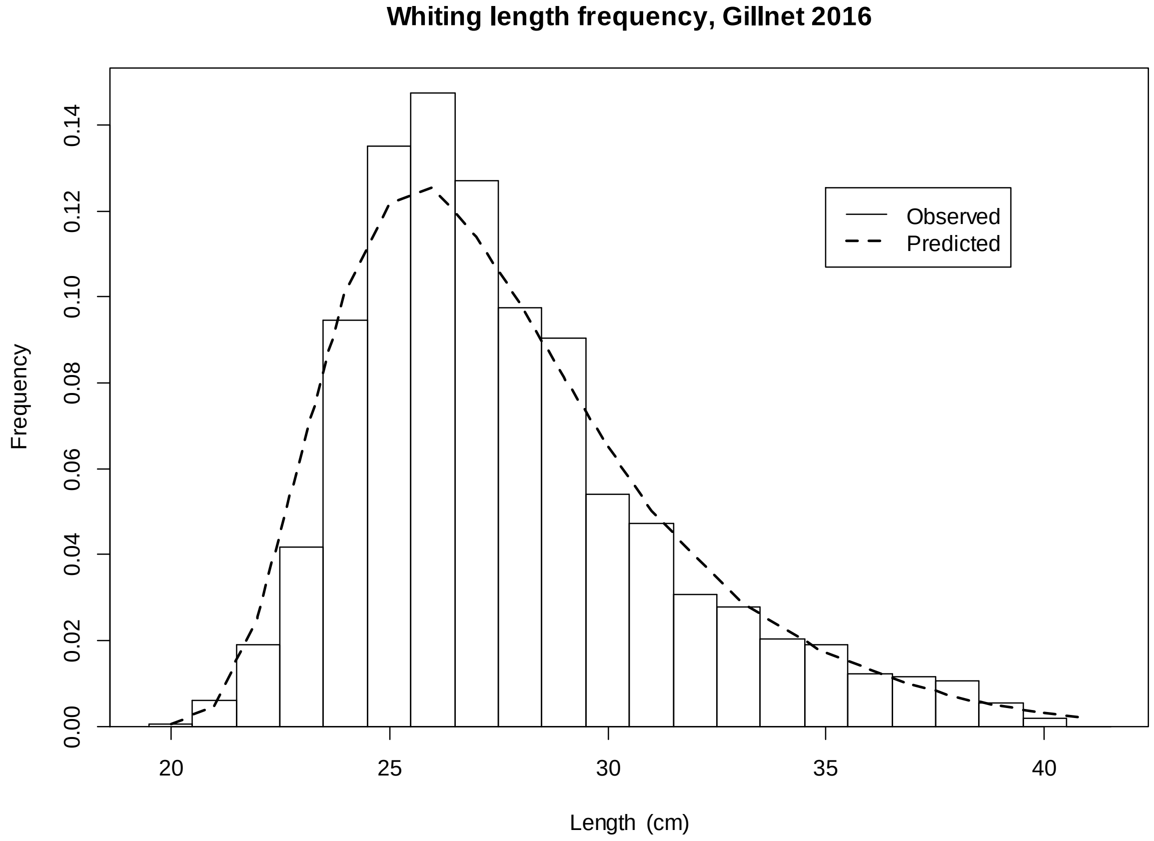

Whiting length frequency, Gillnet 2011
Observed
Predicted
Frequency
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
20
25
30
35
40
Length (cm)

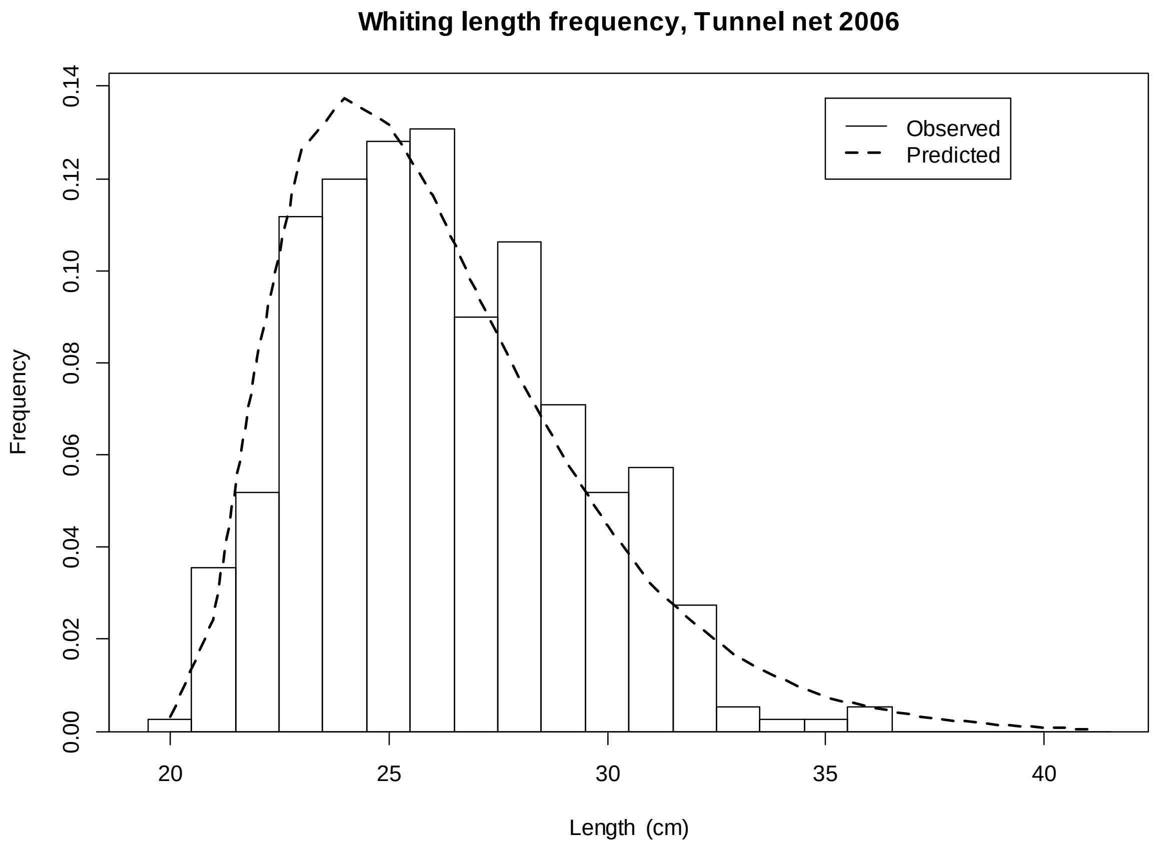

Whiting length frequency, Gillnet 2012
Observed
Predicted
Frequency
0.00
0.05
0.10
0.15
20
25
30
35
40
Length (cm)

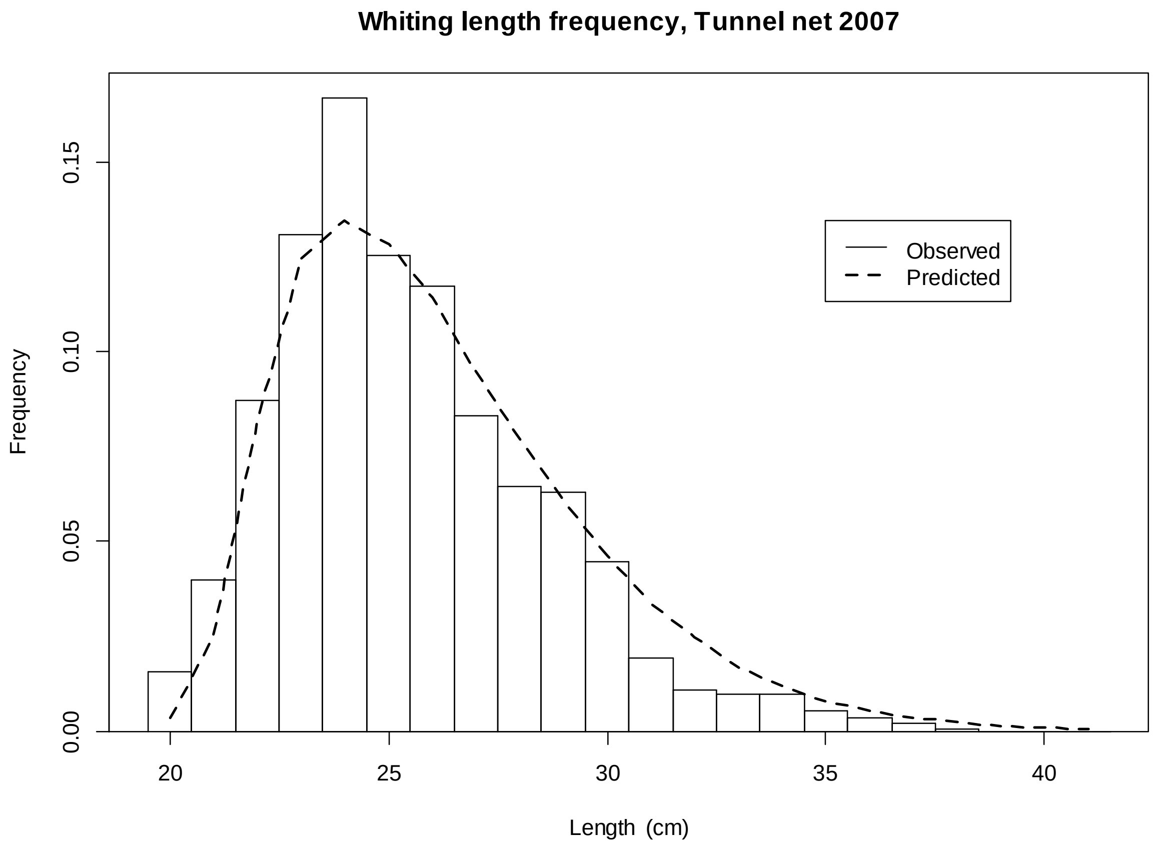

Whiting length frequency, Gillnet 2013
Frequency
0.00
0.05
0.10
0.15
20
25
30
35
40
Length (cm)
Observed
Predicted

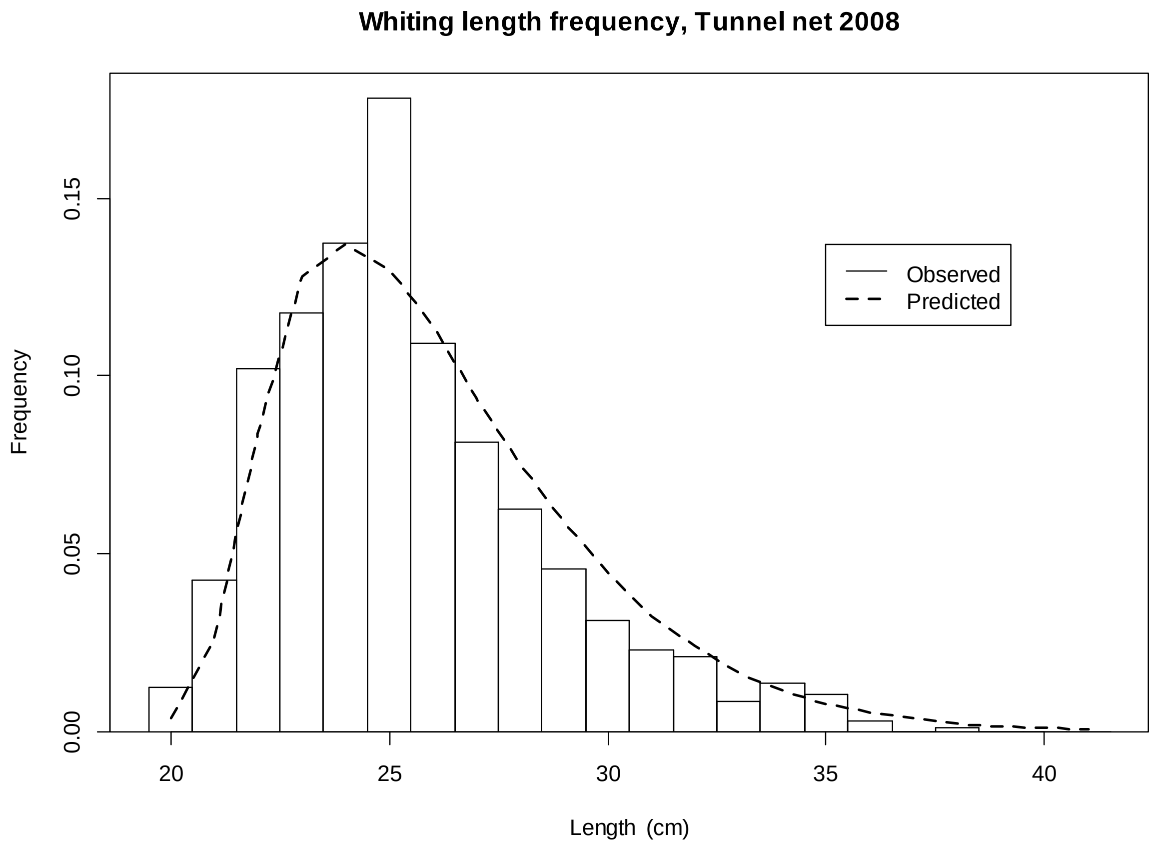

Whiting length frequency, Gillnet 2014
Frequency
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
20
25
30
35
40
Length (cm)
Observed
Predicted

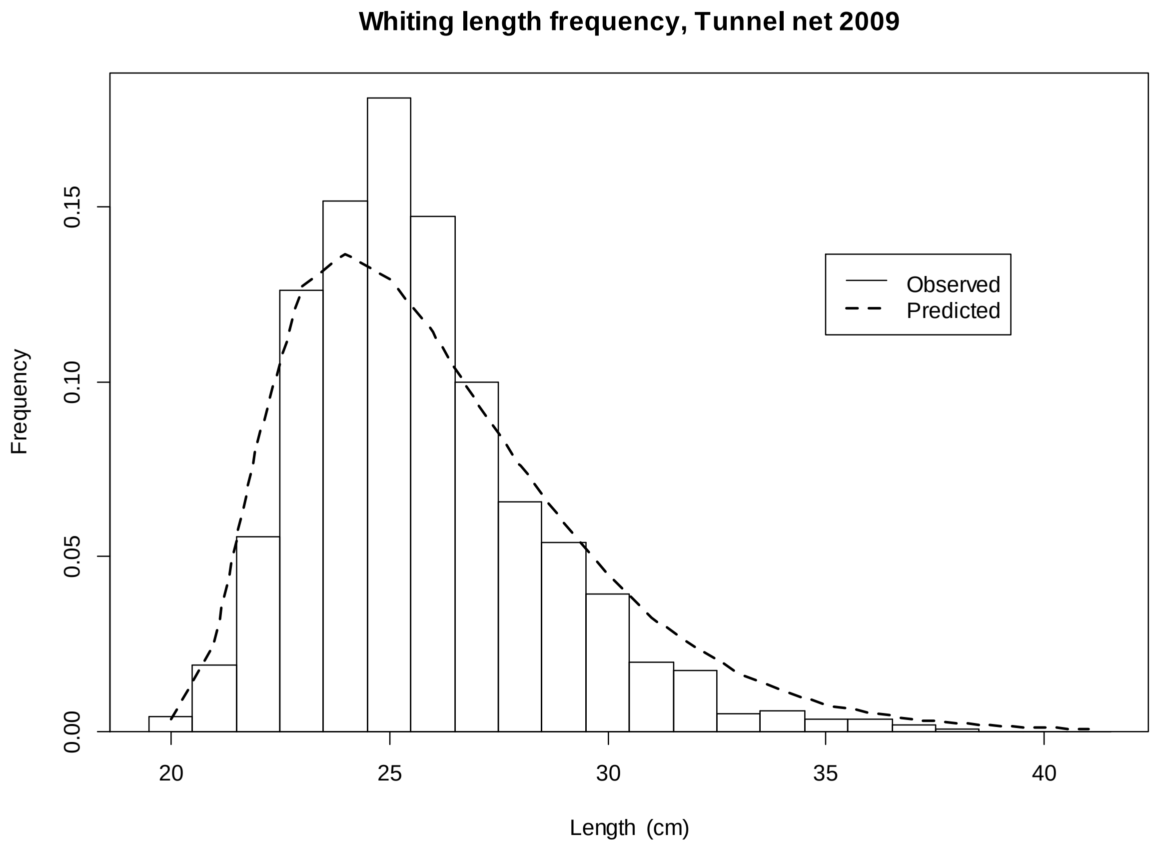

Whiting length frequency, Gillnet 2015
Frequency
0.00
0.05
0.10
0.15
20
25
30
35
40
Length (cm)
Observed
Predicted

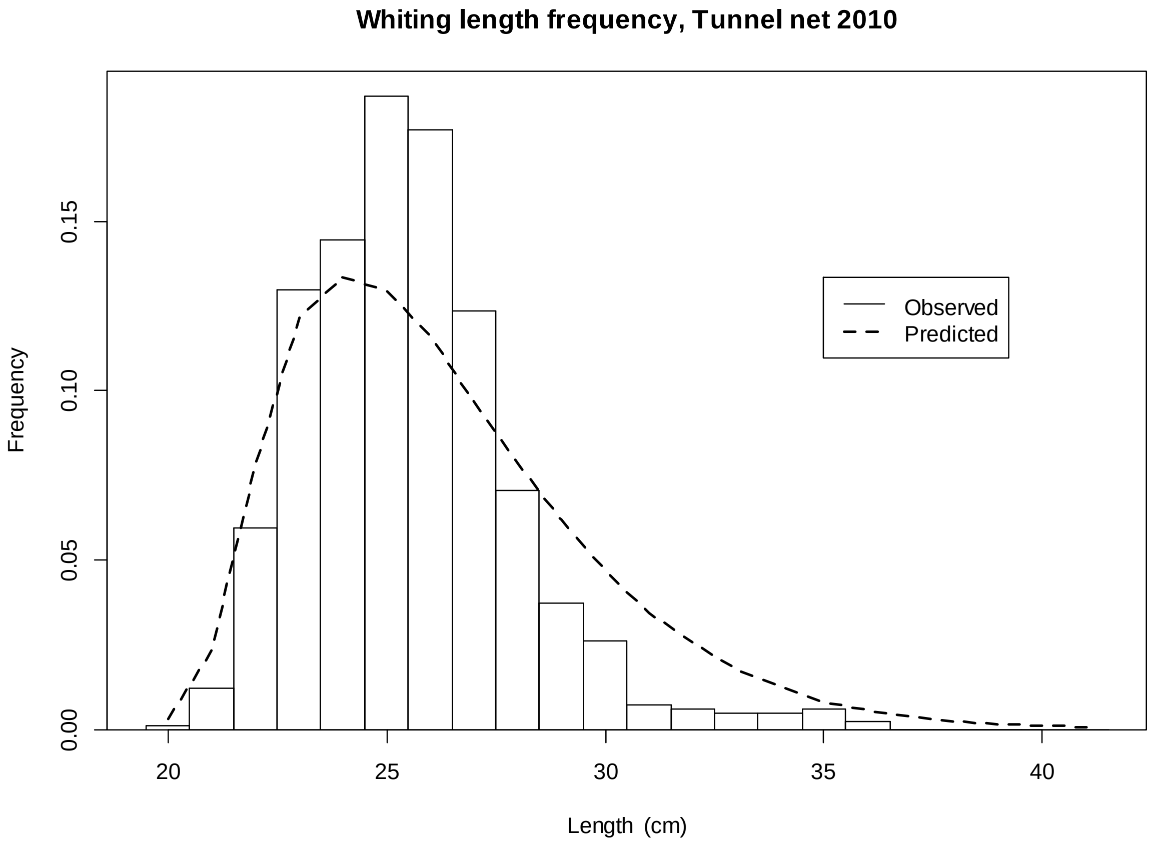

Whiting length frequency, Gillnet 2016
Frequency
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
20
25
30
35
40
Length (cm)
Observed
Predicted

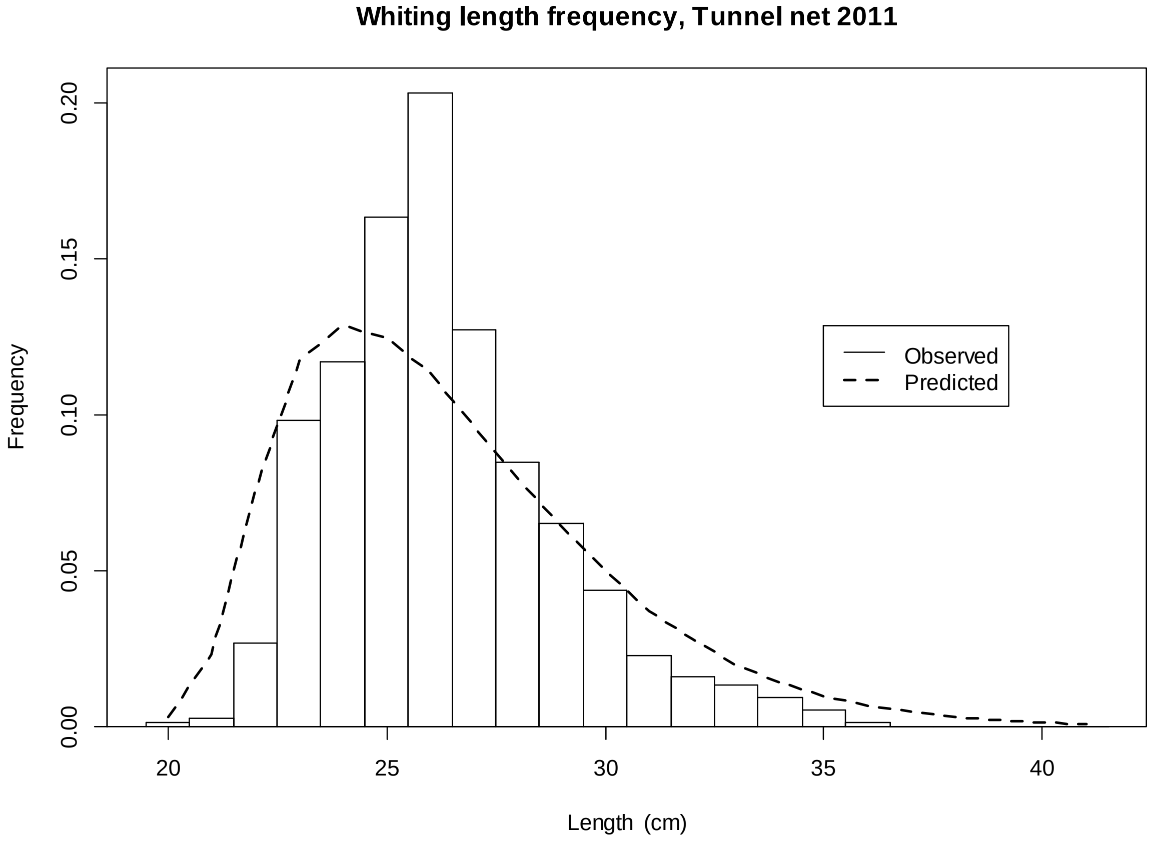

Whiting length frequency, Tunnel net 2006
Observed
Predicted
Frequency
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
20
25
30
35
40
Length (cm)

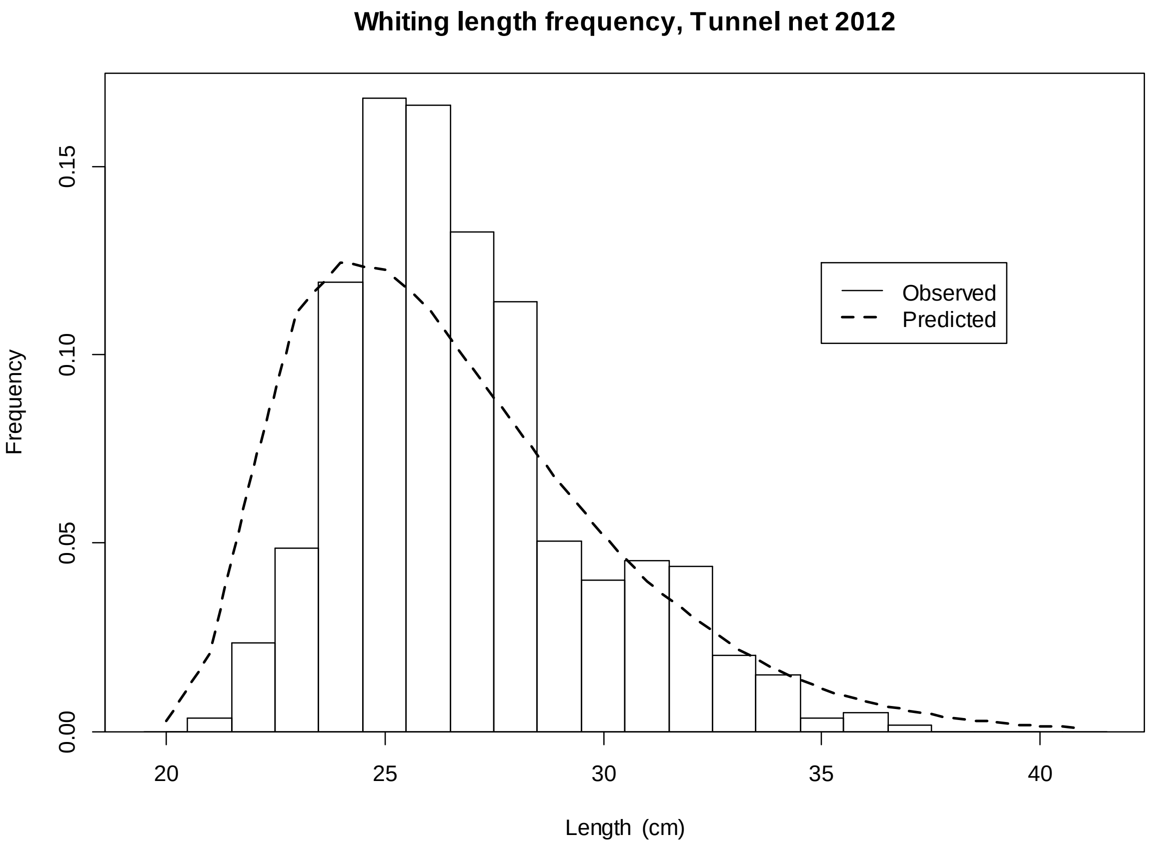

Whiting length frequency, Tunnel net 2007
Observed
Predicted
Frequency
0.00
0.05
0.10
0.15
20
25
30
35
40
Length (cm)

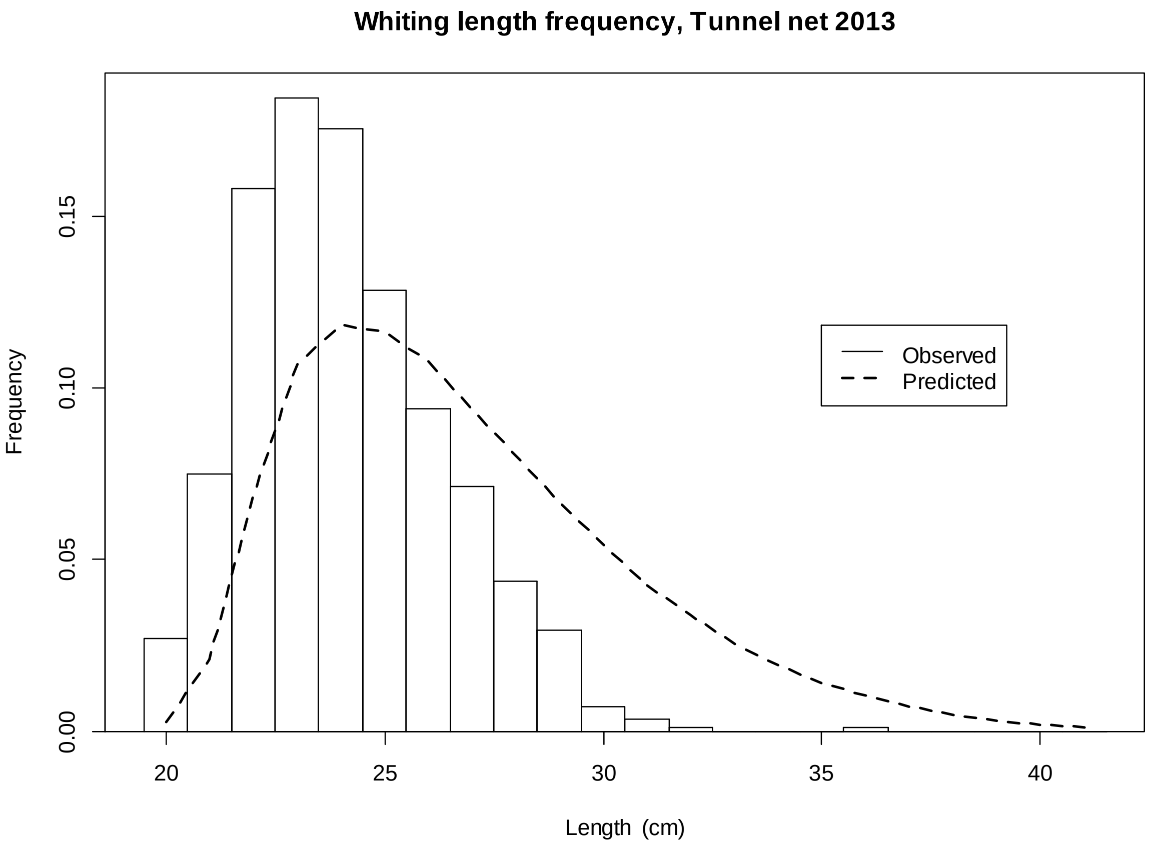

Whiting length frequency, Tunnel net 2008
Frequency
0.00
0.05
0.10
0.15
20
25
30
35
40
Length (cm)
Observed
Predicted

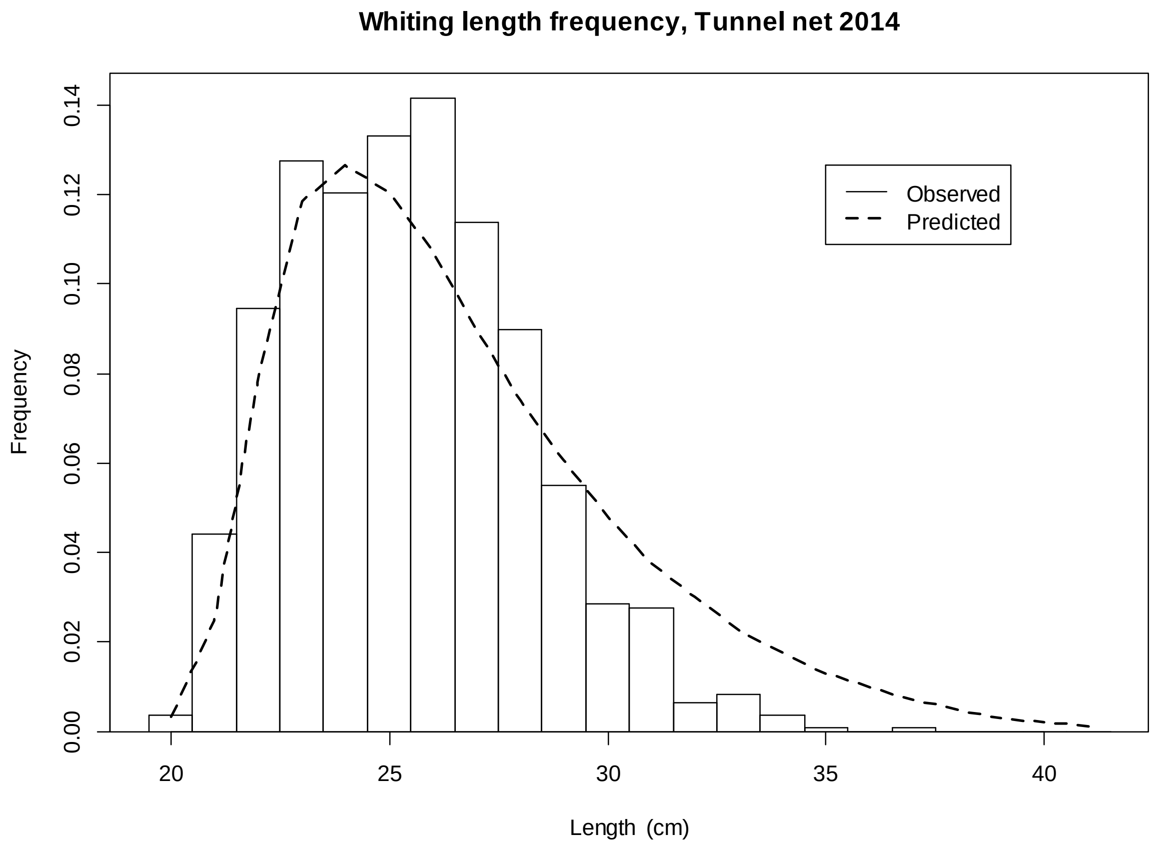

Whiting length frequency, Tunnel net 2009
Frequency
0.00
0.05
0.10
0.15
20
25
30
35
40
Length (cm)
Observed
Predicted

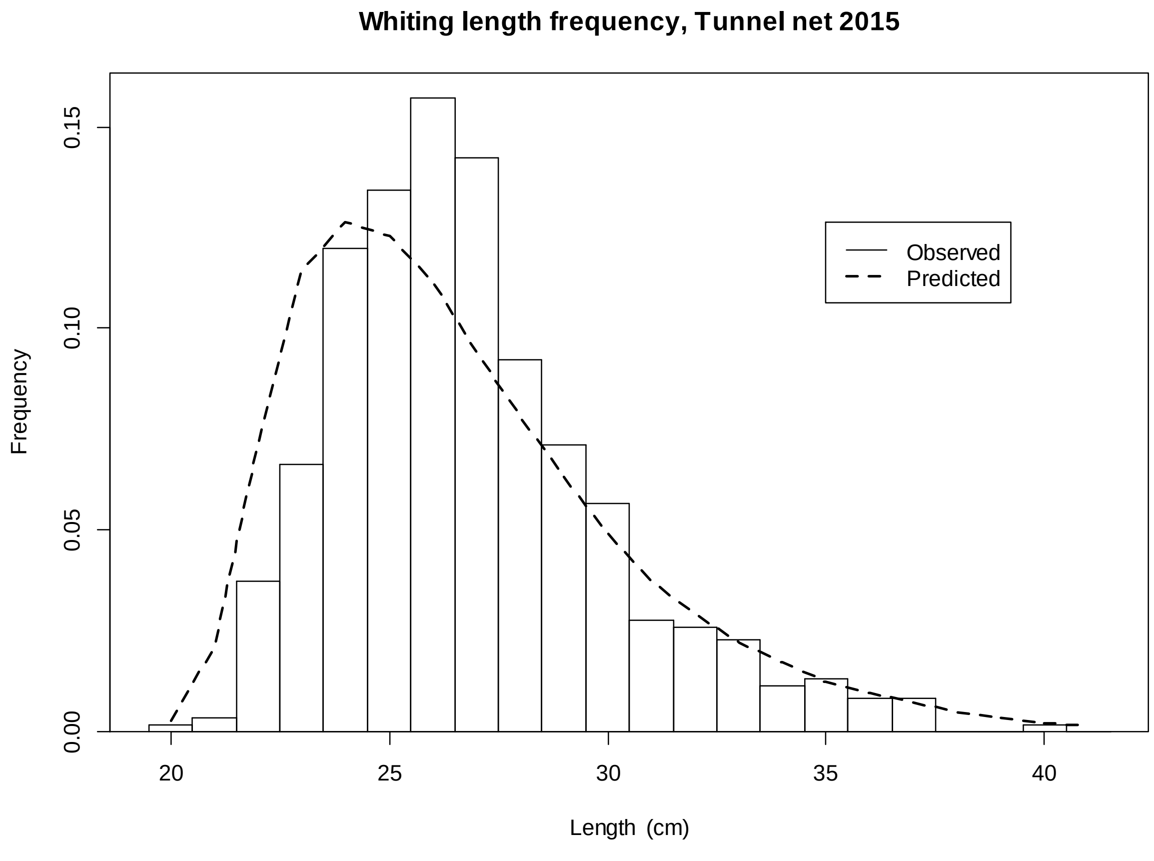

Whiting length frequency, Tunnel net 2010
Frequency
0.00
0.05
0.10
0.15
20
25
30
35
40
Length (cm)
Observed
Predicted

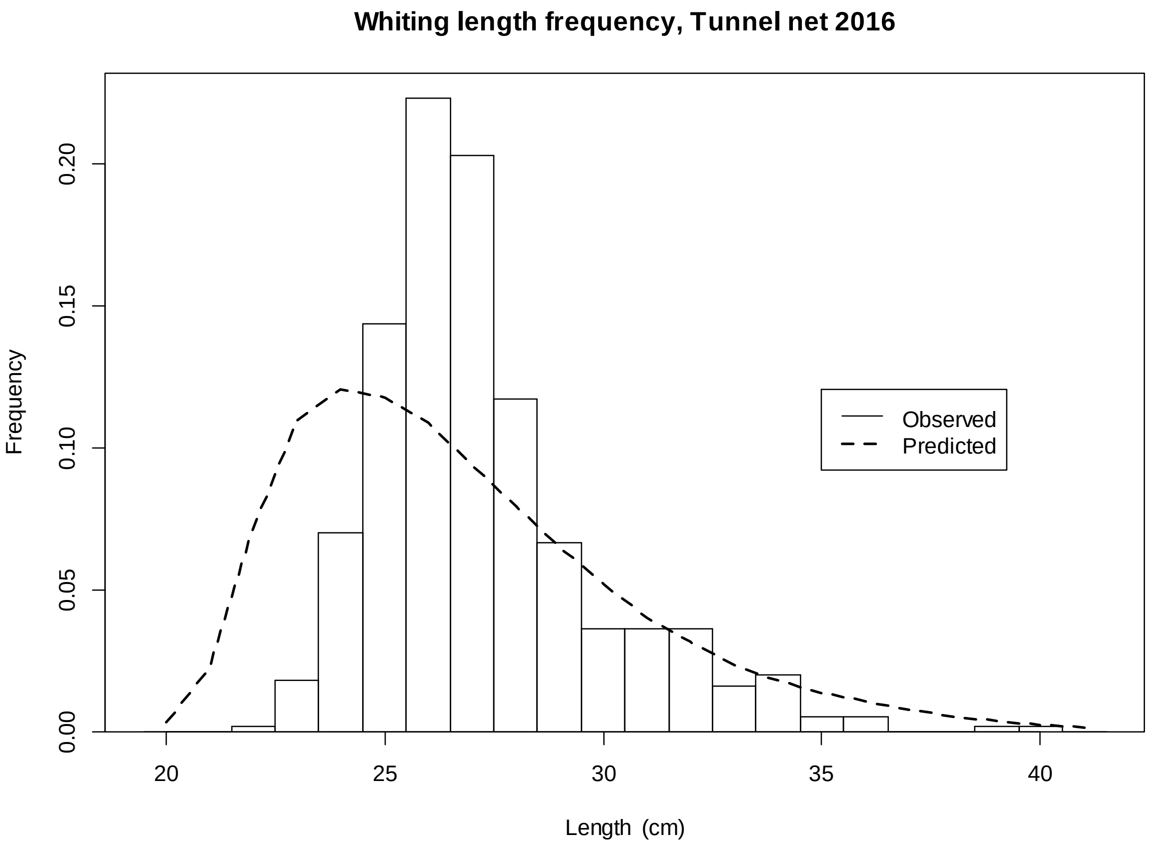

Whiting length frequency, Tunnel net 2011
Frequency
0.00
0.05
0.10
0.15
0.20
20
25
30
35
40
Length (cm)
Observed
Predicted

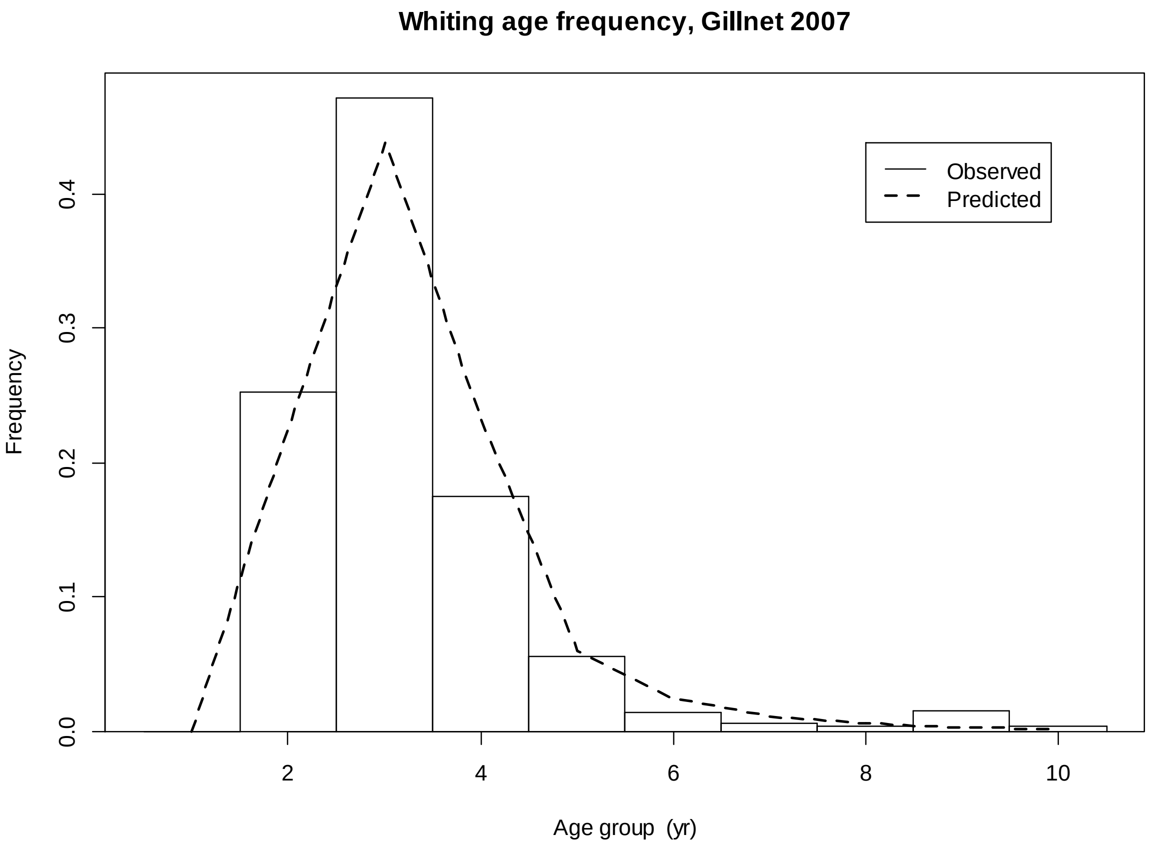

Whiting length frequency, Tunnel net 2012
Frequency
0.00
0.05
0.10
0.15
20
25
30
35
40
Length (cm)
Observed
Predicted

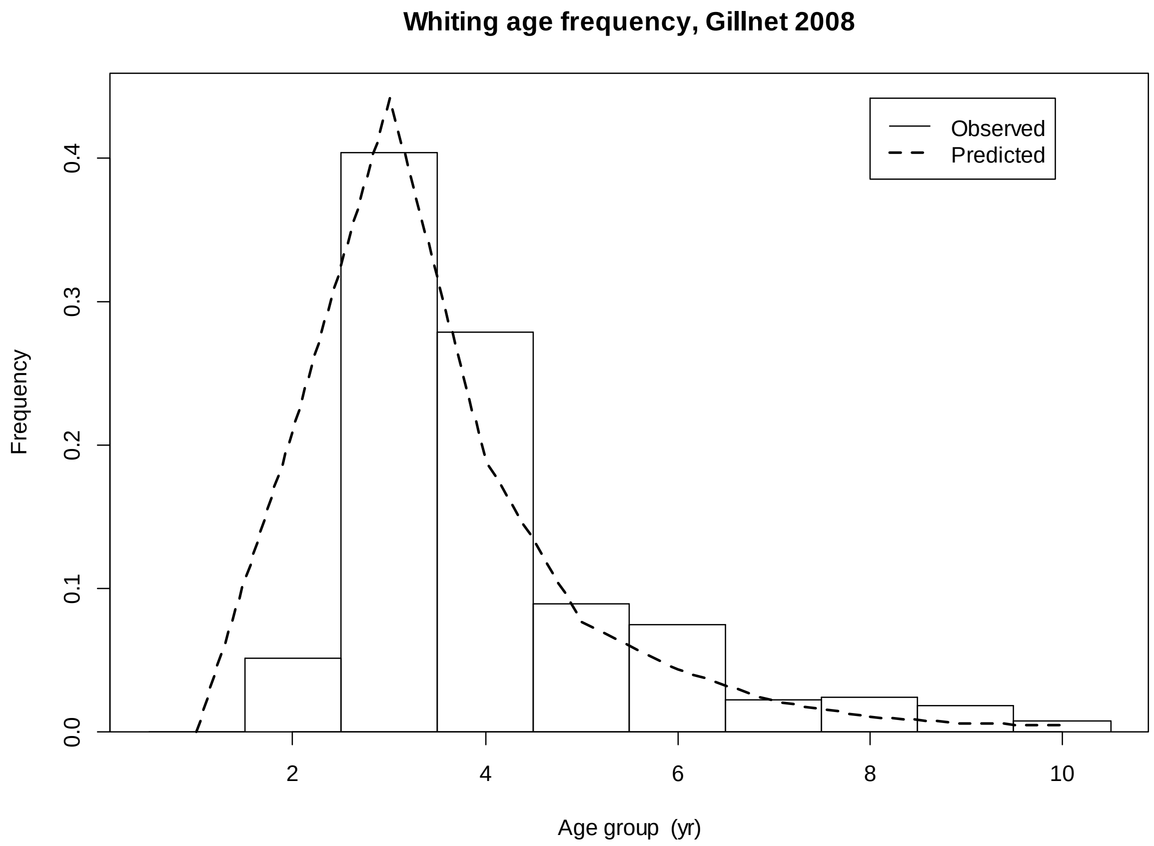

Whiting length frequency, Tunnel net 2013
Frequency
0.00
0.05
0.10
0.15
20
25
30
35
40
Length (cm)
Observed
Predicted

