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Stock assessment of striped marlin (*Tetrapturus audax*) in the southwest Pacific Ocean

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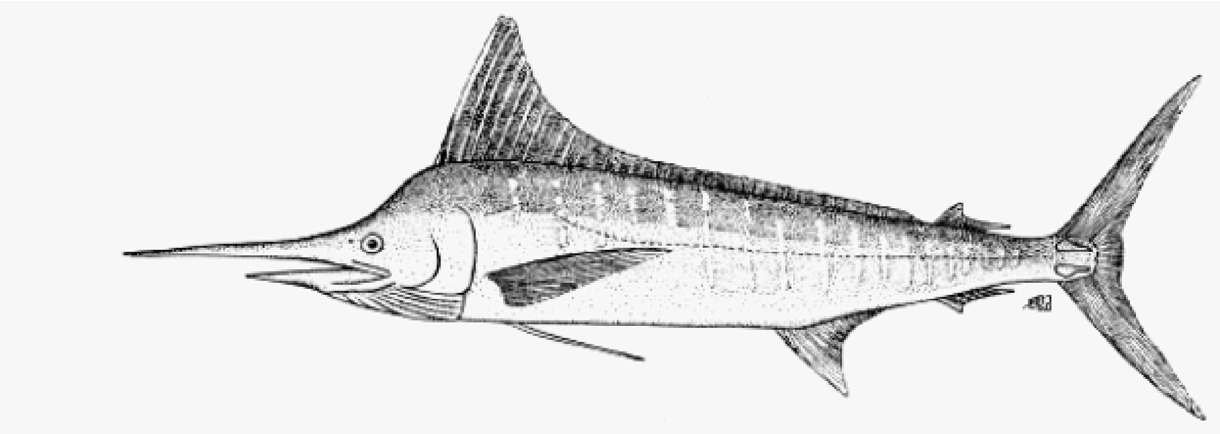

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1. Introduction

Striped marlin (*Tetrapturus audax*) is one of six species of billfishes commonly reported from commercial and recreational fisheries within the western and central Pacific Ocean (WCPO) (Whitelaw 2001, Bromhead et al. 2004, Kopf et al. 2005, Molony 2005). Nearly all commercial catches of striped marlin are made by longline fleets (Bromhead et al. 2004), although small catches of striped marlin have also been reported from purse-seine fisheries of the WCPO (Molony 2005). Striped marlin is also an important recreational species throughout the region (Whitelaw 2001, Bromhead et al. 2004, Kopf et al. 2005).

There is a long history of striped marlin catches by longline fisheries in the southwest Pacific Ocean (Figure 1, Williams 2003) and for some recreational fisheries (Kopf et al. 2005). However, both sectors have shown declines in total catches (Figure 1) and long-term declines in fish size (Kopf et al. 2005, Ward and Myers 2005). In addition, longline vessels in some areas have opportunistically targeted striped marlin (and other billfishes) in the WCPO (e.g. Australia, Bromhead et al. 2004).

Few assessments of striped marlin stocks in the Pacific Ocean have been undertaken. A Pacific-wide striped marlin assessment concluded that longline effort (up to 1980) was well below F_{MSY} (Skillman 1989). Suzuki (1989) considered northern and southern striped marlin as separate stocks and concluded that both stocks were healthy, but the southern stock was being exploited at close to optimum levels (i.e. at about F_{MSY}). Both authors concluded that there were large uncertainties associated with the data sets used. More recent assessments of striped marlin exist for the eastern Pacific Ocean (EPO); these concluded that the stock was under-exploited (Hinton and Maunder 2004). Additional stock assessments for striped marlin in the Pacific Ocean are currently planned (e.g. north Pacific striped marlin, R. A. Skillman, pers. comm.).

This report describes the first stock assessment for striped marlin in the southwest Pacific Ocean. The project was funded, in part, by the Australian Fisheries Management Authority (AFMA) and was undertaken in conjunction with the Bureau of Rural Sciences (BRS), Australia and the National Research Institute of Far Seas Fisheries (NRIFSF), Japan, with additional support from the New Zealand Ministry of Fisheries.

2. Background

2.1. Biology

Striped marlin are a pelagic species with a distribution extending through equatorial to temperate waters, although highest catches and catch rates occur within subequatorial and subtropical areas, particularly in the Pacific Ocean (Nakamura 1985). Most catches of striped marlin have been reported from surface waters (less than 100 m deep) (Brill et al. 1993, Domeier et al. 2003). From archival tagging data, striped marlin spend most time within surface waters (less than 10 m deep), with most dives to about 40 m. Occasional dives have been reported to depths of 40–100 m (Domeier et al. 2003). The habitat preference of striped marlin makes them vulnerable to surface fisheries (longline, recreational and purse-seine method fisheries) from a relatively young age.

Details of the biology and ecology of striped marlin are poorly known, mainly as a result of their relatively low abundances, low catch rates, highly mobile nature and low priority for research funding. Based on the observed distribution of larval striped marlin, spawning occurs between May and June in the north-western Pacific (10–30ºN), June–November in the central-eastern Pacific and between November and December in the southwest Pacific Ocean (10–30ºS) (Nakamura 1985), with recent studies identifying larval fish in waters at the mouth of the Gulf of Mexico, eastern Pacific (González Armas et al. 1999). Based on size frequency distribution of female eggs, Eldridge and Wares (1974) suggest that spawning occurs once per season. However, conclusive results are yet to be obtained and further research is required. Most reproduction appears to be limited to spring periods (Nakamura 1985). Based on length data from the Japanese distant water fleet (see Section 3.5), juvenile striped marlin are predominantly captured in the tropical regions of the Pacific Ocean, recruiting to the longline fishery at approximately 80–100 cm in length (eye orbit–fork length, EFL).

Striped marlin display very high initial growth rates attaining up to 45% of their maximum size in the first year of life (Melo-Barrera et al. 2003), although empirical studies are rare. Striped marlin live for at least 10–12 years (Melo-Barrera et al. 2003, Kopf et al. 2005) and can exceed more than 300 cm (lower jaw–fork length, LJFL) and 240 kg. However, validated age studies for striped marlin have not been conducted to date (Kopf et al. 2005).

Growth rates of striped marlin are lower following the onset of maturity (Melo-Barrera et al. 2003). Striped marlin reach maturity at 140–180 cm EFL and 27–40 kg by 2–4 years of age (Skillman and Yong 1976, Nakamura 1985, see Kopf 2005). Unlike other marlin, no sexual difference in growth rates has been reported, although females tend to be slightly larger than males (Kopf et al. 2005).

Large striped marlin tend to move further into temperate regions on a seasonal basis, especially in the southern WCPO. Relatively large fish are captured by the recreational fisheries in northern New Zealand (Kopf et al. 2005), and by recreational and commercial fisheries off south eastern Australia, with highest catch rates reported during the first two quarters of the year. While several large movements have been reported from fish tagged and released from northern New Zealand (e.g. several recaptures from waters of French Polynesia), clear migration pathways have not been established. Few large-scale movements have been recorded for marlin tagged off eastern Australia, creating some uncertainty about the extent of mixing of fish within the region. Current tag-recapture data suggest some level of broader sub-regional fidelity, however the recent deployment of numerous archival/satellite tags in marlin off eastern Australia and northern New Zealand should increase our understanding of movement and mixing of striped marlin in the southwest Pacific Ocean (Bromhead et al. 2004). In the southwest Pacific Ocean, it is speculated that post-spawning striped marlin move south-eastwards from the Coral Sea into waters around northern New Zealand and south-eastern Australia to feed and recover, before retuning to spawning grounds the following spawning season (Kopf et al. 2005).

Estimates of mortality rates of striped marlin are rare and have generally been generated from modes identified in length-frequency samples. Estimated natural mortality rates (M) vary between sexes, being lower in males (0.57–0.79 year^{-1}) than females (0.82–1.33 year^{-1}) (Boggs 1989, Pauly 1980, in Hinton and Bayliff 2002). However, the mortality rates of striped marlin unable to be sexed or of unreported sex have been estimated to be lower (0.39–0.49 year^{-1}) (Boggs 1989, Pauly 1980, in Hinton and Bayliff 2002). Unsexed fish may be dominated by small, juvenile fish and thus the associated total mortality rates are likely to be lower as few striped marlin below 100 cm EFL are captured by longline fisheries.

The stock structure of striped marlin in the Pacific Ocean is uncertain (Bromhead et al. 2004). A range of stock structures have been proposed for striped marlin in the Pacific Ocean (Graves and McDowell 2003), including a single Pacific-wide stock and a two stock (northern and southern hemisphere) model (Hinton and Bayliff 2002). However, a number of recent studies have strengthened arguments for the occurrence of a semi-independent stock in the southwest Pacific. Conventional tag recapture data indicated no trans-basin movements by striped marlin tagged in the southwest Pacific. This contrasts tag-recapture trends for the two other Pacific marlin species, black and blue marlin. Two recent and separate pop-off satellite archival tagging (PSAT) studies have deployed more than 50 tags in total on striped marlin off New Zealand and Australia and no movements outside the southwest Pacific Ocean have been observed within those studies (M.Domeier, pers.comm; T.Sippel, pers.comm), (although none of these tags remained attached for longer than 9 months). Results of genetic analyses suggest the potential for a significant degree of stock structuring within the Pacific Ocean and support the assumption of a semi-independent stock in the southwest Pacific Ocean (Graves and McDowell, 1994).

Examination of the Pacific-wide spatial trends in Japanese longline CPUE over the past 50 years also supports an argument for stock structuring (Nakamura 1985). Very low catch rates of striped marlin have been reported by longline fleets in equatorial regions of the Pacific Ocean (10ºN–10ºS, Nakamura 1985) despite considerable longline effort. In contrast, high catch rates have been reported adjacent to the Baja coast of the EPO (Nakamura 1985, Hinton and Bayliff 2002). In summary, current information suggests the potential for at least northern and southern stocks of striped marlin in the Pacific Ocean, with stock structure in the eastern Pacific being unclear.

2.2. Fisheries

Striped marlin are captured mainly by longline fisheries and sportfisheries throughout their range in the Pacific Ocean (Figure 1, Appendix 1). Relatively high catches of striped marlin were estimated during the 1950s and early 1960s, with a peak of more than 12,000 mt estimated for 1954. Since the mid 1960s, catches from the southwest Pacific Ocean have varied between approximately 2,000 mt and 4,000 mt with a trend for lower catches in more recent years (Figure 1).

Catches of striped marlin were dominated by the Japanese longline fleet until the early 1990s (Figure 1). Taiwanese and Korean fleets have reported relatively small catches of striped marlin since the mid 1960s and mid 1970s, respectively. However, Taiwanese catches have increased in recent years, mainly due to the high effort of this fleet in the eastern temperate WCPO, targeting mainly albacore tuna. Longline fleets of Pacific Island Countries and Territories (PICTs), and by Australia and New Zealand, have reported increasing catches since the early 1990s mainly due to the development of these domestic fleets. Catches by Australian longline fleets have rapidly increased in recent years due, at least in part, to specific targeting of striped marlin by some vessels during some periods. Since 1987, longline fleets operating in the New Zealand EEZ have been prohibited from landing striped marlin in an attempt support recreational fisheries in the north of the country (Kopf et al. 2005).

Extensive recreational fisheries exist throughout the southwest Pacific Ocean (Whitelaw 2001, Bromhead et al. 2004, Kopf et al. 2005) although total catches by recreational fisheries are very small relative to commercial catches. In addition, a high proportion of striped marlin are (tagged and) released by recreational fisheries in the WCPO (up to 60%, Holdsworth and Saul 2003, in Kopf et al. 2005). However, studies into the survival of recreationally captured marlin have estimated that between 0–50% of marlin suffer post-release mortality due to hook damage, stress or increased susceptibility to predation (Pepperell and Davis 1999), although studies are rare, sample sizes are typically small and the durations of monitoring of post-released fish are relatively short (e.g. maximum of 93 days for striped marlin, Domeier et al. 2003).

2.3. Tagging data

Tagging and recapture data for striped marlin for the southwest Pacific were available from several sources, with most tagged fish released by recreational fishers. Data were available for 24,816 releases of striped marlin within 243 release groups (i.e. stratified by sub-area and quarter) between 1974 and 2003. Approximately 25% of all release groups included only 1–2 fish, mainly released by recreational fisheries.

Only 143 recoveries of tagged and released striped marlin were reported from the model region (Table 2) (see Section 3.1), with all recaptures reported between 1989 and 2003. This represented an overall tag recovery rate of 0.58%, a relatively low recapture rate compared to tunas tagged and released in the WCPO (e.g. Sibert et al. 1999). Most recaptured striped marlin were originally tagged and released within sub-area 2 (26.6%) and sub-area 3 (68.5%) of the model region (Figure 2). Only seven (7) and two (2) tagged striped marlin were released within sub-areas 1 and 4, respectively.

Approximately 69% of all recoveries of tagged striped marlin occurred within the first three months following release and more than 90% of all recoveries made within six months of release (Table 2). More than 60% of recoveries were made within 500 km, or about 5º of latitude or longitude, of the release point (Table 2). However, some large-scale movements and times at liberty were reported. Four recaptured striped marlin moved more than 4,000 km between release and recapture (Table 2), while four other fish were at liberty for more than 12 months. The maximum time at liberty for striped marlin tagged within the assessment region was at least 2.75 years (11 quarters, Table 2) and this individual was recaptured more than 2,000 km from its release point. The maximum distance moved (4,977 km) was reported from a tagged striped marlin that was recaptured within 3 quarters of release. Nonetheless, recapture data were dominated by short periods and relatively small distances between release and recapture.

While MULTIFAN-CL has the capability to integrate tagging data in the assessment model, the tagging data from the striped marlin fishery have limited direct application in the formal assessment procedure. This is principally due to the limited number of recoveries, particularly following significant periods at liberty, and the lack of any information regarding likely levels of reporting of the recapture of tagged fish by the longline fleets. Nevertheless, the tag data are useful in consideration of the appropriate regional structure for the model. The data revealed that while striped marlin were able to make rapid and/or long-distance movements after tagging (Table 2), almost all recoveries of fish tagged within the region were reported within the model region, indicating a relatively high level of fidelity within the assessment region.

Further, most tagged fish recaptured in the second or third quarter following release had moved a considerable distance (500–1500 km) indicating strong seasonal movements (mainly south-north) and, thereby, suggestive of a relatively high level of regional-scale mixing of fish in the population. This observation provides support for the adoption of a single model region (see Section 3.1), particularly in the absence of sufficient tagging data to derive estimates of the magnitude of movement between the various sub-areas of the model region.

3. Spatial structure, data sources and compilation

Data used in the striped marlin assessment for the southwest Pacific Ocean consisted of fishery-specific catch and effort data, length-frequency data, weight-frequency data and tag-release-recapture data.

3.1. Spatial stratification

The stock assessment of striped marlin in the southwest Pacific Ocean covered the area from the equator to latitude 40ºS and from 140ºE to 130ºW (Figure 2). This represents the region of the southwest Pacific Ocean where most striped marlin catches have been reported since 1950. The assessment region excluded areas to the north and east due to little evidence for mixing between these regions (Bromhead et al., 2004). Few striped marlin have been reported from Australian longline fisheries south of 40ºS, or New Zealand longline fisheries south of 38ºS (S. Harley, pers. comm.). Overall, the assessment region is considered to encompass a semi-independent stock of striped marlin and, given the spatial distribution of the catch, represents an appropriate spatial scale for assessment and management of the striped marlin resource in the southwest Pacific Ocean.

The assessment modeled a single population of striped marlin within the region, assuming virtually instantaneous mixing of fish throughout the region. However, four sub-areas were defined within the region based on qualitative and quantitative assessments of the distribution of fishing effort and catch for the major fleets, the size composition of the catch (Figure 3) and the qualitative assessment of available tagging and recapture data. These sub-areas were used to define the spatial boundaries of the individual fisheries operating within the assessment region.

Fleets operating within the equatorial sub-area of the model (sub-area 1) generally target bigeye and yellowfin tunas, with striped marlin being a commercially important bycatch species for most fleets. Japanese vessels have been the dominant fleet within sub-area 1. However, vessels from other distant-water fishing nations have also operated within the sub-area. In addition, domestic fleets of PICTs in the region have developed during the 1990s. Fleets in sub-area 1 have reported relatively low catches of striped marlin dominated by small individuals (Figure 3 and Figure 4).

The highest catches of striped marlin have been reported from sub-area 2 of the model region (Figure 4). Longline fleets in sub-area 2 target bigeye and yellowfin tunas, or albacore tuna, with striped marlin being a commercially important bycatch species. Historically, Japanese vessels were the dominant fleet in this sub-area. However, Japanese effort has declined in this sub-area since the early 1990s. The Australian longline fleet and longline fleets of other PICTs within the sub-area have expanded over the last decade. Some vessels within the Australian longline fleet have opportunistically targeted striped marlin in recent years within this sub-area and in sub-area 3. Catches of striped marlin from sub-area 2 are dominated by relatively large fish.

Catches of striped marlin from sub-area 3 are also dominated by large fish. The Japanese fleet was the dominant fleet in this sub-area until the 1990s. The Australian domestic fleet accounts for most of the recent catches of striped marlin from sub-area 3. With the exception of the Australian fleet, longline fleets in this region do not specifically target striped marlin; it is prohibited to commercially retain striped marlin within the New Zealand EEZ (Kopf et al. 2005). Significant recreational fishing effort also occurs in this sub-area (Figure 4), focused in northern New Zealand and the central-eastern coast of Australia, with striped marlin being a major target species (Bromhead et al. 2004, Kopf et al. 2005). Catches from sub-area 3 are lower than from sub-area 2 (Figure 4).

Catches of striped marlin are relatively low from sub-area 4 (Figure 4). Only the distant water fleet of Taiwan has reported relatively high levels of effort from this sub-area; targeting albacore tuna. Longline fleets of PICTs also operate in sub-area 4, targeting mainly albacore tuna. However, striped marlin contributes to the retained commercial bycatch by longline fleets within this sub-area. Recreational fisheries also exist within this sub-area but are relatively insignificant. Limited size data were available for this sub-area of the model.

3.2. Temporal stratification

Data used in the current analyses covered the period 1952–2003. Catches of striped marlin display strong seasonal variations (Bromhead et al. 2004, Kopf et al. 2005) particularly at the more southern latitudes of their range. Further, some fisheries show strong seasonal variations in effort (e.g. Taiwan distant water fleet, Australian and New Zealand recreational fisheries). As a result, data were divided into quarters (January–March, April–June, July–September, October–December).

3.3. Definition of fisheries

The sub-areas of the model region were applied to define the spatial boundaries of the specific fisheries in the southwest Pacific Ocean. A total of 12 longline fisheries and 2 recreational fisheries were defined (Table 1, Figure 5), based on sub-area boundaries, fishing method and nationality.

The Japanese longline fleet has dominated the effort and catches of striped marlin in the assessment region throughout the time series and a separate Japanese fishery was defined for each sub-area (Fisheries 1–4). A separate Taiwanese fishery (Fishery 5) was defined for sub-area 4 as this fleet has dominated effort and catches of striped marlin in the sub-area, particularly since the mid 1970s (the early 1990s, major longline fisheries have also developed in Australia (one fishery in each of sub-areas 2 and 3, Fisheries 6 and 7) and New Zealand (one fishery in sub-area 3, Fishery 8). Four additional longline fisheries were defined to account for the other sources of longline effort and catch in each of the four sub-areas (Fisheries 11–14, Table 1). These other longline fisheries included effort and catches by recently developed longline fisheries of PICTs.

Major recreational fisheries that target striped marlin were also defined as individual fisheries in sub-area 3 of the assessment model: an Australian recreational fishery (Fishery 9) and a New Zealand recreational fishery (Fishery 10) (Table 1). Other recreational fisheries capturing striped marlin exist in the assessment region (Whitelaw 2001). However, these other recreational fisheries are relatively small and catch and effort data were not readily available.

3.4. Catch and effort data

For all fisheries, catch data were expressed as the number of striped marlin captured (ll longline fisheries, fishing effort was defined as the number of hooks set. For recreational fisheries, effort data were supplied as number of days. Catch and effort data for all fisheries were aggregated within quarterly time intervals.

Data were supplied in a variety of spatial and temporal resolutions. For example, longline catch and effort data from the distant-water fleets were generally available aggregated by month and 5-degree spatial resolution, while operational-level logsheet data were available for many of the domestic longline fleets. Recreational data were supplied for individual sub-areas of the model.

Japanese distant-water longline fisheries (Fisheries 1, 2, 3 and 4, sub-areas 1–4, respectively): Catch and effort data from the Japanese fleet for 1952–2003 were supplied by the NRIFSF stratified by spatial cell (5-degree of latitude and longitude), month, and gear configuration (number of hooks between floats, HBF). The spatial scale of operation of the Japanese longline fleet has declined over the last 20 years. For example, since 1992, limited longline effort was reported by the Japanese fleet in sub-area 4 of the region (Fishery 4).

Fishing effort by the Japanese distant-water fleet (Fisheries 1–4) were standardised using a generalised linear model (GLM) approach. The GLMs included the following variables: year/quarter, spatial cell (5° latitude/longitude cell), and HBF. The resulting CPUE indices are presented in Figure 6. For each year/quarter, an index of standardised effort was calculated by dividing the total quarterly catch by the CPUE index derived the from GLM model.

Taiwanese distant-water longline fishery (Fishery 5, sub-area 4): Catch and effort data for this fleet were available aggregated by 5-degree square and month. Data were supplied by the National Taiwan University (1967–1993) and by the Overseas Fisheries Council of the Republic of China via the Council of Agriculture (1994–2003). Data were raised to represent total catches (see Lawson (2004) for more information). A GLM approach was applied to derive a standardised effort series as described for the Japanese fisheries. The GLM model was limited to include year/quarter and 5-degree spatial cell.

Australian longline fisheries (Fisheries 6 and 7, sub-areas 2 and 3, respectively): Longline catch and effort data were provided on a quarterly basis for each sub-area by the Australian Fisheries Management Authority (AFMA) for the period 1990–2003. Data were raised to provide estimates of total catches applying the scaling factors used by Campbell et al. (2002).

Logsheet data were available for the Australian longline fisheries. A GLM approach was applied these data to derive a standardised effort series for both model fisheries. The two GLM models included the following variables: year/quarter, spatial cell (5° latitude/longitude cell), HBF, and the interaction between the time of set and the number of light sticks deployed on the longline. The resulting CPUE indices are presented in Figure 6.

New Zealand longline fishery (Fishery 8, sub-area 3): Longline data, in both numbers and tonnes of striped marlin, were provided by the Ministry of Fisheries (MFish), New Zealand, for the period 1993–2003. However, the landing of striped marlin by commercial longline vessels fishing within the New Zealand EEZ has been prohibited since 1987 (Kopf et al. 2005). While records of retained and discarded striped marlin do occur in the logsheet data for this fishery, it is likely total catches for this fishery are under-estimated. As a result, MFish raised catches by 20% to account for under-reporting of the discarded catch. Only New Zealand longline data north of 38ºS were included in the analysis as longline vessels operating further south mainly target southern bluefin tuna and catch very few striped marlin (S. Harley, pers. comm.).

Other longline fisheries (Fisheries 11, 12, 13 and 14, sub-areas 1–4, respectively): Other longline fleets have also operated within the model region since 1952, aside from the fisheries identified above. These “other” longline fisheries were pooled into the relevant model sub-areas on a quarterly basis. Fishery 11 (sub-area 1) included fleets from PICTs (e.g. Papua New Guinea, Solomon Islands, Vanuatu, Cook Islands and French Polynesia), plus fleets from distant water fishing nations other than Japan. Fishery 12 (sub-area 2) included catch and effort data from some PICTs (e.g. New Caledonia, Vanuatu, Fiji and Tonga) plus fleets from distant water fishing nations other than Japan. Fishery 13 (sub-area 3) included fleets from all flags other than Australia, Japan and New Zealand. Fishery 14 (sub-area 4) included fleets from some PICTs (e.g. Cook Islands, French Polynesia) and all fleets from other distant water fishing nations other than Japan and Taiwan. All data for these other fisheries were supplied as logsheet data and/or aggregated spatial data, with effort and catches raised as appropriate (see Lawson 2004).

Australian recreational fishery (Fishery 9, sub-area 3): Recreational fishery data were supplied by BRS. It comprised charter boat data collected from operators fishing off south-eastern Australia, which were pooled into quarterly time periods for the period 1990–2003.

