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**FISHERIES BIOLOGY AND ECOLOGY OF HIGHLY MIGRATORY SPECIES THAT
COMMONLY INTERACT WITH INDUSTRIALISED LONGLINE AND PURSE-SEINE
FISHERIES IN THE WESTERN AND CENTRAL PACIFIC OCEAN**

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Executive Summary

Details of the biology and ecology of species are critical in understanding population dynamics and the impact of fisheries on stocks and species in the WCPO. Simple biological information, such as size-at-age, growth rates, mortality rates and movements are required in order to better understand the population dynamics of each species. In addition, these biological data are critical inputs to simple production models and stock assessment models, if such models are to be developed for these species in the future. This paper briefly reviews and describes the fisheries biology and ecology of 19 species commonly captured by industrialised longline and purse-seine fisheries of the WCPO; skipjack tuna, yellowfin tuna, bigeye tuna, albacore tuna, blue marlin, black marlin, striped marlin, shortbill spearfish, Indo-Pacific sailfish, swordfish, wahoo, opah, mahimahi, blue shark, silky shark, oceanic whitetip shark, shortfin mako shark, pelagic stingray and rainbow runner. In addition, trends in sizes and nominal catch rates are used to infer stock status and risk to sustainability of species for which formal assessments are preliminary or do not exist (i.e. non-tuna species).

Acknowledgements

1.   Introduction

While artisanal fishing in the Pacific Ocean has occurred for thousands of years (Dalzell et al. 1996), industrialised fishing only commenced in the mid 20th Century, with longline fishing records dating back to the 1950s for the western central Pacific Ocean (WCPO) (Lawson 2003). However, within 50 years of commencing, industrialised tuna fisheries of the WCPO now account for more than 50% of the global catch of the four major tuna species (albacore, bigeye, skipjack and yellowfin), with catches exceeding 2 million metric tonnes in recent years (William and Reid 2007).

The WCPO is extensive, exceeding 94 million km^2 (Figure 1). The total land area included in the WCPO zone is approximately 2.85 million km^2 or 3% of the total surface area. Of the sea area included in the WCPO, more than 49 million km^2 (52.5%) is within EEZs of sovereign nations and territories of the WCPO, with the remaining ocean area (44.5%) designated as high seas or international waters.

Industrialised fishing in the WCPO is predominately undertaken using longline and purse-seine vessels, with pole-and-line, troll and other techniques landing much lower catches (OFP 2007). While major tuna species dominate catches by industrialised fisheries in the WCPO, observer data and unloading data indicate that more than other 200 taxa (mainly fishes) interact with industrialised fleets in the WCPO (Kirby 2006). While many of these species are non-target bycatch species that are generally discarded (e.g. filefish), some species are retained as part of the commercial catch, including billfishes, other teleost fishes (e.g. mahimahi, wahoo) and sharks. In some areas (e.g. Cook Islands, Niue), catches of non-tuna species rival that of the four main species of tuna.

Although non-tuna species are captured in significant quantities in the WCPO, with few exceptions the basic biology and ecology of many of these other common species are poorly known. In addition, stock assessments have only been undertaken on very few stocks of non-tuna species (e.g. blue marlin, Kleiber et al. 2003; north Pacific blue shark, Kleiber et al. 2001; south-western Pacific striped marlin, Langley et al. 2006; south-western Pacific swordfish, Kolody et al. 2006). The absence of information and assessments means the status of many commercially-retained non-tuna species in the WCPO is currently unknown, impacting the ability to make informed management decisions.

1.1 Why is knowledge of the biology and ecology of exploited species critical?

Details of the biology and ecology of species are critical in understanding population dynamics and the impact of fisheries on stocks and species in the WCPO. Simple biological information, such as size-at-age, growth rates, mortality rates and movements are required in order to better understand the population dynamics of each species. In addition, these biological data are critical inputs to simple production models and stock assessment models, if such models are to be developed for these species in the future.

Ecological information can provide insight to the requirements and preferences of species to particular oceanographic or environmental variables (e.g. temperature preferences). This information can be used to better target or avoid certain species and to provide a broad understanding of the vulnerability of species to fishing (e.g. comparing the range of a species to the areas of operations of major fisheries).

Biological and ecological information become more critical when species are commercially exploited (targeted), in order to better understand population dynamics, estimate the impacts of fishing and to develop sustainable harvest levels and management strategies. These sources of informaiton also allow the relative effects of fishery and environmental variables to be compared, providing further informaiton on which to base management.

In addition, biological and ecological details are essential in the determination of risks of fishing on a species (e.g. ecological risk assessments, Kirby and Hobday 2007) which are being considered within ecosystem approaches to fisheries management (EAFM), like those currently being applied by FFA member countries in the WCPO, and likely to be developed by the Commission for the Conservation and Management of Highly Migratory Fish Stocks in the Western and Central Pacific (referred to as the WCPFC in this document).

1.2 Diversity

The diversity of fishes and other marine animals that interact with industrialised tuna fisheries in the WCPO is high, with over 200 taxa recorded from longline observer data alone (Tables). Although the overall diversity of pelagic species is high, individual species are not found in similar abundances across all areas of the WCPO; some species have an equatorial distribution while others display a sub-equatorial distribution. Thus, fisheries operating within individual EEZs or regions of the WCPO may interact with a sub-set of the 200+ species reported from the WCPO.

With the exception of the four major tuna species and some species of billfish, the distribution and abundance of many species interacting with longline and purse-seine fisheries in the WCPO are still poorly known. In order to potentially explore trends in observer data, records for individual species were pooled into 10-degree latitudinal bands between 50ºN and 50ºS. These bands were further divided into areas east and west of 170ºE resulting in 20 Areas of the WCPO (Figure 1). These areas were designed to broadly be comparable to the regions identified in the stock assessments of the main tuna species, to potentially assess interactions of each species with pelagic longline and purse-seine fisheries of the WCPO.

1.3 Data sources and methods

Extensive logsheet data exists from individual fishing vessels operating within the WCPO and the Western and Central Pacific Convention Area (WCP-CA). However, logsheet data generally records only retained catches, with relatively few records for non-tuna species. Most of the records for non-tuna species are for billfishes, swordfish and sharks, although sharks have typically been recorded as a single group.

Observer and port-sampling data also exists for longline and purse-seine fisheries of the WCPO and WCP-CA. Observers are trained to record catches of all species, regardless of whether an individual fish is retained or not. However, observer coverage (the number of fishing events reported by observers compared to the total number of fishing events) is very low (about 1-2% overall). In addition, observer data are not evenly distributed across the WCPO, or among years or flags. Nonetheless, observer data provides the most powerful data to examine the range of species that interact with industrialised fisheries of the WCPO.

1.4 Aims of document

This document attempts to summarise the biology and ecology of some pelagic species commonly captured by industrialised fisheries in the WCPO. It is hoped that this information will allow a better understanding of these species, permitting more-informed decisions around the management and exploitation of these species within EEZs and across the WCPO/WCP-CA. The document also aims to highlight gaps in the knowledge and data for these species in the WCPO, for consideration by individual countries and the WCPFC.

Secondly, the examination of observer and logsheet data (e.g. CPUE, size data) provides an opportunity to examine and interpret data trends of these species within major fisheries. This information may provide additional insights to the distribution and status of these species. This is important as several countries in the WCPO are already reporting relatively large annual catches of non-tuna species that are important to the economic sustainability of domestic fisheries and food supply to local markets. These analyses were not undertaken for the four main tuna species are details of size and CPUE trends, and stock status, are readily available in stock assessment reports presented to the WCPFC.

Finally, this document will collate estimates of important biological parameters (e.g. growth rate parameters, natural mortality, maturity schedules), which may provide background information required as a starting point to consider future research, potentially including the development of stock assessment models for these species, and identifying gaps or weaknesses in current level of knowledge.
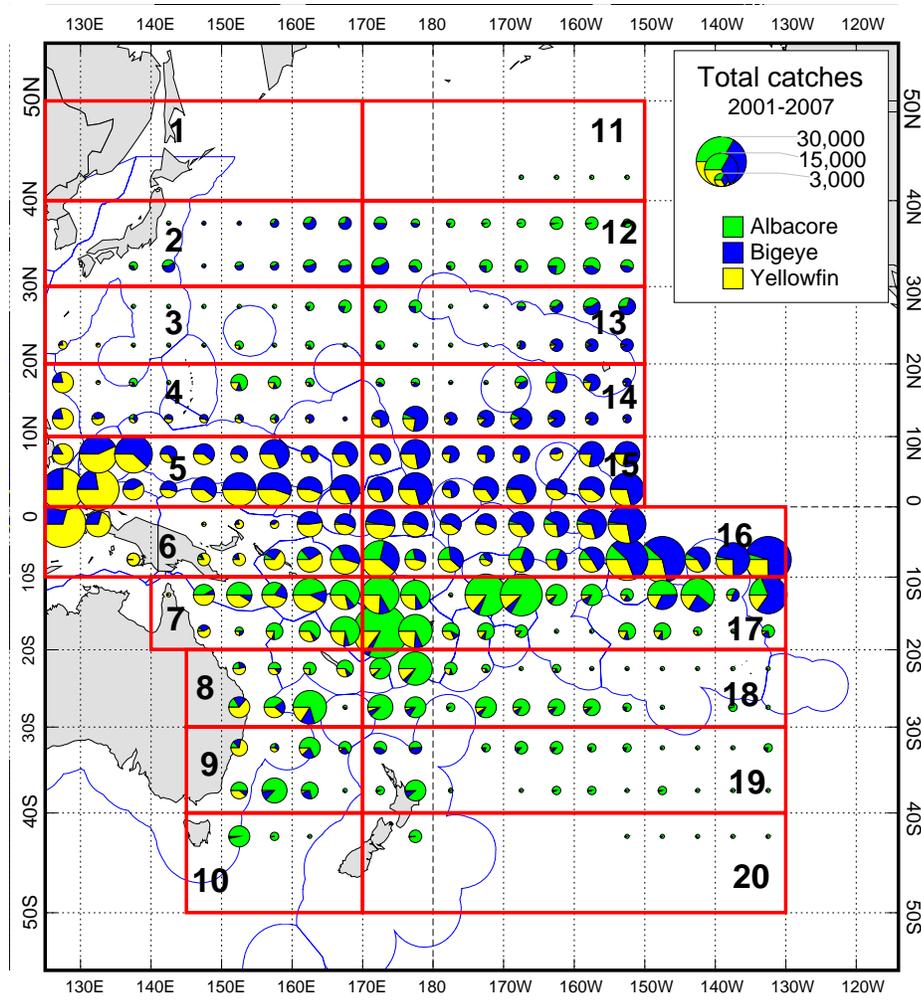
Figure 1. Map of the WCPO displaying the longline catches of albacore, bigeye and yellowfin tuna, 2001–2007. Source, SPC raised data base. The red boxes define the 20-ten degree latitude areas for examining the length and catch rate data for each of the species contained in this report.

2.   Skipjack (*Katsuwonus pelamis*)
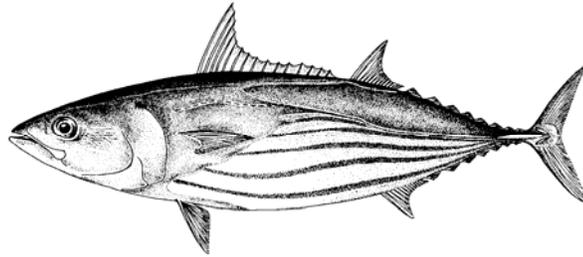
2.1   General description

Skipjack are a small surface–schooling tuna found in warm waters of all oceans (Fontineau 2003). Skipjack are easily distinguished from other species of tuna due to their small size, small dark pectoral fins and three to six distinct dark lines running longitudinally between the pectoral fin and tail below the lateral line (Chapman et al. 2006). Internally, skipjack lack a swim-bladder.

2.2   Distribution

Skipjack are common in surface waters of equatorial and sub- equatorial areas of the Pacific Ocean (Figure 4). In the western Pacific, warm, poleward–flowing currents near northern Japan (Kiroshuro current) and southern Australia (e.g. the eastern Australian current) extend their distribution to 40°N and 40°S. In the eastern Pacific, colder currents flowing towards the equator compress their distribution to about 30°N–30°S. These limits correspond to the 20°C surface isotherm, although larger skipjack are occasionally caught by longline in waters as cold as 15°C. The equatorial distribution of skipjack is more easterly during El Niño years (Lehodey et al. 1997).

2.3   Biology

2.3.1   Age and growth

Skipjack obtain a maximum size of approximately 80 cm FL in the central Pacific and are short lived (maximum longevity of four to five years) (Wild and Hampton 1994). However, skipjack can reach up to 108 cm in length, 34.5 kg and 12 years of age (Collette and Nauen 1983).

Age and growth of skipjack have been estimated from length-frequency analyses, tagging studies, and examination of bands in vertebrae (Maunder 2001), cross-sections of fin spines and otoliths (Tanabe et al. 2003b). Analysis of skipjack length–frequency distributions were the least reliable ageing method because of the uncertainty in demonstrating the progression of length–frequency modes due to year-round reproduction and recruitment.

Tagging and otolith studies on skipjack tuna indicate a rapid growth rate. Skipjack are estimated to obtain 44–48 cm FL by the end of their first year of life and 61–68 cm FL by the end of their second year (Table 1). However, size-at-age estimates from sectioned spines suggest much smaller sizes at age.

Variability in growth rates and estimates of von Bertalanffy growth parameters have been reported from different localities in the western Pacific, at the same locality at different times and among stocks in different oceans (Fonteneau 2003). For example, VBGF parameters, L∞ and k , for skipjack have been estimated at 93.6 cm FL and 0.43.year^{-1} from the western Pacific Ocean (Tanabe et al. 2003a, b), and 117.5 cm FL and 0.191.year^{-1} from the western and central WCPO (Lin et al. 2005). Variability in growth rates among locations and times is estimated for skipjack (Maunder 2001) due to their short life cycle and spatio–temporal variation in environmental conditions. In addition, Maunder (2001) concluded that skipjack growth is not constant and is better described by a model more complex than a VBGF.

2.3.2 Reproduction

Age at first reproduction of skipjack is relatively low compared to other tuna species, with most skipjack spawning by the end of the first year (Fonteneau 2003). In the WCPO, size at 50% maturity was estimated at 41 cm FL for males and 44 cm FL for females (Fu et al. 2005), similar to the size at 50% maturity estimated in stock assessment models (50% maturity during the third quarter of life, at approximately 43 cm FL, Langley et al. 2005). However, a wide size range of size at first maturity has (40–55 cm FL) from different areas, suggesting the existence of numerous small populations of skipjack (Schaefer 2001).

In the western Pacific, skipjack with ripe ovaries and larvae occur year-round, though seasonal peaks in the proportion of mature skipjack may occur. Male skipjack are always in spawning condition (Lewis 1981). Schaefer (2001) concluded that skipjack spawning occurs when SSTs exceed 24°C, resulting in year-round spawning in tropical areas, and seasonal spawning in sub-tropical areas (Scheafer 2001). Based on the area of the WCPO with temperatures typically greater than 24°C, Fonteneau (2003) estimated the area of skipjack spawning grounds to be potentially 17.1 million nm^2 for the WCPO (Table 3), a much greater area than estimated for the EPO (8.9 million nm^2).

Spawning areas been inferred from the distributions of juvenile skipjack found in the stomachs of predators, larvae caught in plankton tows (Leis et al. 1991) and from Sr:Ca ratios from otoliths (Arai et al. 2004). Spawning occurs in the western Pacific between 35°N and 37°S, and is especially frequent between 10°N and 10°S, where most purse-seine fishing also occurs. The latitudinal distribution of skipjack spawning narrows rapidly at 140°W. Spawning appears to be more common near islands and reefs as very high concentrations of tuna larvae, including skipjack, have been identified near coral reefs around the islands of Moorea, Rangiora and Takapoto in French Polynesia (Leis et al. 1991). This may be a general characteristic of archipelagic waters in the WCPO in which current eddies may trap larvae near islands.

Skipjack have a relatively high fecundity (66 eggs.gramme^{-1}, Fu et al. 2005), broadly correlated with size, although a wide range has been reported (40–130 eggs.gramme^{-1}) (Stequert and Ramchurrun 1996). Skipjack are batch spanners with the time between spawning of 1.8 days (Hunter et al. 1986, Fu et al. 2005) for reproductively active females, and 2.7 days between batches for mature females (Fu et al. 2005). However, annual egg production of individual skipjack is difficult to estimate due to the high variability of ova sizes from similar–sized skipjack and the potential for multiple, frequent spawning events by individual females.

Reproduction in skipjack is heavily influenced by oceanographic conditions. Changes in oceanographic conditions associated with the development of *El Niño* conditions result in increased skipjack recruitment, likely as a result of increases in favourable temperature (habitat) for skipjack tuna and productivity of prey suitable for skipjack tuna (Lehodey et al. 2003).

2.3.3 Recruitment

Skipjack start to recruit to the purse-seine fishery at approximately 25 cm FL, and are fully recruited by 45–50 cm FL (Figure 6), at approximately one year of age. This is similar to the size and age of recruitment of skipjack into the pole-and-line fishery. Skipjack commence recruitment to the fisheries of Indonesia and the Philippines at approximately 15 cm FL.

2.3.4 Mortality

The natural mortality rate of skipjack is much higher than for other tuna species (Fonteneau 2003). Hampton (2000), from tagging experiments in the WCPO, estimated that the natural mortality of skipjack was relatively high for small skipjack (21–30 cm FL, ~0.8 month^{-1} or 9.6 year^{-1}), declining to 1.2–2.0 year^{-1} for skipjack 41–70 cm FL, before increasing to approximately 15.0 year^{-1} for large skipjack (greater than 70 cm FL) (Figure 2). Fishing mortality rates were estimated at 1.2 year^{-1} for small skipjack (21–30 cm FL), declining to less than 0.25 year^{-1} for skipjack greater than 51 cm FL (Hampton 2000).

2.4 Ecology

2.4.1 Habitat preference

Skipjack are common in warm tropical surface waters of the WCPO, and dominate the pelagic fish community in terms of biomass, based on catch records (Williams and Reid 2007) and biomass estimates (Langley et al. 2005). This is a result of their ability to quickly exploit suitable conditions (i.e. ability to reproduce year–round, high recruitment, fast growth rate, short life-span and broad distribution). Skipjack are commonly associated with floating objects (e.g. logs, FADs), supporting FAD-based purse-seine and pole-and-line fisheries in the WCPO and elsewhere.

Skipjack display a preference for water temperatures between 20 and 30°C (Barkley et al. 1978, Andrade 2003) with a lower thermal limit for the species of approximately 15°C (Sharp 1978). Smaller skipjack appear more tolerant of high water temperatures than larger skipjack (Barkley et al. 1978). The thermal limits of skipjack are due to the requirement to constantly swim due to a lack of a swim-bladder. As a result, adult skipjack generate high levels of metabolic heat and need to remain in cooler waters. Thus, large skipjack are usually recorded from cooler, more temperate waters (Wild and Hampton 1993).

Skipjack are the least tolerant species of tuna in relation to low dissolved oxygen levels, with a minimum requirement of 2.4–3.0 ml O_2 l^{-1} (Brill 1994) (Table 3), limiting skipjack to surface waters. Part of the reason for the high demand of oxygen for skipjack is due to the absence of a swim–bladder which results in the need to continually swim in order to maintain hydrostatic equilibrium.

Other oceanographic and biological features are also known to influence the distribution and abundance of skipjack tuna, either directly or indirectly (Langley 2004b, c). Environmental influences affecting skipjack distribution and abundance include thermocline structure, water clarity, oceanic currents and productivity (Wild and Hampton 1994). However, the interaction of these variables with skipjack distribution and catches are complex (Langley 2004b, c) and have only recently been explored. For example, Lehodey et al. (1998) identified that the highest catches of skipjack (and therefore highest abundances) were generally associated with the convergence zone between the tropical warm pool and the eastward projection of the cold tongue, as identified by the longitudinal position of the 28.5°C isotherm. However, it is unclear whether temperature preferences of skipjack or the preferences of their prey (i.e. increased feeding opportunities), are the main reason for the association of skipjack with oceanographic fronts (Andrade 2003, Lehodey et al. 2003).

Skipjack larvae are vertically distributed in the upper 70 m of the water column and their distribution is limited to between the northern and southern limits of the 25ºC surface isotherm (Matsumoto et al. 1984 in Wild and Hampton 1994). The larval distribution of skipjack in the western Pacific is between 35°N off Japan to 37°S off south–eastern Australia (Nishikawa et al. 1985). Equatorial larval abundance is greatest between 140°W and 160°E and generally increases from east to west. The concentration of skipjack larvae doubles for every increase in surface water temperature of 1ºC between 24ºC and 29ºC (Forsbergh 1989 in Wild and Hampton 1994).

2.4.2 Movements and migration

A substantial body of information on skipjack migration and movement in general within the WCPO was collected during two SPC tagging programmes. The SSAP (1977–1980) collected information from 7,000 returned skipjack tags from approximately 140,000 releases. A spatially disaggregated population dynamics model was fitted to the SSAP (Sibert et al. 1999). Movement was partitioned into dispersive (also referred to as diffusion) and directed movements. The overall movement patterns had high variability among regions and seasons in both dispersive and directed movements. There was a consistent eastward tendency for directed movements in Micronesian waters between 5°N and 10°N, possibly due to transport by the North Equatorial counter-current. Movement rates in a region south of 10°S and east of 170°E were relatively low.

Numerous long–distance movements of individual tagged skipjack were recorded from skipjack tagged in the SSAP, although only 17% of recaptures moved greater than 200 nm. The low incidence of long–distance movement may be due to most tag recoveries being made shortly after release in the vicinity of intense fishing effort. The modelling effort concluded that there was little coherent pattern or temporal consistency in skipjack movement at the scale of the investigation; however, skipjack movement is non-random. The RTTP (1989–92) conducted tagging throughout the main area of the purse-seine fishery of the WCPO (10°N–10°S, 120°E–180°). Information on skipjack movement was provided by the return of 9,629 tags from 92,376 releases. Data from the RTTP indicated that 45% of the returns had moved more than 200 nmi from the point of release.

A re–examination of both skipjack tagging studies using a spatial model (Sibert and Hampton 2003) has indicated that the median lifetime displacement of skipjack was 420–470 nmi. The new analysis suggests that not all skipjack move as widely as once thought and that long-term residency (3–6 months) is likely. This period of residency has implications for conservation

and management of skipjack within EEZs. The re-examination of the tagging data supports the earlier work by Lewis (1981), who suggested that skipjack within an area comprised both resident and transient components. The analysis by Sibert and Hampton (2003) also puts into question whether skipjack can be validly considered as a highly migratory species.

Large scale oceanographic processes, such as variability in the SOI and of El Niño–La Niño conditions, are thought to be the major influences on skipjack movements (Lehodey et al. 1997). Arai et al. (2004) identified two broad migratory routes via genetic studies on skipjack; a long–distance migration between tropical and northern temperate areas and a local migration within the tropics, supporting earlier work (Lewis, 1981). However, the migratory route is complex and appears highly variable throughout life (Sibert et al. 1999). Movements of skipjack were also found to be highly variable in an Indian Ocean tagging study (Adams and Sibert 2002).

While skipjack are thought to inhabit only surface waters (above the thermocline), recent archival tag studies by Ogura (2003) and Schaefer and Fuller (2007) can access deeper waters. Ogura (2003) showed that skipjack spend approximately 90% of their time in the upper 25 m of the water column at night. While a high proportion of time is spent in the upper 25 m during the day, skipjack also spend approximately 40% of their time at depths between 25 m and 75 m. However, individual fish displayed different movement patterns and depth preferences, with some fish displaying dives to depths greater than 200 m and spending most of the daytime periods below 100 m, although this may be a result of post-tagging stress (Ogura 2003).

Schaefer and Fuller (2007) found that skipjack in the EPO displayed different behaviour depending on whether individuals were associated with a floating object or not. Skipjack associated with floating objects (TAO buoys) spent nearly all their time within the top 50 m of the water column at all times. However, deeper dives to 90 m were frequent at night, likely due to skipjack feeding. This is a similar range of depths as reported by Leroy et al. (2007) from the WCPO, who recorded that sonic-tagged skipjack spent all their time in surface waters, with few records of dives deeper than 100 m, with a tendency for deeper dives during the day.

Skipjack not associated with floating objects remained within 50 m of the surface at night, but displayed frequent dives to depths of more than 150 m (mean, 267m; maximum, 355 m), likely to access prey within the DSL (Schafer and Fuller 2007). The deepest skipjack dive reported by Schaefer and Fuller (2007) was nearly 600 m, where ambient temperature was less than 8°C. Regardless of association, skipjack spend most of their time in waters of 18°C or above.

2.4.3   Diet

The diet of skipjack includes fishes, euphausiids (Andrade 2003), cephalopods, molluscs and planktonic and benthic crustaceans. Cannibalism is also common. The diet of juvenile skipjack tuna (less than 67 mm FL) in the tropical western Pacific Ocean is dominated by fish larvae, but copepods and amphipods are also important throughout their range (Tanabe 2001).

The distribution of suitable forage is important in determining the small–scale distribution of skipjack in the tropics (Lehodey 2001, Kirby et al. 2003a) and temperate areas (Andrade 2003). The patchy distribution of skipjack may be correlated with the patchy distribution of

zooplankton and micronekton (Lewis 1981). Increased skipjack abundance around islands, seamounts and banks may result from increased forage in these areas, probably a result of current eddies concentrating prey. Similarly, the frequent occurrence of skipjack near convergence zones and fronts (Langley 2004b) may result from the increased productivity associated with upwellings of deep, nutrient–rich water and the concentration of planktonic and micronektonic prey species.

2.5 Details of stocks in the WCPO

2.5.1 Stock structure and size

Skipjack stock structure has received considerable attention with studies employing tagging and genetic methodologies (e.g. Lewis 1981). Tagging data indicates unrestricted meridional movement between 120°E and 160°W. Despite the large amount of tagging carried out in the WCPO since the late 1970s, no skipjack tagged in the WCPO have been recovered in the EPO. The distribution of catches also supports the existsnec of a western and eastern Pacific stock of skipjack (Figure 4). For assessment purposes, skipjack in the Pacific Ocean are dived into two stocks, with 150°W considered the longitudinal boundary (Langley et al. 2005).

Genetic studies of skipjack have also been used to infer stock structure. Based on genetic information, two hypotheses of the stock structure of skipjack in the Pacific Ocean have been proposed;
- Isolated subpopulations hypothesis – i.e. a series of genetically distinct stocks that exist across the Pacific Ocean (Sharp 1978);
- Isolation–by–distance hypothesis – i.e. although stocks are free to mix throughout the Pacific, the likelihood of mixing reduces as distance increases (Lewis 1981), as supported by the recent re-analysis of tagging data (Sibert and Hampton 2003).

Significant differences in the esterase allele frequencies indicated two distinct subpopulations of skipjack (western and central–eastern) in the south Pacific, confirming the two stock hypothesis. Additional gene frequency data from previously un-sampled sites in the south Pacific suggested a clinal population structure from 120°E to 150°W, although the discriminatory power of this approach to identify skipjack populations is limited. The use of Sr:Ca ratios from skipjack otoliths by Arai et al. (2004) was not able to discriminate multiple stocks of skipjack tuna in the WCPO, although Arai et al. (2004) did suggest that movement of skipjack between the Pacific and Indian Oceans was possible.

The skipjack stock in the WCPO is the largest of any Ocean due to the extent of favourable skipjack habitat (i.e. area of greater than 24°C surface waters) (Fontineau 2003) (Table 3). Estimates of absolute stock size in the WCPO for skipjack have been derived from tagging experiment and spatially disaggregated modelling of catch, effort and biological data (Langley et al. 2005). Recently, the total biomass of skipjack in the WCPO was estimated at approximately 6.0 million mt (Langley et al. 2005).

2.5.2 Recent stock assessments and status

Stock assessments for skipjack in the WCPO have been performed using MULTIFAN–CL (e.g. Langley et al. 2005). For these assessments, the WCPO is divided into six regions based

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on fishery and catch characteristics (Figure 4). Assessments have indicated that although fishing mortality has recently increased, it is below that estimated to achieve maximum sustainable yield (F_{MSY}) owing to recent high levels of recruitment and a modest level of exploitation relative to the stock's biological potential (Langley et al. 2005). Thus, the skipjack stock in the WCPO is healthy. However, purse-seine fisheries targeting skipjack often capture small bigeye and yellowfin tunas, impacting on these stocks.

2.6   Fisheries

2.6.1   Major fisheries and occurrence

Skipjack are the single most important species of tuna (by weight) captured by industrialised fleets in the WCPO. Catches of skipjack have rapidly increased since the development of the industrialised purse-seine fishery, with total catches exceeding 1.5 million tonnes in recent years (Figure 5). Since 2000, the purse-seine fishery of the WCPO has accounted for 77–86% of total skipjack catches (OFP, 2007, Williams and Reid 2007).

Pole-and-line fisheries of the WCPO also land significant amounts of skipjack tuna, representing between 10% and 20% of total skipjack catches. However, the pole –and-line fisheries have declined with the development and expansion of the purse-seine fishery.

Other fishing methods (longline, fisheries operating in Indonesia and the Philippines) also land skipjack, but in much smaller quantities (less than 7,000 mt and 60,000 mt per year, respectively) (OFP 2007).

2.6.2 Artisanal fishery value

Skipjack are an important food species for many artisanal fisheries throughout equatorial and sub-equatorial areas of the WCPO (Dalzell et al. 1996). In addition, skipjack are also captured from anchored FADs and may be used as bait for other species by artisanal fishers (B. Pasisi, pers. comm.).

2.6.3 Sport and recreational fishery value

Skipjack are not a recognised sportfish species although large skipjack are occasionally landed by sportfishers in small numbers (e.g. www.billfishclub.com), although they may be used as bait for other sportfish species. Overall, skipjack are an minor component of sportfisheries in the WCPO.

Table 1. Comparison of estimated fork length (cm) at age for skipjack tuna in the Pacific based on tagging and otolith analysis. Sources: [a]Bayliff (1988), eastern Pacific Ocean; [b]Langely et al. (2005), WCPO; [c]Uchiyama and Struhsaker (1981) central Pacific; [d]Tanabe et al. (2003a), western Pacific Ocean; [e]Lin et al. (2005), western and central Pacific Ocean.

Age (years)	Tagging[a]	Model[b]	Otolith[c]	Otolith[d]	Spines[e]
1	44	42	44	45	32
2	66	60	68	65	47
3	77		83		
4	83		91		

Table 2. Lower oxygen tolerances (ml O2 litre–1) for skipjack, yellowfin, bigeye and albacore tuna. Sources: [a]Bushnell and Brill (1991); [b]Graham et al. (1989); [c]Dizon et al. (1978); [d]Bushnell and Brill (1992); [e]Sharp (1978).

Species	Physiological	Behavioural	Lethal
Skipjack	3.7[a]	4.0[c]	2.4–3.0[d,e]
Yellowfin	3.7[a]		1.5–1.6[d,e]
Bigeye	3.7[a]	?	0.5[e]
Albacore	3.7[b]	?	1.4[e]

Table 3. Area of skipjack habitat in the major ocean basins, based on the area of ocean with a surface water temperature greater than 24°C. Source, Fontineau (2003).

Ocean Basin	Estimated area of Skipjack habitat (million km²)	Percent of world skipjack habitat
Atlantic Ocean	10.6	22.4
Eastern Pacific Ocean	8.9	18.8
Indian Ocean	10.8	22.8
Western Pacific Ocean	17.1	36.1
Total		100.0
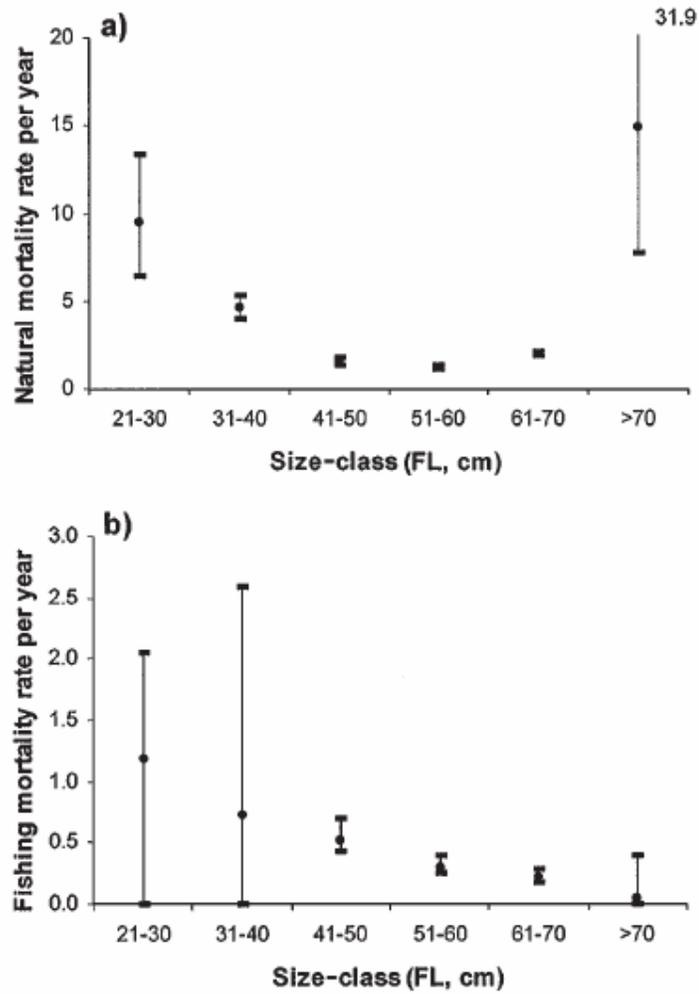
Figure 2. Estimates of annualised rates (year^{-1}) of natural mortality (upper figure) and fishing mortality (lower figure) of skipjack tuna in the WCPO. Source, Hampton (2000). Points represent median values and error bars bound the 2.5 and 97.5 percentiles of 1,000 bootstrap.
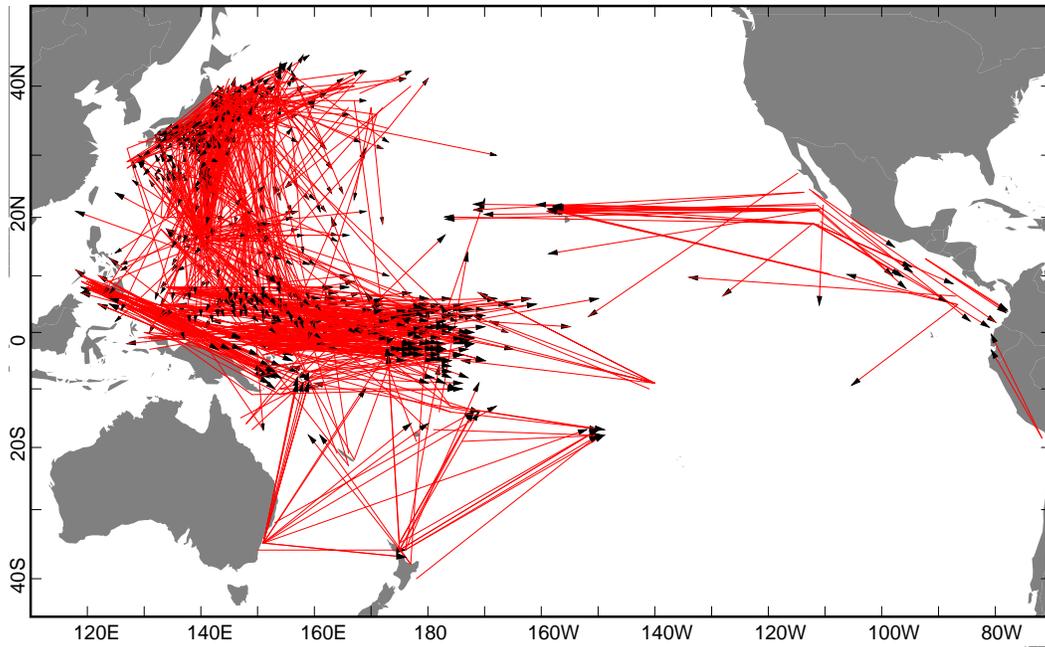
Figure 3. Long distance movement (greater than 1,000 nmi) of tagged skipjack in the Pacific Ocean. Source, Langley et al. (2005).
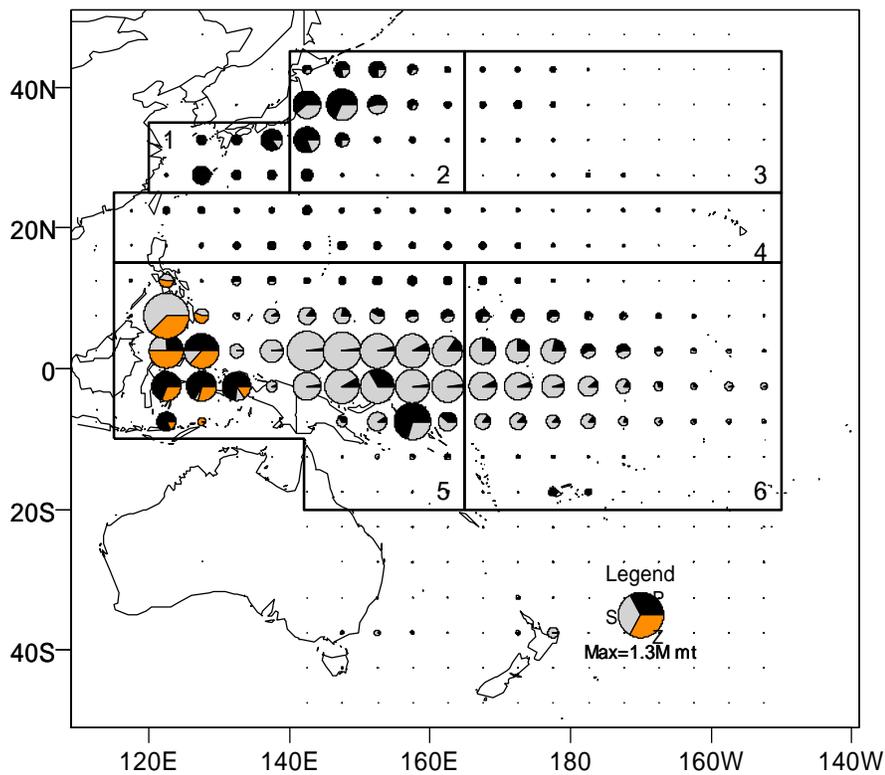
Figure 4. Distribution of total skipjack catches by main fishery methods, 1972–2004. Source, Langley et al. (2005). The six-region spatial stratification used in the 2005 MULTIFAN-CL analysis is also shown. Fishery-method codes: P, pole-and-line; S, purse-seine; Z, other (mainly the fisheries of Indonesia and the Philippines).
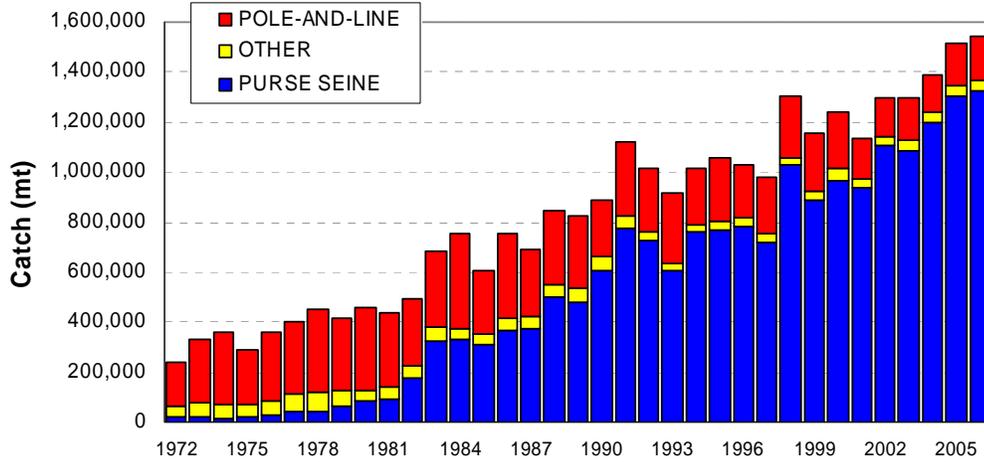
Figure 5. Annual catches of WCPO skipjack tuna by method-fishery, 1972–2006. Source, Williams and Reid (2007). Other includes all other method fisheries.
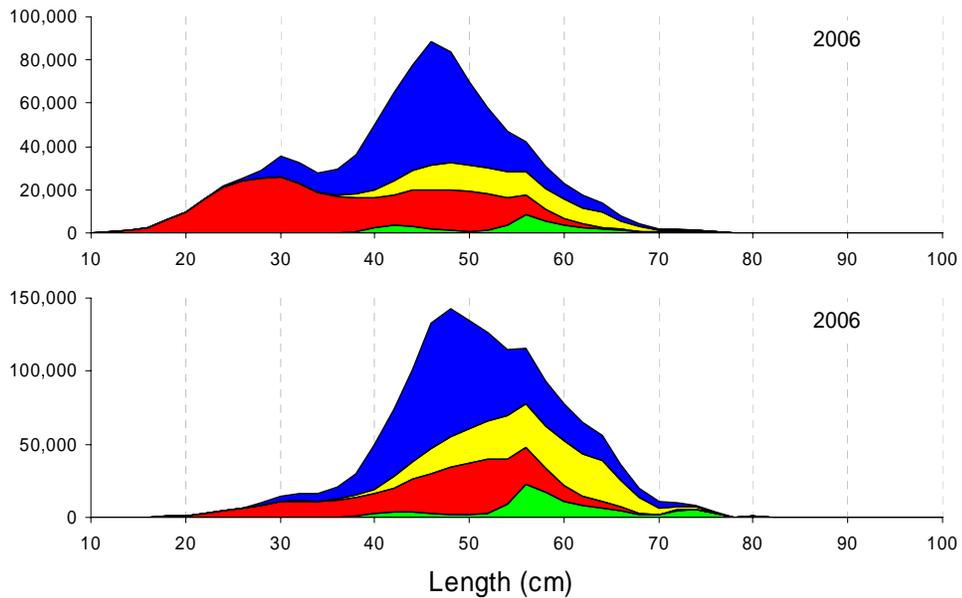
Figure 6. Annual catches of skipjack tuna in thousands of fish (upper figure) and metric tonnes (lower figure) in the WCPO by 2 cm length class and fishery method, 2006. Source, Williams and Reid (2007). Fishery codes: blue, purse-seine fisheries on associated schools (logs, FADs etc); yellow, purse-seine on unassociated schools (free schools); green, pole-and-line; red, fisheries of Indonesia and the Philippines.

3.   Yellowfin (*Thunnus albacares*)
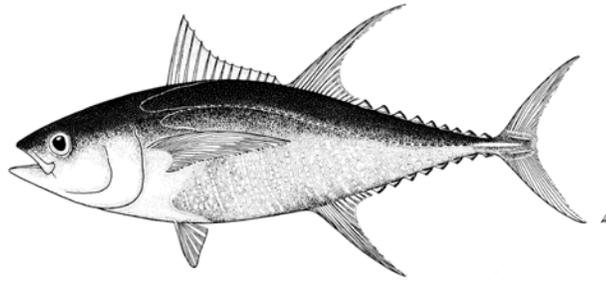
3.1   General description

A large, schooling tuna, common in surface waters of tropical and sub-equatorial oceans. Adult yellowfin are easily distinguished from other tuna by their relatively large second dorsal and anal fins which, along with finlets, are typically bright yellow. However, small yellowfin (less than approximately 70 cm FL) can be confused with small bigeye tuna, especially in purse-seine catches (Lawson 2003, Itano and Fukofuka 2007).

3.2   Distribution

Yellowfin have a global distribution in tropical and sub-equatorial oceans of the world (Sun et al. 2003). Adult yellowfin are distributed between 40°N–40°S in the western Pacific (Lehodey 2003) and at least 35°N–33°S in the eastern Pacific (Blackburn 1965). Small, juvenile yellowfin (less than 70 cm FL) are generally restricted to equatorial areas, resulting in a similar distribution to skipjack. Yellowfin larvae are distributed throughout the Pacific in tropical and subtropical waters between 10°N and 10°N (Lehodey 2003), generally being restricted to the area bounded by the 26°C surface isotherm (Brill et al. 1999). Both adult and juvenile yellowfin are attracted to floating objects including FADs.