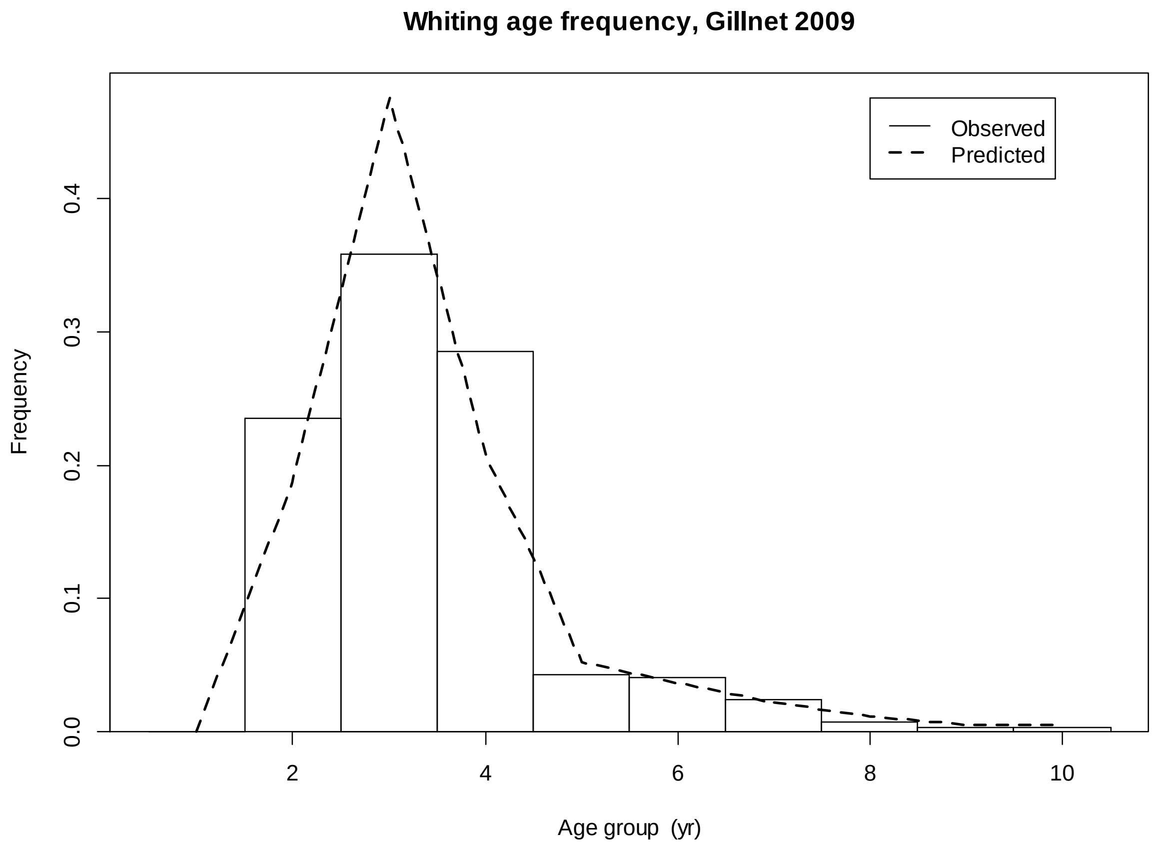

Whiting length frequency, Tunnel net 2014
Frequency
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
20
25
30
35
40
Length (cm)
Observed
Predicted

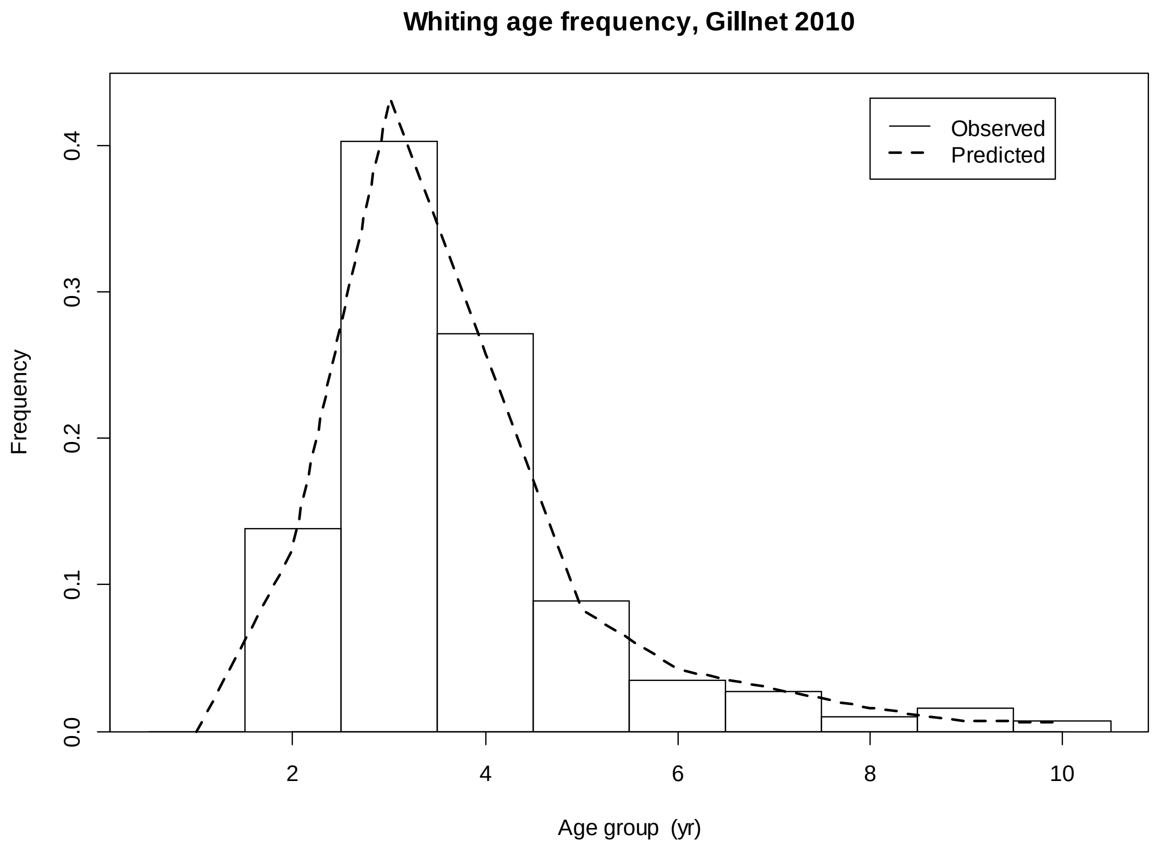

Whiting length frequency, Tunnel net 2015
Frequency
0.00
0.05
0.10
0.15
20
25
30
35
40
Length (cm)
Observed
Predicted


Whiting length frequency, Tunnel net 2016
Frequency
0.00
0.05
0.10
0.15
0.20
20
25
30
35
40
Length (cm)
Observed
Predicted

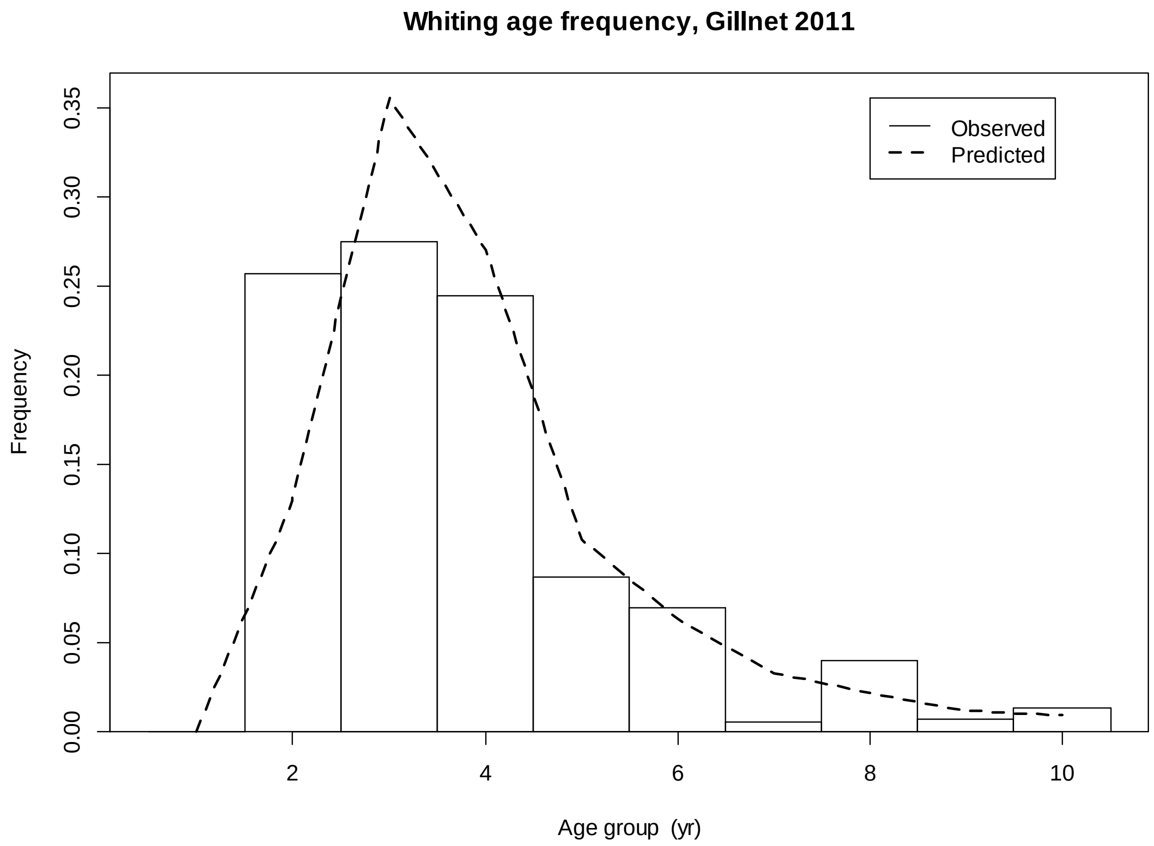

Whiting age frequency, Gillnet 2007
Frequency
0.0
0.1
0.2
0.3
0.4
2
4
6
8
10
Age group (yr)
Observed
Predicted


Whiting age frequency, Gillnet 2008
Observed
Predicted
Frequency
0.0
0.1
0.2
0.3
0.4
2
4
6
8
10
Age group (yr)

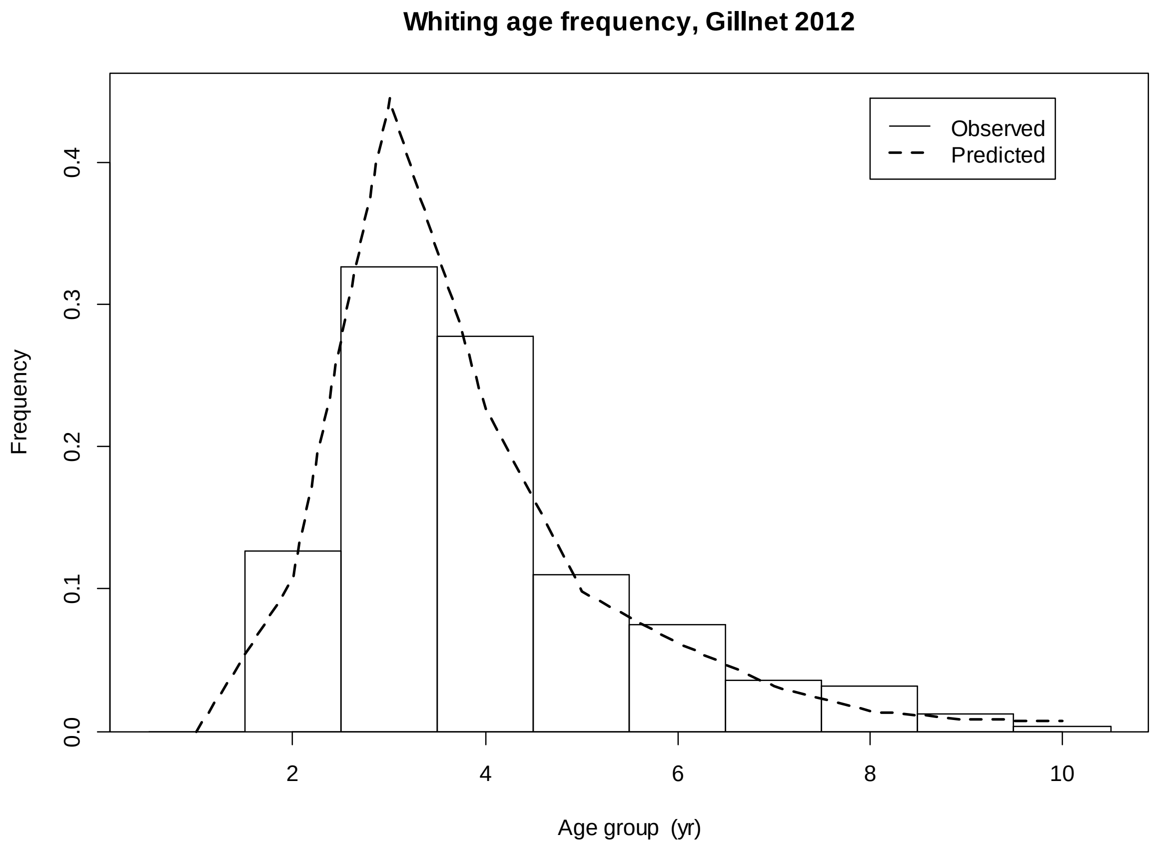

Whiting age frequency, Gillnet 2009
Observed
Predicted
Frequency
0.0
0.1
0.2
0.3
0.4
2
4
6
8
10
Age group (yr)

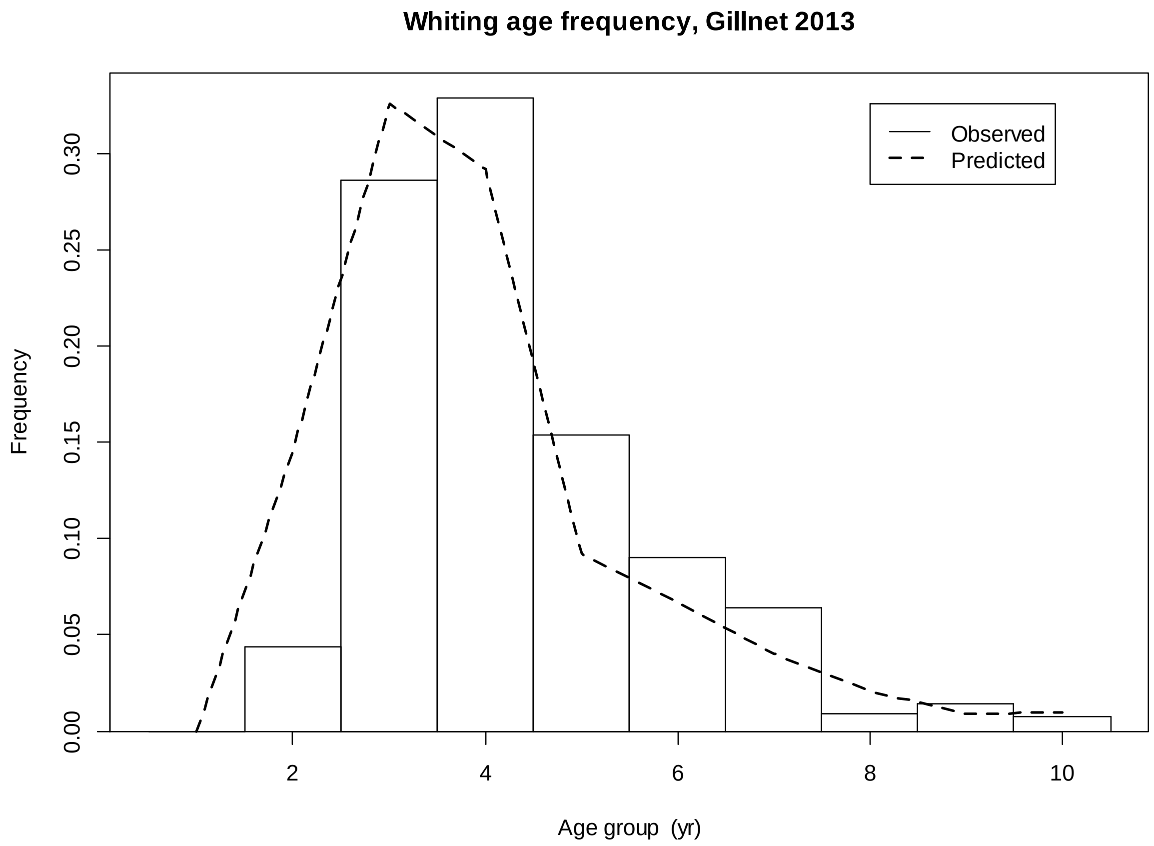


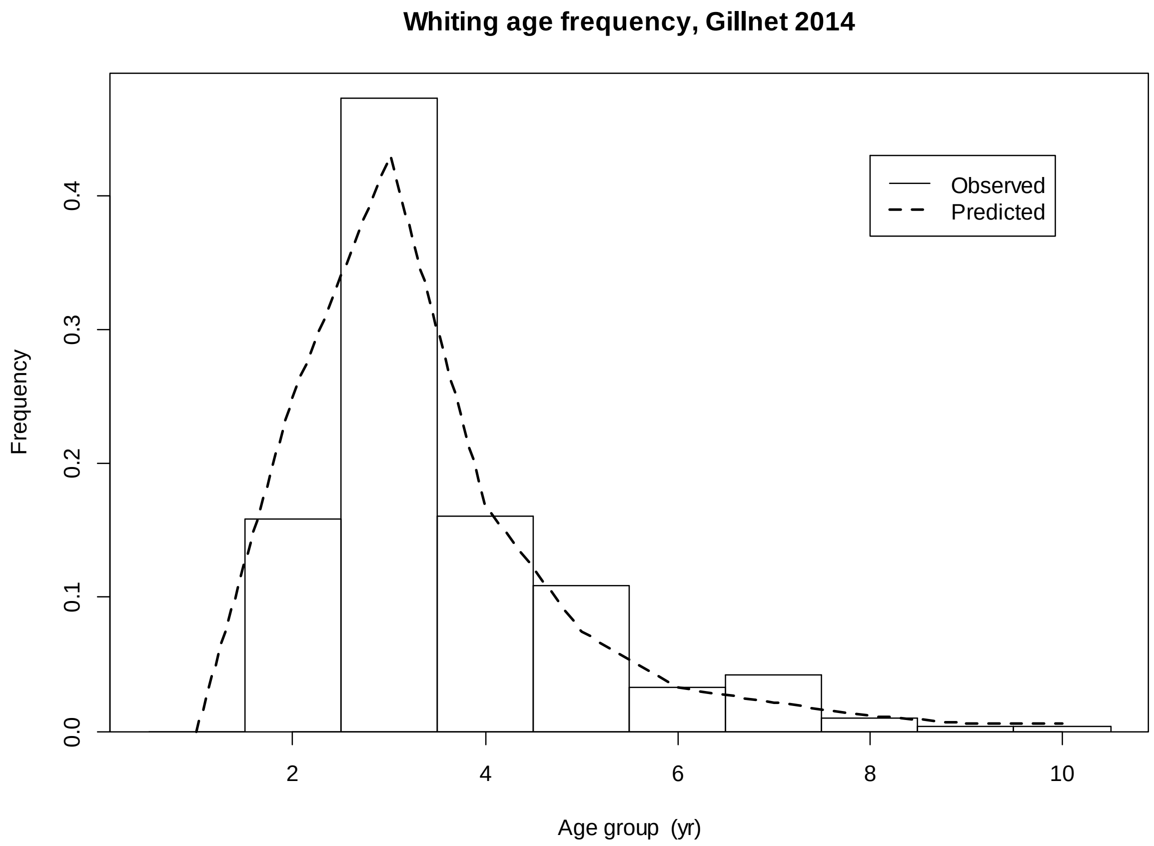
Whiting age frequency, Gillnet 2010

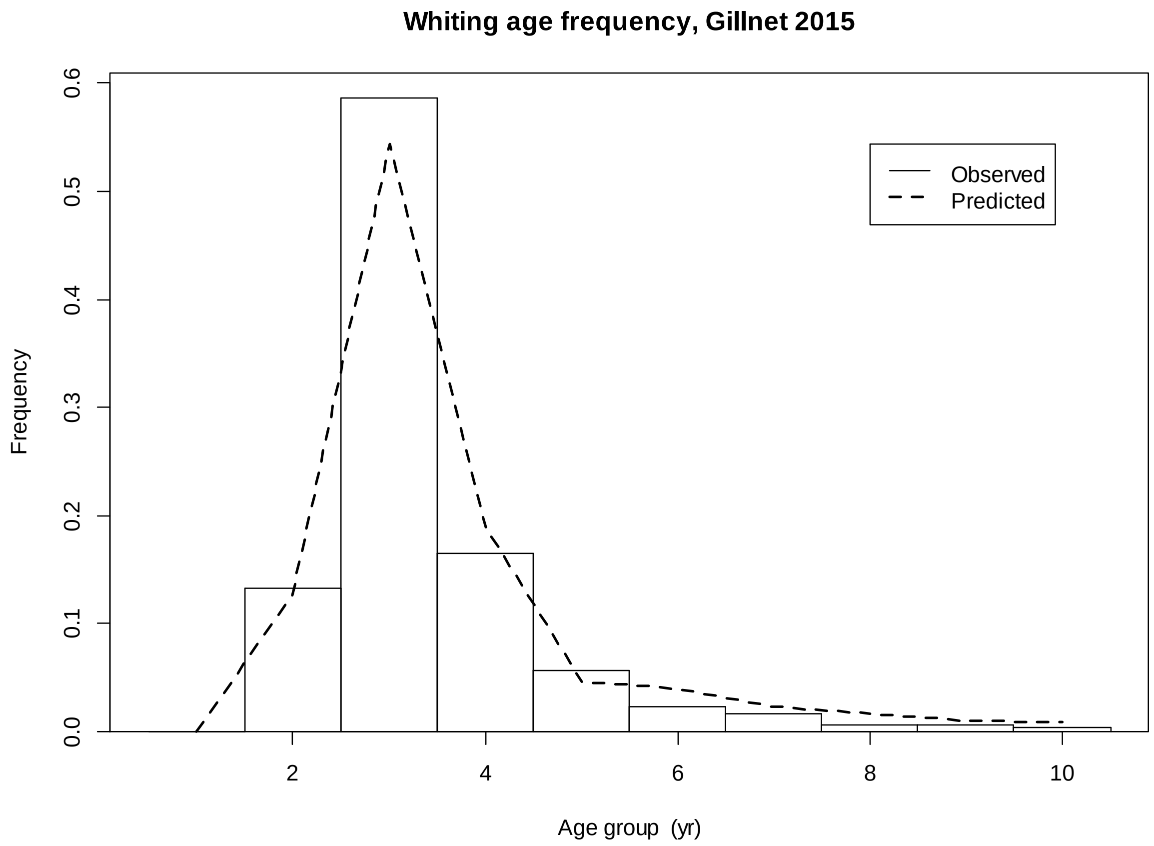


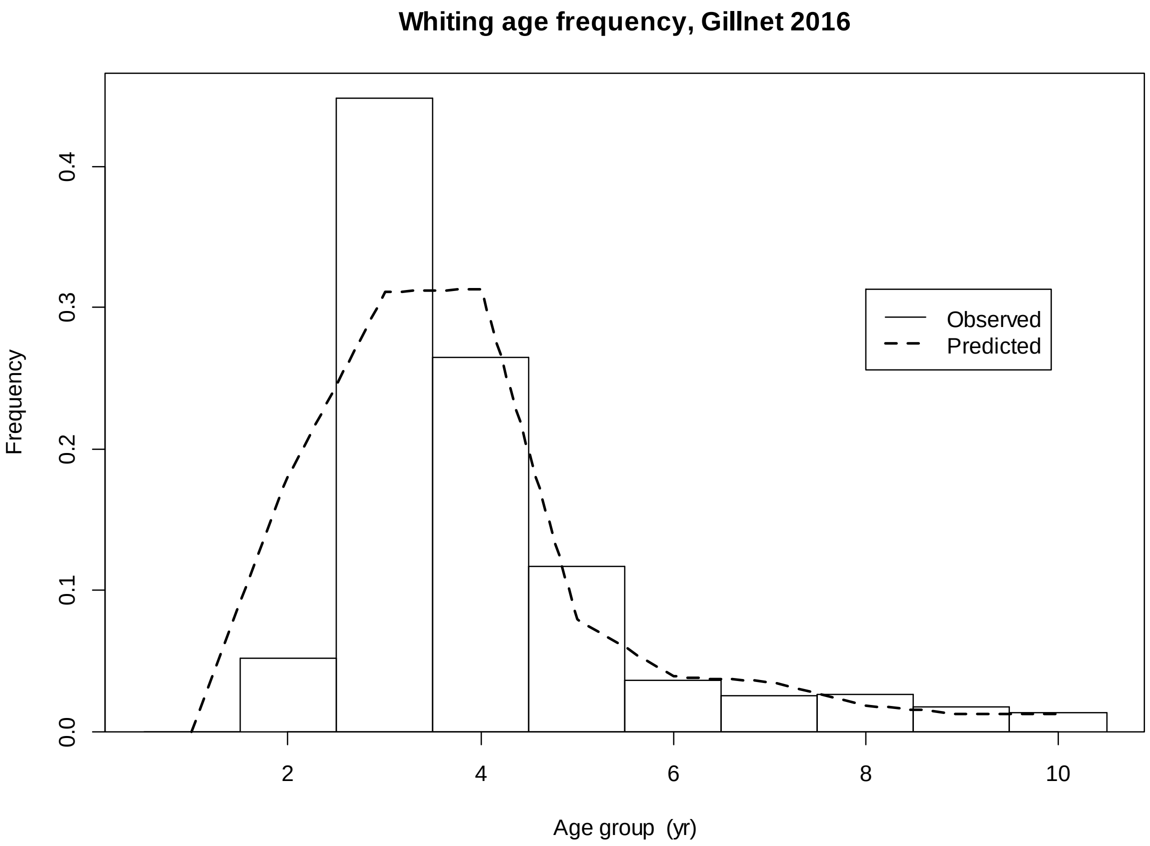
Whiting age frequency, Gillnet 2011


Whiting age frequency, Gillnet 2012
Observed
Predicted
Frequency
0.0
0.1
0.2
0.3
0.4
2
4
6
8
10
Age group (yr)

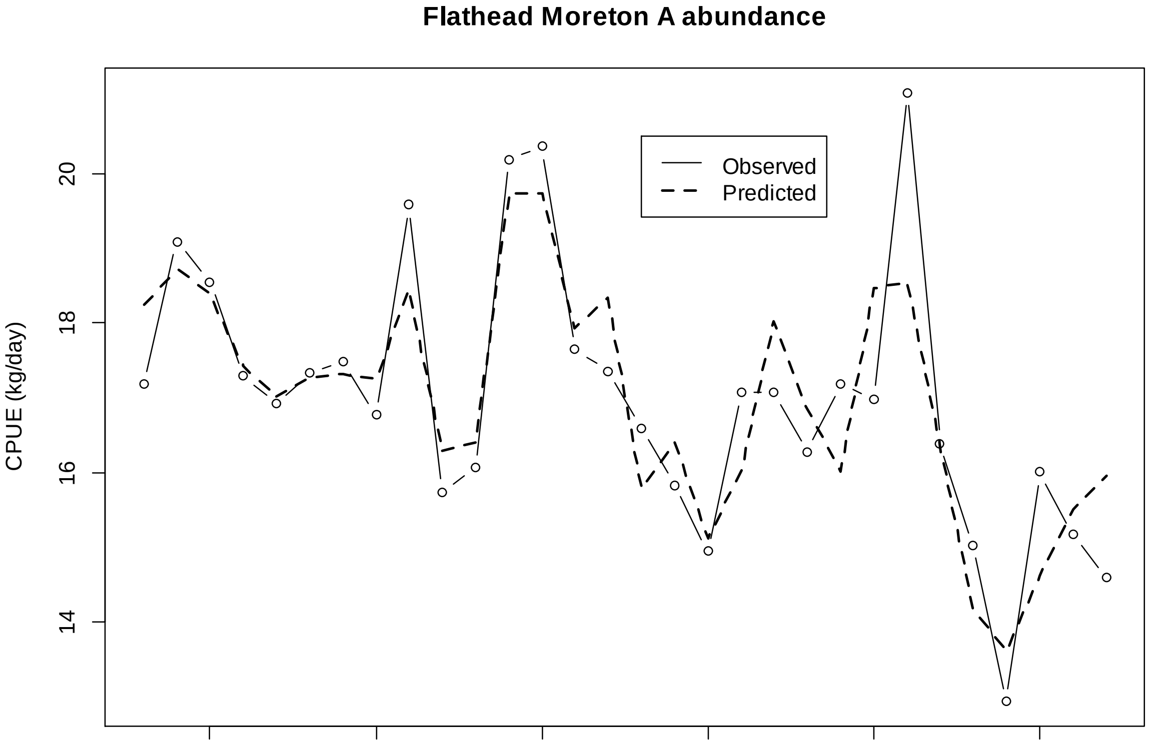

Whiting age frequency, Gillnet 2013
Observed
Predicted
Frequency
0.00
0.05
0.10
0.15
0.20
0.25
0.30
2
4
6
8
10
Age group (yr)


Whiting age frequency, Gillnet 2014
Frequency
0.0
0.1
0.2
0.3
0.4
2
4
6
8
10
Age group (yr)
Observed
Predicted

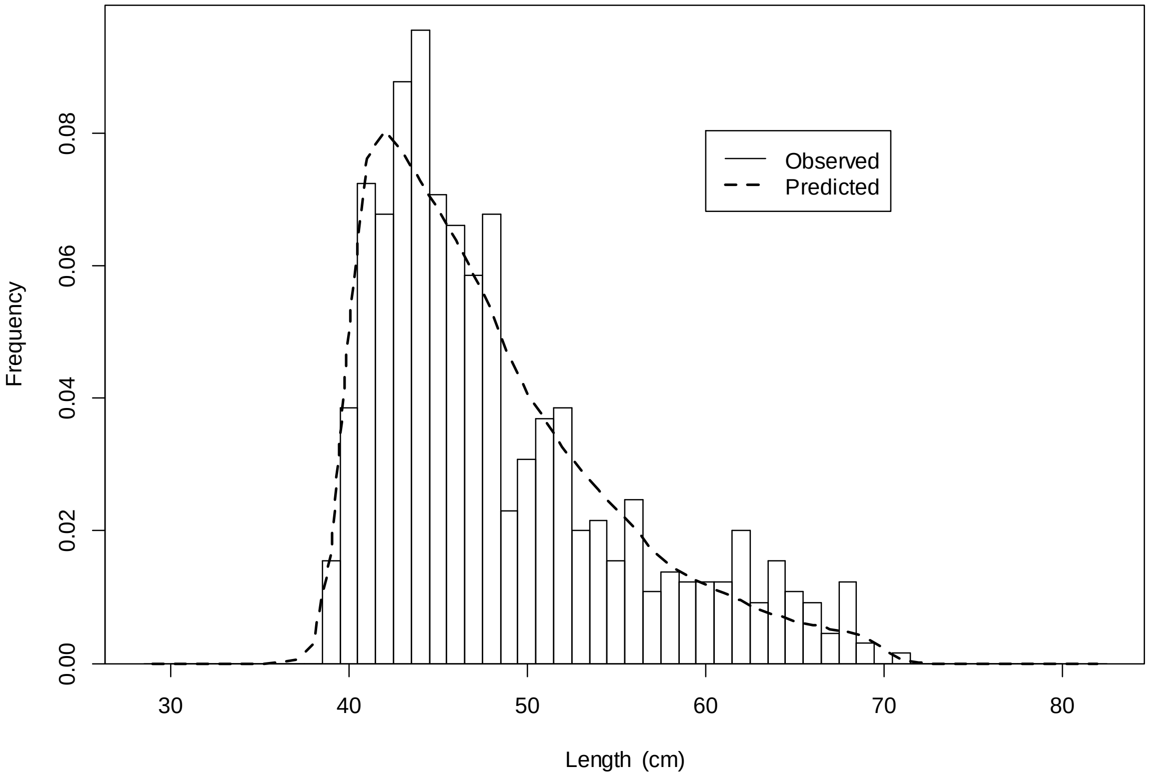

Whiting age frequency, Gillnet 2015
Frequency
0.0
0.1
0.2
0.3
0.4
0.5
0.6
2
4
6
8
10
Age group (yr)
Observed
Predicted



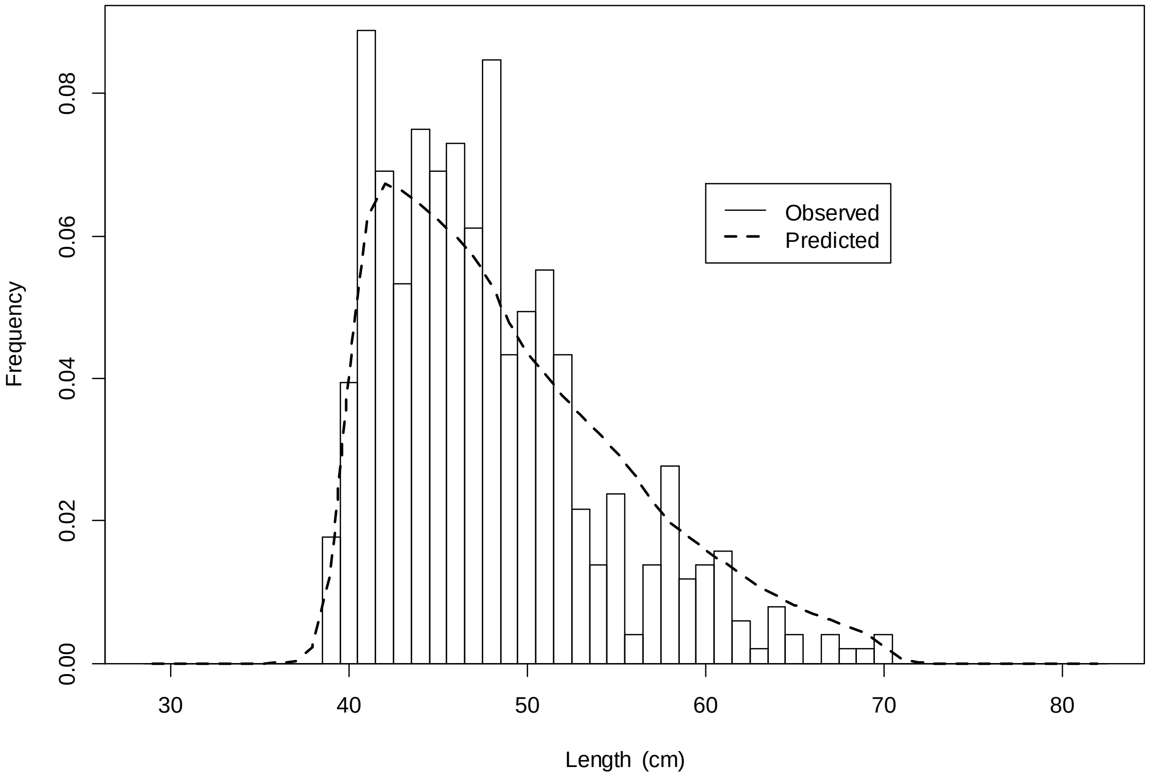
A2.3 Flathead Moreton A: *r* = 8, *M* = 0.7 yr $^{-1}$

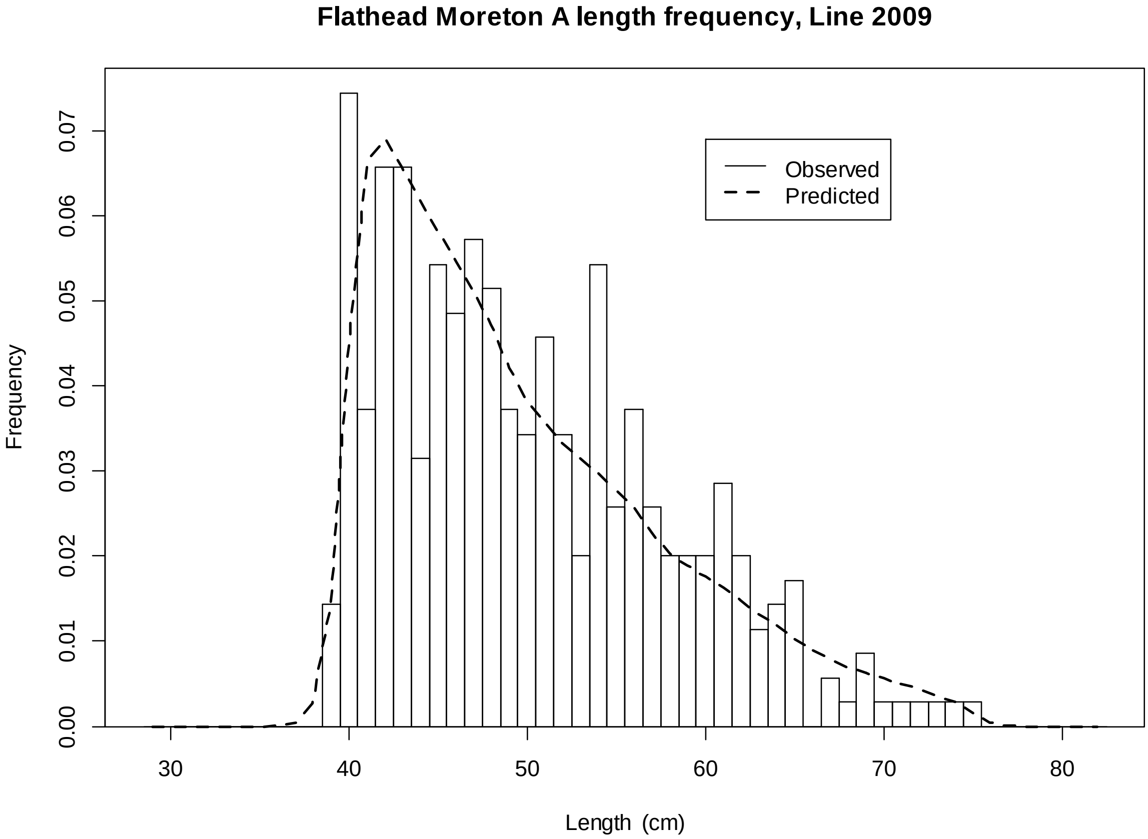


Flathead Moreton A length frequency, Line 2007

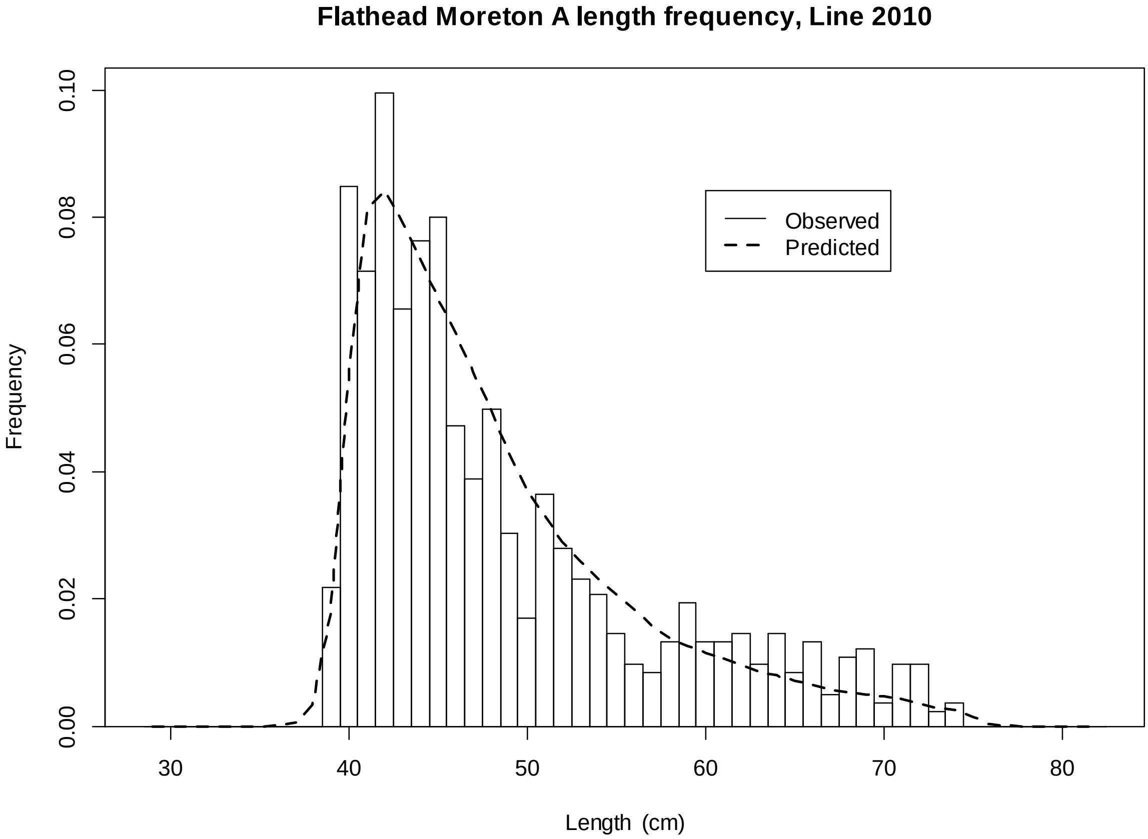


Flathead Moreton A length frequency, Line 2008

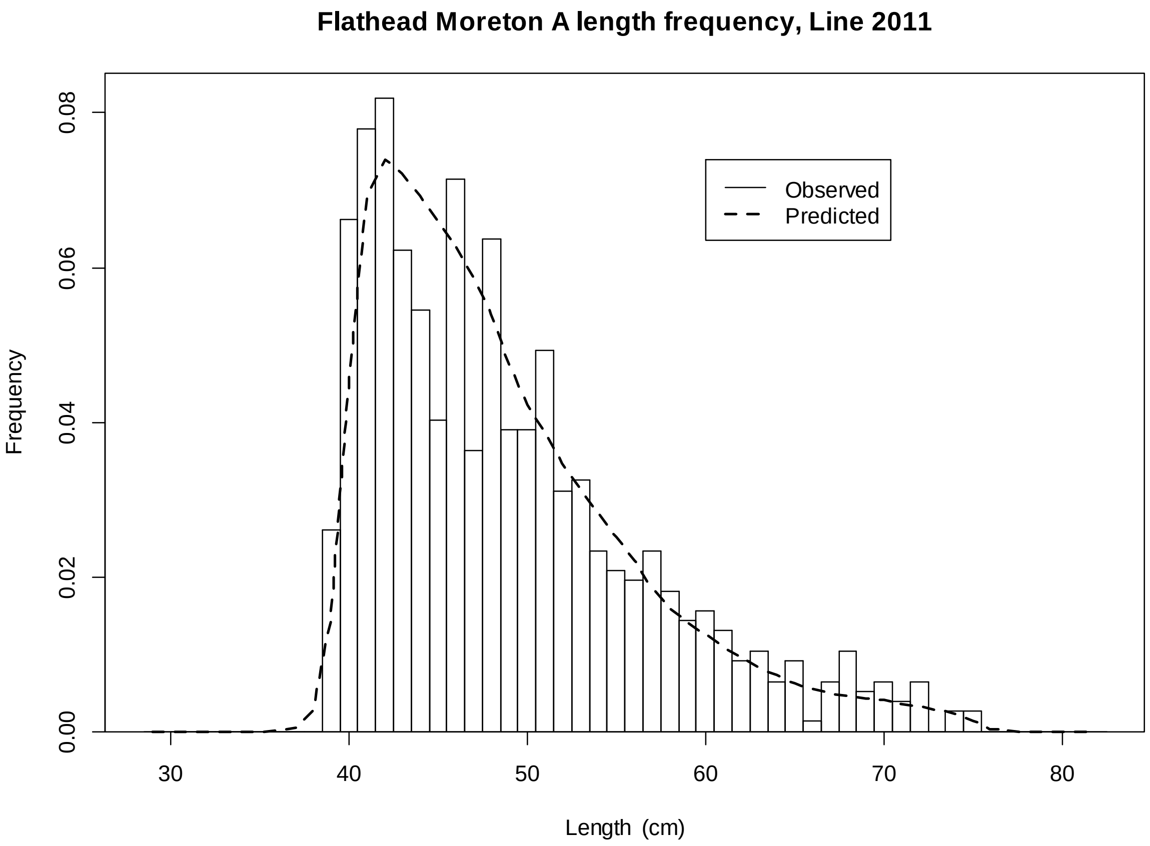


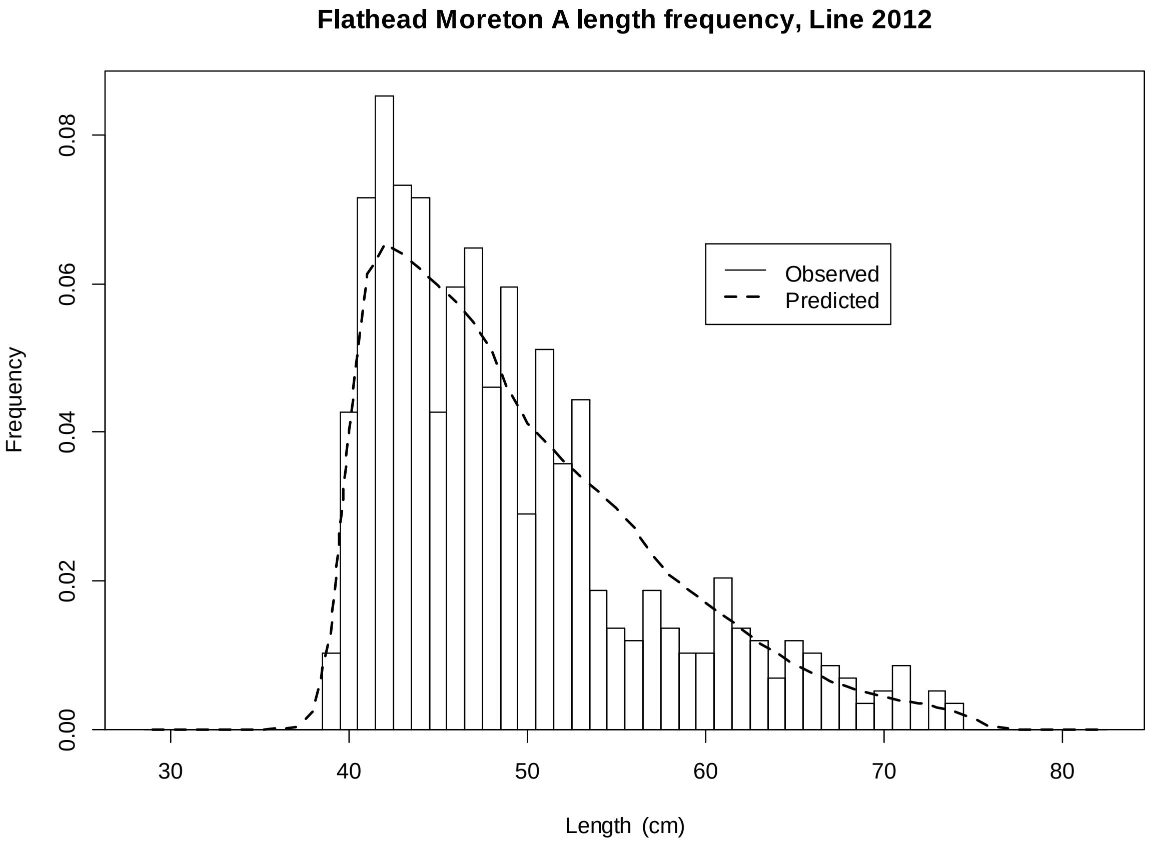


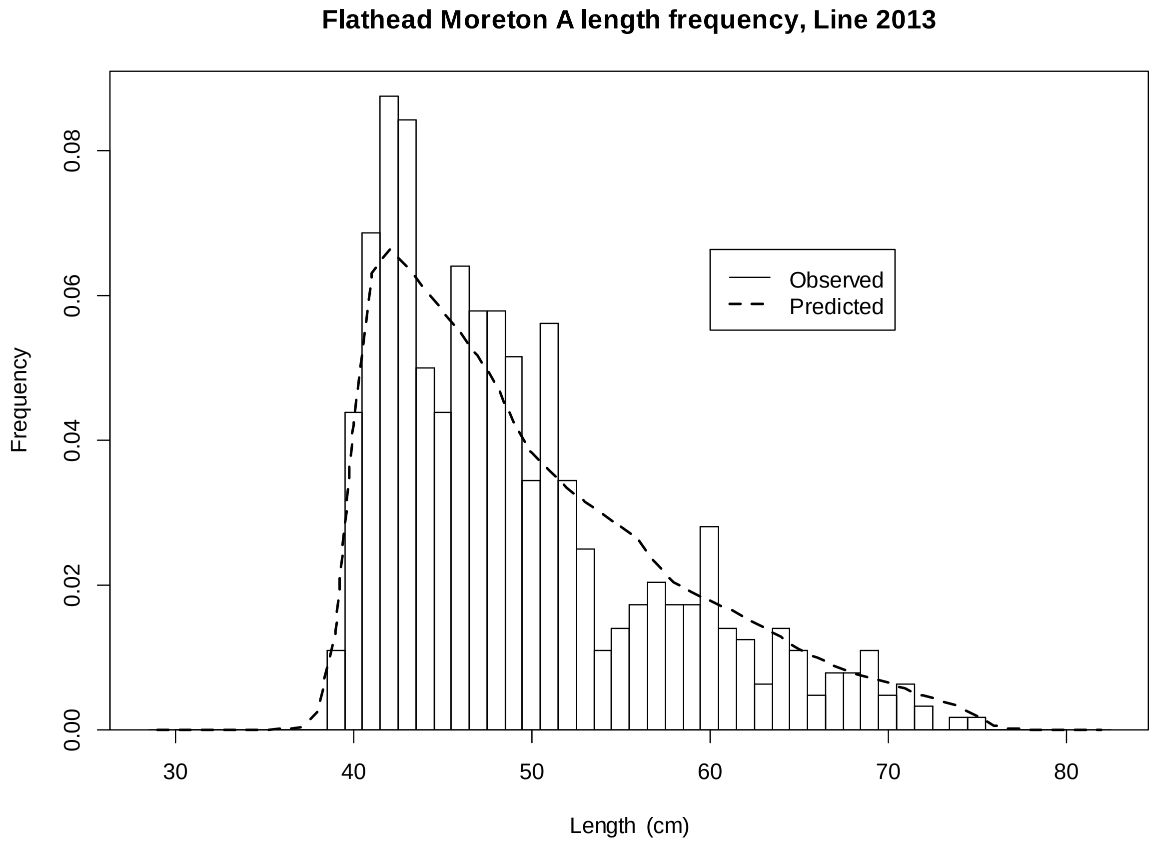
Flathead Moreton A length frequency, Line 2009