New Zealand recreational fishery (Fishery 10, sub-area 3): Information for this fishery was supplied by MFish for the period 1950–2003. Data were obtained from extensive fishing club records (see Kopf et al. 2005). Total numbers of striped marlin captured per quarter were available for the full time series. However, effort data were only available for the periods 1969–1972 and 1975–2003. Due to the seasonal nature of the recreational fishery (Kopf et al. 2005), only data for the first two quarters of each year were included in the analysis.

3.5. Length and weight frequency data

Length-frequency and/or weight-frequency data were available from many of the fisheries defined in Table 1, although data were provided in a number of different formats depending on the specific fishery. For most fisheries, temporal coverage of the size frequency data was relatively limited (Figure 7).

Length data were provided based on three different length measurement methods: eye orbit–fork length (EFL), lower jaw–fork length (LJFL) or pelvic fin–fork length (PFFL). A range of weights were supplied including whole weight, Japanese processed weights (gilled, gutted, head and tail left on, bill removed at a point level with the tip of the lower jaw), and gilled, gutted and headed (i.e. trunked). All length measurements were standardised to EFL and weight measurements were standardised to the equivalent whole (unprocessed) weight.

<u>Japanese longline fisheries</u> (fisheries 1–4, sub-areas 1–4): Data were supplied by the NRIFSF and represented the most extensive size data used in the analysis (approximately 15,000 length measurements and 43,000 weight measurements). Length and/or weight data were available from 1970–2002, although coverage varied between sub-areas. Length data were recorded as EFL while weight data were supplied as Japanese processed weights. The Japanese style of processing removes the gills, guts, and the bill at the point of the lower jaw, while retaining the head and tail. The NRIFSF conversion factor of 1.1 was applied to the processed weights to estimate whole weight.

<u>Australian longline fisheries</u> (fisheries 6 and 7, sub-areas 2 and 3): Weight data were available from the Australian longline fisheries from AFMA for the period 1997–2003. The weight data was originally sourced from the main fish processors receiving striped marlin from Australian longline vessels and represents a comprehensive sample of the entire catch. Weights were supplied as processed (trunked) weights (i.e. gilled, gutted and head removed) to the nearest 0.1 kg. To enable comparisons with whole weights, a conversion factor was calculated using processed and whole weight data for 254 striped marlin, which were collected by Australian observers on Japanese longline vessels operating in Australian waters in the early 1990s. The relationship between the two measures was;

$$\text{Whole weight (kg)} = 1.1788 \times \text{gilled-gutted weight (kg)}^{0.9984}.$$

Until such time as a conversion factor can be calculated directly from data collected on Australian longline vessels, this conversion factor represents the most appropriate (given similarities in fishing methods between the two fleets) and was applied to all processed weights from the Australian longline fisheries prior to analysis.

<u>New Zealand longline fishery</u> (fishery 8, sub-area 3): Only four quarters of length data were available from observers on board New Zealand longline vessels during 1995–1998. Data were supplied by MFish with lengths measured as LJFL and converted to EFL by multiplying by 0.862.

<u>Australian recreational fishery</u> (fishery 9, sub-area 3): Limited weight data were available for the Australian recreational fishery. Most weight data were supplied as estimated weights (from tagged and released fish, ±10 kg) and, due to the imprecision of the weight estimates, were not included in the analysis.

<u>New Zealand recreational fishery</u> (fishery 10, sub-area 3): Weight data were supplied for the New Zealand recreational fishery for all quarters during 1950–2003. All weights were recorded as whole weights and were either from landed fish (therefore accurately measured) or estimated when fish were along-side vessels in the case of tagged and released fish (estimated weights, ± 5 kg). Only landed weights were incorporated into the analysis due to inaccuracies in estimated weights. More details of recreational data are provided in Kopf et al. (2005).

<u>Other longline fisheries</u> (fisheries 11, 12 and 14, sub-areas 1, 2 and 4): Length and/or weight data were available from fishery 11 during the period 1996–2003. Length data were available from fishery 12 for some quarters during 1993–2003 and from fishery 14 for several quarters

during 1996–2003. Data from these fisheries were supplied from a combination of regional observer programmes, regional port-sampling programmes and/or from research institutes of distant water fleets. Length and weight data were unavailable for fishery 13.

Size data were aggregated by fishery and time strata (year/quarter). Length data were aggregated into 154 2-cm size classes (20–326 cm EFL). Weight data were aggregated into 246 1-kg intervals (5–250 kg whole weight). Length or weight data were not available for all quarters for the period of data supplied for each fishery (Table 1). The exception was fishery 10 (New Zealand recreational fishery, sub-area 3) for which there were landed weight data for all years.

Overall, smaller fish were more commonly captured by longline fisheries in sub-area 1 (equatorial areas) with larger fish tending to be captured by longline fisheries in more temperate waters (Figure 3 and Figure 8). Recreational fisheries tended to capture larger striped marlin than the longline fisheries.

3.6. Biological parameters

Parameters such as growth rates, maturity schedule, longevity and mortality are important model parameters for MULTIFAN-CL (Fournier et al. 1998). While MULTIFAN-CL can estimate many of these parameters, starting values are required for all parameters, with some parameters being fixed through time (e.g. the maturity ogive).

Published estimates of starting values were obtained from a literature review of available information (Table 3). A limited amount of published material was available for striped marlin (see Bromhead et al. 2004, Molony 2005). As there is the potential for multiple stocks within the Pacific Ocean and among ocean basins (Graves and McDowell 2003), local estimates were used wherever possible.

Available evidence suggests striped marlin reach sexual maturity at between 2–4 years of age (see Kopf 2005). The maximum longevity is estimated to be at least 10 years of age and they display a rapid growth rate (Melo Barrera et al. 2003, Kopf et al. 2005). The length-weight relationship was estimated from length and weight data supplied for the assessment by NRIFSF. Natural mortality was fixed at 0.4 year^{-1} for all age classes (Table 3).

4. Model description – structural assumptions, parameterisation, and priors

As with any model, various structural assumptions have been made in the southwest Pacific striped marlin model. Such assumptions are always a trade-off to some extent between the need, on the one hand, to keep the parameterization as simple as possible, and on the other, to allow sufficient flexibility so that important characteristics of the fisheries and population are captured in the model. The mathematical specification of structural assumptions is given in Hampton and Fournier (2001). The main structural assumptions used in the striped marlin model are discussed below and summarized in Table 4.

Due to the limited data available and uncertainty concerning some of the key biological parameters, in particularly the movement dynamics of the species, a simple model structure was adopted with a single model region, thereby, assuming instantaneous and complete mixing of the population throughout the spatial extent of the model.

There are observed differences in the size (length and/or weight) structure of the catch among sub-areas of the model region (see Figure 3). These spatial differences were addressed through the method and area specific definitions of the fisheries incorporated in the model and the flexibility to estimate specific size-based selectivity functions for each of the main fisheries within each sub-area. Seasonal and spatial variations in catch rates of striped marlin between fisheries are accounted for in the model by estimating fishery-specific catchability parameters incorporating seasonal variation.

The principal source of abundance information in the model is derived from the catch and (GLM standardised) effort series for the main longline fisheries (Figure 6 and Figure 9). The most significant component of the catch from the model region is from the Japanese longline fisheries in sub-areas 2 and 3 (LL JAP 2 and 3) and, to a lesser extent, the LL TW 4 fishery (these three fisheries are denoted as “key fisheries” in the following sections). The effort series from these fisheries were given a higher weighting in the analysis compared to the other fisheries, thereby, giving these data substantially higher influence in the assessment model.

4.1. Observation models for the data

There are three data components that contribute to the log-likelihood function – the total catch data, the weight-frequency data and the length-frequency data. The observed total catch data are assumed to be unbiased and relatively precise, with the standard deviation (SD) of residuals on the log scale being 0.07.

The probability distributions for the length-frequency proportions are assumed to be approximated by robust normal distributions, with the variance determined by the effective sample size and the observed length-frequency proportion. Effective sample size is assumed to be 0.1 times the actual sample size for all fisheries, with a maximum effective sample size of 100. Reduction of the effective sample size recognises that length-frequency samples are not truly random and would have higher variance as a result. A similar likelihood function was used for the weight-frequency data.

4.2. Recruitment

‘Recruitment’ in terms of the MULTIFAN-CL model is the appearance of age-class 1 fish in the population (Fournier et al. 1998). Striped marlin are assumed to spawn during November–December in the southwest Pacific (see Section 2.1). On this basis, recruitment to the model population was assumed to be an annual event that occurs in November of the year following spawning (i.e. one year old fish).

The time-series variation in recruitment was somewhat constrained by a log-normal prior. The variance of the prior was equivalent to a CV of about 0.2 (log scale). This is a relatively restrictive prior for recruitment variation — recruitment could be expected to vary substantially between years. However, preliminary model runs using a weaker prior revealed a very strong temporal trend in the deviations in recruitment, essentially following the trends in longline CPUE. The more restrictive prior was used to mediate this effect in the model.

Recruitment was assumed to be related to spawning biomass according to the Beverton-Holt stock-recruitment relationship (SRR). The SRR was incorporated mainly so that a yield analysis could be undertaken for stock assessment purposes. A relatively weak penalty was applied to deviation from the SRR so that it would have only a slight effect on the recruitment and other model estimates (Hampton and Fournier 2001).

Typically, fisheries data are very uninformative about SRR parameters and it is generally necessary to constrain the parameterisation to have stable model behaviour. A beta-distributed prior was used for the “steepness” coefficient (S) of the SRR, with S defined as the ratio of the equilibrium recruitment produced by 20% of the equilibrium unexploited spawning biomass to that produced by the equilibrium unexploited spawning biomass. The beta-distribution of the prior has a lower bound at 0.2, a mode at 0.93, and standard deviation of 0.18 (Figure 10).

For comparison, a highly informative prior distribution for steepness was included in a separate model to assess the sensitivity of the model to the SRR. This prior constrained the estimated value of steepness to be very close to 1.0 (lower bound at 0.2, a mode at 0.99, and standard deviation of 0.03).

4.3. Natural mortality

Natural mortality was set at the assumed value of 0.4 for all age classes. This is the mid-point of the range of natural mortalities for small (relatively unexploited) striped marlin reported by Boggs (1989) and Pauly (1980, in Hinton and Bayliff 2002) for the Pacific Ocean. The sensitivity of the model to the assumed value of natural mortality was examined by comparing the results using values of natural mortality of 0.2 and 0.6 (fixed across all age classes).

4.4. Age and growth

The assumptions made concerning age and growth in the MULTIFAN-CL model are (i) the lengths-at-age are normally distributed for each age class; (ii) the mean lengths at age follow a von Bertalanffy growth curve; and (iii) the standard deviations in length-at-age is a linear function of the mean length-at-age (Fournier et al. 1998). The probability distributions of weights-at-age are a deterministic function of the lengths-at-age and a specified weight-length relationship (Table 3).

For any specific model, it is necessary to assume the number of significant age-classes in the exploited population, with the last age-class being defined as a “plus group”, i.e. all fish of the designated age and older. Striped marlin are thought to have a relatively high natural mortality (Boggs 1989) and, consequently, it was considered that 10 yearly age classes (including the 10 year plus group) was sufficient to define the dynamics of the population.

The mean length of the oldest (10+) age-class (essentially the model parameterisation of L_∞) and length-at-first-age parameters of the growth curve were estimated in the fitting procedure. Problems were encountered in attempting to estimate the k parameter of the von Bertalanffy growth curve and, consequently, this parameter was fixed at the initial value (Table 3). This value was within the range of k–values reported by previous authors (e.g. Boggs 1989, Melo-Barrera et al. 2003, Kopf et al. 2005). The sensitivity of the model to the value of *k* was investigated using a low value for the parameter (0.3).

4.5. Selectivity

Selectivity is fishery-specific and assumed to be time-invariant and length-based but modelled as age-based (Kleiber et al. 2003). Differences in selectivities among fisheries using the same methods (longline or recreational gears) in different sub-areas of the model region may be proxies for spatial structuring of the striped marlin population by size. The selectivities at age were estimated using a cubic spline parameterisation. Each selectivity function was parameterised with four nodes allowing considerable flexibility in the functional form while minimizing the number of parameters required to be estimated.

Limited length frequency data were available for a number of fisheries and the selectivities for these fisheries were assumed to be equivalent to other fisheries of the same method operating within the same sub-area. Specifically, the aggregate longline fisheries in each sub-area (Other LL 1–4, Fisheries 11–14) were assumed to have equivalent selectivities to the corresponding Japanese longline fisheries operating within each sub-area. No size data were available from the LL TW 4 fishery and the selectivity was assumed to be equivalent to the LL JAP 4 and Other LL 4 fisheries, although limited size data were available from either fishery. A common selectivity was assumed for the two Australian longline fisheries, the Australian recreational fishery, and the New Zealand longline fishery.

For most of the longline fisheries and the two recreational fisheries, selectivity was assumed to increase with age and remain at full selectivity once attained. The exceptions were the two longline fisheries in the northern sub-area (LL JAP 1 and Other LL 1) which catch relatively small striped marlin (Figure 3). The selectivity for these fisheries was constrained to decline to zero for the two oldest age classes.

A sensitivity analysis was also undertaken to the assumptions regarding the selectivity parameterisation for the key longline fisheries in attempt to improve the fit to the size data. In this case, the selectivities of the longline fisheries in sub-areas 2–4 were not constrained to remain at full selectivity for the oldest age classes.

4.6. Catchability

Catchability was assumed to be constant over time for the four Japanese longline fisheries (LL JAP 1–4) and the LL TW 4 fishery. Fishing effort was standardised for each of these fisheries using a GLM approach to account for systematic trends in catchability associated with temporal and spatial changes in the distribution of fishing effort and changes in gear configuration. While it is considered unlikely that such a statistical approach can account fully for systematic variation in catchability over time, the resulting standardised effort series (Figure 6 and Figure 9) represent the best available indices of relative abundance for the stock.

Catchability for all other fisheries was allowed to vary slowly over time (akin to a random walk) using a structural time-series approach. Random walk steps were taken biennially, and the deviations constrained by a prior distribution of mean zero and a variance equivalent to a CV of 0.1 on a log scale. Seasonal variation in catchability was also allowed to explain the strong seasonal variability in CPUE for most of the fisheries.

4.7. Effort variability

Effort deviations, constrained by prior distributions of zero mean and a specified variance, were used to model the random variation in the effort–fishing mortality relation. For the main longline fisheries (LL JAP 2–3, LL TW 4, LL AU 2–3), the variance of the prior was equivalent to a CV of about 0.2 (log scale). For the other fisheries, a weak penalty was applied to the effort deviations (CV of about 0.7) to reflect the greater uncertainty in the effort data and higher variability in the catch and effort series. For all fisheries, the penalties for individual effort observations were weighted by the square root of the effort.

4.8. Initial population

The population age structure in the initial time period in the region was assumed to be in equilibrium and determined as a function of the average total mortality during the first five years. This assumption avoids having to treat the initial age structure as independent parameters in the model, which is generally poorly determined.

4.9. Parameter estimation

The parameters of the model were estimated by maximizing the log-likelihoods of the data plus the log of the probability density functions of the priors and smoothing penalties specified in the model. The maximization was performed by an efficient optimization using exact derivatives with respect to the model parameters. Estimation was conducted in a series of phases, the first of which used arbitrary starting values for most parameters. Some parameters were assigned specified starting values consistent with available biological information (Table 3).

The Hessian matrix computed at the mode of the posterior distribution was used to obtain estimates of the covariance matrix, which was used in combination with the Delta method to compute approximate confidence intervals for parameters of interest.

4.10. Stock assessment interpretation methods

Several ancillary analyses are conducted in order to interpret the results of the model for stock assessment purposes. The methods involved are summarized below and the details can be found in Kleiber et al. (2003). Note that, in each case, these ancillary analyses are completely integrated into the model, and therefore confidence intervals for quantities of interest are available using the Hessian-Delta approach.

4.10.1 Fishery impact

Many assessments estimate the ratio of recent to initial biomass as an index of fishery depletion. The problem with this approach is that recruitment may vary considerably throughout the time series, and if either the initial or recent biomass estimates (or both) are "non-representative" because of recruitment variability, then the ratio may not measure fishery depletion, but simply reflect recruitment variability.

We approach this problem by computing biomass time-series using the estimated model parameters, but assuming that fishing mortality was zero. Because both the *real* biomass B_t and the *unexploited* biomass $B0_t$ incorporate recruitment variability, their ratio at each time step of the analysis (i.e. $\frac{B_t}{B_{0t}}$) can be interpreted as an index of fishery depletion.

4.10.2 Yield analysis

The yield analysis consists of computing equilibrium catch (or yield) and biomass, conditional on a specified basal level of age-specific fishing mortality (F_a) for the entire model domain, a series of fishing mortality multipliers (*fmult*), the natural mortality (M), the mean weight-at-age (w_a) and the SRR parameters (α and β). All of these parameters, apart from *fmult* which is arbitrarily specified over a range of 0–50 in increments of 0.1, are available from the parameter estimates of the model. The maximum yield with respect to *fmult* can easily be determined and is equivalent to the MSY. Similarly the total and adult biomass at MSY can also be determined. The ratios of the current (or recent average) levels of fishing mortality and biomass to their respective levels at MSY are of management interest as limit reference points.

5. Results

The model results presented in the following section are for the model option with natural mortality fixed at 0.4 and the uninformative prior on steepness. For convenience, this model is referred to as the "base case" assessment. However, this is not meant to infer a higher degree of confidence in the results from this scenario relative to the range of other scenarios considered ("sensitivity analyses"). The section also includes a discussion of the key differences in the results from the "base case" and the alternative model options investigated.

5.1. Fit diagnostics

A summary of the objective function components of the final model are presented in Table 5. The performance of the model can be assessed by comparing the input data (observations) with the two predicted data classes — total catch data and size (weight and length) frequency data. In addition, the estimated effort deviations provide an indication of the consistency of the model with the effort data. The following observations are made concerning the various fit diagnostics:

- Overall, there is a very good fit to the observed catch from all fisheries by the model (Figure 11). The log total catch residuals by fishery are shown in Figure 12. The residuals are all relatively small and, for the key longline fisheries (LL JAP2, LL JAP3 and LL TW4) generally show even distributions about zero. However, a number of other fisheries reveal strong temporal trends in the catch residuals, most notably the LL JAP 1 and the

New Zealand recreational fishery (Figure 12). These trends indicate a systematic lack of fit to the catch data for these fisheries.

- The overall consistency of the model with the observed effort data can be examined in plots of effort deviations against time for each fishery (Figure 13). If the model is coherent with the effort data, we would expect an even scatter of effort deviations about zero. On the other hand, if there was an obvious trend in the effort deviations with time, this may indicate that a trend in catchability had occurred and that this had not been sufficiently captured by the model. For the key longline fisheries, the effort deviations are relatively small and there is no evidence of a strong temporal trend in the effort deviations. This indicates that the catch and effort data from these fisheries are consistent with the estimated trends in the vulnerable biomass for the fishery. This is evident when comparing the exploitable biomass from each fishery with the CPUE from each fishery, with nominal effort scaled by the estimated catchability coefficients (Figure 14). While there is considerable variability in CPUE over the time-series, the general trend is consistent with the estimated exploitable biomass for each of the key fisheries (LL JAP2, LL JAP3 and LL TW4).
- In contrast, there is a strong trend in the effort deviations from the LL JAP 1 fishery (Figure 13). Catchability is assumed to be constant for this fishery, although the variation of the effort deviates is less constrained than for the other Japanese longline fisheries. The effort deviates steadily increase over time as the model attempts to fit the relatively constant catches despite declining fishing effort. This conflict is evident when comparing trends in exploitable biomass and CPUE indices from this fishery (Figure 14). The declining trend in exploitable biomass for all fisheries, including LL JAP 1, is largely driven by the decline in CPUE evident from the other key longline fisheries. However, CPUE for the LL JAP1 fishery has generally increased over the last two decades (see Figure 9). The model attempts to account for this trend by increasing the effort deviations during the period, although as indicated by the catch residuals (see Figure 12), the increase in effort deviations does not completely account for the observed level of catch.
- Strong temporal trends are also evident in the effort deviations for the New Zealand recreational fishery, with strong positive residuals in the 1960s and 1970s (Figure 13). This is despite the flexibility of the model to allow catchability to vary with time. In fact, there is no actual effort data prior to 1969 and the model assumes the level of effort in the early period is equivalent to the first time period with data. Hence, the trends in the effort deviations in the earlier periods are largely an artefact of the relationship between the observed catches and the assumed level of effort.
- For the New Zealand longline fishery (LL NZ3), very low effort deviations were estimated at the start of the time-series (Figure 13). This is due to the negligible catches of striped marlin that were recorded despite a considerable amount of fishing effort. It has been illegal to land commercial catches of striped marlin in New Zealand since 1987 (Kopf et al. 2005) and, consequently, there is little incentive to accurately report when the species is caught. There may have also been confusion regarding the reporting of the species at the start of the fishery that resulted in the catches being rarely reported.
- Overall, there is generally a good fit to the observed and predicted weight data aggregated over time for the main fisheries where weight data were collected (LL JAP1–3, LL AU2 & 3, REC NZ3) (Figure 15). These fisheries are generally characterized by a single size mode comprised of large, adult fish, with the exception of the LL JAP1 fishery that also catches smaller striped marlin. The location of the size mode (weight and length) of these small fish is not well predicted by the model indicating that the initial growth rates may be poorly estimated and/or the assumption regarding a discrete annual spawning period (in November) may not be valid.

- For the LL JAP2 fishery and the New Zealand recreational fishery, there was a consistent bias in the model to under-estimate the weight of fish caught and, in the case of the former fishery, to predict a broader range of fish weights than observed from the fishery (Figure 15). This is particularly evident when the median weight of fish sampled from each time period is compared with the corresponding weight distribution of the population that is vulnerable to the respective fishery (Figure 16). This is most evident for the New Zealand recreational fishery where the median fish weight observed is consistently about 10 kg greater than the predicted median fish weight from the model, although the high discarding rate of relatively small fish (less than 90 kg, Kopf et al. 2005) may partially explain the under-estimation of weights by the model for this fishery. The fish sampled for weight from the LL JAP 3 fishery are also generally larger than the predicted weights from the model. The weight observations from the LL AU 2 fishery are generally consistent with the model over the limited period for which data are available. However, observed weight observations for the LL AU 3 fishery are generally higher than predicted until later in the time-series (Figure 16). Thus, the model predicted lower than observed weights for three major fisheries in sub-area 3 of the model region.
- Limited length frequency data were available for inclusion in the model, mainly from LL JAP1–3 and the domestic longline fisheries in sub-areas 1 and 2 (Other LL1 and 2) (see Figure 7). There was a good fit to the aggregated length data from fisheries LL JAP 2 & 3, while the fit to the data from LL JAP 1 was poor (Figure 17). Limited data were available from the Other LL1 & 2 fisheries and the fit to these data was somewhat constrained by the assumption that selectivity was equivalent to the corresponding Japanese longline fishery in the same sub-area. For those fisheries with sufficient length data, the predicted size of fish caught is generally consistent with length of the individual observations at discrete sampling intervals (Figure 18).

5.2. Model parameter estimates

5.2.1 Catchability

The annual catchability for the four Japanese longline fisheries (LL JAP 1–4) and the Taiwanese longline fishery (LL TW 4) were held constant over the entire period of the model, although allowed to vary seasonally (Figure 19). For these fisheries, catchability was highest in sub-area 2 — consistent with the higher catch rates of striped marlin reported from the Coral Sea.

Catchability was allowed to vary temporally for all other fisheries. The model estimated catchability in the southern Australian longline fishery (LL AU 3) to have steadily increased since the development of the fishery in the early 1990s, despite the attempts to standardise the effort series using the GLM approach. Similarly, catchability for the Australian recreational fishery in the same sub-area (REC AU3) also increased (Figure 19).

For the New Zealand recreational fishery, catchability is estimated to have varied considerably over the history of the fishery. As noted above, effort data from this fishery are not available prior to 1969 and the catchability trend prior to that year is simply the model’s attempt to fit the observed catch given a nominal level of effort. For the latter period, catchability is estimated to have declined to a low level in the mid 1990s and then steadily increased over the subsequent years (Figure 19).

The four composite (‘Other’) longline fisheries all display strong trends in catchability over time. These fisheries are comprised of a range of different fisheries and changes in catchability may simply represent a change in the makeup of these fisheries, including the development of new domestic longline fisheries and/or changes in the area of operation and targeting practises of different fleets.