In the eastern Pacific Ocean, yellowfin larger than 85 cm FL also to aggregate under herds of dolphin, mainly spotted and spinner dolphins (Hall 1998, Heckel et al. 2000). Although this behaviour has been reported from other Oceans (Hall 1998) it has not been observed in the WCPO. This is likely due to the much lower abundance of dolphins in the WCPO compared to the EPO, resulting in smaller herds of dolphin that are below a suitable size for aggregating large yellowfin (M. Hall, pers. comm.).

3.3 Biology

3.3.1   Age and growth

Yellowfin are a large tuna, reaching in excess of 170 cm FL and 80 kg in the WCPO (unpublished observer data held at SPC). The longest period at liberty for a tagged yellowfin in the WCPO is just of seven years for a 34 cm FL fish tagged and recaptured near Palau (SPC unpublished data). Longevity for yellowfin has been estimated at 7.65 years (Su et al. 2003).

Age and growth of yellowfin have been studied with various techniques, including counts of increments on otoliths, scales and vertebrae, modal progression of length frequencies and analysis of tagging data. In the WCPO, growth of small yellowfin (less than 50 cm FL) is very rapid, with the growth diverging from a VBGF until yellowfin attain approximately 100

cm FL. A VBGF approximates the growth of larger yellowfin, with estimates of L∞ of 145 cm FL and K of 0.1.year^{-1} used to model yellowfin growth in the WCPO (Langley et al. 2007). However, alternative VBGF parameter values have been estimated for the western Pacific (e.g. L∞ = 175 cm FL and K = 0.392.year^{-1} (Su et al., 2003)), and there is strong evidence for differential growth of yellowfin with the WCPO. For example, it appears that yellowfin from western equatorial WCPO have slower than growth rates than the WCPO average, at least until 100–120 cm FL (Langley et al. 2007). There is also evidence of a high level of growth plasticity among years in WCPO yellowfin (Kikkawa and Cushing 2002), resulting in a wide range of VBGF parameter estimates (L∞=152.5–195 cm FL, k=0.334–0.775.year^{-1}).

Estimates of yellowfin growth parameters vary among ocean areas. In the EPO, yellowfin is modelled using , L∞ = 186 cm FL and K =0.761.year^{-1} (Maunder 2007). In the western equatorial Atlantic, Lessa and Duarte-Neto (2007) estimated L∞ = 231 cm FL and K =0.267.year^{-1}, while a range of parameter values were estimated for yellowfin from the Indian Ocean (L∞ = 194–273 cm FL and K =0.176–0.20.year^{-1}, Stequert et al. 1996, Somvanshi et al. 2003).

Yellowfin exhibit sexually dimorphic growth in the eastern Pacific with male fish being consistently larger than females of the same age (Schaefer 1998). Yellowfin in the WCPO have also been suspected of sexually dimorphic growth, but the differences have not been supported by ageing studies.

3.3.2   Reproduction

Yellowfin tuna may reach maturity as small as 57 cm FL (Schaefer 1998), but these observations have not been confirmed with histological studies. In the WCPO, the smallest mature yellowfin determined from histological analysis was 78 cm FL, but most females are not reproductively mature until 100–110 cm FL. Histological studies of yellowfin in the Coral Sea found 50% of yellowfin were mature at 120 cm FL in the longline fishery and at 108 cm FL in the handline fishery (McPherson 1991). In the EPO, size at 50% maturity was estimated as 92 cm FL and 2–3 years of age, although variation in size at 50% maturity was reported (Schaefer 1998).

Yellowfin appear to spawn in surface waters at night. Large yellowfin captured in the purse–seine fishery appear to be actively spawning, whereas similar–sized yellowfin captured by longline fisheries were mature but had lower GSIs. This suggests that surface schools of large yellowfin are actually spawning aggregations (Schaefer 1998).

Year-round spawning of yellowfin is possible in area where conditions are suitable. In the EPO, yellowfin spawn year round in the area 1–20°N and west of 140°W. However, outside this region, spawning is restricted to areas where SSTs exceed 24°C (Schaefer 1998). Using the 24°C isotherm as a limit, this implies that yellowfin spawning occurs year-round in the western equatorial WCPO, extending into sub-equatorial areas off eastern Australia (East Australian Current) and north of the Philippines (Kuroshio currents). However, yellowfin larvae are patchily distributed across the equatorial Pacific (Lehodey 2003) and the 26°C SST isotherm appears to bound the northern and southern limits of yellowfin spawning areas in the WCPO (Itano 2000 in Langley et al. 2007).

Yellowfin are serial spawners that can release millions of eggs per batch during extended periods. Batch fecundity from the EPO was estimated at 67 egg.gramme^{-1} (Schaefer 1998). Thus a 120 cm FL yellowfin (30 kgs) would produce approximately 2 million eggs per batch. Data suggest that yellowfin tuna spawn every 1–2 days in the afternoon and night, though it is not known whether individual yellowfin spawn at this frequency throughout year.

Sex ratios of longline–caught yellowfin are usually 1:1 until they reach 120 cm FL after which males predominate. The fate of female yellowfin larger than 120 cm FL is unclear. One hypothesis is that the high physiological demand of spawning increases natural mortality rates of female yellowfin after they reach 80–100 cm FL (Hampton 2000).

3.3.3   Recruitment

Yellowfin commence recruiting to the WCPO purse-seine fishery at 25–30 cm FL, and appear fully recruited by 40–50 cm FL, with small yellowfin captured mainly in associated sets (e.g. logs, FADs) (Figure 11). Large yellowfin (greater than 90–100 cm FL) are also captured by the purse–seine fishery, mainly in sets on free schools (Molony 2004 a). Yellowfin commence recruitment to longline fisheries of the WCPO at approximately 80 cm FL and are fully recruited by approximately 110 cm FL (Figure 11). Recruitment to the fisheries of Indonesia and the Philippines commences at approximately 15 cm FL (Figure 11). Yellowfin of a wide size range are captured by these fisheries.

3.3.4   Mortality

Natural mortality varies throughout the life of yellowfin. Natural mortality is very high in yellowfin up to 30 cm FL, declining to relatively low levels at size of 50–60 cm FL (Figure 8). Natural mortality rates again increase at sizes of 80 cm FL, coincident with the onset of maturity (Hampton 2000), before declining in larger declining. Fishing mortality is estimated to also be relatively high in small fish, declining to relatively low levels at 80 cm FL (Figure 8). The schedule of natural mortality used in the recent stock assessment of yellowfin in the WCPO (Langley et al. 2007) is identical to the schedule used in the EPO assessments (Maunder and Harley 2004).

3.4   Ecology

3.4.1   Habitat preference

Yellowfin are common in warm tropical waters and are the second most common tuna (after skipjack) in the pelagic fish community in terms of biomass, based upon catch records (Williams and Reid 2007) and biomass estimates (Langley et al. 2007).

Yellowfin are a surface dwelling species with both large (greater than 100 cm FL) and small (less than 60 cm FL) individuals captured by the purse-seine fishery in the WCPO (Figure 17, Molony 2004a). Longline CPUE for yellowfin generally declines with increasing hooks between longline floats (HBF, which increases average hook depth) (Molony 2004b), supporting the surface distribution of yellowfin.

Tagging with acoustic transmitters (Block et al. 1997) or ultrasonic tags (Brill et al. 1999) have shown yellowfin (8–16 kg and 63–93 kg, respectively) spend a majority of their time in the upper mixed layer of the ocean (less than 100 m, Brill et al. 1999), typically in

temperatures above 17–18°C. This is despite yellowfin being functional endotherms and being able to conserve and generate muscle heat during activity, potentially enabling yellowfin to diver deeper in the water column (Brill et al. 1999). One explanation for the limited vertical distribution of yellowfin is that cardiac (heart) musculature is downstream of the counter-current system and is exposed to ambient temperature of the surrounding water (Brill et al. 1999).

From laboratory studies, the cardiac musculature of yellowfin could not adjust to a reduction in water temperature from 25°C to 15°C reducing heart rate. Thus the limiting factor appears to be the inability of the heart musculature to deal with low temperatures, reducing the blood flow and therefore oxygen supply to the swimming muscles (Brill et al. 1999). As a consequence, the distribution of yellowfin in the Pacific is limited to approximately the 20°C SST isotherm. Habitat based standardisation models for yellowfin indicate a temperature preference for waters of 25–31°C, further supporting a surface preference. Overall, the a range of data suggest that yellowfin generally remain less than 100 m deep (i.e. within the mixed layer and above the thermocline).

Yellowfin appear to be able to tolerate a wide range of dissolved oxygen levels (Table 9) and do not seem limited by oxygen in their preferred depth range in the WCPO (0–100 m). Thus, the yellowfin distribution in the WCPO does not appear limited by low oxygen concentrations. Habitat-based standardisations of yellowfin have used oxygen preferences for this species, constraining models to have rapidly declining abundances with dissolved oxygen concentrations below 4.0 ml l^{-1} and no yellowfin in waters with dissolved oxygen levels less than 2.5 ml l^{-1} (Bigelow et al. 1999).

As yellowfin grow, they develop a well–formed swim bladder and large pectoral fins. These provide additional lift which allow yellowfin to maintain hydrostatic equilibrium at a lower basal swimming speed than skipjack, reducing basal metabolic rates and oxygen consumption compared to skipjack (Dizon et al 1978). The lower metabolic rate of yellowfin relative to skipjack also lessens the problem of heat retention at large sizes, thus allowing large yellowfin to live in warm surface waters as well as deeper waters. As a result, large yellowfin are often captured in surface schools in purse-seine sets.

Tagging work on yellowfin captured near anchored FADS in Hawai'i have shown that yellowfin may be resident near floating structures and within a small area for extended periods of time (Grubbs et al. 2002, Holland et al. 2003). This supports the concepts of relatively long periods of residence (Sibert and Hampton 2003) and site-fidelity (Klimley and Holloway 1999) of yellowfin at the scale of hundreds of kilometres in at least some waters of the WCPO.

3.4.2   Movements and migration

Until recently, most of the information on yellowfin movements was from the eastern Pacific where the IATTC has carried out many tagging experiments. These showed many large–scale movements along the coast of Baja California and Central America. However, yellowfin did not tend to move offshore as they grew (Suzuki et al. 1978).

In the western and central Pacific, the SSAP tagged 9,464 yellowfin during 1977–80. A total of 219 (2.3%) tags were returned with reliable recovery information. In all cases movement

was confined to the area bounded by 20°N–20°S. Twenty–three percent of the yellowfin recaptured were more than 200 nmi from their point of release. The largest yellowfin movement was 3,800 nmi from a point of release in Fiji to a recovery in the eastern tropical Pacific. Most yellowfin with long–distance movements were recaptured between 10°N and 10°S, which suggest stronger east–west movements than north–south movements. The predominant east–west movement may be explained by the influence of major longitudinal current systems in the equatorial WCPO, restrictive SST and the concentration of industrial tuna fisheries (recapture effort) within this area. However, few movements between the WCPO and EPO have been recorded (Figure 7) (Langley et al. 2007).

The RTTP experiment during 1989–92 focused on yellowfin, with the quantification of movement rates within the western Pacific being a major objective. The RTTP tagged 33,522 yellowfin of which 3,005 (9.0%) have been recaptured and returned with reliable recovery information. Similar to skipjack, yellowfin had a higher percentage of displacements greater than 200 nmi in the RTTP (46%) than the SSAP (23%) due to more homogeneous effort in the tagging area. RTTP analyses indicate a similar east–west movement for yellowfin (Figure 51). Of the 3,005 recaptures, only eight fish had movements beyond 20°N or 20°S. The farthest pole–ward movements were to 34° in both the northern and southern hemisphere.

Rapid, long–distance movements of yellowfin were inferred from the distribution of yellowfin contaminated with radioactivity following nuclear tests at Bikini Atoll (Marshall Islands) during 1954 (Suzuki et al. 1978). Length–frequency distributions suggested that contamination was restricted to a small area, and therefore could be interpreted in a similar fashion to a tagging experiment. The contaminated yellowfin dispersed rapidly east and west in the North Equatorial Current and Counter Current. Some moved north to 40°N in the Kuroshio Current and others moved south to 25°S off eastern Australia.

A recent re–examination of the yellowfin movement patterns from tagging studies using a spatial model (Sibert and Hampton 2003) has indicated that yellowfin are not as highly migratory as previously thought. The model indicated that the median lifetime displacement of yellowfin was less than 400 nautical miles, far smaller than many excusive economic zones (EEZs) of Pacific Island Nations. Therefore, there is likely to be a large component of the yellowfin stock that can be considered as residing within an EEZ.

Modern tagging programmes of yellowfin captured and released near FADs around Hawaii have shown a high degree of return to the site of capture. For example, 27 out of 38 yellowfin (73.7–97.8 cm FL) tagged with ultrasonic tags and released near FADs returned to site of tagging within 1–257 days post-tagging, with up to 17 returns by an individual fish. Further, most returns by tagged fish (73%) were with other fish tagged and released on the same day, suggesting the persistence of yellowfin within a school (Klimley and Holloway 1999). These results imply that most yellowfin display movements to and from specific, predictable sites. Thus fishing methods targeting schools (e.g. purse-seine) may impact on the abundance of yellowfin at other places on their migration paths.

3.4.3   Diet

Although yellowfin consume a wide range of prey types (Grubbs et al. 2001, 2002), they mainly feed on fish and cephalopods, although their diets vary among areas in the WCPO (Allain 2005). The major fish species consumed by yellowfin include skipjack, flying fish and other small tunas, although coral reefs fishes (e.g. acanthurids) and crustaceans are also

consumed in areas where coral reefs are found close to deeper water (e.g. Papua New Guinea). Small yellowfin (less than 45 cm FL) associated with FADs near Hawai'i consumed mainly stomatopods, feeding almost exclusively on vertically–migrating oplophorid shrimps when greater than 45 cm FL. However, the diets of yellowfin around FADs are likely to be different to free–ranging yellowfin.

3.5   Details of stocks in the WCPO

3.5.1   Stock structure and size

The population structure of Pacific yellowfin has been investigated using morphometric comparisons, length–frequency and catch–effort analyses, tagging experiments, spawning and other life–history studies and studies of population genetics.

Tagging data in the western Pacific show extensive meridional movements between 120°E and 170°W (Figure 7). However, there are no records of yellowfin tagged in the WCPO being recaptured east of 150°W. Additionally, there are no records of yellowfin tagged in the EPO being recaptured west of 150°W. The distributions of yellowfin catches (Figure 9) and larvae are also consistent with an existence of separate western–central and eastern Pacific yellowfin stocks. Thus, yellowfin in the Pacific Ocean are divided into two stocks, with the boundary at approximately 150°W (Bigelow et al. 1999, Langley et al. 2007) (Figure 9).

A Pacific–wide population genetics study (Ward et al. 1994) also supports the existence of eastern and western Pacific Ocean stocks of yellowfin. The Pacific–wide distribution of GPI–F allele frequencies show significant heterogeneity between eastern Pacific samples and western–central Pacific samples indicating that there are at least two genetically different groups of yellowfin in the Pacific, one comprising a western Pacific stock (Philippines, Coral Sea, Kiribati, Papua New Guinea, Hawaii) and the other an eastern Pacific stock (California, Mexico, Ecuador). No significant heterogeneity was found among the western and central Pacific samples.

However, the re–examination of yellowfin tagging data using a spatially structured model (Sibert and Hampton 2003) demonstrated that although yellowfin are capable of long–distance movement, the median distance moved is less than 400 km. These results suggest that only limited mixing of yellowfin stocks is likely to occur and that a degree of residency is likely within many EEZs. However, as long–distance movement do occur then complete separation into sub-stocks is unlikely.

Yellowfin catches from the WCPO are have been consistently larger than catches from the EPO (OFP, 2007), suggesting the WCPO stock is larger. Based on catches estimates (Lawson 2003), the yellowfin stock in the WCPO is likely to be the largest of any Ocean.

3.5.2   Recent stock assessments and status

The most recent assessment indicates that that the yellowfin stock in the WCPO is currently not being overfished and is not currently in an overfished state. However, the yellowfin stock is likely to be fully exploited, and increases in fishing mortality (effort) would not result in any long-term increase in yield and may shift the yellowfin stock to an overfished state. Increased yields are theoretically possible if the average size of yellowfin from WCPO fisheries was increased (Langley et al. 2007).

3.6 Fisheries

3.6.1   Major fisheries and occurrence

Purse-seine fisheries have reported the bulk of yellowfin catches from the WCPO since the mid 1980s (OFP 2007). Since 2000, the purse-seine fisheries have accounted for 45–58% of annual yellowfin catches from the WCPO (Figure 10), with the purse-seine fishery representing an increasing proportion of total yellowfin catches. The purse-seine fishery reports significant catches of small and large yellowfin from associated sets (logs FADs etc), and mainly larger adults (greater than 100 cm FL) in unassociated sets of free schools (Figure 11).

Longline fisheries also catch significant quantities of yellowfin (Figure 10), with catches dominated by fish larger than 110 cm FL (Figure 11). Since 2000, the longline fisheries of the WCPO have accounted for approximately 15–20% of yellowfin catches. Fisheries of Indonesia and the Philippines have accounted for approximately 25% of yellowfin catches from the WCPO, with catches dominated by small fish. Pole-and-line fisheries take less than 5% of total WCPO catches of yellowfin.

3.6.2   Artisanal fishery value

Yellowfin are also captured by artisanal fishes throughput the WCPO (Dalzell et al. 1996), especially around anchored FADs. However, estimates of yellowfin catches by artisanal fishers in the WCPO are rare.

3.6.3   Sport and recreational fishery value

Yellowfin are an important sportfishing species in the WCPO due to the large sizes attained (Whitelaw 2001). Throughout the WCPO, sportfishers target yellowfin tuna which can comprise a significant component of the sportfish landings (www.billfishclub.com).
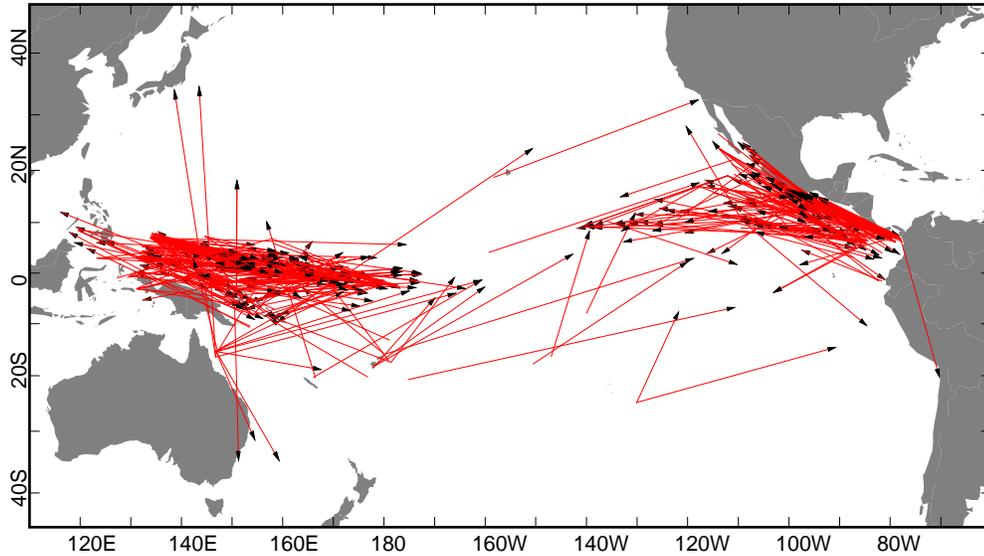
Figure 7. Long distance movement (greater than 1,000 nmi) of tagged yellowfin in the Pacific Ocean. Source, Langley et al. (2007).

Table 11. Estimated size-at-age for yellowfin tuna in the eastern Pacific based on otolith ([1]Wild 1986) and length–frequency analyses ([2]Sun et al. 2003).

Age (years)	Fork length (cm)[1]	Whole wt (kg)[1]	Fork length (cm)[2]
1	45	1.8	56.3
2	85	12.5	95.0
3	122	38.2	121.0
4	160	88.1	138.5
5	-	-	150.3
6	-	-	158.3

Table 12. Estimates and 95% confidence intervals of results from a tag attrition model based on RTTP data for yellowfin tuna in the equatorial western Pacific. Reproduced from Hampton (1993).

Parameter	Mean	95% Confidence intervals	
		Lower	Upper
Monthly natural mortality rate	0.128	0.116	0.139
Monthly fishing mortality rate	0.032	0.025	0.041
Total monthly mortality	0.160	0.141	0.180
Exploitation rate	0.200	0.163	0.250
Standing stock (million mt)	1.431	1.032	1.837
Monthly throughput ('000 mt)	179	132	226
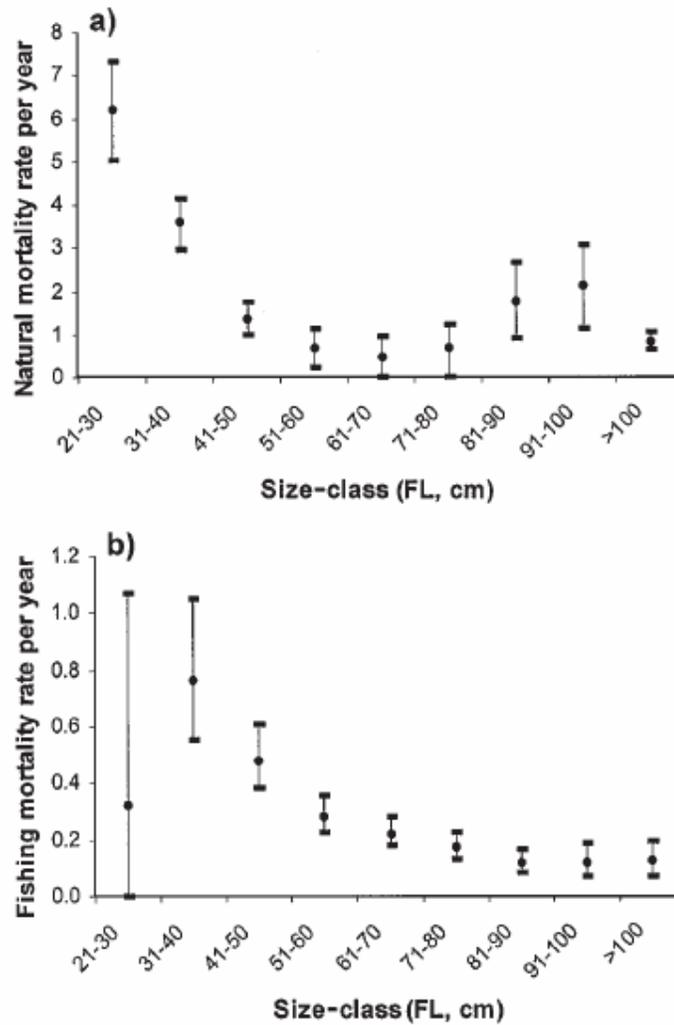
Figure 8. Estimates of annualised rates (year⁻¹) of natural mortality (upper figure) and fishing mortality (lower figure) of yellowfin tuna in the WCPO. Source, Hampton (2000). Points represent median values and error bars bound the 2.5 and 97.5 percentiles of 1,000 bootstrap.
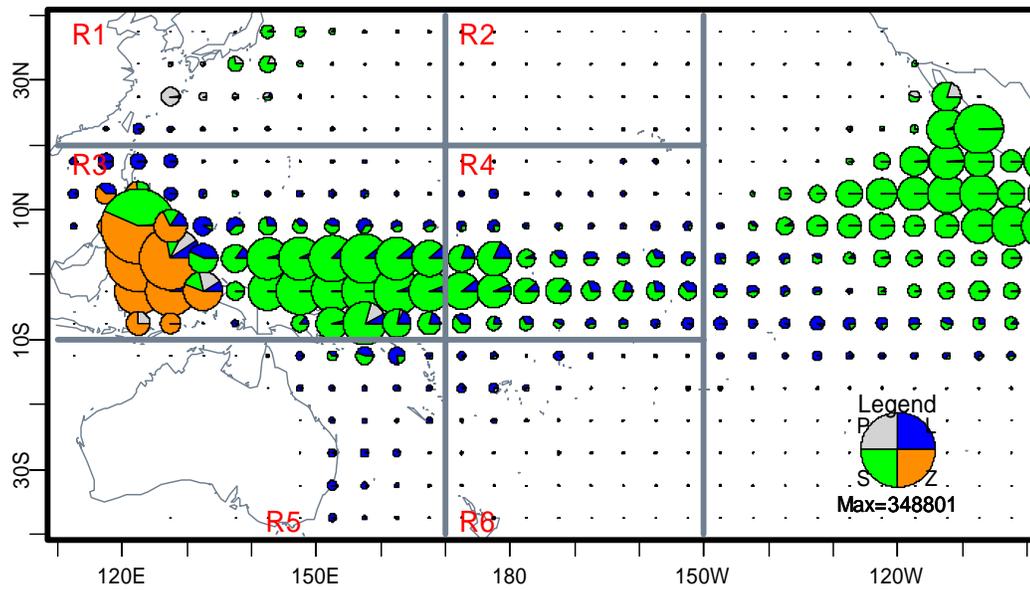
Figure 9. Distribution of total yellowfin catches by main fishery methods, 1990–2005. Source, Langley et al. (2007). The six-region spatial stratification used in the 2007 MULTIFAN-CL analysis is also shown (grey lines). Fishery-method codes: blue (L), longline; green (S), purse-seine; grey (P), pole-and-line; Z, other (mainly the fisheries of Indonesia and the Philippines).
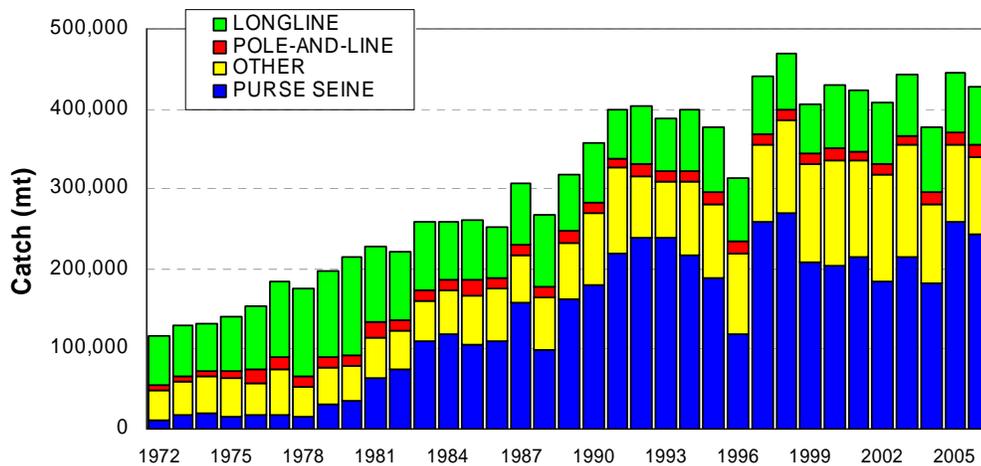
Figure 10. Annual catches of WCPO yellowfin tuna by method-fishery, 1972–2006. Source, Williams and Reid (2007). Other includes all other method fisheries.
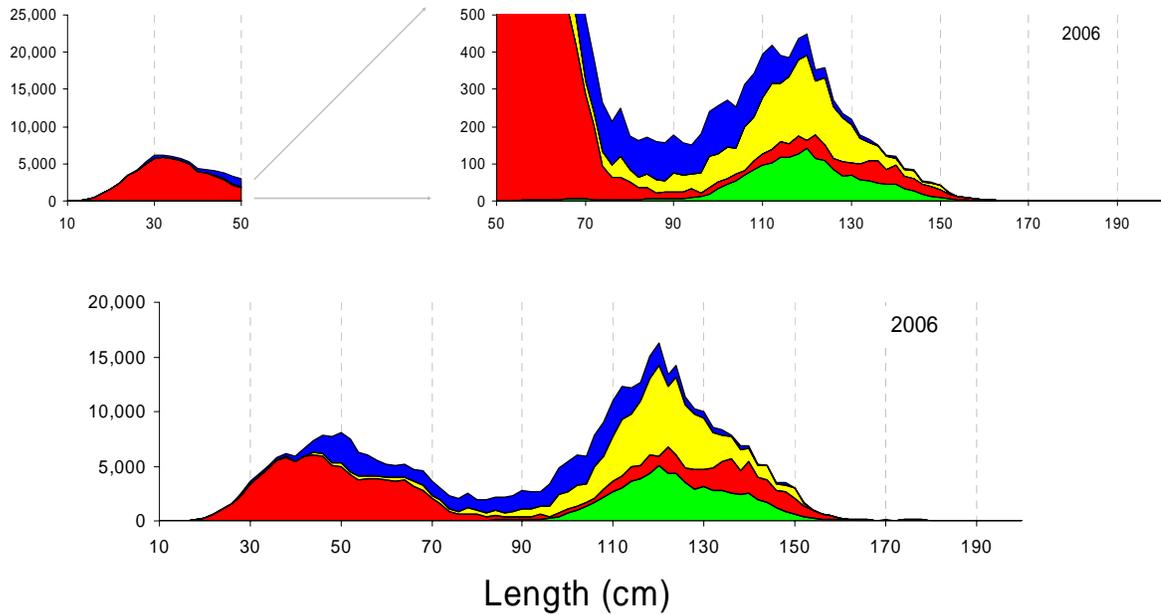
Figure 11. Annual catches of yellowfin tuna in thousands of fish (upper figure) and metric tonnes (lower figure) in the WCPO by 2 cm length class and fishery method, 2006. Source, Williams and Reid (2007). Fishery codes: green, longline; blue, purse-seine fisheries on associated schools (logs, FADs etc); yellow, purse-seine on unassociated schools (free schools); red, fisheries of Indonesia and the Philippines.

4. Bigeye (*Thunnus obesus*)
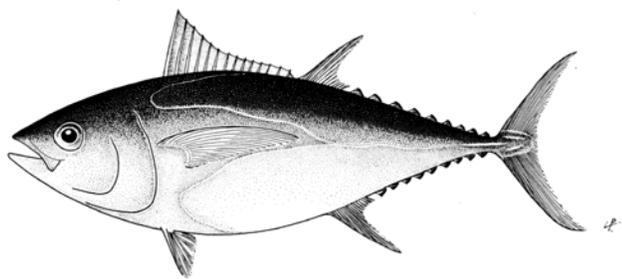
4.1 Description

Bigeye tuna are found in tropical and subtropical waters of the Pacific, Indian and Atlantic Oceans. Large bigeye (greater than 100 cm FL) can be distinguished from other species of tuna as their body depth is deepest under the base of the first dorsal fin and by an iridescent blue band running along the body. Dorsal and ventral fins may be deep yellow, but bigeye do not possess the elongated second dorsal fin of yellowfin. Small bigeye (~50 cm FL) can be confused with small yellowfin tuna, especially in purse-seine catches (Lawson 2003).

4.2 Distribution

Bigeye tuna inhabit the tropical and temperate waters of the Pacific Ocean between northern Japan (40°N) and the north island of New Zealand (40°S) in the west, and from 40°N to 30°S in the east, except near coastal waters of Central America between 5° and 20°N (Hampton et al. 1998). In the WCPO, logsheet and observer records exists between 40°N and 45°S.

4.3 Biology

4.3.1 Age and growth

In the WCPO, bigeye obtain least 170 cm FL and 100 kg. Liu et al. (2005) estimated longevity at greater than 14 years for north-west pacific bigeye, and a single bigeye tagged in the WCPO was at liberty for 12 years (Hampton and Williams 2004). A significant proportion of bigeye survive until approximately eight years of age (Hampton et al. 2006).

Age and growth of bigeye has been inferred from modal progression of length and/or weight frequencies (Kikkawa and Cushing 2001), scales, otoliths (Lehodey et al. 1999, Leroy 2001, Farley et al. 2006) and other hard structures (dorsal spines and vertebrae (Fonteneau et al. 2004), in conjunction with tagging data (Hampton et al. 1998, Lehodey et al. 1999, Schaefer and Fuller 2006).

Bigeye growth rapidly, reaching approximately 40 cm FL within one year of age (Fonteneau et al. 2004) and 80 cm FL within 1.5 (Hampton et al. 1998) to 2 years of age (Kikkawa and Cushing 2001), with linear growth until fish reach 50–100 cm FL (Hampton et al. 2006). The growth of bigeye

Bigeye growth from many areas has been described by VBGF as bigeye reach an asymptotic length by 9–10 years of age (Farley et al. 2006). In the WCPO, estimates of L_∞ and *K* have range from 169 cm FL and 0.238.year^{-1}, respectively, for the south-west Pacific (Farley et al. 2006) to more than 203 cm FL and 0.201–0.212.year^{-1}, respectively (Sun et al. 2001, Liu et

al. 2005) for the northwest Pacific. In the EPO, Schaefer and Fuller (2006) estimated a range of L_∞ (367–513 cm FL) and K (0.079–0.108.year^{-1}), although both parameters are likely to be poorly estimated due to the limited size range of bigeye used in the study; the IATTC estimated an L_∞ of 186.5 cm FL in its recent assessments. Hampton et al. (1998) also concluded that models may underestimate the growth of large bigeye (greater than 110 cm FL) and a range of L_∞ (140–200 cm FL) and K (0–0.3.year^{-1}) have been used in recent stock assessments, with the ,most parsimonious model producing estimates of $L_\infty = 180$ cm FL and $k = 0.075.$year^{-1} (Hampton et al. 2006).

Overall, a large degree of growth plasticity (size-at-age) has been reported from tag (e.g. Hampton et al. 2006, Schaefer and Fuller 2006) and port sampling data (Kikkawa and Cushing 2001). For example, 80 cm FL bigeye sampled from the Guam fish markets ranged in age between 1.5 –2.5 years (mean 1.8 years), as a result of changes in growth rate, likely in response to broad-scale oceanic conditions (El Niño and La Niño periods) in the region (Kikkawa and Cushing 2001).

Males and females grow at approximately the same rate up to 150 cm FL, with males displaying slightly faster growth rates than females beyond this size, although differences are not significant (Schaefer and Fuller 2006). The faster growth rates of large males may be due to the increased demands of reproduction by large females.

4.3.2   Reproduction

Based on macroscopic examination of ovaries, the size at 50% maturity of female bigeye was estimated at 102 cm FL in the south-western WCPO, at an age of 2–2.5 years (Farley et al. 2006). The smallest mature female was 80 cm FL, with most females greater than 100 cm FL being mature. However, Schaefer et al. (2006) suggest that many studies may underestimate size at first maturity if only macroscopic examination of the gonads is undertaken. Bigeye apparently mature at larger sizes in the EPO, with the smallest mature female was 102 cm FL and the size at 50% maturity estimated at 135 cm FL based on microscopic examination, with all females above 150 cm FL being mature (Schaefer et al. 2006). In the EPO, fish of 135 cm FL are approximately 3.0–3.5 years of age (Schaefer and Fuller 2006).

The distribution of larvae suggests that bigeye spawn in the western Pacific between 30°N and 20°S and 15°N and 15°S in the eastern Pacific (Schaefer et al. 2006). In the western Pacific, mature bigeye are reported between at least August and December (Farley et al. 2006) but bigeye may spawn year-round where appropriate conditions are present. Actively spawning females (based on histological examination of gonads) were reported in areas where SSTs were 24–30°C and water temperatures exceeded 24°C from the surface to more than 50 m (Schaefer et al. 2006). In he EPO, these conditions are present in the area 15°N–15°S, 175°–105°W in the EPO.

Histological examination indicates that bigeye are multiple spawners with a spawning frequency of 1.00–2.6 days for individual females (Schaefer et al. 2006). Spawning occurs at night between 1900 hours and 04:00 hours (Schaefer et al. 2006). Schaefer et al. (2006) estimated the batch fecundity of EPO bigeye at 13.8–43.0 eggs/gramme. A 150 cm FL bigeye (approximately 70 kgs) would have an estimated batch fecundity of 0.966–3.010 million eggs.

Examination of sex ratio from the broad area of the equatorial Pacific showed a general tendency of predominance of male fish over the entire size range studied, especially in the

lower and upper size classes (Sun et al. 2004, Fonteneau et al. 2004). However, few significant deviations from a 1:1 sex ratio were recorded (Schaefer et al. 2006). A high degree of variability in the sex ratio was recorded among years and quarters (Sun et al. 2004). The dominance of males tends to become more prominent with increasing size (Fonteneau et al. 2004, Sun et al. 2004).

4.3.3   Recruitment

Bigeye recruit to the longline fisheries of the WCPO from approximately 75 cm FL, being fully recruited by approximately 110 cm FL (Figure 17). WCPO purse-seine fisheries record bigeye as small at 35 cm FL, with full recruitment of bigeye to the fishery by approximately 50 cm FL due to the aggregation of small bigeye to floating objects. Very few bigeye are recorded by the purse-seine fishery on unassociated sets. Bigeye are also captured by the fisheries on Indonesia and the Philippines from approximately 20 cm FL, becoming fully recruited by 40 cm FL. However, some methods used in Indonesia and the Philippines (e.g. handline) also capture much larger fish (greater than 130 cm FL) also captured.

A reconstructed time–series of recruitment bigeye recruitment indicates that the levels of recruitment of bigeye in the late 1990s are at least two times higher than the long–term average (Hampton et al. 2006).

4.3.4   Mortality

Natural mortality rate of bigeye has been estimated to be 0.361 yr^{-1} with total mortality ranging from 0.6 to 1.4 yr^{-1} for the longline fishery during 1957–1964 (Suda and Kume 1967 in Hampton et al. 1998). This analysis suggested that fishing is the major cause of mortality for bigeye age 5 years and older. However, in a subsequent analysis, lower levels of fishing mortality were obtained by using higher values (0.4 or 0.6 yr^{-1}) of natural mortality (Miyabe 1989).

As with other tuna species, bigeye have size-dependant natural mortality rates (Figure 13) (Hampton 2000). Analyses of tag–recapture data suggests a high rate (0.34–0.56 mo^{-1}, 4.08–6.72 yr^{-1}) for small fish (less than 40 cm FL) tagged in the Philippines, intermediate rates (0.08–0.11 mo^{-1}, 1.05–1.39 yr^{-1}) for small–medium (45–65 cm) fish tagged in the western equatorial Pacific and low rates (0.043–0.049 mo^{-1}, 0.46–0.51 yr^{-1}) for medium–large fish (greater than 60 cm FL) tagged in Coral Sea (Hampton et al. 1998, Hampton 2000). However, there is a high degree of variation in the mortality estimates due to movement of tagged fish away from the tagging site (Hampton et al. 1998) and the difficulties in spreading recapture effort throughout the range of bigeye.

4.4 Ecology

4.4.1   Habitat preference

Adult bigeye tend to refer deeper water than yellowfin or skipjack in the WCPO, particularly in equatorial regions. As a consequence, large bigeye (greater than 100 cm FL) are rarely captured by surface fisheries (purse-seine or pole-and-line). However, recent tagging of large bigeye near FADs in Hawaii has indicated the adult bigeye remain around floating objects for short periods of time (several days). Small bigeye are often found associated with floating objects (e.g. FADs, logs) often found in association with yellowfin and skipjack of similar

sizes. However, bigeye schools around floating objects are typically monospecific (Schaefer and Fuller 2005).

Large bigeye tend to be associated with the deep scattering layer (DSL). During daytime, adult bigeye prefer cooler (15–20°C), deeper waters (down to approximately 300–500 m), and migrate with the DSL towards surface waters at night (Figure 12) (Dagorn et al. 2000, Musyl et al. 2003, Matsumoto et al. 2003). However, dives in excess of 800 into waters 4.7–7°C and oxygen concentrations of 1–2 mL.L^{-1} were recorded (Musyl et al. 2003). The diel pattern of movement allows bigeye to with the DSL and therefore their prey at all times. In addition, movements in depth maintains a similar light intensity, with deeper night time depths reported during full moon periods (Schaefer and Fuller 2002).

4.4.2 Movements and migration

Bigeye movements are the least documented of all the commercially important tunas, largely because of the difficulty of tagging fish with a preference for deeper water. Although movements of more than 4,000 nmi have been recorded (
Figure **14**), most tagged bigeye are recaptured close to the site of release (Hampton et al. 2006), suggesting that bigeye may form localised, resident populations at relatively small spatial scales (e.g. the Coral Seas, Gunn et al. 2005). In the most recent stock assessment for WCPO bigeye tuna, Hampton et al. (2006) most movement of bigeye occurs among equatorial areas (east and west of 170°E), with much lower levels of movement between equatorial and sub-equatorial areas.

4.4.4 Diet

Bigeye remain associated with the DSL at all times, maximising feeding opportunities (Musyl et al. 2003) and they have been reported feeding at all times of the day and night (Collette and Nauen 1983). The diets of bigeye consists mainly of mesopelagic fishes (barracudinas, hatchetfishes and skipjack), although molluscs (mainly squids) and crustaceans are also significant components of their diets (Allain 2005).

Differences in the diets of bigeye from different areas have been recorded (Allain 2005). Grubbs et al. (2001) reported that the diets of unassociated bigeye (i.e. those captured by longline in the ocean) and bigeye associated with floating objects were dominated by mesopelagic fishes (about 70 % of their diets) with small amounts of crustacean and cephalopods, similar to yellowfin. However, oplophorid shrimps comprised approximately 90% of the diets of bigeye associated with seamounts, with teleosts comprising a very small percent of the diet and cephalopods rarely recorded. Further, the guts of bigeye collected from seamounts were significantly fuller than the guts from unassociated bigeye or bigeye associated with floating objects.

4.5 Details of stocks in the WCPO

4.5.1 Stock structure and size

There are two hypothesised stock structures for bigeye in the Pacific Ocean; a single Pacific–wide stock; and a two stock structure, east and west of 150ºW (Hampton and Maunder 2005, Hampton et al. 2006).

The existence of a single stock is supported by the continuous distribution of catches of bigeye across the equatorial Pacific Ocean (Figure 15). Further, while bigeye tagging in the Pacific has been relatively limited, a number of movements >1,000 nautical miles have been observed (
Figure **14**). This has included recoveries of bigeye tagged in the western Pacific and recovered by longliners fishing in the EPO. In addition, genetic work did not identify subdivisions of bigeye throughout the Pacific Ocean.

In contrast, Schaefer et al. (2006) did not identify spawning females in the area 145º–130ºE in the equatorial Pacific and larvae were rare between 180º and 150°W (Nishikawa et al. 1985). Both findings are consistent with separate western and eastern Pacific stocks of bigeye. In addition, archival tagging studies in the EPO have not identified long-distance movement between the WCPO and EPO, despite times at liberty of up to 446 days and estimated movements of individual fish up to 32,500 km (Schaefer and Fuller 2002). No tagged bigeye moved more than 20º of longitude of 10º of latitude throughout the study, suggesting localised populations of bigeye (Schaefer and Fuller 2002), similar to the conclusion of Farley et al. (2006) for bigeye in the Coral Sea.

As a result, separate stock assessments for eastern (IATTC 2004) and western (Hampton et al. 2006) Pacific bigeye will continue in the future, with work on a Pacific wide assessment to continue (Hampton and Maunder 2005). All assessments indicate that bigeye are much less abundant than either skipjack or yellowfin in the WCPO. Based on catch estimates (OFP 2007), stocks of bigeye in the eastern and western Pacific appear to be of a similar magnitude.

4.5.2   Recent stock assessments and status

The most recent assessment (Hampton et al. 2006) indicates that there is a high likelihood that the bigeye stock in the WCPO is experiencing overfishing. That is, the recent (2001–2004) levels of fishing mortality (effort) are greater than the levels estimated to obtain MSY. It is estimate that a 25% reduction in fishing mortality is required to reduce fishing mortality to the level estimated to achieve MSY. Although the bigeye stock in the WCPO is not currently overfished, there is a high risk that it could be moved into an overfished state if the current level of fishing mortality is maintained.

The recent recruitment of bigeye in the WCPO is higher than the long-term average. If the recruitment declines to average levels (as has recently occurred in the EPO), a greater reduction in effort would be required to maintain fishing mortality at levels required to achieve MSY.

4.6 Fisheries

4.6.1   Major fisheries and occurrence

Since 2000, approximately 53–66% of total WCPO catches of bigeye have been recorded by longline methods fisheries (OFP 2007). Most bigeye in longline catches are greater than 110 cm FL (Figure 17) and are highly valuable.

The purse-seine fishery in the WCPO also captures significant quantities of bigeye, accounting for 20–33% of annual bigeye catches since 2000 (OFP 2007), with almost all bigeye reported from associated sets (FADs, logs) (Molony 2004a). In contrast to longline

catches, most bigeye in purse-seine catches are less than 70 cm FL (Figure 17) and are of relatively low value.

Other fisheries also record significant catches of bigeye. Fisheries of Indonesia and the Philippines reported annual catches of a similar magnitude of catches from the WCPO purse-seine fishery. The pole-and-line fishery of the WCPO reports very low catches of bigeye (less than 3% of total catches).