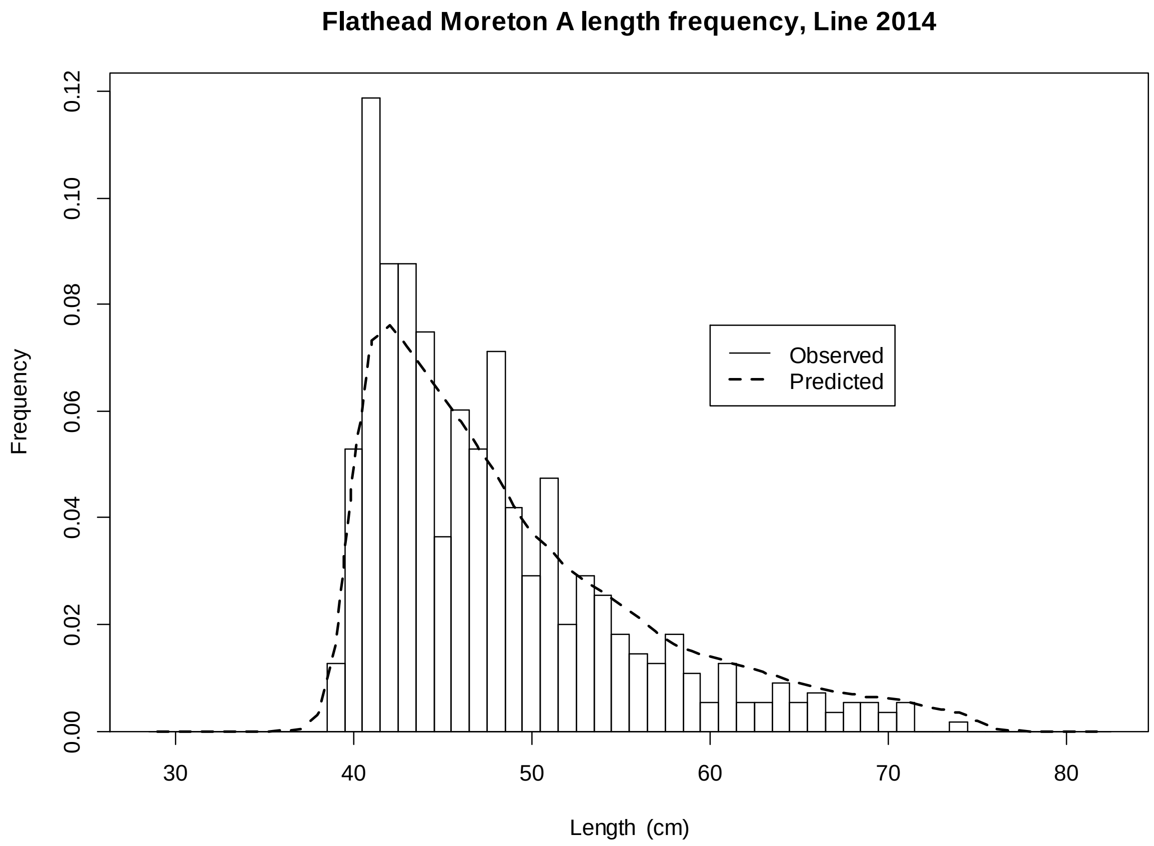


Flathead Moreton A length frequency, Line 2010

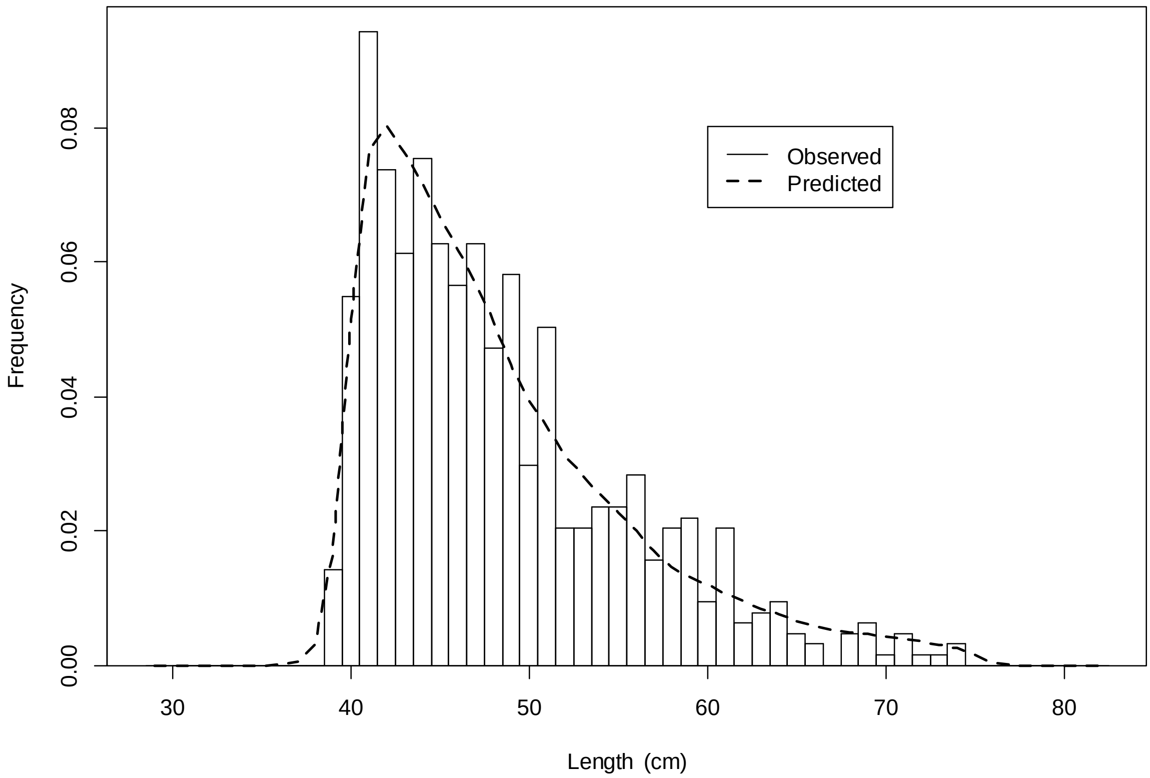

Flathead Moreton A length frequency, Line 2011
Frequency
0.00
0.02
0.04
0.06
0.08
30
40
50
60
70
80
Length (cm)
Observed
Predicted


Flathead Moreton A length frequency, Line 2012
Frequency
0.00
0.02
0.04
0.06
0.08
30
40
50
60
70
80
Length (cm)
Observed
Predicted

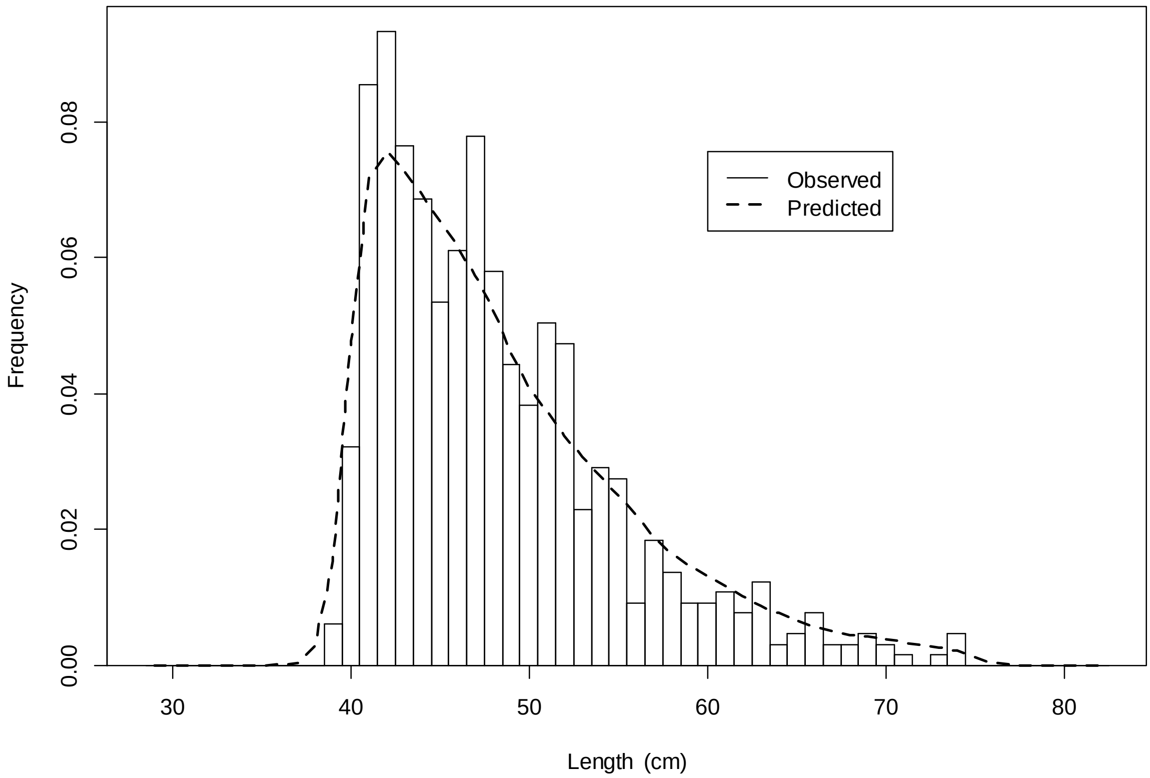

Flathead Moreton A length frequency, Line 2013
Frequency
0.00
0.02
0.04
0.06
0.08
Length (cm)
30
40
50
60
70
80
Observed
Predicted


Flathead Moreton A length frequency, Line 2014
Frequency
0.00
0.02
0.04
0.06
0.08
0.10
0.12
Length (cm)
30
40
50
60
70
80
Observed
Predicted

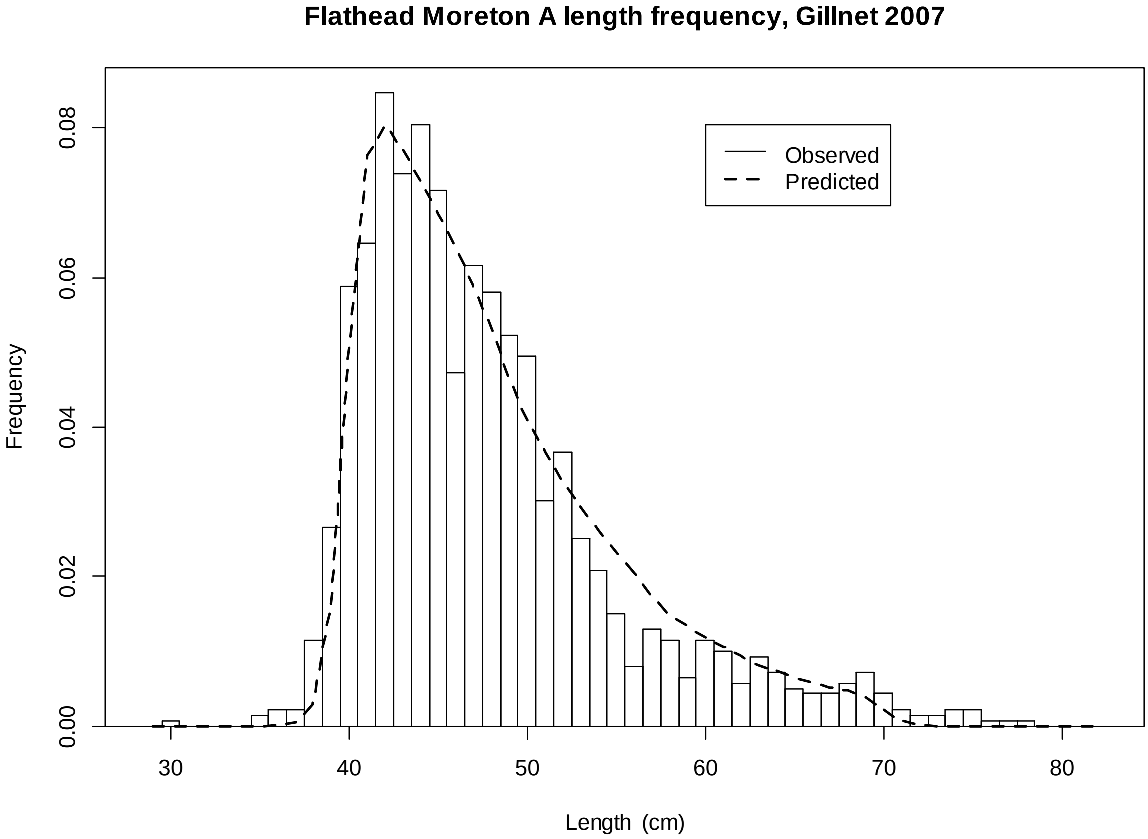
Flathead Moreton A length frequency, Line 2015

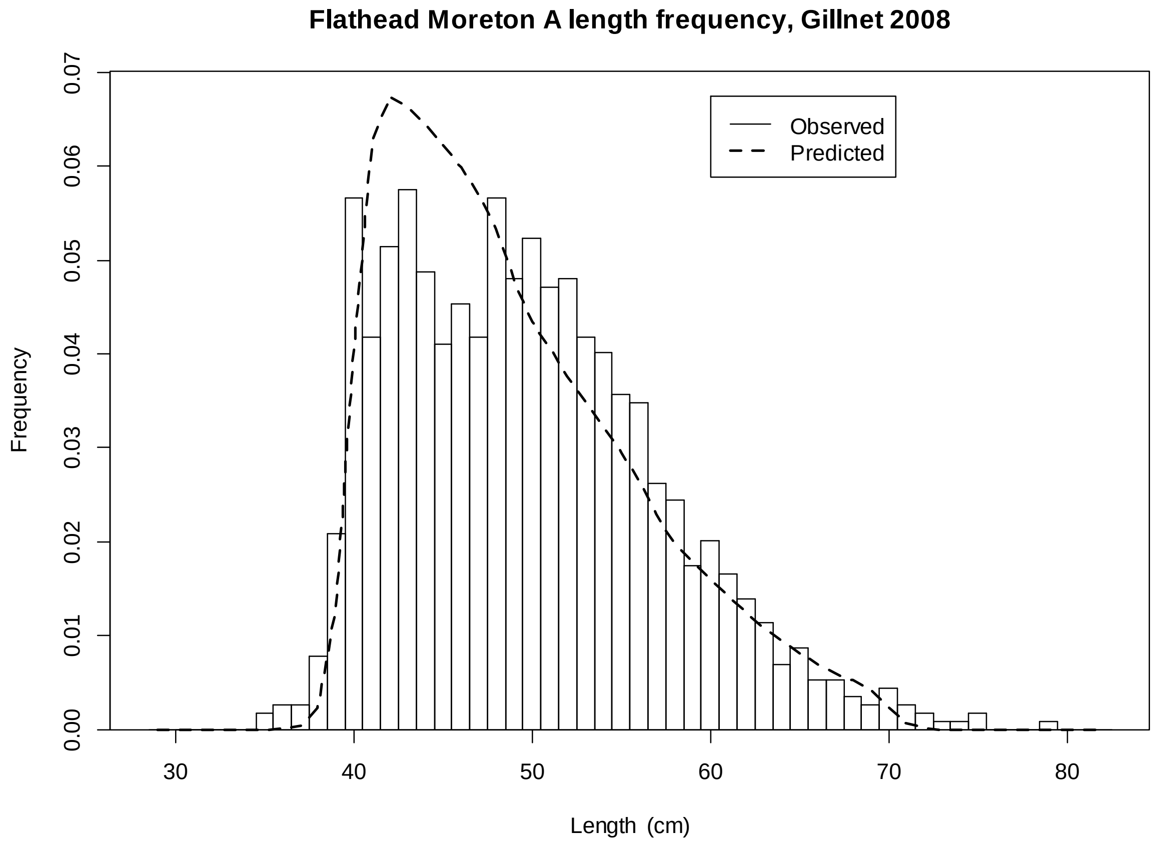


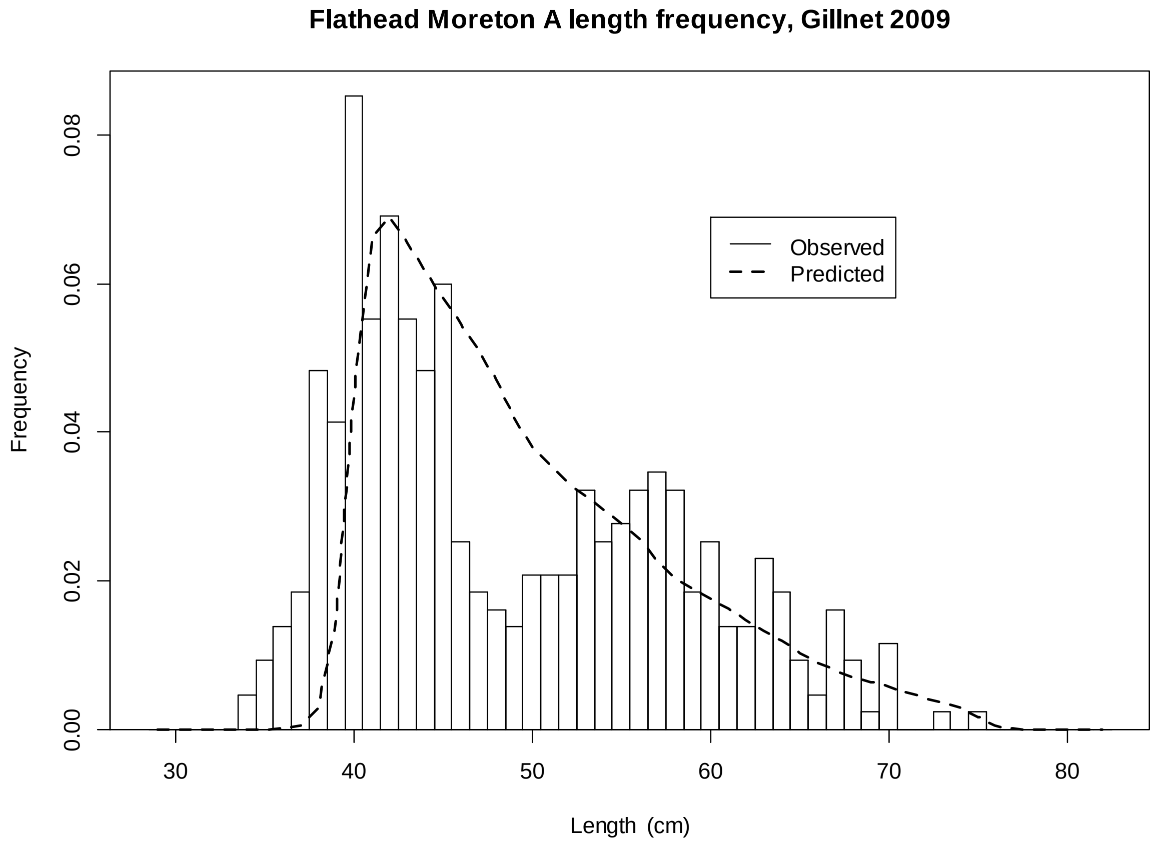
Flathead Moreton A length frequency, Line 2016

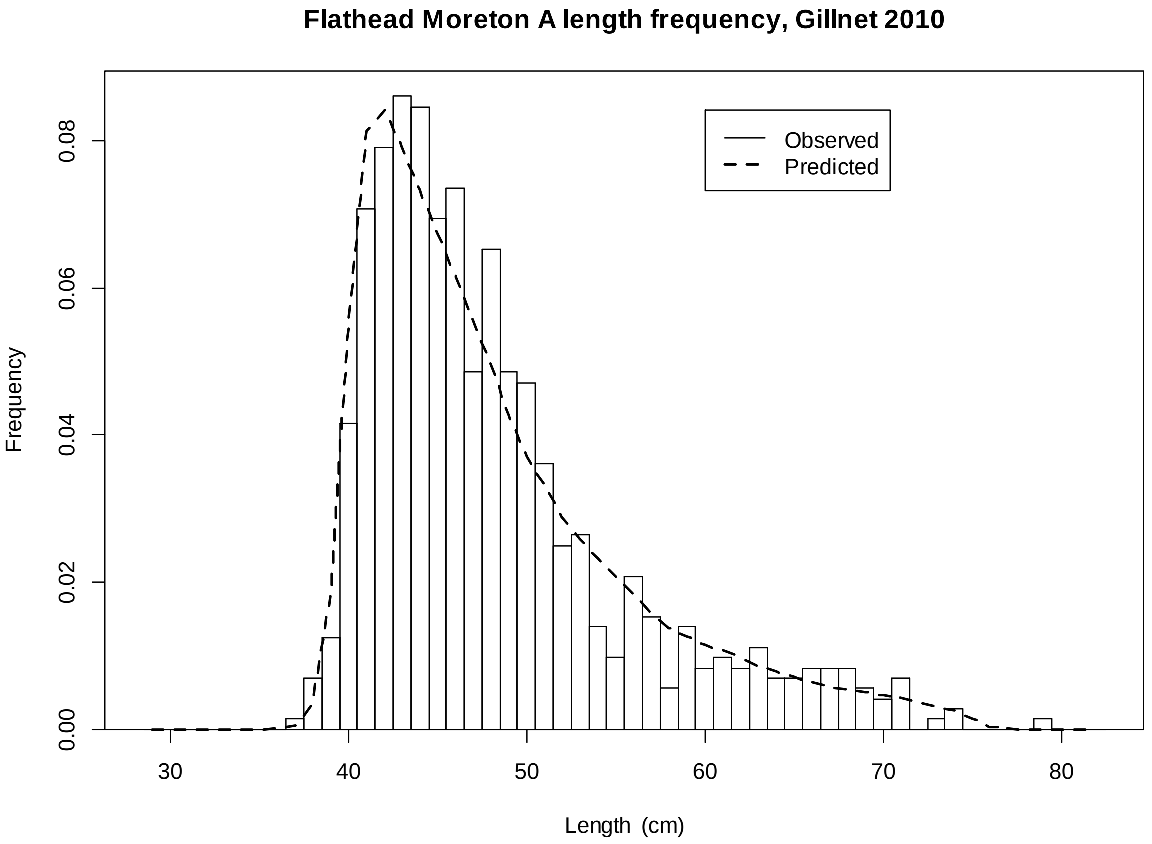


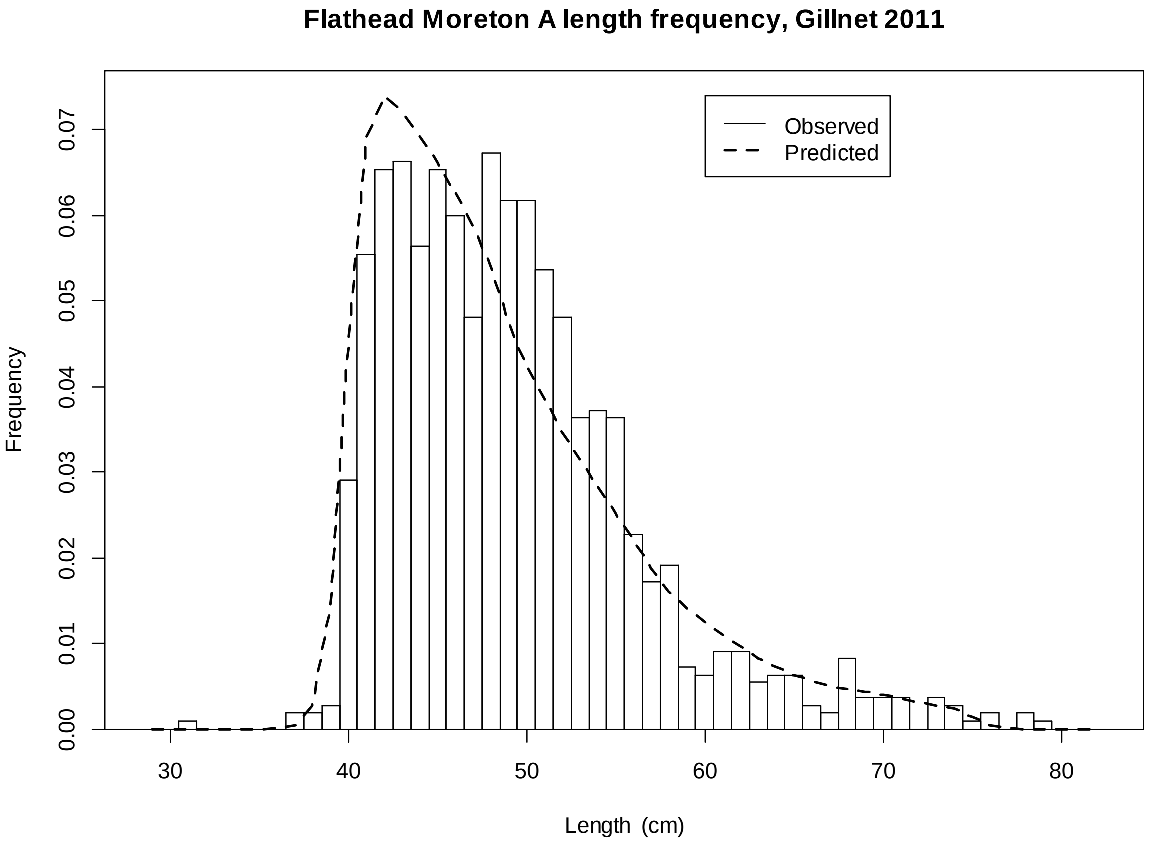

Flathead Moreton A length frequency, Gillnet 2006
Observed
Predicted
Frequency
0.00
0.02
0.04
0.06
0.08
30
40
50
60
70
80
Length (cm)

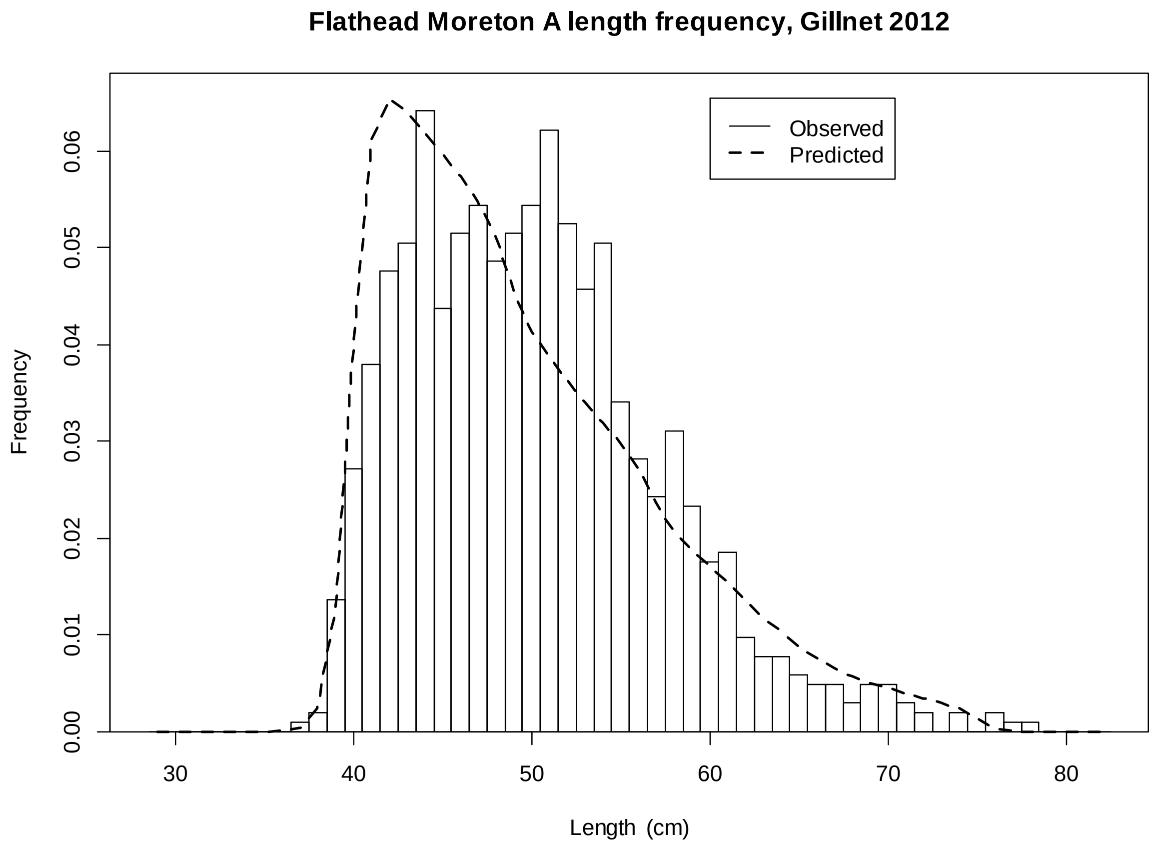

Flathead Moreton A length frequency, Gillnet 2007
Observed
Predicted
Frequency
0.00
0.02
0.04
0.06
0.08
30
40
50
60
70
80
Length (cm)

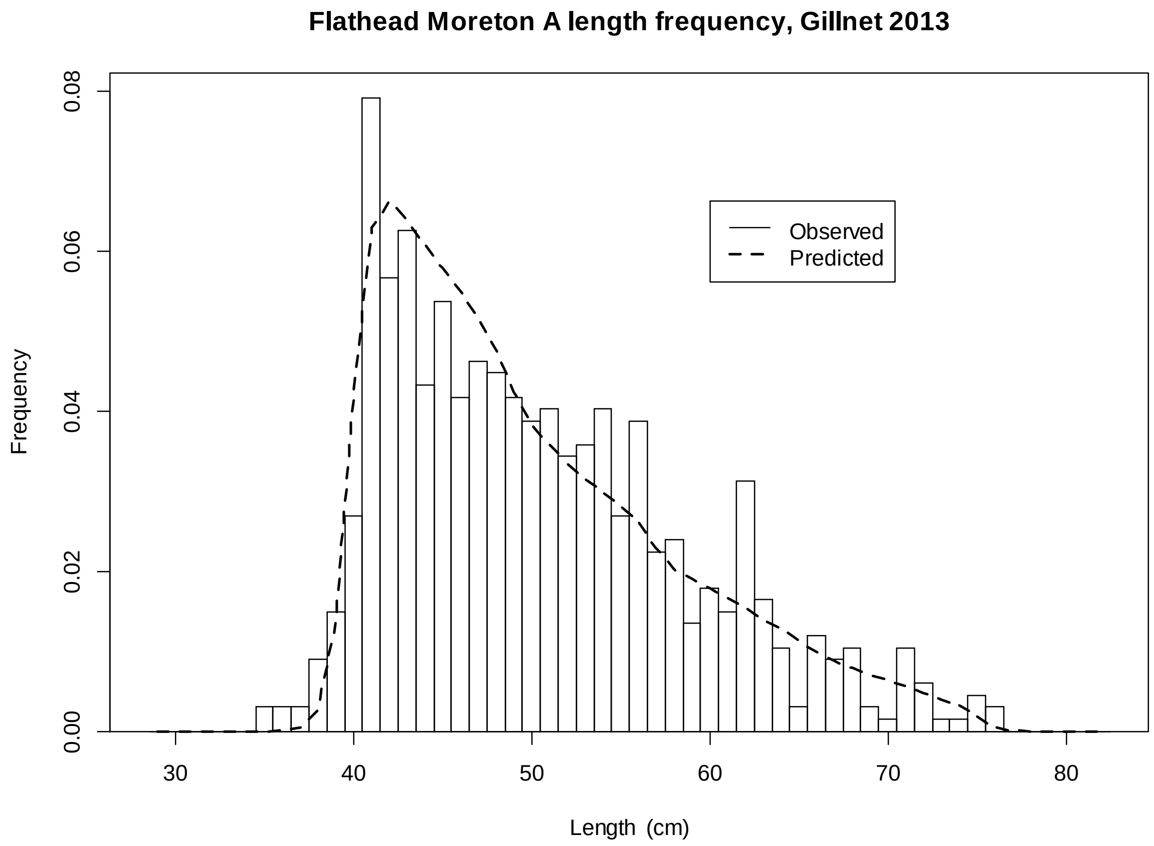

Flathead Moreton A length frequency, Gillnet 2008


Flathead Moreton A length frequency, Gillnet 2009

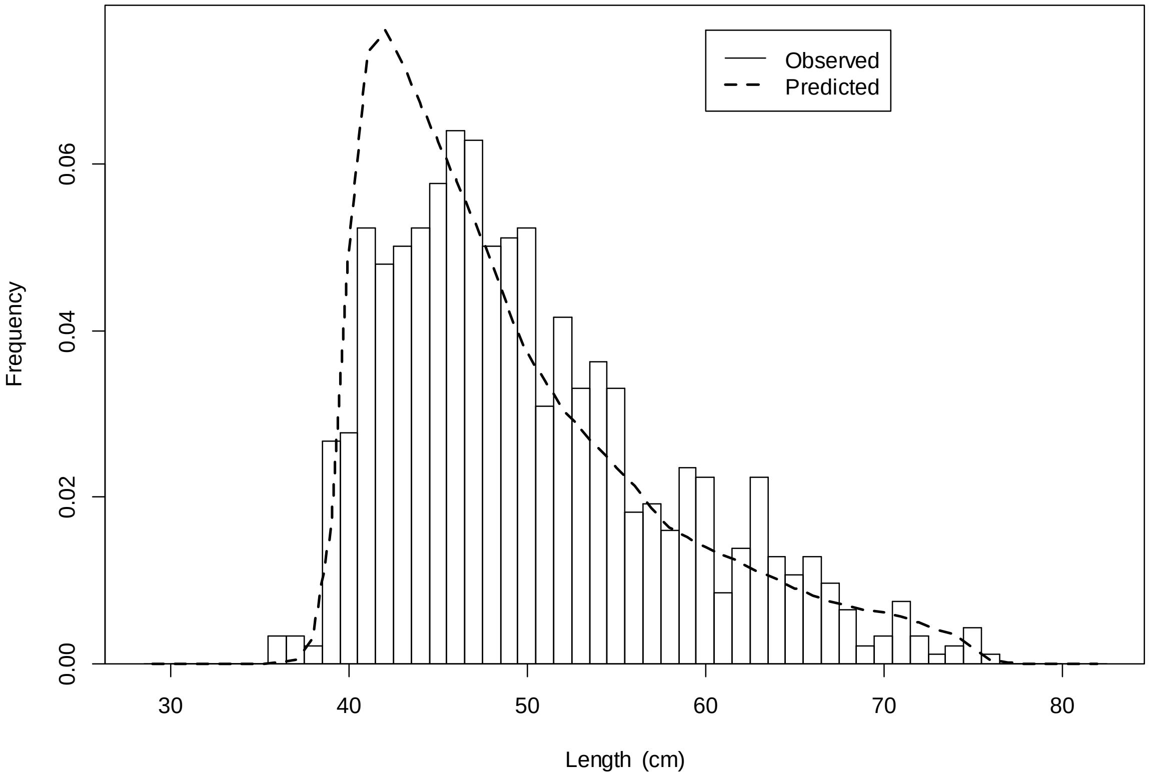

Flathead Moreton A length frequency, Gillnet 2010


Flathead Moreton A length frequency, Gillnet 2011

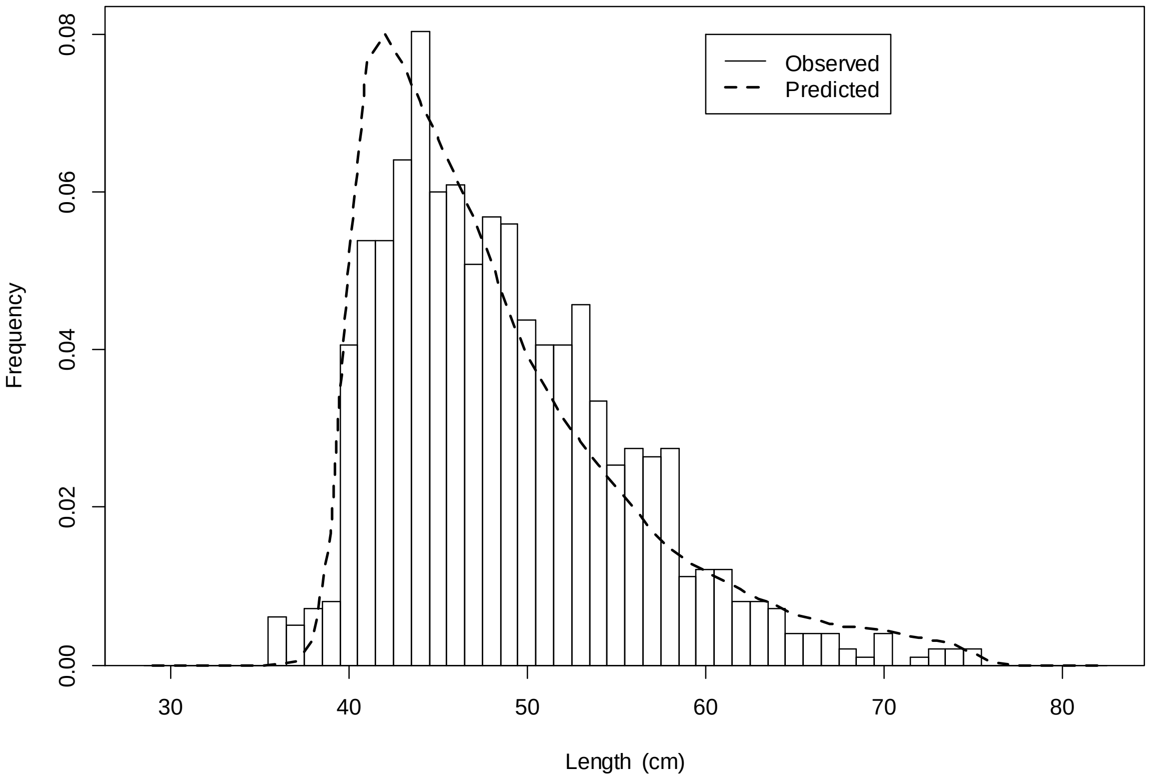

Flathead Moreton A length frequency, Gillnet 2012
Observed
Predicted
Frequency
0.00
0.01
0.02
0.03
0.04
0.05
0.06
30
40
50
60
70
80
Length (cm)

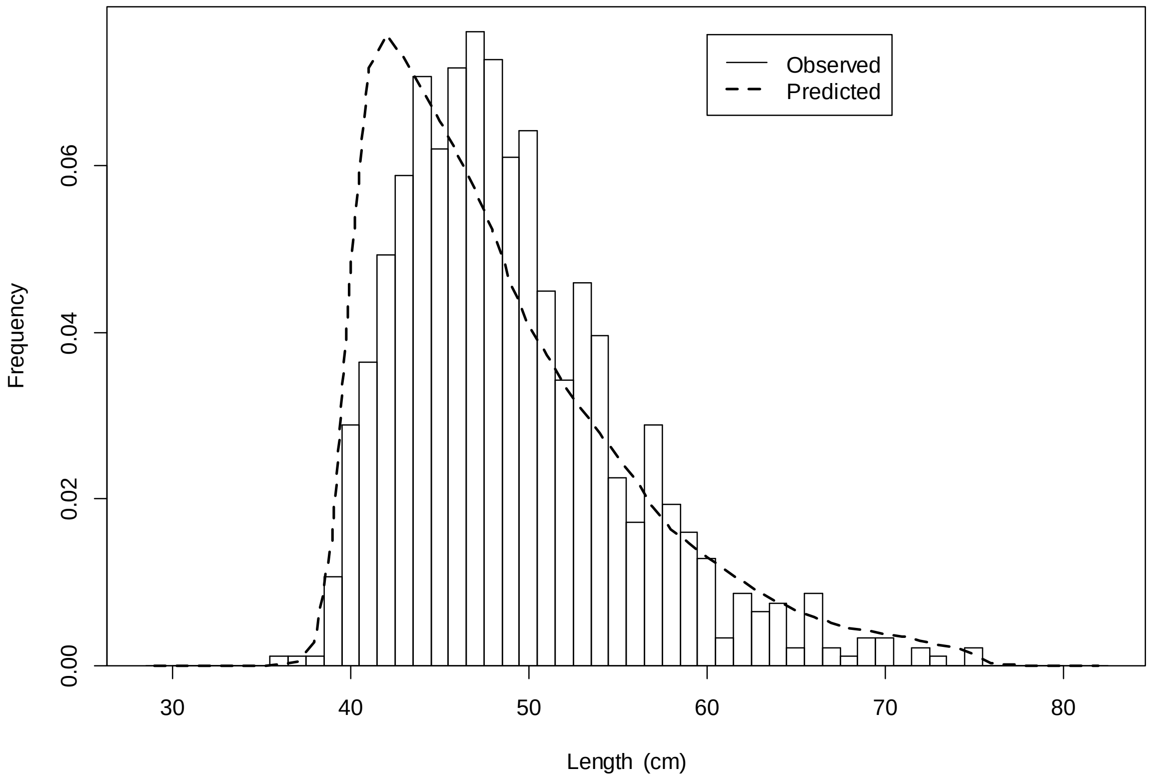

Flathead Moreton A length frequency, Gillnet 2013
Observed
Predicted
Frequency
0.00
0.02
0.04
0.06
0.08
30
40
50
60
70
80
Length (cm)