Strong seasonal trends in catchability are evident from most fisheries, with the exception of those fisheries in the sub-equatorial region (sub-area 1). In general, catchability of the longline fisheries was highest in sub-area 2 during the third and fourth quarters and highest in sub-area 3 in the first and, to a lesser extent, second quarters. The magnitude of the seasonal variability in catchability increased with increasing (southern) latitude, with the greatest variation observed in the New Zealand fisheries.

5.2.2 Selectivity

Striped marlin are vulnerable to the main longline fisheries in sub-areas 2 and 3 (LL JAP 2&3, LL AU 2&3, and LL NZ 3) from about 3 years of age and are fully recruited by age 5 years (Figure 20). In contrast, younger fish are more vulnerable to the longline fisheries operating in the northern sub-area (LL JAP 1 and LL Other 1), where juvenile fish represent a significant component of the catch from these fisheries.

Limited size data of suitable resolution were available from the Australian recreational fishery and the selectivity was assumed to be equivalent to the Australian domestic longline fishery in the same sub-area. Further, limited size data were available from longline fisheries in sub-area 4, although these data suggest fish may be fully vulnerable to these fisheries from about 3 years old.

The New Zealand recreational fishery principally catches large, old fish with catches estimated to be comprised mainly of fish in the 4–7 year age classes. However, fish are not fully vulnerable until the 10+ year age group (Figure 20).

5.2.3 Growth

The estimated growth curve is shown in Figure 21. Growth rates are estimated to be slightly higher during the first 5 years compared to the published growth parameters derived from a small number (n=94) of aged striped marlin sampled in New Zealand waters (Kopf et al. 2005). These differences may be attributable to the fixed value assumed for the k parameter of the von Bertalanffy growth curve. Problems were encountered in the fitting procedure when this parameter was estimated. However, the data from Kopf et al. (2005) represent a small number of fish collected from New Zealand waters, an area well away from the equatorial regions where juvenile fish are common and thus may under-estimate actual growth rates of young fish. For example, Melo-Barrera et al. (2003) estimated that striped marlin reach approximately 100 cm LJFL (approximately 86 cm EFL) by the end of their first year in waters off Mexico, much larger than the estimated size of one-year old fish used in the current analysis (Table 3).

5.3. Stock assessment results

This section principally documents the results of a single model run using the parameters presented in Table 3. A range of other analyses were undertaken investigating the sensitivity of the model to various changes in the biological parameters. Many of the trends in the parameter estimates for the sensitivity analyses were similar to the trends described for the single model run described below, although the magnitude of the estimates of key parameters varied among runs. The focus of the results on the single model run does not imply a specific preference for this option, rather it serves to illustrate some of the main observations for the range of model options considered. The differences between the various model results are discussed in Section 5.3.6.

5.3.1 Recruitment

There is considerable temporal variation in recruitment over the model period (Figure 22). Annual recruitment is estimated to have been high prior to 1970 (30% greater than the mean recruitment) and fluctuated about a lower level (80% of the mean) for the subsequent period. From 1980 onwards, recruitment has fluctuated on approximately a 5-yearly cycle. The recruitment estimates have broad confidence intervals indicating substantial uncertainty, particularly during the early period (1950s and 1960s) (Figure 22), prior to the availability of size data.

There are very limited size data from the early period of the fishery; only New Zealand recreational (REC NZ3) size data were available prior to 1970 (see Figure 3). Catch rates from the main Japanese longline fisheries (LL JAP 2&3) declined rapidly during this period (Figure 9), while relatively high catches were taken (Figure 1). The model is accounting for this initial decline in CPUE, in part, by a decline in recruitment from 1950 to 1970. In the absence of size data from the key longline fisheries, the model estimates of recruitment for this period should be interpreted with some caution.

5.3.2 Biomass

The annual trends in total and adult biomass are consistent with the temporal trend in recruitment described in the previous section. Biomass was estimated to be high during the 1950s and declined sharply during the late 1950s and early 1960s (Figure 23). There is a high level of uncertainty associated with the annual biomass estimates, particularly for the 1970s and early 1980s. This may be also a result of size data only being available since 1970 for the key longline fisheries.

5.3.3 Fishing mortality

Fishing mortality (exploitation) rates for adult striped marlin are estimated to have increased sharply in the mid 1950s (Figure 24) following the development of the Japanese longline fishery in sub-area 2 and the initial period of high catches (see Figure 4). Higher exploitation rates were maintained over the following decade, but were lower during the 1970s when total catches from the fishery were lower. Since 1980, fishing mortality rates for adult striped marlin have remained relatively constant, averaging 0.285 per annum (Figure 24). Fishing mortality rates for juvenile striped marlin have remained at a low level throughout the model period (Figure 24), although they have slowly increased through time, perhaps as a result of the development of domestic longline fisheries by PICTs in the equatorial sub-area of the model.

An examination of age-specific fishing mortality is presented in Figure 25. As previously noted, mortality rates are low for fish younger than four years. Fishing mortality is relatively constant with respect to age following full recruitment to the main longline fishery at about 5 years old. The very high mortality rate for the oldest age classes in the last decade is largely due to observed catches from the New Zealand recreational fishery. While these catches are very small, they represent a significant proportion of the total number of fish reaching the oldest age classes (Figure 25).

The general decline in fishing mortality rates between the 1960s and 1980s (Figure 25) is likely a result of declining Japanese catches of striped marlin (Figure 1 and Figure 4), the major fleet in the model region. The decline in fishing mortality rates may reflect shifts in target species of the Japanese fleet during this period. The increases in fishing mortality for all age classes during the 1990s and 2000s may be a result of the development of new longline fisheries in all sub-areas in recent periods, especially by PICTs, and the development of Australian longline fisheries, sectors of which have opportunistically targeted striped marlin (Figure 4).

5.3.4 Fishery impact

An indicator of the impact of fishing on the stock is to compare the biomass trajectories with fishing and the predicted biomass trajectory in the absence of fishing. The impact can be expressed as a proportional reduction in biomass ($1 - B_t / B_{0t}$) and calculated for different components of the stock; juvenile, adult, and the proportion of the stock vulnerable to the main longline fisheries.

Overall, total fishery impacts on the juvenile component of the biomass have been low (less than 5%) over the model period, consistent with the low fishing mortality on this portion of the population. Fishery impacts have been considerably higher on the adult component of the stock, with the fishery reducing the adult biomass by about 50% since 1970.

For most of the main longline fisheries, the model indicates that the entire fishery has had a substantial impact on the level of biomass vulnerable to these fisheries (Figure 26). The impact of the entire fishery is estimated to have increased sharply in the 1950s and 1960s and remained at about 60% since 1970; i.e., the level of catch from the entire fishery has reduced the vulnerable biomass to about 60% of the unfished level. The fishery impacts are slightly lower for the fisheries within sub-areas 1 and 4 due to the higher proportion of juvenile fish in the catches from these areas (Figure 26).

Fishery impacts are considered to be extreme for the proportion of the population vulnerable to the New Zealand recreational fishery as the level of impact has been approaching 100% since the 1970s (Figure 26). This is due to the model's prediction that the fishing mortality rates are sufficiently high to remove most of the large, old fish from the population — the fish that comprise the main component of the catch from this fishery — prior to being exposed to effort from the New Zealand recreational fishery. Thus the relatively small catches (and effort) of the New Zealand recreational fishery impose a relatively high impact on the proportion of the stock surviving to these older age classes. These results contradict the observations of increasing catch rates from the fishery in the last two decades and the continued availability of large fish to the fishery. This suggests that the model is under-estimating the abundance of these old fish, possibly related to selectivity assumptions for the longline fisheries.

5.3.5 Yield analysis

The yield analyses conducted in this assessment incorporate the SRR (Figure 27) into the equilibrium biomass and yield computations. The steepness coefficient of the SRR is estimated to be 0.51, considerably lower than the prior mode of 0.94 (see Figure 10). The low value of steepness is due to the steady decline in both estimated recruitment and spawning biomass during the early period of the model (prior to 1970 and the availability of size data for the key longline fisheries).

Equilibrium yield and total biomass as functions of multiples of the 2001–2003 average fishing mortality-at-age (fmult) are shown in Figure 28. Yield is maximized at fmult = 0.8 for a MSY of 2,600 t per annum, similar to the average annual catch from the model region since 1984 (Figure 1 and Figure 4). This implies that the ratio $F_{current} / \widetilde{F}_{MSY}$ is approximately 1.25. The equilibrium total biomass at MSY is estimated at 13,800 t, approximately 44% of the equilibrium unexploited biomass (Table 7).

5.3.6 Sensitivity analyses

There is a high level of uncertainty regarding the natural mortality of striped marlin. The sensitivity of the model to the assumed value of natural mortality (0.4, for all age classes) was investigated by comparing separate analyses using an extremely low value for M (0.2) and a higher value (0.6).

Further, the impact of the prior distribution on the value of steepness of the SRR was examined. The uninformative prior resulted in a very low value for steepness. This was compared to an analysis that highly penalised the value of steepness from deviating substantially lower than 1.0; i.e., effectively meaning that there is no relationship between spawning biomass and recruitment.

Similarly, growth parameters for striped marlin are uncertain, particularly initial growth. The sensitivity to the model to a lower value (0.3) of the *k* parameter of the von Bertalanffy growth function was also examined.

The four alternative scenarios resulted in a weaker fit to the data, particularly the size data, than the "base case" model option (Table 5). Overall, the five analyses provide comparable estimates of MSY (2,600–3,000 mt), while the fishing mortality based reference point ($F_{current} / \widetilde{F}_{MSY}$) differs considerably among models (0.50–2.50) (Figure 29 and Table 7).

5.3.7 Stock assessment conclusions

A number of quantities of potential management interest (Table 6) associated with the yield analyses are presented in Table 7. In the upper half of Table 7, absolute quantities are provided, while the lower half of Table 7 contains ratios of various biomass and fishing mortality measures that might be useful for stock monitoring purposes. It is useful to distinguish three different types of ratio: (i) ratios comparing a measure for a particular time period with the corresponding equilibrium measure; (ii) ratios comparing two equilibrium measures (rows shaded grey); and (iii) ratios comparing two measures pertaining to the same time period (row shaded black). Several commonly used reference points, such as $B_{current} / \widetilde{B}_{MSY}$ and $F_{current} / \widetilde{F}_{MSY}$ fall into the first category. These ratios are usually subject to greater variability than the second category of ratios because recruitment variability is present in the numerator but not in the denominator. The ratio $B_{current} / B_{current,F=0}$ provides a time-series index of population depletion by the fisheries.

For the current assessment, estimates of MSY were similar for all model scenarios examined (Table 7). This is due to the assessment being strongly influenced by the initial decline in CPUE when catches were relatively high followed by a period of relatively constant catches with CPUE at a correspondingly lower level. MSY is a function of the overall level of recruitment that is required to explain these trends in observed catches and CPUE. Differences in the assumed productivity of the species will influence the level of recruitment required to generate the MSY. For a longer lived species (e.g. M = 0.2), the level of recruitment required to generate the observed catches will be lower than for a shorter-lived species (e.g. M = 0.4). Therefore, while these two scenarios may yield comparable estimates of MSY through scaling the level of recruitment required to generate the observed catches, the differences in the productivity of the two scenarios will determine the other biological reference points for the stock ($\widetilde{B}_{F_{current}} / \widetilde{B}_{MSY}$ and $F_{current} / \widetilde{F}_{MSY}$).

For the lower productivity stock scenario (M = 0.2), the level of fishing effort required to achieve the MSY is considerably lower than for the more productive (M = 0.4) stock scenario ($F_{current} / \widetilde{F}_{MSY}$ = 2.50 and 1.25, respectively) (Table 7). For the low productivity scenario, the current levels of fishing effort have resulted in a substantially higher level of depletion ($\widetilde{B}_{F_{current}} / \widetilde{B}_{MSY}$ = 0.50, $B_{current} / B_{current,F=0}$ = 0.23) compared to the higher productivity scenario ($\widetilde{B}_{F_{current}} / \widetilde{B}_{MSY}$ = 0.87, $B_{current} / B_{current,F=0}$ = 0.53).

The converse is the case for the scenario where natural mortality is assumed to be high (M = 0.6). The overall level of recruitment is increased accordingly and the higher productivity means that MSY is achieved at a higher level of fishing effort ($F_{current} / \widetilde{F}_{MSY}$ = 0.63) (Table 7), while levels of depletion are lower ($\widetilde{B}_{F_{current}} / \widetilde{B}_{MSY}$ = 1.23, $B_{current} / B_{current,F=0}$ = 0.70).

The value of steepness of the SSR is also highly influential in determining the biological parameters. A high value of steepness, approaching 1.0, means that there is virtually no relationship between spawning biomass and recruitment and, consequently, the stock can sustain a higher level of fishing mortality without impacting on the spawning potential. Conversely, a lower value of steepness, such as the values estimated from the uninformative steepness prior (about 0.50–0.60), means the spawning potential of the stock is reduced at lower levels of spawner biomass, in this case by about 40–50% when spawner biomass is reduced to 20% of the unexploited level.

Consequently, for the scenario with a high steepness (informative prior), a higher MSY can be achieved at a lower level of reference biomass ($\widetilde{B}_{MSY}$ and $S\widetilde{B}_{MSY}$) compared to the scenarios where a lower value of steepness was estimated (from the uninformative prior) (Table 7). This results in a more optimistic stock status with respect to both the fishing mortality and biomass based reference points compared to the corresponding model with an equivalent value assumed for natural mortality (M = 0.4).

Another source of considerable uncertainty in the model is the growth parameters. The model scenario with slower growth (growth parameter $k = 0.3$) estimated a higher overall level of recruitment, as fish were generally caught at an older age and, therefore, a higher level of recruitment was required to account for the observed catches. The maturity OGIVE was shifted to older age classes to account for the slower growth (as information on maturation was length- rather than age-based). By contrast, for the scenario assuming slower growth, most of the fish are not vulnerable to the fishery until age 6 years. This resulted in a more optimistic stock status than the comparable model with faster growth ($k = 0.6$) and a higher spawning biomass maintained at an equivalent level of fishing effort (Table 7).

In summary, the various scenarios investigated indicate the conclusions regarding stock status are highly sensitive to the assumed biological parameters incorporated in the assessment. For the more plausible scenarios, with natural mortality of 0.4 per annum, current (equilibrium) biomass levels ($\widetilde{B}_{F_{current}}$ and $S\widetilde{B}_{F_{current}}$) are either slightly below or above the corresponding reference level ($\widetilde{B}_{MSY}$ and $S\widetilde{B}_{MSY}$) depending on whether or not a strong relationship exists between spawning biomass and recruitment. For these two scenarios, current exploitation rates are either slightly higher than the fishing mortality based reference point ($F_{current} \big/ \widetilde{F}_{MSY} > 1$) or considerably lower than the reference level ($F_{current} \big/ \widetilde{F}_{MSY} < 1$) (Table 7). In both cases, the yield-based reference point $\widetilde{Y}_{F_{current}} \big/ MSY$ indicates that there is no potential to expand long-term yields from the fishery at the current pattern of age-specific selectivity.

It is important to emphasise that the reference points presented in Table 7 are point estimates and do not take into account the uncertainty associated with these values. There are two components to the uncertainty: the precision of the parameter estimates in the model and the uncertainty regarding the various structural assumptions of the model. The model diagnostics summarised in the previous sections indicate there are some obvious issues with some of the current model assumptions. These will be discussed in more detail in the following section.

6. Discussion and conclusions

This report presents the results of the first assessment of striped marlin in the southwest Pacific Ocean. In many respects, the assessment should be considered preliminary as there remains a great deal of uncertainty regarding some of the key parameters included in the assessment model, in particular natural mortality and growth.

Limited information is also available concerning the changes in spatial distribution associated with different phases of the life history and seasonal variations in habitat. For this reason a single region model was adopted, thereby avoiding the need to parameterise the movement dynamics of the species. This simplifying assumption is likely to provide a more robust assessment model in the absence of strong evidence of spatially distinct sub-populations within the southwest Pacific. The assumption of a single, separate population in the model region is generally supported by the available tagging data (potential for rapid, long-distance movements; few recaptures reported outside the region) and genetic data which suggests discrete populations in different geographic regions of the Pacific Ocean (Graves and McDowell, 1994, Graves and McDowell 2003). The large proportion of small striped marlin reported from longline fisheries in the equatorial sub-area of the model supports the existence of a juvenile component of the population within the model region, further supporting the assumption that the region defines a separate stock.

A key assumption of the assessment is that the catch and effort data from the Japanese longline fleet represent a reliable index of relative abundance for the stock. In general, the three longline fisheries in the subtropical areas of the model region (LL JAP2–4) display broadly similar trends in catch rate with a general decline in CPUE from the mid 1970s to the early 1990s and an increase in CPUE in the late 1990s.

These trends in catch rate are also evident in the longline fishery within the subequatorial waters (LL JAP 1) although the magnitude in the variation in CPUE is considerably higher than for the other fisheries. This fishery is comprised of smaller, younger fish and, consequently, larger fluctuations in catch rate (expressed in number of fish) would be expected in response to recruitment variations than would be expected from the other longline fisheries that principally catch larger, adult fish.

However, the current model was unable to resolve the differences in the trends in catch rate between the subequatorial and the subtropical fisheries as indicated by the strong trend in the effort deviations for the former fishery. The current model gave greater emphasis to the (standardised) effort data from the subtropical longline fisheries than the subequatorial fishery. This assumption was based on the significant component of the total catch that is taken from the subtropical areas, particularly from the longline fisheries in sub-area 2, and the presumption that these fisheries provided a more reliable index of the trends in stock abundance.

The assessment model was sensitive to the weighting assigned to the subequatorial longline fishery (LL JAP 1). A comparable weighting to the effort data from the subtropical longline fisheries resulted in similar levels of stock biomass, although the current stock status was considerably more optimistic ($\widetilde{B}_{F_{current}} \big/ \widetilde{B}_{MSY} \approx 1$ and $F_{current} \big/ \widetilde{F}_{MSY} < 1$). The model's apparent conflict may indicate deficiencies in the standardisation procedure applied to the longline data from the individual fisheries and further detailed analysis of catch and effort data is warranted. The apparent conflict may also represent some unaccounted-for spatial structure of the stock within the model region.

The incompatibility between the CPUE data from the main fisheries may also indicate inadequacies in the assumed biological parameters included in the model. For example, the assumed rate of natural mortality and/or the estimated growth rates of the younger fish may be inconsistent with the true population dynamics of the stock. Few published estimates of mortality or growth of striped marlin are available, and a wide range of estimates have been presented (e.g. natural mortality, 0.389–1.33 per year; k, 0.22–0.696 per year, see Boggs 1989, Hinton and Bayliff 2002, Melo-Barrera 2003, Kopf et al. 2005). Additionally, currently used aging methods for striped marlin are yet to be validated (Kopf et al. 2005), increasing the uncertainty of published estimates of biological parameters. As a consequence, variations in recruitment, as indicated by changes in catch rate and the size composition of the catch from the subtropical longline fishery, may not be accurately promulgated through the model population to those fisheries catching the older age classes.

The down-weighting of the data from the subequatorial longline fishery (LL JAP 1) means that these data are considerably less influential in the estimation of the recruitment deviations, even though this sub-area in the model is where significant numbers of small striped marlin have been captured. Instead, the recruitment series appears to be largely influenced by the trend in the catch and effort series from the other key longline fisheries. This is particularly evident for the early period of the model (pre 1970) for which few size frequency data are available. The model estimates of recruitment in the initial period were high and subsequently declined during the 1960s, thus providing a partial explanation for the strong decline in catch rates observed from the Japanese longline fishery in sub area 2 (LL JAP 2). This observed decline in both recruitment and exploitable (essentially adult) biomass explains the very low value of steepness (0.51) derived for the spawning stock-recruitment relationship. While uncertain and most likely to be conservative, this value of steepness has a strong influence on the key biological reference points derived for the stock (Table 7).

There is also a clear conflict in the observed size data, particularly the weight data, and the biological parameters included in the model and/or the parameterisation of the selectivity function. This is most evident in the size data from the Japanese longline fisheries and the New Zealand recreational fishery which are both consistently larger (heavier) than predicted from the population model. This is attributable to the fishery principally catching the larger (heavier) individuals within the oldest age classes of the model population. The model applies an age-based selectivity with, particularly for the case of the New Zealand recreational fishery, full selectivity of the oldest age classes. Consequently, the vulnerable component of the model population also includes the smaller fish within these old age classes. Hence, the predicted size composition is considerably smaller than the observed size composition of the catch.

This issue was not resolved by increasing the number of age classes in the population as maximum average length (and weight) was estimated to have been attained at age 9 years and there was no further increase in size with increased age (beyond 10 years). The growth estimates from the model were generally comparable with published growth parameters, although estimates of length-at-age for south-western Pacific striped marlin are not available for the older age classes included in the model.

There is also an apparent discrepancy in the model between the assumed value of natural mortality and the presence of sufficient large fish in the population to sustain some of the fisheries that principally catch large fish. This is particularly evident in the New Zealand recreational fishery which catches very large fish. However, due to the high assumed value for natural mortality for all age classes (M=0.4), only a small number of fish are predicted to attain this size and, consequently the estimated level of vulnerable biomass for this fishery is very small. This explains why this component of the stock was estimated to have been depleted so rapidly during the early period of the fishery and why the fishery impact on this component of the population continues to be extremely (implausibly) high.

An alternative explanation for the poor fit to the data from the New Zealand recreational fishery is that this fishery exploits a component of the stock (comprised of large fish) that has a relatively limited spatial distribution and, therefore, not fully vulnerable to the main commercial longline fisheries. Ongoing tagging of fish captured in the New Zealand recreational fishery may enable an improved understanding of the spatial dynamics of these fish.

A number of other biological parameters are incorporated in the assessment, principally the starting values for the growth function and the length-weight relationship. Size frequency data were derived from a number of sources and required considerable manipulation to be standardised in comparable units. These conversions included the recalculation of lengths to EFL and processed weights to whole (unprocessed) fish weights using fishery specific scaling factors. Most of these factors have been derived from sufficient data to be confident in their application. However, there still remain some inconsistencies in the length and weight data collected from the same fishery that suggests a bias in the correction factors and/or the length-weight relationship. Additionally, there is the potential for the misidentification of billfish, particularly the potential for small blue marlin being misidentified as striped marlin, which may bias resulting length and weight data.

Given the uncertainty associated with many of the variables included in the model, a wide range of sensitivity analyses could have been undertaken to explore the variables most likely to be influential in the assessment. The wide ranges of previously published estimates for key biological variables, the lack of validated ageing data and the (likely) under-estimation the rapid growth rate of young fish, did not provide guidance to select alternative values for these key variables. Thus, it is difficult to define the scope of sensitivities that could be undertaken.

Instead, the sensitivity of the model to various assumed biological parameters was investigated by comparing an extreme range of values for natural mortality (low 0.2, high 0.6) and an alternative parameterisation of the spawner-recruitment relationship (SRR). The alternative scenarios revealed that MSY was rather insensitive to these values although the current stock status, with respect to the biomass and fishing mortality based reference points, was sensitive to the biological parameters investigated.

Consequently, there is a clear need to obtain more reliable estimates of most of the key biological parameters to improve the quality of the current assessment. To progress the assessment, it is recommended that further research is conducted in the following areas:

1. Age and growth studies to improve estimates of growth, particularly for younger age classes, and to provide more information concerning the likely range of values for natural mortality. Accurate ageing of striped marlin is complicated by the lack of validation studies and the potential for loss of inner (younger) increments in cross-sections of dorsal spines of older fish (Yatomi 1990). Age and growth estimates for striped marlin are rare and recently published estimates diverge widely, especially for striped marlin less than two (2) years of age (Melo-Barrera et al. 2003, Kopf et al. 2005).
2. Verification of the current assumptions regarding age-at-maturity and spawning frequency. It is currently assumed that striped marlin reproduce only during local spring periods. Additional information (e.g. ovary samples) collected by observers on longline vessels may be better resolve the spawning frequency and spawning areas for striped marlin.
3. Improved estimates for the parameters of the length-weight relationship, particularly for the relationship between EFL and whole weight. Improved estimates of key conversion factors may also be required, especially for smaller fish (less than 100 cm EFL).
4. Increased understanding of the movement dynamics in the southwest Pacific and the potential linkages with striped marlin in other areas of the Pacific. While long-distance movements were observed within the model region, the recapture rate was very low. Consequently, tagging data were not included in the model. Increased emphasis on tagging and recapture of striped marlin, particularly tagging large numbers within relatively small time-area strata, would potentially allow movement parameters to be estimated. This would potentially allow movements among sub-areas within the model, and links with other areas beyond the model region, to be estimated.