4.6.2   Artisanal fishery value

Bigeye are rarely captured by artisanal fishers in the WCPO, likely due to their preference for deeper water during daytime. However, the reporting of bigeye from handline fisheries in the WCPO suggests that bigeye may be of minor importance to artisanal fishers, especially near artisanal FADs.

4.6.3   Sport and recreational fishery value

Bigeye are not considered a recreational fish, likely a result of their preference for deep waters (greater than 200 m) during daylight hours, beyond the reach of most recreational or sportfishers.
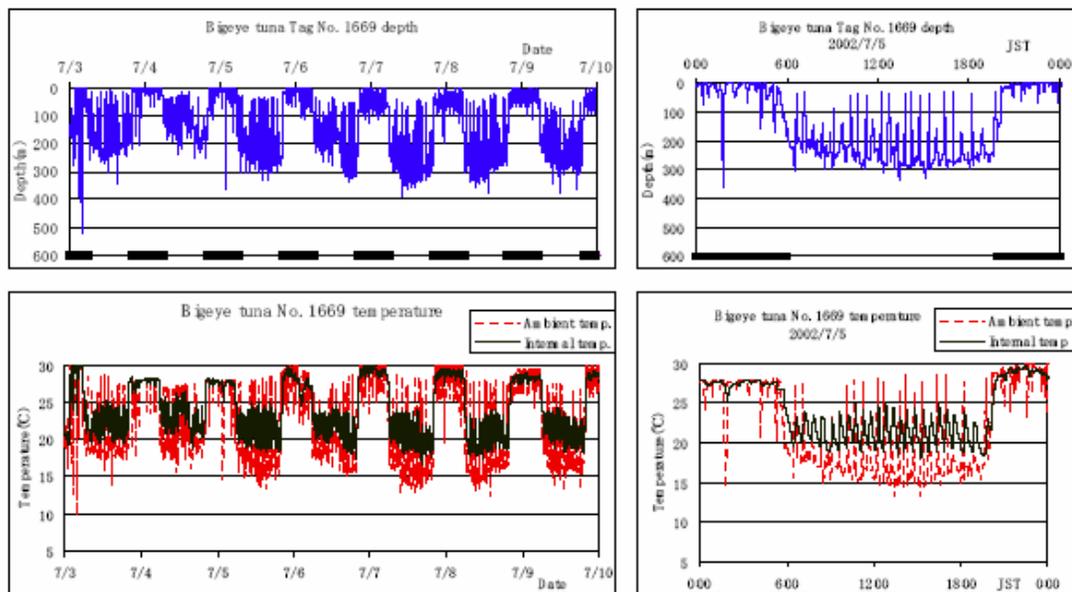
Fig. 9. Typical pattern for the movement (swimming depth) and ambient/internal temperature of bigeye tuna. Upper left: swimming depth for one week, upper right: daily pattern of swimming depth, lower left: ambient and external temperature for one week, lower right: daily pattern for ambient and external temperature. Solid bars mean nighttime. From Matsumoto et al. (2003).
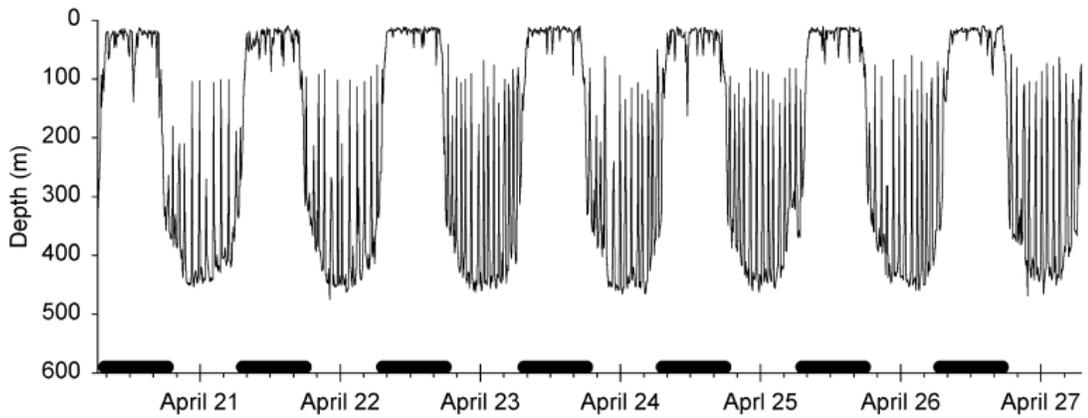
Figure 12. Six-day record of depths for a 131 cm FL bigeye tuna tagged around Hawaii. The black horizontal bars denote night-time periods. From Musly et al. (2003).
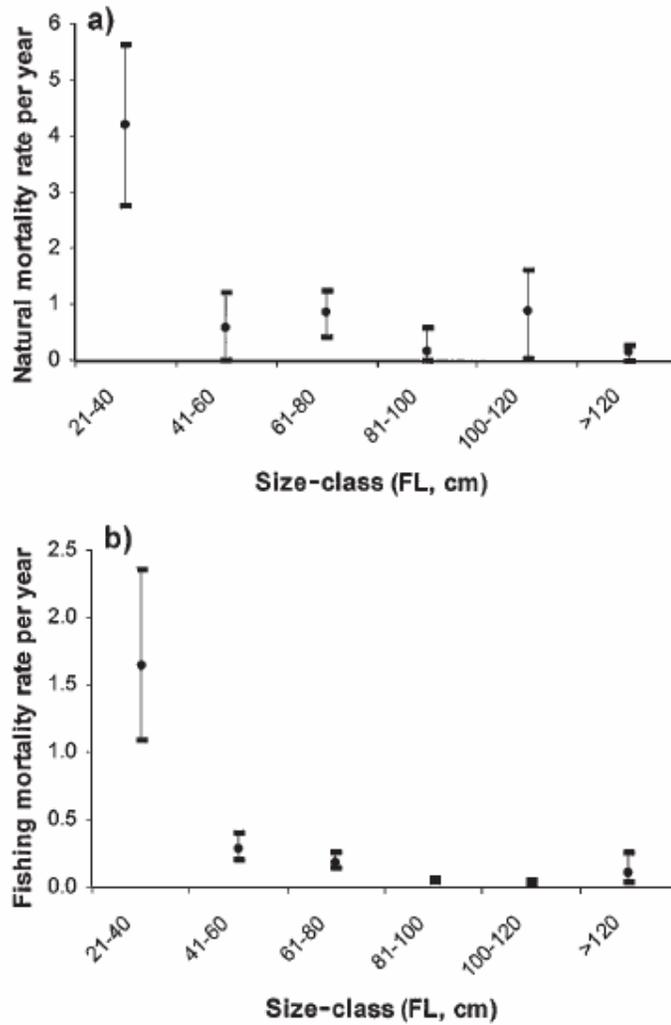
Figure 13. Estimates of annualised rates (year^{-1}) of natural mortality (upper figure) and fishing mortality (lower figure) of bigeye tuna in the WCPO. Source, Hampton (2000). Points represent median values and error bars bound the 2.5 and 97.5 percentiles of 1,000 bootstrap.
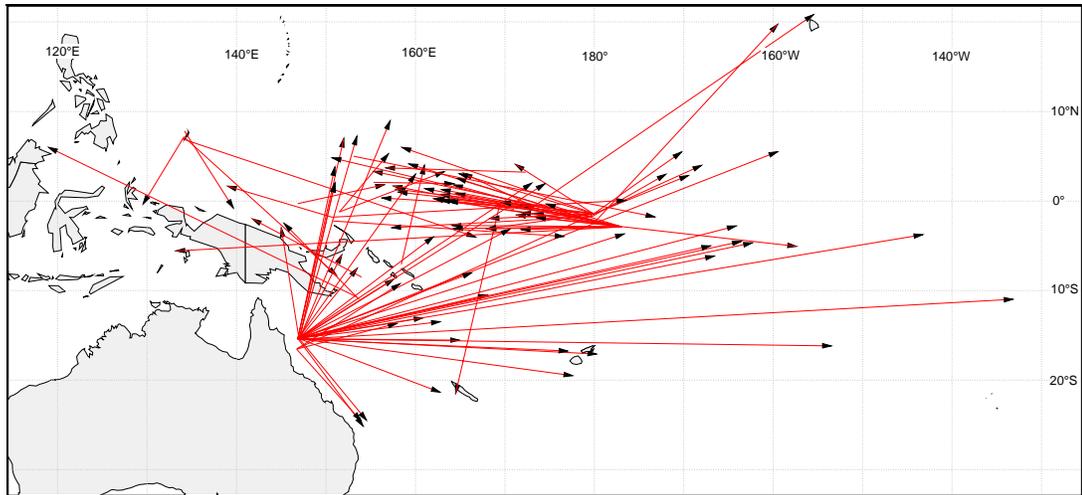
Figure 14. Long distance movement (greater than 500 nmi) of tagged bigeye in the Pacific Ocean. Source, Hampton et al. (2006).
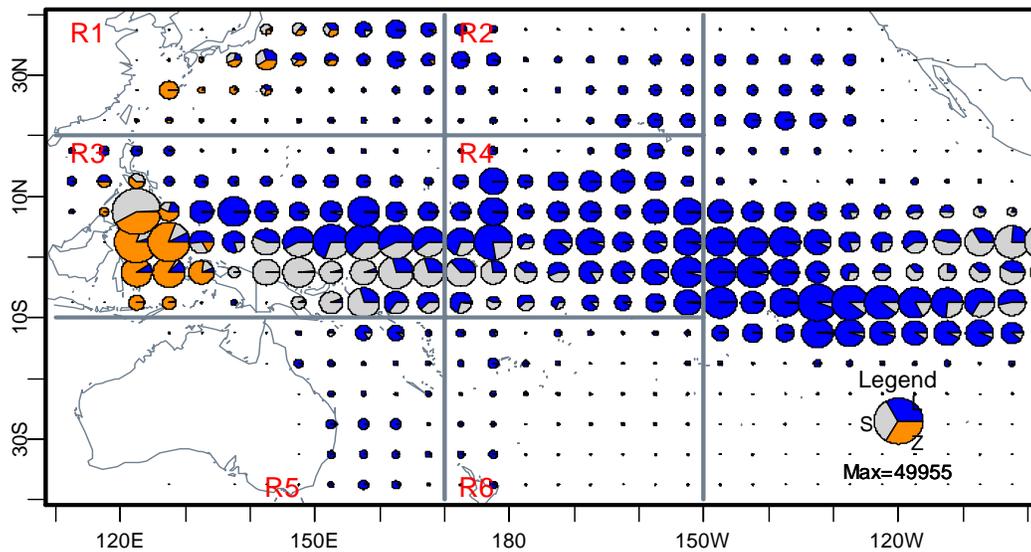
Figure 15. Distribution of total bigeye catches by main fishery methods, 1990–2004. Source, Hampton et al. (2006). The six-region spatial stratification used in the 2006 MULTIFAN-CL analysis is also shown. Fishery-method codes: blue (L), longline; grey (S), purse-seine; orange (Z), other (mainly the fisheries of Indonesia and the Philippines).
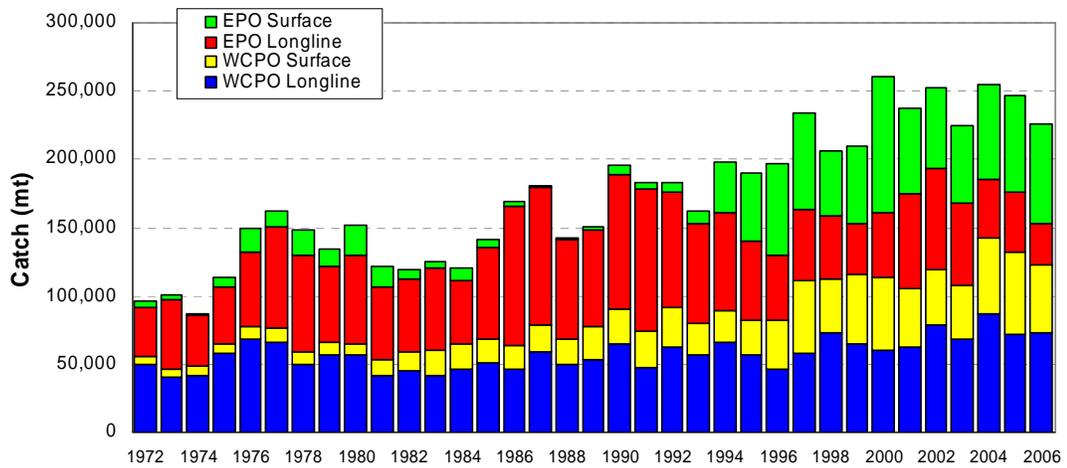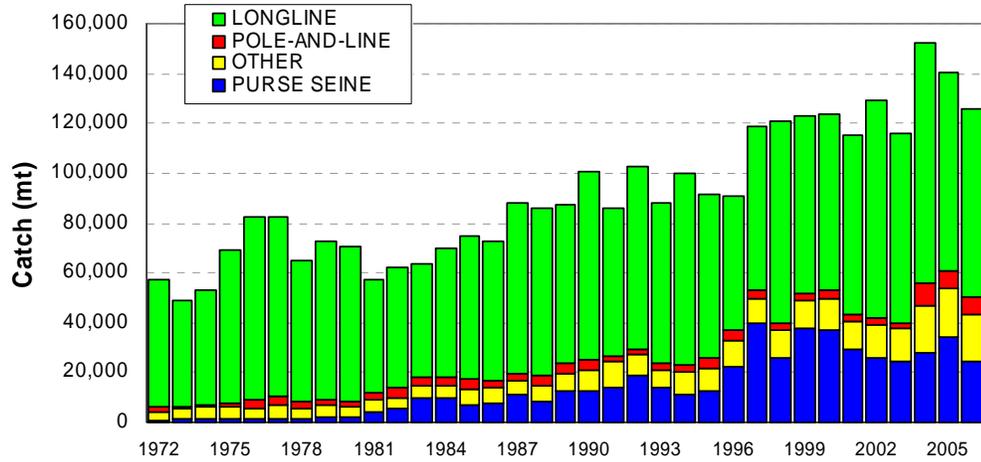
Figure 16. Annual catches of WCPO bigeye tuna (upper figure) and Pacific-wide catches of bigeye tuna (lower figure) by method-fishery, 1972–2006. Source, Williams and Reid (2007). Other includes all other method fisheries.
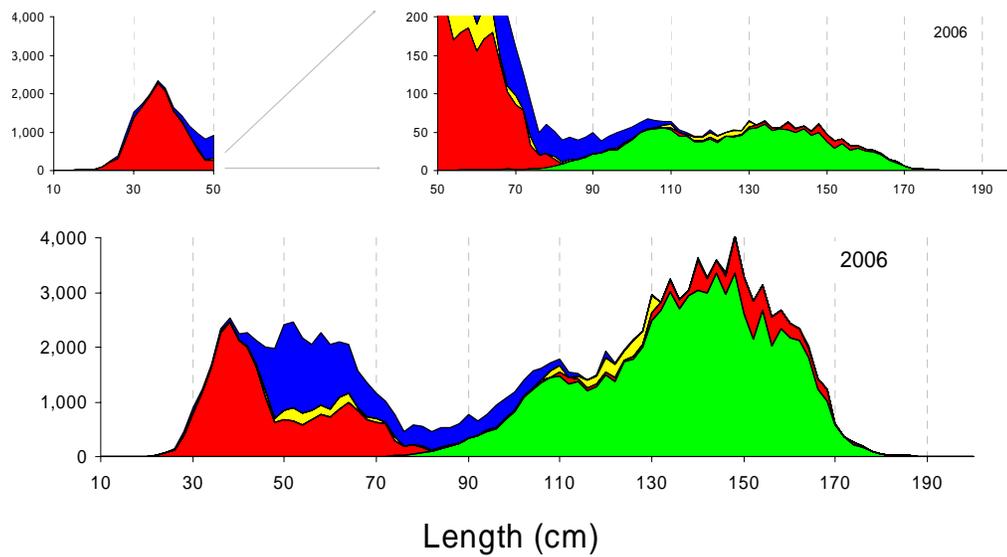
Figure 17. Annual catches of bigeye tuna in thousands of fish (upper figure) and metric tonnes (lower figure) in the WCPO by 2 cm length class and fishery method, 2006. Source, Williams and Reid (2007). Fishery codes: green, longline; blue, purse-seine fisheries on associated schools (logs, FADs etc); yellow, purse-seine on unassociated schools (free schools); red, fisheries of Indonesia and the Philippines.

5. Albacore (*Thunnus alalunga*)
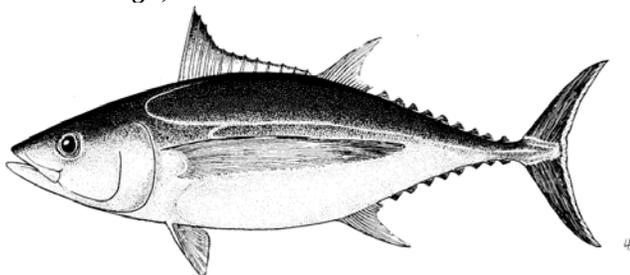
5.1 Description

Albacore are a large species of tuna that obtains more than 100 cm FL in size. Although colour and shape are similar to other species of tuna, albacore are distinguish by their very long pectoral fins, which may be longer than 50% of their body length. Adult albacore may be found in mixed schools with yellowfin and skipjack tuna. Small albacore have occasionally been reported in catches from the purse-seine fishery in the WCPO.

5.2 Distribution

Albacore are found in all tropical and temperate Oceans of the world (Collette and Nauen 1983) although they are rare in equatorial surface. Albacore distribution in the Pacific Ocean is quite different to that of skipjack, yellowfin and bigeye. Albacore show separate concentrations north (20°–45°N) and south (10°–40°S) of the equator. In the south, the albacore distribution is Pacific–wide, extending from eastern Australia to Chile (Griggs 2004) with higher concentrations away from the equator between 10°S–30°S (ECOTAP 1999). Juveniles are found in temperate waters, (e.g. south of 30ºS in the WCPO).

5.3 Biology

5.3.1 Age and growth

Age and growth of south Pacific albacore have been studied by counting increments on otoliths and vertebrae, modal progression of length–frequencies and analysis of tagging data. Absolute age estimates derived from otolith (Griggs 2004) and vertebral analysis (Labelle et al. 1993) have been validated (Leroy and Lehodey 2004). Growth data suggests that very high growth rates occur in young fish (up to 2.0 cm mo^{-1} for 45–49 cm fish) (Leroy and Lehodey 2004), with growth reducing in older fish (1.0 cm mo^{-1} for 60 cm fish) (Griggs 2004). Growth rates from the length–frequency (Labelle et al. 1993) and tag–recapture analyses (Bertignac et al. 1996) averaged 0.73 cm mo^{-1} and 0.64 cm mo^{-1}, respectively (Table 9). These values are approximately half the value obtained by otolith analysis but are consistent with the growth rates obtained by vertebral analysis. The longest period at liberty for a tagged albacore is over 7 years.

Variation in growth rates and size-at-age has been recorded among areas (Collette and Nauen 1983), with estimates of VBGF parameters varying between 0.190–0.258.year^{-1} for k and 94.7–119.2 cm for L∞ (Wu et al. 1997, Fournier et al. 1998). Langley and Hampton (2005) applied k=0.2.year^{-1} and L∞ = 100 cm FL for describing VBGF parameters in a recetn stock assessment for the south Pacific albacore stock. For the north Pacific albacore stock, a range of estimates of k (0.184–0.505.year^{-1}) and L∞ (94.5–125.0 cm FL) exist (IATTC 2002).

5.3.2 Reproduction

For the south Pacific stock, reproductively active albacore have been found in most waters of the south Pacific Ocean between 10°S and 30°S and 165°E and 115°W (ECOTAP 1999). Histological examination of albacore sampled from Tonga and New Caledonia suggest that albacore are annual spawners with most spawning limited to the austral summer months from November to February (Ramon and Bailey 1996). Albacore larvae have been reported to occur south of 10°S for all months between October and June, indicating that spawning may be protracted.

Gonadosomatic data indicate that female albacore in Tonga and New Caledonia reach maturity at about 80 cm FL (Griggs 2004), corresponding to an age of 4–5 years (Leroy and Lehodey 2004). Albacore approximately five years of age at 50% (Langely 2006). Similar to other scombrids, albacore may be serial spawners that spawn during extended periods. Estimated fecundity for north Pacific albacore ranges from 0.8–2.6 million eggs, assuming release of all advanced eggs occurs in a single spawning, although at least two batches of eggs were identified by Collette and Nauen (1983). However, there is a weak relationship between fish size and ovary size and therefore the number of eggs produced by a female (Collette and Nauen 1983).

Albacore have no external characteristics to distinguish gender. Sex ratio for immature albacore is usually 1:1, but males predominate in longline catches, similar to yellowfin and bigeye, suggesting differential growth or mortality between sexes (Collette and Nauen 1983). However, more recent studies have failed to detect significant differences in growth between males and females (Labelle et al. 1993). This suggests that females may suffer a higher mortality than males, possibly as a result of spawning or that sexually mature females are less vulnerable to longline gear.

5.3.3 Recruitment

In the south Pacific, albacore recruit to the troll fishery at approximately 50 cm FL (Figure 22), and two years of age (Griggs 2004). Recruitment to the longline fishery usually commences at 75 cm FL, with full recruitment at approximately 95 cm FL (Figure 22). Significantly, most fish that recruit to the longline fishery in the WCPO are above size of first maturity, making the stock relatively robust to exploitation.

Estimates of recruitment strength of south Pacific albacore have been generated within MULTIFAN-CL assessments (Fournier et al. 1998, Labelle and Hampton 2003, Langley and Hampton 2005). Recruitment estimates have show a high degree of variability since the early. Periods of weak recruitment coincide with *El Niño* conditions in the Pacific Ocean, with strong recruitment periods coinciding *La Niña* periods (Lehodey et al. 2003).

5.3.4 Mortality

Mortality rates have been estimated from analyses of albacore tag and recapture data (Bertignac et al. 1999) and from the MULTIFAN-CL stock assessments (Fournier et al. 1998, Labelle and Hampton 2003, Langley and Hampton 2005) (Figure 18).

In an analysis of tag and recapture data for the south pacific albacore stock, exploitation rates natural mortality was estimated at $0.47.\text{year}^{-1}$ (Bertignac et al. 1996). A lower estimate generated from the 2005 stock assessment ($0.343.\text{year}^{-1}$, Langley and Hampton 2005) although there is a high level of uncertainty about the estimate of natural mortality, due to uninformative size and tagging data (Langley and Hampton 2006). However, levels of fishing mortality are much lower than level of natural mortality for the south Pacific albacore stock.

Bertignac et al. (1999) estimated levels of natural mortality for the north Pacific albacore stock up to $0.608.\text{year}^{-1}$, assuming a tag return rate of 90%. However, estimates of natural mortality reduced rapidly with lower tag return rates. Nonetheless, estimates of fishing mortality rates (less than $0.1.\text{year}^{-1}$) on the north Pacific stock of albacore were much lower than estimates of natural mortality.

5.4 Ecology

5.4.1 Habitat preference

Adult albacore are common in sub-equatorial waters (10–30ºS), at depths of 100–300 m (ECOTAP 1999, Domokos et al. 2007). In the south Pacific, adult albacore are commonly caught in depths of 170–220 m off Chile, 100–220 m off Easter Island (Ichikawa and Shirasawa 1980) and 150–300 m in the area west of Fiji. Albacore do not appear to following the scattering layer and do not appear to vertically migrate. Adult albacore have a preference for temperatures between 15ºC and 21–25ºC, with an optimum of 18–19ºC, resulting in the vertical distribution becoming shallower at higher latitudes (Lu et al. 1998, Chen et al. 2005). However, spawning adults having a preference for higher water temperatures (24.9°C) than non-spawning adults (19.1°C) (Chen et al. 2005). This may result in spawning albacore having a shallower distribution.

Adult albacore are often associated with oceanographic features, particularly temperature and oxygen fronts (Collette and Nauen 1983) and eddies produced by current shear, for example between the south equatorial counter-current and the south-equatorial current (Domokos et al. 2007).

Albacore distribution is linked with the distribution of prey species, bathymetry and temperature fronts (Langley 2004a). The North Pacific Transition Zone (NPTZ), the Kuroshio Front east of Japan, and the Sub–Tropical Convergence Zone (STCZ) of the temperate south Pacific are examples of frontal zones where albacore are abundant. Albacore tend to occur within frontal zones rather than in the colder (<15ºC) poleward water (Sund et al. 1980). Troll fishermen operating near the continental shelf edge have found that albacore aggregate near bathymetric features, such as canyons. Albacore fishing and therefore albacore distribution has not been associated with FADs.

Larval albacore are restricted to waters warmer than 24°C, whereas juveniles (50–80 cm FL) are distributed in cooler water (16–20°C) in the temperate north and south Pacific (Murray 1994), where they support troll fisheries. Albacore larvae are rare to the east of 140°W, and there are separate northern (5°–25°N) and southern (5°–25°S) concentrations. Larval densities are highest in the respective summer months in each hemisphere (Nishikawa et al. 1985). Small albacore (less than 70 cm FL) are also rarely reported from the tropical purse-seine fishery in the WCPO, in mixed schools with skipjack and yellowfin tuna associated with floating objects (FADS, logs) (unpublished Observer data held at SPC). Research surveys

indicate that juvenile albacore are largely distributed in the upper 100–120 m and tend to stay deeper during daylight hours (Griggs 2004).

The minimum oxygen requirement of albacore is 2 ml O_2 l^{-1} (Collette and Nauen 1983) (Table 3), with higher abundances of albacore in water with dissolved oxygen levels greater than 3.0 ml.l^{-1} (ECOTAP 1999).

5.4.2 Movements and migration

The general migration pattern of south Pacific albacore is based on tag return data, seasonal patterns of fishing effort and parasite fauna studies (reviewed by Murray 1994). Albacore tagged from troll vessels in the SCTZ and along the coasts of New Zealand have shown extensive movements to the east, west and north. The average distance between release and recapture is 950 nautical miles; however, a large proportion of albacore tagged have moved less than 600 nautical miles. The largest movement was 3,813 nautical miles. No fish has been recovered to the south of 45°S.

Juvenile albacore move from the tropics to temperate waters at about 35 cm FL and then generally move eastward along the Sub-tropical Convergence Zone (STCZ). Based on the loss of tropical parasites with increasing fish size, larger juveniles (50–80 cm FL) do not appear to return to tropical waters north of 30°S. Mature albacore migrate between temperate areas and spawning grounds in tropical waters, resulting in a strong seasonality in catch rates sub-equatorial areas (Langley and Hampton 2005). This pattern is similar to the movement patterns of albacore of different life stages in the Indian Ocean (Chen et al. 2005).

Since the early 1980's, 17,226 albacore have been tagged in the south Pacific, with over half of these fish being tagged in a dedicated SPC programme during 1991–92. Most of the fish (76%) were released along the STCZ between 35° to 37°S and 130° to 170°W. Only 178 tags were been returned for an overall return rate of 1% (Bertignac et al. 1996). Albacore have been recovered by several gears, with the vast majorities of recoveries (~91%) being made by longline vessels.

Albacore tagged from troll vessels in the SCTZ and along the coasts of New Zealand have shown extensive movements to the east, west and north. The average distance between release and recapture is 950 nautical miles; however, a large proportion of albacore tagged have moved less than 600 nautical miles. The largest movement was 3,813 nautical miles. No fish has been recovered to the south of 45°S (Murray 1994).

Diel movement patterns have not been extensively studied in albacore tuna. Preliminary results suggest that adult albacore display a diel pattern of movement, rising to approximately 50 m during the night and descending to depths of greater than 150 m during the day, although a high level of variation was seen among individual fish (www.swfsc.nmfs.noaa.gov/frd/HMS/Large%20Pelagics/ Albacore/archival%20tagging/default.htm).

5.4.3 Diet

Albacore are described as opportunistic carnivores (Kailola et al. 1993) consuming a range of mickronecton (Domokos et al. 2007) including fish (mackerels and small tuna), crustaceans and cephalopods.

5.5   Details of stocks in the WCPO

5.5.1   Stock structure and size

It is generally accepted that two Pacific albacore stocks exist (northern and southern), with the equator being accepted as the boundary and a wide range of evidence support this hypothesis. Catch rates for albacore are extremely low in equatorial regions, with highest catches recorded between 10°S and 30°S (Langley and Hampton 2005, Molony 2007). Further, separate spawning areas have been identified at approximately 20° north and south of the equator, based on the distribution and abundance of albacore larvae in the Pacific (Nisjikawa et al. 1985). From approximately 40,000 albacore tagged in the south Pacific, only a single tag return has been reported in the northern hemisphere from fish tagged in the southern hemisphere (Labelle and Hampton 2003). No recaptures of fish tagged in the northern hemisphere have been reported from the southern hemisphere.

Recent results using mitochondrial DNA support the separation of Pacific albacore into northern and southern stocks (Takagi et al. 2001), while Arrizabalaga et al. (2004) agree with the separation of the Pacific albacore into two stocks although only used samples from the southern hemisphere. There is the potential for sub-stocks in the southern hemisphere albacore based on external parasites of albacore (Jones 1991) although tagging studies do not support his separation (Murray 1994).

Separate assessments are undertaken on the northern and southern stocks. The stock assessments undertaken to date suggest that the northern stock is more productive than the southern stock (IATTC 2002) although current assessments for both are uncertain. Albacore catches from the northern Pacific have been much greater than from the south Pacific until 2004 (OFP 2007).

5.5.3   Recent stock assessments and status

Stock assessments for south-Pacific albacore have indicated that the stock is the least commercially exploited of the four major tuna species in the WCPO. While the effects of fishing have increased over the past few decades, the impact of fishing on south Pacific albacore is currently less than 5% (Langley and Hampton 2005, 2006). Further, the longline fishery targets adult albacore above the size of first maturity, the risk of over-exploitation of the stock is low. Similarly, the north Pacific stock is not overfished (IATTC 2002).

5.6   Fisheries

5.6.1   Major fisheries and occurrence

The longline method fishery captures the majority of albacore in the south Pacific Ocean, accounting for approximately 80% of all albacore catches (OFP 2007). Most albacore captured by the longline fishery are greater than 90 cm FL and are taken in sub-equatorial areas (10–30ºS). The troll fishery operates south of approximately 30°S and account for approximately 10% of south Pacific albacore (OFP 2007). Most albacore captured by the troll

fishery are generally juveniles and most fish are between 50 cm FL and 80 cm FL (Figure 22). Albacore are also captured by other method fisheries including purse-seine and pole-and-line but in insignificant amounts (OFP 2007).

In the north Pacific, troll, longline and pole-and-line method-fisheries tend to capture similar quantities of albacore (OFP 2007).

5.6.2 Artisanal fishery value

Albacore have not been reported from artisanal fisheries in the WCPO, likely a result of their depth preferences (greater than 100 m).

5.6.3 Sport and recreational fishery value

In more temperate latitudes around southern Australia and New Zealand, albacore are considered a recreational species (Kailola et al. 1993), although they are not a recognised sportfish species in most of the WCPO (Whitelaw 2001). Recreational captures albacore are typically juvenile fish (40–60 cm FL) that are captured during shallow trolling. More than 3,600 recreationally captured albacore have been tagged and released in NSW since 1973 (Kailoloa et al. 1993). Adult albacore contribute a small proportion of the sportfishing catches in some sub-equatorial countries in the WCPO (e.g. Vanuatu, pers. obs.).
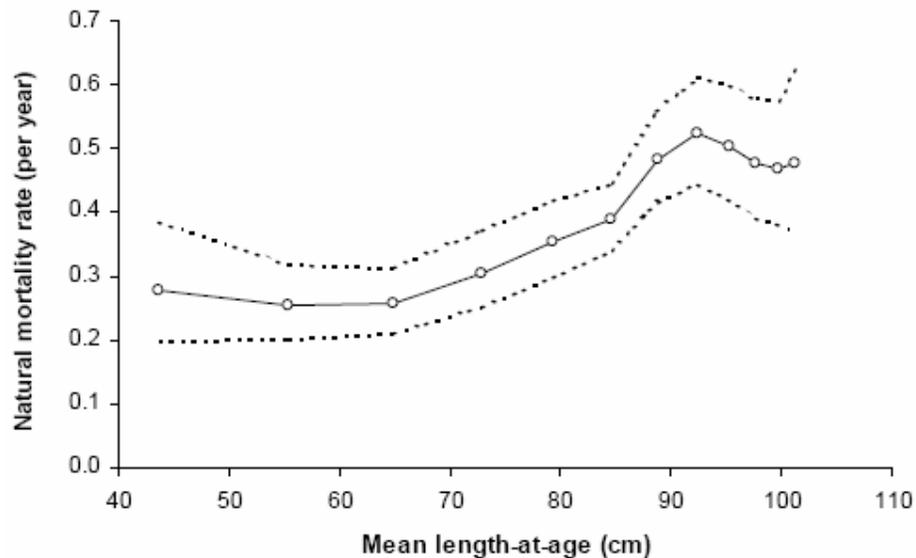
Figure 18. Mean natural mortality rate at age of south Pacific albacore tuna, with 95% confidence intervals, scaled to the average of the point estimates. From Labelle and Hampton (2003).

Table 9. Comparison of estimated fork length (cm) at 1–year intervals for albacore tuna in the south Pacific. [a] Labelle et al. 1993, [b] Bertignac et al. 1996

Age (years)	Vertebrae[a]	Length– frequency[a]	Tagging[b]
1	39	21	28
2	49	37	48
3	58	50	63
4	66	60	73
5	73	68	80
6	79	74	85
7	84	79	89
8	89	83	92
9	93	86	93
10	97	88	95
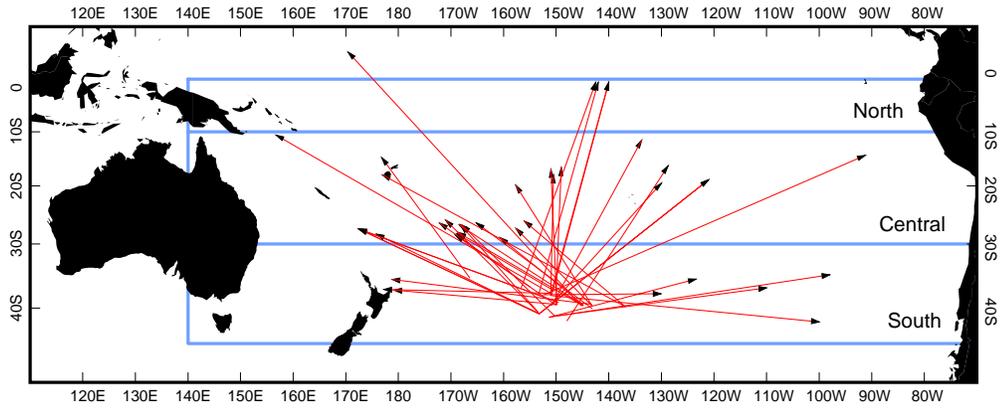
Figure 19. Movement of tagged south Pacific albacore. Source, Labelle and Hampton (2003), in Langley and Hampton (2005).
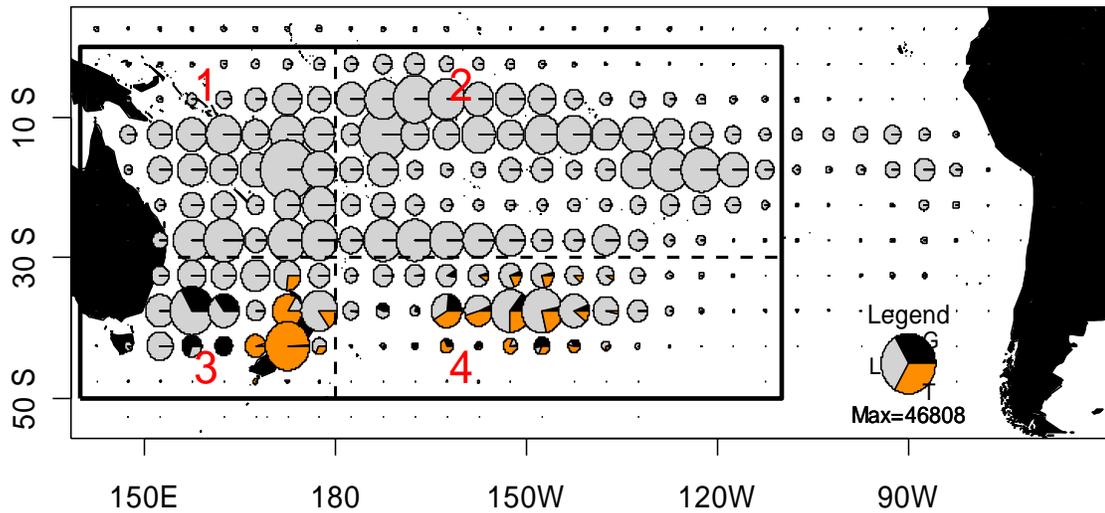
Figure 20. Distribution of south Pacific albacore catches by main fishery methods, 1960–2003. Source, Langley and Hampton (2005). The spatial extent of the 2005 stock assessment is defined by the solid black line, with the sub-regions defined by dotted lines. Fishery-method codes: grey (L), longline; orange (T), troll; black (G), driftnet. The driftnet fishery ceased operating in the early 1990s due to an United Nations moratorium on industrial scale driftnet fishing.

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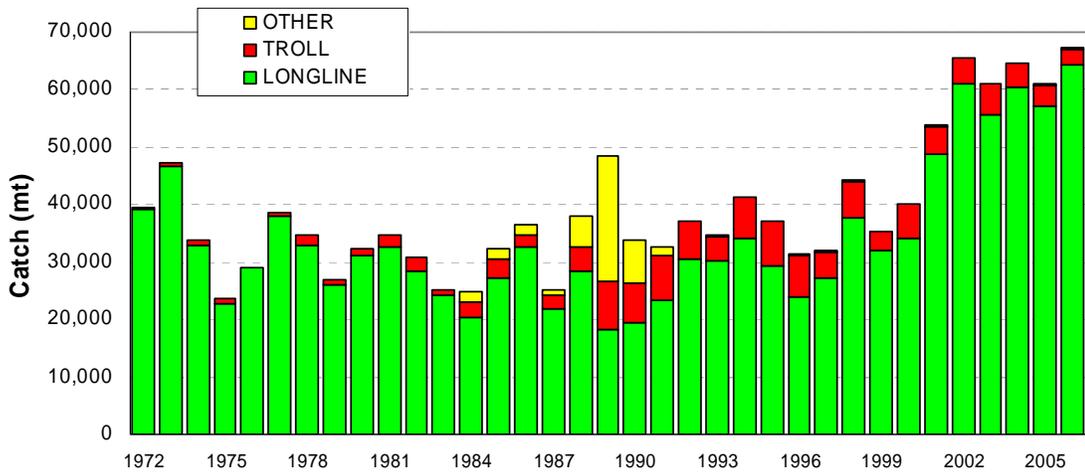
Figure 21. Annual catches of south Pacific albacore tuna by method-fishery, 1972–2006. Source, Williams and Reid (2007). Other includes all other method fisheries.
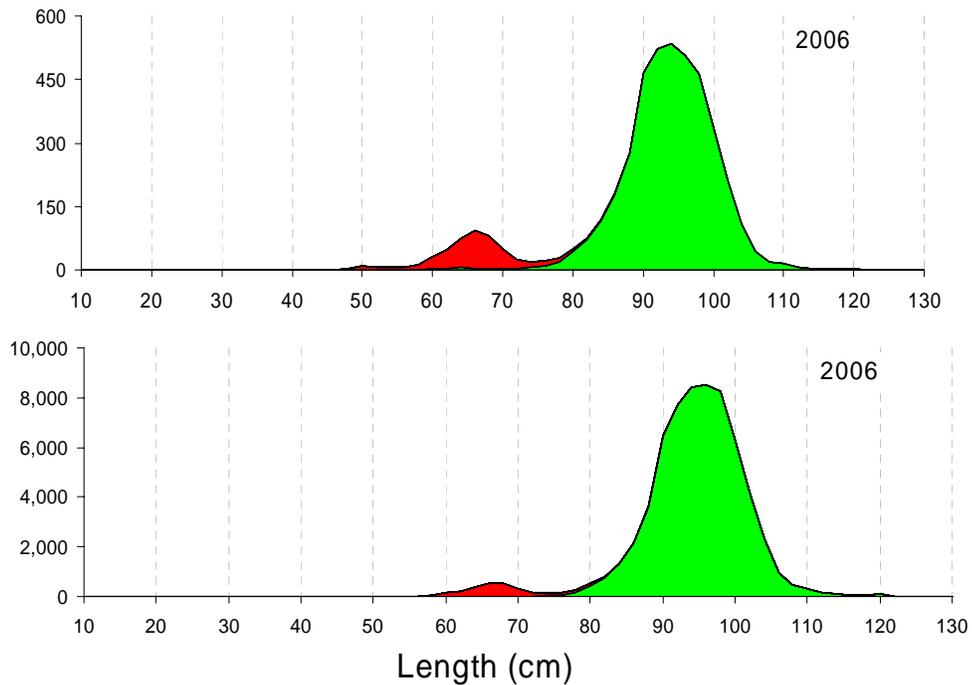
Length (cm)

Figure 22. Catches of albacore tuna in thousands of fish (upper figure) and metric tonnes (lower figure) in the south Pacific Ocean by 2 cm length class and fishery method, 2006. Source, Williams and Reid (2007). Fishery codes: green, longline; red, troll.

6.   Blue marlin (*Makaira mazara*)
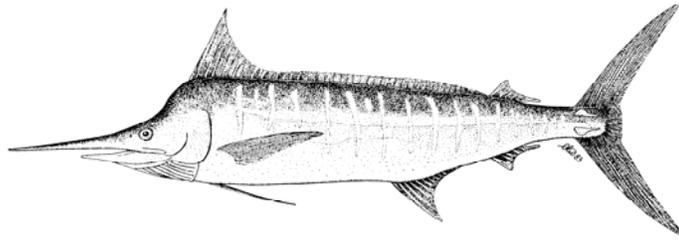
6.1 Description

Blue marlin are a large surface species of tropical waters, reaching up to 500 cm in TL^2 and 906 kg in (www.fishbase.org) although most blue marlin encountered in the Pacific Ocean are much smaller. The body of blue marlin is black-blue on the dorsal side and sliver-white on the ventral side. The body is vertically striped with 15 (Kailola et al. 1993) to 25 (www.fishbase.org) light blue lines, each unusually consisting of round dots. The bill is long and almost round in cross-section.

Blue marlin are distinguished from other marlin (black marlin and striped marlin) as their pectoral fins can be laid flat along the body and the second (small) dorsal fin starts slightly posterior to the second anal fin (unlike black marlin). The body is deepest at the start of the first dorsal fin (unlike striped marlin). Blue marlin have two large lateral keels at the base of the caudal fin. Small blue marlin (less than 100 kg) may be confused with similarly sized striped marlin (Holdsworth and Saul 2003).

6.2 Distribution

Blue marlin (*Makaira mazara*) are the dominant billfish species of the central tropical Pacific (Whitelaw 2001). Blue marlin are found principally in tropical and sub–tropical waters of the Pacific and Indian Oceans between 45°N–35°S in the western Pacific Ocean and 35°N–25°S in the eastern Pacific Ocean (Nakamura 1985). The range of blue marlin is consistent with the 24°C isotherm of the Pacific ocean (Nakamura 1985) although blue marlin have been captured in surface waters with temperatures as low as 21°C (Kailola et al 1993).

Blue marlin are rarely found in coastal waters or near islands preferring oceanic areas over deep water. However, blue marlin have been recorded near coasts and islands in areas associated with drop-offs (greater than 100 m). Blue marlin are a surface species with fish spending most of their time within 40 m of the surface, as highlighted by increasing catch rates in shallow longline sets (fewer than 10 HBF, Figure 28).

6.3 Biology

6.3.1   Age and growth

Due to the difficulties in ageing billfish limited research has been carried out on the age structure of blue marlin. Males and females can exceed 21 years of age (Hill et al. 1989), and

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^{2} The length of billfishes is typically measured from the lower jaw to the caudal fork (LJFL) and rarely in total (TL) length as the bill may be damaged during fishing activities.

recent stock assessment model have included 22 age classes, with the last age-class including fish greater than 21 years (Kleiber et al. 2003). However, the limited studies on age and growth of blue marlin reveal high levels of variation in size at age (Table 4).