Flathead Moreton A length frequency, Gillnet 2014

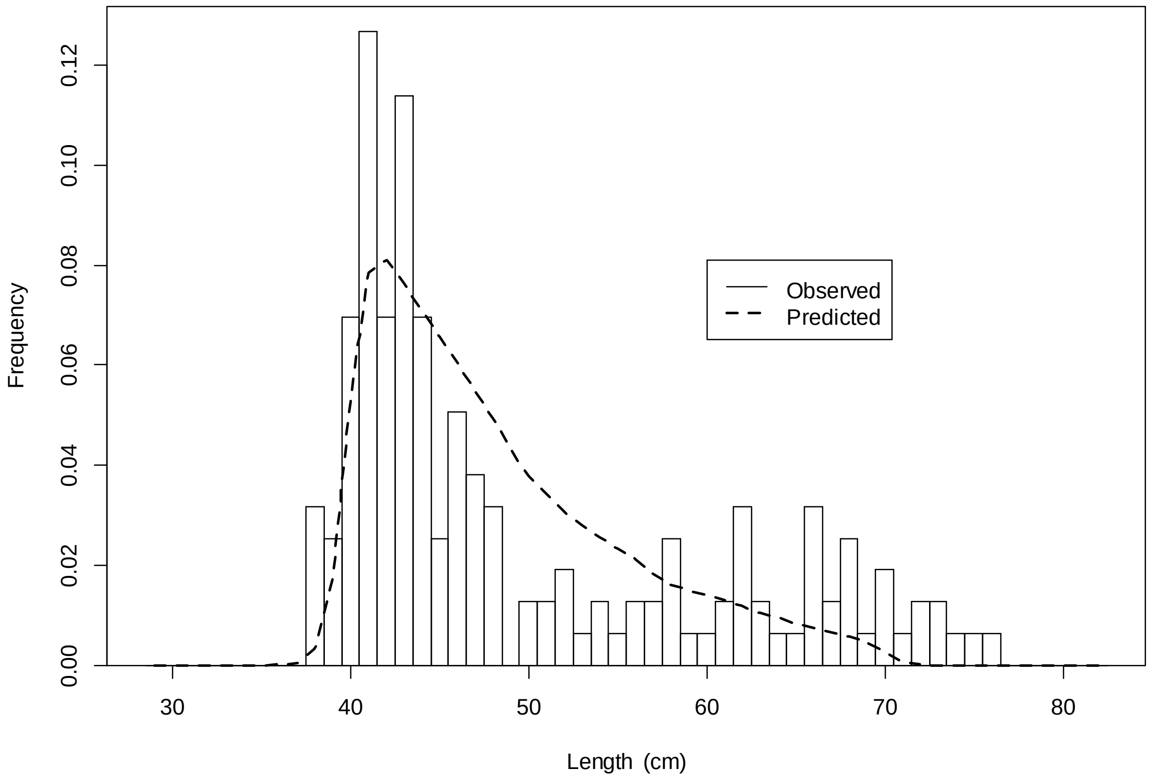


Flathead Moreton A length frequency, Gillnet 2015

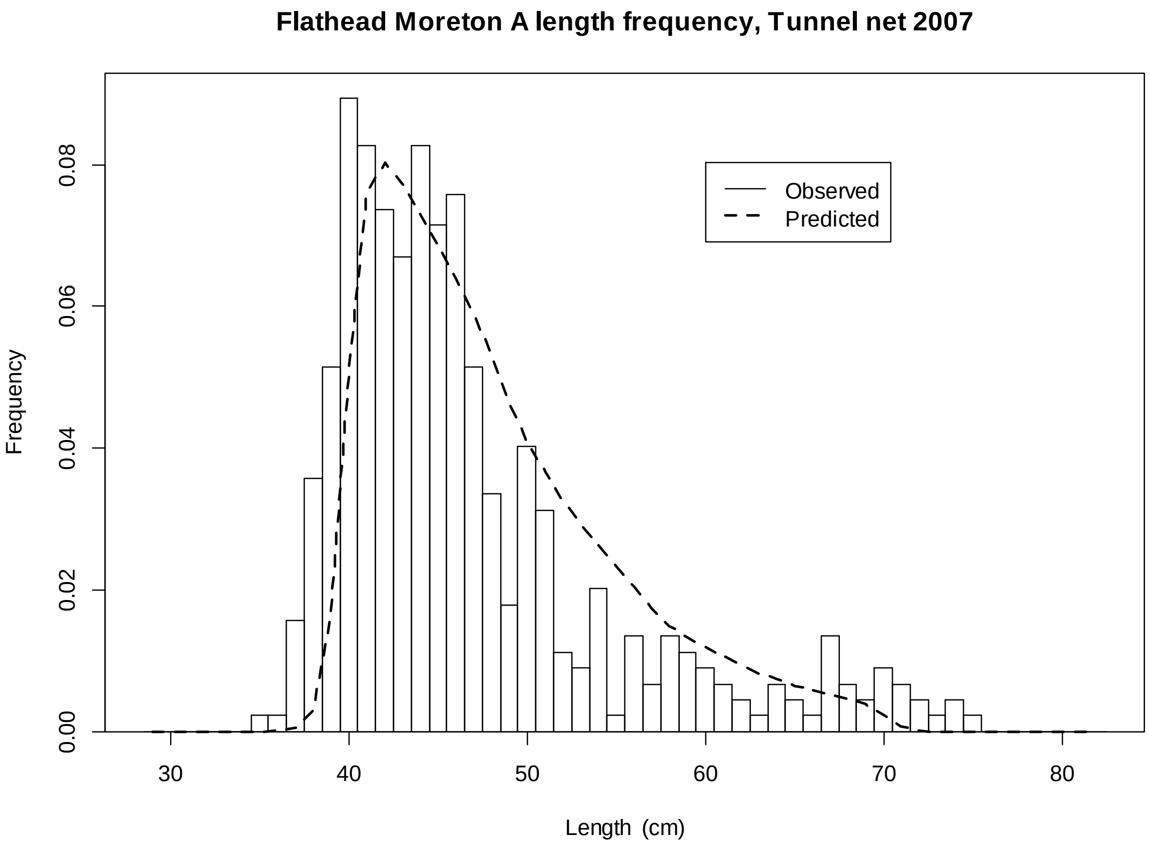


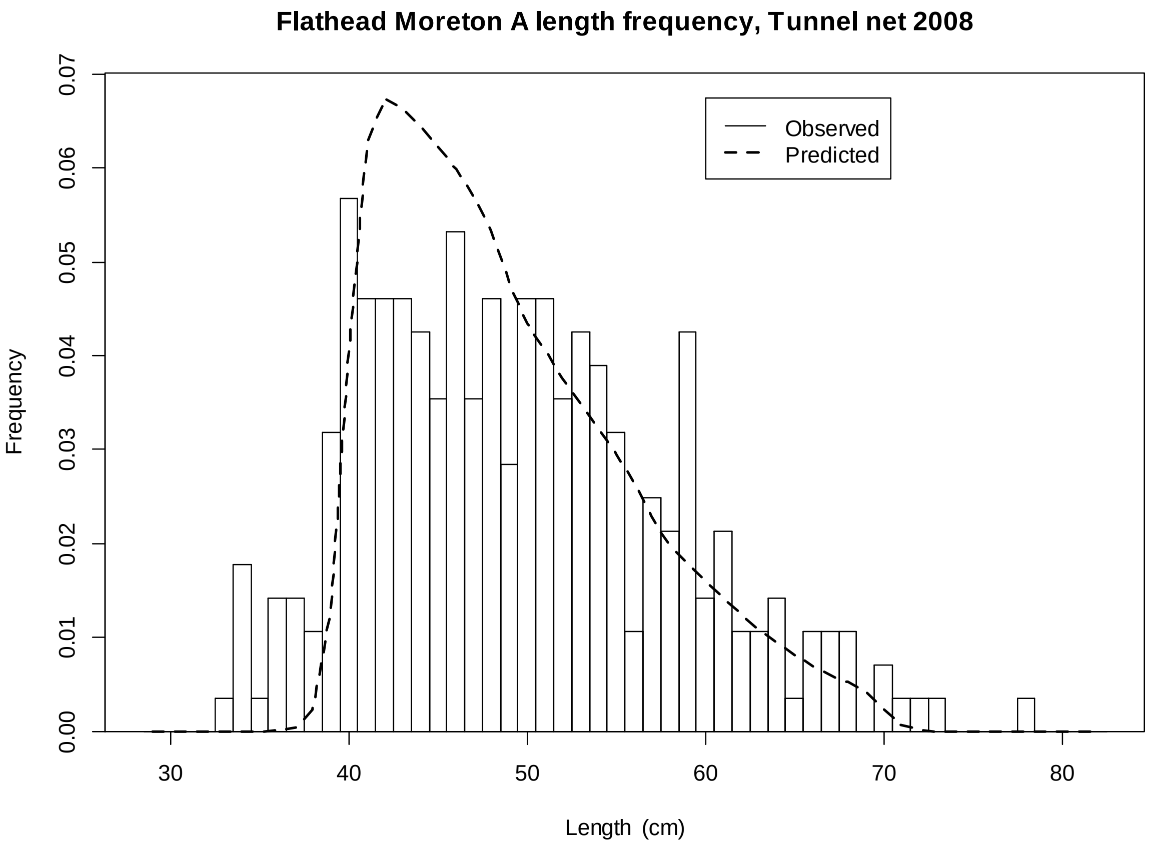


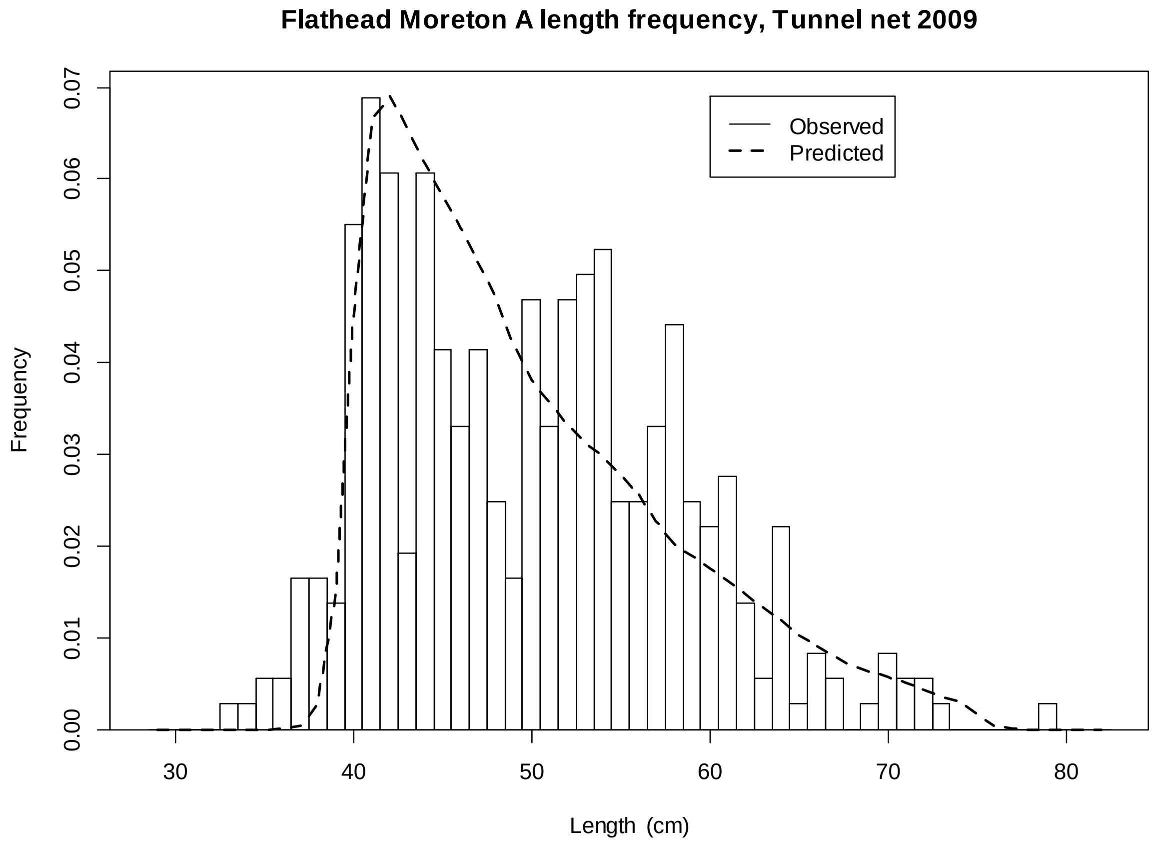
Flathead Moreton A length frequency, Gillnet 2016

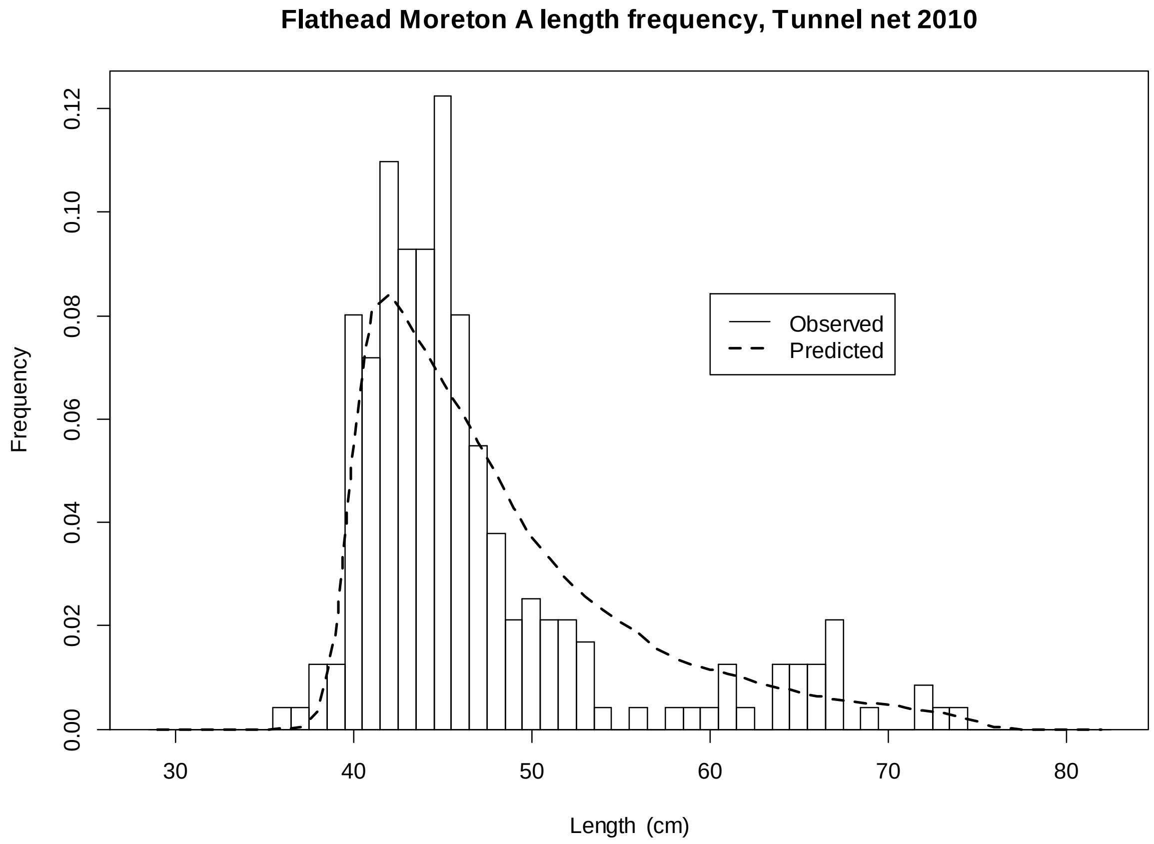


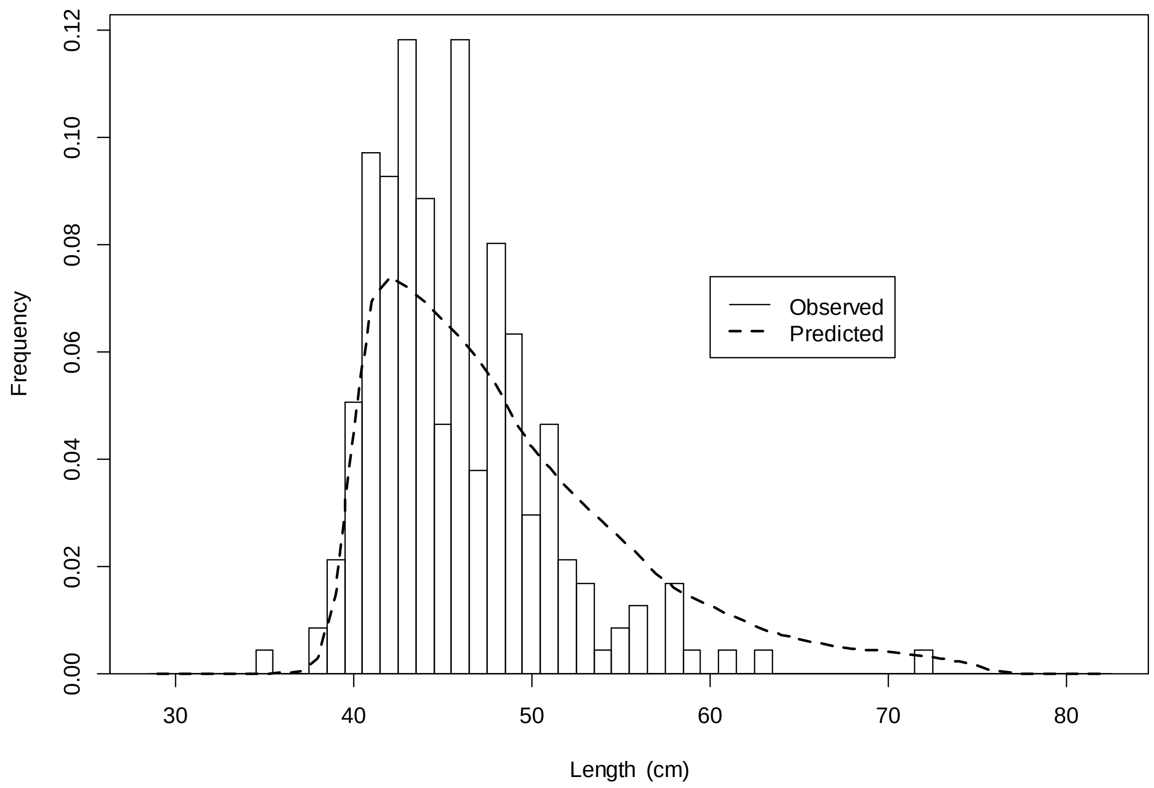
Flathead Moreton A length frequency, Tunnel net 2006


Flathead Moreton A length frequency, Tunnel net 2007
Observed
Predicted
Frequency
0.00
0.02
0.04
0.06
0.08
30
40
50
60
70
80
Length (cm)

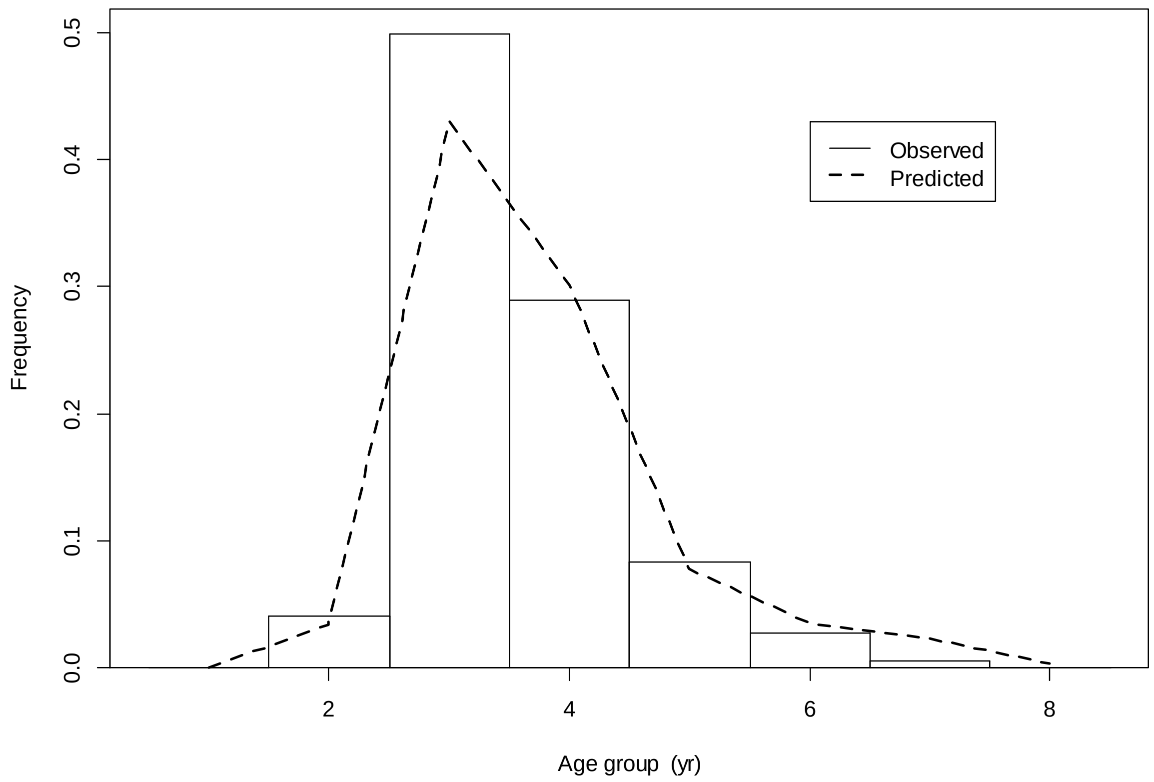

Flathead Moreton A length frequency, Tunnel net 2008
Observed
Predicted
Frequency
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
30
40
50
60
70
80
Length (cm)


Flathead Moreton A length frequency, Tunnel net 2009
Observed
Predicted
Frequency
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
30
40
50
60
70
80
Length (cm)

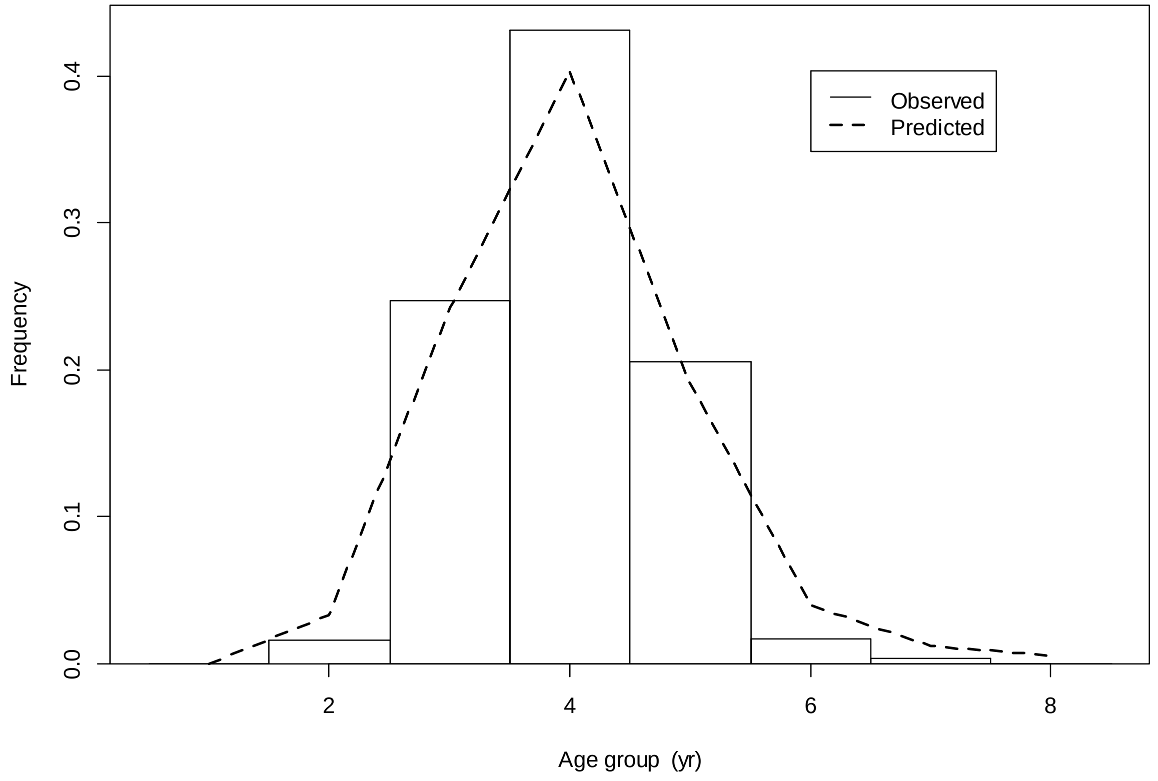

Flathead Moreton A length frequency, Tunnel net 2010
Observed
Predicted
Frequency
0.00
0.02
0.04
0.06
0.08
0.10
0.12
30
40
50
60
70
80
Length (cm)

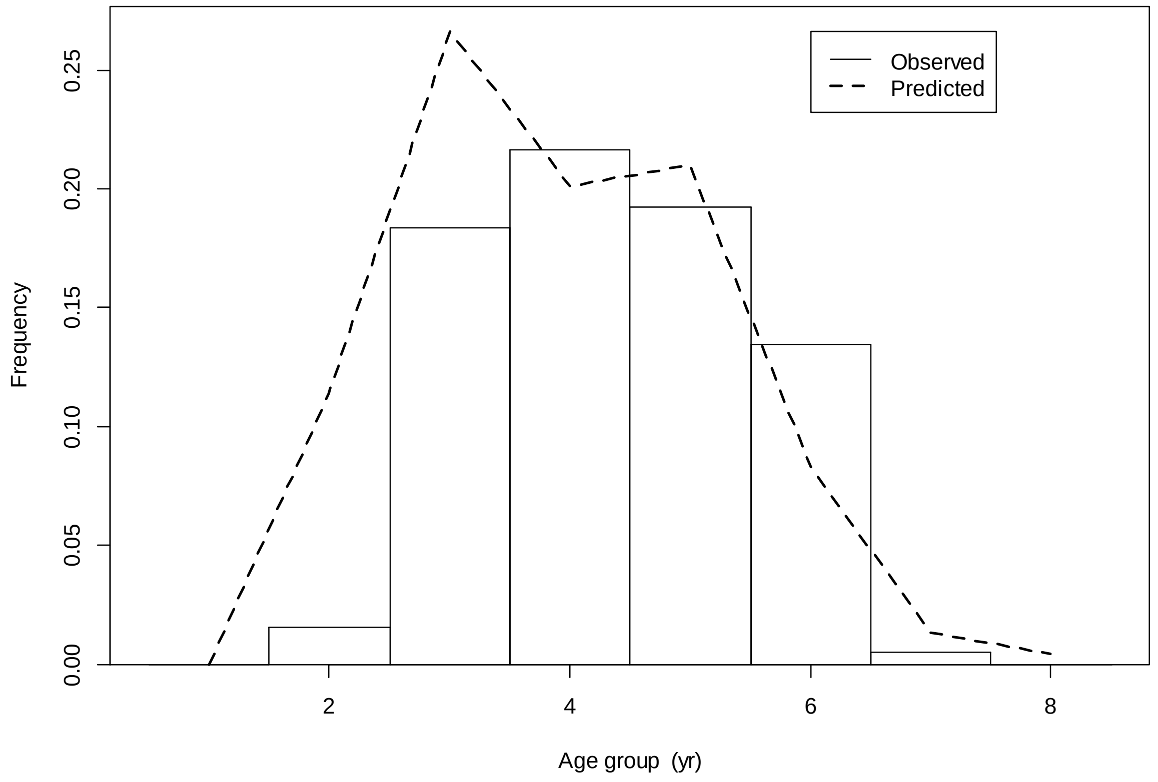


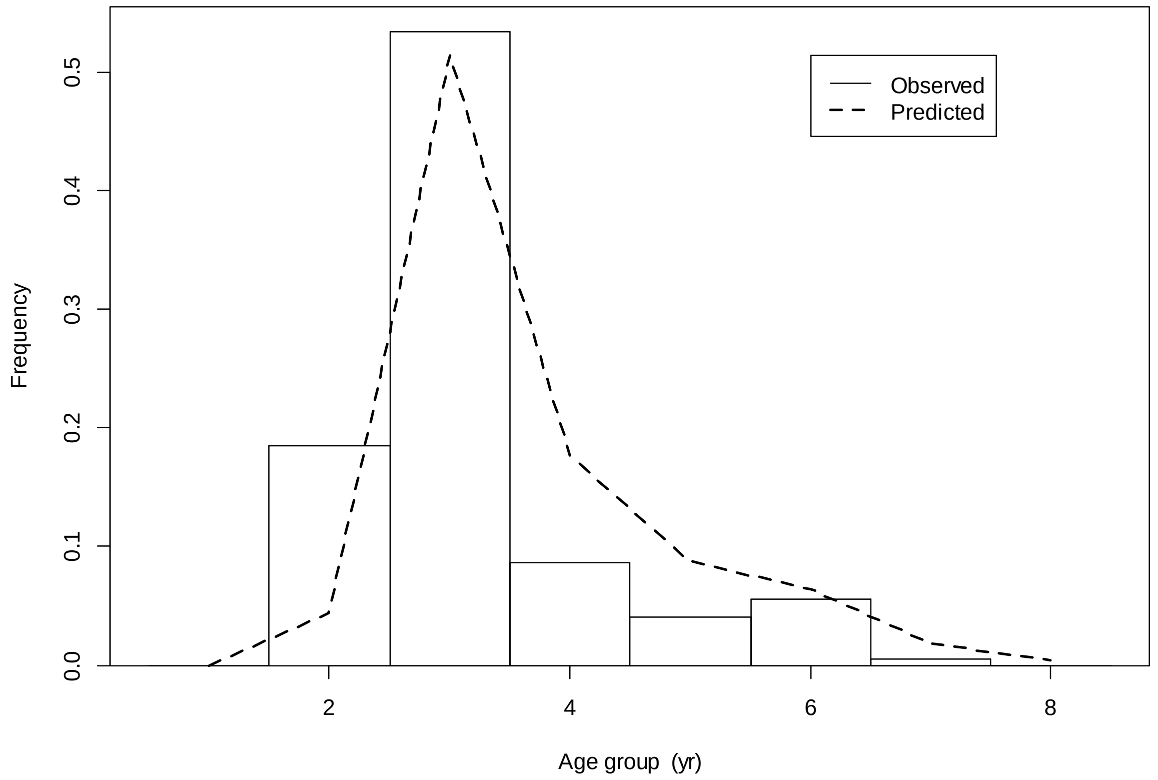
Flathead Moreton A length frequency, Tunnel net 2011



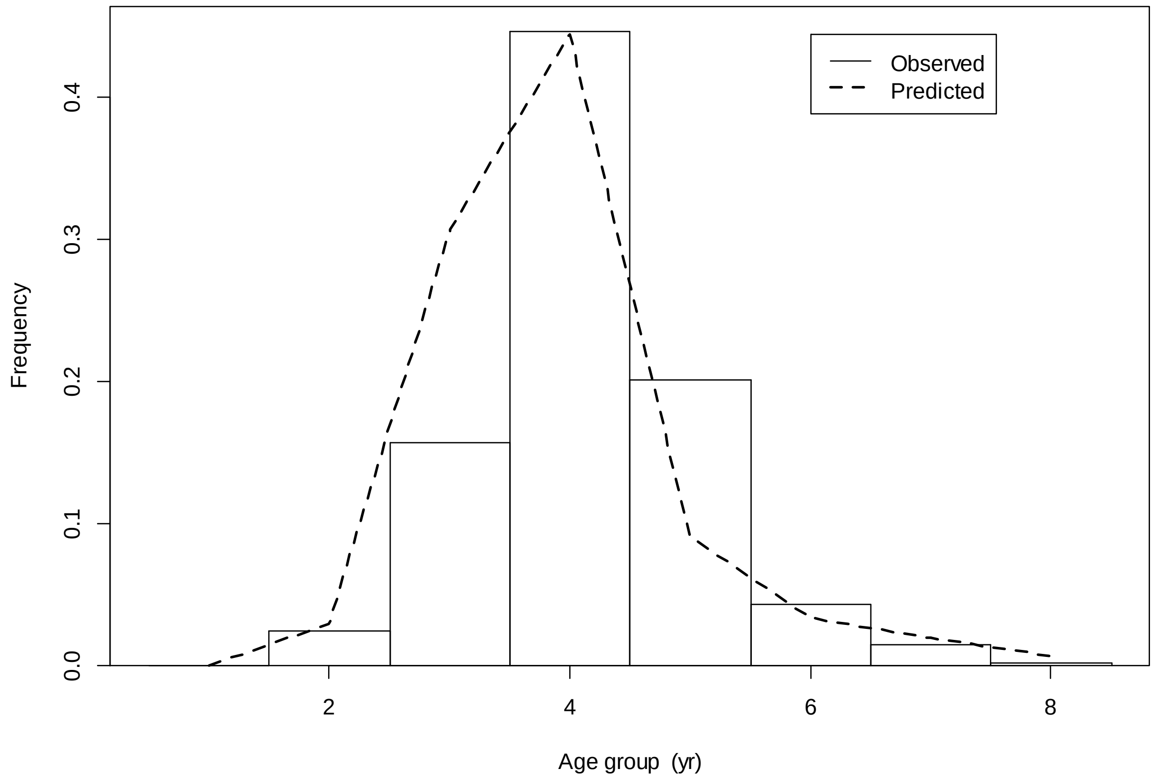
Flathead Moreton A female age frequency, Gillnet 2007


Flathead Moreton A female age frequency, Gillnet 2008


Flathead Moreton A female age frequency, Gillnet 2009

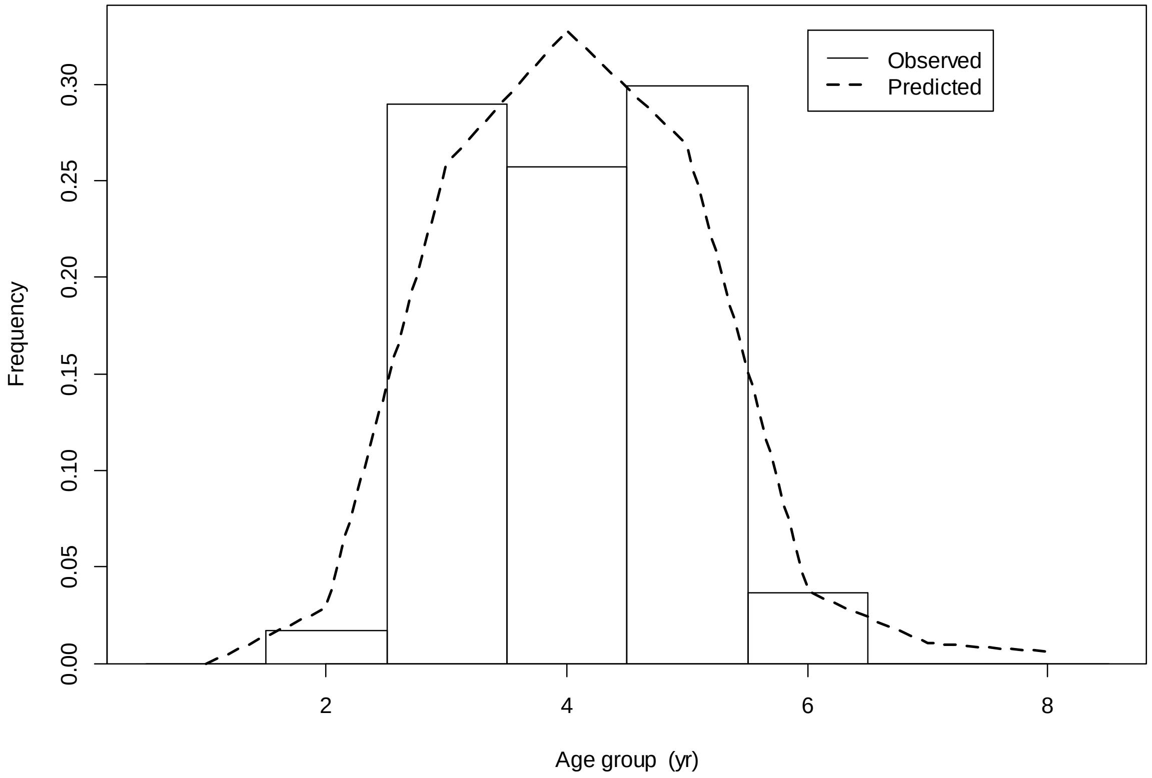


Flathead Moreton A female age frequency, Gillnet 2010

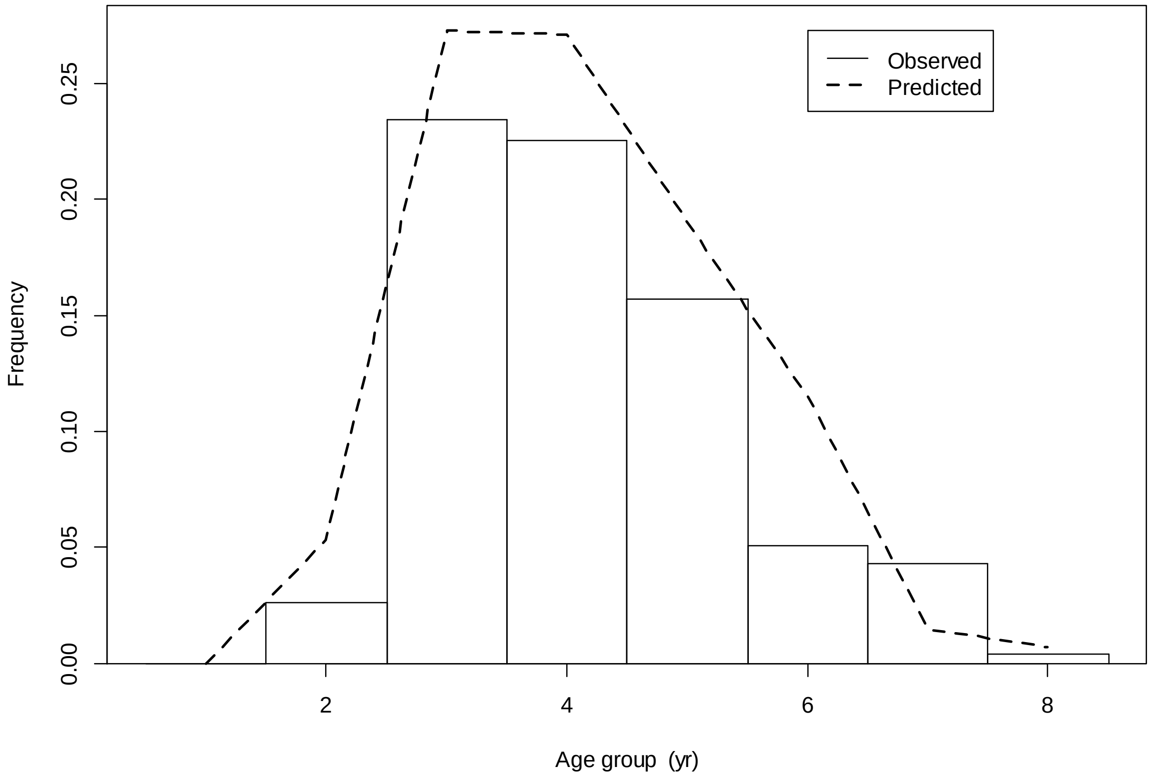


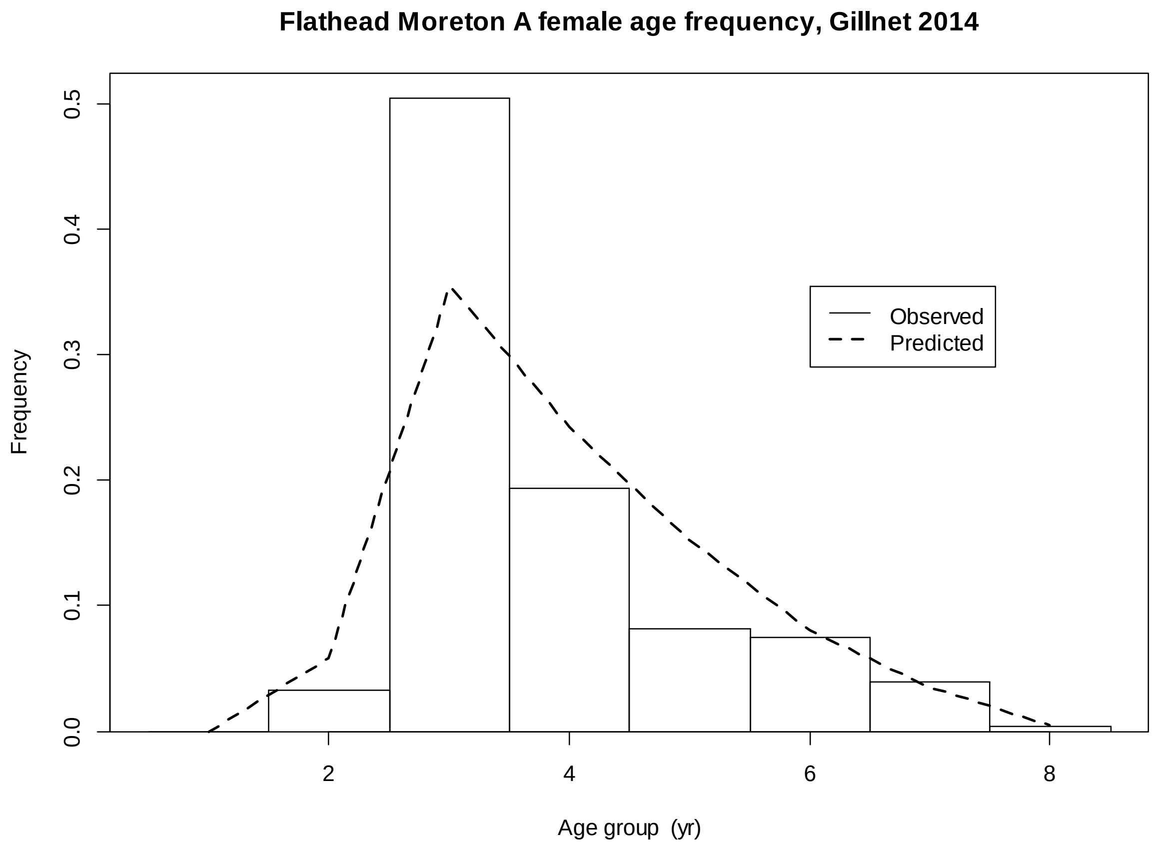
Flathead Moreton A female age frequency, Gillnet 2011

Flathead Moreton A female age frequency, Gillnet 2012

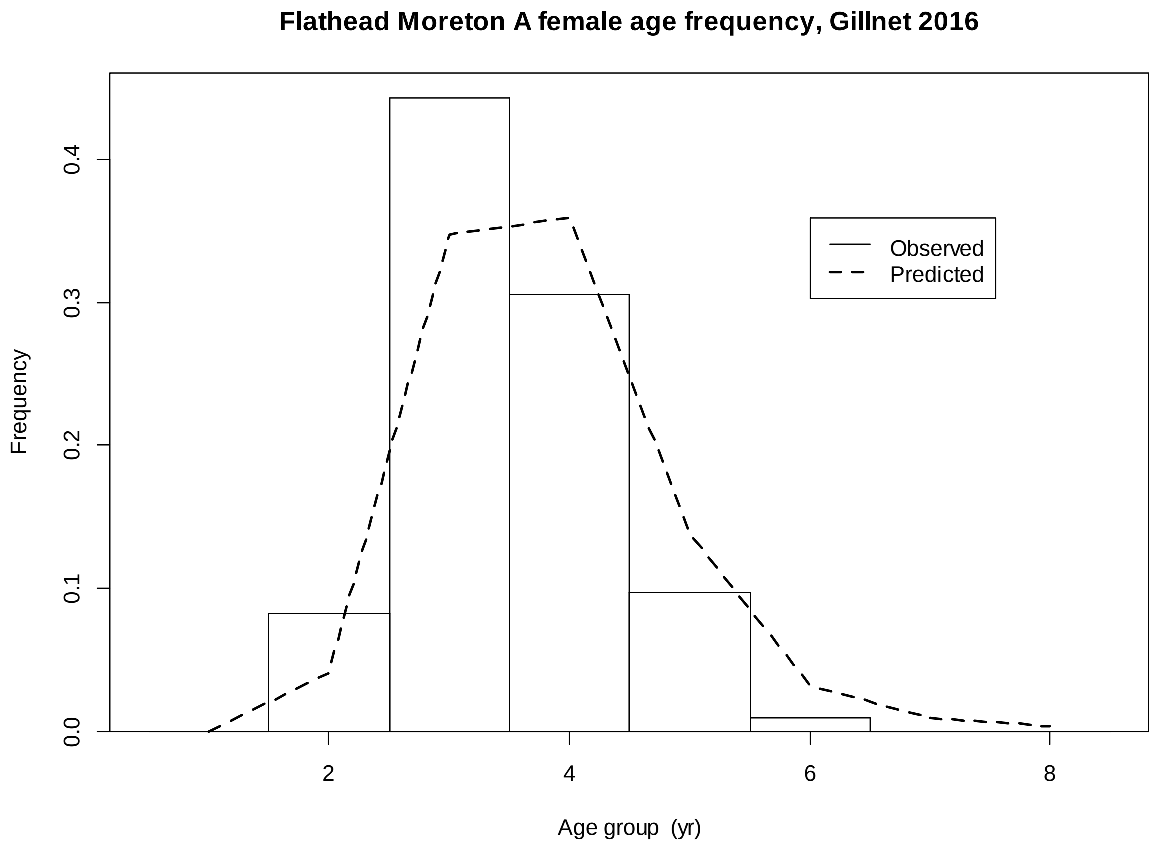


Flathead Moreton A female age frequency, Gillnet 2013

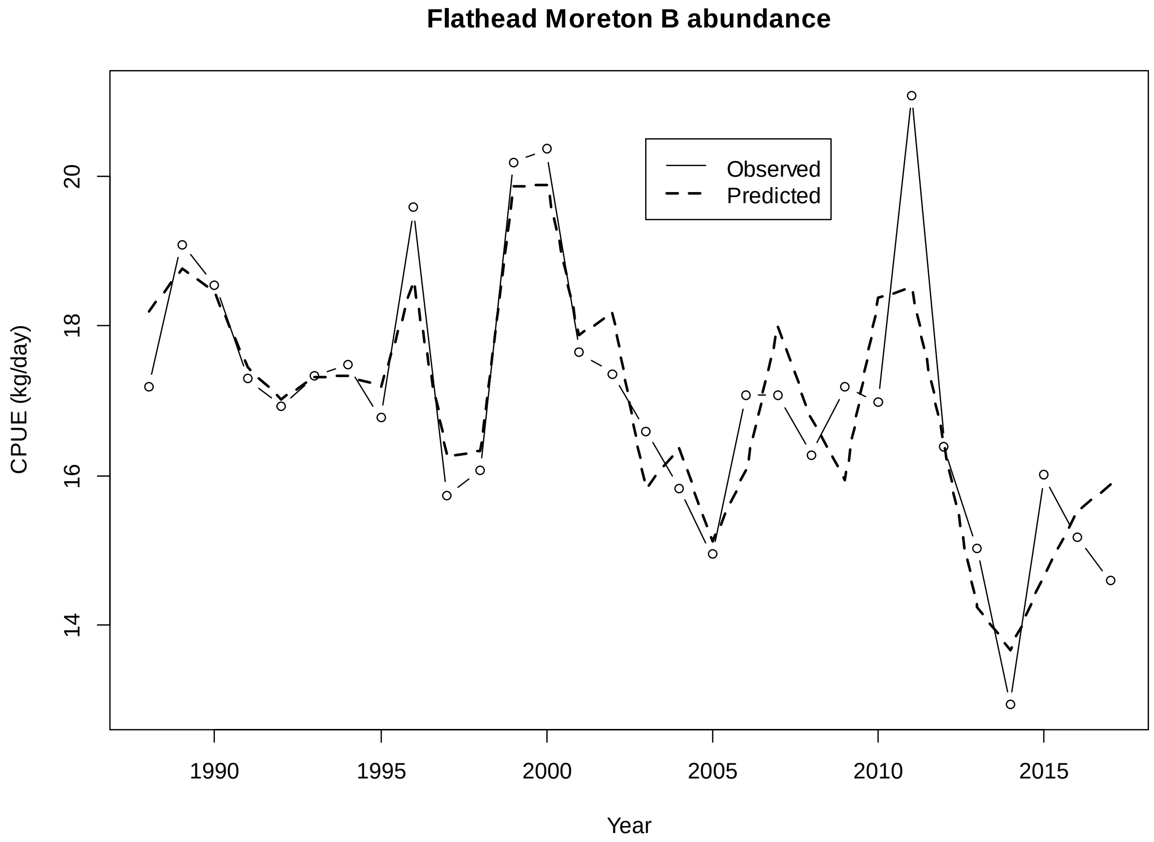


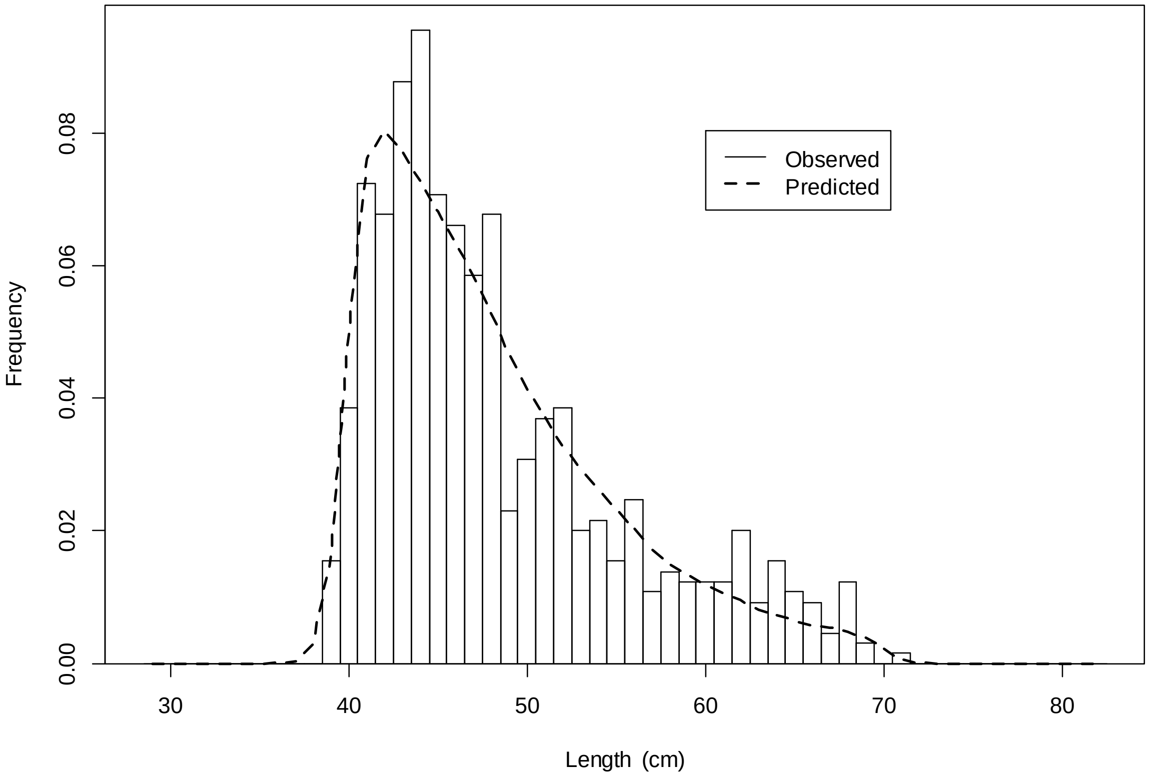

Flathead Moreton A female age frequency, Gillnet 2014
Frequency
0.0
0.1
0.2
0.3
0.4
0.5
2
4
6
8
Age group (yr)
Observed
Predicted