5. A more comprehensive analysis of catch and effort data, particularly variations in targeting and fishing power of the Japanese longline fleet, to increase the confidence in the application of these data as an index of stock abundance. In addition, fine-scale analysis of these CPUE data may identify seasonal shifts in areas of relatively high CPUEs which may assist in defining movements of striped marlin in the model region.
6. Better estimates of catches, retention rates and discarding rates of striped marlin by the New Zealand longline fleet. The prohibition of landing striped marlin by the domestic longline fleet since 1987 (Kopf et al. 2005) has likely resulted in the under-estimation of catch rates and fishing mortality by this fleet.
7. The incorporation of historical size data from the commercial catch. While finalising the assessment, an additional source of length data from the Japanese longline catch was identified. These data are from the early period of the fishery (1953–1960) for which no commercial size data were previously available (P. Ward, BRS, *pers.comm.*). Incorporation of these data in the next iteration of the assessment may improve estimates of annual recruitment in the early period of the model.

Research is currently underway to refine estimates of age and growth of striped marlin in the southwest Pacific Ocean. This work may yield improved estimates of key biological parameters and, thereby, enable the assessment to be updated in several years time.

The previous discussion has highlighted the main sources of uncertainty in the current assessment. Nevertheless, some tentative conclusions are available from these results. While the current stock status is uncertain, largely influenced by the assumed value for natural mortality and the SRR, current levels of catch are comparable to the range of MSY estimates. On this basis, there appears to be no potential to substantially increase the current level of yield from the stock. However, the fishery has supported catches at about the MSY level for the last 20 years (average annual catch 1984–2003 of 2,400 mt) at a relatively constant level of fishing effort. Consequently, there is no indication that current exploitation rates are having a deleterious impact on the productivity of the stock.

Regardless, several of the plausible model scenarios investigated indicate that current levels of fishing mortality may approximate or exceed the reference level (F_{MSY}) and current biomass levels may approximate or be below the biomass based reference point ($\widetilde{SB}_{MSY}$). On this basis, it is recommended that there be no increase in fishing mortality (fishing effort) on striped marlin. This recommendation applies particularly to the area encompassing the Coral Sea and the Tasman Sea (sub-areas 2 and 3) as the longline fisheries in this area have a relatively high catchability for striped marlin.

The assessment results also provide some insights into interactions between fisheries at a sub-regional scale. For the Australian recreational and commercial fisheries operating in the Tasman Sea (sub-area 3), the model estimates a strong increase in catchability over a three year period in the late 1990s coinciding with a sharp decline in the striped marlin catch by the Japanese longline fishery in the same area (Figure 30), although this is also the period where a sector of the Australian longline fleet also commenced opportunistically targeting striped marlin. Similarly, following the sharp decline in striped marlin catch by the Japanese longline fleet in the northern waters of New Zealand in the mid-1980s (sub-area 3) there was a steady increase in the catchability of striped marlin by the New Zealand recreational fishery (REC NZ3, Figure 30). These observations are suggestive of an increase in the availability of striped marlin to the domestic fisheries following the withdrawal of the Japanese fleet from these areas, implying a high level of hook competition among longline fleets capturing this species. In addition, the increased availability may have also encouraged increased effort towards striped marlin, which may partially explain the trends of increasing (standardised) effort in the Australian longline fisheries (LL AU2 and 3).

This paper presents the results of the first assessment of striped marlin in the southwestern Pacific Ocean. The assessment provides some tentative conclusions regarding the status of the stock and represents a starting point for the consideration of the management of species in the region. However, there remains considerable uncertainty regarding some of the key inputs to the model and further refinement of the assessment will be dependent on an increased understanding of the biology of the species. Some further research is currently being undertaken, principally refining estimates of age and growth for striped marlin, and these results may enable a substantive update of the assessment in the next few years.

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Table 1. Description of the fisheries and summary of information used in the assessment.

Fishery	Sub-area	Label	Method	Flag	Catch	Effort	Years
1	**1**	**LL JAP1**	**Longline**	**Japan**	**Number**	**Hooks**	**1952–2003**
2	**2**	**LL JAP2**	**Longline**	**Japan**	**Number**	**Hooks**	**1952–2003**
3	**3**	**LL JAP3**	**Longline**	**Japan**	**Number**	**Hooks**	**1952–2003**
4	**4**	**LL JAP4**	**Longline**	**Japan**	**Number**	**Hooks**	**1954–1992**
5	**4**	**LL TW4**	**Longline**	**Taiwan**	**Number**	**Hooks**	**1967–2003**
6	**2**	**LL AU2**	**Longline**	**Australia**	**Number**	**Hooks**	**1990–2003**
7	**3**	**LL AU3**	**Longline**	**Australia**	**Number**	**Hooks**	**1990–2003**
8	**3**	**LL NZ3**	**Longline**	**New Zealand**	**Number**	**Hooks**	**1993–2003**
9	**3**	**REC AU3**	**Recreational**	**Australia**	**Number**	**Days**	**1990–2003**
10	**3**	**REC NZ3**	**Recreational**	**New Zealand**	**Number**	**Days**	**1950–2003**
11	**1**	**Other LL 1**	**Longline**	**Other flags**	**Number**	**Hooks**	**1967–2003**
12	**2**	**Other LL 2**	**Longline**	**Other flags**	**Number**	**Hooks**	**1967–2003**
13	**3**	**Other LL 3**	**Longline**	**Other flags**	**Number**	**Hooks**	**1968–2003**
14	**4**	**Other LL 4**	**Longline**	**Other flags**	**Number**	**Hooks**	**1976–2003**

Table 2. Number of tagged striped marlin recaptured in the model region by time at liberty (in quarters) and distance moved (kilometres). No tagged striped marlin were recaptured for times at liberty of 6–10 quarters. All distances calculated as straight line distances. Total number of recaptures = 143. Empty cells indicate no recaptures for that distance-quarter combination.

Distance	**Quarters at Liberty**						
moved (km)	**1**	**2**	**3**	**4**	**5**	**6–10**	**11**
100	47			2			
500	22	11	2		3		
1,000	8	7					
1,500	11	6	1	1			
2,000	7	1					1
2,500	1		1	1			
3,000	2	2					
3,500		1	1				
4,000							
4,500	1	1					
5,000		1	1				

Table 3. Biological parameters and starting values (in brackets) used in the assessment.

Parameter	Value	Comment	Source
Number of age classes	10	Fixed. Pools all fish 10 years and older together in the oldest age class.	See sources under other parameters.
Length-weight relationship ($L = aW^b$)	a= 8.1147e-07; b= 3.47	Fixed	Estimated from data supplied for the model region
Growth parameters (von Bertalanffy)	Mean length at age 1: 65 cm (60–70 cm); Mean length at age 10+: 300 cm (275–350 cm); k: 0.60 $year^{-1}$ (0.55–0.65 $year^{-1}$) Sensitivity: k = 0.3	Estimated Estimated Fixed	Skillman and Yong 1976; Boggs 1989; Melo-Barrera 2003; Kopf et al. 2005
Natural mortality	0.4 $year^{-1}$ Sensitivity: 0.2, 0.6	Fixed	Boggs 1989: Hinton and Bayliff, 2002.
Maturity ogive	Age: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 Proportion: 0, 0.5, 0.75, 1, 1, 1, 1, 1, 1, 1	Fixed	Skillman and Yong 1976; see Kopf 2005.

Table 4. Main structural assumptions used in the analysis.

Category	Assumption
Observation model for total catch data	Observation errors small, equivalent to a residual SD on the log scale of 0.07.
Observation model for length- and weight-frequency data	Normal probability distribution of frequencies with variance determined by sample size and observed frequency. Effective sample size is assumed to be 0.1 times actual sample size with a maximum effective sample size of 100.
Recruitment	Occurs as discrete events in November of each year. Recruitment is weakly related to spawning biomass with a 1 year lag via a Beverton-Holt SRR (beta prior for steepness lower bound at 0.2, a mode = 0.93 and standard deviation = 0.18). Alternative, highly informative prior constraining steepness to be close to 1.0.
Initial population	Equilibrium age structure in the region as a function of the estimated natural mortality.
Age and growth	10 annual age-classes, with the last representing a 10+ age group. Age-class 1 was allowed an independent mean length; other age-class mean lengths constrained by von Bertalanffy growth curve. Mean weights (W_j) computed internally by estimating the distribution of weight-at-age from the distribution of length-at-age and applying the weight-length relationship $W = aL^b$ (*a*=8.1147e-07, *b*=3.47 estimated from available length-weight data).
Selectivity	Constant over time. Coefficients for the last 2 age-classes are constrained to be equal. Longline selectivities are non-decreasing with increasing age except for fisheries in the subequatorial area.
Catchability	Seasonal variation for all fisheries. All fisheries, except Taiwanese longline, have structural time-series variation, with random steps (catchability deviations) taken every 2 years. Catchability deviations constrained by a prior distribution with (on the log scale) mean 0 and SD 0.1.
Fishing effort	Variability of effort deviations constrained by a prior distribution with (on the log scale) mean 0 and SD 0.22 for all fisheries.
Natural mortality	Constant at 0.4 per year for all age classes. Sensitivities 0.2, 0.6.
Movement	Not relevant for the single region model.

Table 5. Details of objective function components of the models.

Objective function component	**M=0.4, uninformative prior on steepness**	**M=0.2, uninformative prior on steepness**	**M=0.6, uninformative prior on steepness**	**M=0.4, informative prior on steepness**	**M=0.4, *k*=0.3 uninformative prior on steepness**
Number of parameters	1,849	1,849	1,849	1,849	1,849
Total catch log-likelihood	78	75	78	79	80
Length frequency log-likelihood	-42,416	-42,313	-42,243	-42,279	-42,320
Weight frequency log-likelihood	-248,738	-248,661	-248,639	-248,655	-248,711
Penalties	2,103	2,158	2,142	2,155	2,166
Total function value	-288,973	-288,741	-288,662	-288,700	-288,785
Maximum gradient at termination	6.5×10^{-6}	9.8×10^{-6}	8.5×10^{-5}	2.1×10^{-4}	4.1×10^{-5}

Table 6. Description of symbols used in the yield analysis.

Symbol	Description
$F_{current}$	Average fishing mortality-at-age for 2001–2003
F_{MSY}	Fishing mortality-at-age producing the maximum sustainable yield (MSY)
$\widetilde{Y}_{F_{current}}$	Equilibrium yield at $F_{current}$
$\widetilde{Y}_{F_{MSY}}$ (or MSY)	Equilibrium yield at F_{MSY} , or maximum sustainable yield
$\widetilde{B}_0$	Equilibrium unexploited total biomass
$\widetilde{B}_{F_{current}}$	Equilibrium total biomass at $F_{current}$
$\widetilde{B}_{MSY}$	Equilibrium total biomass at MSY
$S\widetilde{B}_0$	Equilibrium unexploited adult biomass
$S\widetilde{B}_{F_{current}}$	Equilibrium adult biomass at $F_{current}$
$S\widetilde{B}_{MSY}$	Equilibrium adult biomass at MSY
$B_{current}$	Average current (2001–2003) total biomass
$SB_{current}$	Average current (2001–2003) adult biomass
$B_{current,F=0}$	Average current (2001–2003) total biomass in the absence of fishing.

Table 7. Estimates of management quantities for the various model options. The highlighted rows are ratios of comparable quantities at the same point in time (black shading) and ratios of comparable equilibrium quantities (gray shading).

Management quantity	Units	M=0.4, uninformative prior on steepness	M=0.2, uninformative prior on steepness	M=0.6, uninformative prior on steepness	M=0.4, informative prior on steepness	M=0.4, Low k, uninformative prior on steepness
$\tilde{Y}_{F_{current}}$	t per year	2,590	2,202	2,776	2,844	2,537
$\tilde{Y}_{F_{MSY}}$ (or MSY)	t per year	2,610	2,622	2,918	3,003	2,555
$\tilde{B}_0$	t	31,300	36,660	29,910	22,640	33,390
$\tilde{B}_{F_{current}}$	t	12,000	6,524	17,140	11,360	16,830
$\tilde{B}_{MSY}$	t	13,800	12,970	13,890	8,831	15,610
$\tilde{SB}_0$	t	27,300	34,810	24,500	20,100	26,650
$\tilde{SB}_{F_{current}}$	t	9,300	5,373	12,970	8,973	11,570
$\tilde{SB}_{MSY}$	t	10,900	11,450	10,200	6,568	10,550
$B_{current}$	t	9,700	5,576	12,970	7,924	13,811
$SB_{current}$	t	7,400	4,489	9,463	6,055	8,692
$B_{current,F=0}$	t	18,400	23,778	18,409	16,557	22,219
$B_{current} / \tilde{B}_0$		0.31	0.15	0.43	0.35	0.41
$B_{current} / \tilde{B}_{F_{current}}$		0.81	0.85	0.76	0.70	0.82
$B_{current} / \tilde{B}_{MSY}$		0.70	0.43	0.93	0.90	0.88
$B_{current} / B_{current,F=0}$		0.53	0.23	0.70	0.48	0.62
$SB_{current} / \tilde{SB}_0$		0.27	0.13	0.39	0.30	0.33
$SB_{current} / \tilde{SB}_{F_{current}}$		0.80	0.84	0.73	0.67	0.75
$SB_{current} / \tilde{SB}_{MSY}$		0.68	0.39	0.93	0.92	0.82
$\tilde{B}_{F_{current}} / \tilde{B}_0$		0.38	0.18	0.57	0.50	0.50
$\tilde{SB}_{F_{current}} / \tilde{SB}_0$		0.34	0.15	0.53	0.45	0.43
$\tilde{B}_{MSY} / \tilde{B}_0$		0.44	0.35	0.46	0.39	0.47
$\tilde{SB}_{MSY} / \tilde{SB}_0$		0.40	0.33	0.42	0.33	0.40
F_{MSY}		0.19	0.20	0.21	0.34	0.16
$F_{current} / \tilde{F}_{MSY}$		1.25	2.50	0.63	0.50	0.83
$\tilde{B}_{F_{current}} / \tilde{B}_{MSY}$		0.87	0.50	1.23	1.29	1.08
$\tilde{SB}_{F_{current}} / \tilde{SB}_{MSY}$		0.85	0.47	1.27	1.37	1.10
$\tilde{Y}_{F_{current}} / MSY$		0.99	0.84	0.95	0.95	0.99

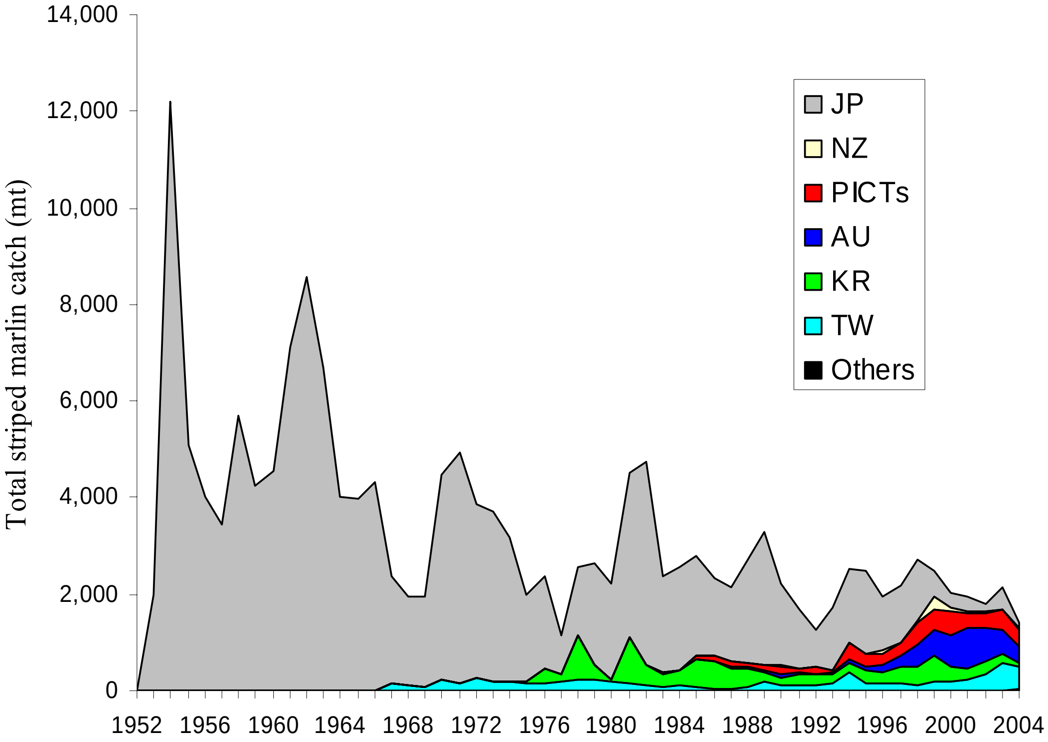

Figure 1. Estimated total striped marlin catches by major longline-method fisheries in the model region, 1952–2004. Source: raised estimates of catches from logsheet data held at SPC. Country codes: JP, Japan; NZ, New Zealand; PICTs, Pacific Island States and Territories; AU, Australia; KR, Korea; TW, Taiwan; Others, longline vessels from China, Indonesia, the Philippines and the United States.

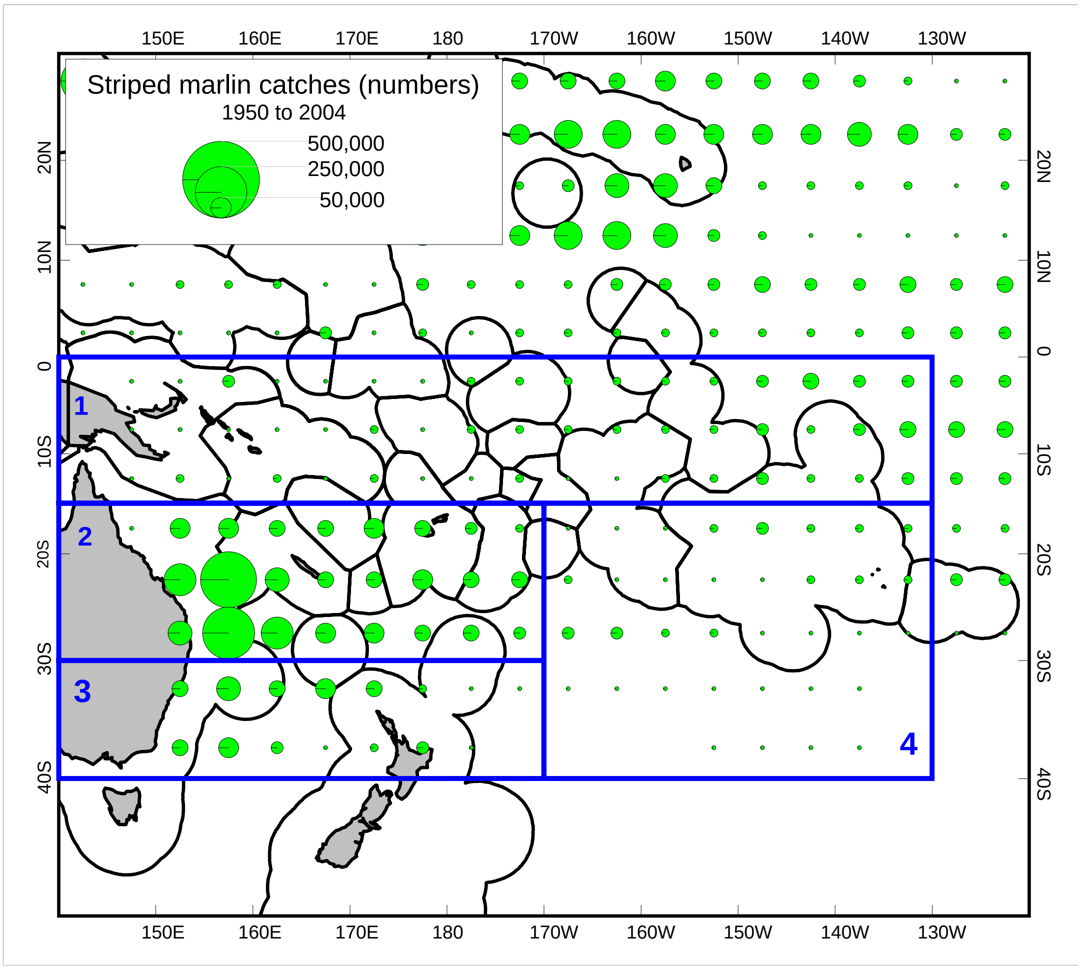

Figure 2. Catches of striped marlin (numbers) in the southwest Pacific, 1950–2004. Source, raised catch estimates available from the SPC. The blue lines represent the spatial limits of the assessment region (outer lines) for striped marlin in the southwest Pacific Ocean and sub-areas within the assessment region.

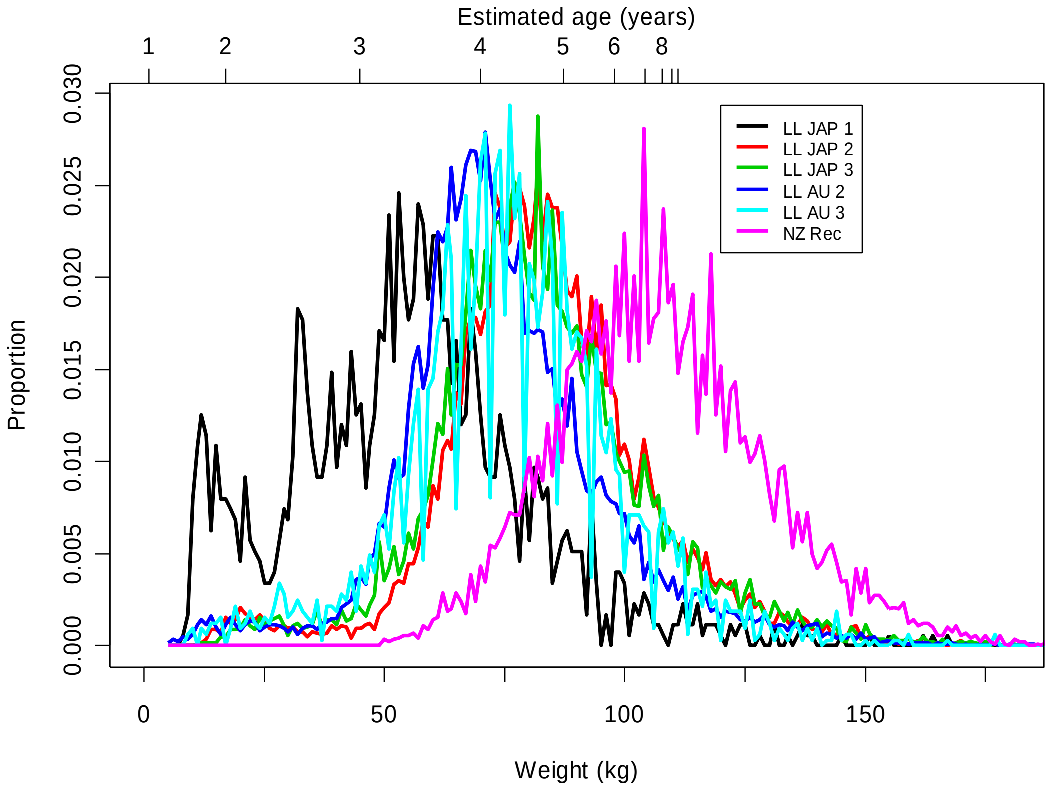

Figure 3. A comparison of the weight (whole weight, kilogrammes) frequency distributions of the sampled catches from the main fisheries, all years combined.