Growth is similar between the sexes until approximately 140 cm LJFL at about 2–4 years of age (Table 4). The growth rate of males declines after this point. From a study in Hawaii, Hill et al. (1989) indicated that males reached approximately 200 cm LJFL by six years of age and do not grow significantly larger. In contrast, females maintain high growth rates until at least 360 cm LJFL. Hill et al. (1989) did not find data to suggest that growth reduced in larger female blue marlin. As a consequence, while females can obtain large sizes, up to 450 cm LJFL and over 900 kg, males rarely exceed 200 cm LJFL and 170 kg. Wilson et al. (1991) concluded that sex–related size differences were due to differential growth between sexes and not a result of differential mortality, with longevity similar between sexes. As growth data are rare, stock assessment models have not attempted to factor in sex– specific growth data at this stage (Kleiber et al. 2003). Kleiber et al. (2003) assumed a fixed growth rate (k) of 0.2.year^{-1} and an L∞ of approximately 260 cm EFL (approximately 295 cm LJFL) for Pacific-wide blue marlin.

6.3.2   Reproduction

From a limited sample size, it appears that blue marlin are serial spawners and very fecund (nearly 100 million eggs from a 420 kg female) (Hopper 1990 in Kailola et al. 1993). Spawning is believed to occur year–around in equatorial waters (10°S–10°N) and during summer periods in the southern (10°S–30°S) and northern (20°N–30°N) hemispheres (Kailola et al. 1993; Whitelaw 2001). However, there may be a peak spawning period during warmer months, especially in sub-equatorial areas.

There is considerable variation in size at first reproduction. Females reach maturity at approximately 80 kg (206 cm LJFL) and males at 31 kg (145 cm LJFL), though females in the eastern Pacific may mature at 47 kg (169 cm LJFL[3]) and males at 35 kg (152 cm LJFL). Nakamura (1985) only provides information for size at first reproduction for males of 130–140 cm EFL (approximately 156–165 cm LJFL), corresponding to an estimated age of less than 5 years (based on estimates of Hill et al. (1989)).

Blue marlin larvae have been recorded occur over a broad area of the tropical and sub-tropical WCPO (Nakamura 1985) as well as from the Coral Sea (Leis et al 1987 in Kailola et al. 1993). No blue marlin larvae have been reported from the eastern Pacific Ocean (Whitelaw 2001), suggesting that blue marlin recruit to the EPO from the WCPO. Williams (unpl.) reports that post–larval blue marlin (10–50 cm) have been collected in Micronesia and south of Fiji, as well as east of New Caledonia. Juveniles of approximately 15–20 kg have been caught in the North Equatorial Current waters of Micronesia and around the Tuamoto Islands in French Polynesia.

6.3.3   Recruitment

From observer data in the WCPO, blue marlin commerce recruiting to longline fisheries at less than 100 cm FL, becoming fully recruited by approximately 170 cm LJFL (Figure 23).

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[3] The length-weight relationship for blue marlin is, weight (kg) = 0.00004221 x LJFL$^{2.713587}$ (length-weight relationship used at OFP).

Fewer blue marlin are reported from purse-seine fisheries, although individuals as small as 25 cm LJFL have been recorded (Figure 23), corresponding to an age of approximately 40 days.

6.3.4   Mortality

There are few estimates of mortality for this species. Kleiber et al. (2003) estimated the natural mortality of blue marlin in the Pacific at $0.38.\text{year}^{-1}$ (range, 0.30–$0.45.\text{year}^{-1}$). Kleiber et al. (2003) estimated that fishing mortality increased between the 1950s and 1960s and remained at relatively high levels until the early 1990s, when fishing mortality rapidly reduced. The decline may be due to a shift in the number of hooks per basket (HBF) by many longline fleets, increasing the depth of many longline hooks beyond the preferred depth of blue marlin (less than 125 m) and reducing catch rates (Figure 28).

6.4   Ecology

6.4.1   Habitat preference

Most information on the habitat preference of blue marlin comes from logsheet and observer data for commercial fisheries, especially longline fisheries. Catch rates increase as the number of hooks between floats declines below approximately 10 HBF (Figure 32), confirming the shallow distribution of blue marlin. Five blue marlin tagged with archival tags off Hawaii in the early 1970s showed that fish preferred swimming over deeper waters (183–1830 m) although fish remained in the top 73 m of the water column at all times (Nakamura 1985). This is supported by sportfishing catches as sportfishes typically use shallow surface gears and blue marlin are a major sportfish species in the WCPO (Whitelaw 2001). Observers have reported the highest numbers of blue marlin between 20ºN and 20ºS in the WCPO (Figure 25, Figure 26), with higher catch rates in the western equatorial Pacific (Figure 27).

Most blue marlin reported by purse-seine fisheries in the WCPO are from associated sets (logs, FADs).

6.4.2   Movements and migration

Blue marlin can travel long distances and may have established, seasonal migratory patterns, which can include trans–oceanic and trans–equatorial crossings which are currently undefined. One of the difficulties in defining movement and migration pathways of large pelagic, highly mobile species is that tag return rates are typically low. For example, Holts and Prescott (1997) recorded only 38 recaptures from 4,410 blue marlin releases (a recovery rate of 0.86%) during an 32 year period. Most blue marlin were recaptured within a short time period and close to location of release, though there have been some fish recovered up to 3,000 nmi away (Figure 55). Two blue marlin tagged off Baja California, Mexico travelled westward, one to Oahu, Hawaii (2,929 nm) in 427 days and the other to the Isles du Marquesis, (French Polynesia) (2,228 nm) in 484 days (Holts and Prescott 1997). An additional blue marlin travelled south from Kailua–Kona, Hawaii to the Marquesas Islands (2,357 nm) within 102 days. The longest time at liberty for a blue marlin has been 1,503 days.

The New South Wales (Australia) Fisheries Research Institute (NSWFRI), has had a recreational tagging program for many years and over 1,000 blue marlin had been tagged and released in NSW waters up to 1995. Up until 1995 there was only been a single recovery. However, this fish was recorded by a longline vessel approximately 300 nmi to the south of

Sri Lanka, indicating that the individual fish travelled a minimum (straight line) distance of 5,520 nm. Thus, blue marlin are capable of long-distance movement.

Recent tagging studies carried out by the Southwest Fisheries Science Centre (Holts and Prescott 1997) on blue marlin, similar to many tuna and billfish species, tend to indicate an annual cyclic movement of fish back to the site where they were initially tagged, though this depends on the size and maturity of the fish.

6.4.3 Diet

Analysis of gut contents indicates that blue marlin rely heavily on nektonic fishes and cephalopods, although benthic fishes have also been found (www.fishbase.org). Tunas (skipjack, yellowfin and bigeye tunas) made up over 85% of the diet of blue marlin from Hawaiian waters with the guts of a single blue marlin containing a 29 kg bigeye tuna (Nakamura 1985). Blue marlin are also reported to consume swordfish (*Xiphias gladius*) and fishes the families Bramidae and Carangidae (trevallys) (Nakamura 1985). Benthic, deep sea fishes (such as Holocentridae, squirrel fishes) have also been recorded in the guts of blue marlin indicating that feeding in deeper waters also occurs (Nakamura 1985).

6.5 Details of stocks in the WCPO

6.5.1 Stock structure and size

It is assumed that the blue marlin from a single stock in the Pacific Ocean (Nakamura 1985, Kailola et al. 1993, Hinton 2001, Kleiber et al. 2003). The limited number of recaptures from tagging studies, and the recording of long-distance movements support the hypothesis that a single stock of blue marlin exists in the Pacific Ocean.

Tagging studies also suggest that there is some mixing of stocks among oceans. While the Atlantic blue marlin are considered a separate species, differences between the Atlantic and Pacific blue marlin are minor (Nakamura 1985, Kailola et al. 1993) and some authors make no distinction between the two species (e.g. Hill et al. 1989; Kleiber et al. 2003). However, the vast distances and land masses separating the Indian, Atlantic and Pacific Oceans suggest that levels of mixing are likely to be low.

From catch estimates, the stock size of blue marlin is smaller than the stock sizes of the main species of tuna but larger than other billfish species. The stock assessment by Kleiber et al. (2003) estimated a total biomass of 40,000–50,000 mt in the Pacific Ocean and had been relatively stable within this range since the mid 1970s.

6.5.2 Recent stock assessments and status

Due to the limited data on biology, ecology and catches of blue marlin in the Pacific Ocean, many early stock assessments produced conflicting reports, partially due to uncertainty in some parameters of the various models (e.g. size at age, catchability). Conclusions on the status of Pacific blue marlin stocks ranged from the stock being overfished to the stock was at maximum sustainable yield (IATTC 2004). Kleiber et al. (2003), using MULTIFAN-CL, concluded that the most pessimistic status of Pacific blue marlin is that the stock is close to being fully-exploited.

Analysis of standardised catch rate data (Figure 28) suggests that catch rates in the longline fishery have decline since the early 1990s, stylising at relatively low levels since the early 2000s. However, there has also been a shift to deeper longline sets (greater than 10 HBF) where the catch rates are predicted to be lower.

Size data indicates that the median size of blue marlin in the longline fisheries fluctuated above the size at first maturity until the early 2000s (Figure 23). Median size of blue marlin then reduced before increasing again in late 2005. Median sizes of blue marlin have been relatively stable from most areas of the WCPO since the early to mid 1990s (Figure 26). Catch rate data from the longline fisheries have shown fluctuations and recent declines (Figure 27), although the declines may be a result of recent shifts in regretting deeper species (e.g. bigeye tuna).

6.6 Fisheries

6.6.1 Major fisheries and occurrence

The longline fishery in the WCPO accounts for a majority of blue marlin captured by industrialised fisheries in the WCPFC (Figure 24) and EPO (IATTC 2004). Blue marlin catches in the WCPFC have generally increased since the mid 1970s, with catches exceeding 20,000 mt per year since 2002.

The purse-seine fishery also records catches of blue marlin in the WCPO at much lower levels than the longline fishery (Molony 2005b). Although catches of blue marlin increased with the expansion of the purse-seine fleet since 1970, annual catches of blue marlin in the WCPO purse-seine fishery since 1990 have fluctuated between 200 mt and 300 mt per year. More than 92% of purse-seine sets in which blue marlin are reported are associated sets (logs, FADs, animals) (unpublished Observer Data).

6.6.2 Artisanal fishery value

Blue marlin may contribute to artisanal catches in areas of the WCPO where deep waters are found adjacent to coasts and islands (e.g. Guam, Dalzell et al. 1996), including by longline, troll and harpoon method fisheries (Kleiber et al. 2003). However, blue marlin are likely to represent a small proportion of total artisanal catches in the WCPO.

6.6.3 Sport and recreational fishery value

Blue marlin are arguably the highest profile sportfish species in the WCPO, due to their large size and sport qualities. Blue marlin are likely to support sportfisheries in many Pacific Island Countries (e.g. Marshall Islands, Tonga, Vanuatu, pers. obs.) and competitions and the economic value of this species for sportfishing tourism are likely to be very high in the WCPO (Whitelaw 2001).

Table 4. Estimated size–at-age of blue marlin from the Pacific Ocean. All lengths as LJFL in cm.

A). Estimated size–at-age from Hill et al. (1989).

Male			Female		
Age	Length (cm)	Weight (kg)	Age	Length (cm)	Weight (kg)
2	70	2	2	70	2
5	170	39	5	155	30
10	205	70	10	240	124
15	210	75	15	260	161
18	213	79			
			20	310	286
			25	345	406

B). Estimated weight–at-age from Radtke (1982, in Nakamura 1985).

Males		Females	
Age	Weight (kg)	Age	Weight (kg)
6	52.1	8	135.4–147.4
7–8	68.3–71.2	13–15	209.2–228.8
9	82	16	286.3
11–12	96.9–114.2	17	336.5
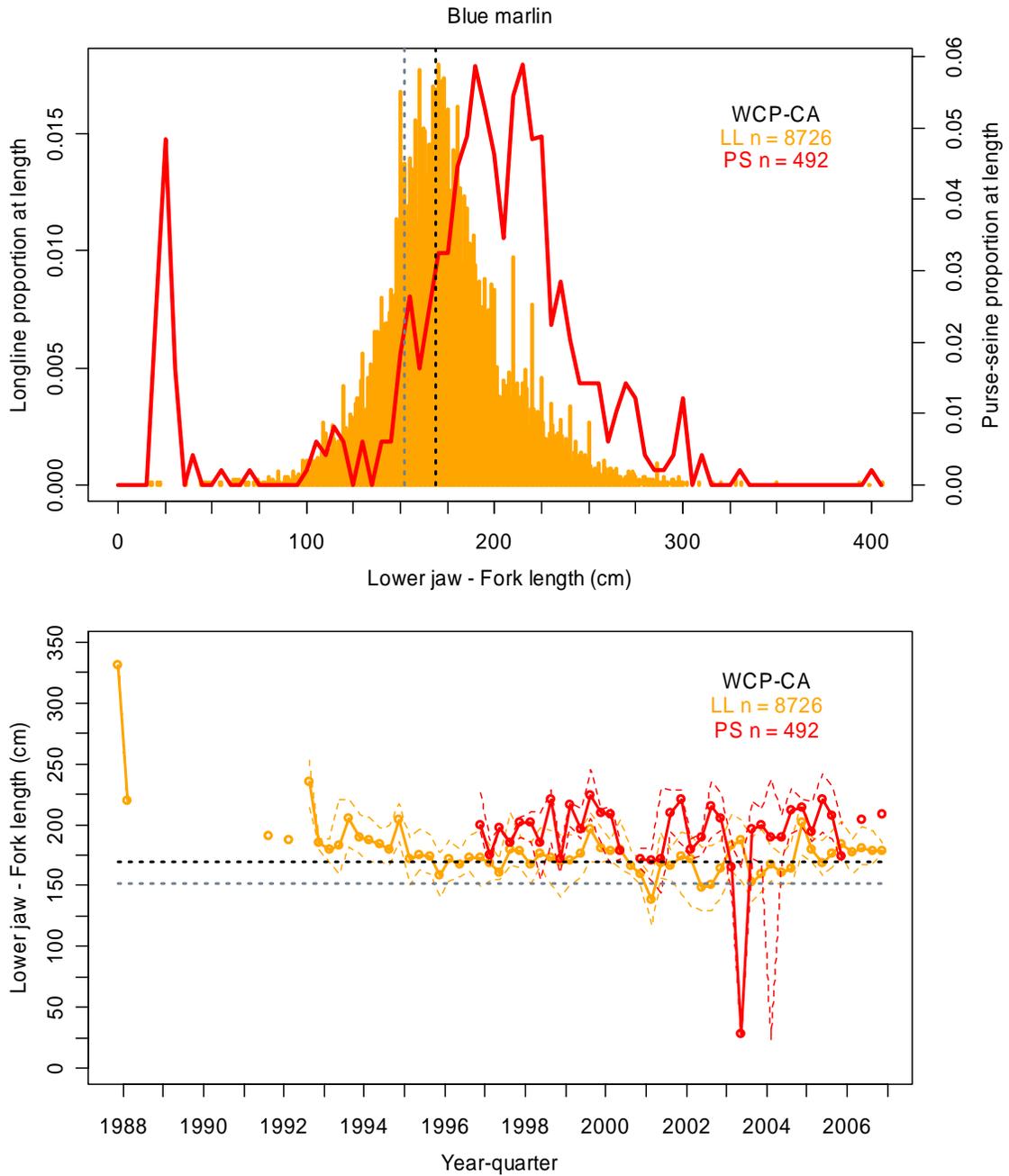
Figure 23. Combined length-frequency distributions (upper figure) and trends in quarterly median size (lower figure) of blue marlin reported by observers in longline and purse-seine vessels in the WCPO, 1984–2006. Source, SPC observer 5 x 5 data base. n, represents the total number of individuals from each method-fishery. Thin dashed lines represent the 25th and 75th quartiles of the size data. Heavy dashed lines represent lowess fits to the median size data. Dotted lines represent estimates of size at first maturity for females (black, 169 cm LJFL) and males (grey, 152 cm LJFL). In the upper figure, 1 cm and 5 cm size class bins were used for fish from the longline fishery and purse-seine fishery, respectively.
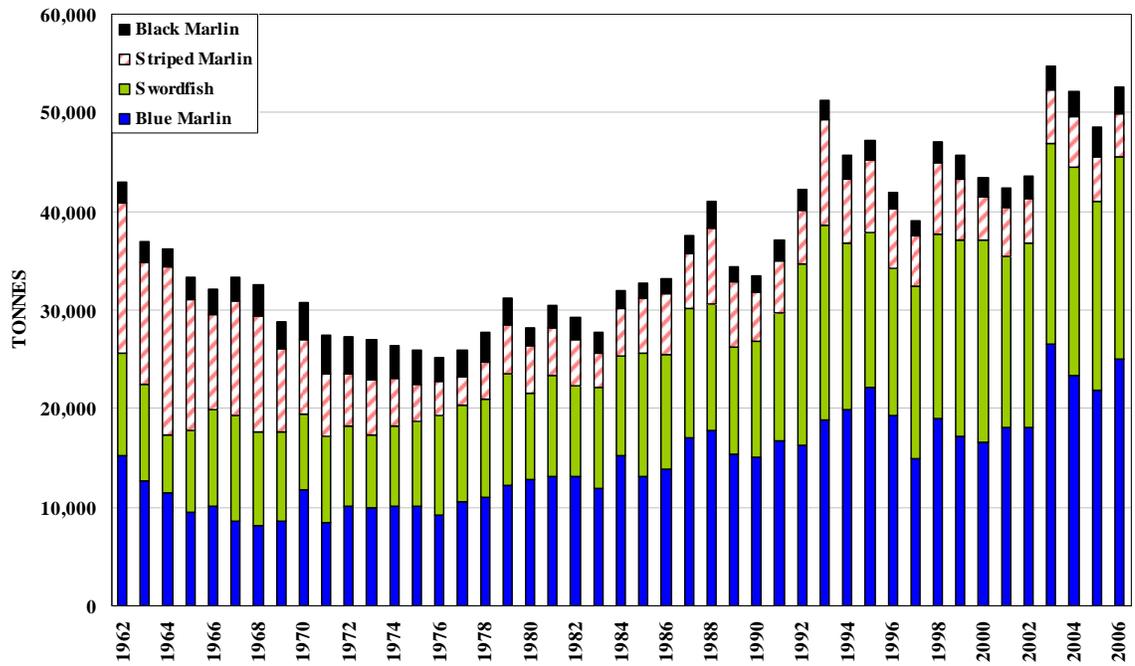
Figure 24. Annual commercial catches of major billfish species from the WCPFC Convention area , 1962–2006. Source (OFP 2007).
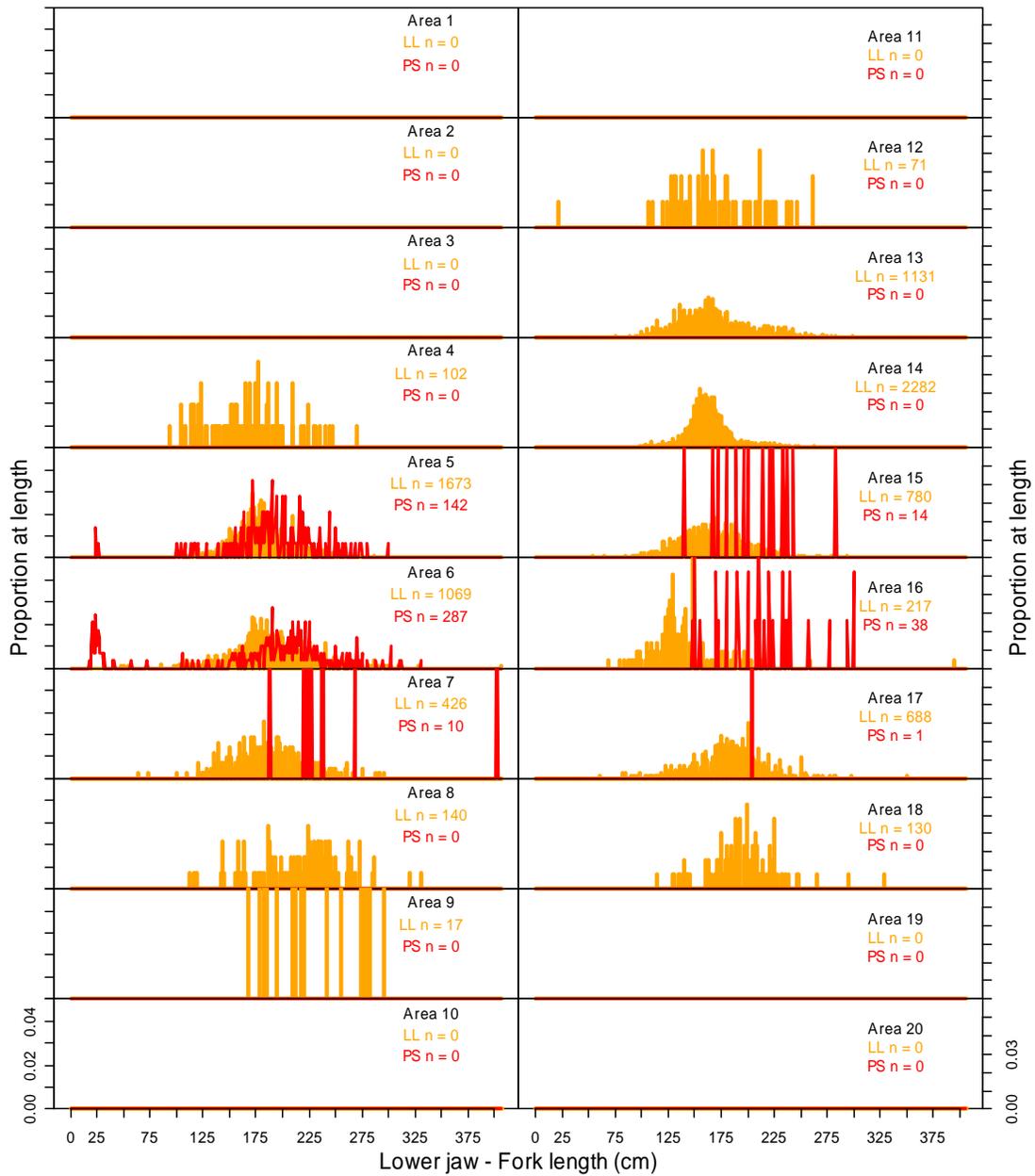
Figure 25. Length-frequency distributions of blue marlin pooled into 10º latitude bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as lower-jaw to fork-lengths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively.
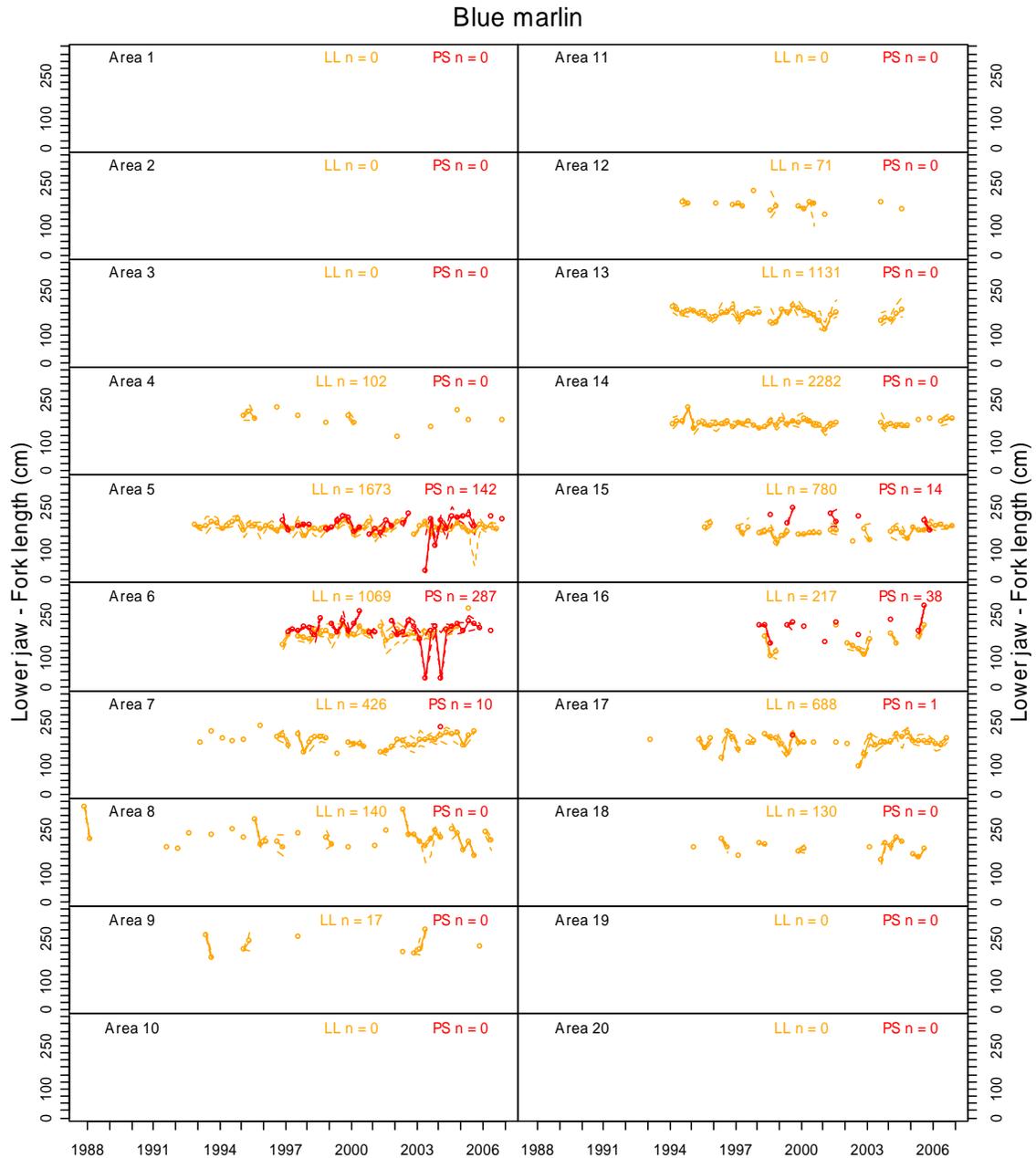
Figure 26. Trends in median size of blue marlin pooled into 10º latitudinal bands (Areas) in the WCPO, 1987–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as lower-jaw to fork-lengths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively. Points represent median size, dotted lines represent 25th and 75th quartiles.
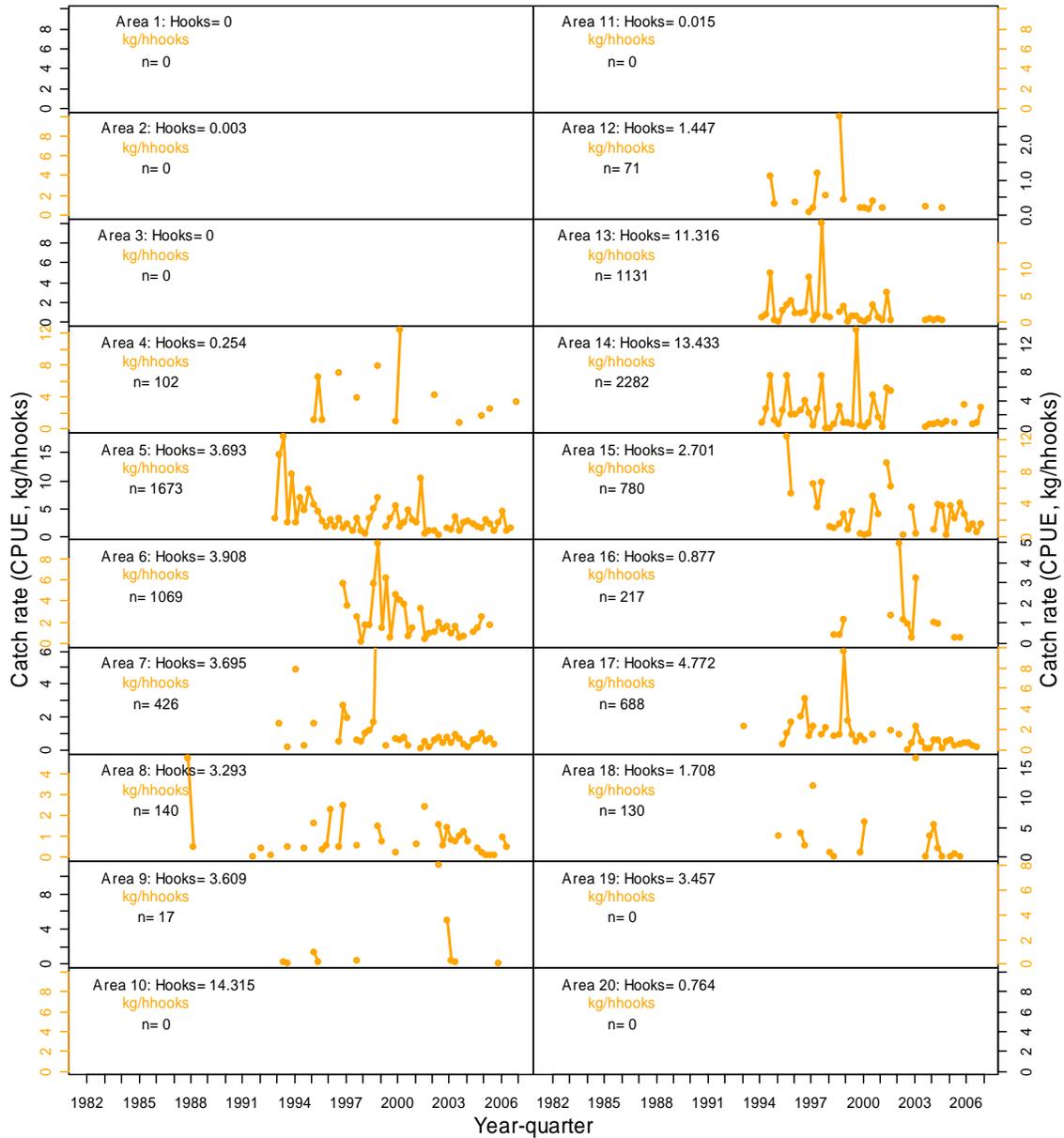
**Figure 27. Quarterly catch rates (kg.hhooks^{-1}) of blue marlin reported by observers pooled into 10°
latitudinal bands (Areas) in the WCPO, 1982–2006. Source, SPC observer data base. Hooks, is the total
number of observed hooks (millions) in each Area; n, represents the total number of individuals from
each method-fishery within each Area. Scales of the y-axes vary among Areas. Left-hand figures are west
of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–
10ºS of the equator, respectively. Length-weight relationship: whole weight (kg) = (0.00004221 x
LJFL$^{2.7134}$) (OFP database).**
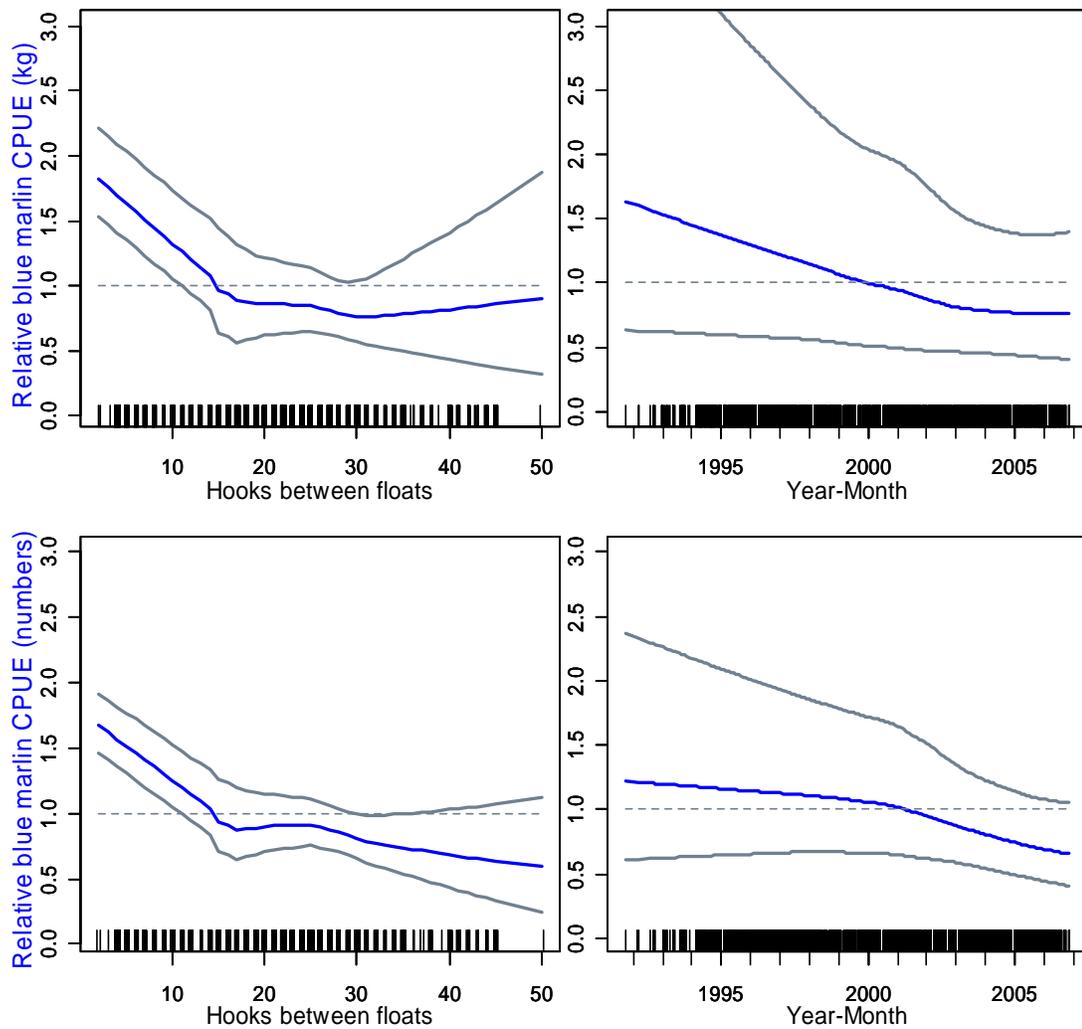
Figure 28. Changes in relative monthly blue marlin longline catch rates (blue lines; upper figure, number/hhooks; lower figure, kg/hhooks) for the WCPO under the influence of longitude, latitude, hooks between floats and time period (year-month) as predicted by GLMs, 1991–2006. Sources, observer data held at SPC. Grey lines represent 95% confidence levels. The 'rug' plot along the inside of each x-axis displays the data density along the range of each variable. Weight: r^2 – 0.259, adjusted r^2 – 0.175; Numbers: r^2 – 0.336, adjusted r^2 – 0.260.

7. Black marlin (*Makaira indica*)
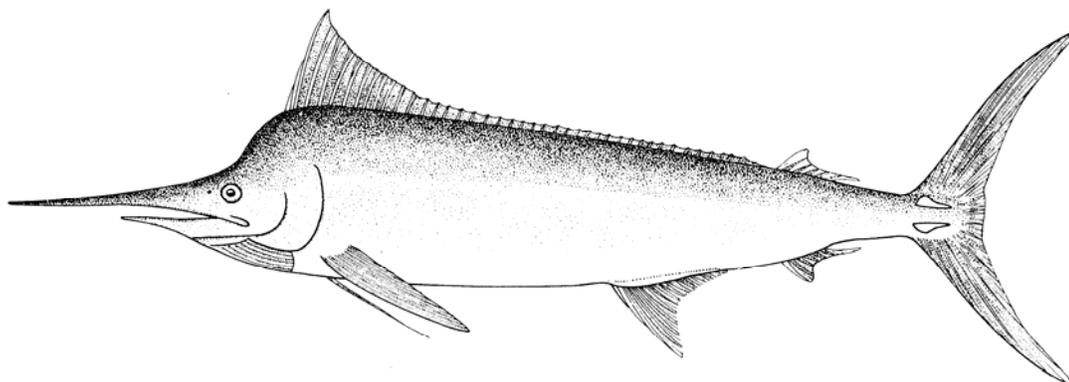
7.1 Description

Black marlin are a large tropical billfish species frequently found in surface waters of the WCPO. While not attaining the large size of blue marlin, black marlin have been recorded up to 400 kg (400 cm LJFL) in the south-western Pacific (Pepperell and Davis 1999).

Black marlin are distinguished from other marlin as the base of the second dorsal fin starts slightly in front of the anal fin (unlike in blue marlin) and the pectoral fins are rigid, unable to be folded flat against the body (Nakamura 1985). Pectoral fins become more rigid in larger black marlin (Kailola et al. 1993).

7.2 Distribution

Black marlin are the most widely distributed billfishes, inhabiting almost all WCPO waters between 40°N and 40°S, but the latitudinal range in the EPO declines to between 30°N and 30°S (Nakamura 1985). In the Indian Ocean, blue marlin are found in all waters to a latitude of approximately 40°S. Blue marlin are not found throughout the Atlantic but are occasionally captured along the west coast of Africa, although these do not constitute a breeding populations (Nakamura 1985, Kailola et al 1993).

Black marlin are captured from a range of depths (Kailola et al. 1993). In addition, black marlin can be found in close proximity to islands and coasts, more so than blue or striped marlin (Kailola et al 1993, Whitelaw 2001).

7.3 Biology

7.3.1   Age and growth

Ageing estimates for black marlin are rare (Kailola et al 1993). Speare (2003) recently compared counts and radii of presumed annual bands in cross sections of the third dorsal and third anal spines with deposition rate of increments and radii from a single recaptured blue marlin at liberty for approximately 6 months. While only a single fish was recaptured, the presumed annual bands and radii between bands agreed well with the deposition rates of spines from the recaptured fish and with previously published age estimates of blue marlin based on length-frequency analyses (Pepperell 2000).

The estimated ages indicated that black marlin are among the fastest growing fishes, exceeding 100 cm and 10 kg within their first year (Table 5). However, Pepperell (2000) suggests that black marlin may reach 25 kg by the end of their first year, reaching 100 kg within 3–4 years. Growth declines after the first four years of age, likely a result of the onset of sexual maturity. While males and female grow at similar rates during the first four years of life, males attain smaller sizes than females, most fish over 170 kg are females (Pepperell 2000). The estimated longevity of black marlin is approximately 18 years (www.aims.gov.au/pages/research/marlin/black). Black marlin are reported to regularly exceed 100 kg (230 cm LJFL[4]), with individual fish exceeding 400 kg (400 cm LJFL) in the south-western Pacific (Pepperell and Davis 1999).

7.3.2   Reproduction

Males reach sexual maturity at approximately 30 kg (approximately 147 cm LJFL) while females are approximately 100 kg (approximately 233 cm LJFL) at first maturity (www.aims.gov.au/ pages/research/marlin/black/pages/bm-03.html). These estimates vary from those estimated for black marlin from the Indian Ocean (males, 60 kg and 2–3 years; females, 70 kg and 3–4 years) (Pepperell 2000), albeit from limited sampling.

Suspected spawning areas for black marlin in the Pacific Ocean have been identified in the south China Sea (May-June), near Taiwan (August-September) and in the north-west of the Coral Sea (October-December) (Nakamura 1983, Pepperell 2000). The water temperatures in these areas at the indicated times of the year are 27–28°C, suggesting a requirement of high surface water temperatures for spawning for this species. Although large black marlin (up to 350 kg) are captured in the EPO all fish examined to date do not possess mature gonads and thus there is no evidence of black marlin spawning in the EPO (www.aims.gov.au/pages/research/marlin/black/pages/bm-03.html). Thus, all spawning of black marlin may occur in the western Pacific Ocean. Waters immediately south of Java and around the Lesser Sunda Islands appear to be the main spawning areas for Black marlin in the Indian Ocean (Pepperell 2000).

Although few estimates have been reported, fecundity of black marlin is relatively high (Nakamura 1983). Estimates of individual fecundity ranged between 67 million and 262 million eggs per females from a sample of 13 females between 322 kg and 427 kg collected from the Coral Sea (Kailola et al. 1993). It is suspected that black marlin spawn multiple times within each spawning season (Pepperell 2000, www.aims.gov.au/pages/research/marlin/black/pages/bm-03.html).

7.3.3   Recruitment

Little information on recruitment of black marlin is currently known. Larvae have been identified in the north-west Coral Sea and near the edge of the continental slopes (Leis et al. 1987), although black marlin larvae are rare (Pepperell 2000). Black marlin start to recruitment into the WCPO longline at 75–100 cm LJFL (approximately one year of age), becoming fully recruitment by approximately 175 cm LJFL (2–3 years of age) (Figure 29).

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[4] The length-weight relationship for black marlin is, weight (kg) = 0.00006614 x $LJFL^{2.611088}$ (length-weight relationship used at OFP).

While fewer black marlin have been reported from the WCPO purse-seine fishery, the size at recruitment is similar as for the longline fishery.

7.3.4   Mortality

Little is known about the mortality rates of black marlin. Applying Hoenig's estimate of mortality, assuming that 1% of black marlin reach 20 years of age, M is approximately $0.23.year^{-1}$. As longline catches of black marlin from the WCPFC (Figure 24) and EPO (IATTC 2004) have been relatively stable for several decades, it is assumed that fishing mortality is also likely to have remained stable.

7.4   Ecology

7.4.1   Habitat preference

Similar to other billfish species, black marlin are a surface associated species. However, black marlin are more often found in waters close to coasts and islands than other species of billfishes (Kailola et al. 1993). Although recorded from a wide range of depths (Kailola et al. 1993), recent tagging studies in the Coral Sea have indicated that black marlin spend most of their within the top 120 m of the water column (Gunn et al. 2003).

A recent study on black marlin using pop-up satellite tags revealed that black marlin spent most of their time in the mixed layer within water temperatures greater than 24°C, however deeper dives were also reported (Gunn et al. 2003). From catch rates data, higher than average CPUEs are reported from longline gears with 10 or fewer HBF, with catch rates again increasing in deeper set gears (with more than 25–30 HBF) (Figure 33).

Based on catch rates by longline fleets, black marlin are more abundant near the edges of continental slopes and in strong oceanographic systems (e.g. East Australian Current, Kailola et al. 1993). This may be due to bathymetric structures and oceanographic systems concentrating suitable prey species in high densities. In addition, nearly 90% of all purse-seine captured black marlin have come from associated sets (unpublished observer data at SPC).

7.4.2   Movements and migration

Black marlin are high mobile species that show rapid and extensive movements. The movements of five black marlin in the short-term tagging study of Gunn et al. (2003) revealed movement between 200 km and 1,200 km although no consistent direction was shown. It has been concluded that black marlin are highly mobile and show seasonal movements but clear migration routes do not exist (Pepperell 2000). While other tagging studies have revealed larger movements (up to 7,200 km in 359 days) they have also indicated that many recaptures are made at a similar location to the tagging site after a period of one or more years, suggesting that individual fish may return to the same site each year (www.aims.gov.au/pages/research/marlin/black). It has also been suggested that movements and migrations vary among age and sexes (Pepperell 1990, in Kailola et al. 1993).

7.4.3   Diet

Like other billfish, black marlin use their bills to stun prey, as evidenced by prey with large slash marks recovered from the stomachs of black marlin (Nakamura 1983). The diets of black marlin vary among areas although much of the diet is comprised of species of tuna, including skipjack, yellowfin and bigeye. However, cephalopods, other fishes (including trevally, mahimahi, swordfish and other scombrids) are also important prey species (Nakamura 1983). The diets of juvenile (10–40 kg) black marlin from Australian waters are dominated   by   baitfishes   (pilchards   and   herrings) (www.aims.gov.au/pages/research/marlin/black).

7.5   Details of stocks in the WCPO

7.5.1 Stock structure and size

Little is known of the stock structure of black marlin due to the relatively low catches and catch rates of this species and limited tagging undertaken to data. Broadly, black marlin are distributed in the tropical and subtropical Pacific and Indian Ocean (Pepperell 2000). Black marlin are also recorded from the Atlantic Ocean along the east coast of Africa but this is not considered to be a spawning population (Nakamura 1983).

It is likely that black marlin in the Pacific Ocean may constitute a single stock. From tagging studies, low frequency movements of individuals have been recorded between the eastern and south-western Pacific (Pepperell 2000). In addition, histological studies of gonads of eastern Pacific black marlin have revealed little spawning activity, while records of larvae and mature females have been reported in temporal sequence from the Coral Sea (October to December), the Timor Sea (October to April), the South China Sea (May to June) and in the vicinity of Taiwan Island (August to October) (www.aims.gov.au/pages/research/marlin/black).

There are no estimates of stock sizes for black marlin in the Pacific Ocean. However, the stock size is likely to be smaller than that of blue or striped marlin due to lower catches of black marlin (Molony 2005b).