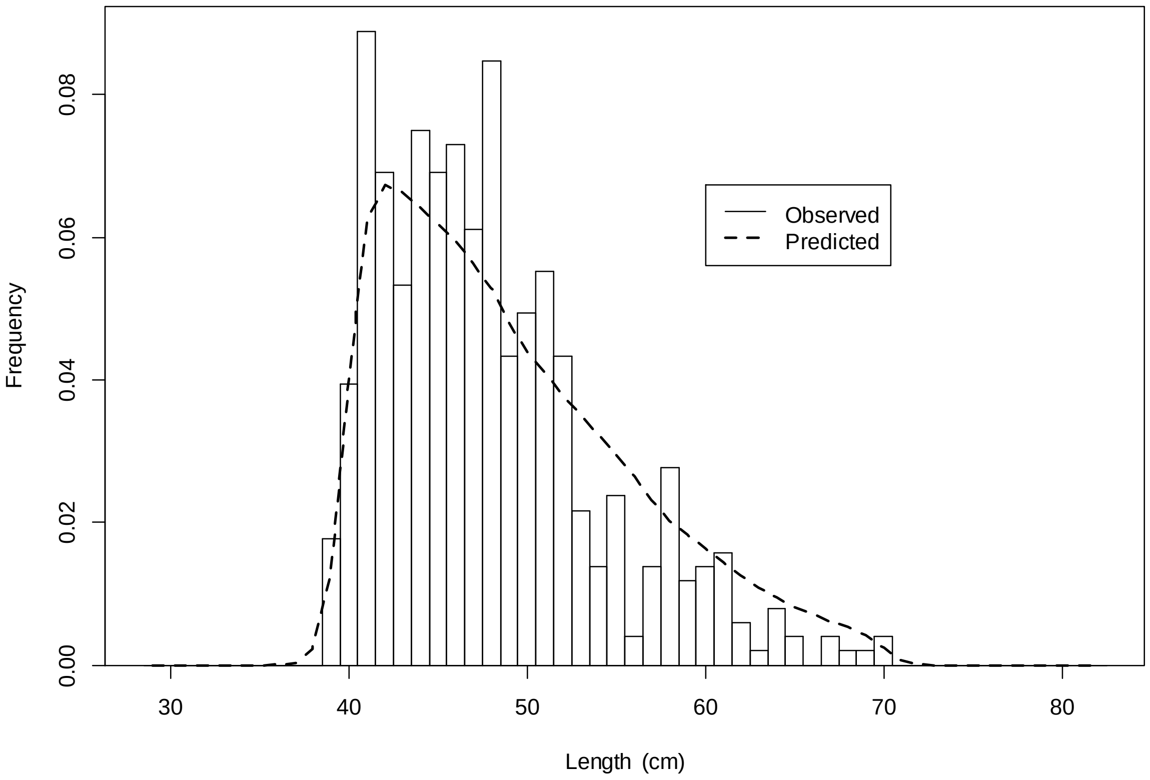

Flathead Moreton A female age frequency, Gillnet 2015
Frequency
0.0
0.1
0.2
0.3
0.4
2
4
6
8
Age group (yr)
Observed
Predicted

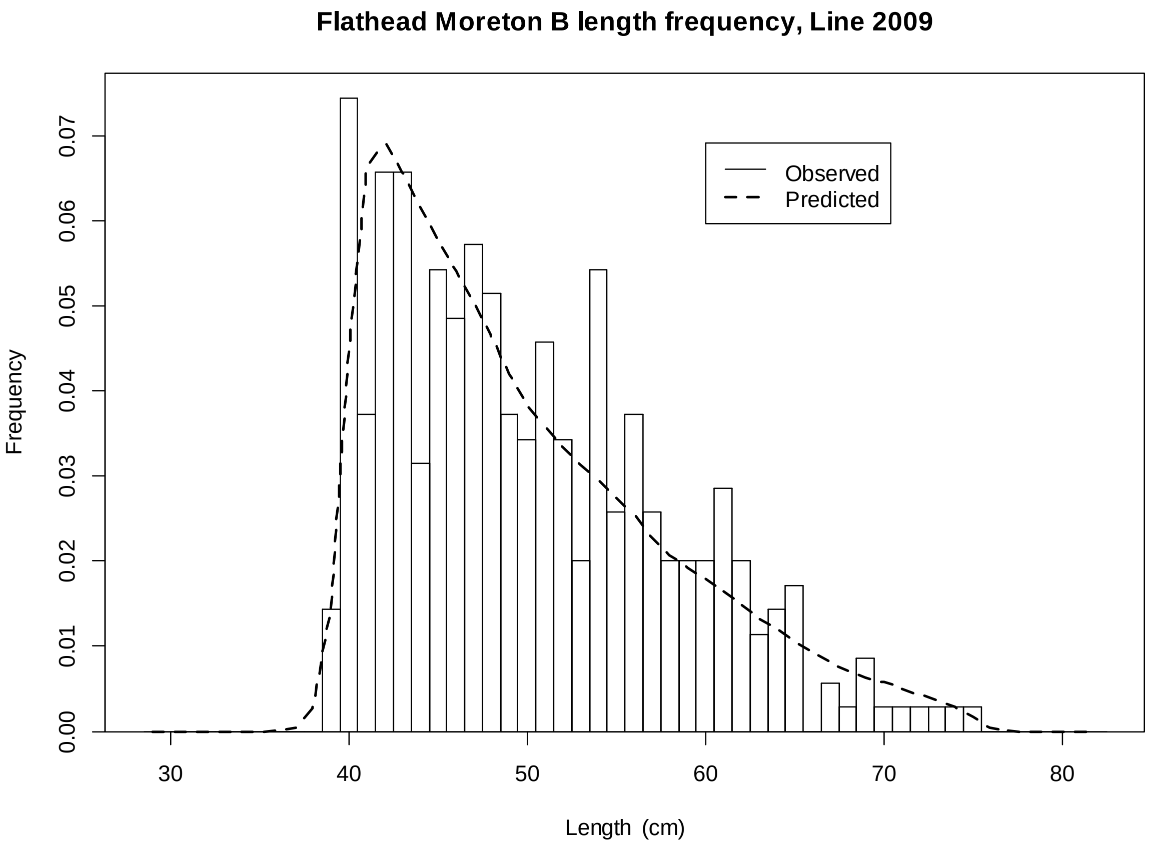


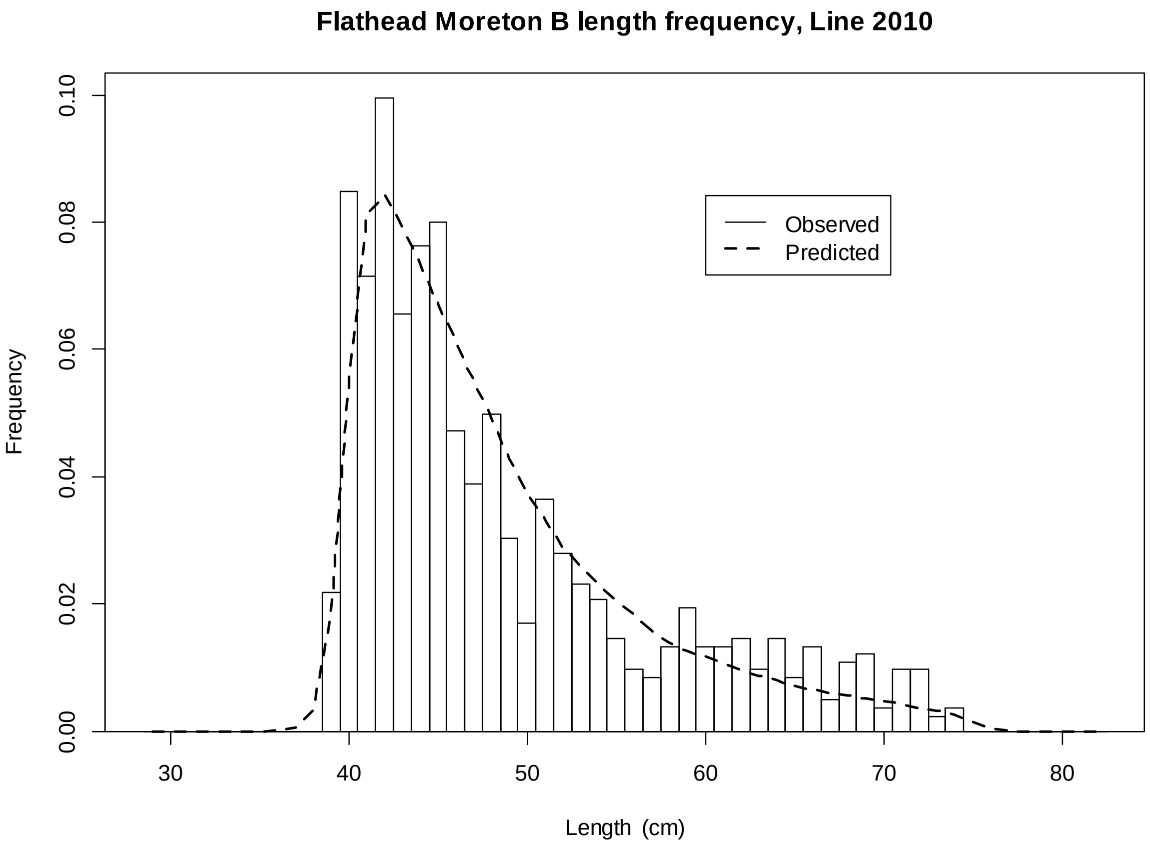
A2.4 Flathead Moreton B: $r = 4$, $M = 0.75$ yr $^{-1}$

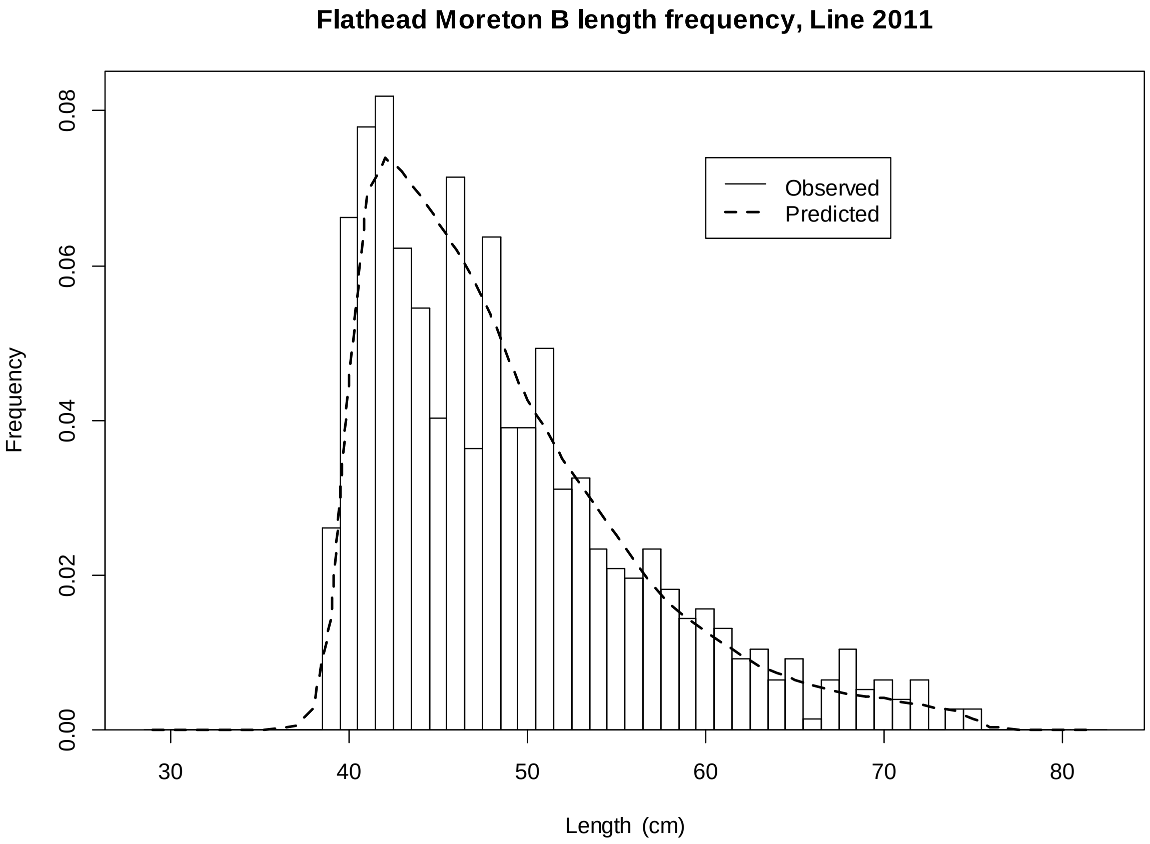


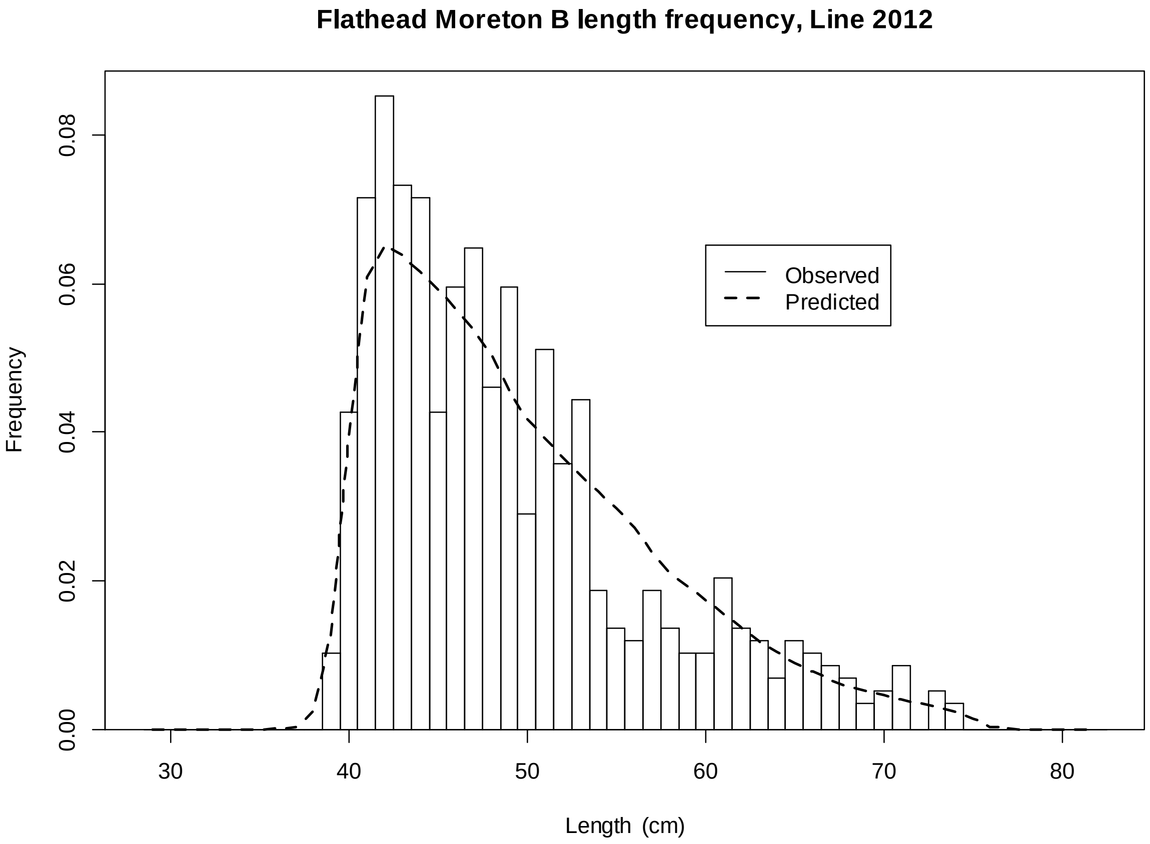

Flathead Moreton B length frequency, Line 2007


Flathead Moreton B length frequency, Line 2008

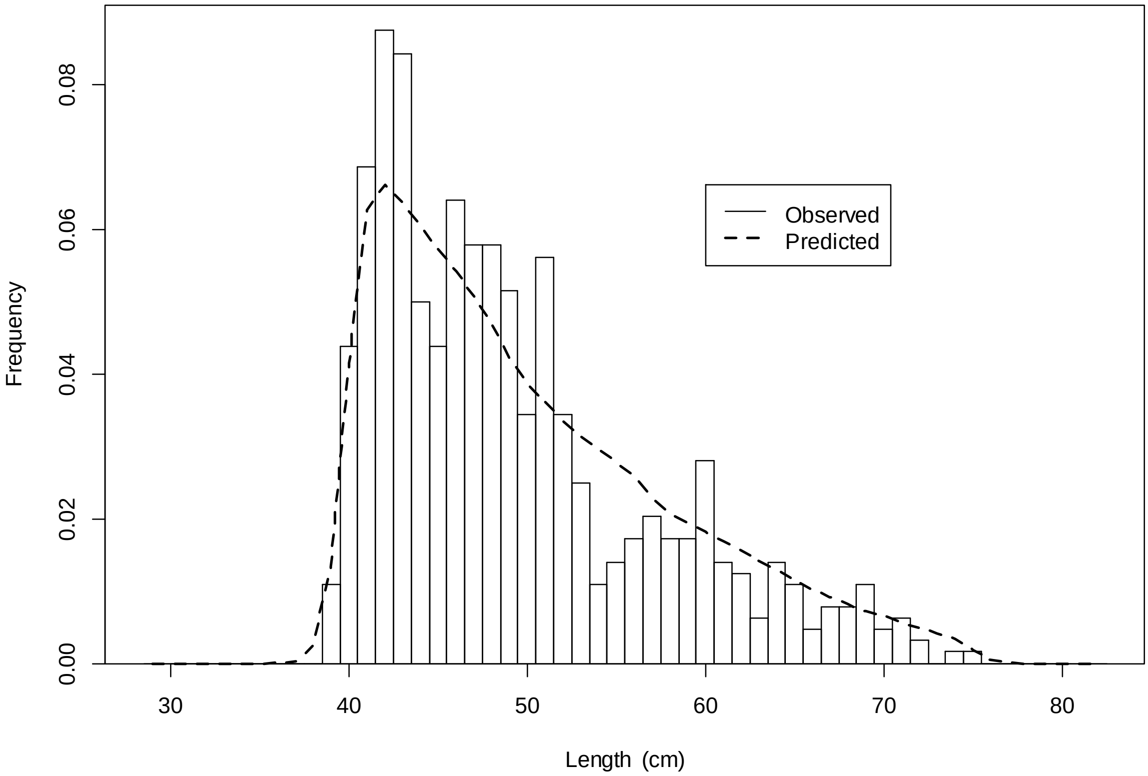

Flathead Moreton B length frequency, Line 2009
Frequency
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
30
40
50
60
70
80
Length (cm)
Observed
Predicted


Flathead Moreton B length frequency, Line 2010
Frequency
0.00
0.02
0.04
0.06
0.08
0.10
30
40
50
60
70
80
Length (cm)
Observed
Predicted

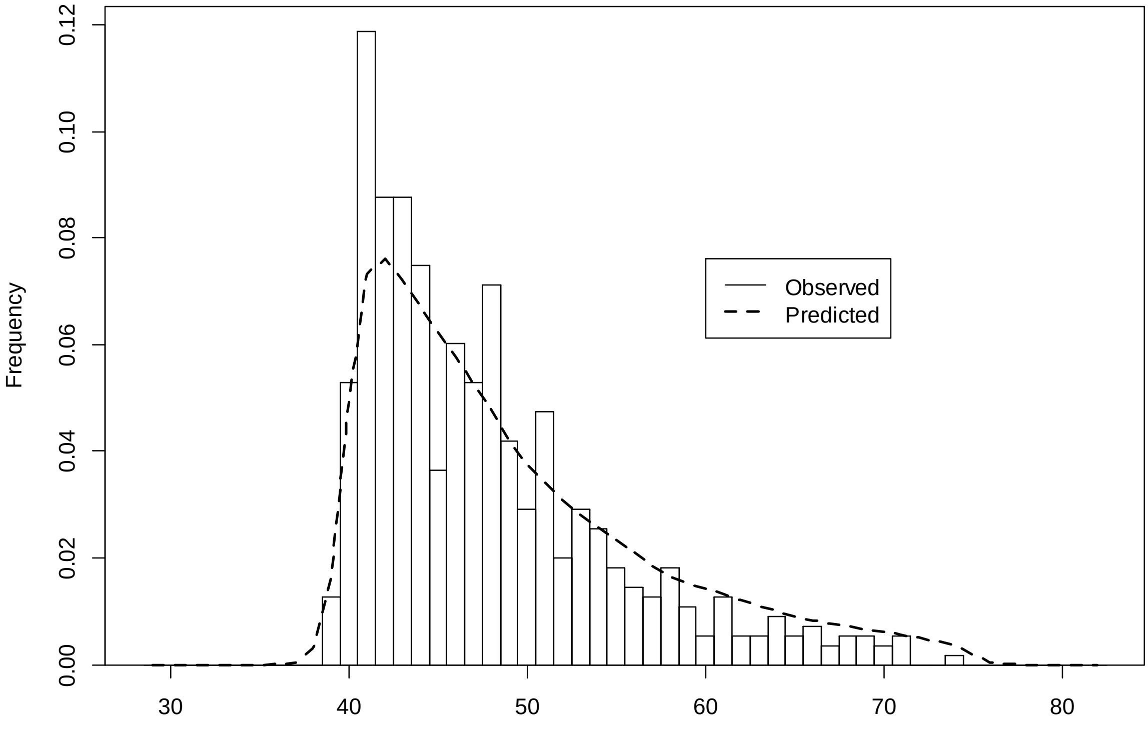

Flathead Moreton B length frequency, Line 2011
Frequency
0.00
0.02
0.04
0.06
0.08
30
40
50
60
70
80
Length (cm)
Observed
Predicted

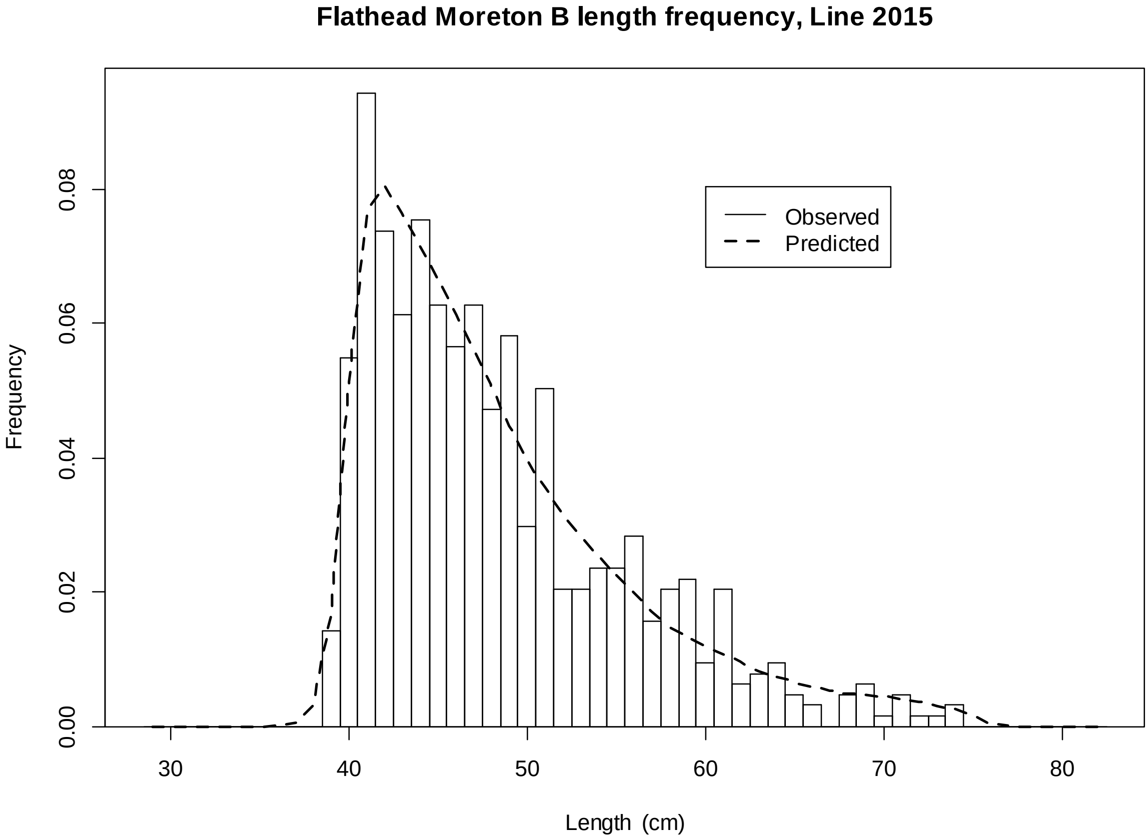

Flathead Moreton B length frequency, Line 2012
Frequency
0.00
0.02
0.04
0.06
0.08
30
40
50
60
70
80
Length (cm)
Observed
Predicted

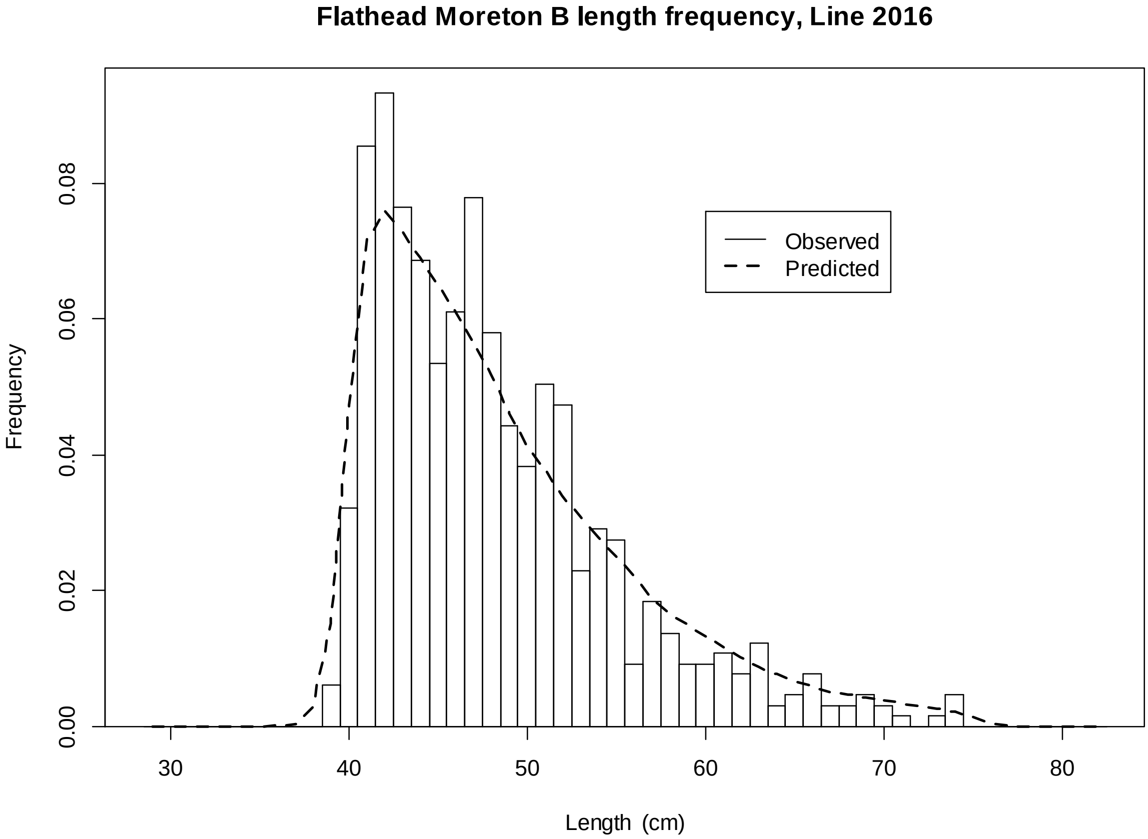
Flathead Moreton B length frequency, Line 2013

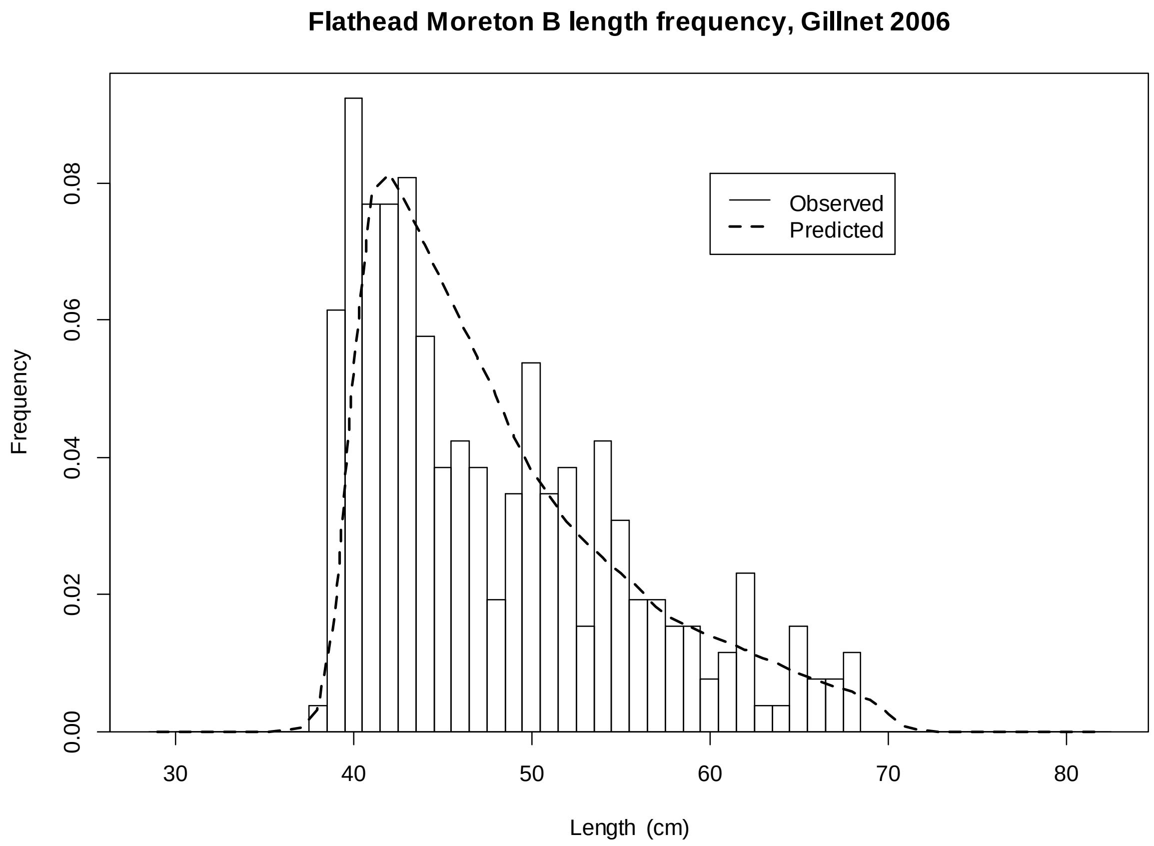


Flathead Moreton B length frequency, Line 2014

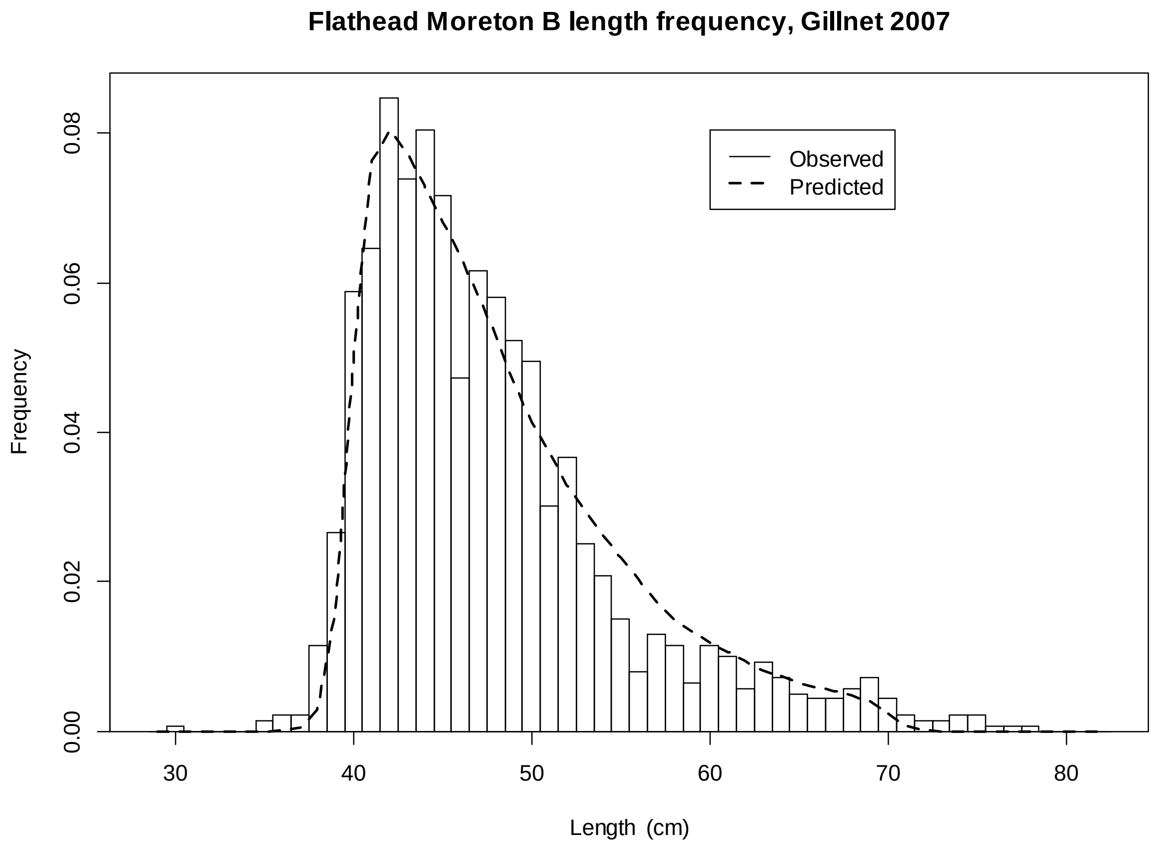



Flathead Moreton B length frequency, Line 2015
Observed
Predicted
Frequency
0.00
0.02
0.04
0.06
0.08
30
40
50
60
70
80
Length (cm)


Flathead Moreton B length frequency, Line 2016
Observed
Predicted
Frequency
0.00
0.02
0.04
0.06
0.08
30
40
50
60
70
80
Length (cm)

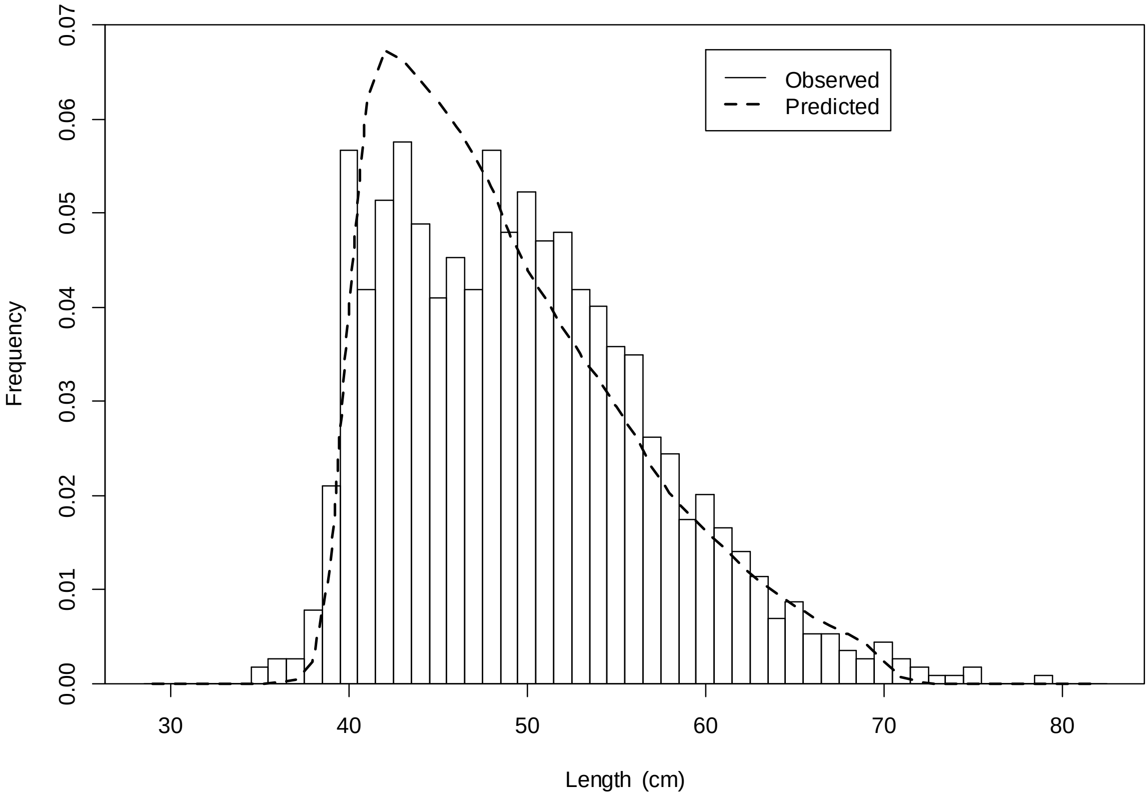


Flathead Moreton B length frequency, Gillnet 2006

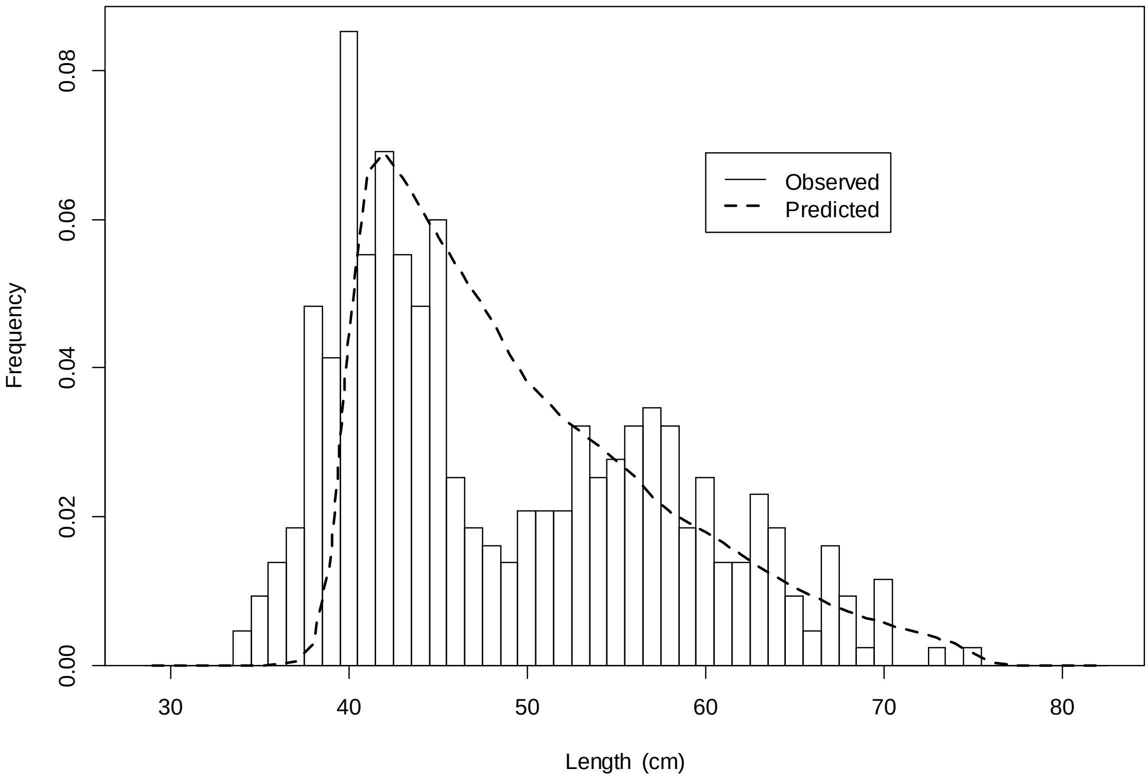


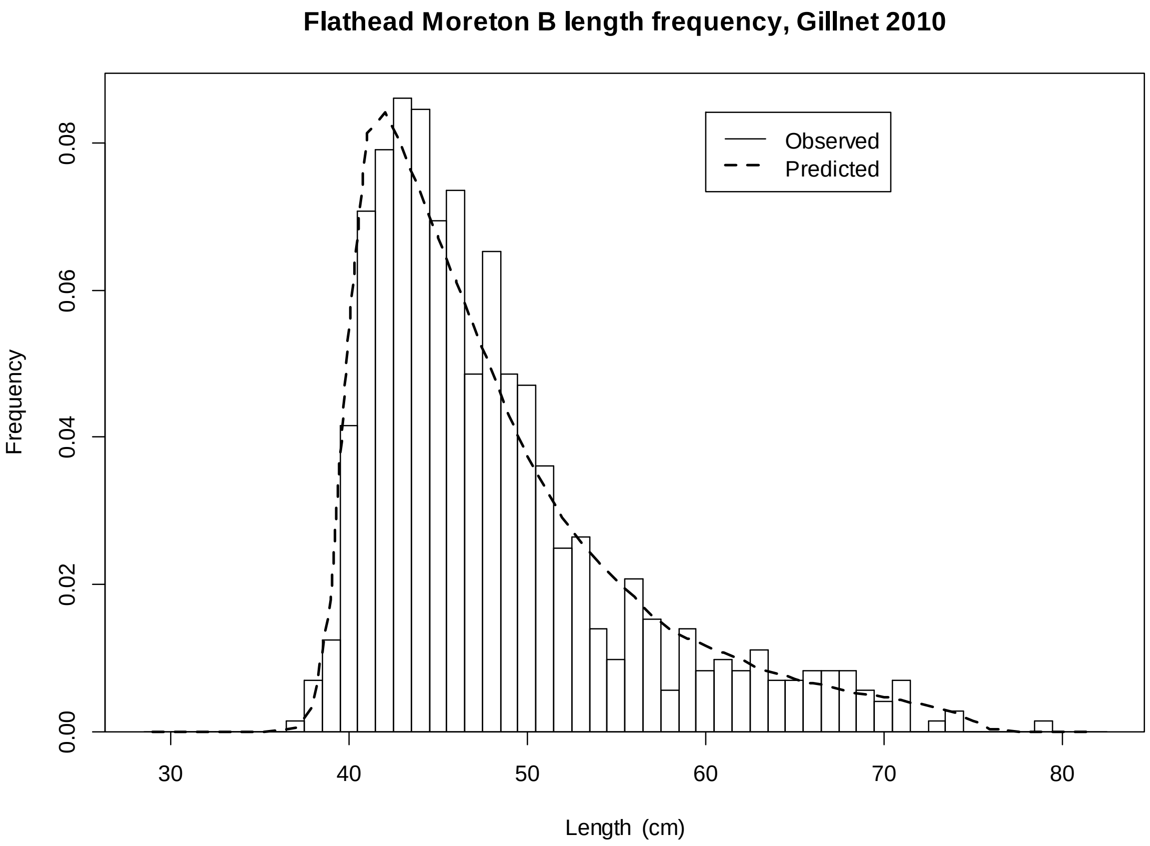
Flathead Moreton B length frequency, Gillnet 2007