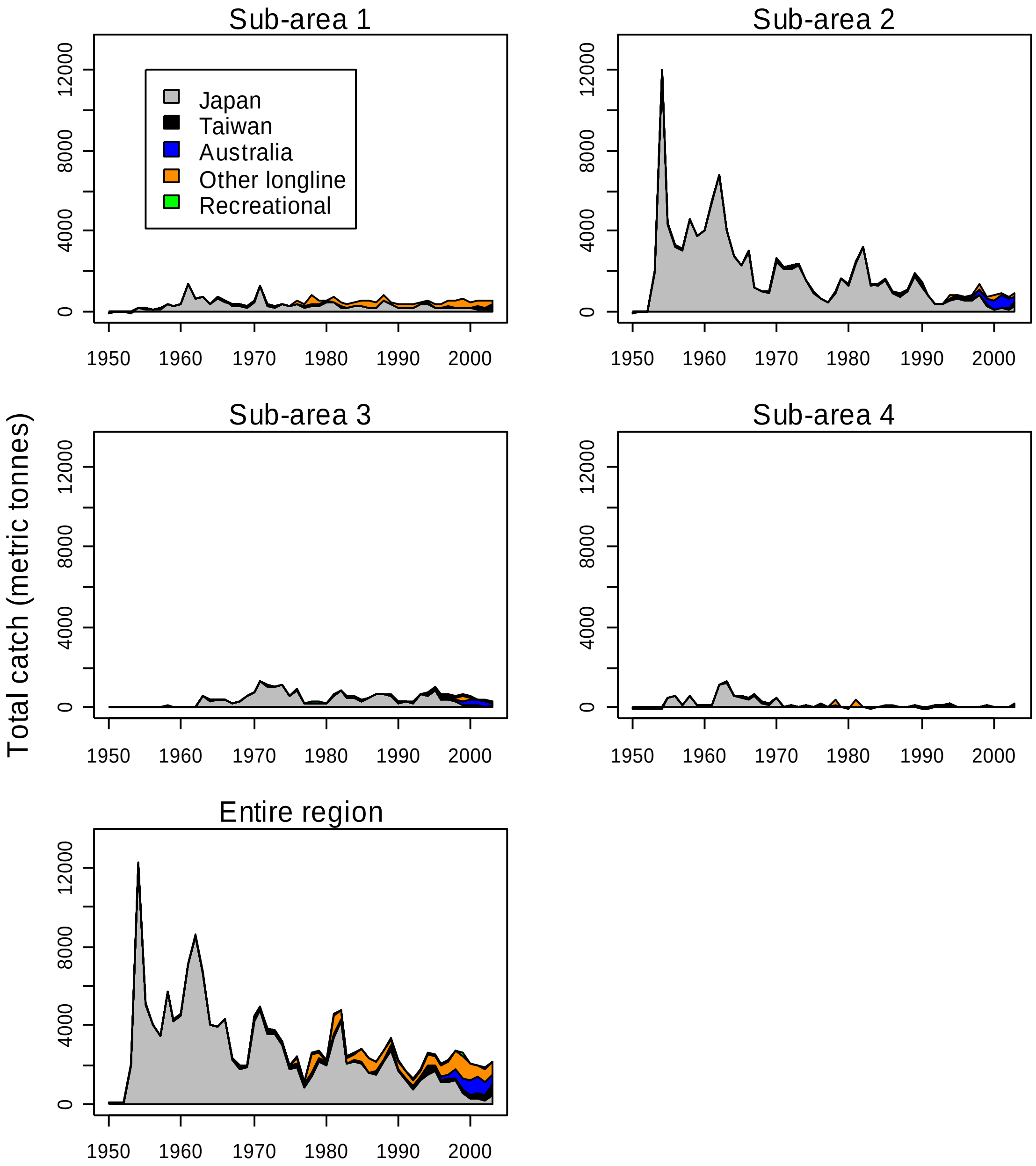

Figure 4. Total estimated catches of striped marlin (metric tonnes) by major flag, method-fishery and sub-area for the assessment model for the southwest Pacific, 1950–2003. Estimates for the recreational fisheries were generated by pooling total catches in numbers and dividing by 10, as the weight of striped marlin reported by the New Zealand recreational fishery (fishery 10) has averaged 100 kg since 1965 (see Kopf et al. 2005).

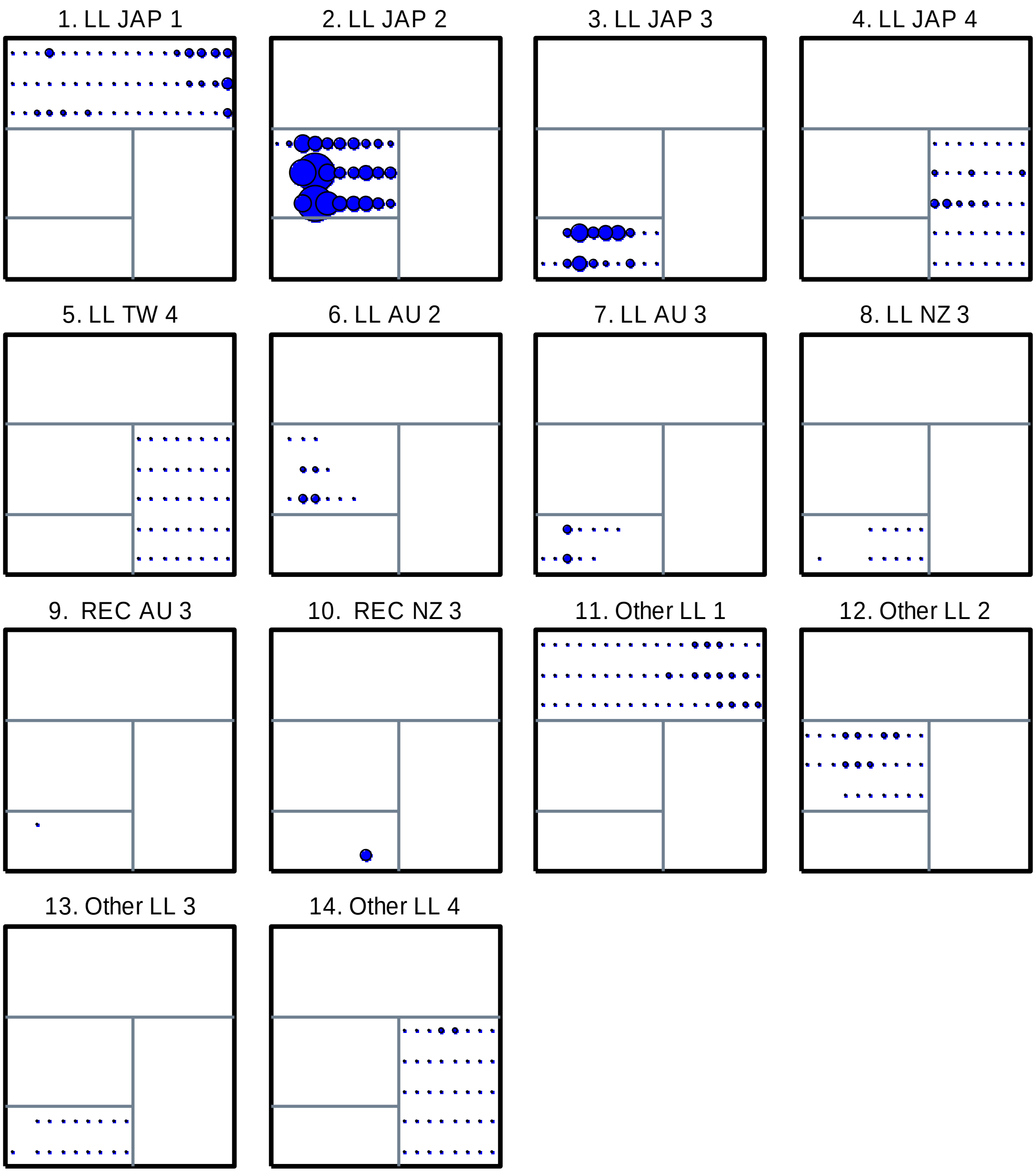

Figure 5. Cumulative catches of striped marlin by 5 x 5 degree of latitude and longitude for each fishery defined in the assessment model, 1950–2003. Labels on each fishery represent the fishery number as defined in the assessment (i.e. 1–14), the flag of the fishery (JP, Japan; TW, Taiwan; AU, Australia; NZ, New Zealand; Other, other flags operating in the region not otherwise defined), the gear type (L, longline; REC, recreational) and the model sub-area (1–4). The size of each circle is proportional to the maximum catch (approximately 105 mt). Estimates for the recreational fisheries were generated by pooling total catches in numbers and dividing by 10, as the weight of striped marlin reported by the New Zealand recreational fishery (fishery 10) has averaged 100 kg since 1965 (see Kopf et al. 2005). Black lines represent the spatial limits of the model region (0–40°S, 140°E–130°W). Grey lines represent the boundaries of the four sub-areas defined in the assessment.

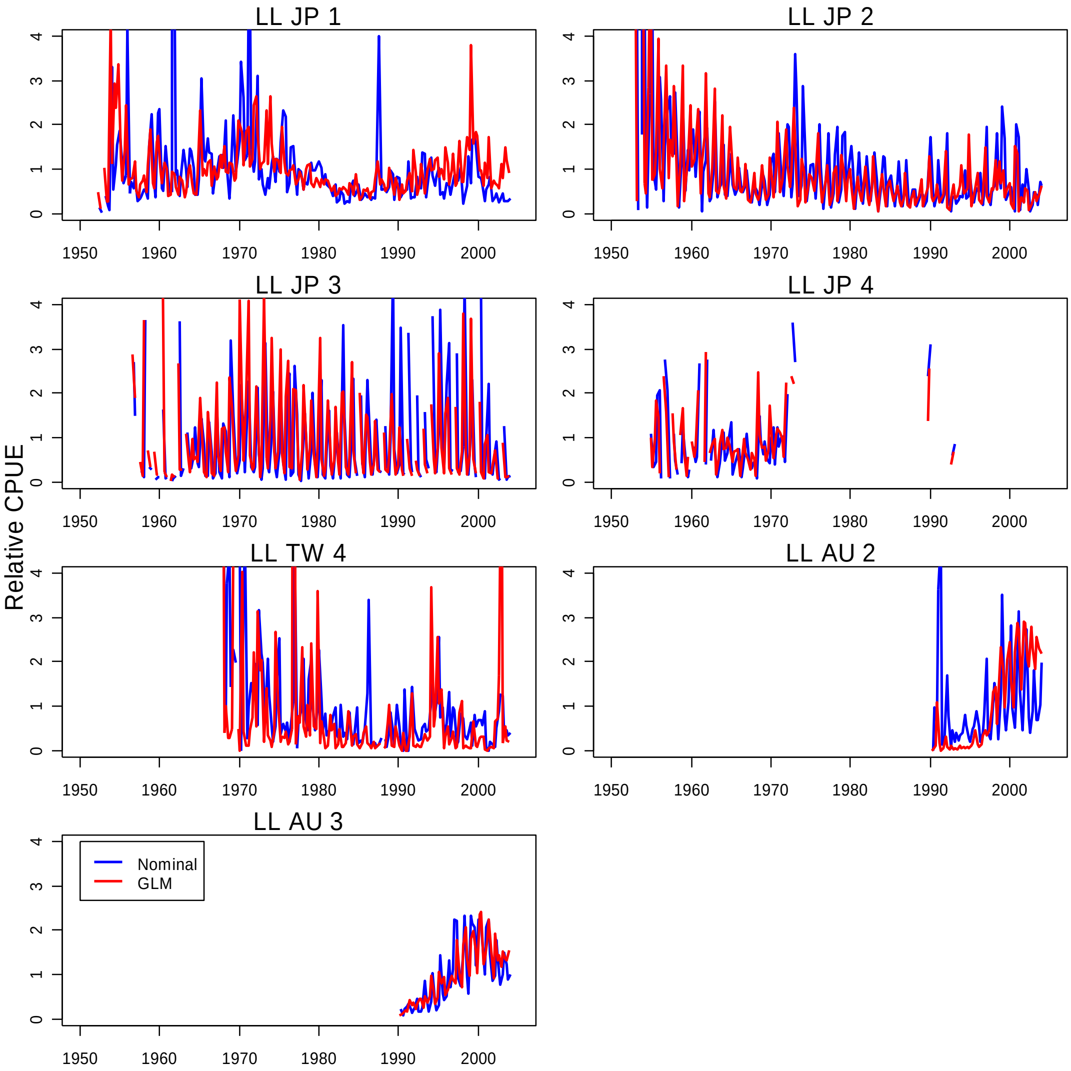

Figure 6. A comparison of nominal (blue series) and standardised (red series) quarterly CPUEs for the main longline fisheries. The CPUE indices have been normalised to the mean of the series.

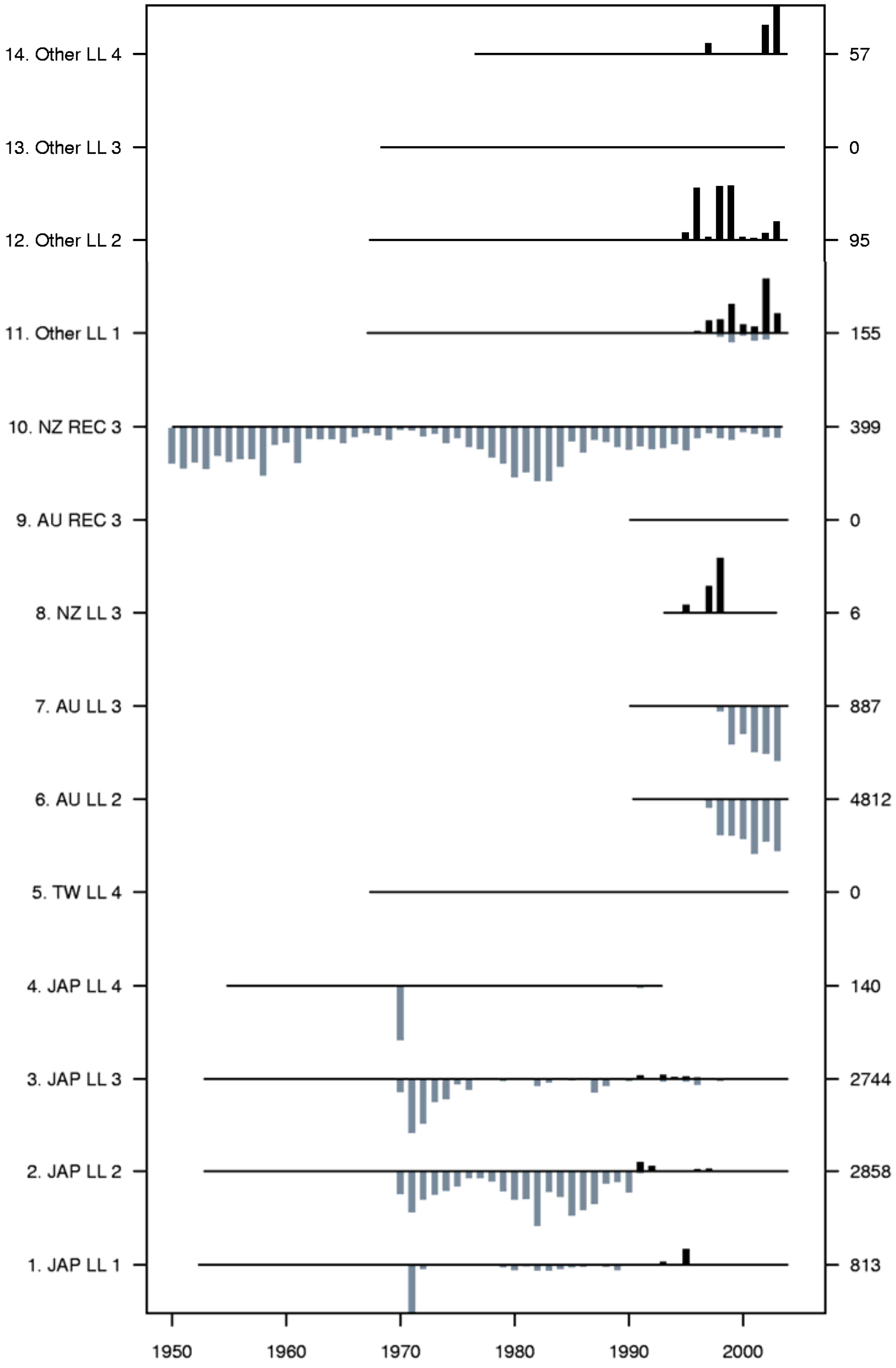

Figure 7. Number of fish size measurements by year for each fishery. The upper black bars represent length measurements and the lower grey bars represent weight measurements. The maximum bar length for each fishery is given on the right-hand side. The extent of the horizontal lines indicates the period over which each fishery occurred.

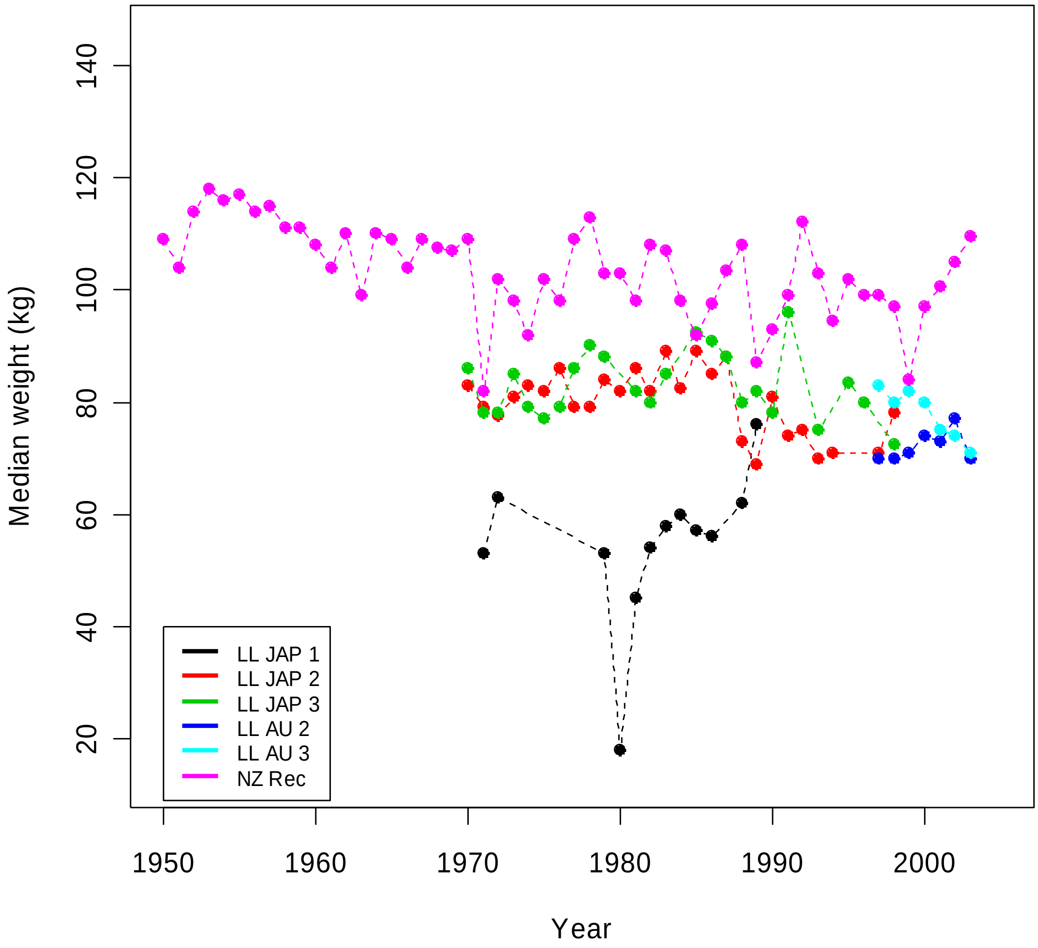

Figure 8. Trends in median fish weight (whole weight, kilogrammes) by year for the main fisheries providing size frequency data. Only years with at least 30 sampled fish are presented.

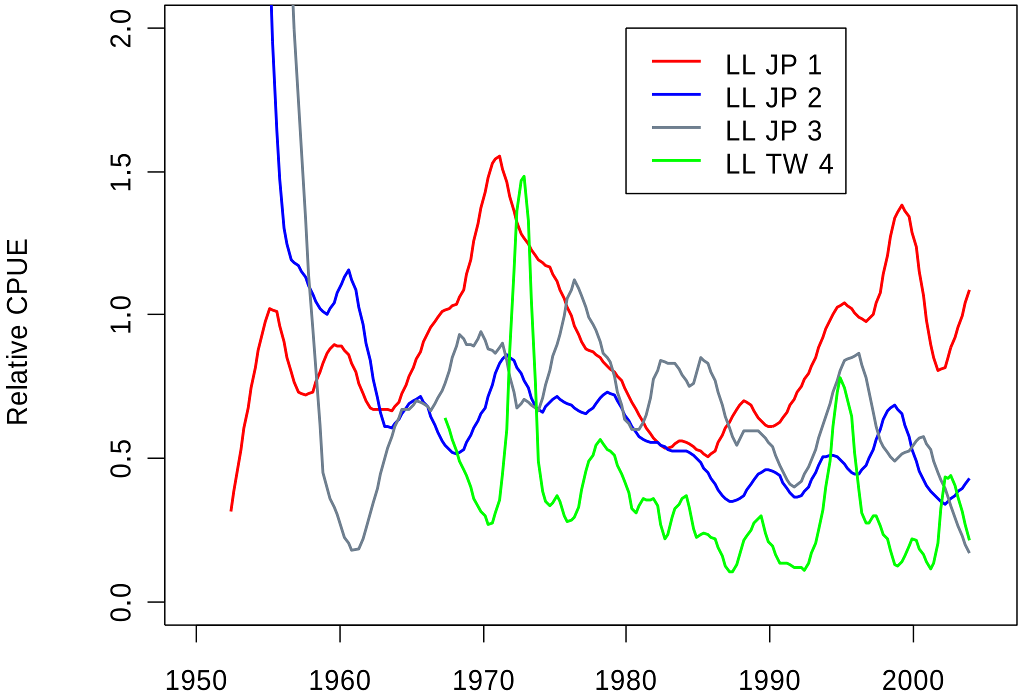

Figure 9. A comparison of the main CPUE indices for the four main fisheries included in the model. The CPUE series are normalised to the mean of each series and smoothed using a lowess function.

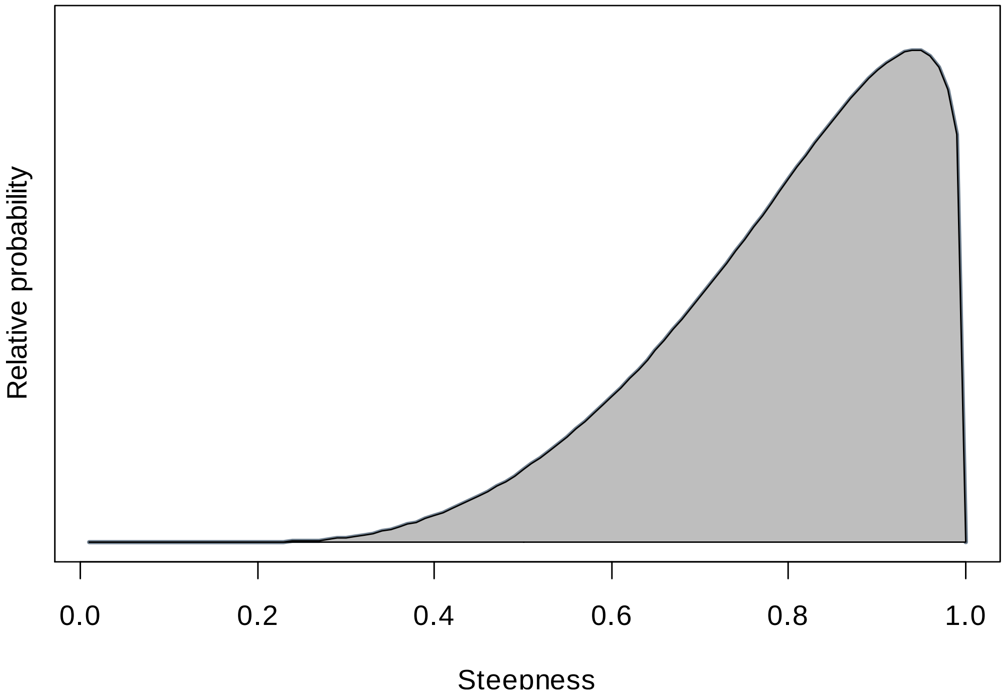

Figure 10. Prior for the steepness parameter of the relationship between spawning biomass and recruitment (SSR) (mode = 0.93, standard deviation = 0.18).