7.5.2   Recent stock assessments and status

No stock assessments of this species have been undertaken and the status of the black marlin stock in the Pacific Ocean is uncertain. Catch (Figure 24) and catch rate (Figure 33) information suggest that the stocks are stable in the WCPO, and Pacific Ocean (www.aims.gov.au/ pages/research/marlin/black; IATTC 2004).

Median size data from both the longline and purse-seine fisheries have been relatively stable since the mid 1990s throughout the WCPO (Figure 29, Figure 31). However, the median size is below the estimated size of reproduction of female black marlin (Figure 29). Catch rates in the longline fishery have displayed a high degree of variability and a decline in equatorial areas (Figure 32), although changes in targeting (HBF) to deeper sets may have reduced catch rates. Overall, the status of the black marlin stock in the Pacific and WCPO is uncertain.

7.6 Fisheries

7.6.1 Major fisheries and occurrence

Commercial catches of black marlin in the WCPO are dominated by the longline method fishery longline fishery in tropical and subtropical waters. Most black marlin captured by the longline fishery are greater than 150 cm LJFL and the median size been relatively stable since the mid 1990s (Figure 31). Very few black marlin have been captured by the purse-seine fisheries in the WCPO (Williams 2003), with catches being less than 300 mt al all years since 1962. Black marlin are more commonly reported from associated sets (logs, FADs, animals) (i.e. more than 89% of sets capturing a black marlin were associated sets).

7.6.2 Artisanal fishery value

Black marlin are captured by artisanal fishes in the WCPO (Dalzel et al. 1996) due to their nearshore distribution. However, black marlin catches are likely to be of relatively minor importance due to the low frequency of occurrence in the WCPO compared to other billfish and tuna species.

7.6.3 Sport and recreational fishery value

Black marlin are one of the premiere sport fishery species in the WCPO (Whitelaw 2001), including s in north-eastern Australia (Kailola et al. 1993). This is a result of their relatively large sizes and their high abundances in waters close to islands and reefs (Nakamura 1983), within the range of sportfishing vessels.

Table 5. Size at age of black marlin estimated from length-frequency of tag returns and counts of annuli in otoliths and fin spines (from Speare 2003 and www.aims.gov.au/pages/research/marlin/black).

Age (years)	Weight (kg)	Estimated length (LJFL cm)
0+	9.0–13.6	120
1+	18.2–22.7	130–135
2+	29.6–35.6	155–165
3+	32.9–55.9	175
4+	77.5	185–200
5+	91.5	200–220
6+	154.0	240–260
7–13	313–424	
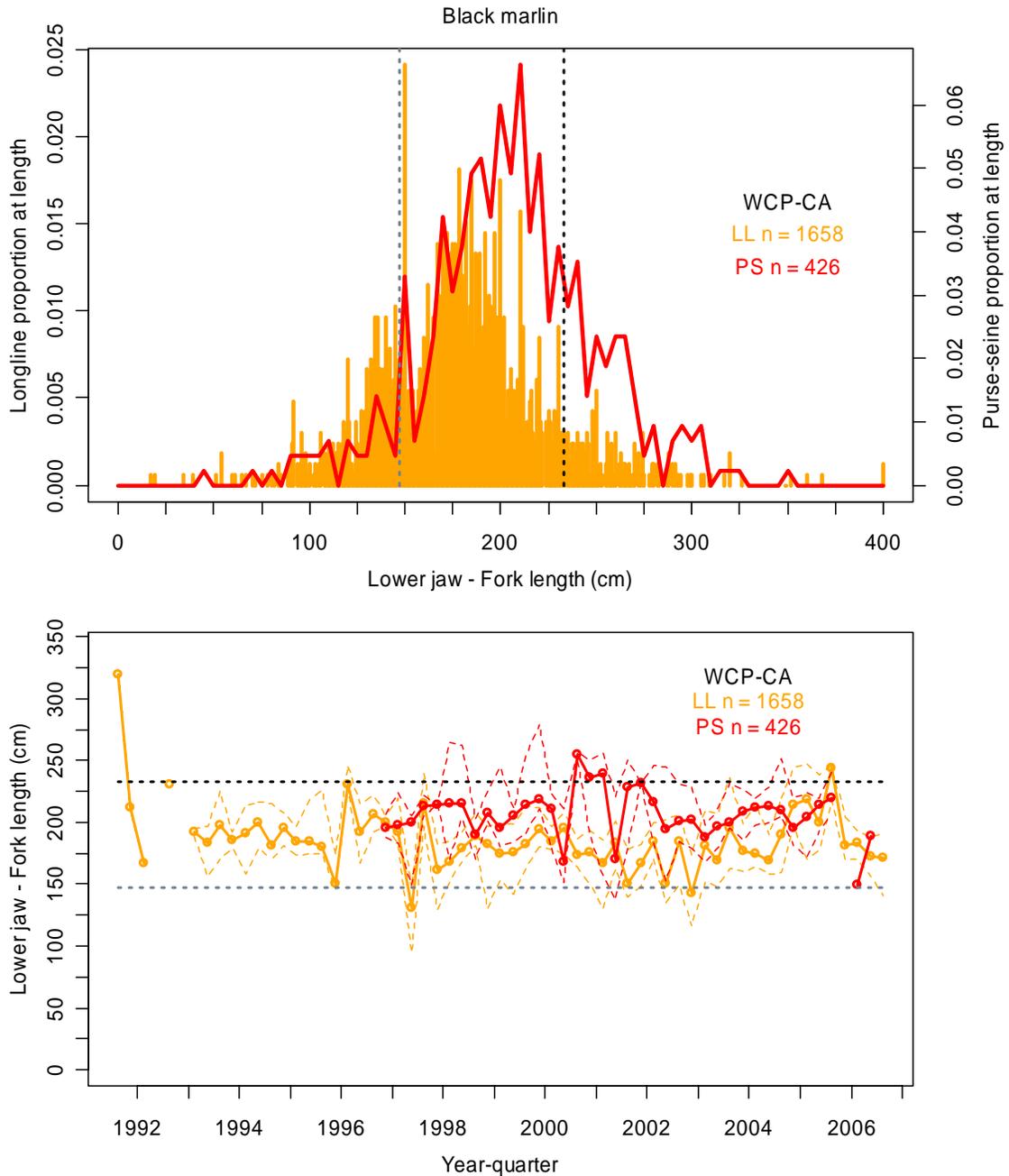
Figure 29. Combined length-frequency distributions (upper figure) and trends in quarterly median size (lower figure) of black marlin reported by observers in longline and purse-seine vessels in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery. Thin dashed lines represent the 25th and 75th quartiles of the size data. Heavy dashed lines represent lowess fits to the median size data. Dotted lines represent estimates of size at first maturity for females (black, 233 cm LJFL) and males (grey, 147 cm LJFL) (from www.aims.gov.au/pages/research/marlin/black/pages/bm-03.html) for the south-western Pacific. In the upper figure, 1 cm and 5 cm size class bins were used for fish from the longline fishery and purse-seine fishery, respectively.
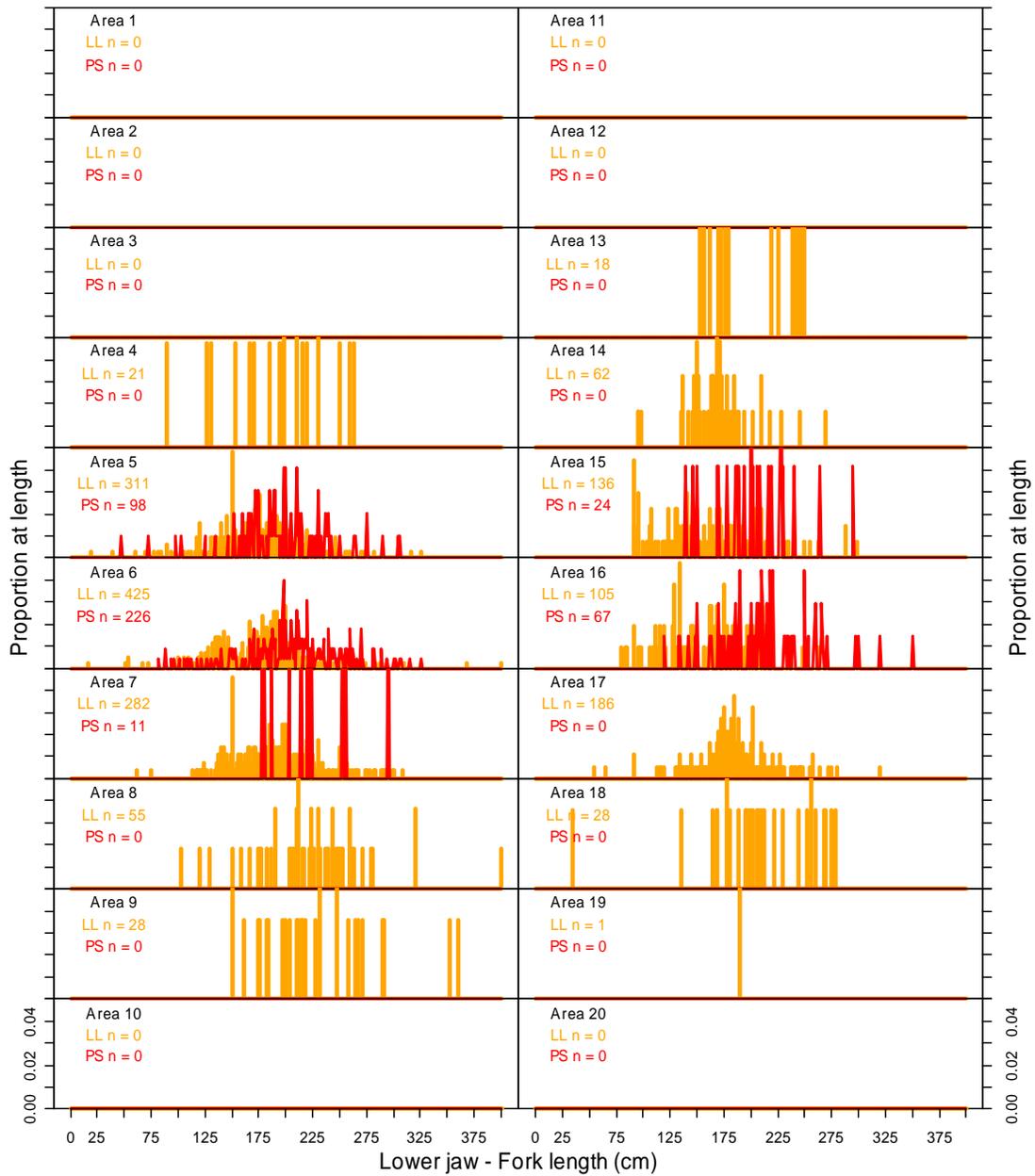
Figure 30. Length-frequency distributions of black marlin pooled into 10º latitude bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as lower-jaw to fork-lengths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively.
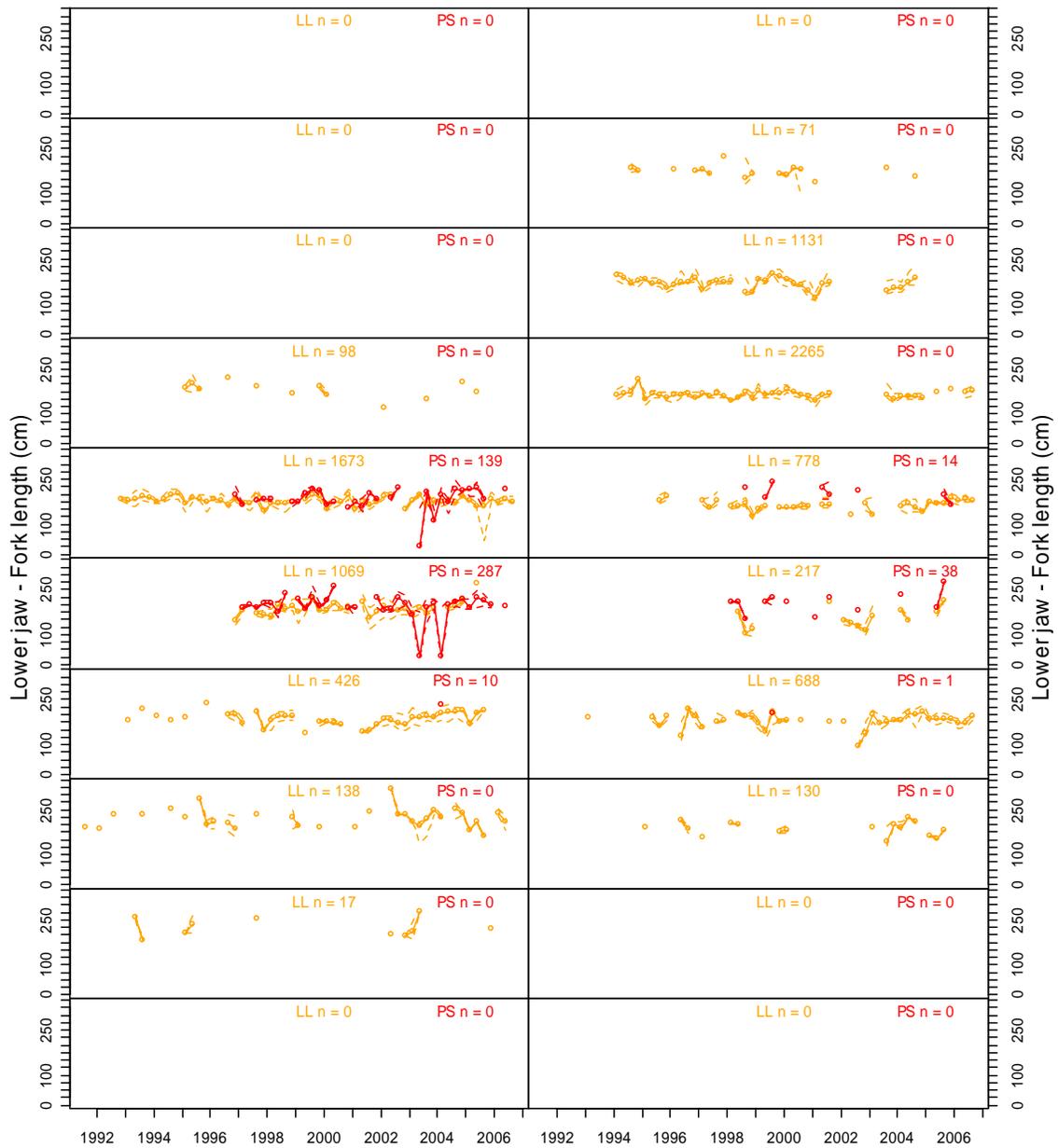
Figure 31. Trends in median size of black marlin pooled into 10º latitudinal bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as lower-jaw to fork-lengths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively. Points represent median size, dotted lines represent 25th and 75th quartiles, solid lines represent lowess fits to each data series.
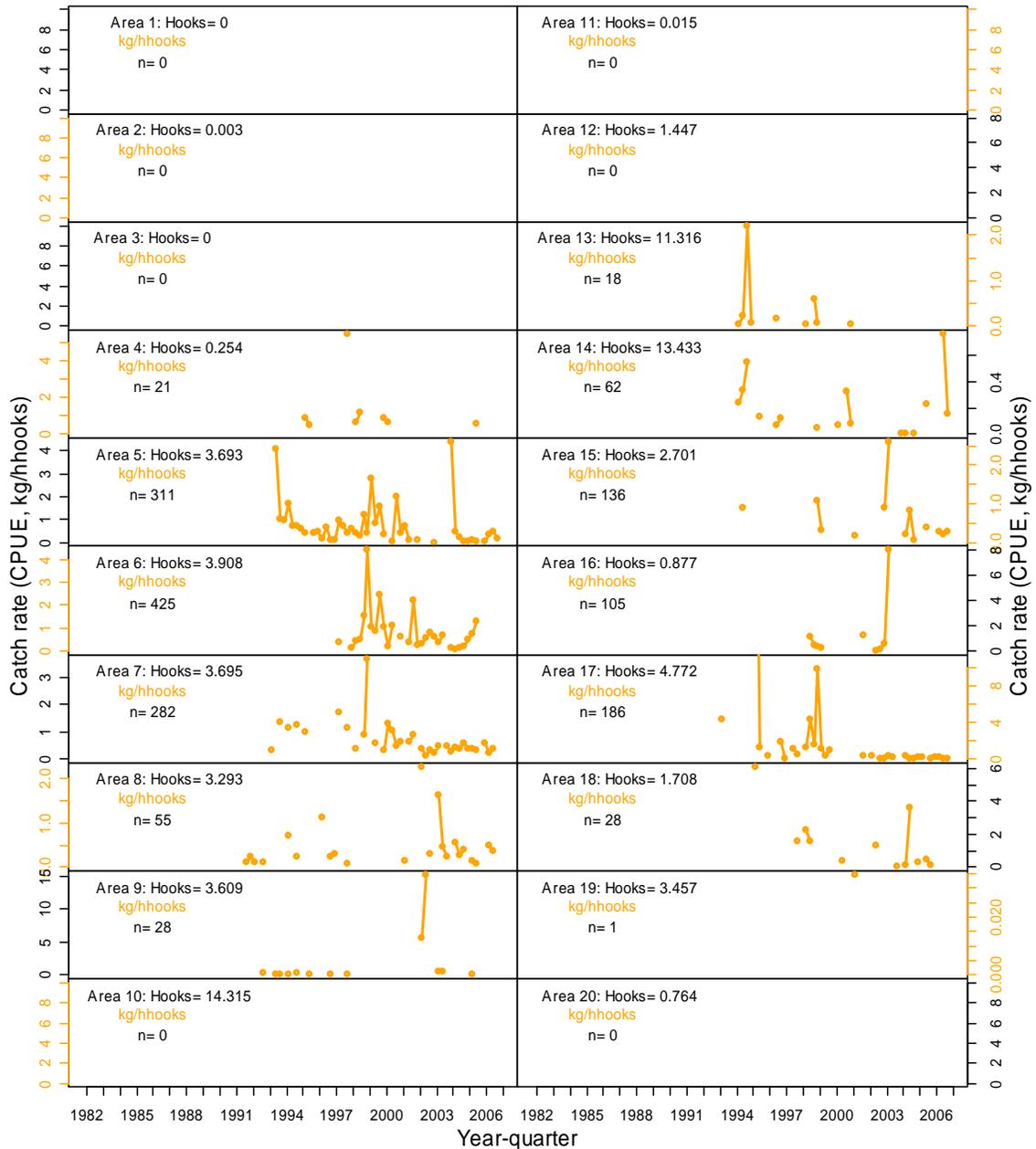
Figure 32. Quarterly catch rates (kg.hhooks^{-1}) of black marlin reported by observers pooled into 10º latitudinal bands (Areas) in the WCPO, 1982–2006. Source, SPC observer data base. Hooks, is the total number of observed hooks (millions) in each Area; n, represents the total number of individuals from each method-fishery within each Area. Scales of the y-axes vary among Areas. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively. Length-weight relationship: whole weight (kg) = (0.00000119 x LJFL$^{3.22}$) (OFP database).
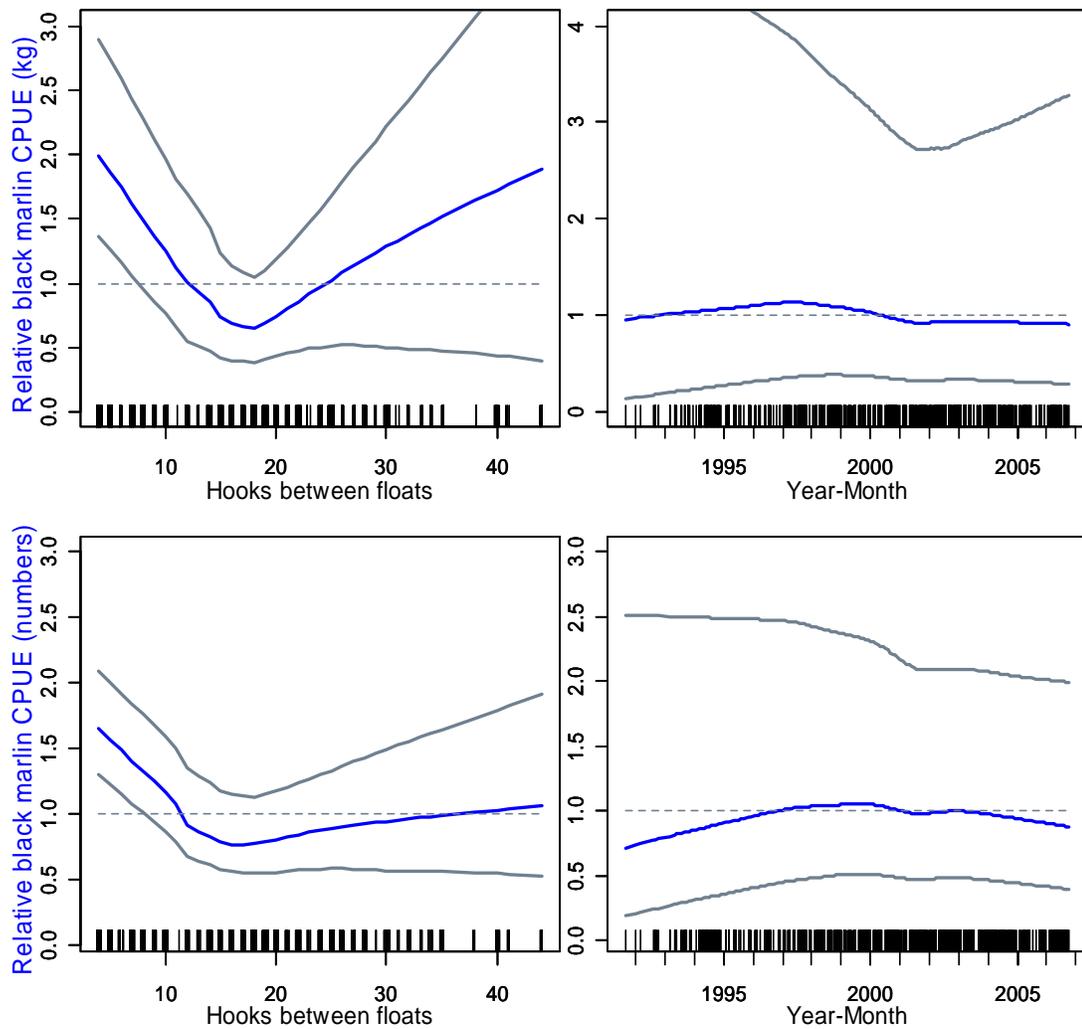
Figure 33. Changes in relative monthly black marlin longline catch rates (blue lines; upper figure, number/hhooks; lower figure, kg/hhooks) for the WCPO under the influence of longitude, latitude, hooks between floats and time period (year-month) as predicted by GLMs, 1991–2006. Sources, observer data held at SPC. Grey lines represent 95% confidence levels. The 'rug' plot along the inside of each x-axis displays the data density along the range of each variable. Weight: $r^2 = 0.449$, adjusted $r^2 = 0.196$; Numbers: $r^2 = 0.461$, adjusted $r^2 = 0.213$.

8. Striped marlin (*Tetrapturus audax*)
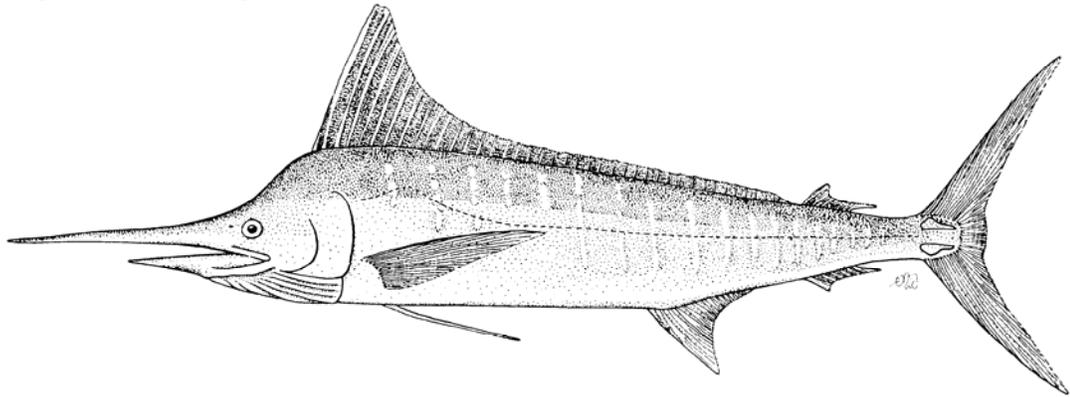
8.1 Description

Striped marlin are a large billfish commonly found in tropical and temperate waters of the Pacific and Indian Oceans, although they are more common in temperate waters (Whitelaw 2001). Striped marlin are distinguished from other billfishes by their large dorsal fin, which is similar in height to body depth (Chapman et al. 2006). In addition, the relatively long pectoral fins can be folded flat along the body (Kailola et al. 1993, Chapman et al. 2006). The flesh is typically a pink colour. Striped marlin may be misidentified with blue marlin, especially small individuals (less than 100 cm LJFL).

8.2 Distribution

Striped marlin are found in tropical and temperate zones of the Pacific and Indian Oceans. Occasionally striped marlin have been reported from the Atlantic Ocean along the south-west African coast but these individuals are likely be stragglers from the Indian Ocean and it is unlikely that self-sustaining populations of striped marlin are resident in the Atlantic Ocean (Nakamura 1983).

The distribution of striped marlin in the Pacific Ocean is more similar to that of albacore and bluefin tuna than other tuna or billfishes in the Pacific Ocean (Nakamura 1983). While striped marlin are reported between at least 40ºN and 40ºS, they relatively rare in equatorial regions of the WCPO, between 10°N and 10°S (Bromhead et al. 2004, Langley et al. 2006). In the EPO, high catch rates are reported between 35°N and 35°S including in equatorial areas. This results in a broadly horseshoe shaped distribution of striped marlin across the Pacific.

8.3 Biology

8.3.1 Age and growth

Ageing studies on striped marlin have enumerated increments in cross sections of dorsal spines (e.g. Yatomi 1990). However, this is limited by the increase in spongy bone area in cross sections of dorsal spines with increase in size (Yatomi 1990), resulting in the loss of inner increments formed at young ages. Ageing is further complicated as small, young fish (less than 100 cm LJFL) are rarely captured and therefore rarely studied. Striped marlin show little sexual dimorphism in growth (Bromhead and Pepperell 2004) although females may be slightly larger than males.

Similar to other of marlin species, striped marlin display very high growth rates although empirical studies are rare. From a recent review, Bromhead and Pepperell (2004) indicated that striped marlin live for at least 10 years and reach a size of at least 290 cm LJFL. Striped marlin grow rapidly until at least the onset of maturity (2–4 years of age at a size of 140–180 cm LJFL (Nakamura 1985)). Growth rates then reduce in older fish. Kopf et al. (2005) constructed a VBGF for large striped marlin captured by recreational gears off New Zealand, estimating k at 0.22.year^{-1} and L∞ at 301 cm LJFL. However, the growth rate estimates by Kopf et al. (2005) may under-estimate the growth rates of smaller fish of (Langley et al. 2006), with an estimate of $k = 0.60$.year^{-1} modelled by Langley et al. (2006)

8.3.2   Reproduction

The size of first maturity for striped marlin is between 140 cm and 180 cm LJFL (Nakamura 1985) and 27–40 kg (www.aims.gov.au) at an age of 2–4 years (Bromhead and Pepperell 2004). Based on the size-frequency of eggs within the ovaries, female striped marlin are presumed to spawn only once per season (Eldridge and Wares 1974, in Bromhead and Pepperell 2004). However, the eggs studied to date are relatively small (ca. 0.85 mm diameter), much smaller than for other billfishes (1.3–1.4 mm) and it is thought that most eggs measured to date from striped marlin are immature. It is likely that striped marlin are multiple spawners, similar to other species of marlin.

Mature females have been reported from a small area near the Pitcairn Islands EEZ (Bromhead and Pepperell 2004) and from the Coral Sea between 17–30°S between Australia and New Caledonia (www.aims.gov.au) during November and December (Nakamura 1983).

Striped marlin larvae have been recorded from a large region south-west of Japan (10–30°N, 130–170°E), east of northern and central Australia (10–30°S, 150–180°E), off the north-west coast of Mexico and in the north-central region of the French Polynesian EEZ (Bromhead and Pepperell 2004). However, the total number of larvae collected during sampling have generally been too low to confirm the existence of larval and spawning areas for striped marlin. Based on the presence of larvae, spawning of striped marlin occurs between May and June in the north-western Pacific (10–30°N), June to November near the Gulf of California, and between November and December in the south-western Pacific (Nakamura 1985, Armas et al. 1999, 2001 in Bromhead and Pepperell 2004). These periods coincide with late spring and the onset of summer in both hemispheres.

A recent analysis indicated that the average weight and condition of striped marlin from northern New Zealand increased during the recreational fishing season (December to May), suggesting that post-spawning fish move from north-eastern Australian to northern New Zealand waters to regain condition (Kopf et al. 2005).

8.3.3   Recruitment

Striped marlin commence recruiting to longline fisheries of the WCPO at approximately 75 cm LJFL , becoming fully recruited by approximately 110 cm LJFL (Figure 34). Most small striped marlin (less than 100 cm LJFL are reported from western equatorial areas of the WCPO, as far south as 15–20ºS (Figure 35). Striped marlin are rarely captured in purse-seine fisheries of the WCPO, although a wide size range has been recorded by observers (Figure 34).

8.3.4   Mortality

Few estimates of natural mortality rates exist for striped marlin. Boggs (1989) presented estimates of natural mortality rates of striped marlin of 0.49.year^{-1} for unsexed fish, 0.79.year^{-1} for males and 1.33 year^{-1} for males, based on length-frequency analyses. Pauly (1980, in Hinton and Bayliff 2003) provided lower estimates of mortality rates for striped marlin: 0.389. year^{-1} for unsexed fish, 0.569 year^{-1} for males and 0.818.year^{-1} for females. However, these estimates are not specific to striped marlin from the WCPO. An estimate of natural mortality of 0.4.year^{-1} was applied to all age classes and sexes in a stock assessment model for south-western Pacific striped marlin (Langley et al. 2006).

8.4   Ecology

8.4.1   Habitat preference

Striped marlin spend there entire lives in the (epipelagic zone) (Bromhead and Pepperell 2004) and most of their time is spend in the upper 100 m of the water column (Brill et al. 1993, Domeier et al. 2003), making them available to longline and sportfishing gears. From a recent tagging study using pop-up archival transmitting tags, Domeier et al. (2003) recorded a maximum depth between 48 m and 192 m from 49 striped marlin released in a healthy condition, with most individuals remaining within 50 m of the surface. This is highlighted by the rapidly declining catch rates with increasing HBF, with the highest catch rates from the shallowest sets (Figure 38). However, dives exceeding 100 m are reported, especially at night. Most striped marlin captured in the purse-seine fishery of the WCPO are from associated sets (logs, FADs), suggesting they may be attracted to floating objects,

Striped marlin tolerate water temperatures of 16–29ºC, with preference for waters of 18.5–24ºC (Uda 1957, in Bromhead and Pepperell 2004). However, 97% of longline captured striped marlin within the Australian EEZ were reported from waters between 18ºC and 27ºC (Bromhead and Pepperell 2004). Sea surface temperature has a major role in limiting the abundance of striped marlin. Squire (1974, in Hinton and Bayliff 2002) reported that catch rates of striped marlin increased from 40.5 fish per half month in waters less than 20ºC, to almost 100 fish per half month in waters 20–21.1 ºC, to 122.7 fish per half month when surface water temperatures exceeded 21.1ºC. This was supported by the observation of relatively high striped marlin catch rates extending northwards in the eastern Pacific during the El Niño event of 1983, as a result of warmer sea surface temperatures (Squire 1987a, b).

Due to their preference for shallow waters, striped marlin are not likely to be limited by oxygen concentrations. However, the broadly horseshoe-shaped distribution of striped marlin catch rates in the Pacific Ocean (Bromhead and Pepperell 2004) is coincident with dissolved oxygen concentrations of approximately 3.0–5.1 mg.ml^{-1} in surface waters.

8.4.2   Movements and migration

The most compressive assessment of striped marlin movements and migrations was reported by Squire and Suzuki (1990) using longline CPUE, length-frequency, morphometric and tag-recapture data, plus evidence from known spawning areas for striped marlin. Broadly, striped marlin in both hemispheres of the Pacific Ocean show movement away from the equator during summer, consistent with their temperature preferences for striped marlin of 18.5–24ºC.

Striped marlin in the south-west Pacific tend to move to the Coral Sea between November and December to spawn before migrating south down the Australian coast to the Tasman Sea and then east to northern New Zealand (Squire and Suzuki 1990, Bromhead and Pepperell 2004). In the central southern regions of the WCPO, striped marlin tend to move south-eastward during the middle of the year and eastward during the third quarter of each year about a latitude of 25°S near the French Polynesian EEZ. Although data on movement of striped marlin back towards this area is lacking, CPUE data implies a westward movement of striped marlin from about 110°W between the first and second quarters of each year (Squire and Suzuki 1990).

In the eastern Pacific Ocean, the movement of striped marlin is northeast from the vicinity of Easter Island to towards central America during the last and first quarters of the year. Opposite movements are recorded in the second and third quarters of each year, although more westerly movements at latitudes of 5–15 °S are also recorded (Squire and Suzuki 1990). Movements of striped marlin in the eastern Pacific around Ecuador and the Galapagos Islands indicate a north-easterly movement during the first quarter of the year. In the second quarter of the year, some striped marlin (based on CPUE) then to continue the north-west movement broadly following the coast of north America to the coats of Baja California, while other fish return towards Ecuador. Between the third and fourth quarters of the year, striped marlin tend to return towards the Galapagos and Ecuador, moving south-east from the Baja coast (Squire 1987b, Squire and Suzuki 1990). Striped marlin tend to move away from the Baja coast in the last half of the year and return during the first half. However, striped marlin do not appear to move as far in this region of the Pacific Ocean compared to other areas, resulting in relatively high CPUEs maintained in this area throughout the year (Squire 1987b, Squire and Suzuki 1990).

In the north Pacific, striped marlin tend to move from an area north of Wake Island, north-westerly towards Japan or easterly towards Hawaii during between the second and third quarters of the year (Squire and Suzuki 1990). Striped marlin tend to show an opposite pattern of movement between the third and fourth quarters of each year. Around Hawaii however, smaller striped marlin tend to move towards Hawaii between the last and fourth quarters of the years from a north-east direction, moving north westerly past Hawaii between the first and second quarters of the year (Squire and Suzuki 1990). This movement is mainly of small fish (about 10 kg in size) and may represent the movement of juveniles into a feeding area (Squire and Suzuki 1990).

Although this movement pattern is broadly accepted, limited tagging information shows individual variation. For example, tag-recapture records exist for individuals moving between northern New Zealand to Fiji and the Iles des Marquises (French Polynesia) (Bromhead and Pepperell 2004). Other records exist for tagged striped marlin moving from New Zealand, north-westerly into the eastern New Guinea EEZ and from Hawaii into the Marshall Islands EEZ. These recaptures suggest that clear migration pathways and times may not exists, and that relatively large striped marlin may move as individuals (Nakamura 1985). However, the recapture rates of striped marlin are relatively low (less than 1%, Squire and Suzuki 1990, Langley et al. 2006) and most marlin are recaptured within 6–9 months relatively close to the site of release (Bromhead et al. 2004, Langley et al. 2006).

8.4.3   Diet

The diet of striped marlin consists mainly of epipelagic organisms, pelagic fishes (Abitia-Cardenas et al. 1997) and pelagic cephalopods. Common fish species in the diet of striped marlin vary among regions (Nakamura 1985) and include scombrids and carangids (Bromhead and Pepperell 2004). Abitia-Cardenas et al. (1997) also noted that presence of benthic species of fishes in the guts of some striped marlin collected near Mexico, highlighting the ability of striped marlin to utilise a wide range of prey species. This flexibility in diet reduces the potential of competition with tunas, other billfishes and pelagic sharks (Nakamura 1983, Abitia-Cardenas et al. 1997, Bromhead and Pepperell 2004), making striped marlin more of a generalist feeder than other pelagic species.

8.5   Details of stocks in the WCPO

8.5.1   Stock structure and size

There is currently a similar weight of evidence from tagging and catch rate data to support or refute one, two or three stocks of striped marlin in the Pacific Ocean (Bromhead and Pepperell 2004). However, molecular studies indicate slight but significant differences in striped marlin from different areas of the Pacific Ocean (Graves and McDowell 1994), suggesting a complex stock structure.

Langley et al. (2006) assumed a south-west Pacific stock (0–40ºS, 140ºE–130ºW) based on catch rate and tagging data in a stock assessment model for striped marlin. The model estimated a total biomass of approximately 14,000 mt, with an adult biomass fluctuating in the range of 8,000–11,000 mt since the early 1980s. Comparing estimates of billfish catches in the WCPFC (Figure 24), the stock size of striped marlin is likely to be smaller than those of blue marlin and swordfish but larger than that of black marlin.

8.5.2   Recent stock assessments and status

A preliminary stock assessment for striped marlin (Langley et al. 2006), while uncertain, indicated that the annual catches of striped marlin since 1984 have fluctuated around the level estimated at MSY (approximately 2,400 mt per year), suggesting that there is little scope to increase catches from the stock. Langley et al. (2006) concluded that recent levels of exploitation were negatively impacting on the productivity of the stock.

This is supported by the median size data for the WCPO (Figure 34) which has displayed an increasing trend in median size since 1998 to above the size at first maturity for both sexes. In addition, median size trends have been stable or increasing for all Areas of the WCPFC where good levels of size data exist (Figure 35). Catch rates trends have revealed strong seasonality and declines in many Areas (Figure 36), although the declines may be due to the use of deeper gears (higher HBF) to target deeper-living species (e.g. bigeye and albacore) (Figure 38). The shift to deeper gears may explain the recent increase in relative CPUE in terms of weight but decrease in terms of numbers (Figure 38), as deeper gears are more likely to capture larger, but fewer, striped marlin.

A recent preliminary stock assessment for striped marlin for the EPO estimated that recent levels of biomass were between 50% and 70% of the unfished levels, suggesting that the EPO stock was in a healthy condition (IATTC 2004).

8.6   Fisheries

8.6.1 Major fisheries and occurrence

Striped marlin in the WCPO are captured mainly by the longline method fisheries, with some fleets targeting striped marlin during some times of the year (Bromhead et al. 2003). Most striped marlin captured by the longline method fisheries in the WCPO are greater than 125 cm LJFL (Figure 34). Catches of striped marlin from the WCPFC have been relatively stable at between 3,000 mt and 5,000 mt per year since 1970 (Figure 24), with catches exceeding 14,000 mt in earlier years. In the south-west Pacific, catches have been stable at approximately 2,400 mt per year since the mid 1980s (Langley et al. 2006).

Very small catches of striped marlin are reported by the purse-seine fishery in the WCPO (less than 100 mt per year). Approximately 94% of sets in which one or more striped marlin were recorded were associated sets (logs, FADs, animals).

8.6.2 Artisanal fishery value

Striped marlin are an insignificant component of artisanal fisheries due to their offshore distribution. They may rarely be captured by artisanal fishers in areas where deep drop-offs exist near coasts and islands.