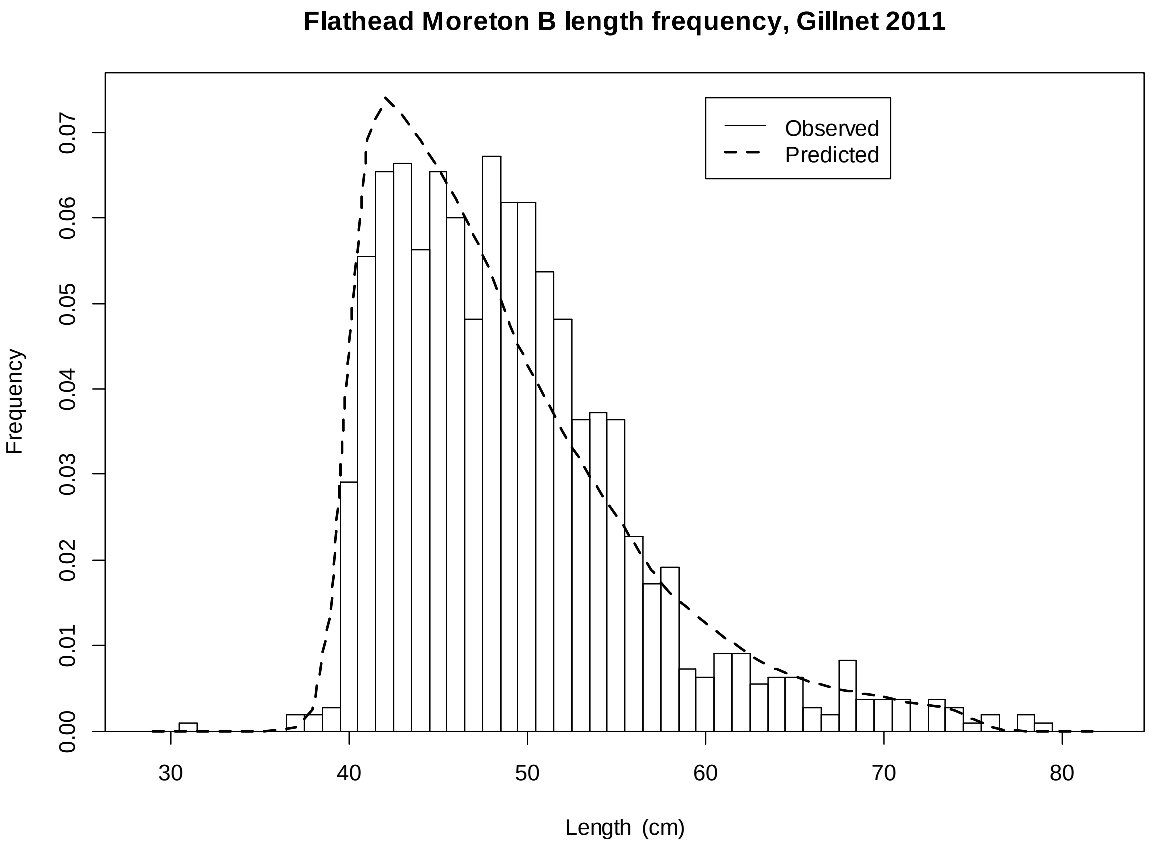
Flathead Moreton B length frequency, Gillnet 2008



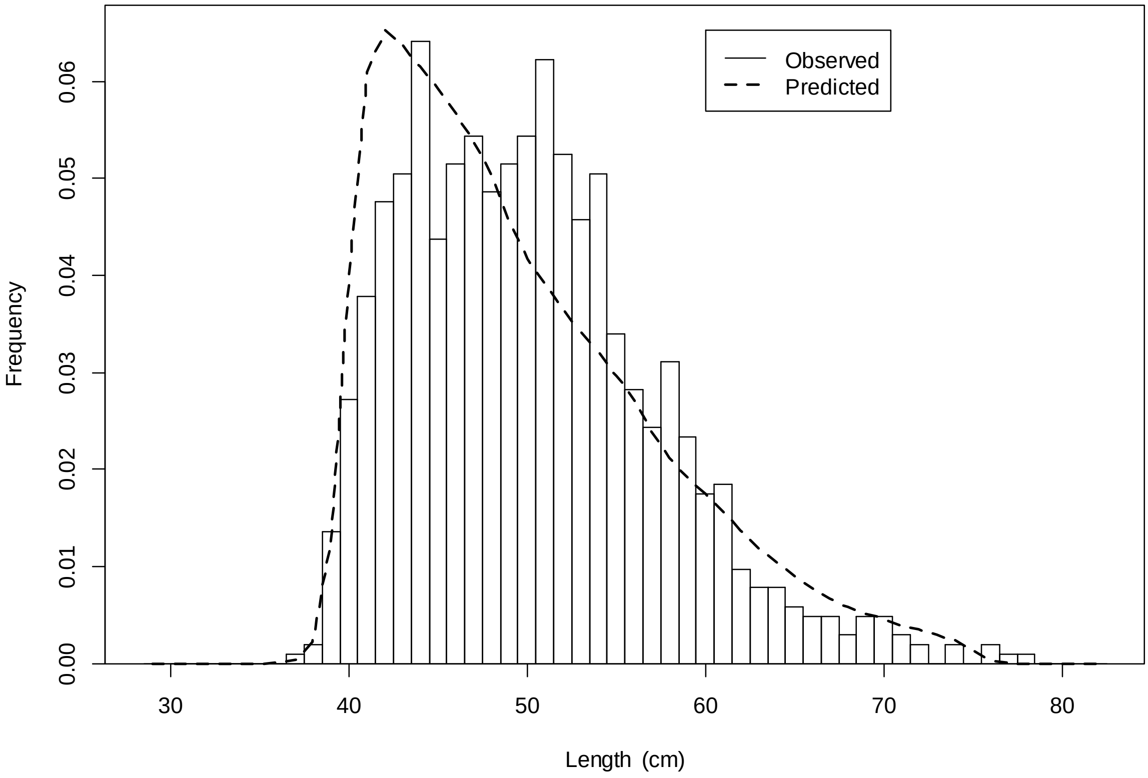
Flathead Moreton B length frequency, Gillnet 2009



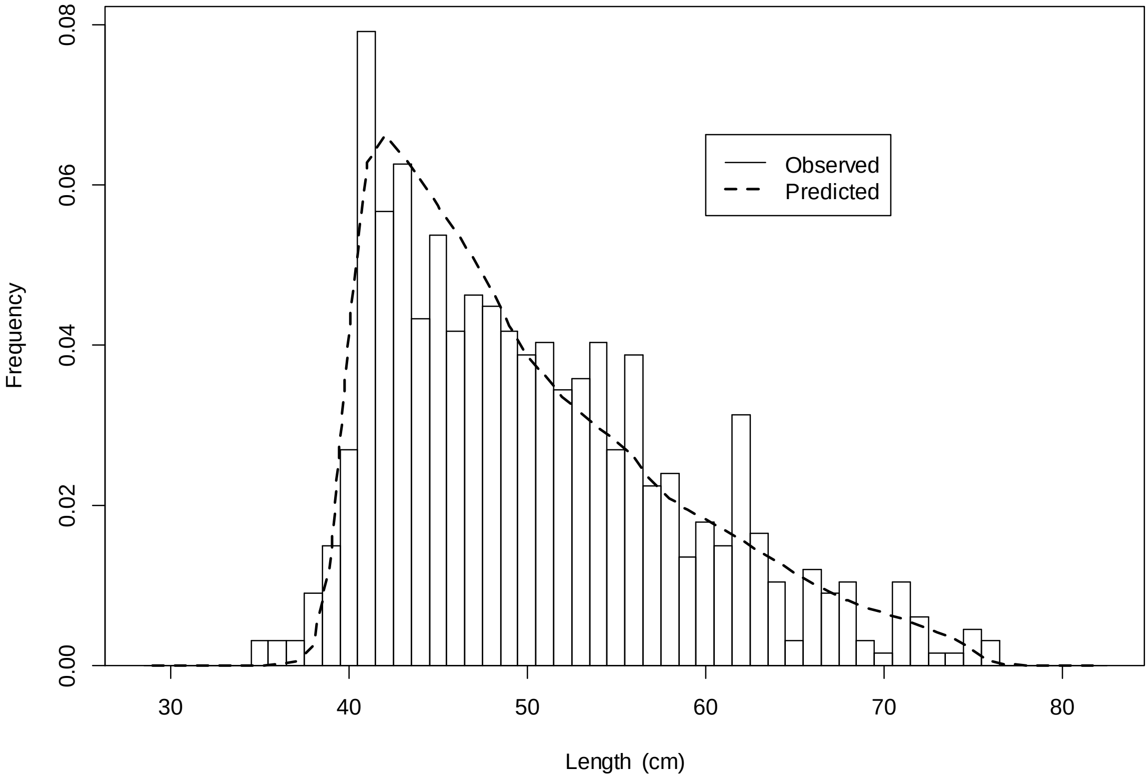

Flathead Moreton B length frequency, Gillnet 2010
Frequency
0.00
0.02
0.04
0.06
0.08
30
40
50
60
70
80
Length (cm)
Observed
Predicted

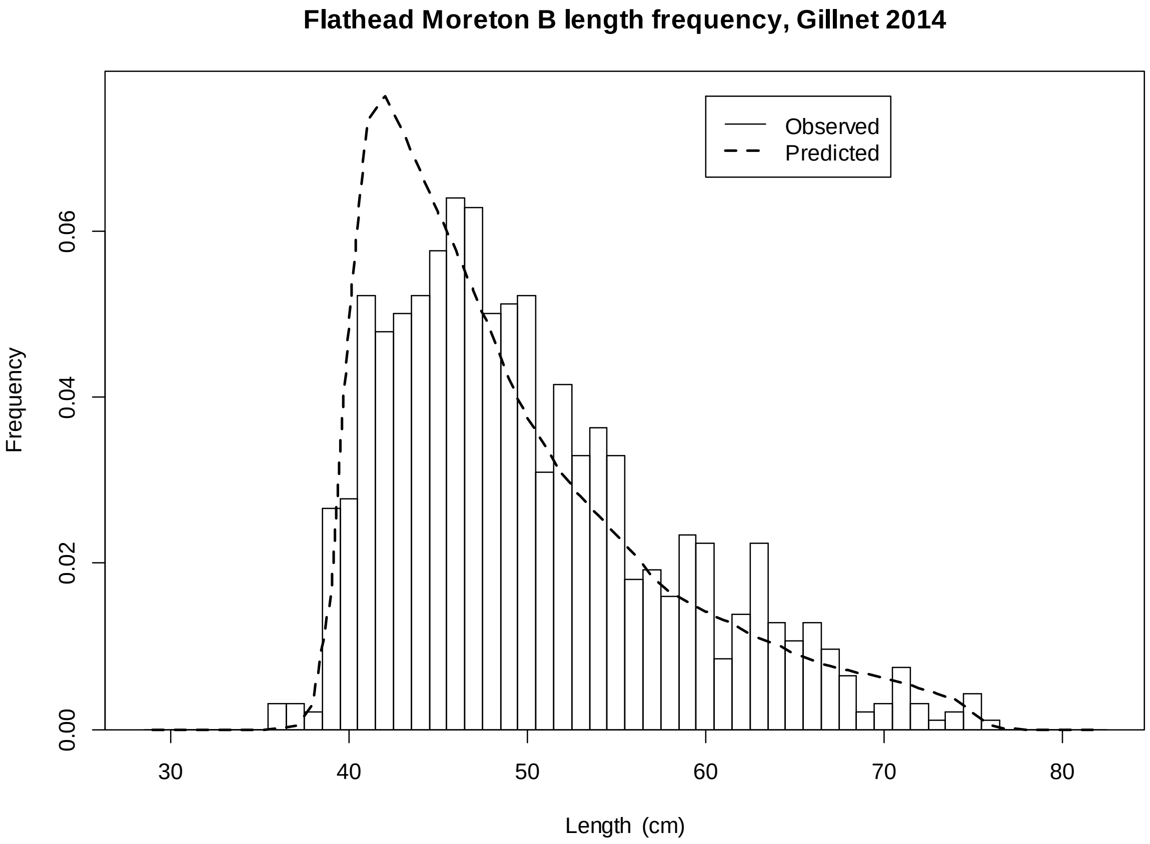

Flathead Moreton B length frequency, Gillnet 2011
Frequency
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
30
40
50
60
70
80
Length (cm)
Observed
Predicted

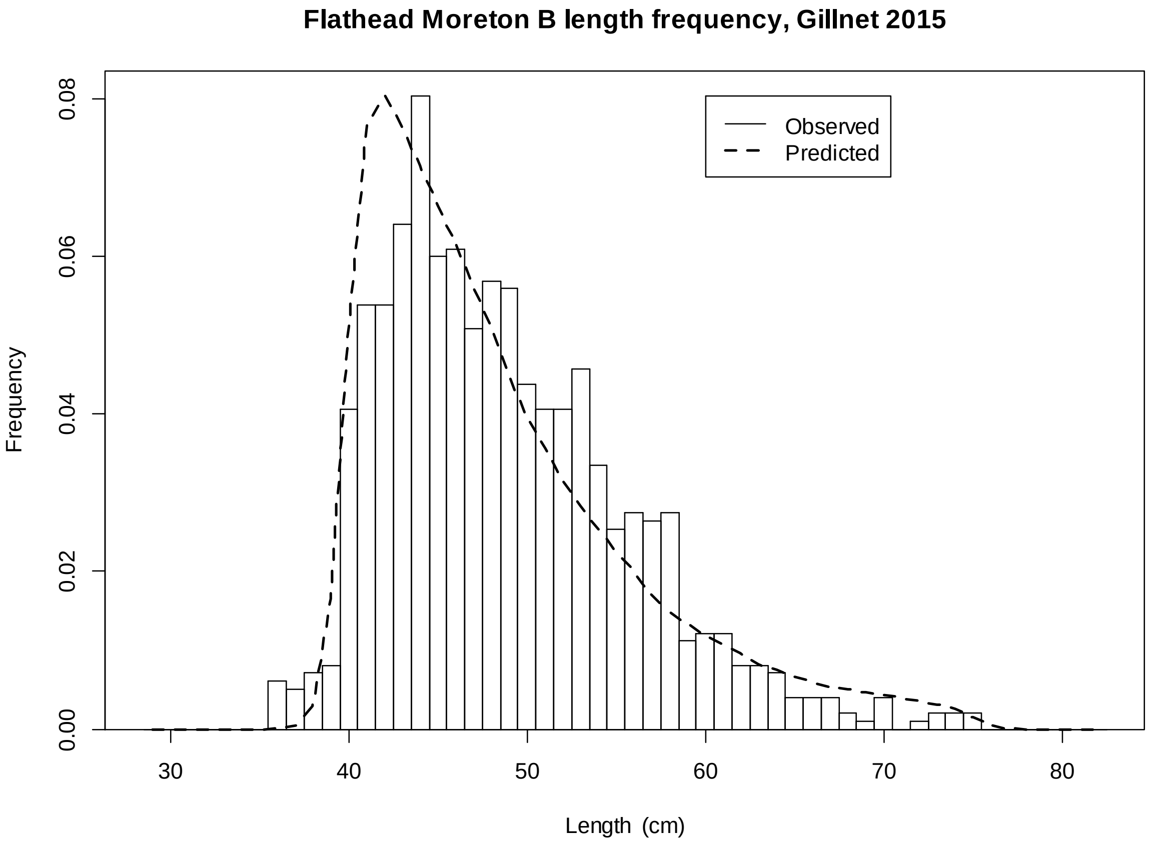
Flathead Moreton B length frequency, Gillnet 2012

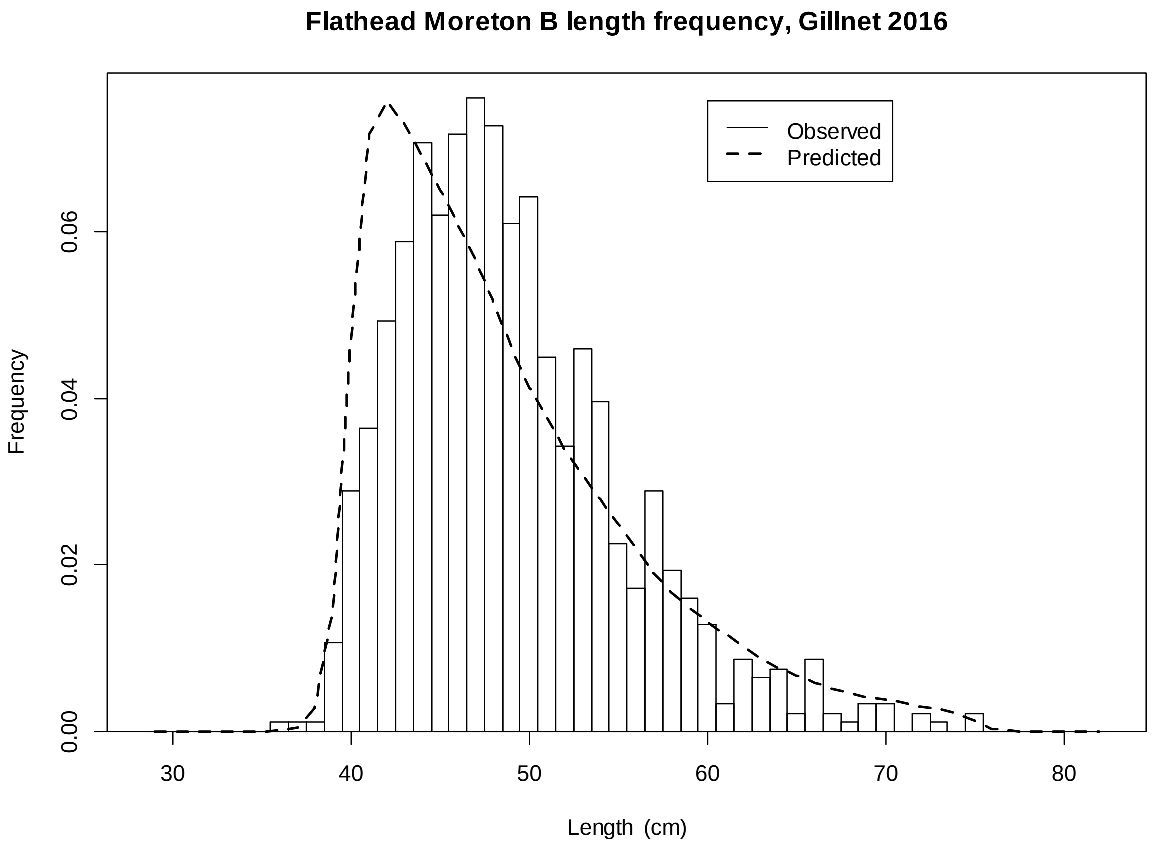


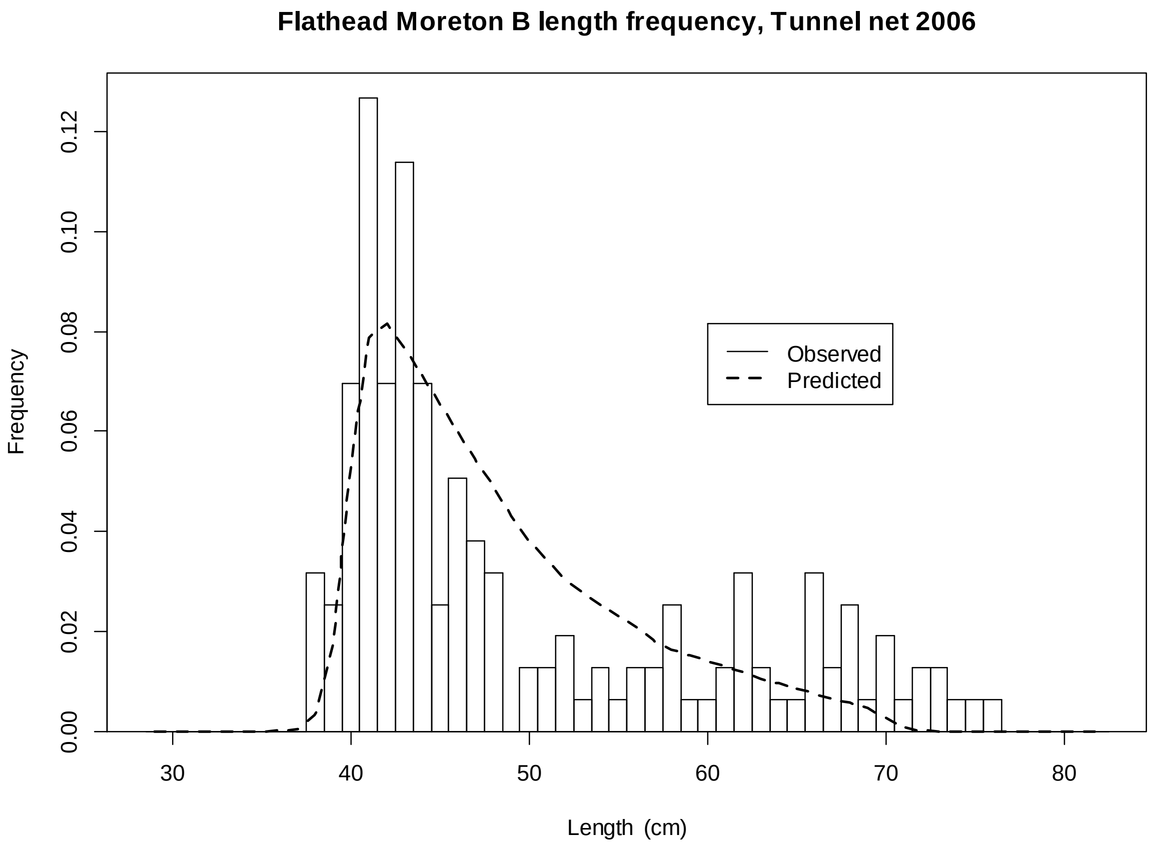
Flathead Moreton B length frequency, Gillnet 2013

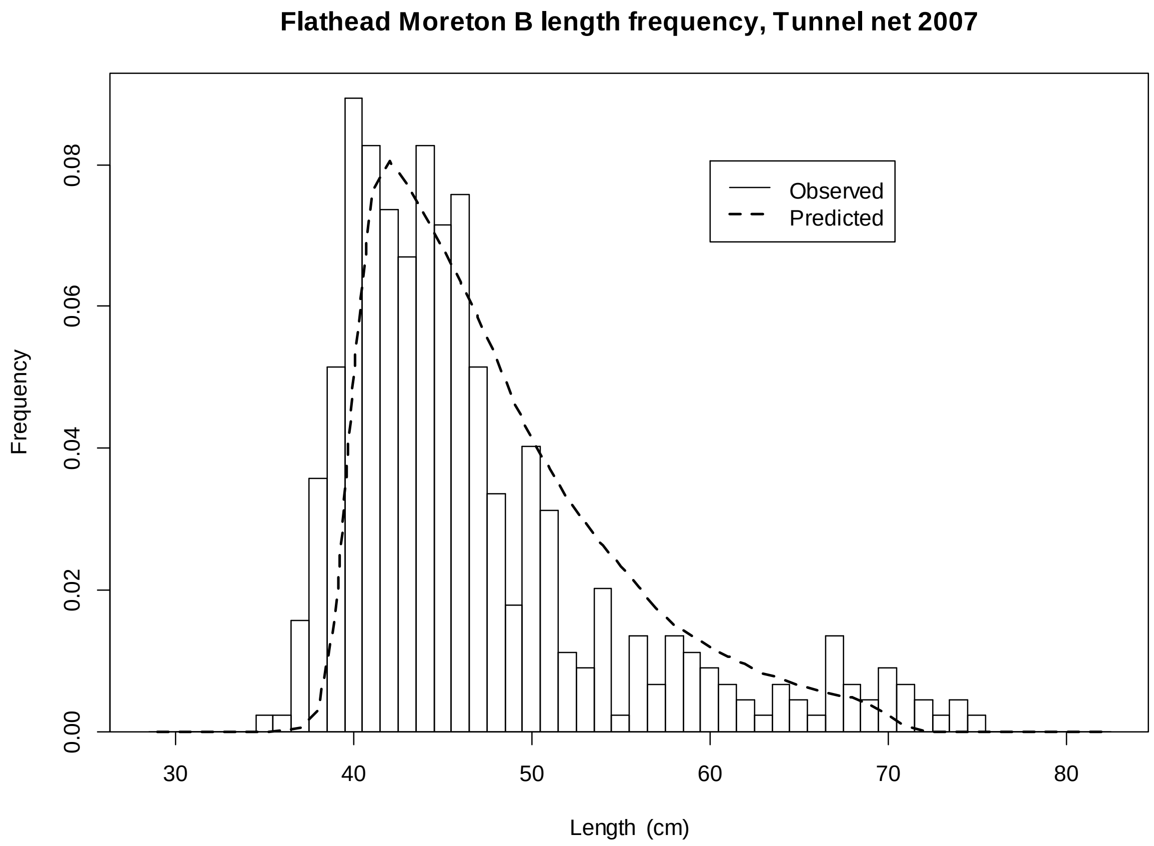



Flathead Moreton B length frequency, Gillnet 2014
Observed
Predicted
Frequency
0.00
0.02
0.04
0.06
30
40
50
60
70
80
Length (cm)

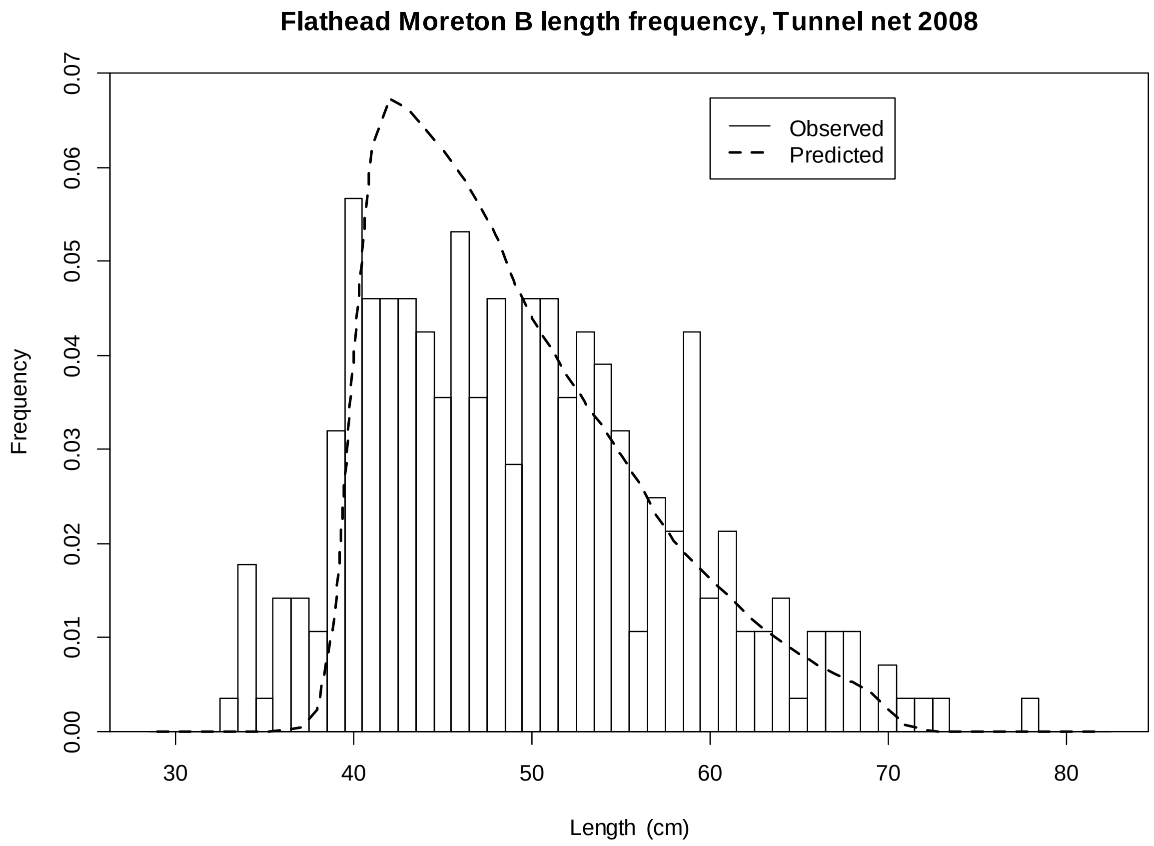

Flathead Moreton B length frequency, Gillnet 2015
Observed
Predicted
Frequency
0.00
0.02
0.04
0.06
0.08
30
40
50
60
70
80
Length (cm)


Flathead Moreton B length frequency, Gillnet 2016
Observed
Predicted
Frequency
0.00
0.02
0.04
0.06
30
40
50
60
70
80
Length (cm)


Flathead Moreton B length frequency, Tunnel net 2006
Observed
Predicted
Frequency
0.00
0.02
0.04
0.06
0.08
0.10
0.12
30
40
50
60
70
80
Length (cm)

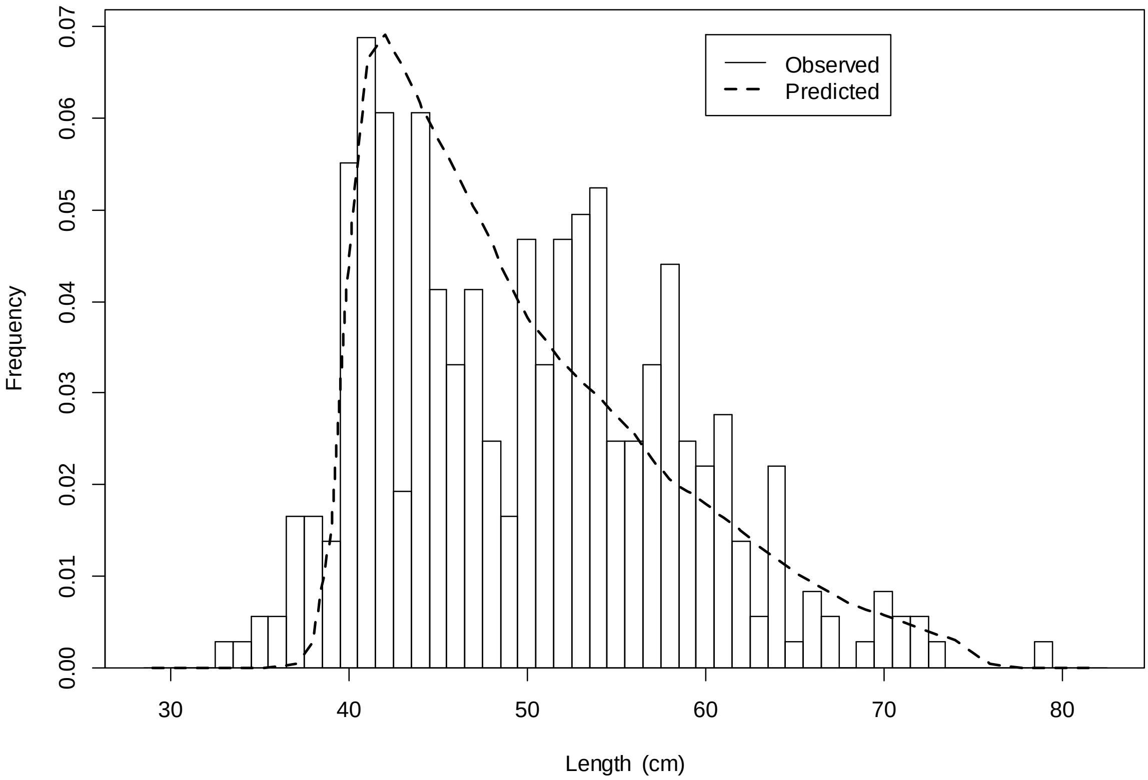


Flathead Moreton B length frequency, Tunnel net 2007

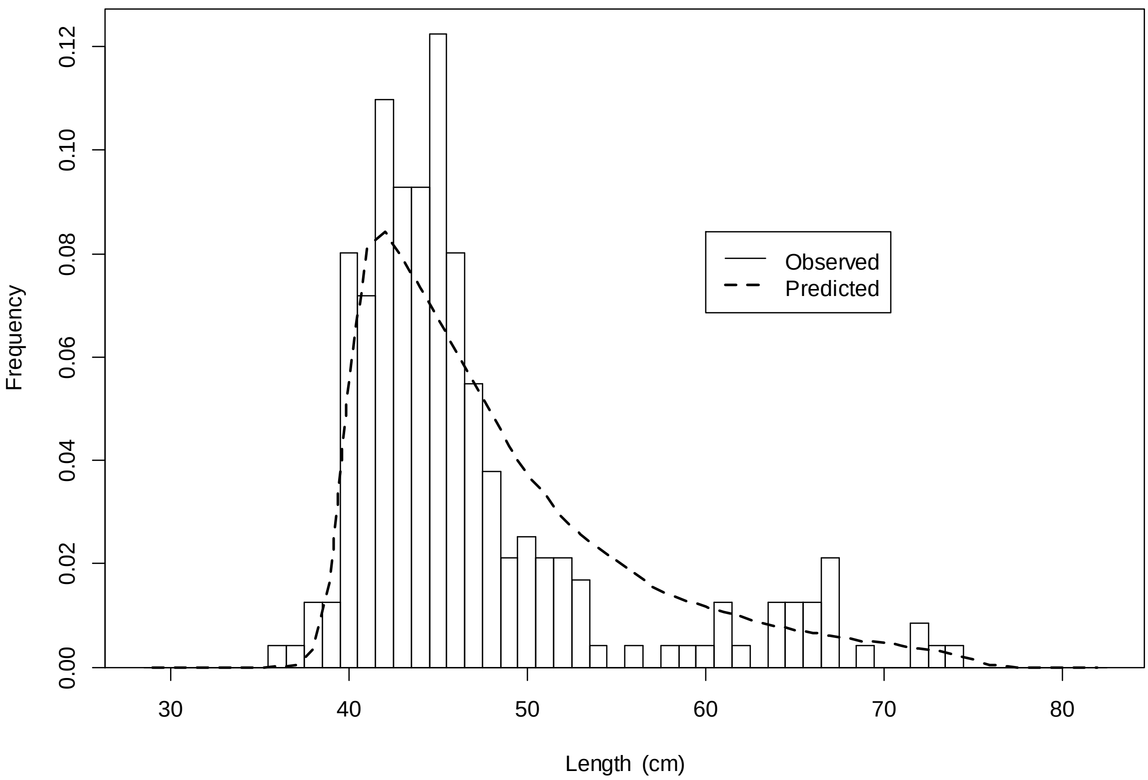


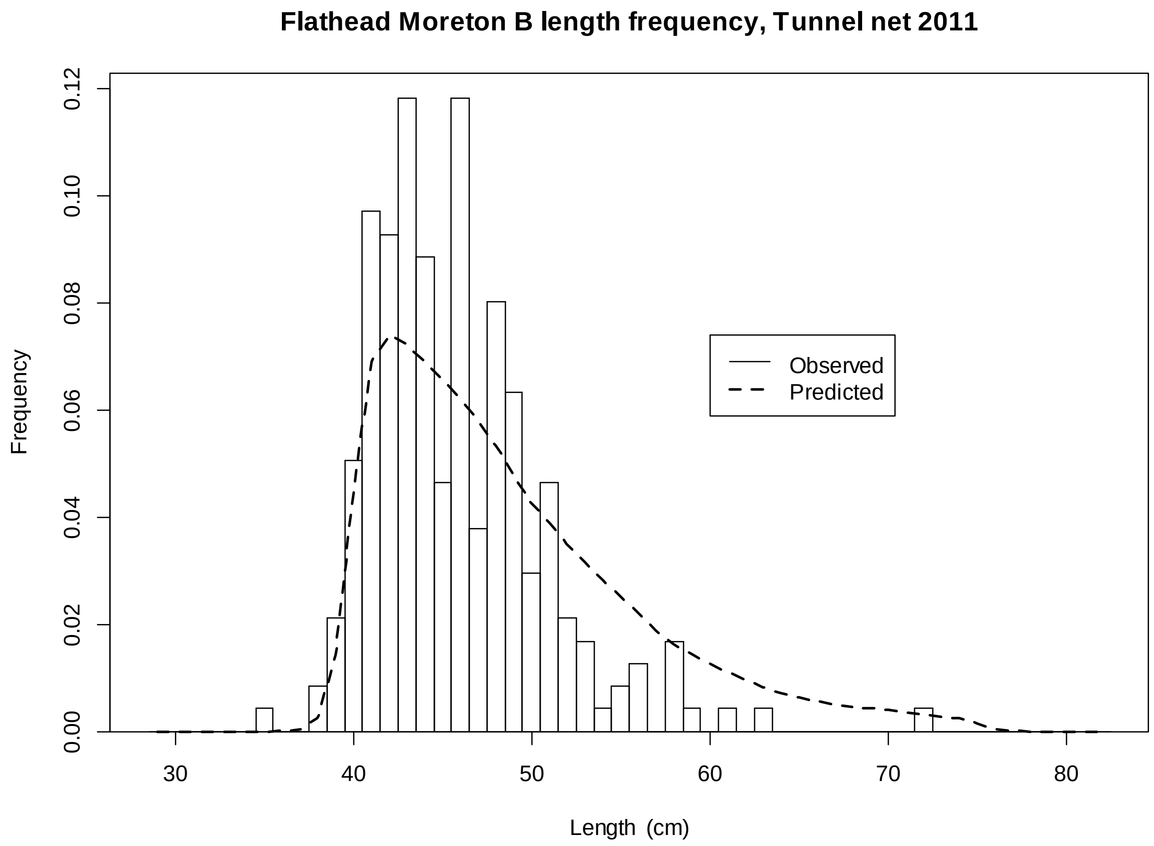
Flathead Moreton B length frequency, Tunnel net 2008

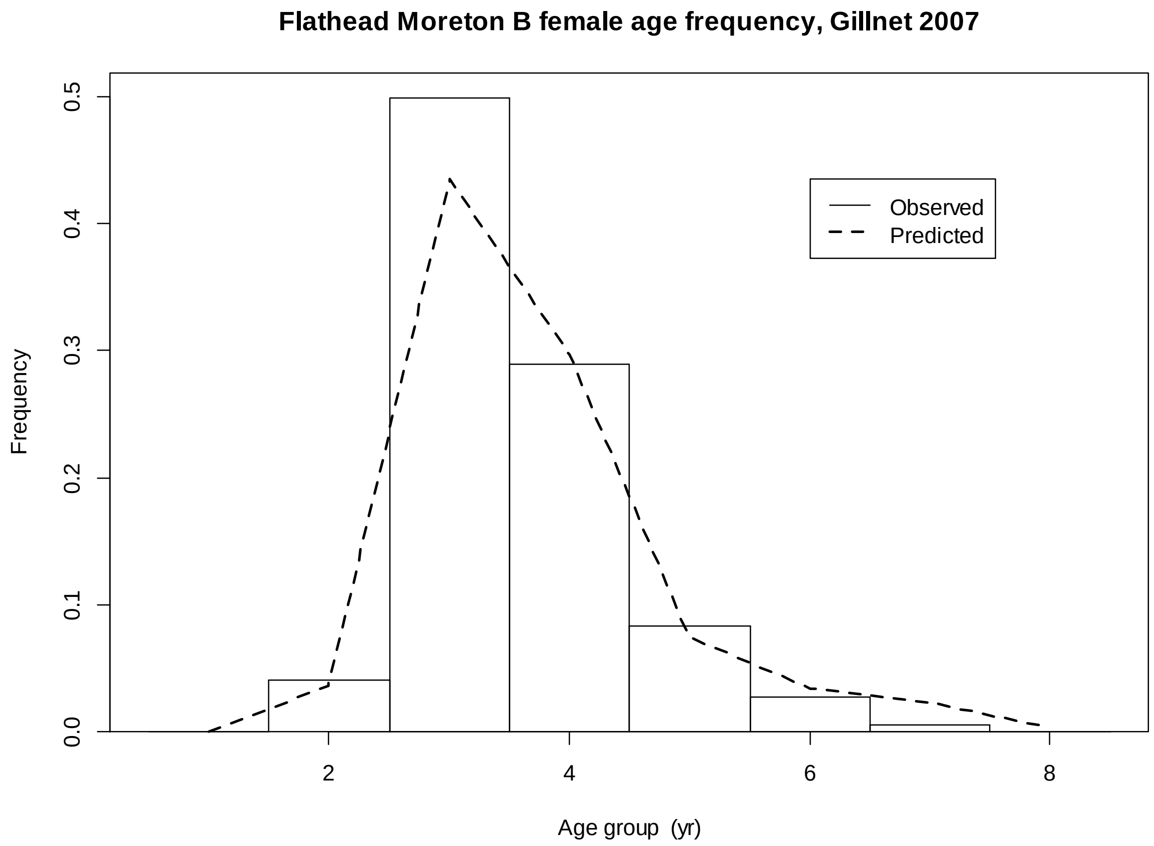
Flathead Moreton B length frequency, Tunnel net 2009



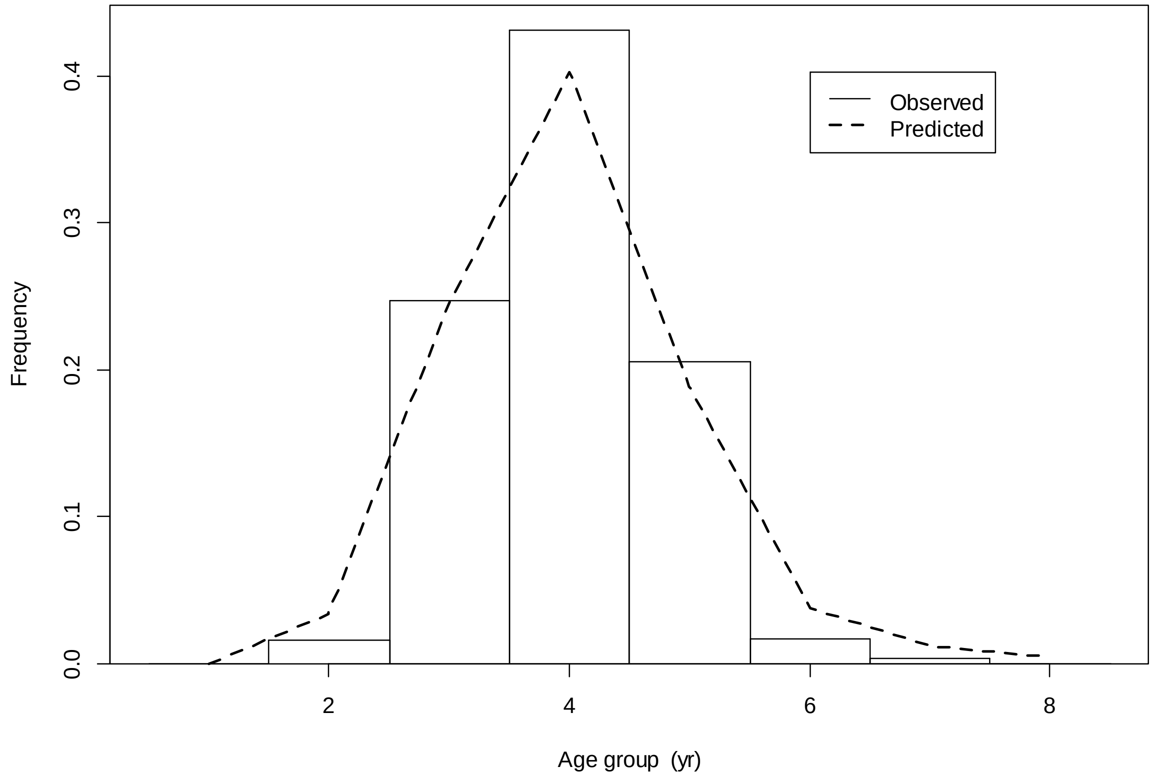
Flathead Moreton B length frequency, Tunnel net 2010



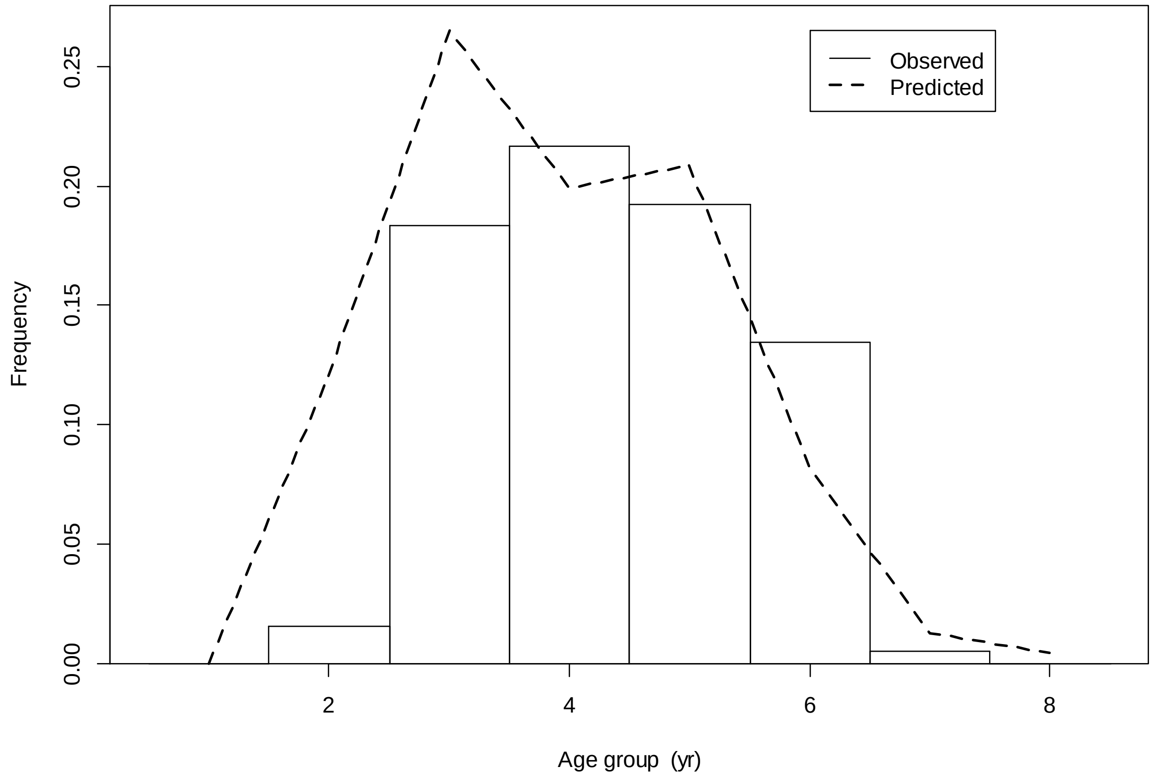

Flathead Moreton B length frequency, Tunnel net 2011
Frequency
0.00
0.02
0.04
0.06
0.08
0.10
0.12
30
40
50
60
70
80
Length (cm)
Observed
Predicted