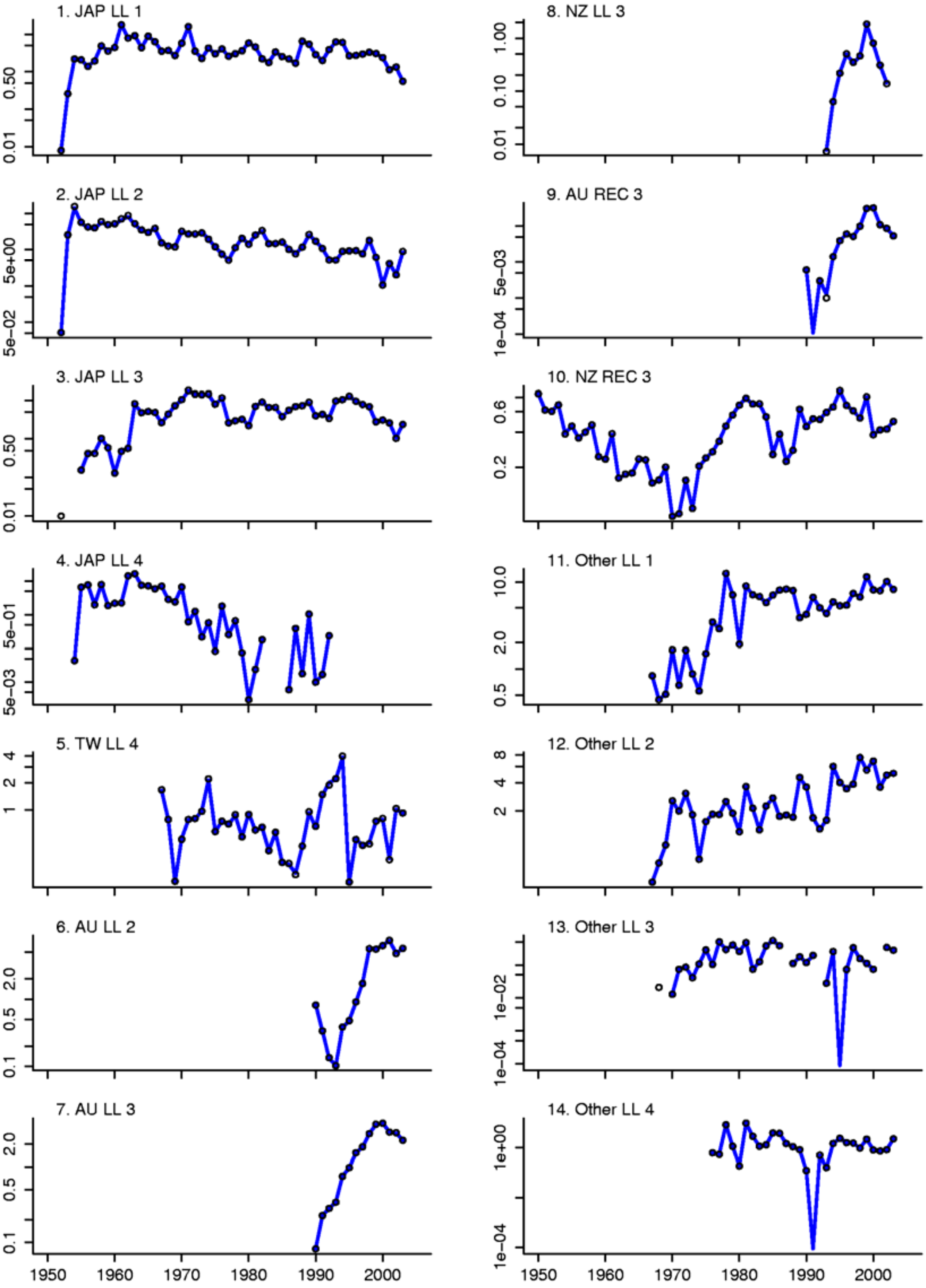

Figure 11. Observed (points) and predicted (blue line) annual catches, by fishery. Catches are expressed as number of fish. The y-axes are plotted on a logarithmic scale. Model estimates are from the model using natural mortality of 0.4 per year, *k* = 0.6, and the uninformative prior on steepness of the SSR.

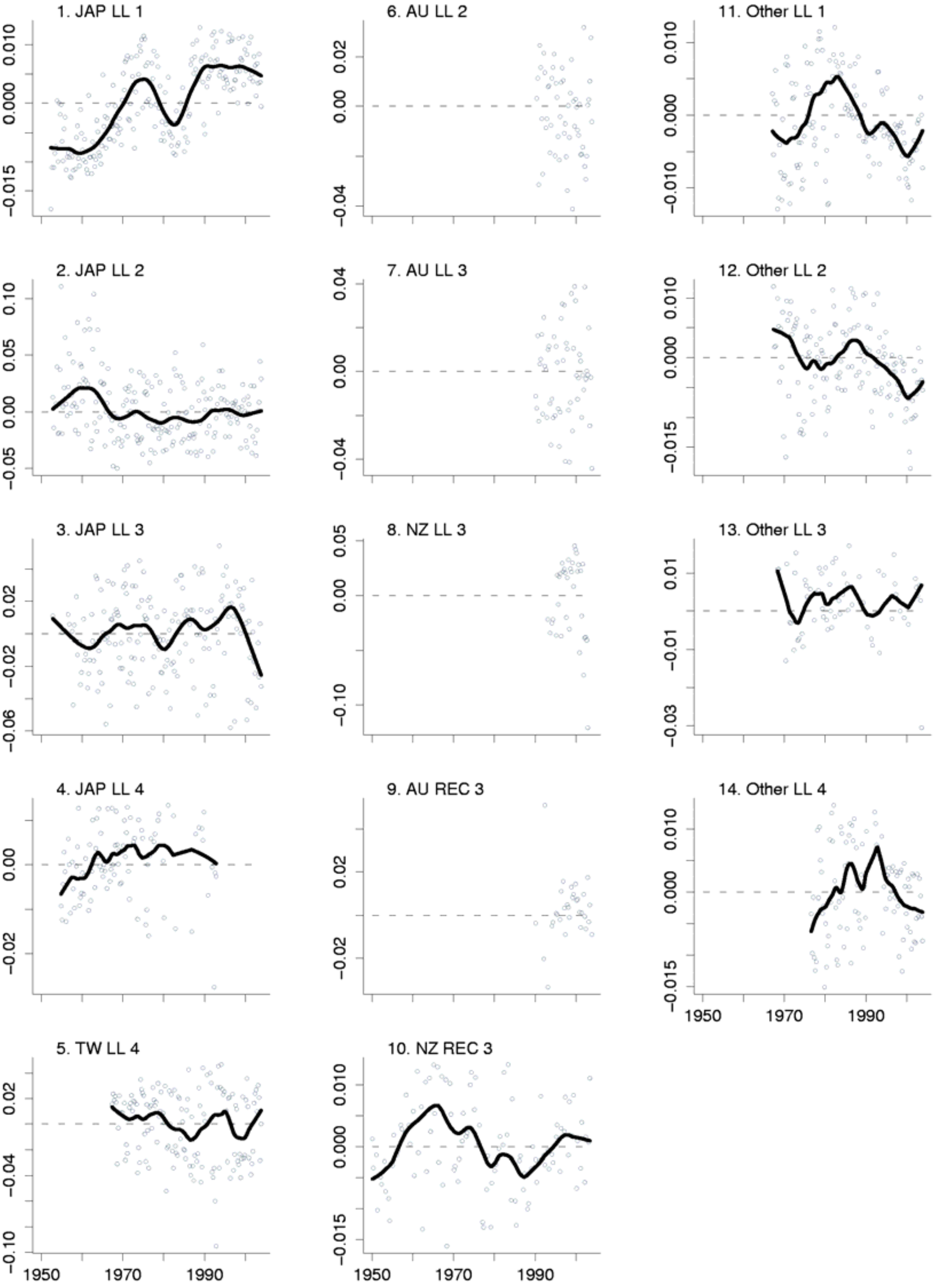

Figure 12. Residuals (ln) of total catch for each fishery. Solid lines represent lowess fits to the data.

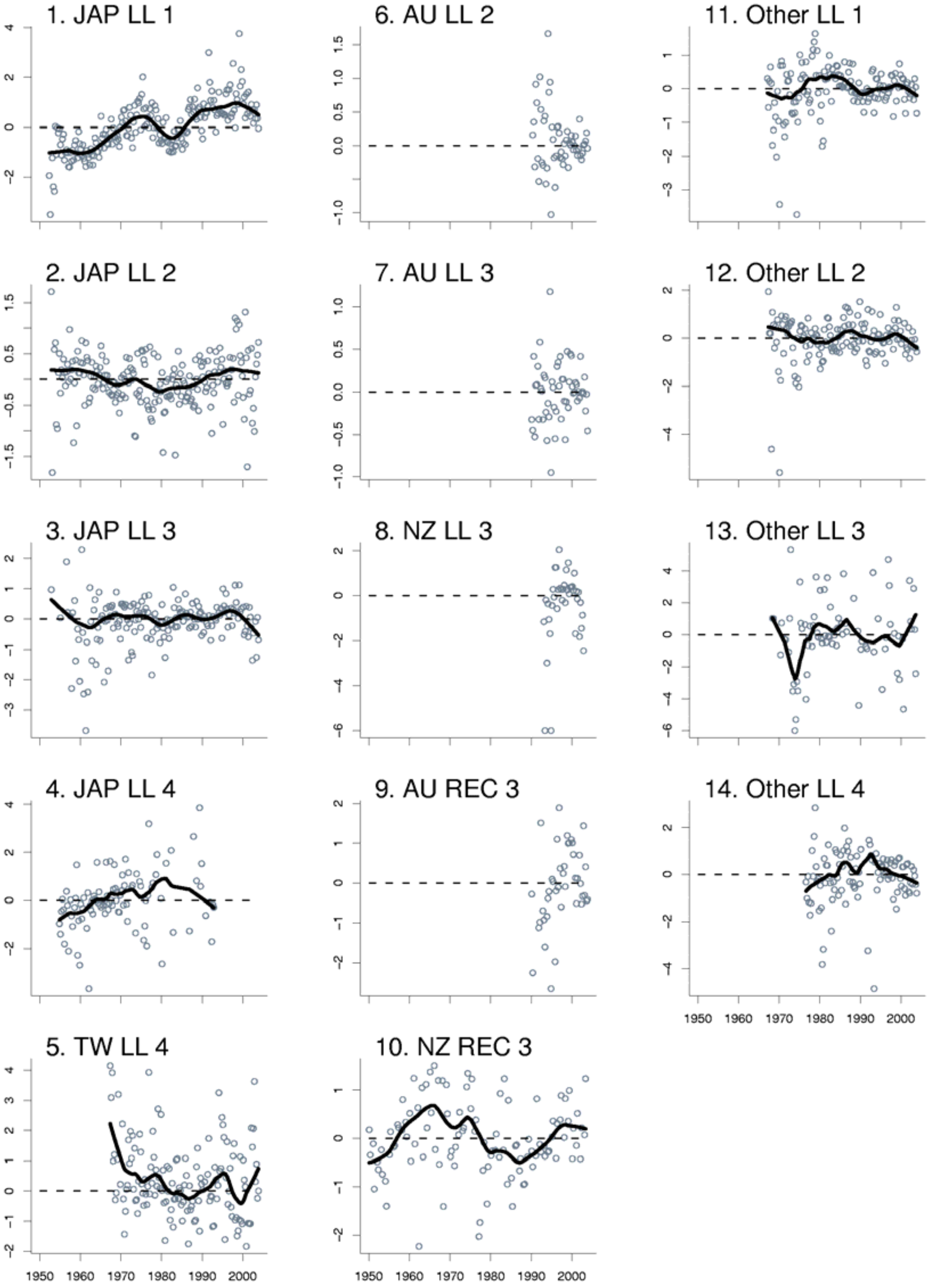

Figure 13. Effort deviations by time period for each fishery. Solid lines represent lowess fits to the data. Model estimates are from the model using natural mortality of 0.4 per year, *k* = 0.6, and the uninformative prior on steepness of the SSR.

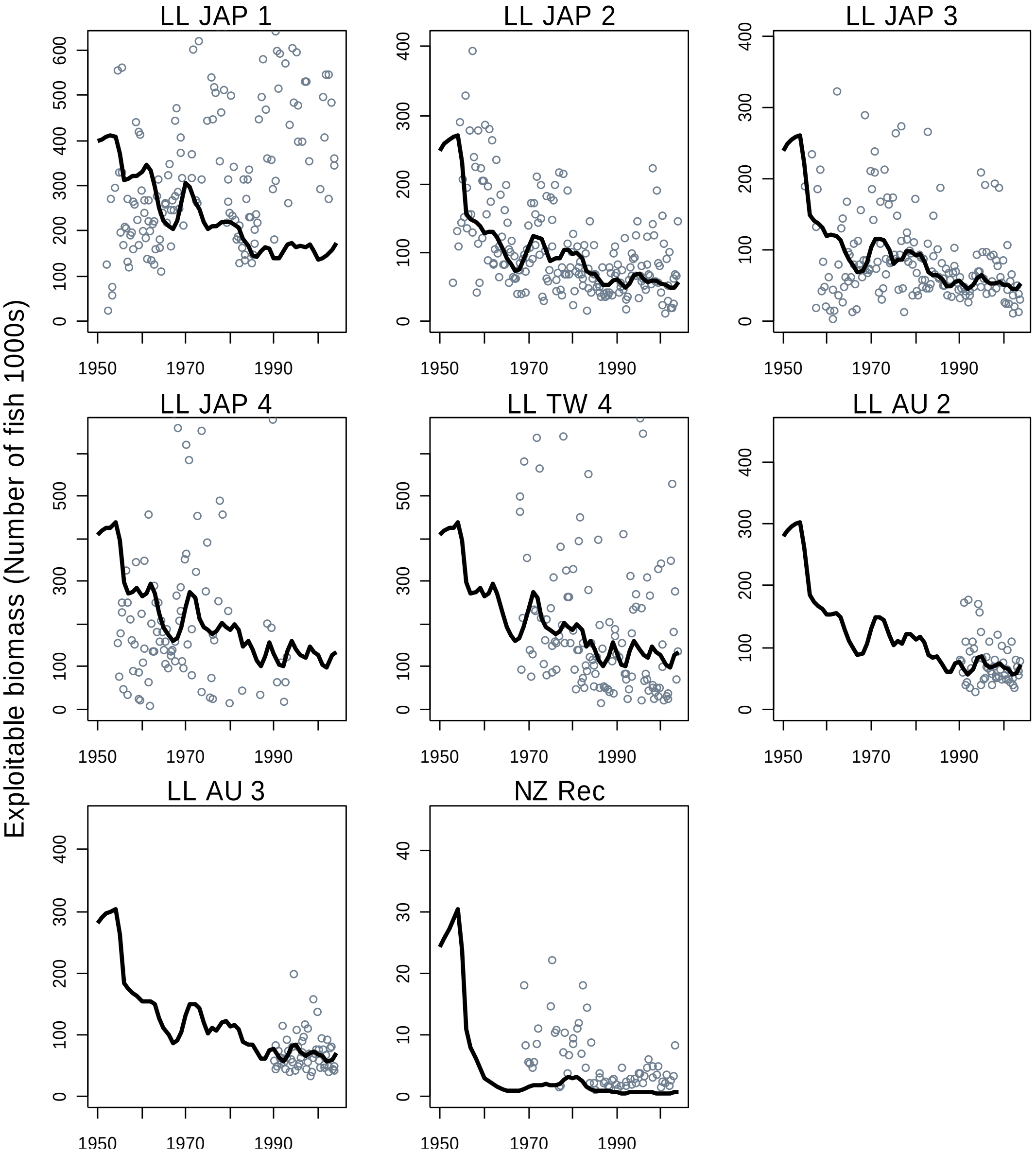

Figure 14. A comparison between observed CPUE (points) and fishery specific exploitable biomass (line) for the main fisheries included in the model. Model estimates are from the model using natural mortality of 0.4 per year, *k* = 0.6, and the uninformative prior on steepness of the SSR.

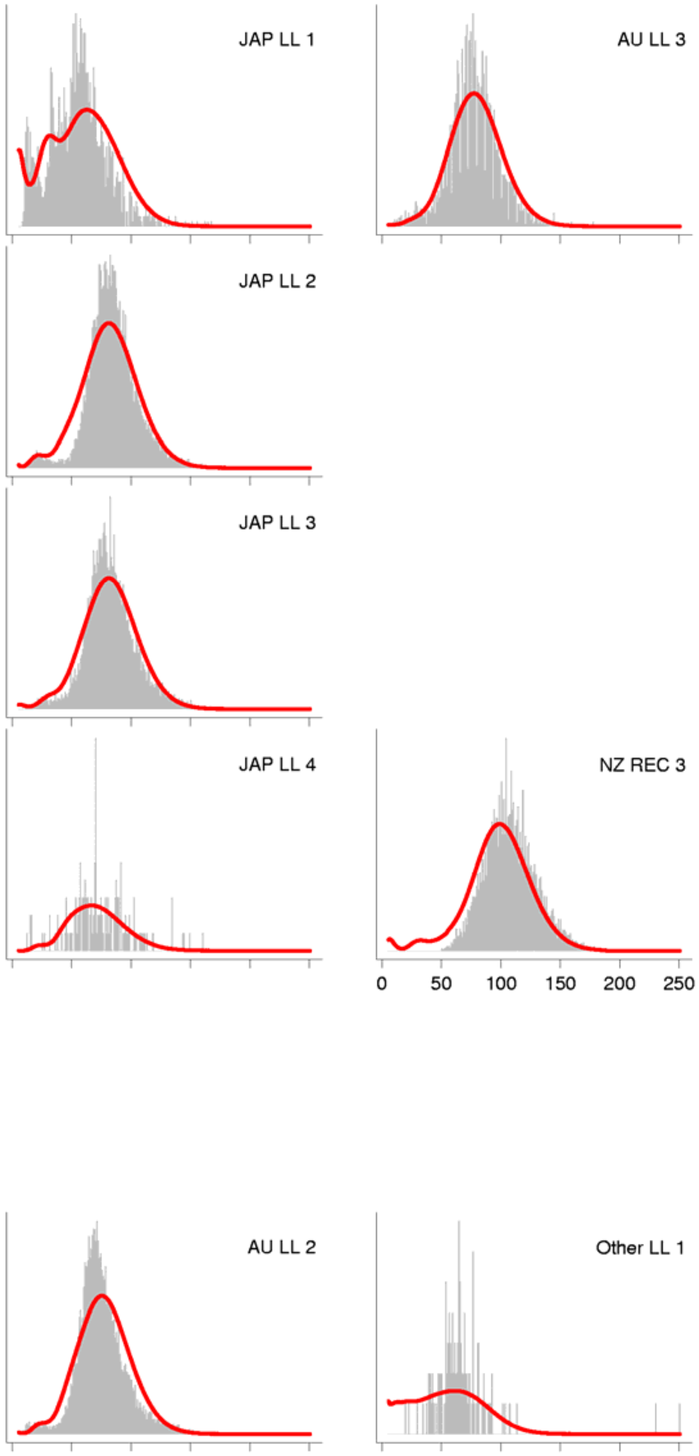

Figure 15. Observed (histograms) and predicted (red lines) weight frequencies (whole weight, kilogrammes) for each fishery aggregated over time. Only fisheries with size data are plotted. Model estimates are from the model using natural mortality of 0.4 per year, *k* = 0.6, and the uninformative prior on steepness of the SSR.

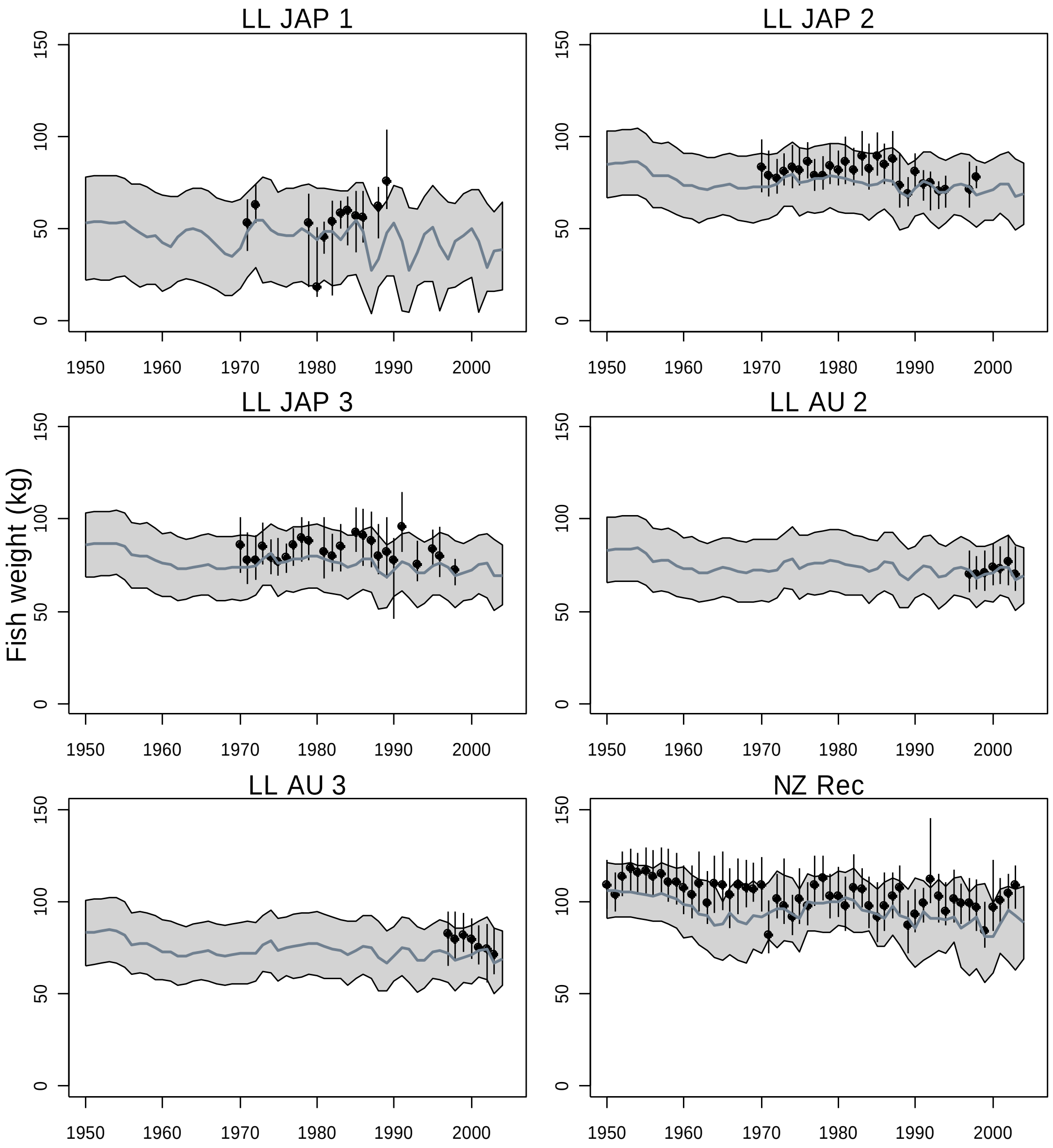

Figure 16. A comparison of the observed (points) and predicted (grey line) annual median weight (whole weight, kilogrammes) of striped marlin by fishery for the main fisheries with weight data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Model estimates are from the model using natural mortality of 0.4 per year, *k* = 0.6, and the uninformative prior on steepness of the SSR. Only weight samples with a minimum of 30 fish per year are plotted.