8.6.3 Sport and recreational fishery value

Striped marlin are a significant gamefish species in the Pacific Ocean, being reported from most EEZs in the Pacific (Whitelaw 2001), especially in the eastern central Pacific, eastern Australia and New Zealand (Bromhead and Pepperell 2004). The largest striped marlin are typically reported from the south-west Pacific Ocean and most world records for this species have been reported from the New Zealand EEZ (Nakamura 1983).
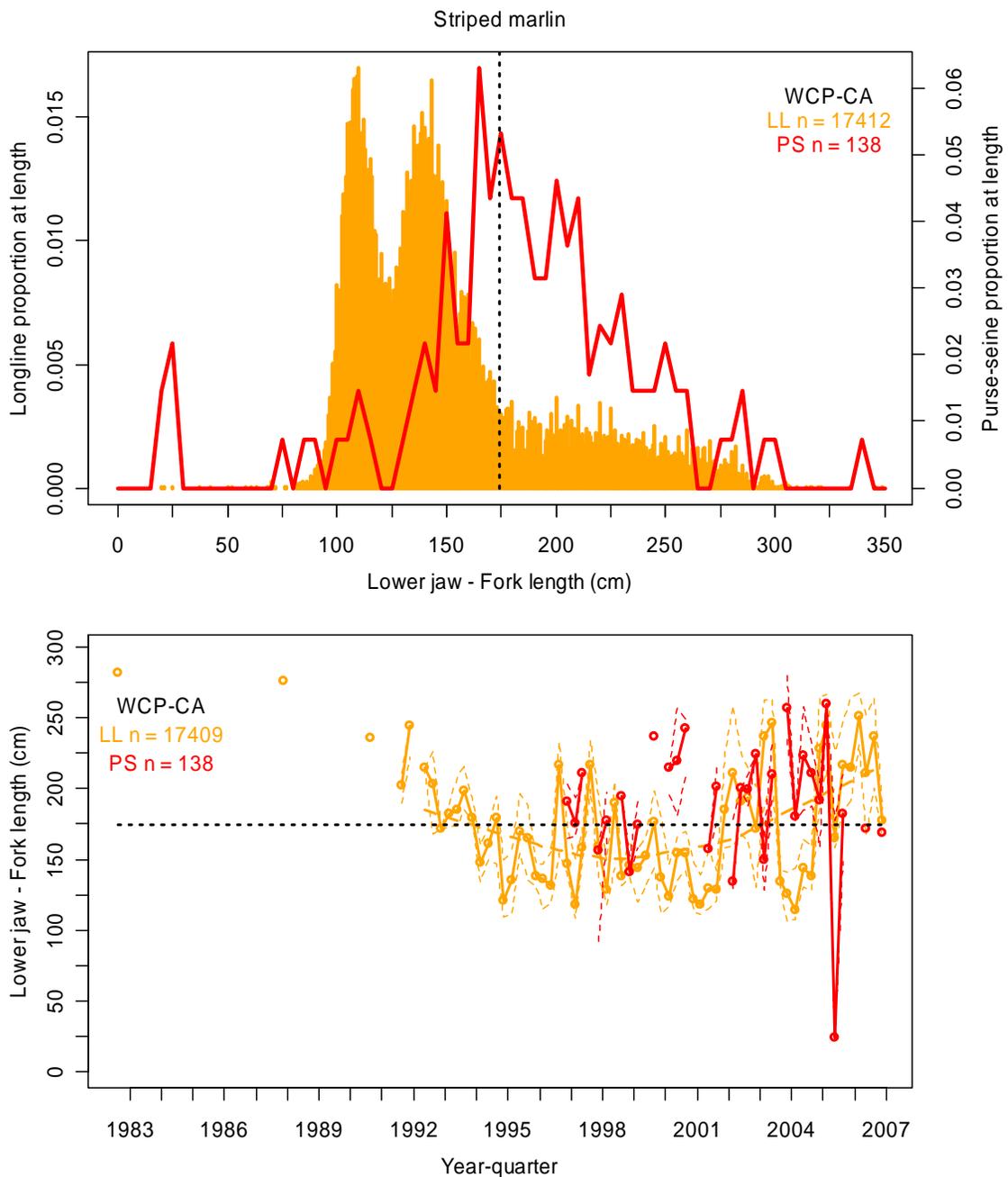
Figure 34. Combined length-frequency distributions (upper figure) and trends in quarterly median size (lower figure) of striped marlin reported by observers in longline and purse-seine vessels in the WCPO, 1982–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery. Thin dashed lines represent the 25th and 75th quartiles of the size data. Heavy dashed lines represent lowess fits to the median size data. Dotted line represents estimates of size at first maturity for both sexes (black, 174 cm LJFL) (from Hanamoto 1977, in Bromhead et al. 2003 from the Coral Sea). In the upper figure, 1 cm and 5 cm size class bins were used for fish from the longline fishery and purse-seine fishery, respectively.
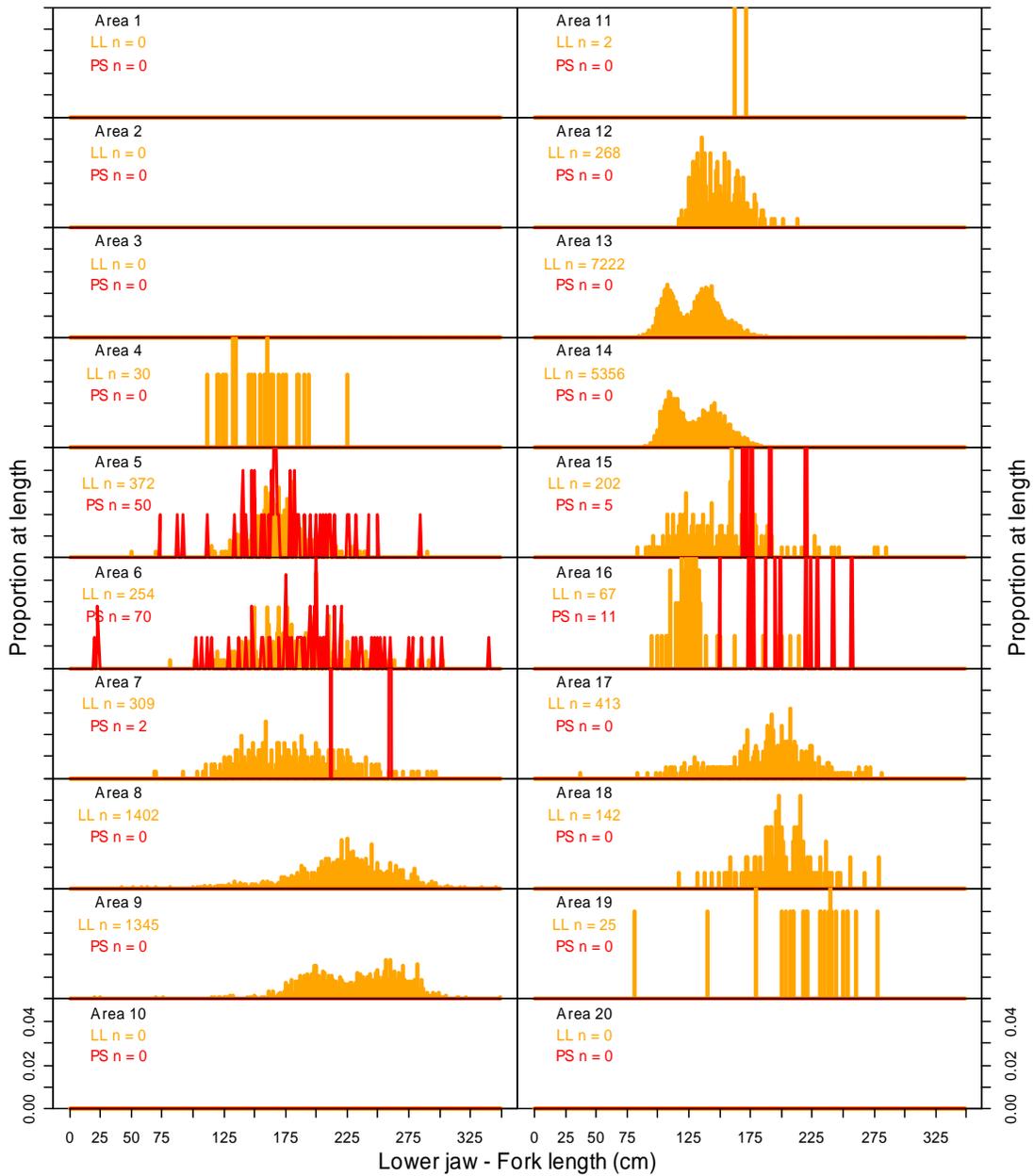
Figure 35. Length-frequency distributions of striped marlin pooled into 10º latitude bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as lower-jaw to fork-lengths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively.
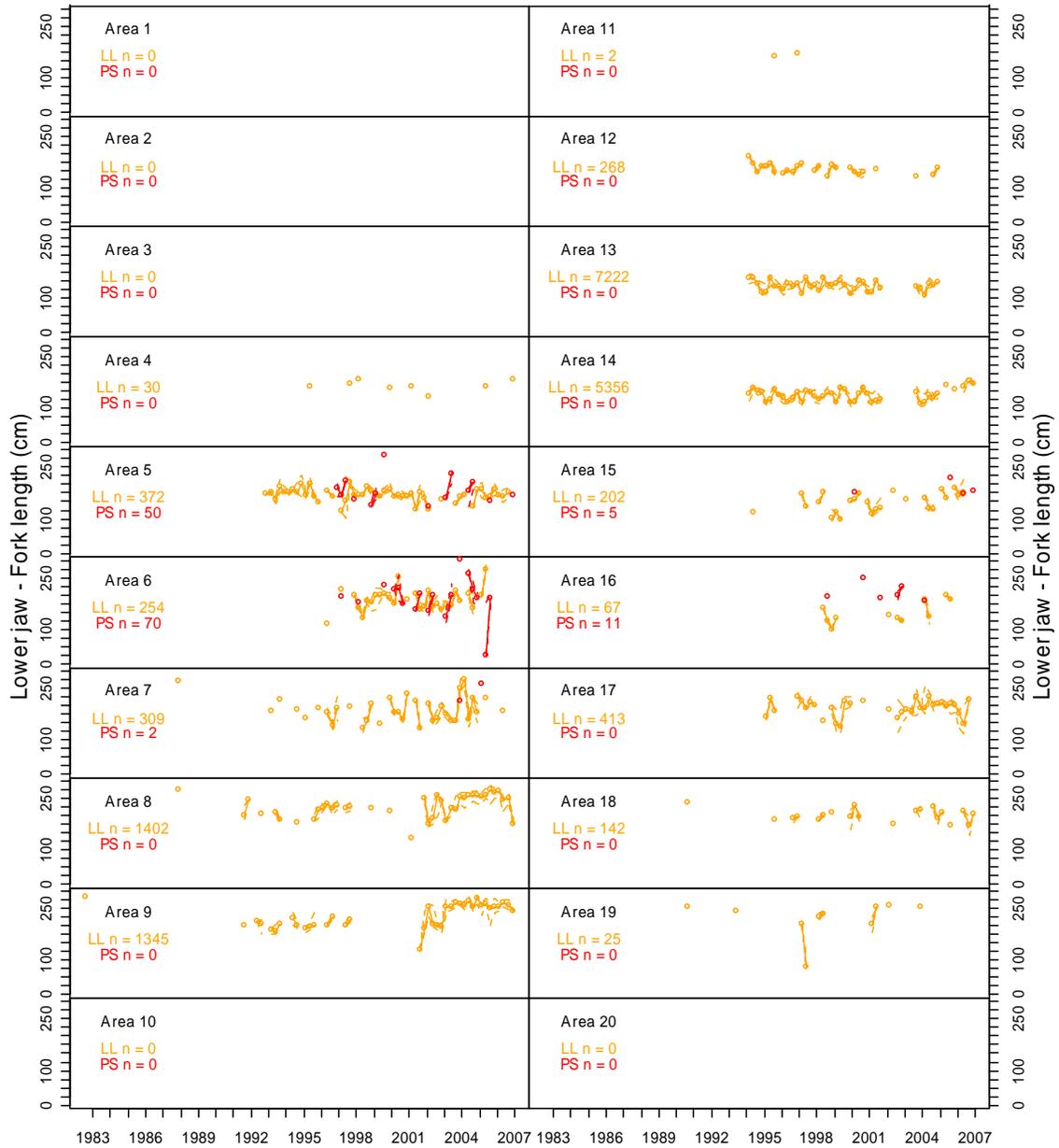
Figure 36. Trends in median size of striped marlin pooled into 10º latitudinal bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as lower-jaw to fork-lengths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively. Points represent median size, dotted lines represent 25th and 75th quartiles.
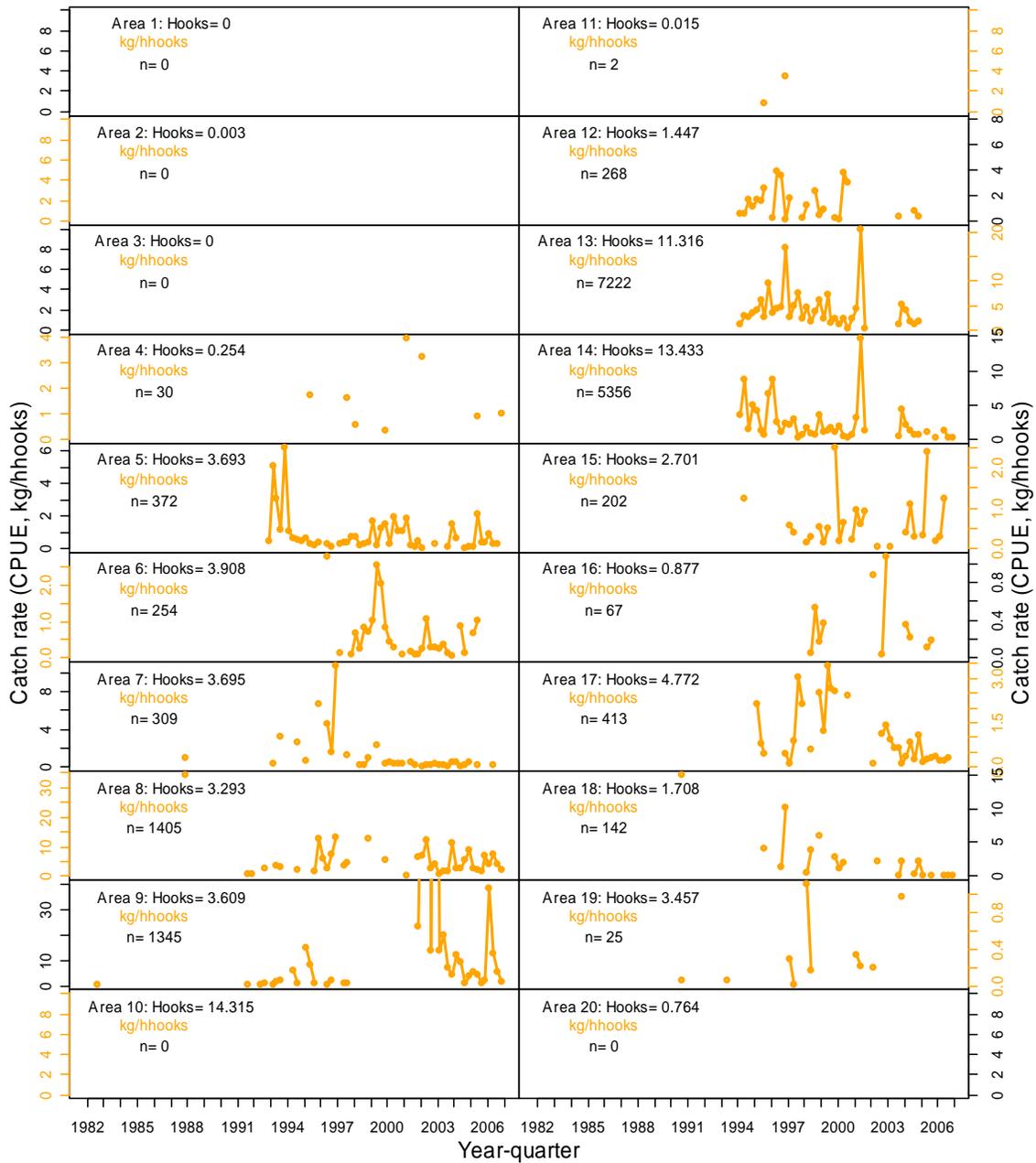
Figure 37. Quarterly catch rates (kg.hhooks⁻¹) of striped marlin reported by observers pooled into 10º latitudinal bands (Areas) in the WCPO, 1982–2006. Source, SPC observer data base. Hooks, is the total number of observed hooks (millions) in each Area; n, represents the total number of individuals from each method-fishery within each Area. Scales of the y-axes vary among Areas. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively. Length-weight relationship: whole weight (kg) = (0.0022 x LJFL$^{1.9555}$) (OFP database).
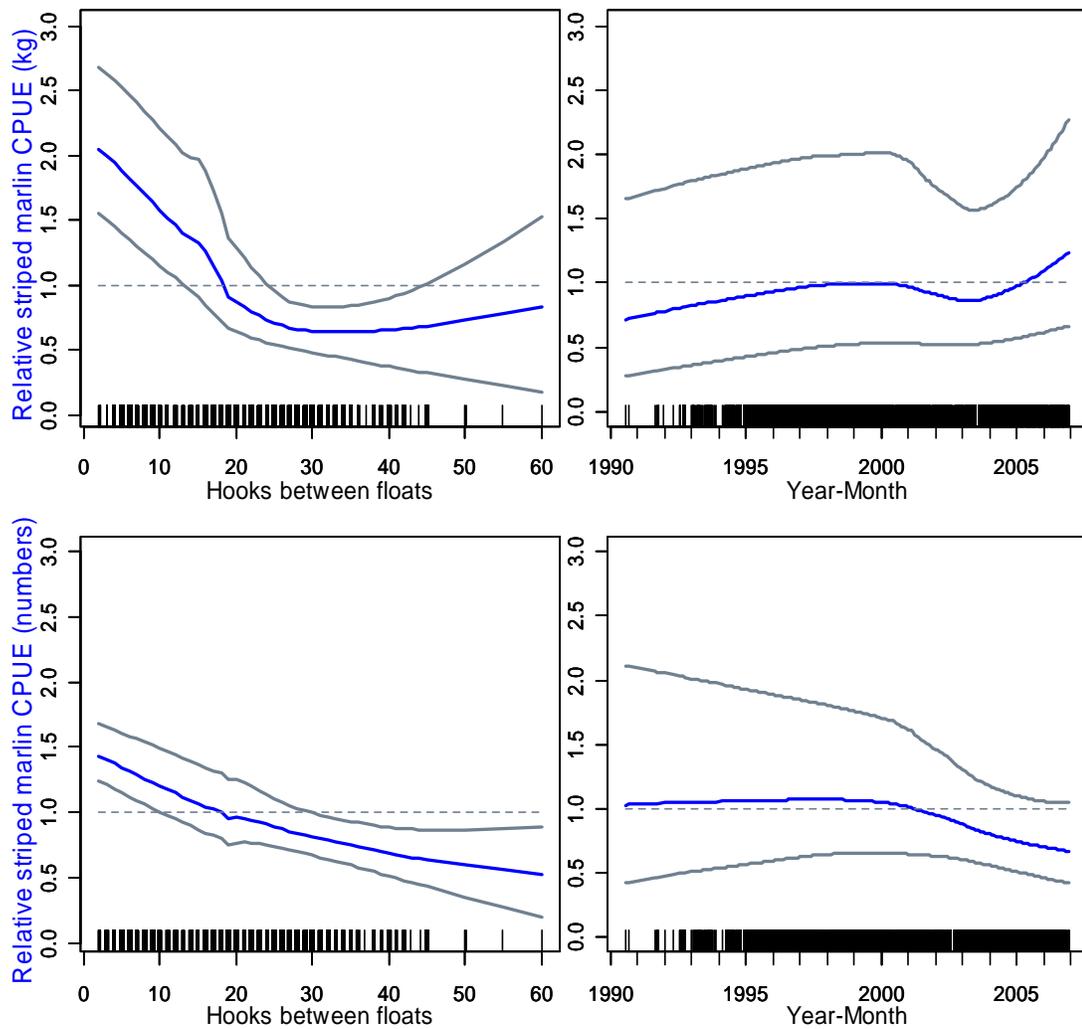
Figure 38. Changes in relative monthly striped marlin longline catch rates (blue lines; upper figure, number/hhooks; lower figure, kg/hhooks) for the WCPO under the influence of longitude, latitude, hooks between floats and time period (year-month) as predicted by GLMs, 1991–2006. Sources, observer data held at SPC. Grey lines represent 95% confidence levels. The 'rug' plot along the inside of each x-axis displays the data density along the range of each variable. Weight: $r^2 = 0.323$, adjusted $r^2 = 0.255$; Numbers: $r^2 = 0.303$, adjusted $r^2 = 0.233$.

9. Indo-Pacific sailfish (*Istiophorus platypterus*)
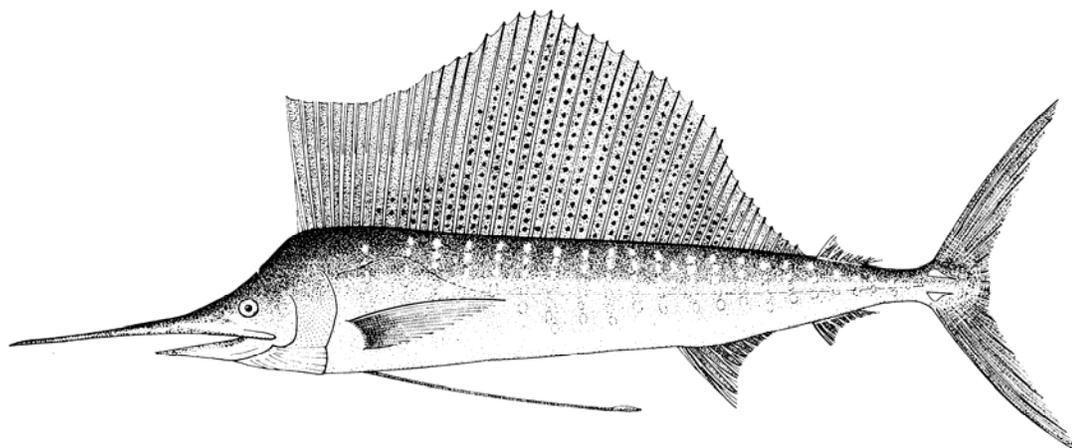
9.1 Description

Indo-Pacific sailfish are the most slender of all billfish and although they can attain lengths over 300 cm (EFL, eye-fork length) they rarely exceed 100 kg in weight (Nakamura 1985). Sailfish are easily distinguished from other billfishes by the presence of an exceptionally large first dorsal fin that when raised easily exceeds maximum body depth and very long and thin pelvic fins (Nakamura 1985). Similar to other billfishes, the dorsal surfaces are bark blue and the ventral surface is silver-white. The body may also have up to 20 vertical striped composed of light blue dots. The sail-like first dorsal fin may also contain numerous black dots.

9.2 Distribution

Indo-Pacific sailfish are found in tropical and sub-tropical waters of the Indian and Pacific Oceans. Indo-Pacific sailfish are recorded 40°N and 40°S in the WCPO and 30°N to 25°S in the eastern Pacific Ocean (Nakamura 1985). Within their range, Indo-Pacific sailfish are most common around coasts, islands, reefs (Nakamura 1983) and are typically found year-round in many locations (www.aims.gov.au).

Indo-Pacific sailfish have also been reported to have entered the eastern Mediterranean Sea, likely via the Suez Canal (www.fishbase.org), but have not been reported in large numbers. A closely related species, *Istiophorus albicans*, is found in a similar latitudinal range in the Atlantic Ocean (Nakamura 1985). While some authors have suggested a single world-wide species of sailfish, Nakamura (1985) argued for two separate species.

9.3 Biology

9.3.1 Age and growth

Like other billfish species, few ageing studies of Indo-Pacific sailfish have been undertaken due to the difficulties of collecting samples and validating ages. Growth increments from the fourth dorsal spine of Indo-Pacific sailfish are most often used to estimate age (Vidurri Sotelo et al. 2001), although otolith microstructure structure has also been examined (Radtke and Dean 1981, Prince et al. 1986). Indo-Pacific sailfish have an estimated longevity of up to 15 years (www.aims.gov.au) although fish of 10 years and older are rare in at least the eastern Pacific (Vidurri Sotelo et al. 2001); most authors report fishes between 2 and 6 years of age.

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A single tagged sailfish recaptured after more than 10 years at liberty increased the estimated longevity of *Istiophorus platypterus* to more than 15 years (Prince et al. 1986). Ageing of this specimen by the use of sagittal otoliths resulted in an estimate of 13+ years (Prince et al. 1986).

Estimates of absolute ages of sailfish are difficult due to reabsorption of the core area of spine (and loss of early increments) and low recapture rates of tagged fish. Castillo and Uraga (1996) used marginal increment analysis of monthly captured *Istiophorus platypterus* from the Gulf of Mexico and were able to demonstrate the annual deposition of a hyaline band. They subsequently identified 8 age groups (years) of sportfish-captured sailfish from the Gulf of Mexico (*Istiophorus platypterus*) and suggested that sailfish 180–210 cm in body length were 2–4 years of age, supporting the very rapid growth rate assumed for this species. This is supported by the lack of growth increments observed in cross sections of dorsal spines in individuals of up to 110 cm EFL (Vidurri Sotelo et al. 2001) suggesting that these individuals are less than one year old. Individuals may reach more than 100 cm EFL within four months (Nakamura 1985).

An age and growth study by Hoolihan (2006) derived VBGFs for a small number (n=84) of female and male sailfish from the Arabian Gulf (Indian Ocean). Hoolihan (2006) estimated k as 0.29.year^{-1} and 0.42.year^{-1} and L∞ at 191 cm LJFL and 160 cm LJFL for females and males, respectively.

9.3.2   Reproduction

Males start to mature at 20–25 kg (~175 cm LJFL) and with females approximately 30–35 kg (~200 cm LJFL) at maturity (Nakamura 1985), with most sailfish above 40 kg being mature (www.aims.gov.au). Sailfish in the EPO tend to be larger at first maturity than those from the WCPO (www.aims.gov.au), although it is unclear whether the growth rates of sailfish vary between the WCPO and EPO. Indo-Pacific sailfish are larger at first reproduction than Atlantic sailfish (De Sylva and Breder 1997).

Reproduction of Indo-Pacific sailfish is year-round in equatorial waters (www.aims.gov.au), with peaks during local summer periods (Nakamura 1985) and autumn (Hernandez and Ramirez 1998) in both hemispheres of the Pacific Ocean. Sailfish have the smallest ova of any istiophorid (mean 1.3 mm) (De Sylva and Breder 1997) and estimated fecundities are very high, up to 1.71 million +/- 0.6 million ova per female per spawning (Hernadez et al. 2000). Female sailfish are likely to be batch spawners, with less than 4 days between spawning events (Hernadez et al 2000). Reproductive studies from the Atlantic suggested that male sailfish are mature throughout the year (De Sylva and Breder 1997).

9.3.3   Recruitment

Indo-Pacific sailfish start to recruit to the longline fishery of the WCPFC at approximately 75 cm LJFL and are fully recruited by approximately 140 cm LJFL (Figure 40). This most Indo-Pacific sailfish captured by the longline fishery are likely to be immature. Indo-Pacific sailfish are rarely captured by purse-seine fisheries of the WCPO, with observers reporting a wide size range (Figure 40).

9.3.4   Mortality

Vidaurri Sotelo et al. (2001) estimated the total mortality rate (Z) of EPO sailfish of 1.08.year[-1] using the capture-curve method. Applying Hoenig's length-based method and assuming that 1% of Indo-Pacific Sailfish survive to 13 years, the total mortality (Z) is estimate as 0.354. year[-1].

9.4 Ecology

9.4.1 Habitat preference

Indo-Pacific sailfish are a moderately common billfish in the WCPO. Although epipelagic and an oceanic species, Indo-Pacific sailfish are common around coasts and reefs (Nakamura 1985). Indo-Pacific sailfish display a preference for shallow waters within the mixed layer. They are rarely encountered below the thermocline (Nakamura 1985). Hoolihan (2005) reported that Indo-pacific sailfish spent approximately 85% of their time in the top 10 m of the surface at all times, despite being very little temperature change with increased depth in the study area. The maximum depth of a dive reported by Hoolihan (2005) was less than 30 m. The shallow preference is highlighted by the rapidly increasing relative catch rates from longline sets with less than 10 HBF (Figure 44).

9.4.2 Movements and migration

Broad-scale, regular movements of Indo-Pacific sailfish are recorded. A single size class (modal size of 160 cm EFL (185 cm LJFL) of Indo-Pacific sailfish migrate northwards in the Tsushima current (a branch of the Kuroshio Current) in summer, and two size classes (small fish, 55–110 cm EFL (65–130 cm LJFL) and adults, 145–235 cm EFL (170–270 cm LJFL)) migrate southward in autumn (Nakamura 1985). This suggests a migration of adults northward and a return migration of adults and a new cohort southward. North-south movements of Indo-Pacific sailfish in the EPO also correspond with changes in surface water temperatures, with sailfish following the movement of the 28°C isotherm (Okamoto and Bayliff 2003). Indo-Pacific sailfish may form small schools of similar-sized individuals during long distance movements (Nakamura 1985).

There is no evidence of differences in habitat preferences (depth) between day and night, with very few dives greater than 20 m recorded from eight Indo-Pacific sailfish tagged with PSAT and ultrasonic tags and followed for between 3.5 and 52 hours (Hoolihan 2005).

9.4.3 Diet

Indo-Pacific sailfish are considered a generalist feeder, with gut contents reflecting the relative abundance of local prey species rather than feeding preferences (Rosas-Alayola et al. 2001). Various species of pelagic fishes make up most of the diet, especially schooling fishes such as clupeoid fishes (Nakamura 1985, www.fishbase.org). However, cephalopods and demersal species of fishes (Rosas-Alayola et al. 2002) are also common in the gut contents of sailfish from some regions.

Cooperative feeding behaviours have been observed in Indo-Pacific sailfish. Feeding aggregations of up to 30–40 individual sailfish have been observed around baitfish schools (www.aims.gov.au). Sailfish have been observed to 'ball-up' schools of baitfish near the surface, suddenly raise their large dorsal fish before using their bills to hit prey fish.

9.5 Details of stocks in the WCPO

There is ongoing debate in regards to the number of sailfish species worldwide. While early taxonomic references identify both an Indo-pacific species (*Istiophorus* platypterus) and an Atlantic species (*Istiophorus albicans*) (Nakamura 1985), later research has identified a single, global species of sailfish, *Istiophorus platypterus*. Regardless, sailfish in the Pacific Ocean are largely isolated from the Atlantic and Indian Oceans and are at least a sub-stock.

9.5.1 Stock structure and size

There is evidence to suggest that sailfish in the Pacific Ocean are comprised of eastern and western stocks. There is some evidence that sailfish in the EPO are larger at first maturity and attain larger sizes than those in the WCPO (Nakamura 1985). Pacific-wide catch and CPUE data also suggest at least two an EPO and a WCPO sub-population. However, the lack of definitive growth studies and the limited number of tagged and recaptured sailfish from the WCPO and EPO do not allow definitive stock structure to be identified.

While Indo-Pacific sailfish are considered a highly migratory species, they display more localised movement than other billfish species, suggesting the existence of many small sub-stocks (www.aims.gov.au). Recapture information from previously tagged sailfish the Coral Sea in the WCPO suggested the presence of many small, semi-isolated stocks of sailfish, potentially sustained by the ability to use a wide range of food types and therefore not requiring migrations to follow food sources. (www.aims.gov.au). If small sub-populations exist elsewhere, then the potential of fishing activities impacting on these sub-populations may be relatively high.

No estimates of stock size are available for Indo-Pacific sailfish in the WCPFC.

9.5.2 Recent stock assessments and status

The stock status of Indo-Pacific sailfish is uncertain.

As a result of limited biological information and relatively low catches compared to tunas and other billfishes, formal stock assessments for sailfish are generally lacking. Further, catch information from some sources pooled catches of sailfish and short-billed spearfish together until relatively recently (e.g. Okamoto and Bayliff 2003).

Catches of Indo-Pacific sailfish from the WCPFC have been less than 1,500 mt per years since 1994 (Figure 39). Catches increased from approximately 600 mt in 1996 to exceed 1,400 mt in 2002, before declining. A decline in relative catch rates is also observed from 2002 (Figure 44) although no spatial trends are observed (Figure 43). Median size data of longline captured fish has been stable since the early 1990s at the approximately the size of first maturity for males (175 cm LJFL), but below the size of first maturity for females (200 cm LJFL) (Figure 39). Median size data for purse-seine captured fish displayed and increase to 180 cm LJFL and then a decline to approximately 150 cm LJFL, although length data are limited.

9.6 Fisheries

9.6.1   Major fisheries and occurrence

Sailfish are principally captured by longline fleets in the all oceans (Nakamura 1985, Okamoto and Bayliff 2003). However, limited catches have also reported from troll, harpoon and set-net fisheries. Longline catches from the WCPFC have approached 1,500 mt in recent years (Figure 39), representing an very small component of total longline catches.

Indo-Pacific sailfish are reported from less than 1% of all sets from the purse-seine fishery of the WCPO, with approximately 93% of purse-seine catches of sailfish reported from associated sets (logs, FADs, animals).

9.6.2   Artisanal fishery value

Indo-Pacific sailfish are common in coastal waters and are typically found within 10 m of the surface. However billfish generally contribute an insignificant proportion of artisanal catches in the Pacific Ocean (Dalzell et al. 1996).

9.6.3   Sport and recreational fishery value

In the WCPO, sailfish are a popular sportfish species but secondary to the three species of marlin WCPO. They are regularly encountered by sportfishers in many Pacific Island Countries of the WCPO (Whitelaw 2001) due to their occurrence close to coasts and reefs and shallow distribution. However, details for the size of sportfish catches are currently unavailable.
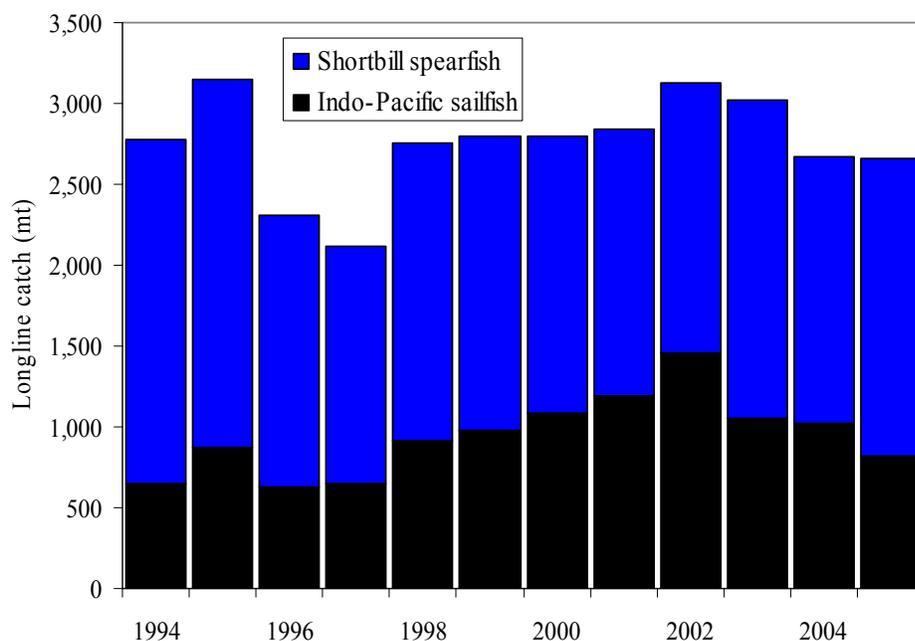
Figure 39. Estimated annual catches of Indo-Pacific Sailfish and Shortbill spearfish by longline vessels in the WCPFC, 1994–2005, excluding the domestic fleets of Indonesia, the Philippines and Taiwan. Source, OFP (2007).
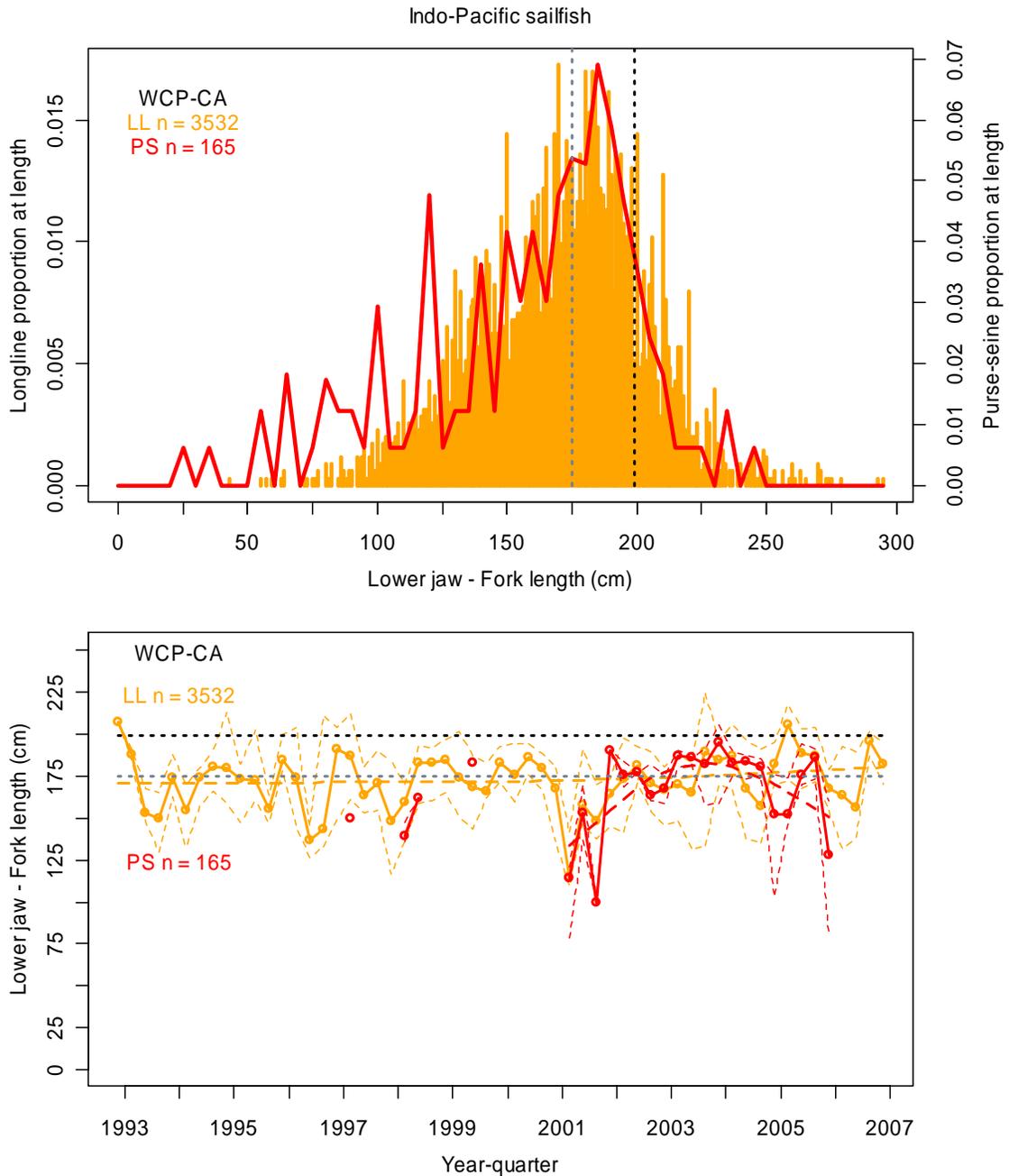
Figure 40. Combined length-frequency distributions (upper figure) and trends in quarterly median size (lower figure) of Indo-Pacific sailfish reported by observers in longline and purse-seine vessels in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery. Thin dashed lines represent the 25th and 75th quartiles of the size data. Heavy dashed lines represent lowess fits to the median size data. Dotted lines represent estimates of size at first maturity for females (black, 200 cm LJFL) and males (grey, 175 cm LJFL) (from Nakamura 1985). In the upper figure, 1 cm and 5 cm size class bins were used for fish from the longline fishery and purse-seine fishery, respectively.
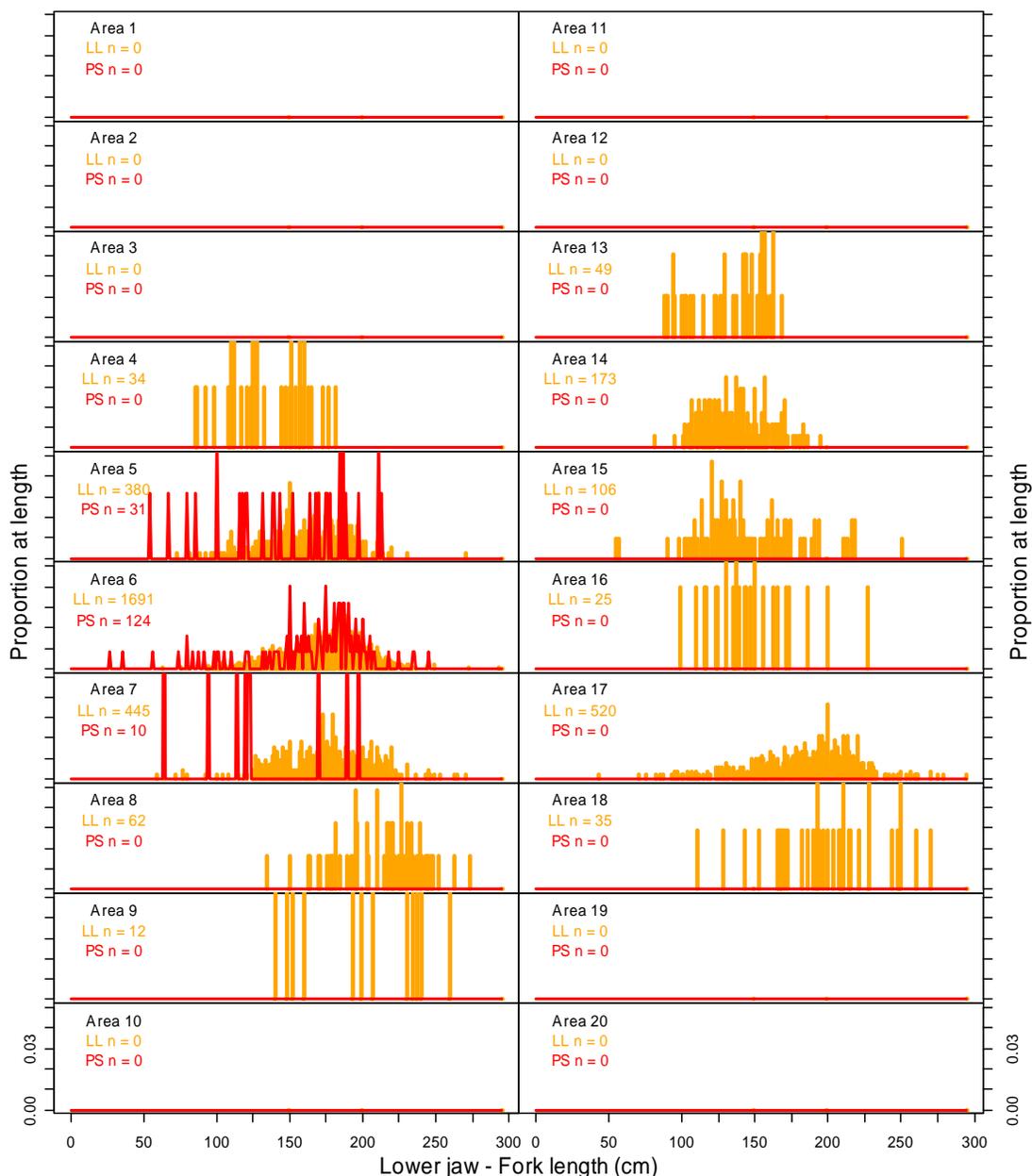
Figure 41. Length-frequency distributions of Indo-Pacific sailfish pooled into 10º latitude bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as lower-jaw to fork-lengths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively.
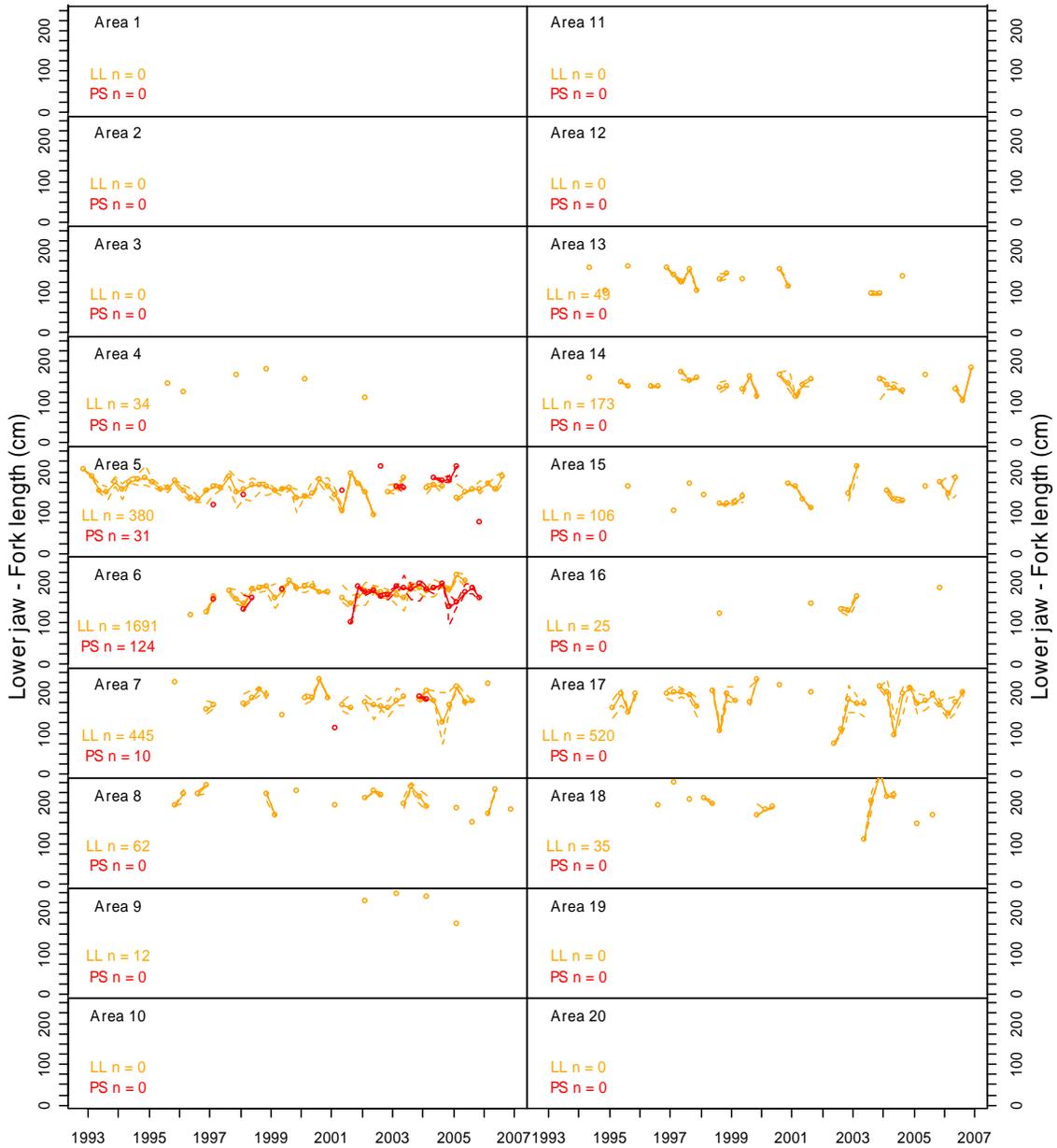
Figure 42. Trends in median size of Indo-Pacific sailfish pooled into 10º latitudinal bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as lower-jaw to fork-lengths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively. Points represent median size, dotted lines represent 25th and 75th quartiles, solid lines represent lowess fits to each data series.
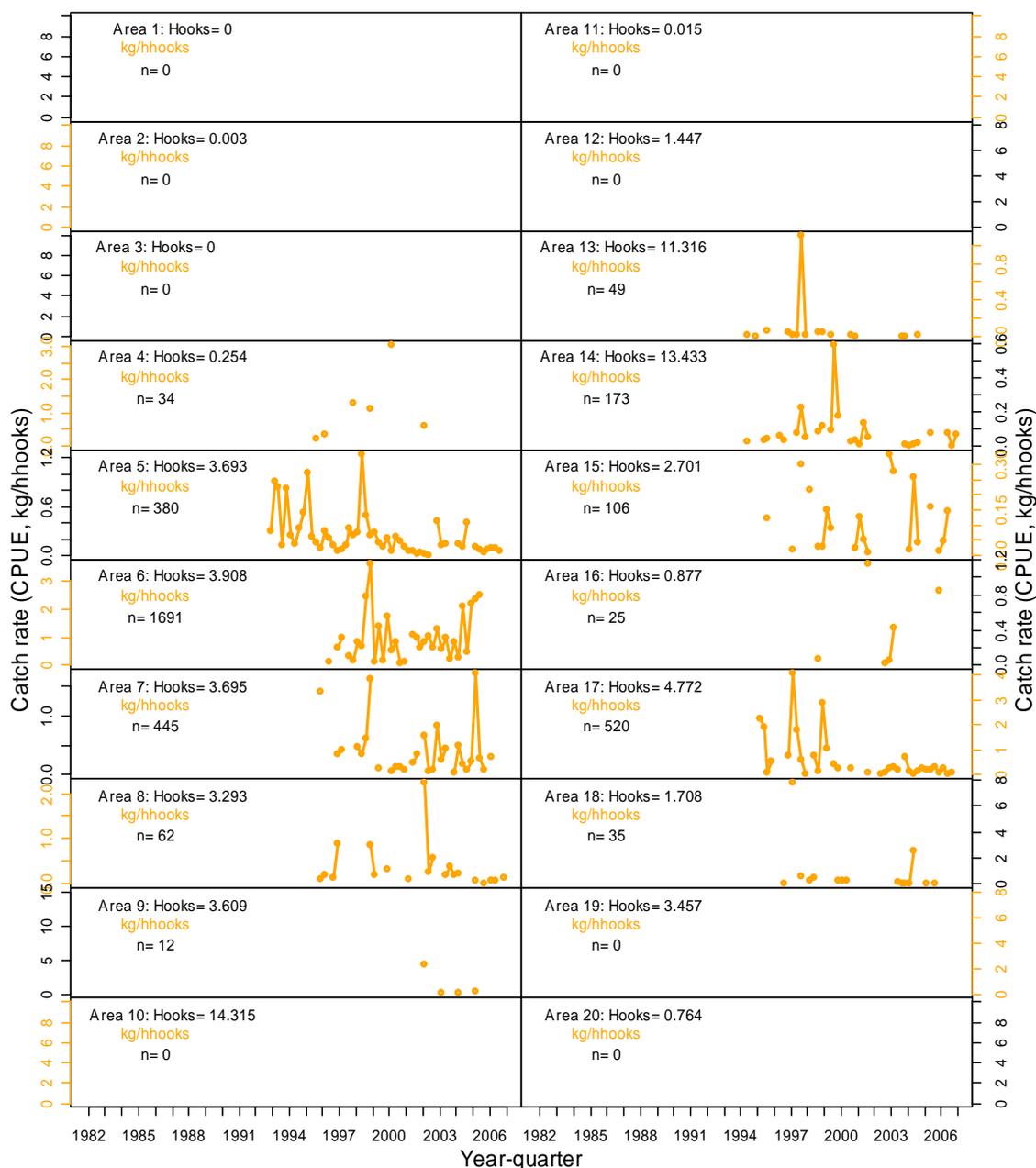
Figure 43. Quarterly catch rates (kg.hhooks^{-1}) of Indo-Pacific sailfish reported by observers pooled into 10° latitudinal bands (Areas) in the WCPO, 1982–2006. Source, SPC observer data base. Hooks, is the total number of observed hooks (millions) in each Area; n, represents the total number of individuals from each method-fishery within each Area. Scales of the y-axes vary among Areas. Left-hand figures are west of 170°E; right hand figures are east of 170°E. Areas 5 and 15, and 6 and 16 represent the 0–10°N and 0–10°S of the equator, respectively. Length-weight relationship: whole weight (kg) = (0.00000119 x LJFL$^{3.22}$) (OFP database).