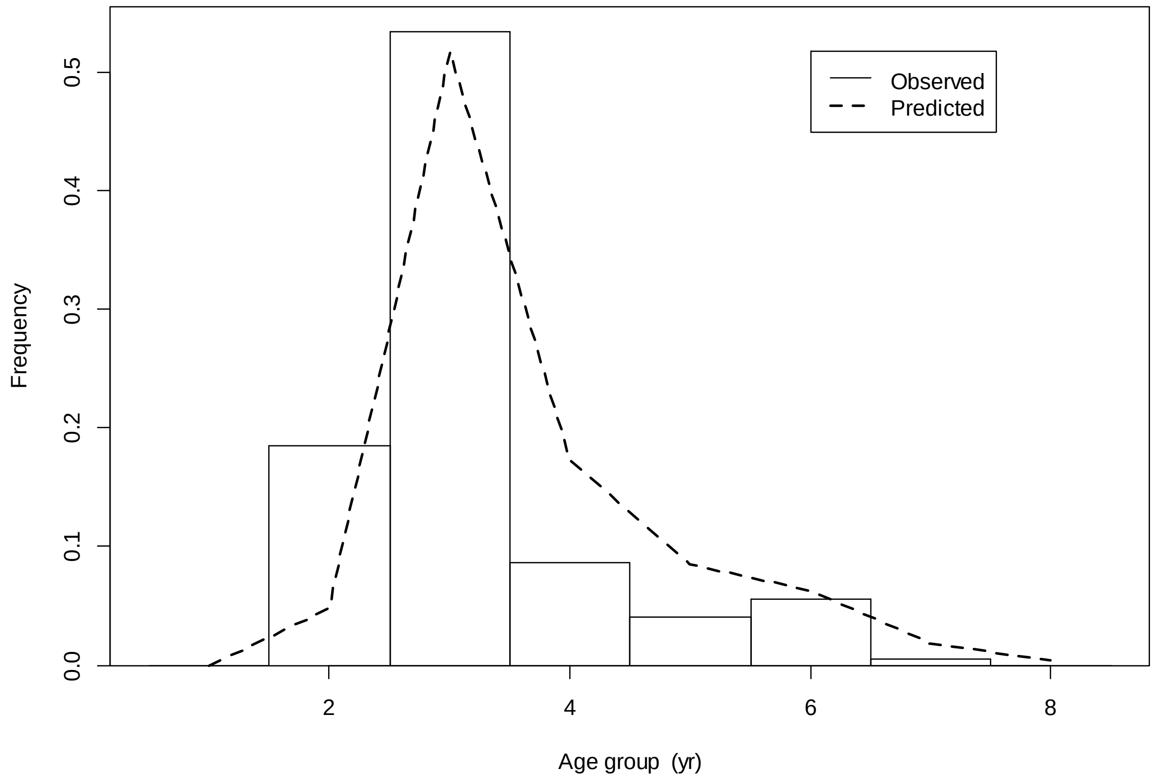

Flathead Moreton B female age frequency, Gillnet 2007
Frequency
0.0
0.1
0.2
0.3
0.4
0.5
2
4
6
8
Age group (yr)
Observed
Predicted

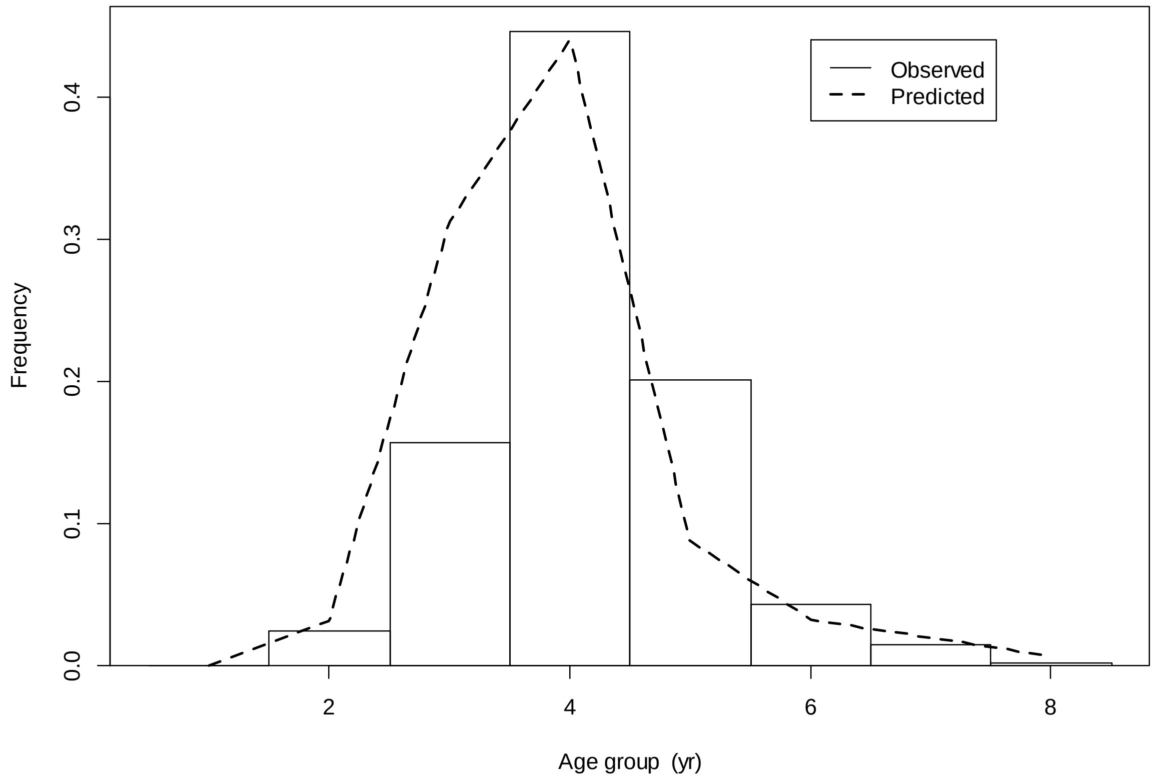
Flathead Moreton B female age frequency, Gillnet 2008



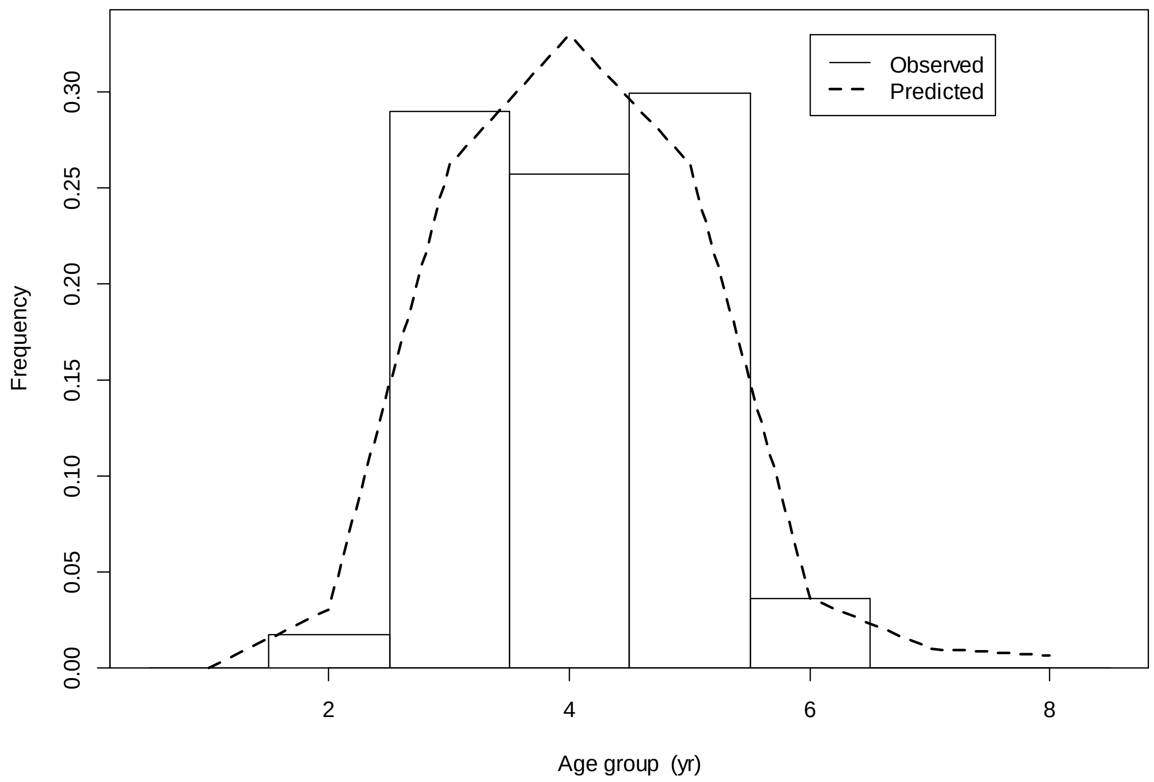
Flathead Moreton B female age frequency, Gillnet 2009



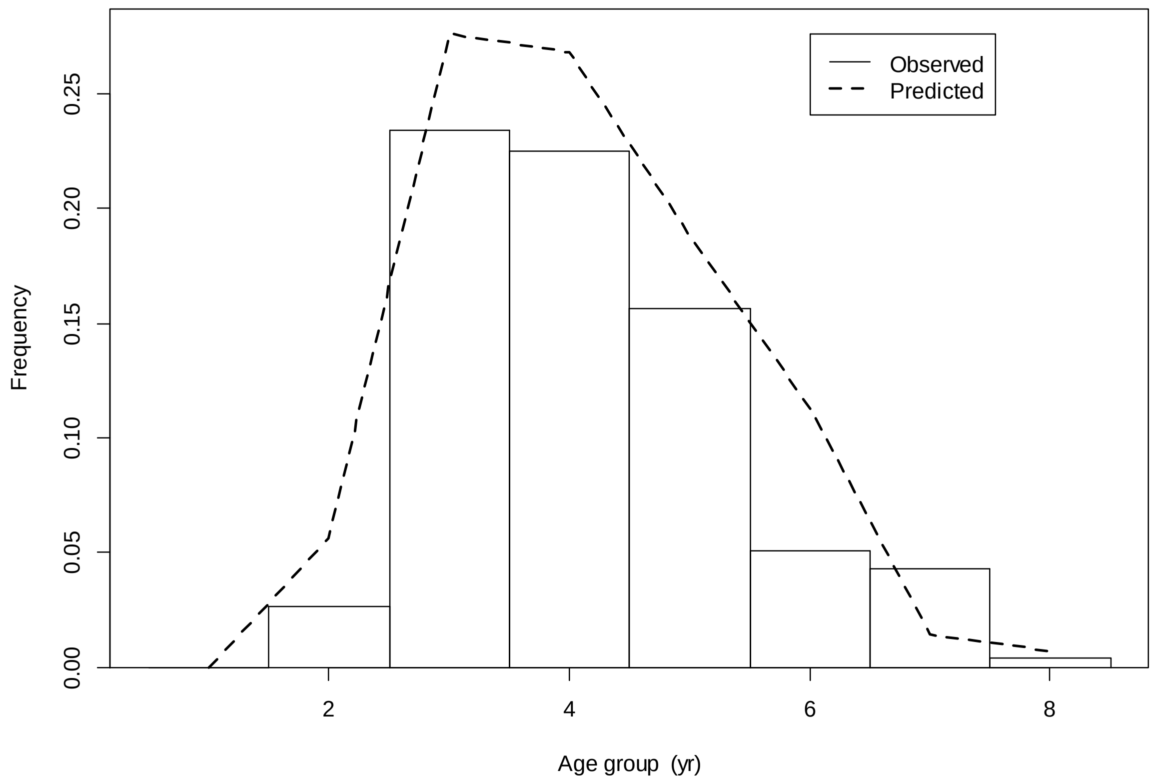

Flathead Moreton B female age frequency, Gillnet 2010


Flathead Moreton B female age frequency, Gillnet 2011

Flathead Moreton B female age frequency, Gillnet 2012

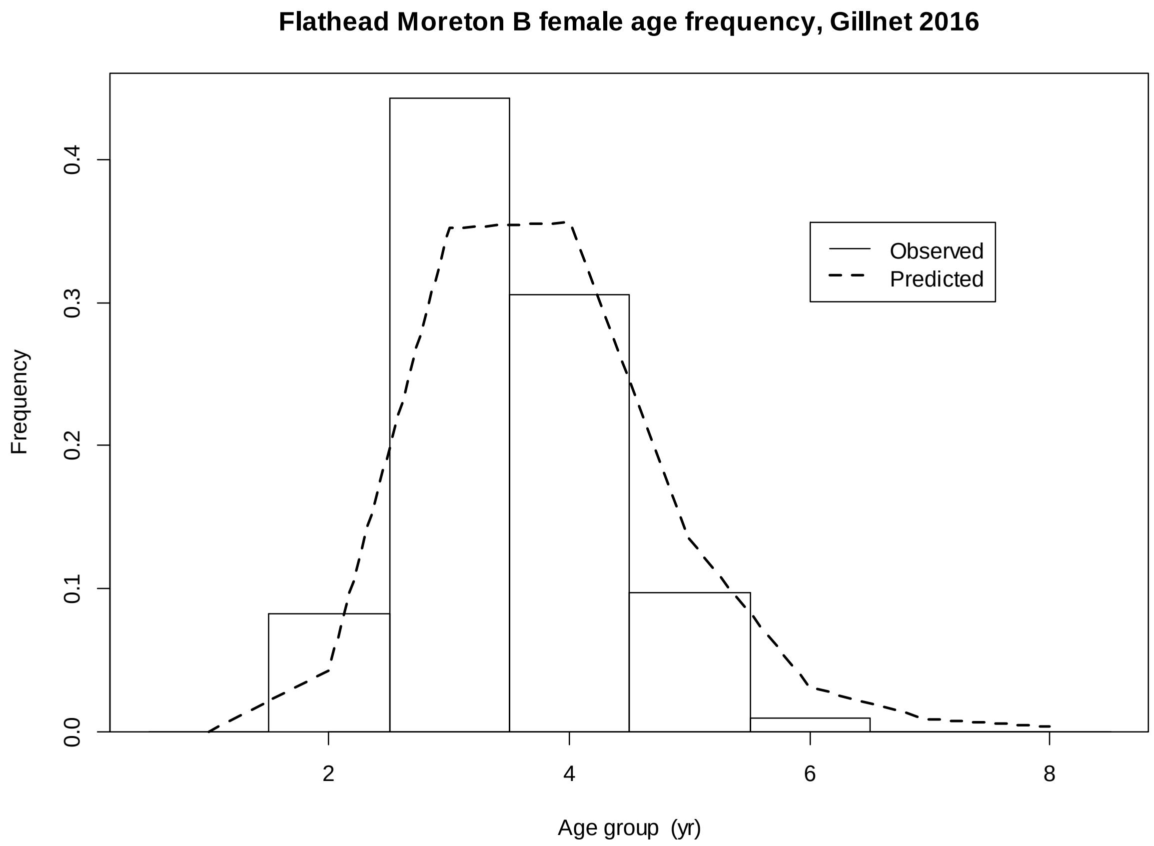


Flathead Moreton B female age frequency, Gillnet 2013

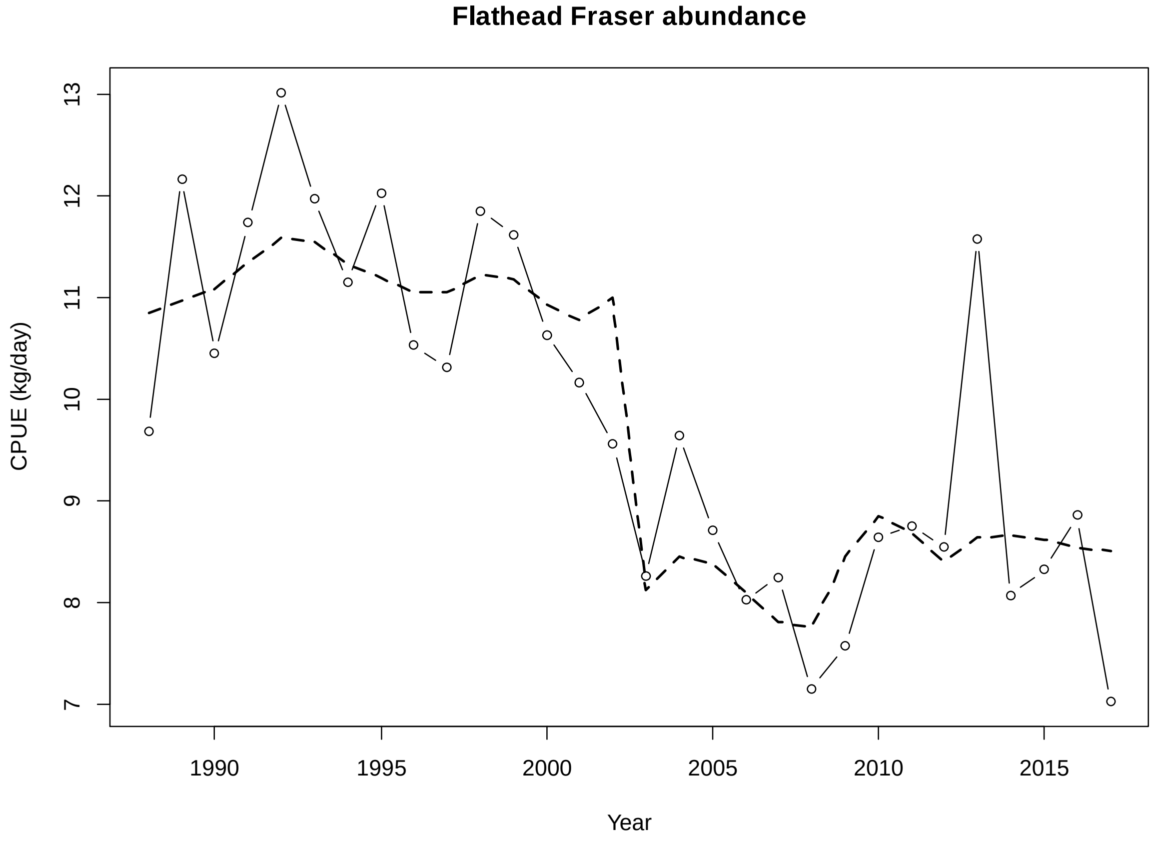


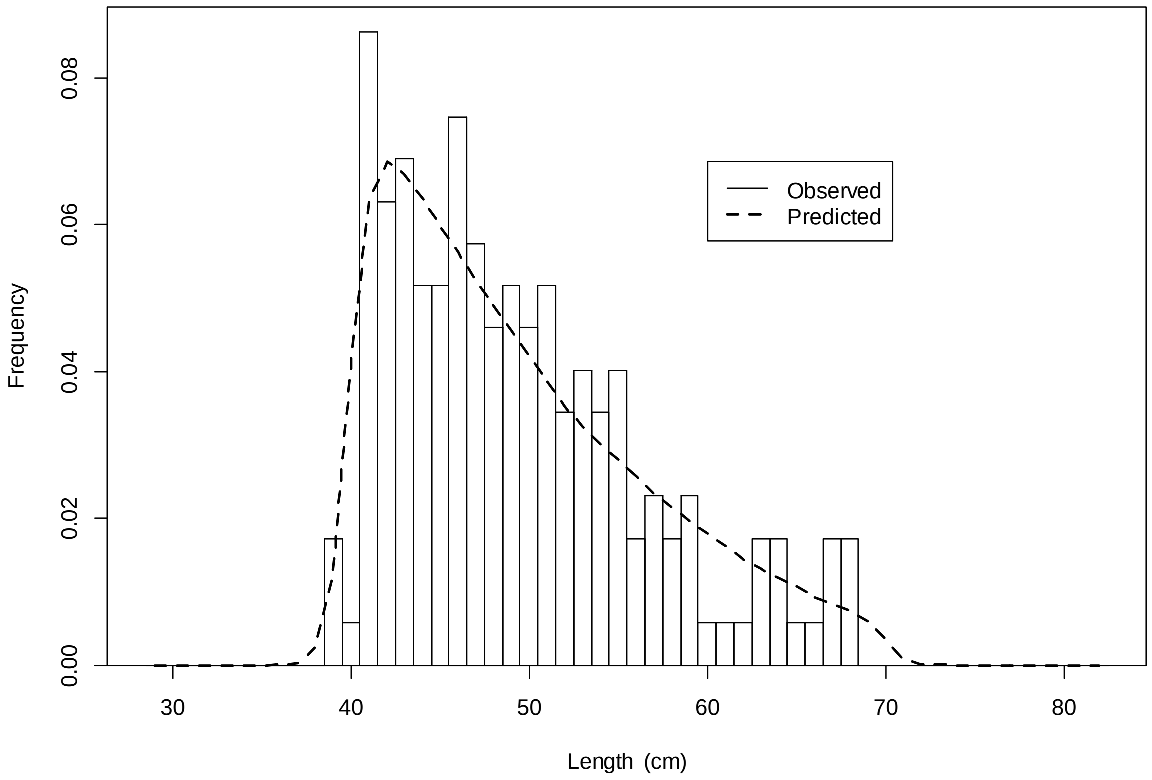

Flathead Moreton B female age frequency, Gillnet 2014


Flathead Moreton B female age frequency, Gillnet 2015

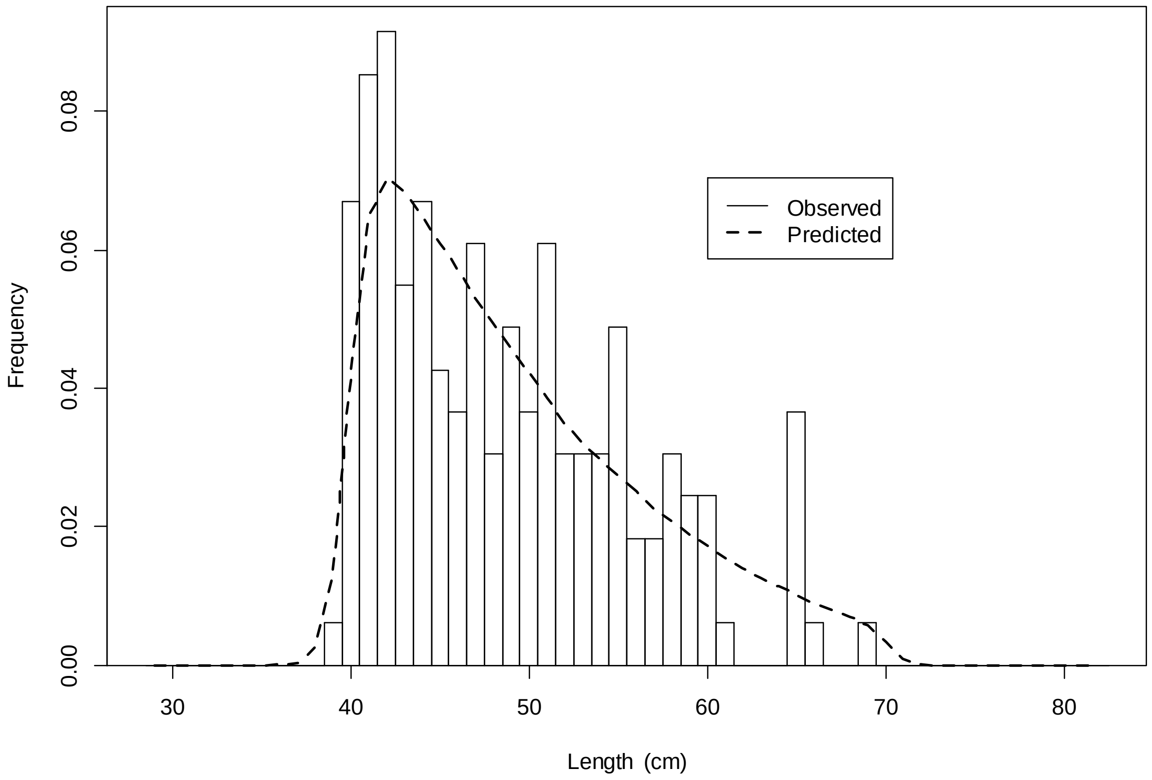


A2.5 Flathead Fraser

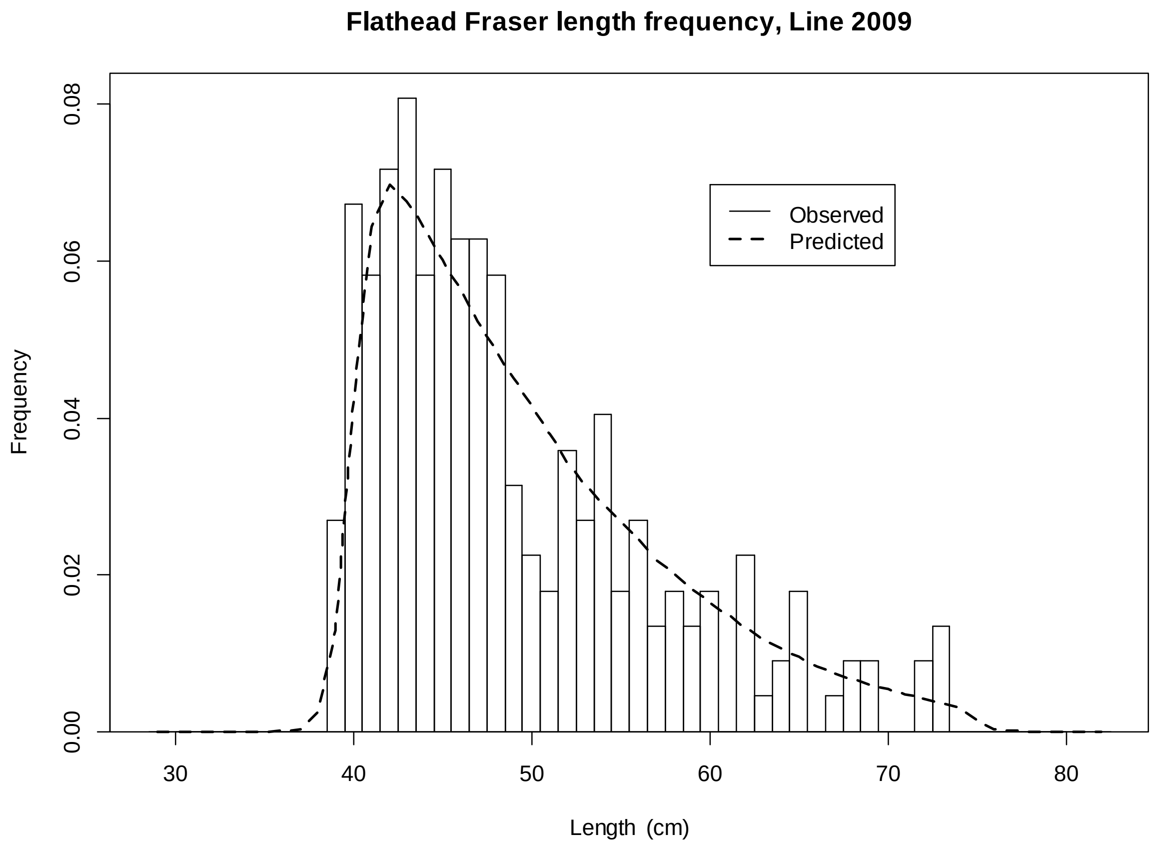


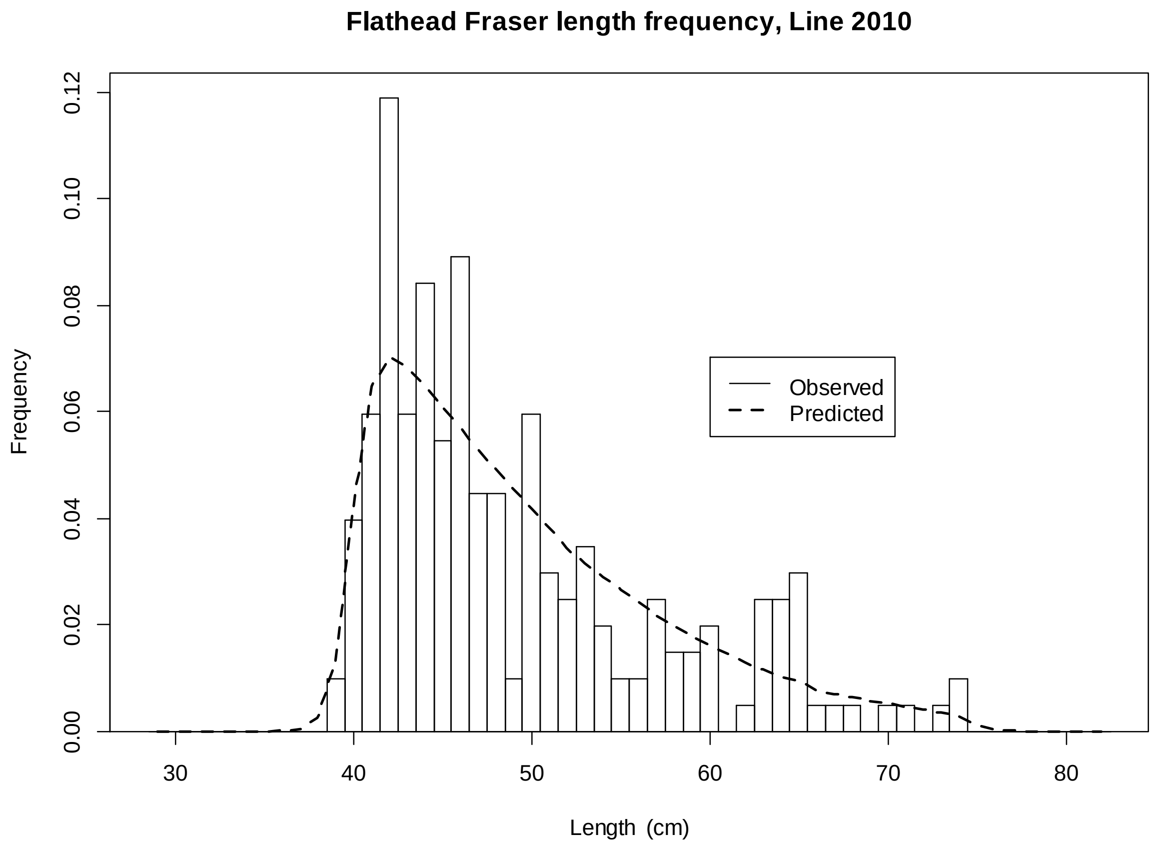


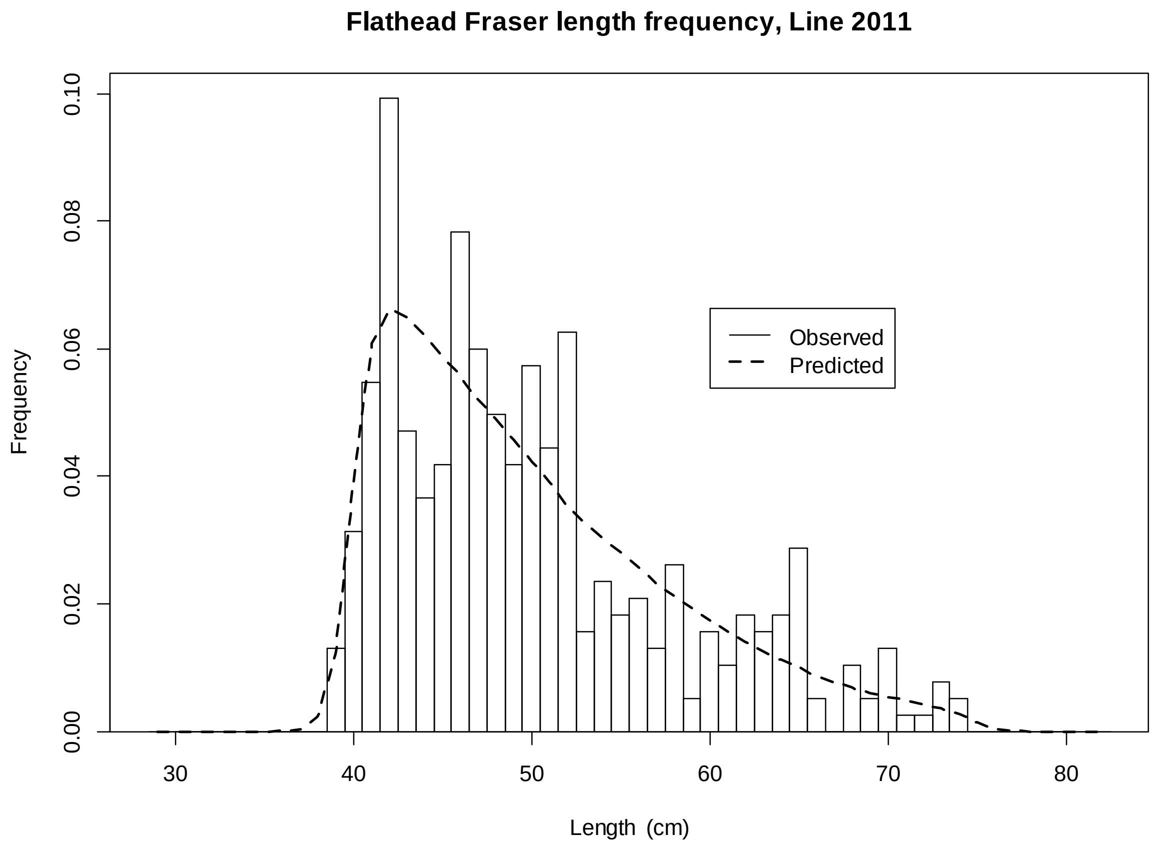
Flathead Fraser length frequency, Line 2007

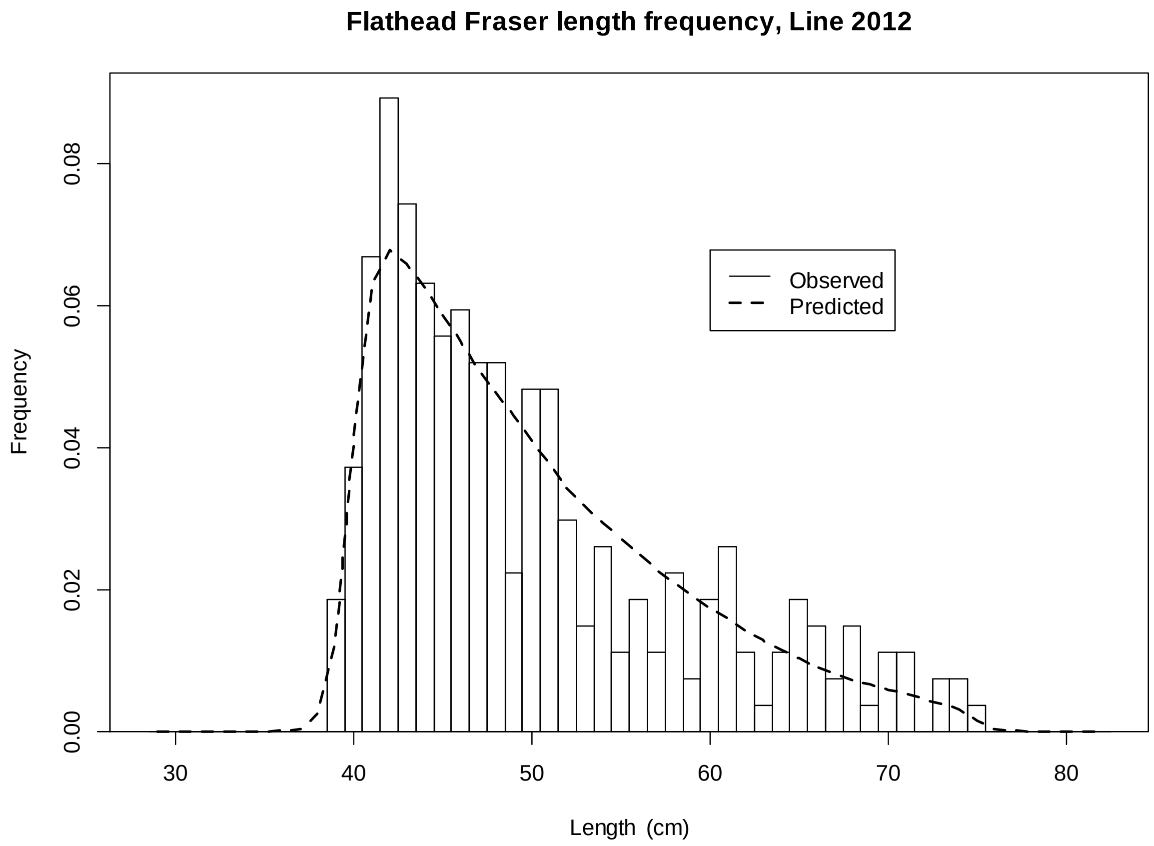


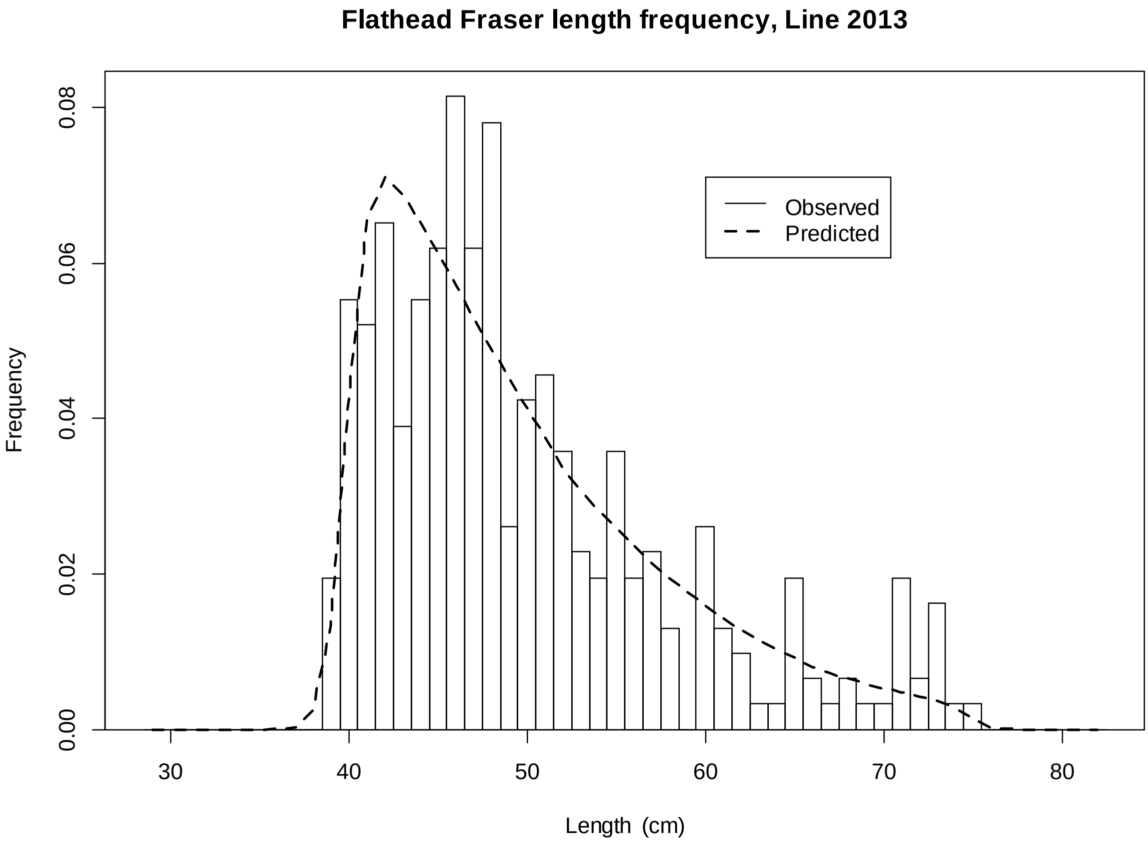
Flathead Fraser length frequency, Line 2008

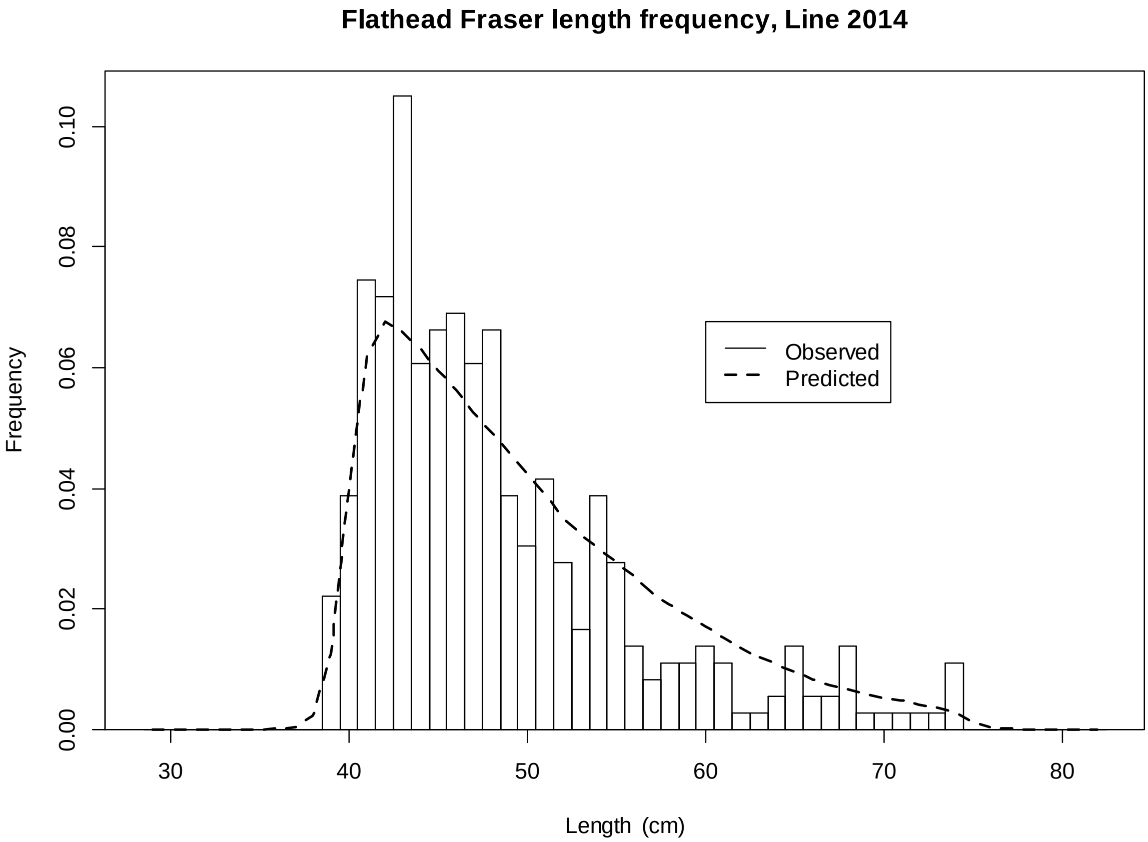

Flathead Fraser length frequency, Line 2009
Frequency
0.00
0.02
0.04
0.06
0.08
30
40
50
60
70
80
Length (cm)
Observed
Predicted


Flathead Fraser length frequency, Line 2010
Frequency
0.00
0.02
0.04
0.06
0.08
0.10
0.12
30
40
50
60
70
80
Length (cm)
Observed
Predicted

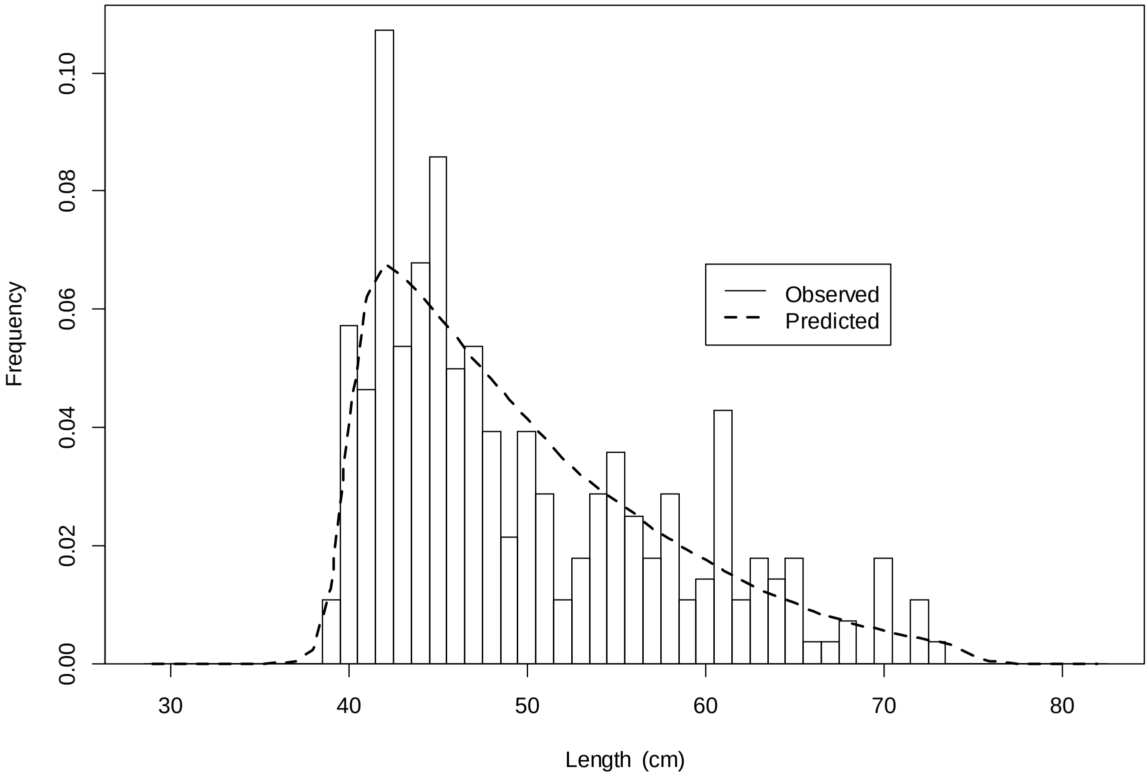

Flathead Fraser length frequency, Line 2011
Frequency
0.00
0.02
0.04
0.06
0.08
0.10
30
40
50
60
70
80
Length (cm)
Observed
Predicted