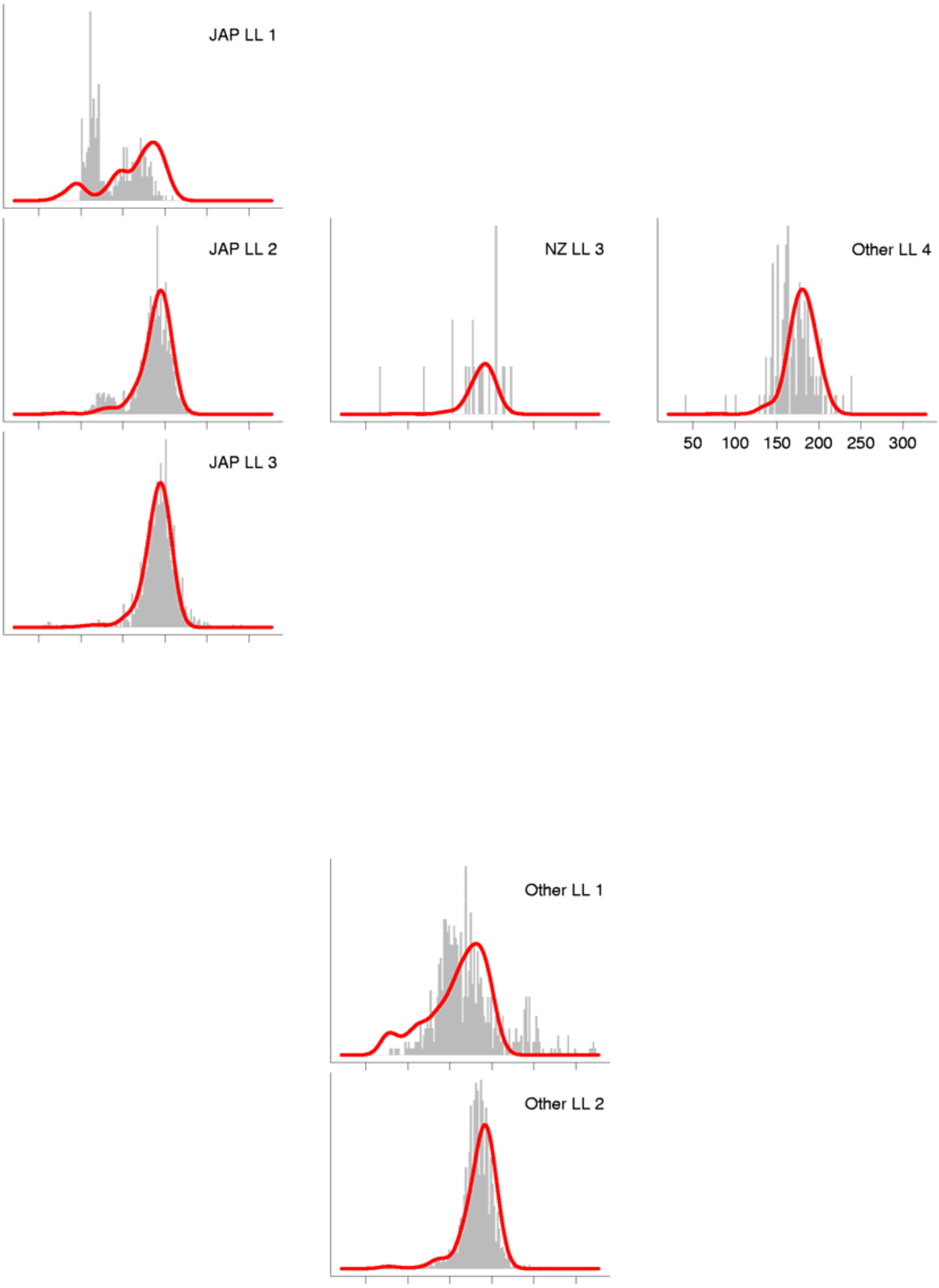

Figure 17. Observed (histograms) and predicted (red line) length frequencies (EFL, cm) for each fishery aggregated over time. Only fisheries with size data are plotted. Model estimates are from the model using natural mortality of 0.4 per year, *k* = 0.6, and the uninformative prior on steepness of the SSR.

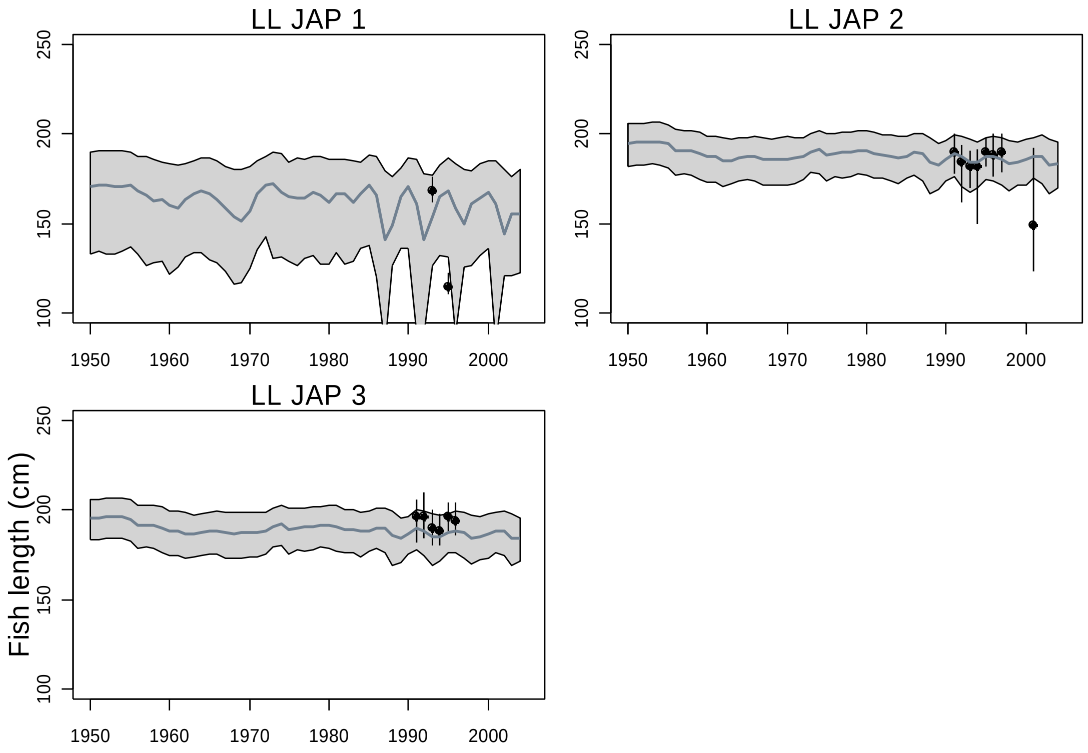

Figure 18. A comparison of the observed (points) and predicted (grey line) annual median length (EFL, cm) of striped marlin by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Model estimates are from the model using natural mortality of 0.4 per year, *k* = 0.6, and the uninformative prior on steepness of the SSR. Only length samples with a minimum of 30 fish per year are plotted.

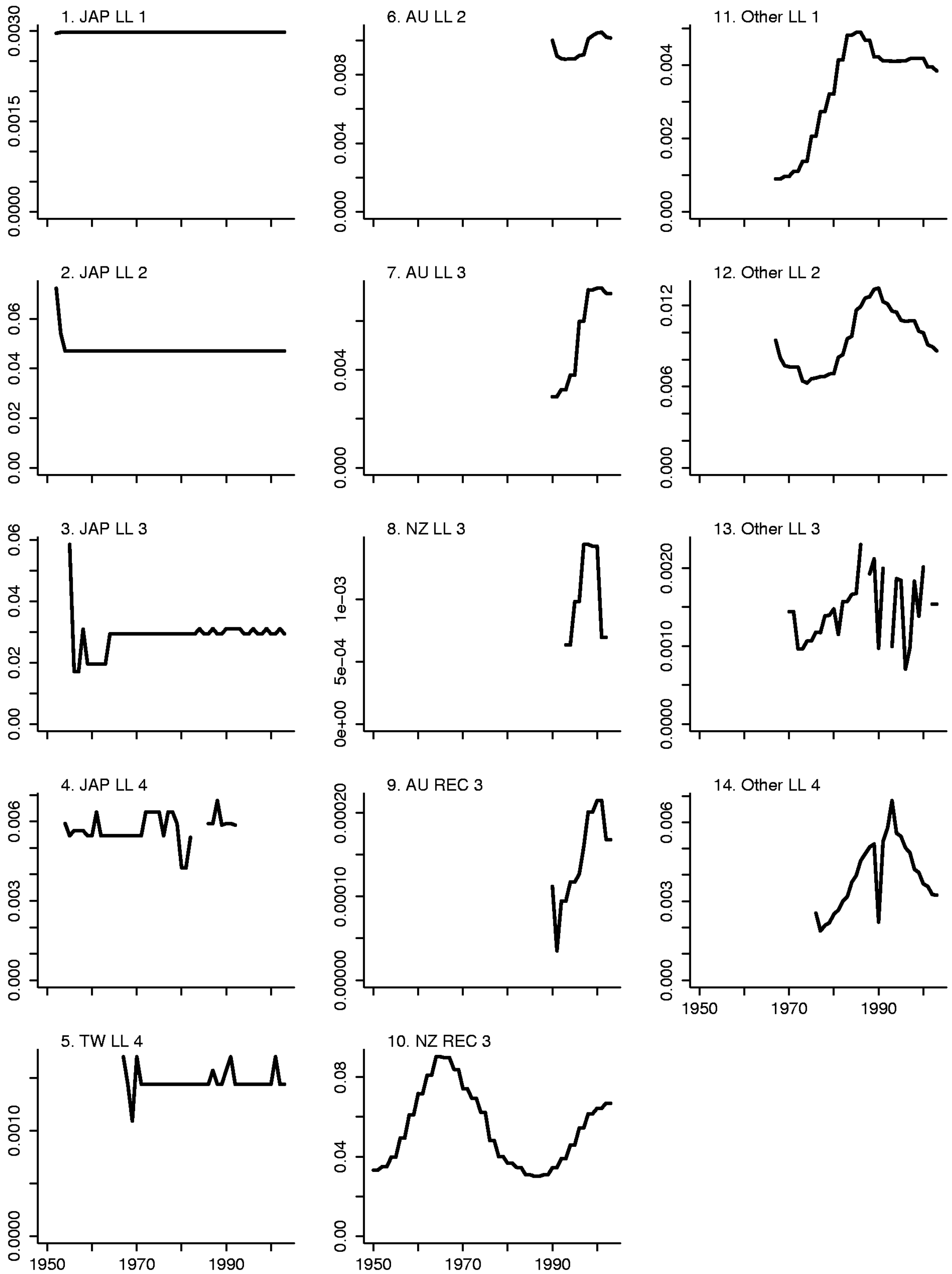

Figure 19. Average annual catchability time series for each fishery in the model region. Model estimates are from the model using natural mortality of 0.4 per year, *k* = 0.6, and the uninformative prior on steepness of the SSR.

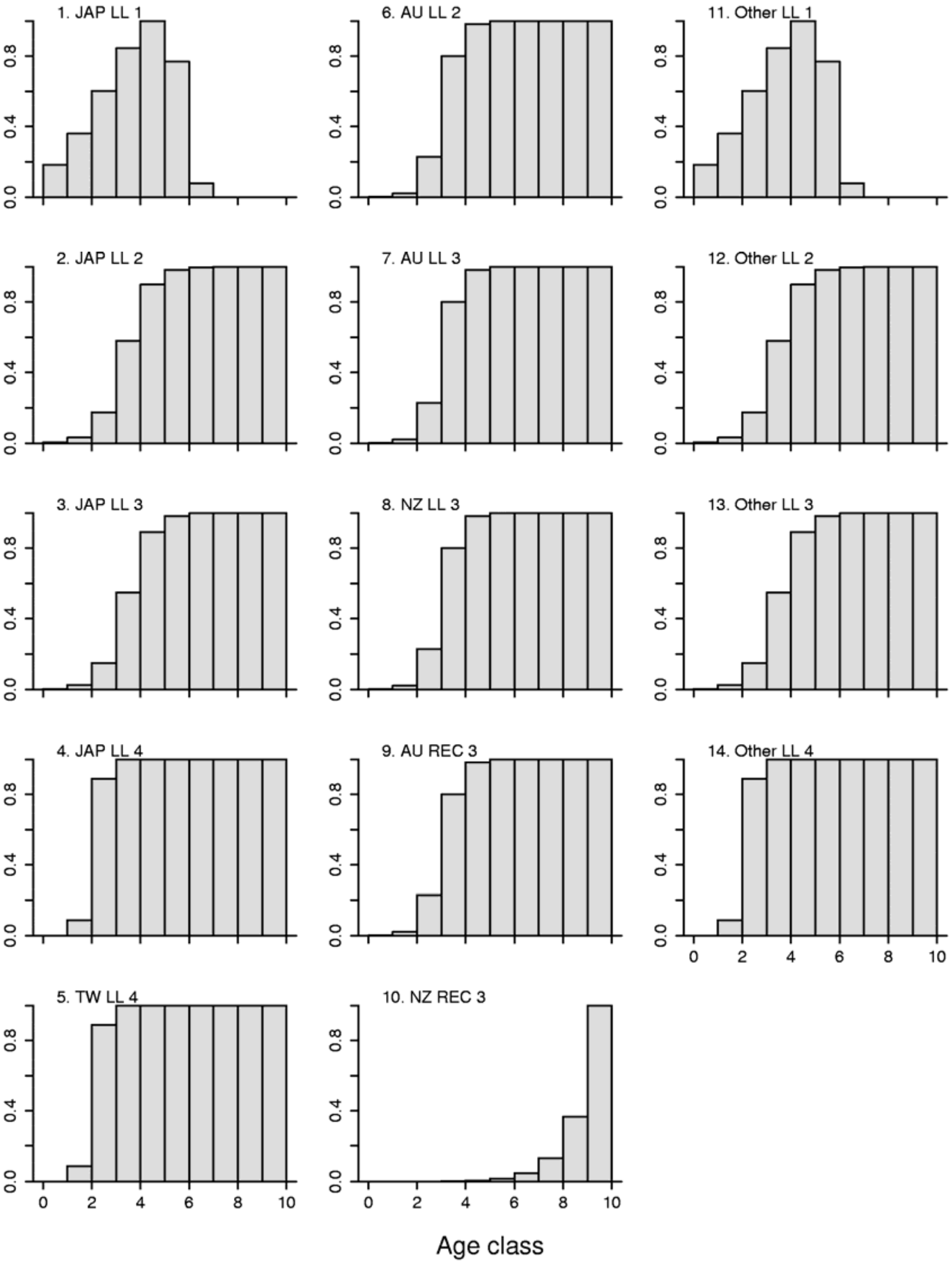

Figure 20. Selectivity coefficients for each fishery in the model region. Model estimates are from the model using natural mortality of 0.4 per year, k = 0.6, and the uninformative prior on steepness of the SSR.

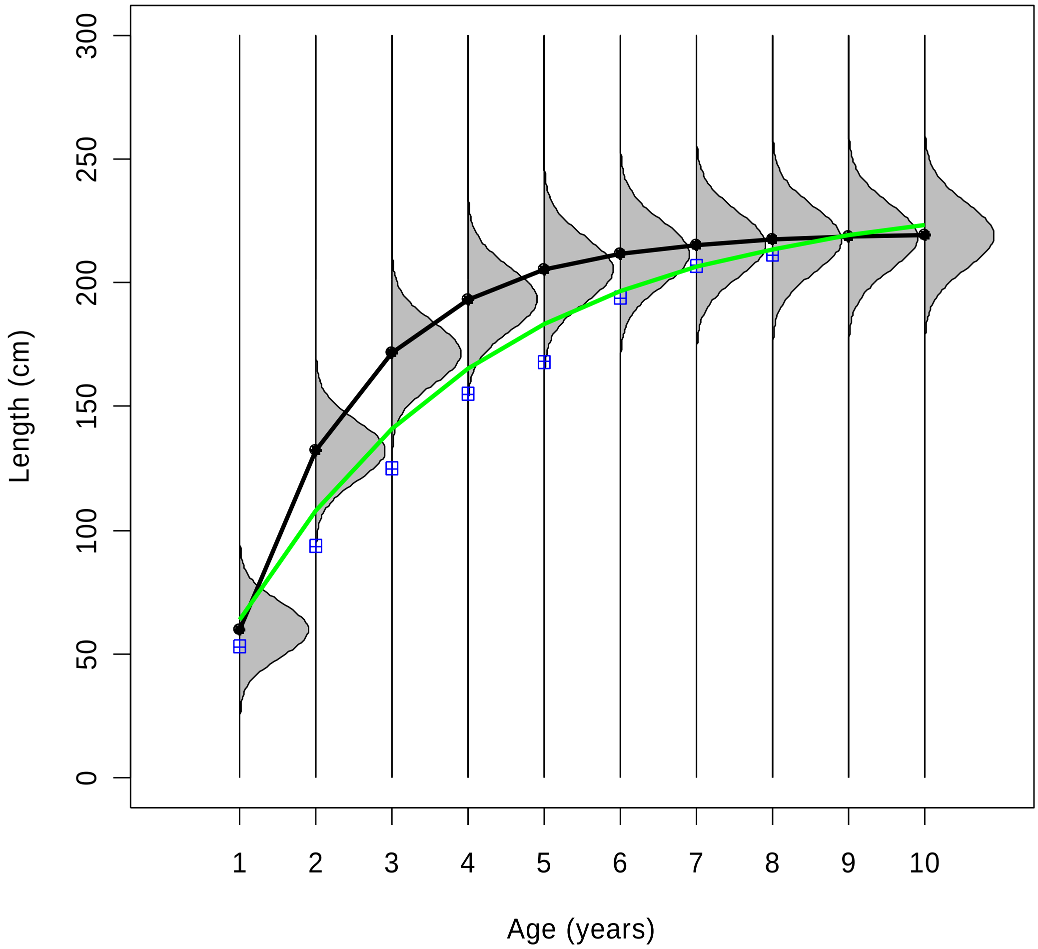

Figure 21. Estimated growth parameters from the striped marlin assessment. The black line represents the estimated length (EFL, cm) at age and the grey area represents the estimated distribution of length at age. The blue points represent observations of age at length from Kopf et al. (2005) converted to the EFL measurement. Model estimates are from the model using natural mortality of 0.4 per year, *k* = 0.6, and the uninformative prior on steepness of the SSR. The green line represents the growth function used in the slower growth sensitivity analysis (*k* = 0.3).

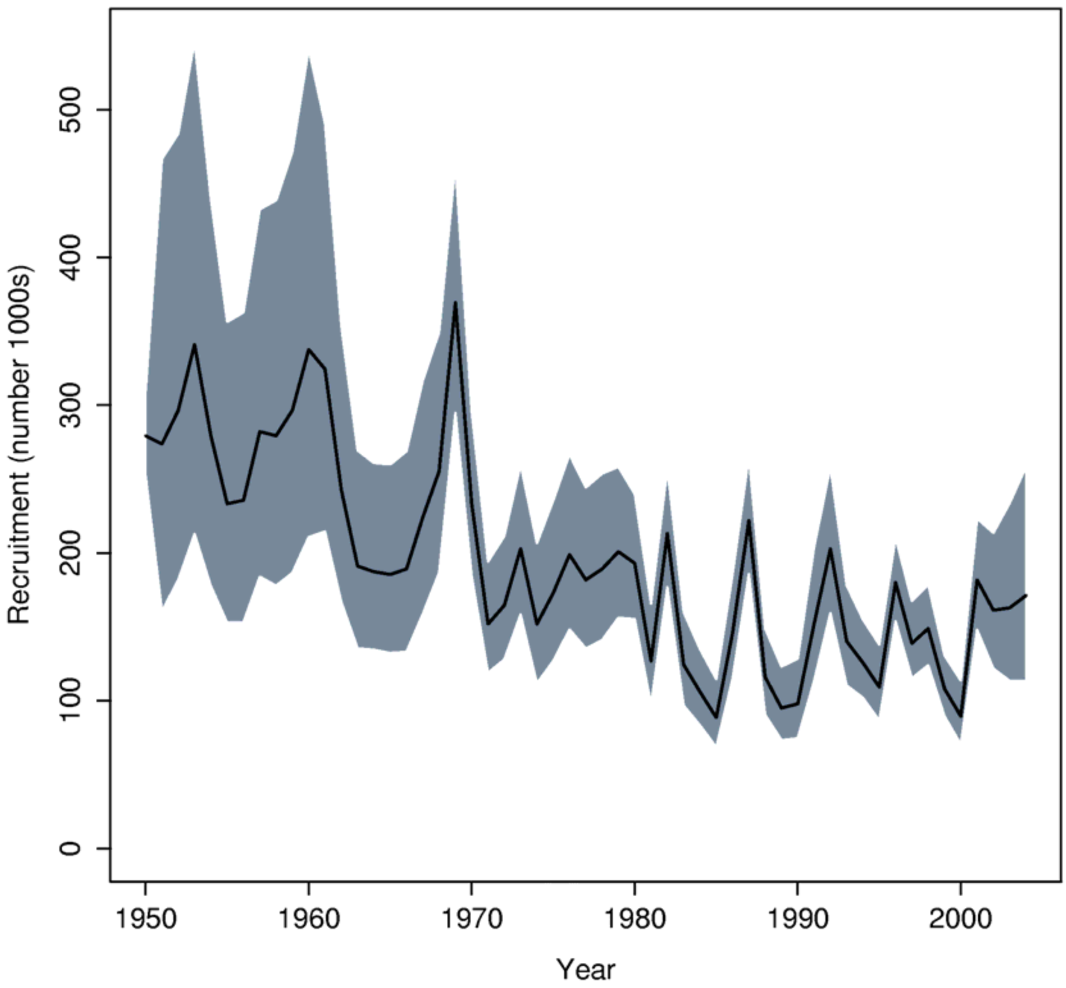

Figure 22. Annual recruitment estimates (number of fish) of striped marlin in the model region. The shaded area indicates the approximate 95% confidence intervals. Model estimates are from the model using natural mortality of 0.4 per year, *k* = 0.6, and the uninformative prior on steepness of the SSR.

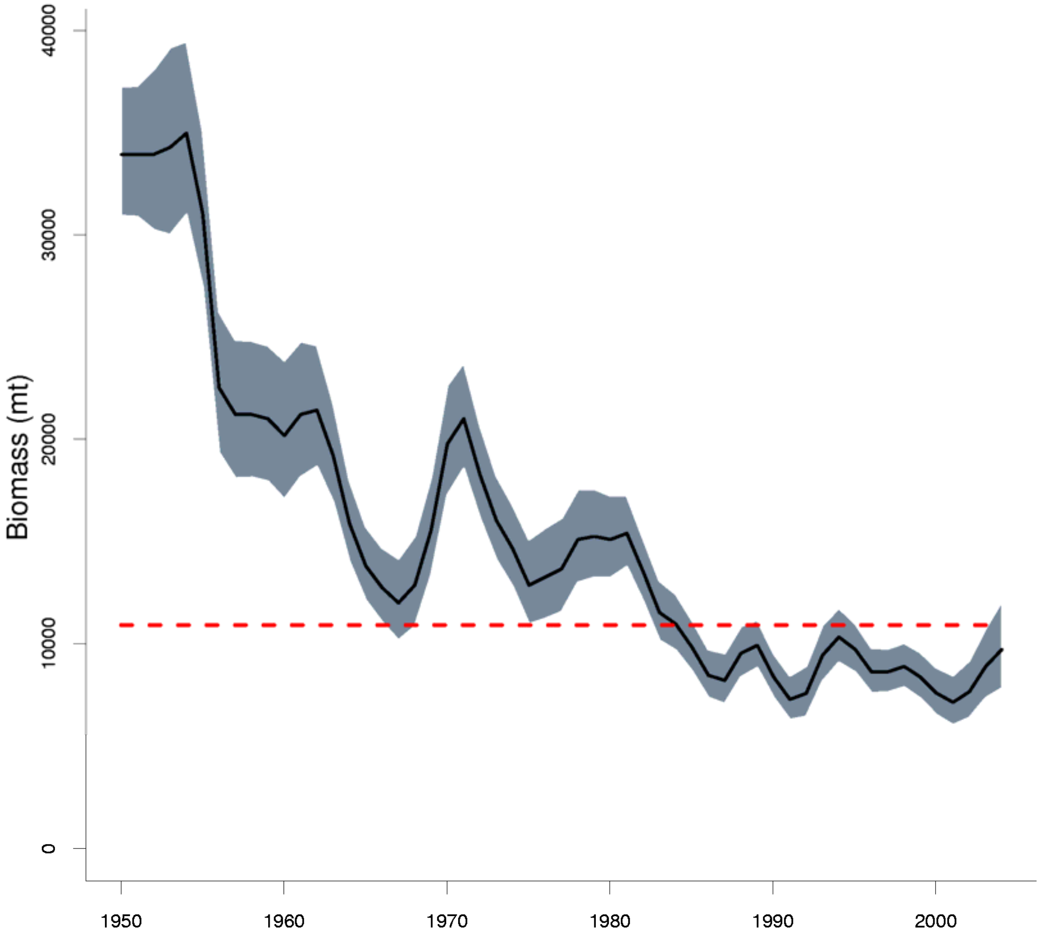

Figure 23. Annual estimates adult biomass (metric tonnes) of striped marlin in the model region. The dashed line represents the SB_{MSY} level. The shaded area indicates the approximate 95% confidence intervals. Model estimates are from the model using natural mortality of 0.4 per year, *k* = 0.6, and the uninformative prior on steepness of the SSR.