Figure 44. Changes in relative monthly Indo-Pacific sailfish longline catch rates (blue lines; upper figure, number/hhooks; lower figure, kg/hhooks) for the WCPO under the influence of longitude, latitude, hooks between floats and time period (year-month) as predicted by GLMs, 1991–2006. Sources, observer data held at SPC. Grey lines represent 95% confidence levels. The 'rug' plot along the inside of each x-axis displays the data density along the range of each variable. Weight: $r^2 = 0.311$, adjusted $r^2 = 0.133$; Numbers: $r^2 = 0.353$, adjusted $r^2 = 0.185$.

10. Swordfish (*Xiphias gladius*)
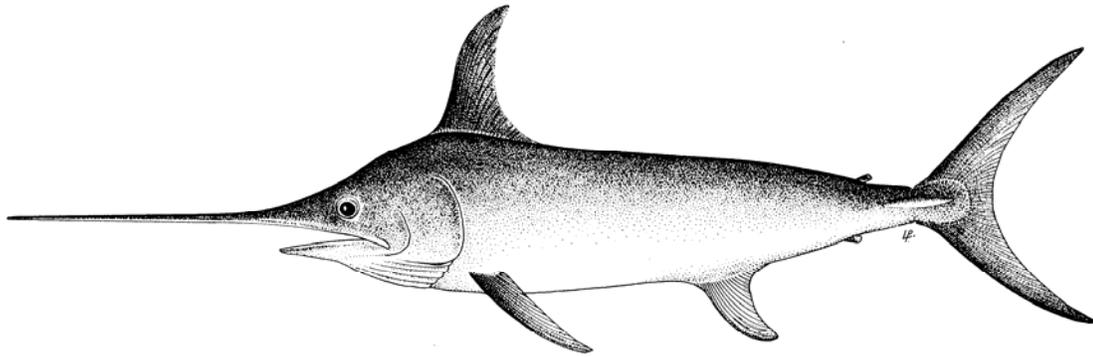
10.1 Description

The swordfish, *Xiphias gladius*, is the only member of the family Xiphidae. Swordfish tend to be brown-black on their dorsal surfaces, fading to white-brown laterally and ventrally. Swordfish are easily recognisable from other billfishes as swordfish lack pelvic fins (Kailola et al. 1993) have a single, large keel situated laterally along the caudal peduncle, with a deep-notch on the dorsal and lateral surfaces of the body immediately before the tail. The bill of swordfish is oval-shaped in cross section in adult fish and lacks teeth (Fierstrine and Voigt 1996). Fish larger than 100 cm FL are generally scaleless and lack a lateral line (Nakamura 1985).

10.2 Distribution

Swordfish has a cosmopolitan distribution, found in all oceans and seas between approximately 45ºN and 45ºS, with highest abundances in sub-equatorial areas. In the Pacific ocean, swordfish have been captured by longline method fisheries between 50ºN and 45ºS in the WCPO and 50ºN and 35ºS in the EPO (Nakamura 1985).

10.3 Biology

10.3.1 Age and growth

Juveniles display a rapid growth rate (Ehrhardt 1992) of approximately 2.3 cm.d^{-1} for at least the first six months of life (Megalofonou et al. 1995), with growth rate reducing after the first year (Ehrhardt 1992). Swordfish are estimated to reach 74 cm LJFL within 6 months (Megalofonou et al. 1995) and 90 cm LJFL by the end of their first year (Sun et al. 2002). Swordfish can reach a total length of more than 450 cm and more than 540 kg (Nakamura 1985). The maximum longevity is estimated at greater than 20 years (Kolody et al. 2006b).

Growth rates for males and females are approximately linear after the first year of life with females growing slightly faster than males (Sun et al. 2002). Females maintain a slightly larger size at age than males throughout life (Table 7), reaching much larger sizes than males. In a recent study of north-west Pacific swordfish, Sun et al. (2002) concluded that males obtain at least 191 cm LJFL and 10 years of age, while females exceed 226 cm LJFL and 12 years of age (Table 7).

VBGF growth parameters for swordfish have been estimated from different regions of the WCPO (Table 6). Differences among estimates may be due to potential differences in growth rates between the (proposed) northern and southern WCPO stocks.

10.3.2   Reproduction

A wide range of sizes and ages at first maturity for swordfish have been reported. In the WCPO males start to become mature at approximately 90 cm EFL (104 cm LJFL), with females maturing at approximately 150 cm EFL (174 cm LJFL) (Young et al. 2003). This corresponds to estimated ages of one year and four years for males and females, respectively (Table 7) (Sun et al. 2002). However, Kolody et al. (2006) assumed that 50% maturity was obtained by 10 years of age (approximately 175 cm LJFL), a larger size and much greater age compared to other studies and in contrast to estimates from New Zealand (50% maturity: males, 101 cm LJFL; females, 221 cm LJFL, (www.fish.govt.nz/en-nz/SOF/Species.htm?code=SWO&list=name).

In the EPO, swordfish reach maturity at about 5 to 6 years of age, at 150–170 cm EFL (175–200 cm LJFL[5]) (IATTC 2004). In the north-eastern Pacific near Hawaii, males (102 ± 2.5 cm EFL, or 118 cm LJFL) are also much smaller than females (144 ± 2.8 cm EFL, or 167 cm LJFL) at sizes when 50% of the population reach first maturity (DeMartini et al. 2000). These differences among studies may reflect differences among (sub-stocks) of Pacific swordfish.

Spawning and the presence of larvae are usually reported in waters with temperatures above 24ºC (Nakamura 1985, Young et al. 2003), and therefore may occur year-round in equatorial waters and during spring and summer in sub-equatorial waters (Nakamura 1985). Based on histological examination, females in the WCPO tend to spawn between September and March in waters off eastern Australia, with a peak between December and February. Mature males were identified between October and May in waters off eastern Australia. Females were more reproductively active in water temperatures above 24ºC and relatively low chlorophyll a concentrations (Young et al. 2003). In the south-west Pacific, spawning was reported west of 158ºE in areas where water temperatures were greater than 24ºC, with no reproductively active females reported further east, in New Zealand waters. (Young et al. 2003).

Due to the presence of oocytes of various stages of maturity within a single ovary, swordfish are likely to be batch spawner, with multiple reproductive events per season (Arocha 2002, Young et al. 2003, IATTC 2004). Fecundity is relatively high with an average of 1.66 million eggs per batch for females 173–232 cm LJFL (Young et al. 2003).

The proportion of females increases with increasing length (IATTC 2004), with all fish greater than 210 cm LJFL off Taiwan being females (Wang et al. 2003). A similar finding was reported by Young et al. (2003) from eastern Australia. This may be a result of the slower growth rates and maximum size of males compared to females, and/or due to the higher levels of natural mortality estimated for males. Regardless, reports of strongly female-biased sex ratios exist (e.g. 1.0:3.13, see http://services.fish.govt.nz/fishresourcespublic/Plenary2007/SWO_07.pdf).

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[5] The relationship between eye-orbit to fork length (EFL) and lower-jaw to fork-length (LJFL) for swordfish is approximately, LJFL = 1.160 x EFL
(www.fishbase.org/PopDyn/LLRelationshipList.php?ID=226&GenusName=Xiphias&SpeciesName=gladius&fc=417).

10.3.3   Recruitment

Observer data from longline the WCPO records swordfish recruiting to longline gears at less than 50 cm LJFL (Figure 47). A strong mode is observed at approximately 65 cm LJFL in overall length-frequency data (Figure 47) suggesting that swordfish may be fully recruited around this size, although the strongest mode is at a size of approximately 130 cm LJFL. This pattern may reflect differences in size structure of swordfish in different areas of the WCPO, and/or differences in targeting by longline fisheries. For example, smaller fish (less than 50 cm LJFL) appear to be confirmed between 20ºN and 20ºS in the WCPO (Figure 48).

Relatively few swordfish, of a wide range of sizes, have been reported by observers on purse-seine fisheries in the WCPO (Figure 47).

10.3.4   Mortality

Several estimates of mortality are available for swordfish in the WCPO. Boggs (1989) estimated a natural mortality rate of $0.22.yr^{-1}$ for swordfish in the Pacific Ocean. Sun et al. (2005) estimated that total (Z) and natural mortality (M) were $0.35.yr^{-1}$ and $0.27.yr^{-1}$ for males, and $0.30.yr^{-1}$ and $0.25.yr^{-1}$ for females, respectively. Kolody et al. (2006a) trialed a range of values of natural mortality estimates between $0.16.yr^{-1}$ and $0.41.yr^{-1}$ that were allowed to vary with age under various stock assessment scenarios (Figure 45). However, the assessment remains preliminary.

10.4   Ecology

10.4.1   Habitat preference

Swordfish are relatively common in sub-equatorial and temperature areas in areas over deep waters (greater than 900 m) where surface temperatures are greater than 12º (Takahashi et al. 2003) to 17ºC (Seki et al. 2002). Highest swordfish abundances are generally found in areas where the surface temperatures are between 18ºC and 22ºC (Nakamura 1985). However, water temperatures above 24ºC and relatively low chlorophyll concentrations are required during spawning (Young et al. 2003). Swordfish are associated with submarine features such as seamounts and canyons (Sedberry and Loefer 2001). Observers in the WCPO purse-seine fishery have reported that more than 95% of all swordfish catches are from associated sets. This suggests that swordfish may aggregate around floating objects (especially at night), possibly to feed.

10.4.2   Movements and migration

Swordfish display both daily and seasonal patterns of movement and are classified as highly migratory.

A single archival-tagged swordfish in the north-east Pacific Ocean remained at depths greater than 200 m in water of 3–6ºC during daytime hours, with occasional deeper dives (maximum of 900 m). [A reported attack on an Alvin submarine at 610 m by a swordfish estimated to be 87 kg (Zarudzki and Haedrich 1975) confirms the deep diving of this species]. At night, this swordfish remained in surface waters of 12-27 ºC (Takahashi et al. 2003). This is similar to findings of Sedberry and Loefer (2001) in the Atlantic Ocean. Carey and Robison (1979) suggested that depth was limited by low oxygen concentrations.

Sedberry and Loefer (2001) tagged 29 swordfish in the North Atlantic Ocean and found most swordfish moved rapidly after tagging (averaging 34 km per day for 10–20 days; maximum of 2,497 km in 90 days) along thermal fronts, with most swordfish found in associated with offshore seamounts and other submarine features. Seki et al. (2002) similarly reported swordfish associated with frontal systems in the north east Pacific. Takahashi et al. (2003) proposed that swordfish in the north-east Pacific move seasonally, spending summer months at high latitudes (40–45ºN) in food rich areas (e.g. the Oyashio cold current) and over-winter in sub-equatorial areas (10–20ºN). A similar seasonal pattern is also likely for south-west Pacific swordfish (e.g. Kolody et al. 2006).

10.4.3 Diet

The diets of swordfish are dominated by squids and other cephalopods throughout their range (south-west Pacific, Young et al. 2006; eastern Pacific, Markaida and Hochberg 2005; North Atlantic, Chancollon et al. 2006). Most cephalopods are likely to be consumed in surface waters at night (Markaida and Hochberg 2005). Fishes are also an important component of the diets of swordfish, with crustaceans rarely found in gut contents. Larval swordfish, as small at 11 mm standard length, have been found with fish larvae in their guts (Govoni et al. 2003).

10.5 Details of stocks in the WCPO

10.5.1 Stock structure and size

There are likely to be at least two or three stocks of swordfish in the Pacific Ocean. Kolody et al. (2006) defined a south-west Pacific stock, while Hinton (2004) assumed an eastern Pacific stock. The differences between the eastern and south-western stocks was based on differences in reproductive characteristics (Sun et al. 2002, Young et al. 2003, IATTC 2004). Lu et al. (2006) identified separate western Pacific and Indian Ocean stocks by DNA sequencing (Lu et al. 2006).

Observer data from the WCPO records high proportions of small swordfish (less than 100 cm LJFL) between 20ºN and 20ºS west of 170ºE, and between 30ºN and 30ºS east of 170ºE (Figure 48). A review of the stock structure of Pacific swordfish is planned for 2008 with Kolody (2006) suggesting that equator defines the boundary between northern and southern WCPFC stocks.

A wide range of potential stock sizes were presented for the south-west Pacific swordfish stock by Davies et al. (2006).

10.5.2 Recent stock assessments and status

Kolody et al. (2006a, b) and Davies et al. (2006) presented preliminary stock assessments for south-west Pacific swordfish using a range of scenarios and two different modelling programmes (MFCL and CASAL). It was concluded that for most plausible model options, total biomass is probably above a level that would sustain maximum sustainable yield (MSY) and fishing mortality is probably below that at MSY. However, there have been recent increases in effort towards this species and stock projections indicate that it is likely that swordfish biomass would be significantly reduced within a short time period (5 years) if

fishing mortality (effort) was maintained at 2004 levels. However, catches of swordfish have been steadily increasing since the late 1980s (Figure 24).

Observer data reveals relatively stable median sizes of swordfish from most 10º bands of latitude in the WCPO, albeit strongly seasonal (Figure 49). However, the median size of longline captured swordfish in the WCPO has be below the size of 50% maturity of females since at least the early 1990s (Figure 47). In addition, longline catch rate shave declined in equatorial areas of the WCPFC while increasing in sub-equatorial areas (Figure 50). However, relative catch rates have been stable at the average level since the late 1990s (Figure 51).

Hinton (2004) stated that swordfish are not overfished in the EPO, due to the stable annual catches recorded since 1989. However, Hinton (2004) cautioned that longline and gillnet fisheries can rapidly change their target species and that trends in standardised swordfish CPUE be monitored to assess changes in stock status.

10.6 Fisheries

10.6.1   Major fisheries and occurrence

In the WCPO, nearly all swordfish are captured by longline fisheries, with targeted swordfish fisheries operating in many areas. Targeted fisheries typically operate shallow longline sets (less than approximately 10 hooks between floats) at night, when swordfish are feeding in surface waters. Other method-fisheries (e.g. gillnet,) operating in other areas (e.g. the EPO).

Catches of swordfish from the WCPFC have increased from approximately 10,000 mt per year in the late 1980s to exceed 20,000 mt per year in recent years (OFP 2007). Similar amounts of swordfish have been captured north and south of the equator in the WCPFC in recent years.

Few records exists for purse-seine captured swordfish in the WCPFC, with approximately 95% of all swordfish catches reported from associated sets (i.e. logs, FADs etc).

10.6.2   Artisanal fishery value

Swordfish are seldom caught by artisanal fishermen (IATTC 2004), likely due to the preference of swordfish for deep waters (greater than 900 m deep). However, artisanal fishing for swordfish (e.g. harpoon fishing) has occurred in some areas (Nakamura 1985, Ward and Elscot 2000).

10.6.3   Sport and recreational fishery value

Limited sportfishing occurs for swordfish in the WCPO (Whitelaw 2001). However, targeted recreational fishing for swordfish does occur in some areas of the WCPO (e.g. New Zealand) (see http://services.fish.govt.nz/fishresourcespublic/Plenary2007/SWO_07.pdf).

Table 6. Estimated VBGF parameters of length (L∞) and growth rate (k) from swordfish studies within the WCPO. (Davies et al. (2006) obtained their estimates from unpublished research reports, see http://services.fish.govt.nz/fishresourcespublic/Plenary2007/SWO_07.pdf).

Source	WCPO Area	Sex	L∞ (LJFL cm)	K (yr^{-1})
Sun et al. (2002)	Taiwan	Males	213	0.086
		Females	301	0.040
Young et al. (2003)	Eastern Australia	Males	249	0.130
		Females	323	0.082
Davies et al. (2006)	South-west Pacific	Combined	256	0.102

Table 7. Estimated lengths at age of swordfish in the Pacific Ocean. Estimates are based on 293 males and 334 females from waters near Taiwan. Source, Sun et al. (2002). Weights estimated from the length-weight relationships for swordfish from, 1, New Zealand waters (a = 0.0078, b = 3.21), 2, New Zealand waters (a = 2.237 x 10^{-5}, b = 2.896) (Griggs and Richardson 2005), and 3, Venezuela (a = 2.991 x 10^{-6}, b = 3.2941) (Eslava et al. 2006).

		Males				Females		
Age (years)	LJFL (cm)	Weight (kg)			LJFL (cm)	Weight (kg)		
		1	2	3		1	2	3
1	88.5	14	10	8	90.4	15	10	8
2	115.0	32	21	18	116.2	33	21	19
3	133.8	52	32	30	136.5	56	34	32
4	145.2	68	41	40	150.4	76	45	44
5	154.4	83	49	48	162.9	98	57	58
6	161.4	95	55	56	175.3	124	70	74
7	167.8	108	62	64	186.4	151	84	90
8	176.9	128	72	76	195.8	177	97	106
9	185.2	148	83	88	204.6	204	110	123
10	191.6	165	91	99	214.2	237	126	142
11	-				220.6	260	137	157
12	-				226.6	283	148	172
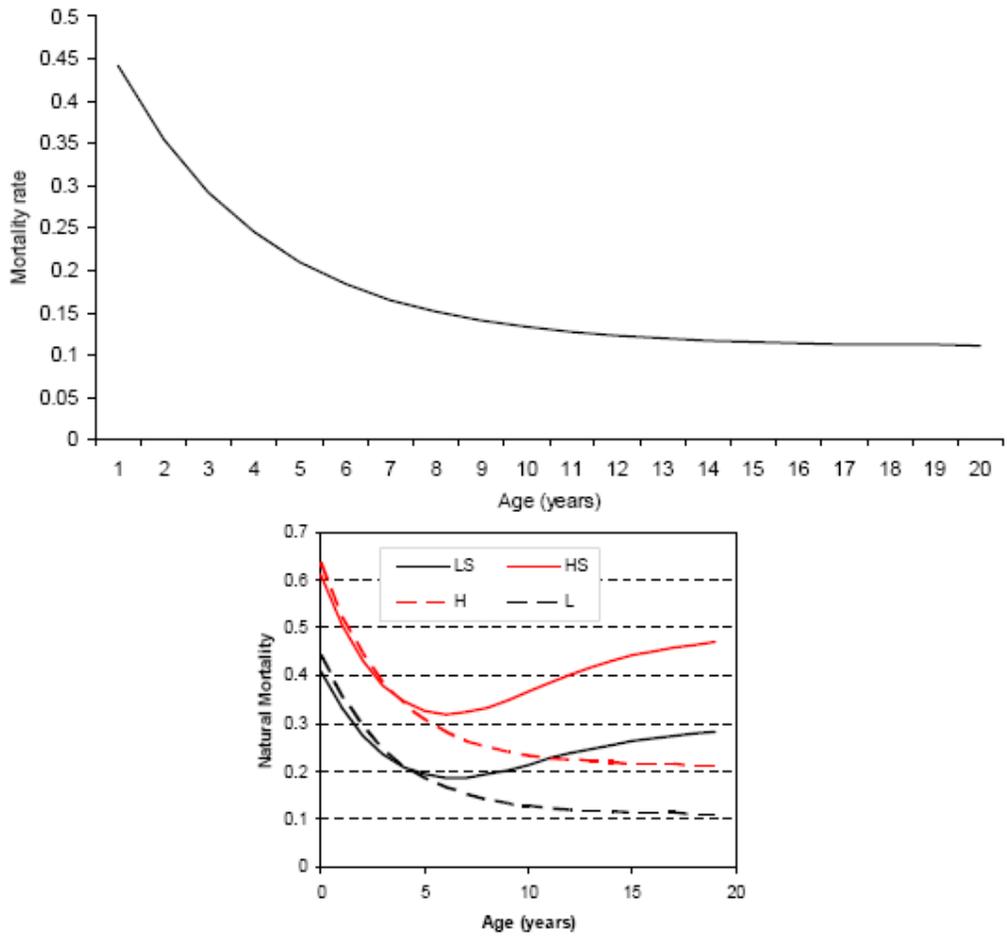
Figure 45. Natural mortality estimates for swordfish in the south-west Pacific Ocean. Upper figure, age-specific natural mortality of south-west Pacific Swordfish as used by Davies et al. (2006). Lower figure, alternative swordfish natural mortality vectors (annual units) used in different the stock assessment scenarios undertaken by Kolody et al. (2006a).
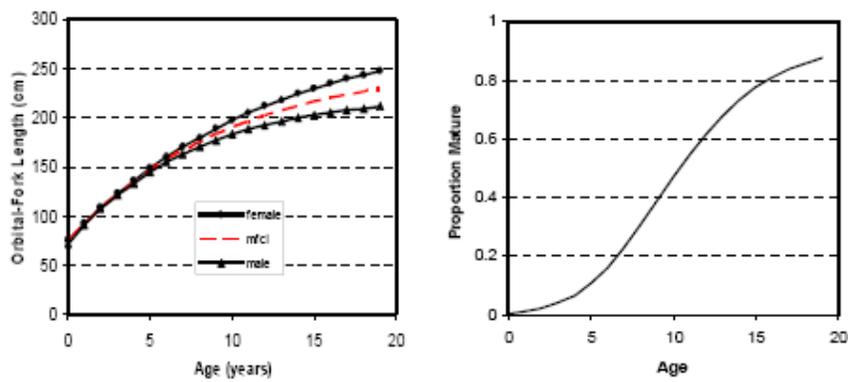
Figure 46. Length-at-age (left figure) and maturity-at-age for females (right figure) of south-west Pacific swordfish. From Kolody et al. (2006a).
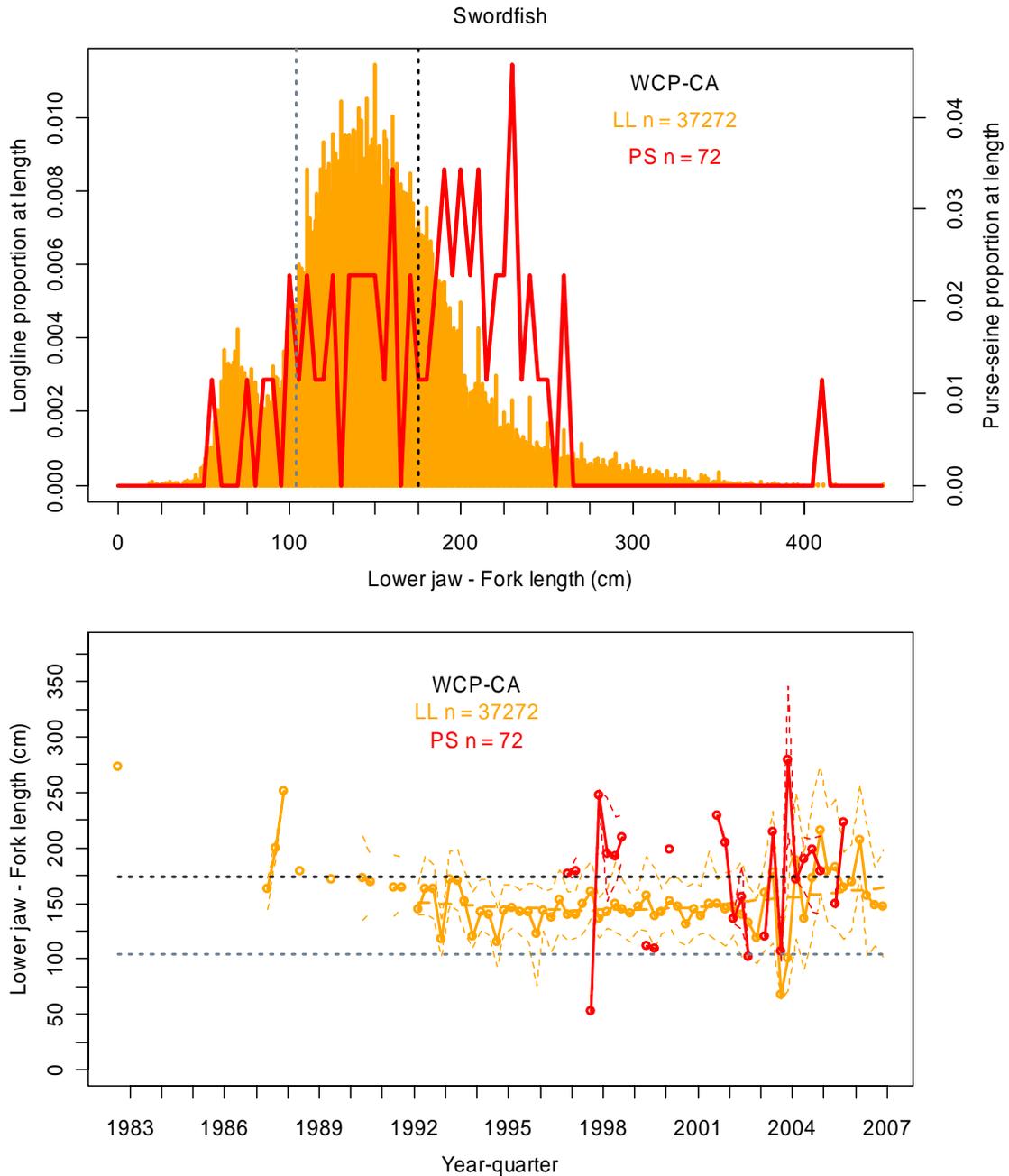
Figure 47. Combined length-frequency distributions (upper figure) and trends in quarterly median size (lower figure) of swordfish reported by observers in longline and purse-seine vessels in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery. Thin dashed lines represent the 25th and 75th quartiles of the size data. Heavy dashed lines represent lowess fits to the median size data. Dotted lines represent estimates of size at first maturity for females (black, 174 cm EFL) and males (grey, 104 cm EFL) (from Young et al. 2003, for the western Pacific). In the upper figure, 1 cm and 5 cm size class bins were used for fish from the longline fishery and purse-seine fishery, respectively.
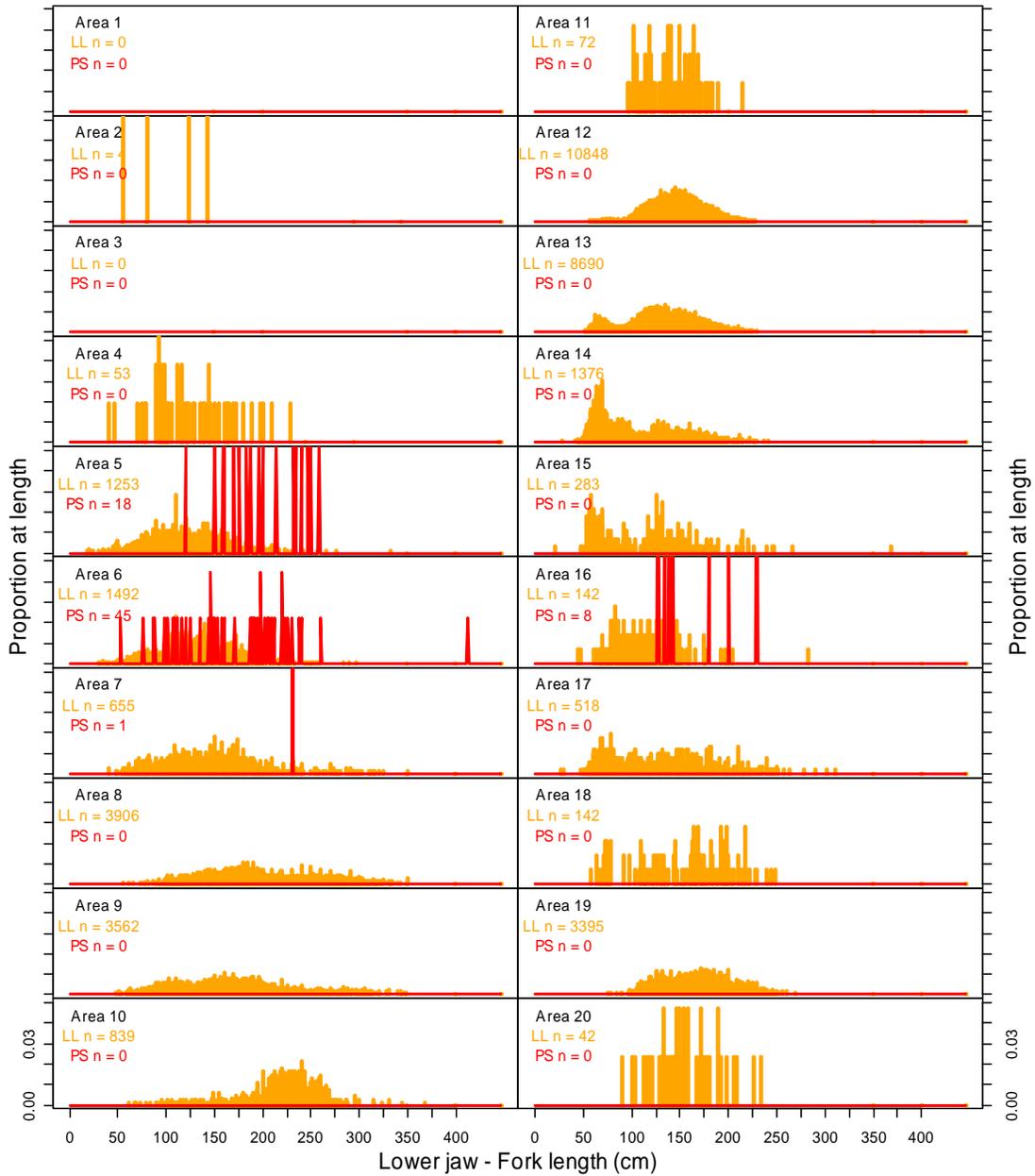
Figure 48. Length-frequency distributions of swordfish pooled into 10º latitude bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as fork lengths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively.
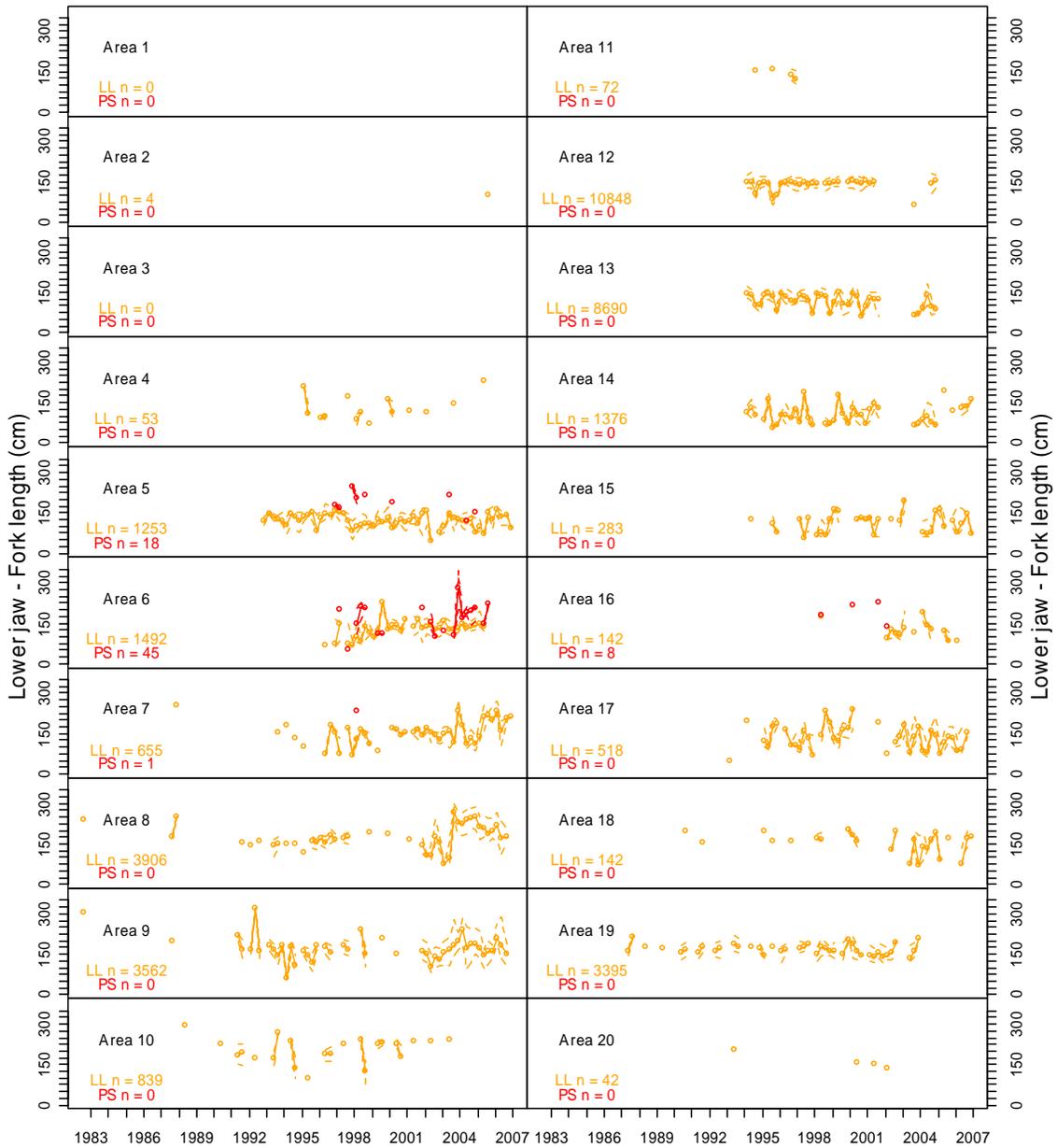
Figure 49. Trends in median size of swordfish pooled into 10º latitudinal bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as lower-jaw to fork-lengths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively. Points represent median size. Dotted lines represent 25th and 75th quartiles of each data series.
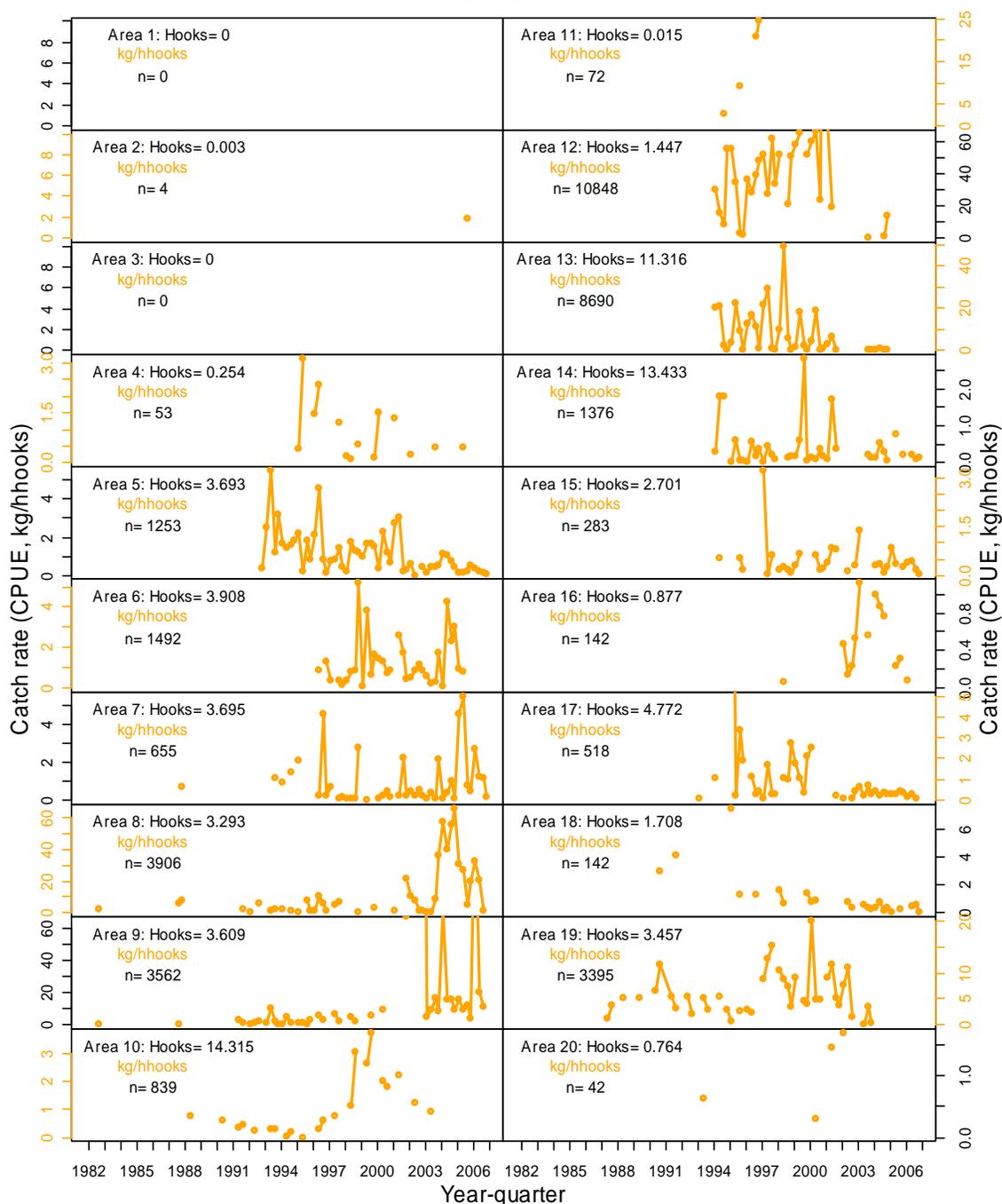
Figure 50. Quarterly catch rates (kg.hhooks^{-1}) of swordfish reported by observers pooled into 10º latitudinal bands (Areas) in the WCPO, 1982–2006. Source, SPC observer data base. Hooks, is the total number of observed hooks (millions) in each Area; n, represents the total number of individuals from each method-fishery within each Area. Scales of the y-axes vary among Areas. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively. Length-weight relationship: whole weight (kg) = (0.0075 x LJFL$^{3.062}$)/1000 (Tsimenides and Tserpes 1989).
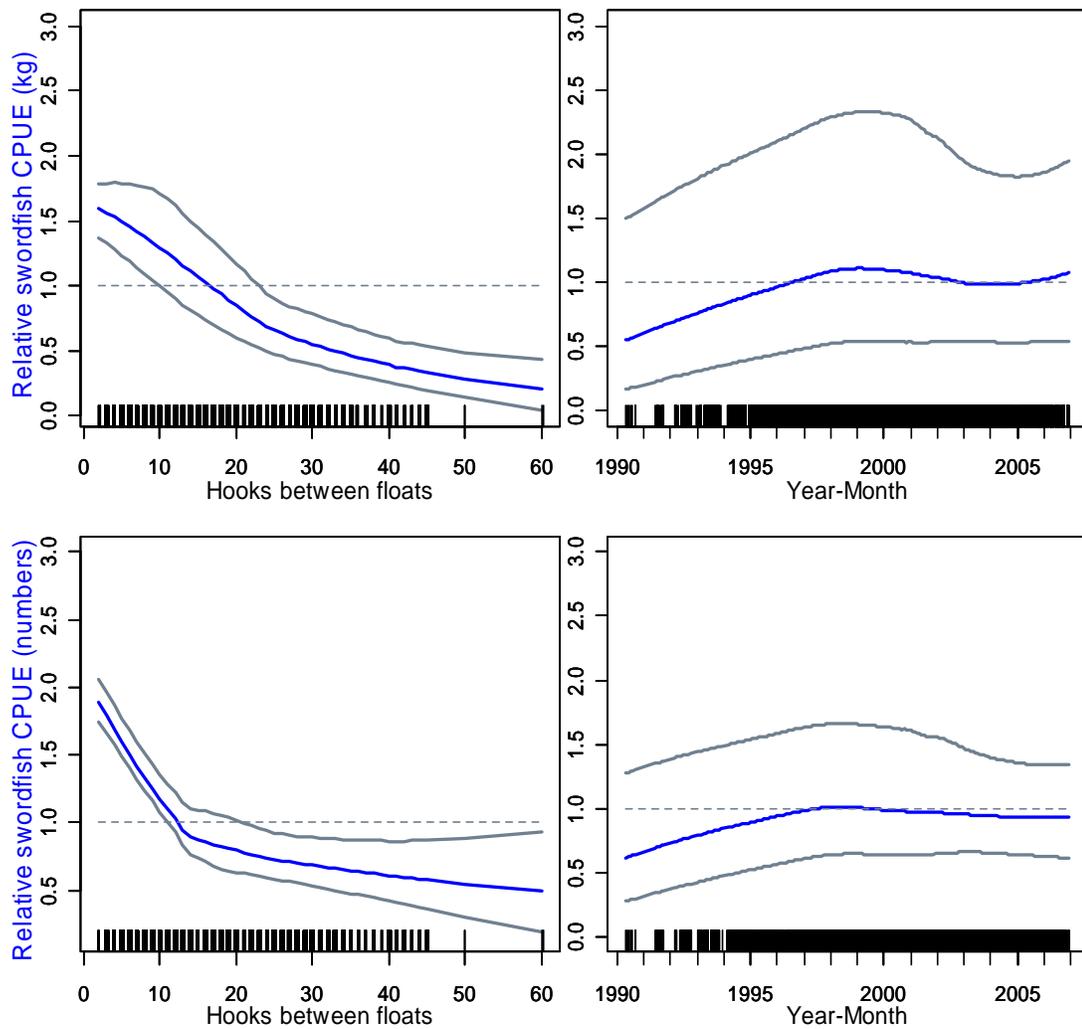
Figure 51. Changes in relative monthly swordfish longline catch rates (blue lines; upper figure, number/hhooks; lower figure, kg/hhooks) for the WCPO under the influence of longitude, latitude, hooks between floats and time period (year-month) as predicted by GLMs, 1991–2006. Sources, observer data held at SPC. Grey lines represent 95% confidence levels. The 'rug' plot along the inside of each x-axis displays the data density along the range of each variable. Weight: $r^2 = 0.223$, adjusted $r^2 = 0.162$; Numbers: $r^2 = 0.297$, adjusted $r^2 = 0.241$.