Flathead Fraser length frequency, Line 2012
Frequency
0.00
0.02
0.04
0.06
0.08
30
40
50
60
70
80
Length (cm)
Observed
Predicted

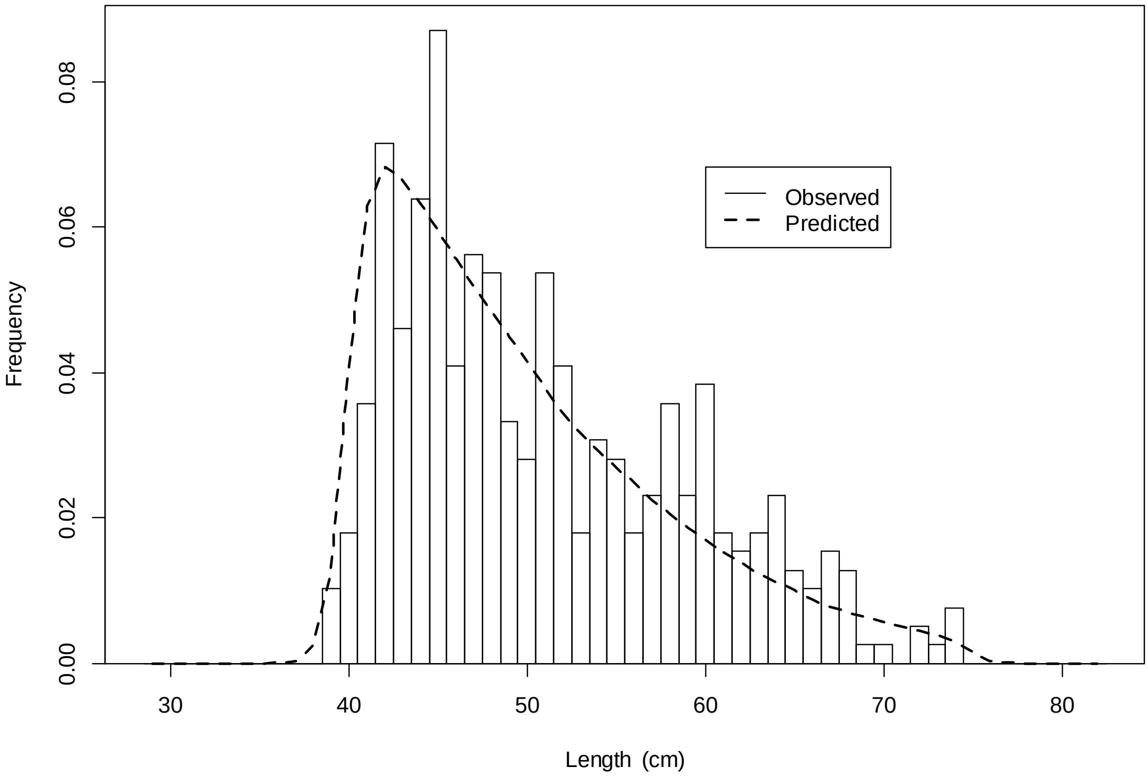

Flathead Fraser length frequency, Line 2013
Frequency
0.00
0.02
0.04
0.06
0.08
30
40
50
60
70
80
Length (cm)
Observed
Predicted

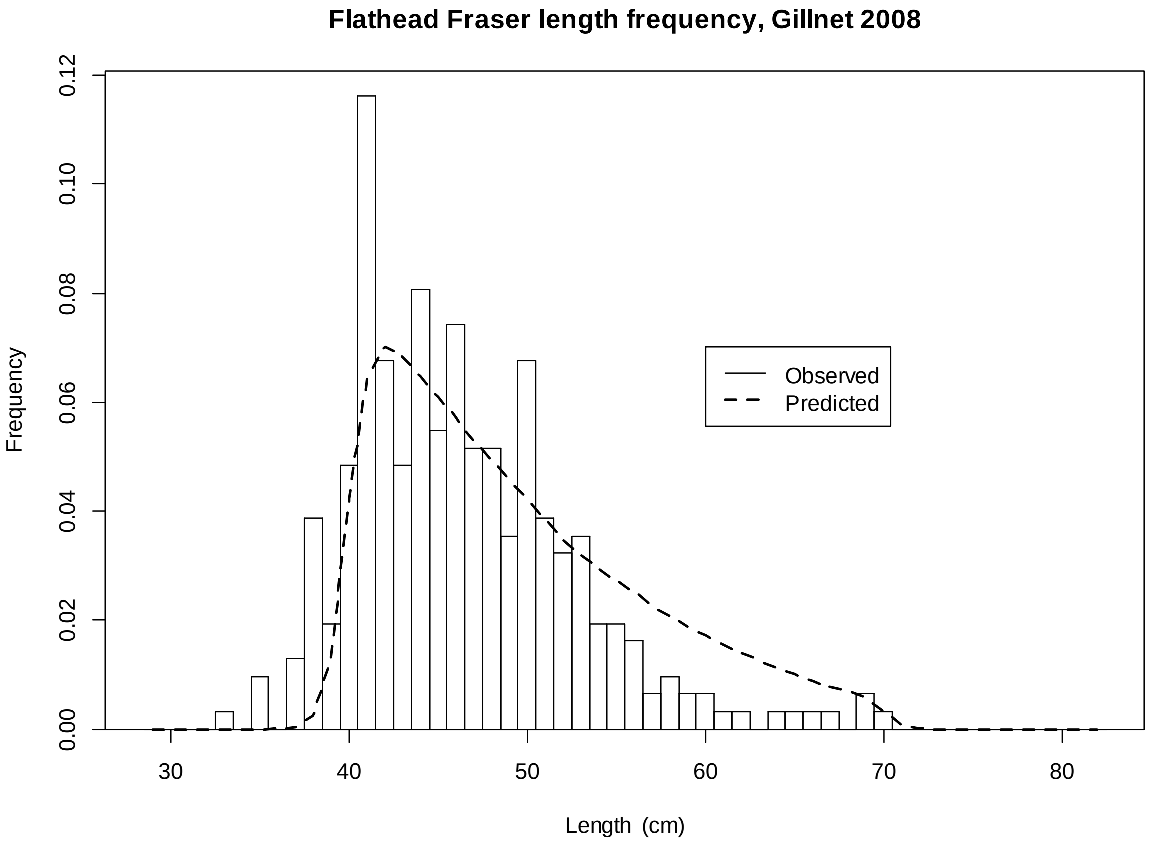

Flathead Fraser length frequency, Line 2014
Frequency
0.00
0.02
0.04
0.06
0.08
0.10
30
40
50
60
70
80
Length (cm)
Observed
Predicted

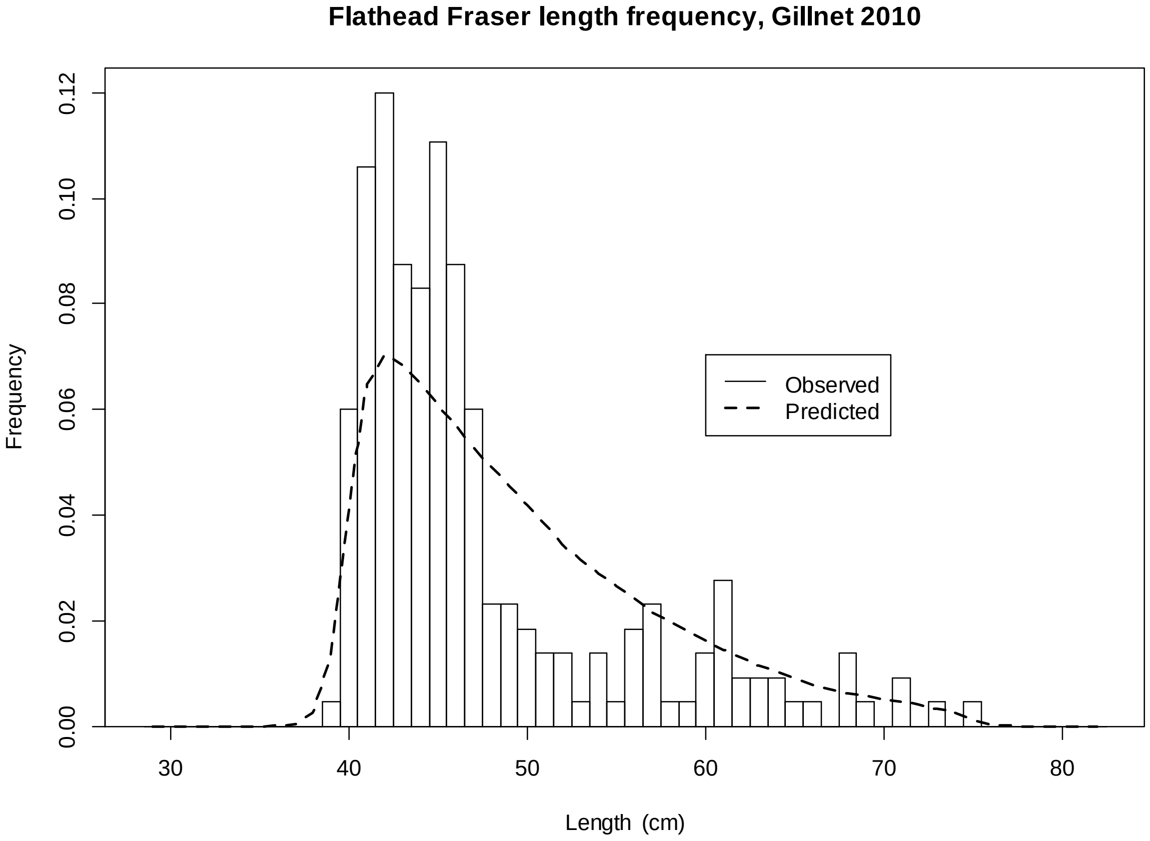
Flathead Fraser length frequency, Line 2015



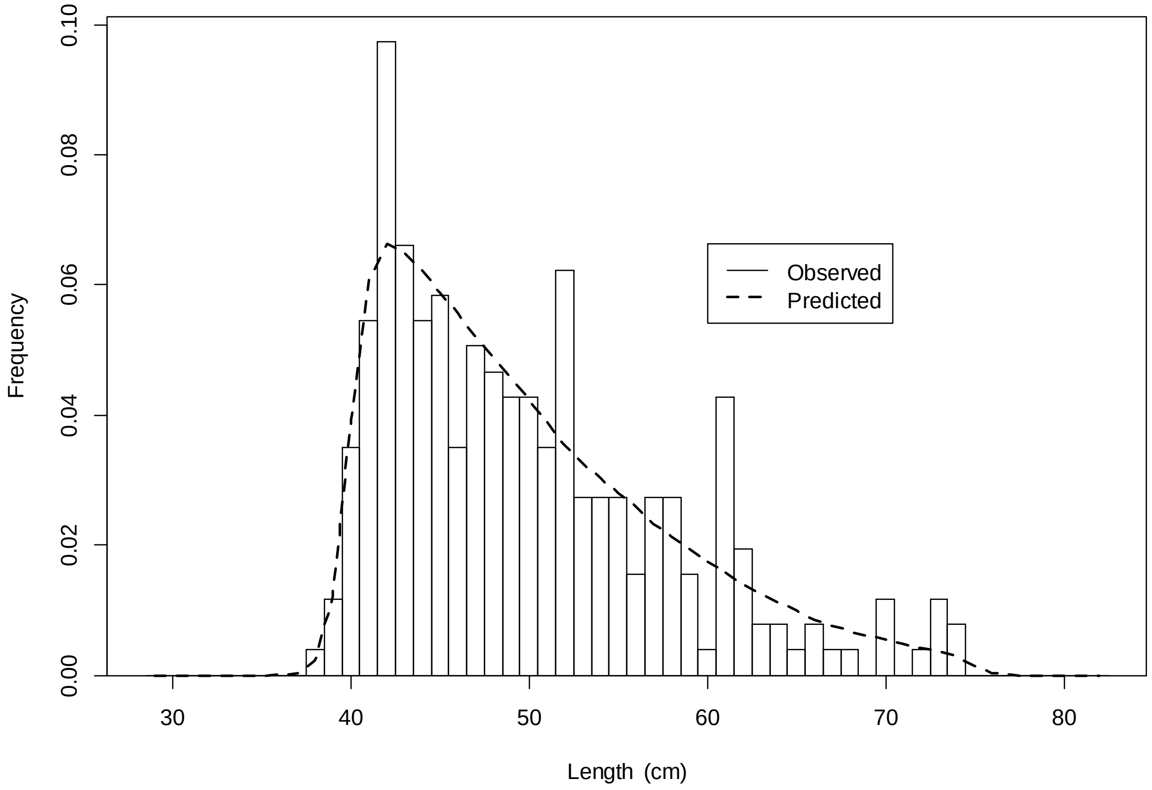
Flathead Fraser length frequency, Line 2016



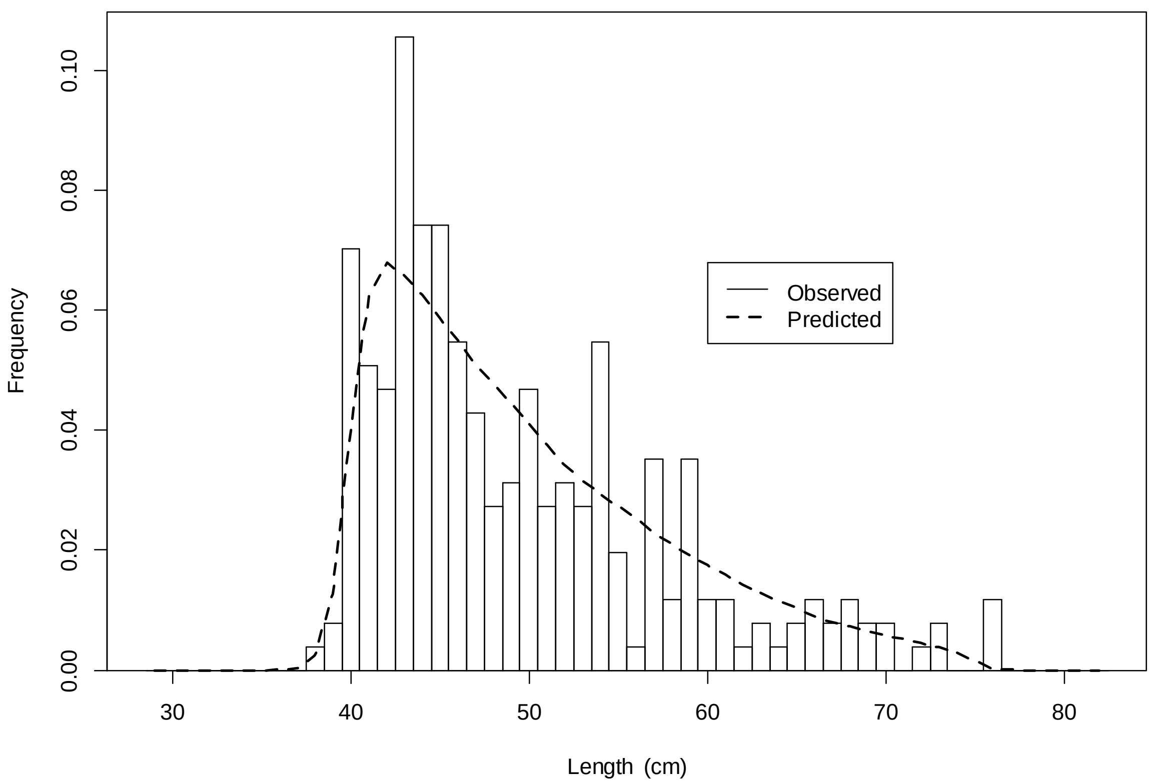

Flathead Fraser length frequency, Gillnet 2008
Frequency
0.00
0.02
0.04
0.06
0.08
0.10
0.12
30
40
50
60
70
80
Length (cm)
Observed
Predicted

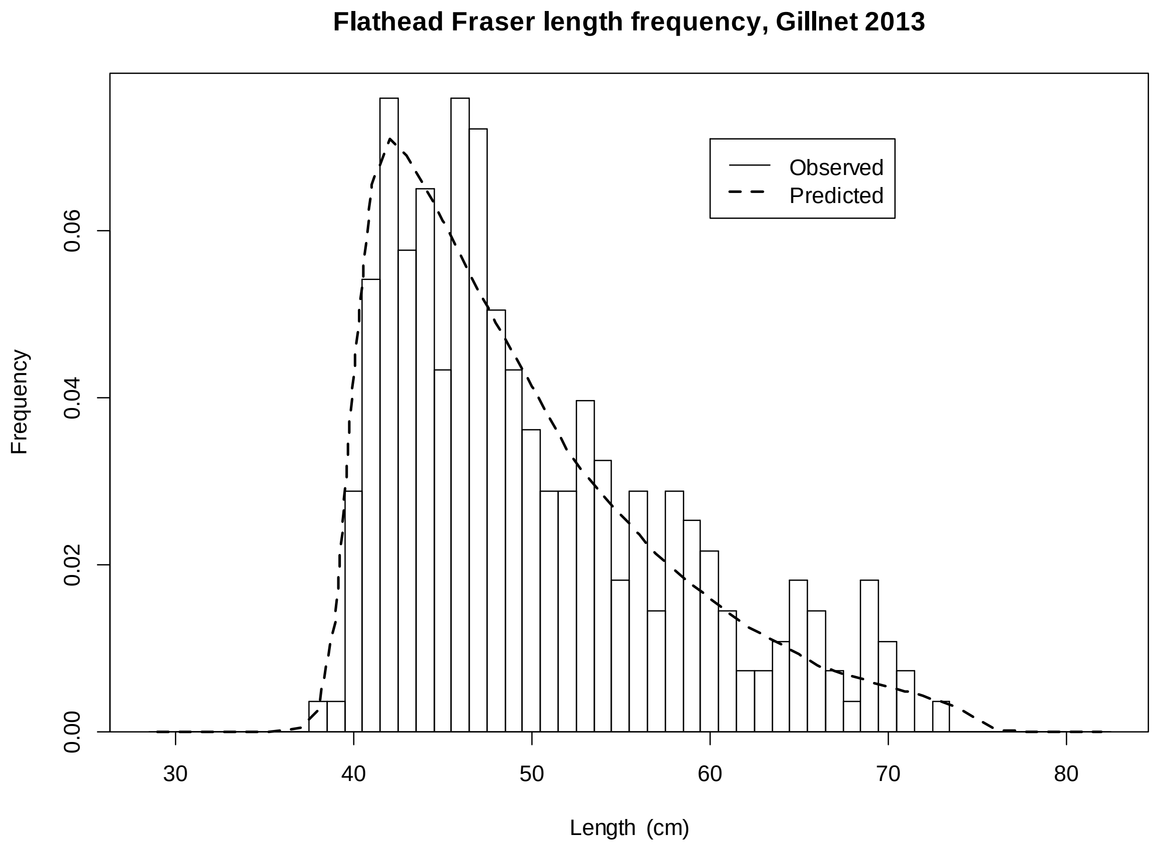

Flathead Fraser length frequency, Gillnet 2010
Frequency
0.00
0.02
0.04
0.06
0.08
0.10
0.12
30
40
50
60
70
80
Length (cm)
Observed
Predicted

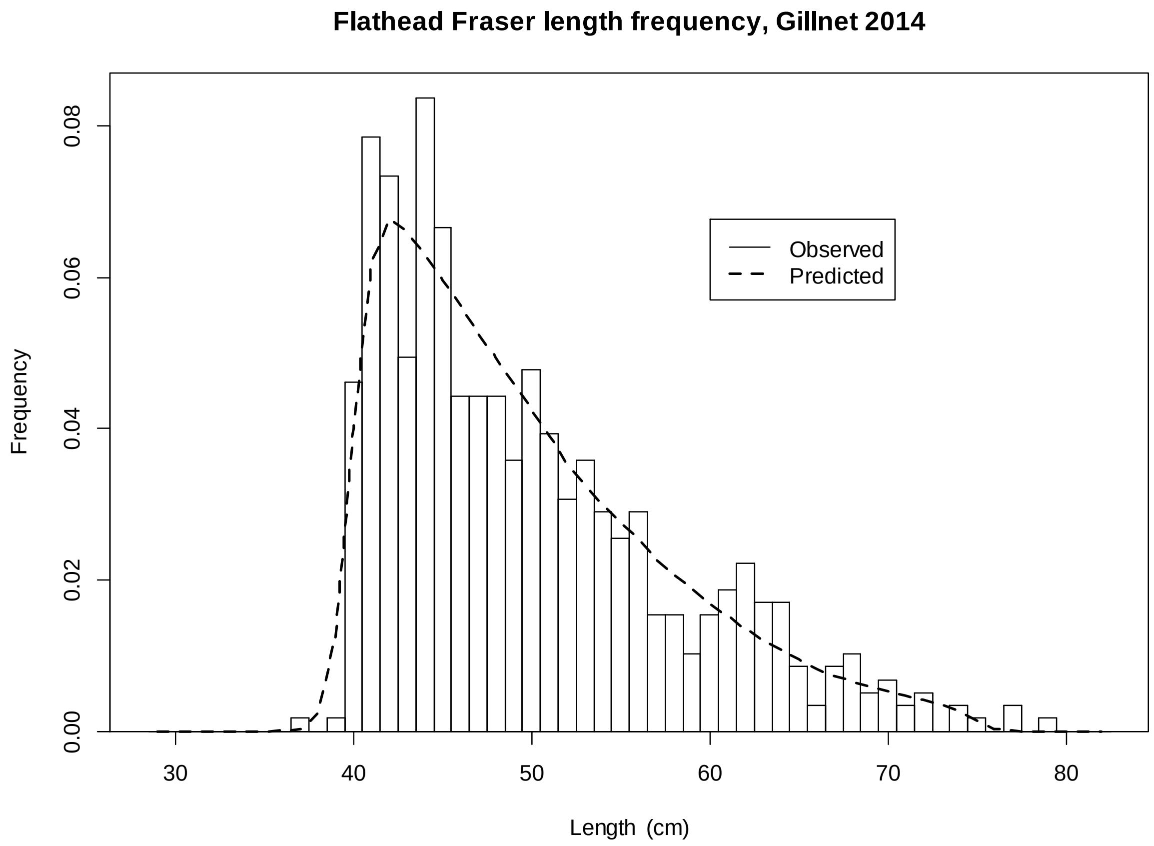
Flathead Fraser length frequency, Gillnet 2011

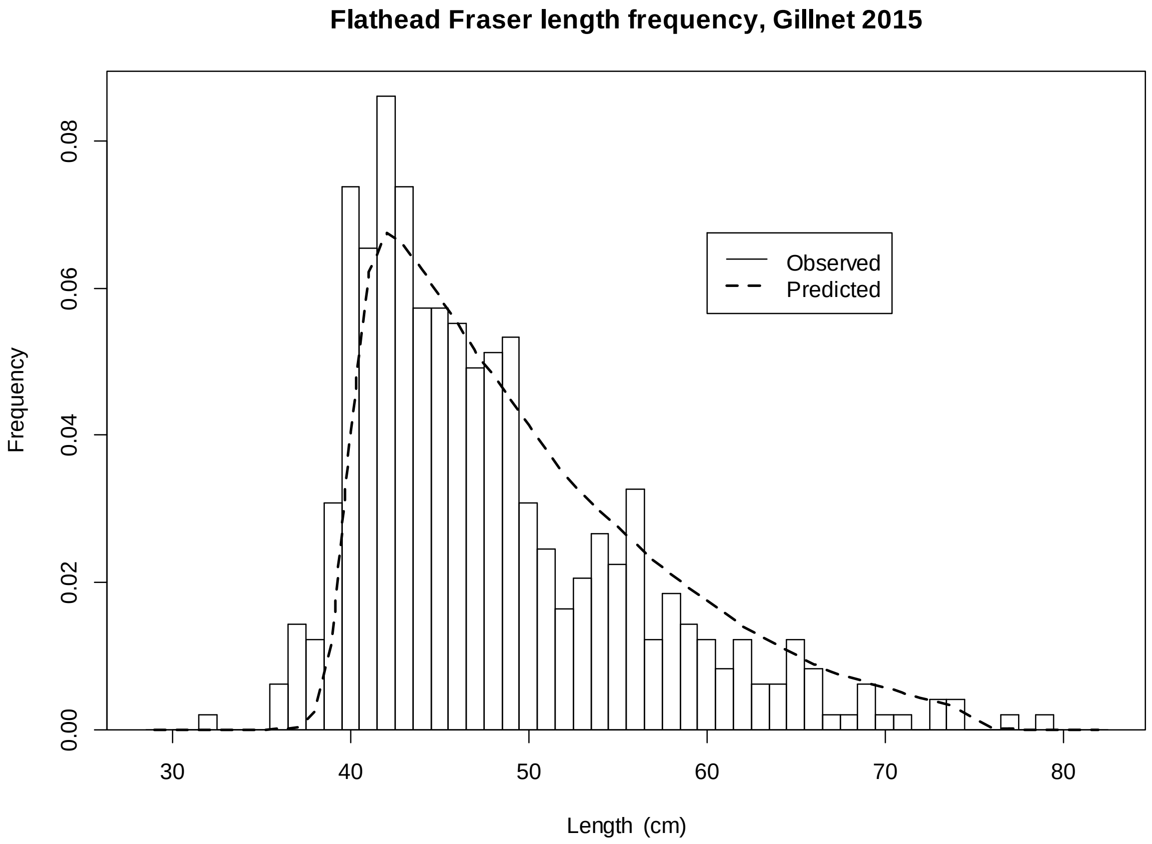


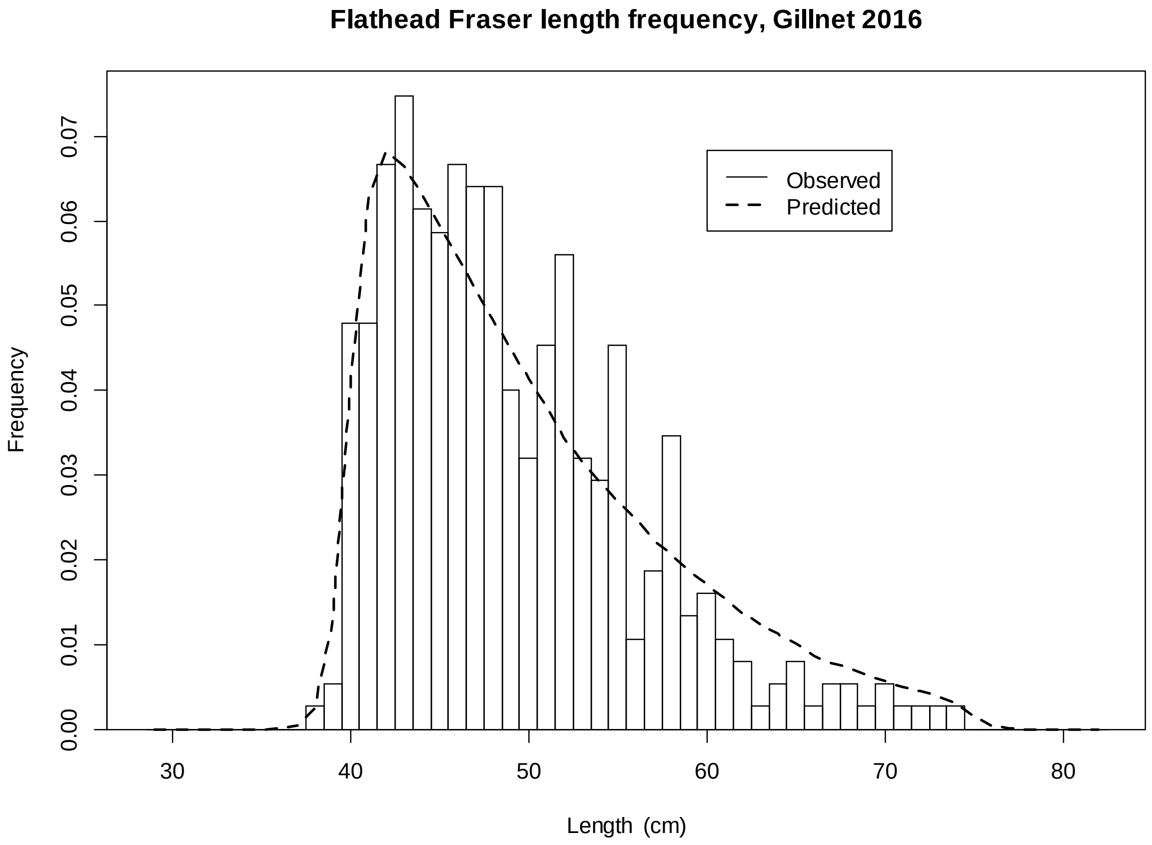
Flathead Fraser length frequency, Gillnet 2012



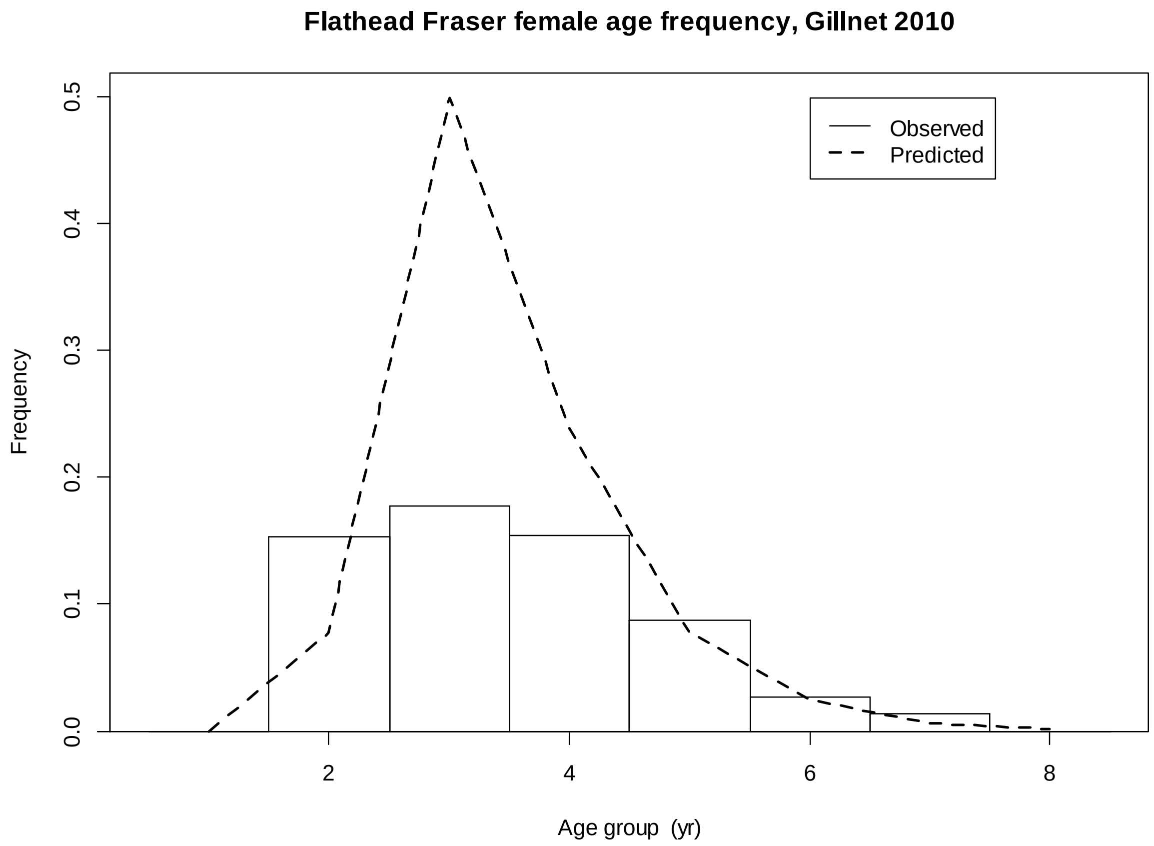

Flathead Fraser length frequency, Gillnet 2013
Observed
Predicted
Frequency
0.00
0.02
0.04
0.06
30
40
50
60
70
80
Length (cm)

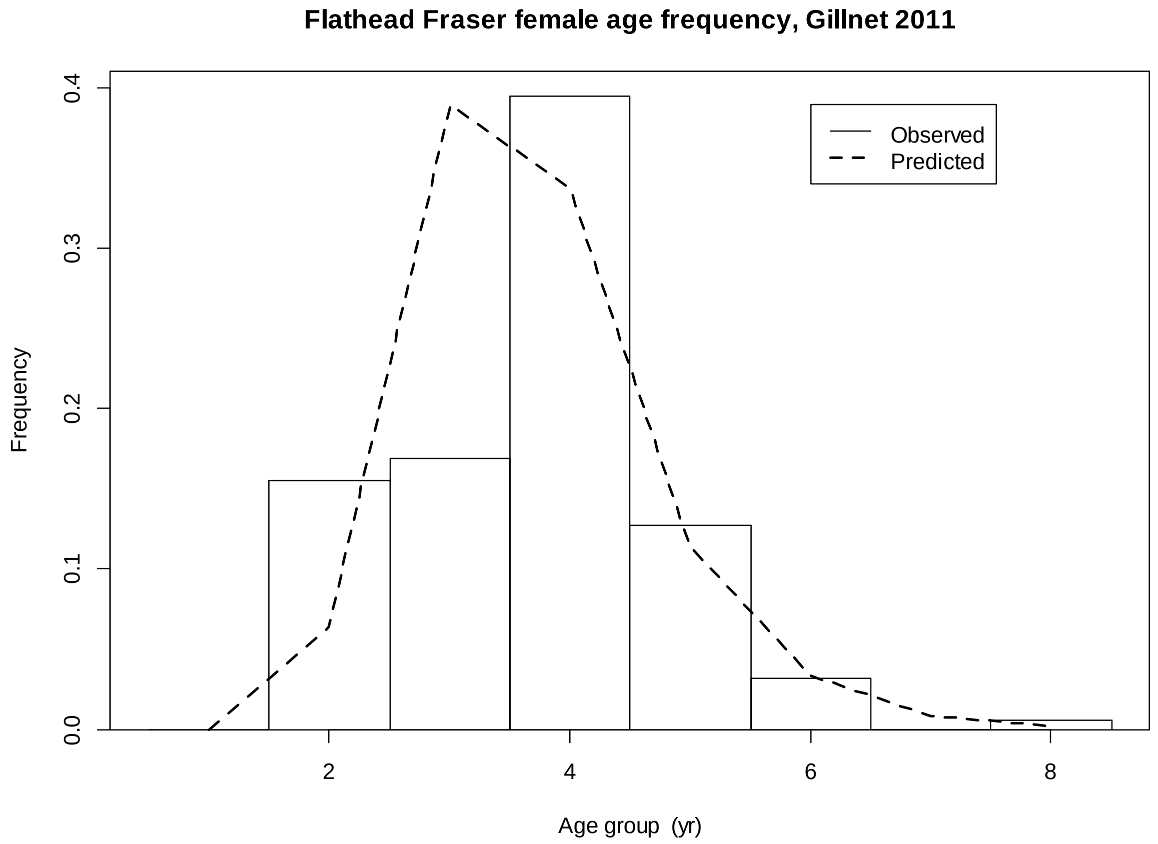

Flathead Fraser length frequency, Gillnet 2014
Observed
Predicted
Frequency
0.00
0.02
0.04
0.06
0.08
30
40
50
60
70
80
Length (cm)

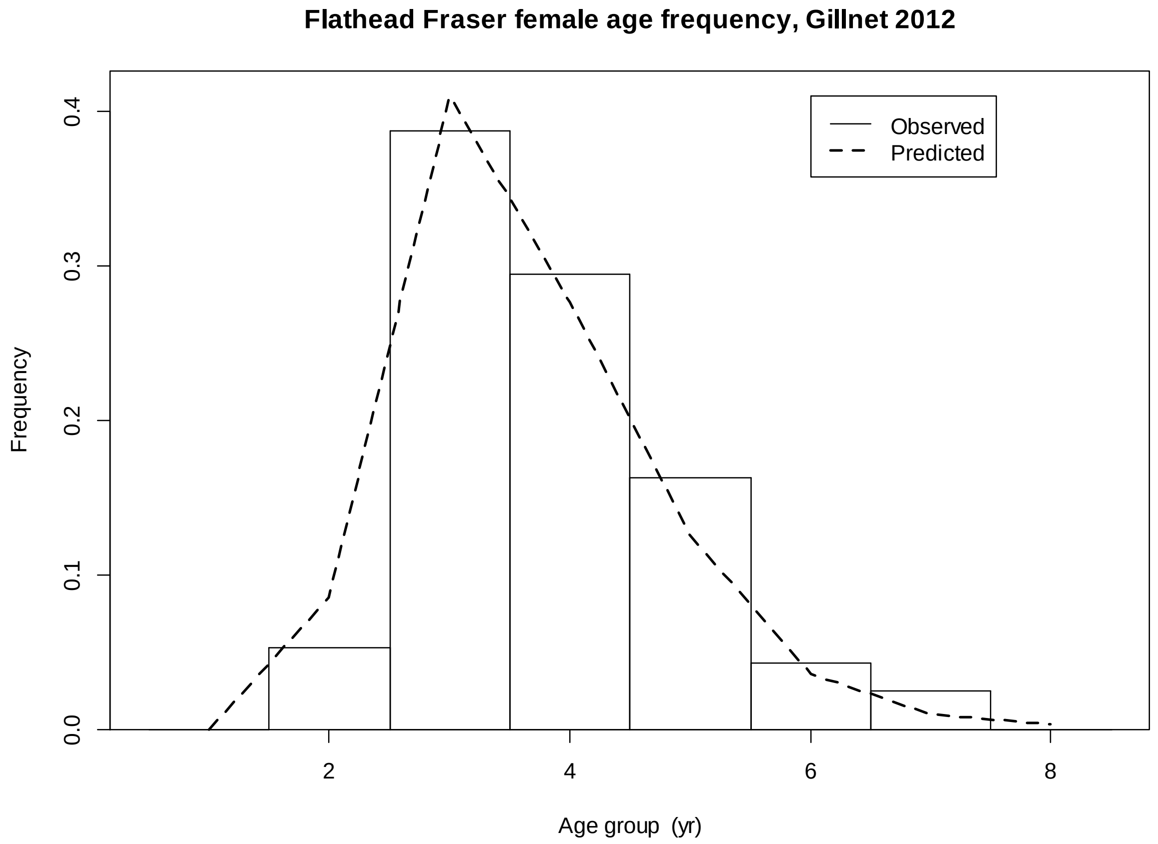

Flathead Fraser length frequency, Gillnet 2015
Frequency
0.00
0.02
0.04
0.06
0.08
Length (cm)
30
40
50
60
70
80
Observed
Predicted

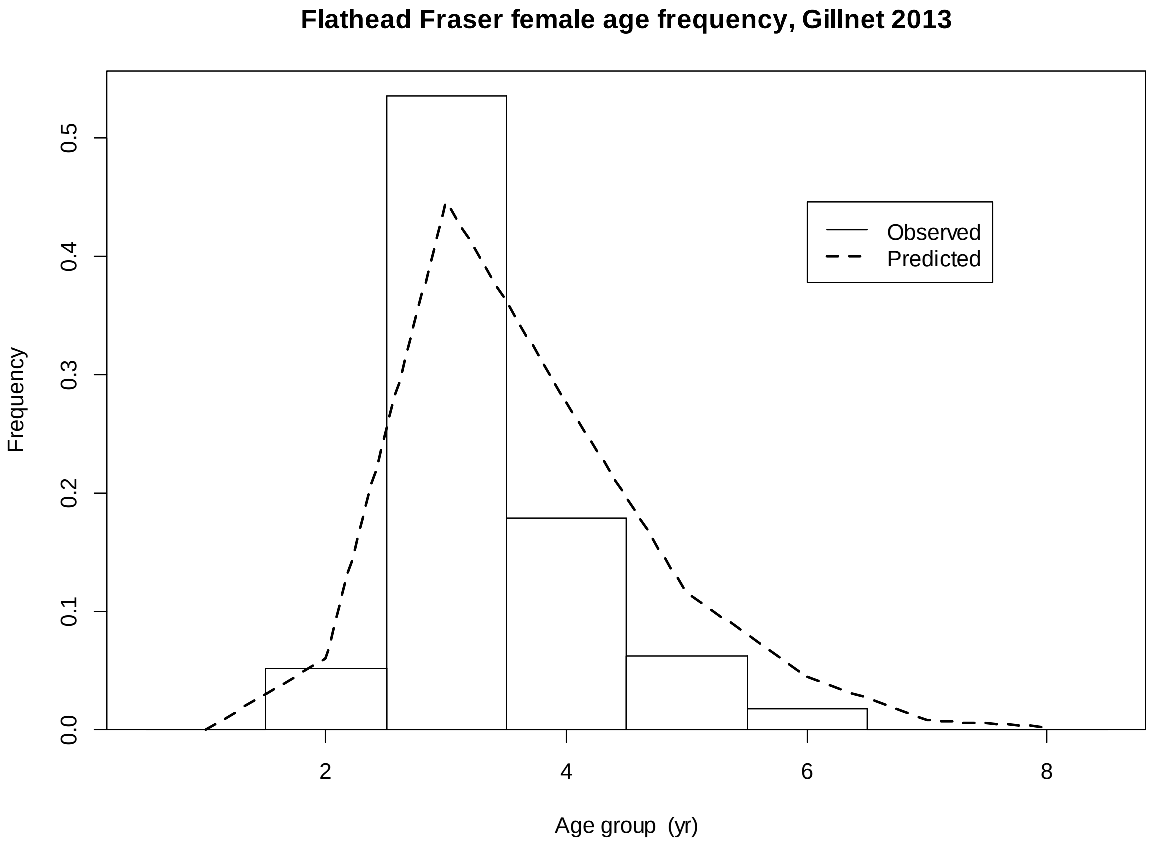

Flathead Fraser length frequency, Gillnet 2016
Frequency
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
Length (cm)
30
40
50
60
70
80
Observed
Predicted

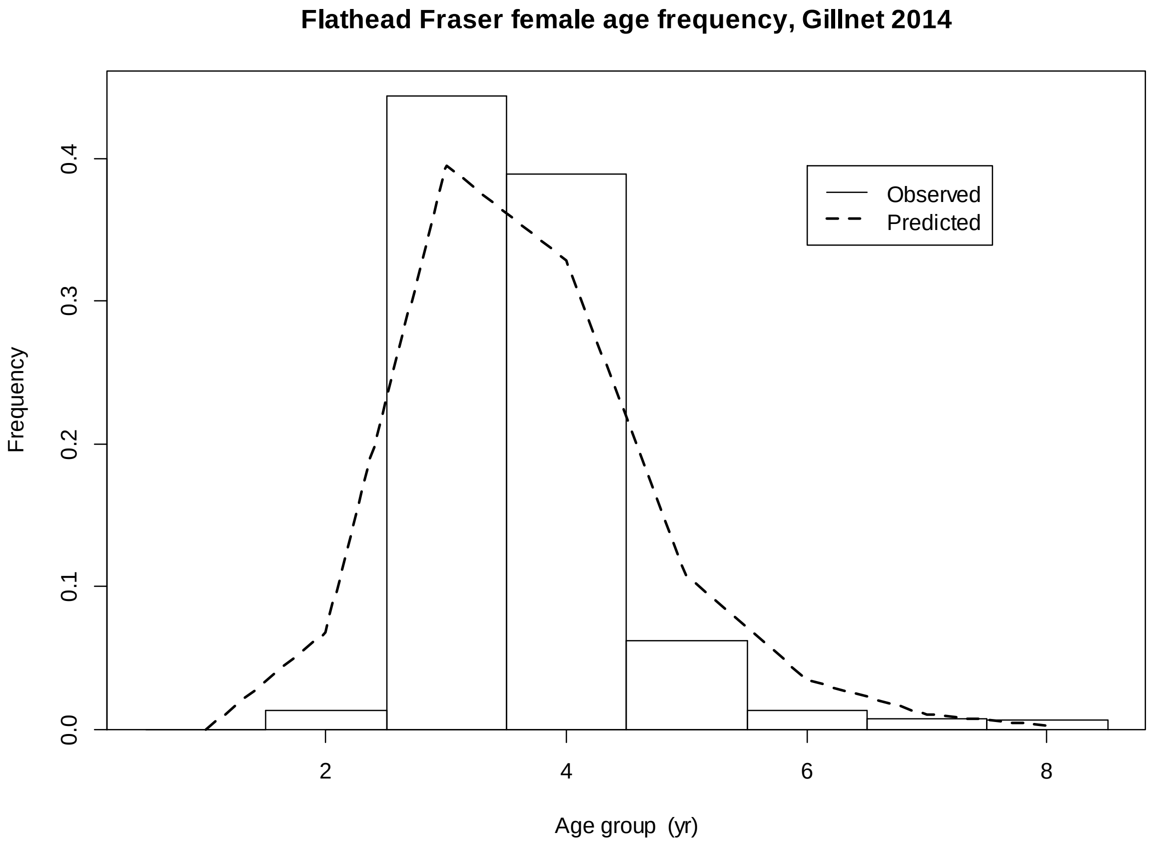

Flathead Fraser female age frequency, Gillnet 2008
Observed
Predicted
Frequency
0.0
0.1
0.2
0.3
0.4
0.5
2
4
6
8
Age group (yr)


Flathead Fraser female age frequency, Gillnet 2010
Observed
Predicted
Frequency
0.0
0.1
0.2
0.3
0.4
0.5
2
4
6
8
Age group (yr)


Flathead Fraser female age frequency, Gillnet 2011


Flathead Fraser female age frequency, Gillnet 2012


Flathead Fraser female age frequency, Gillnet 2013
Frequency
0.0
0.1
0.2
0.3
0.4
0.5
Age group (yr)
2
4
6
8
Observed
Predicted


Flathead Fraser female age frequency, Gillnet 2014
Frequency
0.0
0.1
0.2
0.3
0.4
Age group (yr)
2
4
6
8
Observed
Predicted


Flathead Fraser female age frequency, Gillnet 2015


Flathead Fraser female age frequency, Gillnet 2016