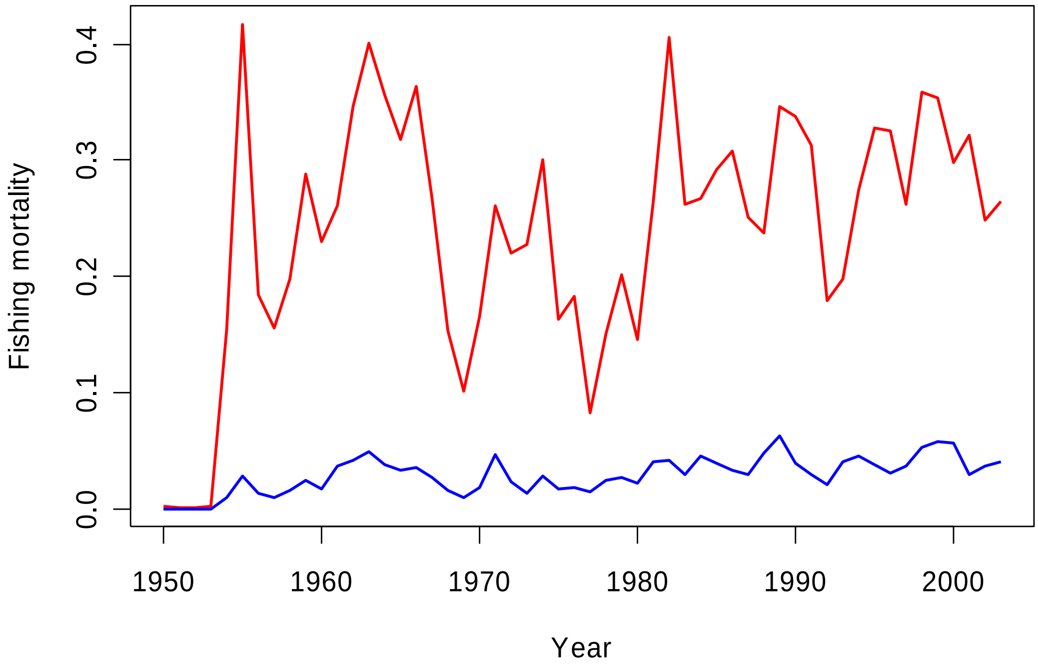

Figure 24. Annual estimates fishing mortality for juvenile (blue line) adult (red line) striped marlin in the model region. Model estimates are from the model using natural mortality of 0.4 per year, *k* = 0.6, and the uninformative prior on steepness of the SSR.

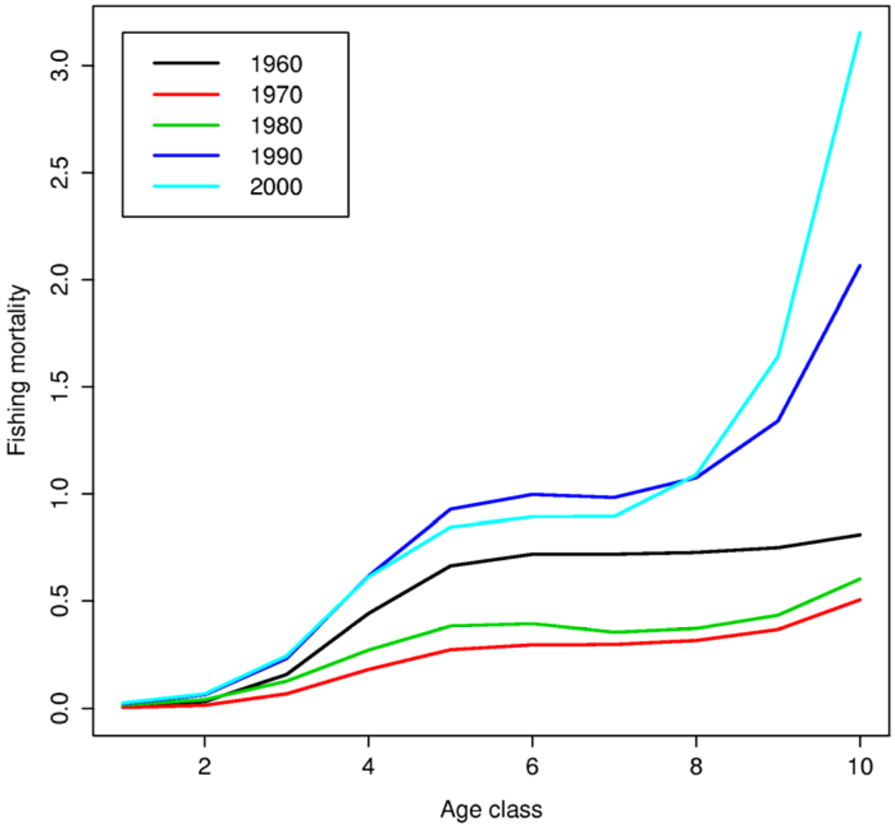

Figure 25. Estimated fishing mortality of striped marlin at age in the model region by year (at decade intervals). Model estimates are from the model using natural mortality of 0.4 per year, *k* = 0.6, and the uninformative prior on steepness of the SSR.

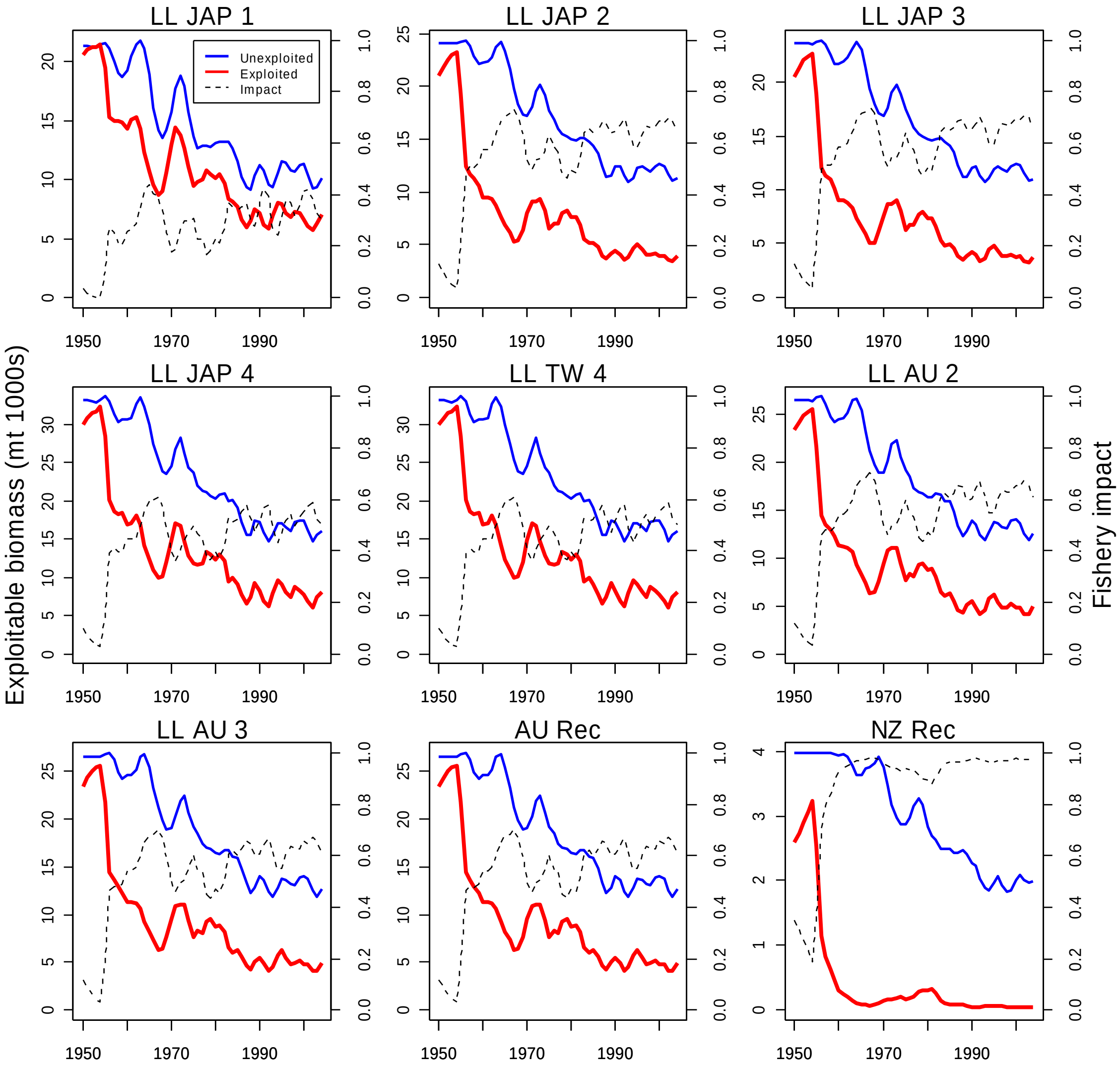

Figure 26. A comparison of the estimated biomass trajectories (red lines) with biomass trajectories that would have occurred in the absence of all fishing (blue lines) for the fishery-specific vulnerable biomass. The impact of the total fishery on the vulnerable biomass (1-exploitable biomass/unexploited biomass) is also presented (dashed line). Model estimates are from the model using natural mortality of 0.4 per year, *k* = 0.6, and the uninformative prior on steepness of the SSR.

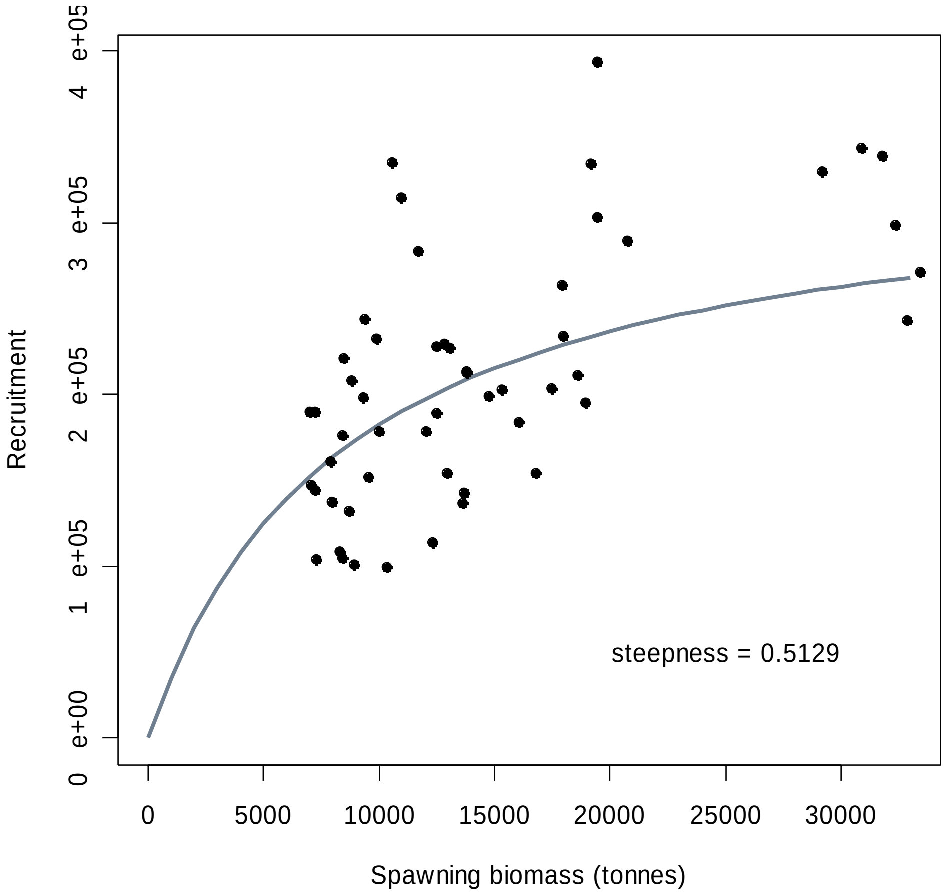

Figure 27. Spawning biomass – recruitment estimates and the fitted Beverton and Holt stock-recruitment relationship (SRR) for striped marlin in the model region. Model estimates are from the model using natural mortality of 0.4 per year, *k* = 0.6, and the uninformative prior on steepness of the SSR.

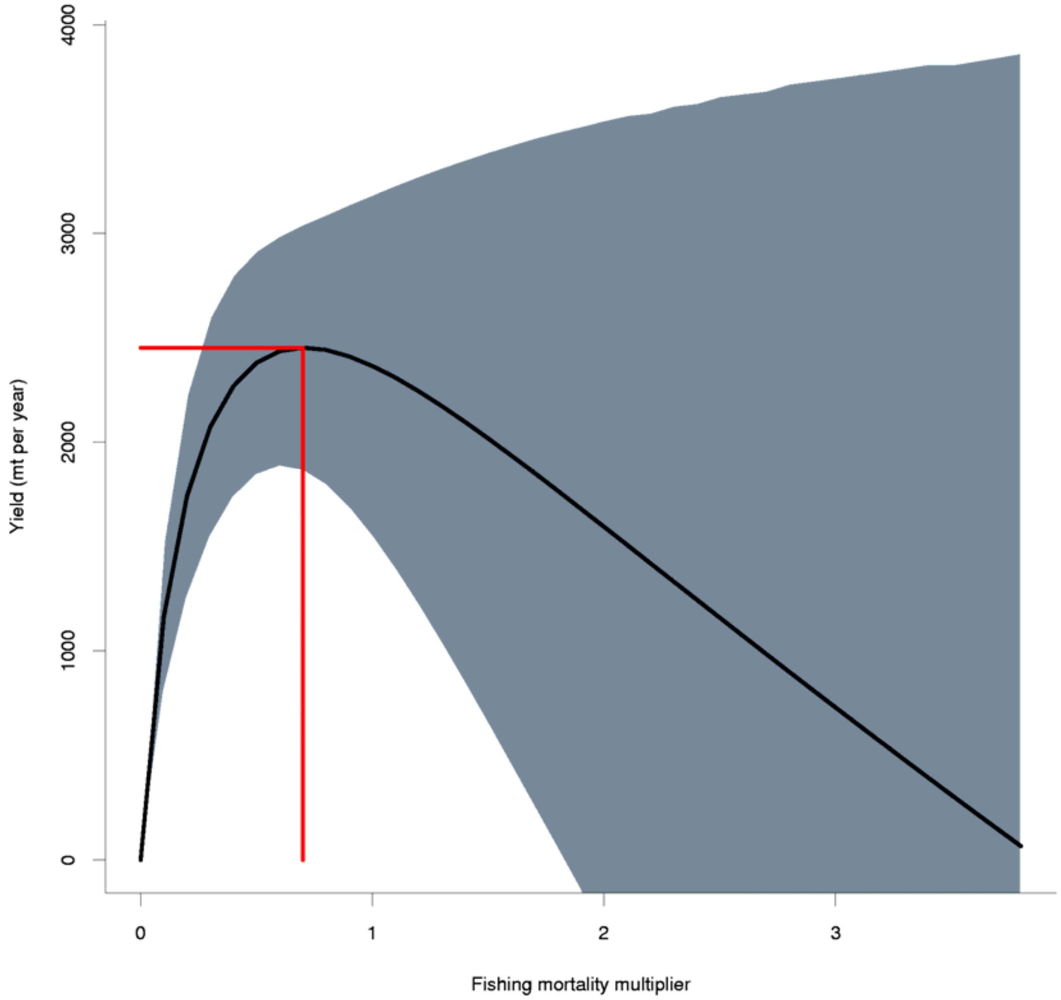

Figure 28. Equilibrium yield (metric tonnes) as a function of fishing mortality multiplier (*fmult*) for the model using an uninformative prior on steepness and M = 0.4. The vertical line represents F_{MSY}. The shaded areas represent approximate 95% confidence intervals.

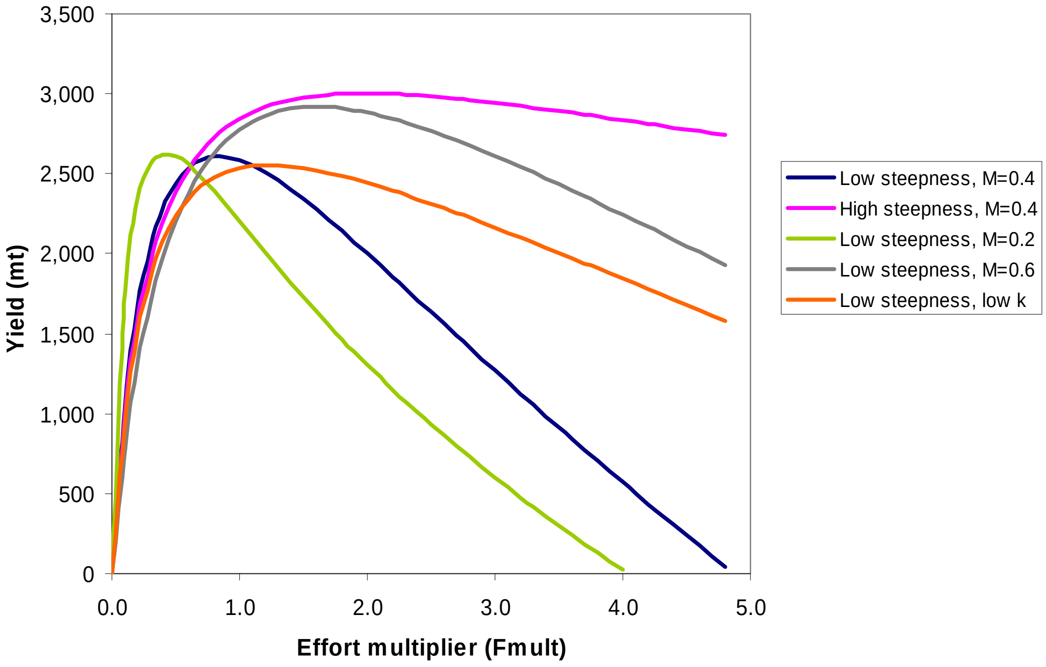

Figure 29. Estimated yields (mt) of striped marlin at different levels of effort under different scenarios of natural mortality, the growth parameter *k* and steepness of the SRR. The “base case” analysis (low steepness, M=0.4) is shown in blue.

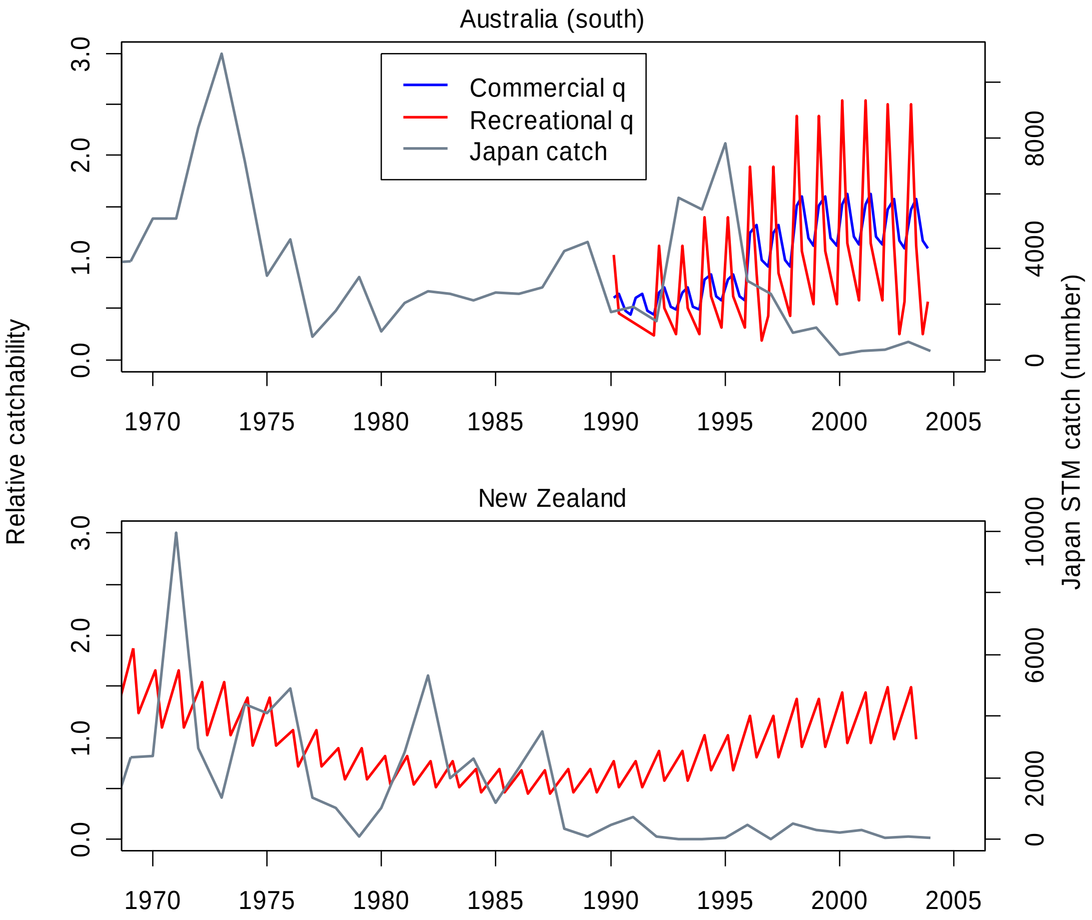

Figure 30. A comparison of trends in catchability from the two recreational fisheries (red lines) in sub-area 3 and the LL AU3 fishery (blue line) with the annual Japanese longline catch of striped marlin (grey lines) from the area of the respective fisheries (New Zealand 30-38°S 170-180° E; Australia 30-40°S 150-160°E).

Appendix 1. Estimated striped marlin catches (in metric tonnes) by major longline-method fisheries in the model region, 1952–2004. Source: raised estimates of catches from logsheet data held at SPC. The Others category includes longline vessels from China, Indonesia, New Zealand, the Philippines, Pacific Island States and Territories and the United States.

Year	Australia	Japan	Korea	Taiwan	Others	Total catch
1952		5				5
1953		2,004				2,004
1954		12,197				12,197
1955		5,074				5,074
1956		4,005				4,005
1957		3,435				3,435
1958		5,682				5,682
1959		4,254				4,254
1960		4,538				4,538
1961		7,097				7,097
1962		8,569	0			8,569
1963		6,695	0			6,695
1964		4,011	0	0		4,011
1965		3,964	0	0		3,964
1966		4,310	0	0		4,310
1967		2,216	0	165		2,381
1968		1,821	0	121		1,942
1969		1,877	0	84		1,961
1970		4,251	0	226		4,478
1971		4,763	0	159		4,922
1972		3,567	0	280		3,847
1973		3,531	0	181		3,712
1974		2,992	0	180		3,172
1975		1,783	26	169		1,978
1976		1,928	318	140		2,385
1977		817	131	196		1,144
1978		1,392	948	213		2,553
1979		2,130	312	216		2,658
1980		1,977	59	173		2,208
1981		3,424	925	166	1	4,517
1982		4,216	409	122	1	4,748
1983		2,025	271	70	23	2,389
1984		2,121	287	122	24	2,554
1985	0	2,075	569	62	78	2,785
1986	0	1,614	600	29	86	2,329
1987	51	1,554	398	50	100	2,153
1988	48	2,142	402	64	63	2,719
1989	26	2,759	216	178	124	3,303
1990	60	1,666	176	99	204	2,205
1991	34	1,195	249	102	87	1,668
1992	27	767	225	112	118	1,248
1993	32	1,269	195	148	59	1,702
1994	74	1,537	197	368	353	2,529
1995	93	1,709	272	141	272	2,487
1996	152	1,121	227	138	322	1,961
1997	209	1,175	351	153	297	2,185
1998	481	1,233	381	101	506	2,702
1999	518	544	543	197	686	2,488
2000	680	320	289	195	555	2,038
2001	836	314	234	228	348	1,960
2002	667	171	286	331	341	1,797
2003	499	440	200	577	421	2,136
2004	337	125	87	477	386	1,412