11. Shortbill spearfish (*Tetrapturus angustirostris*)
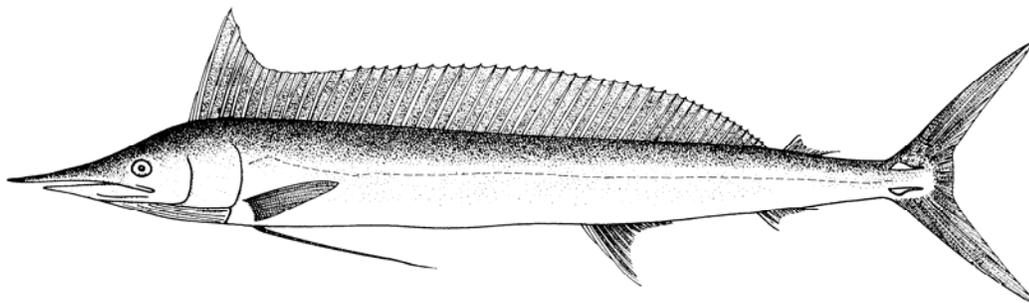
11.1 Description

Shortbill spearfish are a relatively small species of billfish that rarely exceed 200 cm LJFL and 50 kg (Nakamura 1985). This species is slender compared to other billfish and is easily identified from other species as the upper jaw (bill) is only marginally longer than its lower jaw. Body colour is similar to most other billfish; dark blue on the dorsal surface and silver-white on the ventral surface.

11.2 Distribution

Shortbill spearfish are relatively rare (Nakamura 1985) and information about distribution is generally lacking. Shortbill spearfish are found the tropical and subtropical areas of the Pacific and Indian Oceans. In the WCPO, records exist between at least 40ºN and 40ºS, although logsheet records north of the equator area rare. This is despite the highest densities reported in the western Pacific between 15–30ºN between November and February (Nakamura 1985). The lack of logsheet records may be due to Indo-Pacific sailfish and spearfish being reported together by the FAO and on logsheets of distant water fleets (Skillman, 1989) until 1994 (Okamoto and Bayliff 2003). Consequently, very little information is currently available for this species.

11.3 Biology

11.3.1   Age and growth

No ageing information is currently available for this species. However, the species has a maximum recorded weight of 52 kg (Nakamura 1985) (225 cm LJFL), much smaller than other species of billfish. In the WCPO, very few spearfish are reported below 100 cm LJFL (Figure 52, Figure 53), suggesting a relatively fast growth rate of small fish, similar to other billfish of the genus *Tetrapturus*. Strong modes are observed at approximately 130 cm LJFL and 160 cm LJFL (Figure 52). If these modes represent two year classes then, the growth rate of larger spearfish may approximate 30 cm per year.

Preliminary age and growth studies for a similar species (Mediterranean spearfish, *Tetrapturus belone*) identified 5 age classes, with the fish reaching 104–129 cm TL (87–103 cm LJFL) and 3–5 kg at one year of age (Potoschi 2000).

11.3.2   Reproduction

In the EPO, Okamoto and Bayliff (2003) concluded that female spearfish with gonad indices greater than 4.1 were mature. Based on this information, spearfish in the EPO have a size of first maturity of approximately 115 cm EFL (132 cm LJFL) with nearly all females greater than 125 cm EFL (142 cm LJFL) being mature.

Okamoto and Bayliff (2003) identified that spawning of spearfish in the EPO is likely to occur year-round in the area of 150º–125ºW and 35ºN–15ºS. The highest concentrations of mature fish were found north 5ºN during the second half of the year. In the first, third and fourth quarters of the year, the highest concentrations of mature female spearfish were found south of 10ºS.

The peak in spawning of spearfish in the north western Pacific occurs during the winter months, commencing in November near Taiwan. In the central Pacific Ocean, spawning commences in March and has been reported between 25ºN and 25ºS, based on the presence of larvae and mature females. Spawning is generally associated with surface water temperatures of approximately 25ºC (Nakamura 1985).

11.3.3   Recruitment

Shortbill spearfish start to recruit to the longline fisheries of the WCPO at approximately 100 cm LJFL, becoming fully recruit at approximately 130 cm LJFL (Figure 52). Very few fish below 100 cm LJFL have been reported. This is similar to the size at recruitment estimated in the EPO (Okamoto and Bayliff 2003). Spearfish are rarely reported from the purse-seine fisheries of the WCPO (Figure 52).

11.3.4   Mortality

No published estimates of mortality are currently available for this species. Assuming 1% of spearfish attain an age of 6 years (Potoschi 2000), total mortality (Z) is estimated at 0.77.year⁻¹ using Hoenig's equation.

11.4 Ecology

11.4.1   Habitat preference

Shortbill spearfish are a truly oceanic species, being rarely recorded in coastal waters (Joseph et al. 1974). Based on catch rate data, spearfish are the rarest of the billfish species in the WCPO and other oceans (Joseph et al. 1974, Nakamura 1985).

Spearfish are usually captured in surface waters as indicated by the declining CPUEs with increasing numbers of hooks between floats (Figure 56). However, the highest catch rates are reported in surface waters over depths greater than 900 m (Nakamura 1985). Although rarely captured in the Atlantic, spearfish have been recorded from a depths of 60–180 m (Nakamura and Nakano 1978). Nakamura (1985) suggested 28 that 28ºC was the maximum preferred temperature of this species.

Most records (20 individuals from a total of 26 individuals or 76%) of spearfish from the purse-seine fishery have been reported from associated sets (e.g. logs, FADs).

11.4.2 Movements and migration

Movement information for spearfish is rare. Seasonal movements appear to respond to changes in surface water temperatures, especially the 28ºC isotherm (Nakamura 1985). Most movements are likely to be related to reproduction (Okamoto and Bayliff 2003). The strong seasonality in catch rates in equatorial area of the WCPO suggest regular movement of this species (Figure 55). Limited tagging data exist.

11.4.3 Diet

The diets of juvenile and adult spearfish are composed mainly of fish and cephalopods, although the species that dominate the diet vary from area to area (Nakamura 1985). Deep water species of fishes are generally lacking suggesting a shallower depth distribution for feeding than other billfish species. The size of prey items in spearfish is smaller than for other billfish species (Nakamura 1985). Larvae (2.5–46.9 mm total length) consume mainly flying fish larvae, with copepods being of secondary importance. Larvae commence piscivory at about 7 mm SL (Uotani and Ueyanagi 1997).

11.5 Details of stocks in the WCPO

11.5.1 Stock structure and size

Limited information is known about the stock structure or size of spearfish stocks in the WCPO. However, Skillman (1989) suggested that two stocks of spearfish are likely to exist in the Pacific Ocean, separated by the equator. This was supported by differences in the trends of CPUE from reference areas in the north and south of the Pacific Ocean, with the CPUE in the north Pacific generally being at least two-times greater than in the south Pacific (Skillman 1989).

In the WCPO, relatively low catch rates of spearfish are also reported from equatorial areas (Figure 55). Highest catch rates are recorded between 20–40ºS west of 170ºE, and 10–30ºN and south of the equator east of 170ºE (Figure 55). Observer data from the WCPO indicates that the median size of spearfish increases away from the equator (Figure 53), with strong modes at higher latitudes. Overall, observer data from the WCPO is broadly supportive of the suggestion of Skillman (1989) of separate northern and south stocks of spearfish in the Pacific Ocean. However, the data are not conclusive.

The stock size of spearfish in the WCPO is has not been estimated. Based on catches however, the size of the spearfish stock in the WCPO is likely to be smaller than for marlin and swordfish (Figure 24) but larger than that of Indo-Pacific sailfish (Figure 39).

11.5.2 Recent stock assessments and status

There are no stock assessments for spearfish.

Size data collected by observers in the WCPO (Figure 52) revealed a mild decline in median size until the mid to late 1990s. Median size was then stable at approximately 130 cm LJFL but has increased since the early 2000s. Most spearfish captured by longline fisheries in the

WCPO are above the size of female maturity (Figure 52) and the median size of spearfish has been above the size at female maturity since at least the early 1990s.

Median size data examined in 10º bands of latitude reveal stable or increasing trend in median size (Figure 54). This data suggests that the status of the spearfish stock in the WCPO is likely to be able to sustain the recent levels of fishing effort (mortality). Estimates of total catches of spearfish by the WCPO longline fishery have varied between 1,461 mt and 2,271 mt per year during 1994–2005 with no clear trend (OFP 2007), supporting that the WCPO stock can sustain the levels of effort in recent times. However, relative catch rate have displayed a decline since the early 2000s (Figure 56).

11.6 Fisheries

11.6.1   Major fisheries and occurrence

Nearly all spearfish captured in the WCPO are reported by the longline method fisheries, with little or no catches by the purse-seine fisheries (Figure 52). Approximately 76% of spearfish records from the purse-seine fishery are reported from associated sets. As total catches and CPUE are very low, the importance of spearfish to the longline fisheries in the WCPO is also relatively low. Spearfish are also captured in very low numbers in troll fisheries (Nakamura 1985).

11.6.2   Artisanal fishery value

Spearfish are unlikely to be an important component of artisanal catches in the WCPO, due to the species preferring open ocean areas. However, catches of spearfish in artisanal fisheries of the Indian Ocean are relatively high and the IOTC have suggested that estimating artisanal catches and CPUE for this species will be essential for providing future advice on stock status in this ocean (IOTC 2001).

11.6.3   Sport and recreational fishery value

Due to the offshore distribution and low abundances, the importance of spearfish to sport and recreational fisheries is assumed to be relatively low (Whitelaw 2001).
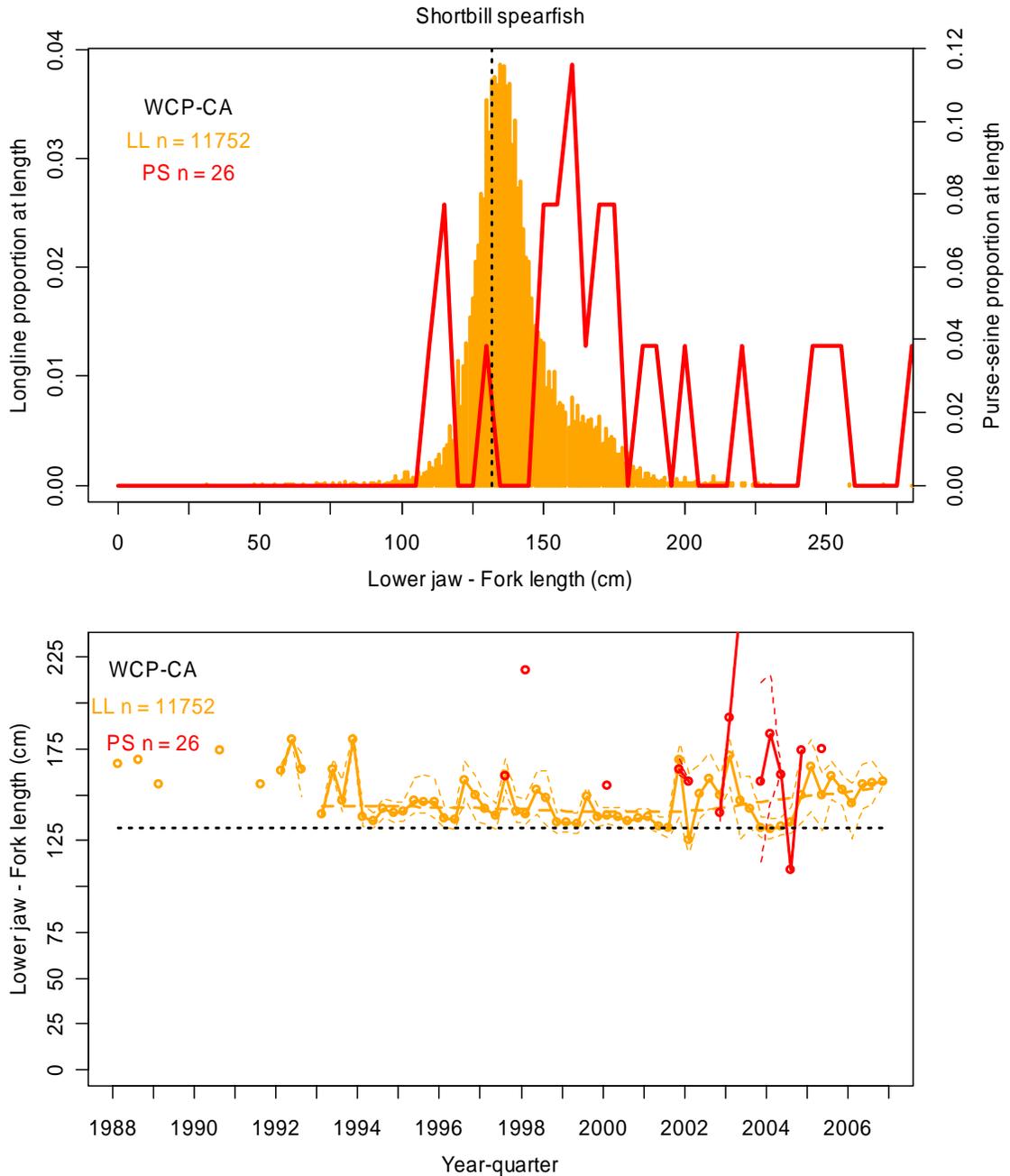
Figure 52. Combined length-frequency distributions (upper figure) and trends in quarterly median size (lower figure) of shortbill spearfish reported by observers in longline and purse-seine vessels in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery. Thin dashed lines represent the 25th and 75th quartiles of the size data. Heavy dashed lines represent lowess fits to the median size data. Dotted lines represent estimates of size at first maturity for female shortbill spearfish (black, 132 cm LJFL) (from Okamoto and Bayliff 2003 for the eastern Pacific). In the upper figure, 1 cm and 5 cm size class bins were used for fish from the longline fishery and purse-seine fishery, respectively.
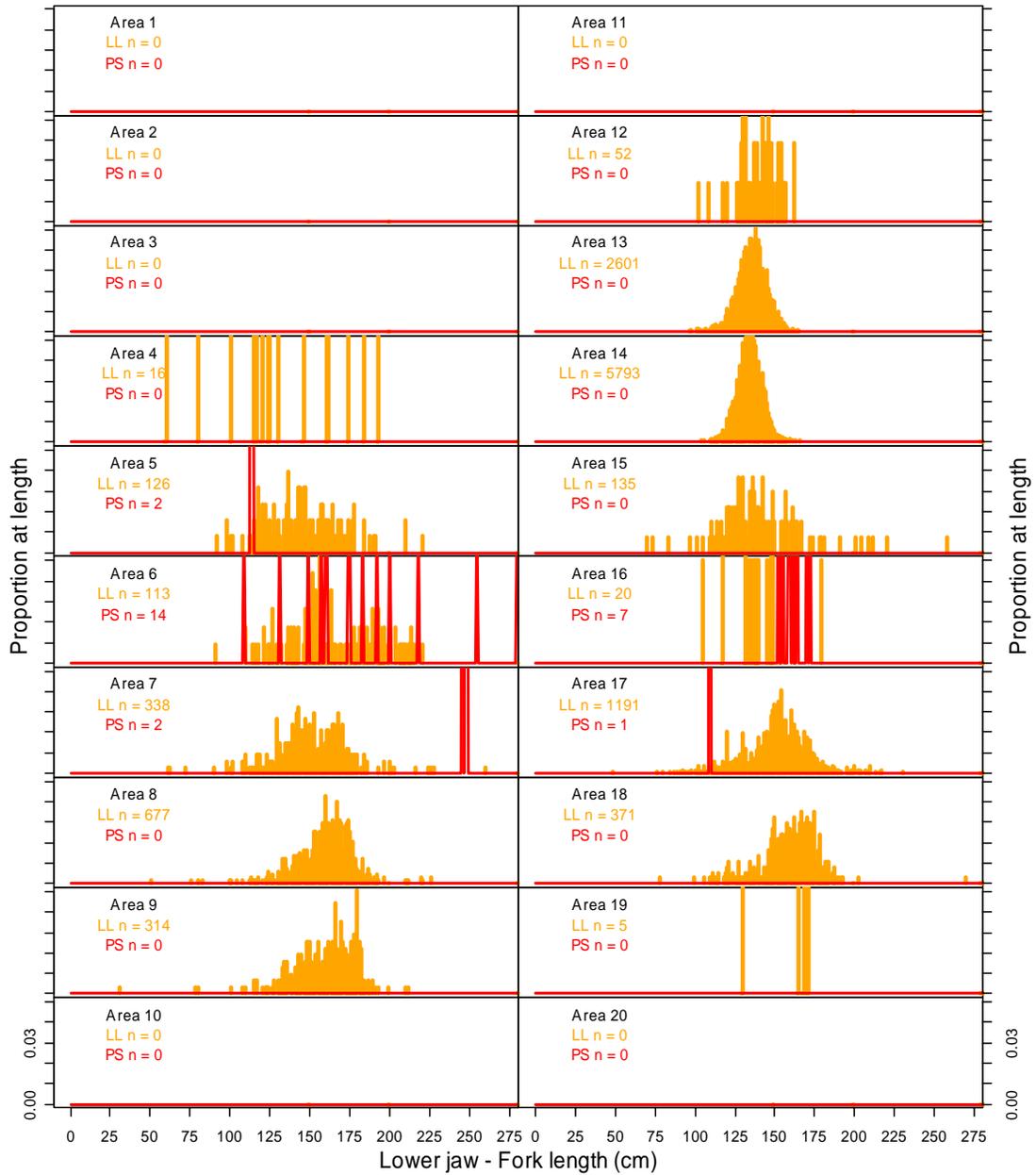
Figure 53. Length-frequency distributions of shortbill spearfish pooled into 10º latitude bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as fork lengths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively.
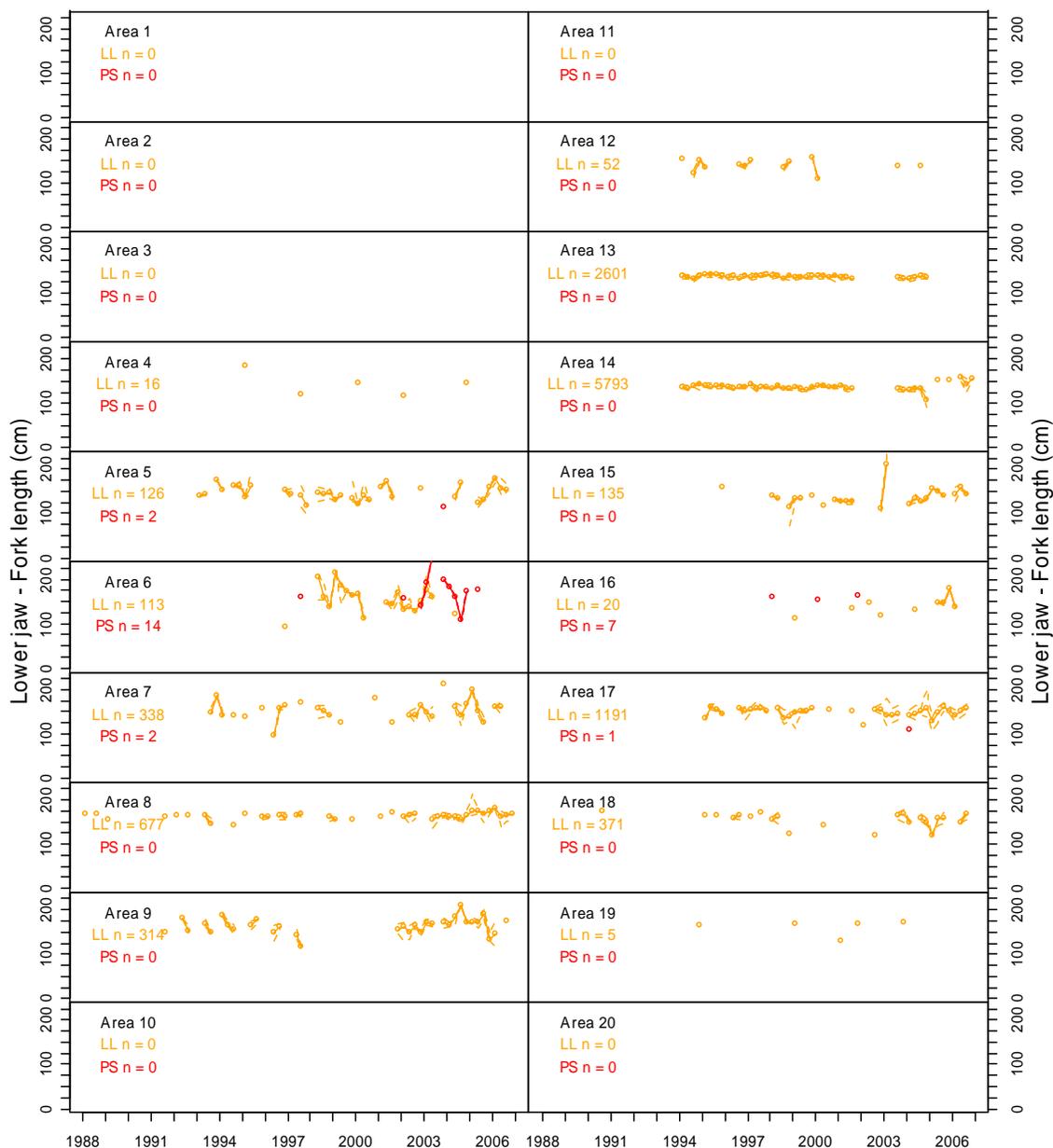
Figure 54. Trends in median size of shortbill spearfish pooled into 10° latitudinal bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as fork lengths. Left-hand figures are west of 170°E; right hand figures are east of 170°E. Areas 5 and 15, and 6 and 16 represent the 0–10°N and 0–10°S of the equator, respectively. Points represent median size and dotted lines represent 25th and 75th of each data series.
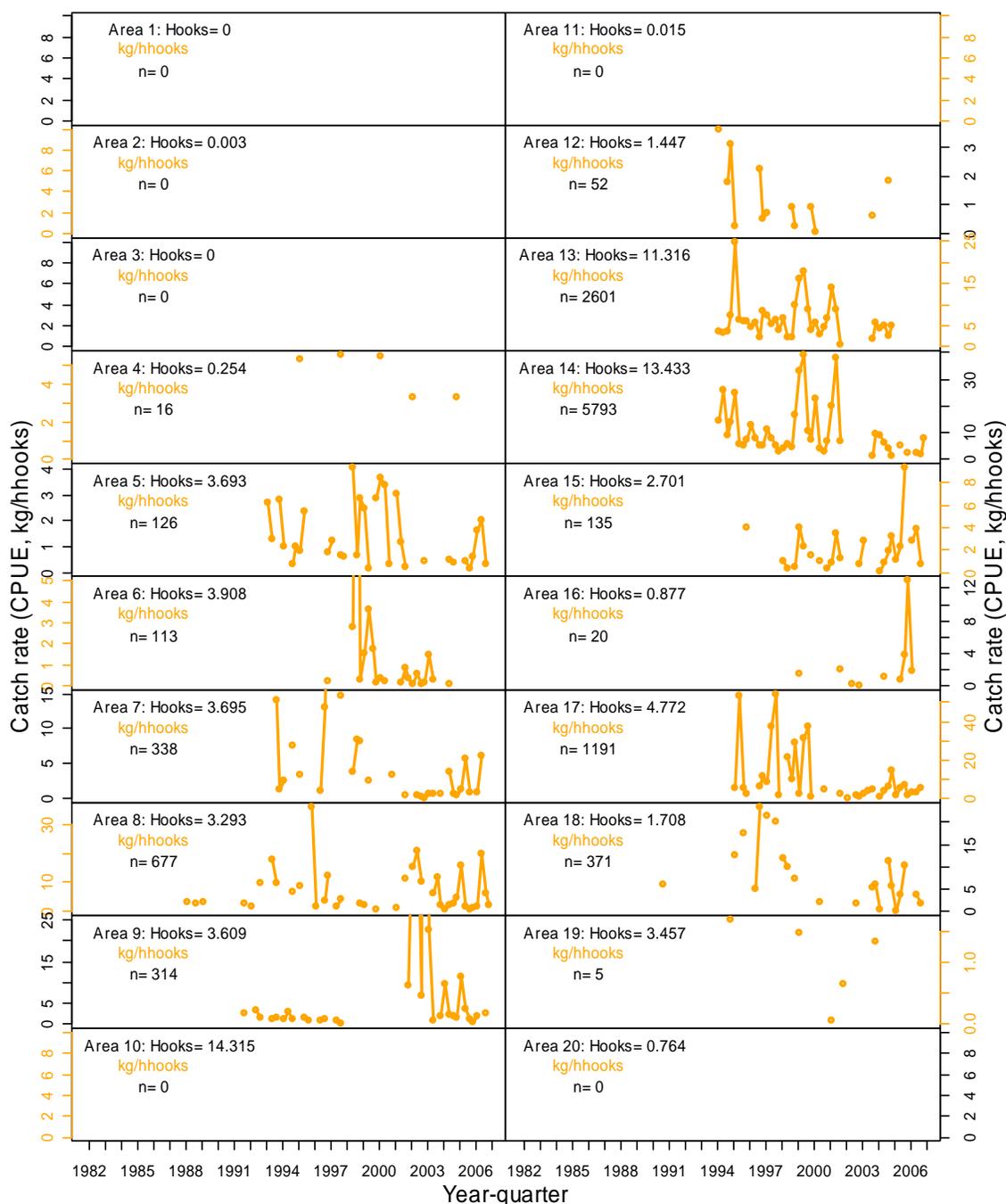
Figure 55. Quarterly catch rates (kg.hhooks⁻¹) of Shortbill spearfish reported by observers pooled into 10º latitudinal bands (Areas) in the WCPO, 1982–2006. Source, SPC observer data base. Hooks, is the total number of observed hooks (millions) in each Area; n, represents the total number of individuals from each method-fishery within each Area. Scales of the y-axes vary among Areas. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0– 10ºS of the equator, respectively. Length-weight relationship: whole weight (kg) = (0.0015 x LJFL$^{3.724}$)/1000 (Squire and Suzuki 1980).
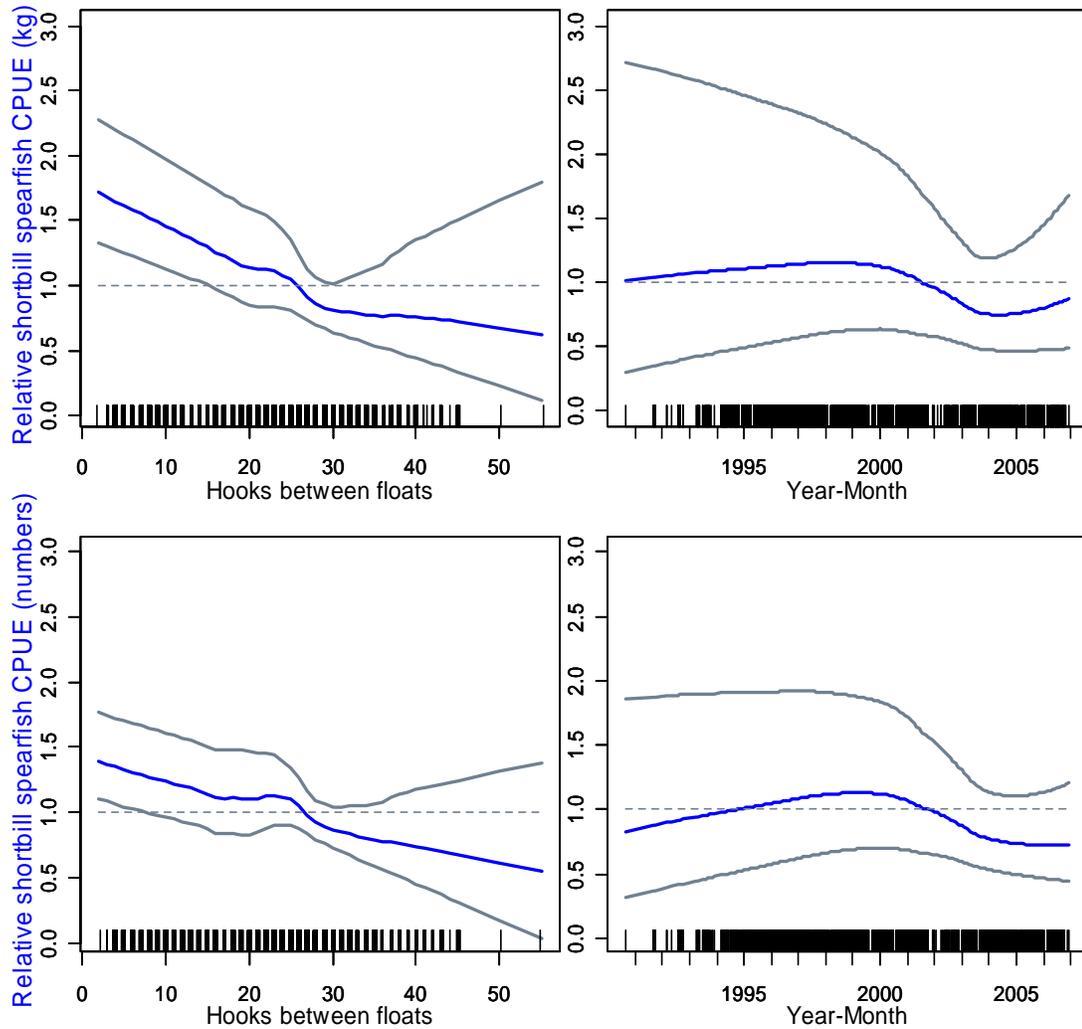
Figure 56. Changes in relative monthly Shortbill spearfish longline catch rates (blue lines; upper figure, number/hhooks; lower figure, kg/hhooks) for the WCPO under the influence of longitude, latitude, hooks between floats and time period (year-month) as predicted by GLMs, 1991–2006. Sources, observer data held at SPC. Grey lines represent 95% confidence levels. The 'rug' plot along the inside of each x-axis displays the data density along the range of each variable. Weight: $r^2 = 0.292$, adjusted $r^2 = 0.207$; Numbers: $r^2 = 0.322$, adjusted $r^2 = 0.241$.

12. Wahoo (*Acanthocybium solandri*)
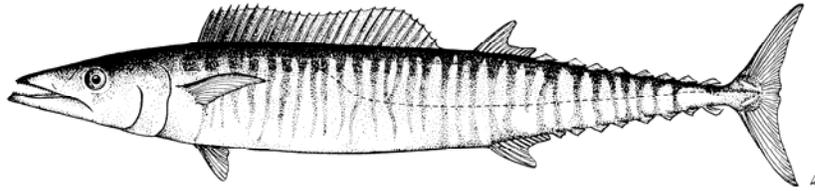
12.1 Description

A large, slender pelagic fish commonly found in tropical and subtropical waters. Blue-green dorsal surface with silver sides and 24–30 cobalt-grey vertical bands that extend well below the lateral line. Large, stiff, un-forked tail. May be confused with Spanish mackerels. However, the wahoo mouth (pre-orbital) is as long as the rest of the head and the lateral line dips sharply midway along the first dorsal fin (Chapman et al. 2006).

12.2 Distribution

Wahoo have a world-wide distribution, occurring in oceanic and pelagic waters of all oceans throughout tropical and warm temperate areas between approximately 45°N and 35°S (Garber et al. 2003). They are also reported from the Mediterranean and Caribbean Seas (www.fishbase.org). Wahoo are common in warm surface waters around coasts and islands and are often associated with floating objects (Bard et al. 1999).

12.3 Biology

12.3.1 Age and growth

Wahoo are fast growing (Hogarth 1976) (Table 8) with a longevity of 5–6 years (Oxenford et al. 2003), although growth rates appear to be highly variable among sites (Devaraj et al. 1999) (Table 8). Wahoo have been reported up to 210 cm FL and 83 kg (Collette and Nauen, 1983). Age estimates from otolith studies on a small number of wahoo (38 males; 93.5–139 cm FL, and 47 females, 87.5–180 cm FL) indicated that all individuals were between one and six years of age (Franks et al. 2000).

No estimates of VBGF growth parameters have been estimated for wahoo. Applying a Walford plot and the size-at-age data presented by Hogarth (1976) (Table 8), L∞ was estimated at approximately 230 cm FL and k at 0.151 year^{-1} for south Pacific wahoo. However, these estimates are preliminary and based on very small sample sizes and therefore estimates of VBGF parameters remain uncertain.

12.3.2 Reproduction

Wahoo in the western central Atlantic start to mature before the end of their first year (Oxenford et al. 2003). The size at 50% maturity was estimated at 102 cm FL for males and less than 94 cm FL for females (Brown-Peterson et al. 2000).

Female wahoo are multiple spawners, capable of spawning every 2–6 days (Brown-Peterson et al. 2000) over an extended breeding period (Oxenford et al. 2003), with the potential for

year-round spawning in equatorial areas. Females are highly fecund (approximately 57 eggs per gramme of body weight) (Brown-Peterson et al. 2000); that is, a 120 cm FL individual (10 kg weight) is estimated to be able to produce approximately 600,000 eggs per batch. Males have been reported in spawning condition for most of each year (Brown-Peterson et al. 2000). Spawning is likely to occur in equatorial areas due to the high proportion of small wahoo reported from these areas of the WCPO (Figure 58).

12.3.3 Recruitment

Wahoo recruit to the longline fishery of the WCPO at approximately 30–50 cm FL, being fully recruited at approximately 120 cm FL (Figure 57). Wahoo are also captured by purse-seine fisheries of the WCPO, recruiting at approximately 30 cm FL and are fully recruited by approximately 70 cm FL (Figure 57). Thus wahoo are less than one year old when they commence recruiting to longline and purse-seine fisheries of the WCPO.

12.3.4 Mortality

Natural mortality for wahoo is assumed to be relatively high due to other life history characteristics of this species (e.g. young age at maturity, moderate longevity, high fecundity, high growth rate) (Oxenford et al. 2003), with Hogarth (1976) estimating M at 0.38 year^{-1}. Assuming 5% of wahoo reach their sixth year of age, total mortality for wahoo is approximately 0.50 year^{-1} using Hoenig's equation. However, this estimate remains highly uncertain until more robust ageing data area available.

12.4 Ecology

12.4.1 Habitat preference

Wahoo are relatively common in tropical and warm sub-equatorial shallow waters, often associated with floating objects. Most wahoo are reported from depths of less than 100 m and may be found near coasts and islands (Collette and Nauen, 1983). The shallow distribution of wahoo is highlighted by the increasing relative catch rates in longline fisheries setting fewer than 12 hooks between floats (HBF) (Figure 63).

Temperature preferences for wahoo have not been reported. However, as most wahoo are reported between 20ºN and 30ºS (Figure 58), it is inferred that they prefer water temperatures greater than approximately 20ºC.

Wahoo are the 6th most commonly reported species from sub-equatorial longline fisheries, and are also very common in tropical shallow and deep longline fisheries. Wahoo are commonly captured by purse-seine fisheries in the WCPO around FADs and logs (Langley et al 2006). Wahoo are reported to form small, loose aggregations, although large wahoo may be solitary (Collette and Nauen, 1983).

12.4.2 Movements and migration

Wahoo are considered a highly migratory species (Garber et al. 2003). Limited tagging studies have been undertaken and recaptures are rare. Genetic studies of wahoo suggest a high degree of mixing and thus movements over large distances are likely to be relatively common (Garber et al. 2003).

12.4.3 Diet

Wahoo are a predatory species and their diet consists mainly of fish and squids, with frigate mackerel dominating the diet in a study conducted in the Gulf of Mexico and along the south-eastern United States (Manooch and Hogarth 1983). Allain (2003) identified that fish, squid and shrimps made up more than 80% of the diet of wahoo sampled mainly from waters of New Caledonia and French Polynesia, with more than 68% (by weight) of the diet consisting of epi-pelagic/pelagic prey, further supporting their shallow distribution. Small prey are unlikely to compose a large proportion of the diet as wahoo lack gill rakers.

12.5 Details of stocks in the WCPO

12.5.1 Stock structure and size

Stock structure of wahoo is unknown. In the WCPO, wahoo are commonly reported between 10ºN and 30ºS, although records exist for wahoo between 20ºN and 40ºS (Figure 58). There is a trend for fewer, smaller wahoo from equatorial areas of the WCPO, and larger fish in areas south of 20ºS suggesting that a single stock may exist in the WCPO. However, there is the potential for the eastern WCPO stock boundary to extend into the EPO, similar to the extensive spatial extent of a single wahoo stock in the western central Atlantic (Oxenford et al. 2003) and other areas (Garber et al. 2003).

The size of the wahoo stock in the WCPO is unknown.

12.5.2 Recent stock assessments and status

The stock status of wahoo in the WCPO is uncertain and no formal stock assessments exist for wahoo in the WCPO or globally. An analysis of the main trends in the data available at SPC is presented below.

Across the WCPO, the median size of wahoo from longline fisheries has been relatively stable at approximately 120 cm FL since the late 1990s (Figure 57). This is above the size estimated at 50% maturity (♂: 102 cm FL, ♀: 94 cm FL, Brown-Peterson et al. 2000). Stable median sizes of wahoo are observed in most areas of the WCPO (Figure 59), although size data is limited in many areas. Catches and catch rates of wahoo of longline fisheries in the WCPO have displayed increasing trends (Figure 61), with recent catches approaching 5,000 mt per year. GLMs on observer data suggested that the catch rates in numbers per hundred hooks has been relatively stable across the WCPO since at least the early 1990s, although a trend of declining catch rates in terms of weight (as kg.hhooks^{-1}) is observed (Figure 63), suggesting that fish size is decreasing.

The median size of wahoo captured from the purse-seine fisheries of the WCPO has declined since 2000, from approximately 90 cm FL to 75 cm FL (Figure 57 and Figure 59), below the estimated size at 50% maturity. However, it is uncertain if these declines in median size reflect an impact of fishing or increases in recruitment of wahoo, especially if smaller (and younger) wahoo are more common in equatorial areas of the WCPO (Figure 63). Catches and catch rates of wahoo estimated from the WCPO purse-seine fisheries have been stable or increasing since the late 1990s (Figure 60) and estimated catches have not exceeded 500 mt per year.

Due to their low age at maturity, suspected rapid growth rate, moderate longevity and high fecundity, it is likely that wahoo may be relatively robust to fishery exploitation. Nonetheless, Devaraj et al. (1999), concluded that wahoo are likely to be over-exploited in coastal areas of India. Based on frequency of capture, the total stock size of wahoo is likely to be significantly smaller than for any of the main species of tunas and common shark and billfish species. Given the uncertainties in biological parameters and catches, the stock status of wahoo in the WCPO is uncertain and a precautionary approach to exploitation is recommended.

12.6 Fisheries

12.6.1 Major fisheries and occurrence

Wahoo are reported from longline and purse-seine fisheries of the WCPO (Langley et al. 2005a) (Figure 57) and elsewhere (e.g. Beerkircher 2005). Wahoo are an important component of the retained bycatch in many longline fisheries, particularly those in the sub-equatorial WCPO. Domestic longline fleets target wahoo in some areas of the WCPO (e.g. Niue) at least at certain times of the year. Estimates of annual longline catches of wahoo in the WCPO steadily increased from 2,000 mt in 1994 to more than 4,500 mt in 2005 (Figure 61).

Wahoo are often discarded by purse-seine fisheries of the WCPO (observer data held at SPC). Catches of wahoo are estimated to be relatively small, with catches increasing from approximately 50 mt to more than 300 mt per year since 1995 (Figure 60). From observer data, approximately 97% of purse-seine records of wahoo catches are reported from associated sets (logs, FADs, animals), with catch rates of wahoo generally being much higher from associated sets than from unassociated sets.

Wahoo are also likely to represent a small component of the retained catch of pole-and-line fisheries (pers. obs.). Wahoo contribute an unknown proportion of catches by fisheries of Indonesia and the Philippines.

12.6.2 Artisanal fishery value

Due to their near-shore occurrence and preference for shallow waters, wahoo are an important component of the artisanal catch from the WCPO and are captured on a wide range of gears (Tafatu 2007).

12.6.3 Sport and recreational fishery value

Wahoo are a prized gamefish in the WCPO (Whitelaw 2001) and elsewhere (Beerkircher 2005).

Table 8. Size- at- age estimates for wahoo from the western central Atlantic (Hogarth 1976, length-frequency) and the Bahamas (Brown-Peterson et al. 2000). All lengths as FL (cm).

Age (years)	Hogarth (1976)	Brown-Peterson et al. (2000)
1	112	
2	128	102
3	141	
4	153	
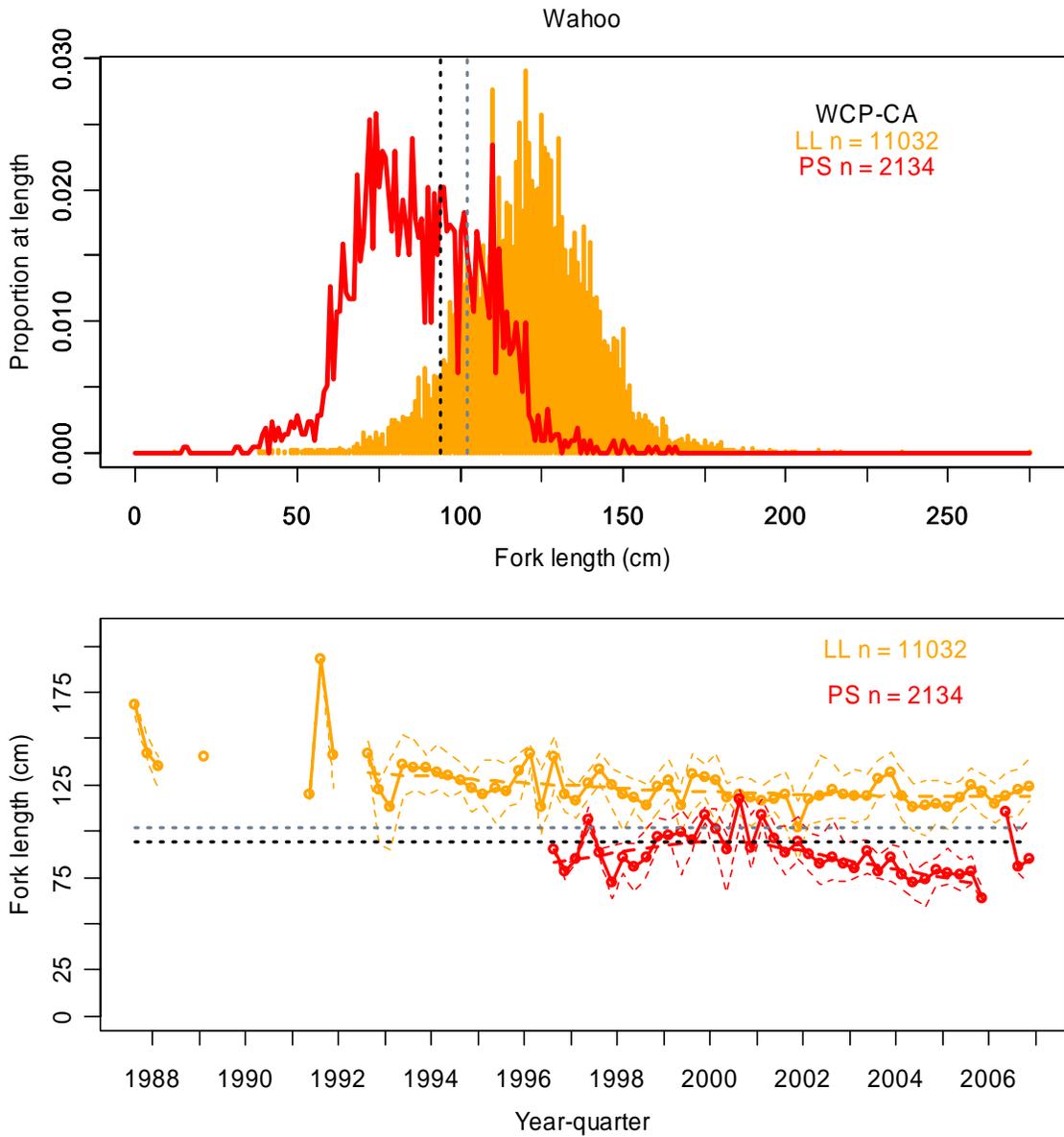
Figure 57. Combined length-frequency distributions (upper figure) and trends in quarterly median size (lower figure) of wahoo reported by observers in longline and purse-seine vessels in the WCPO, 1984–2006. Source, SPC observer data base. All sizes as fork lengths. n, represents the total number of individuals from each method-fishery. Thin dashed lines represent the 25th and 75th quartiles of the size data. Dashed lines represent lowess fits to the median size data. Dotted lines represent estimates of size at 50% maturity for females (black, 94 cm FL) and males (grey, 102 cm FL) (from Brown Peterson et al. 2000).
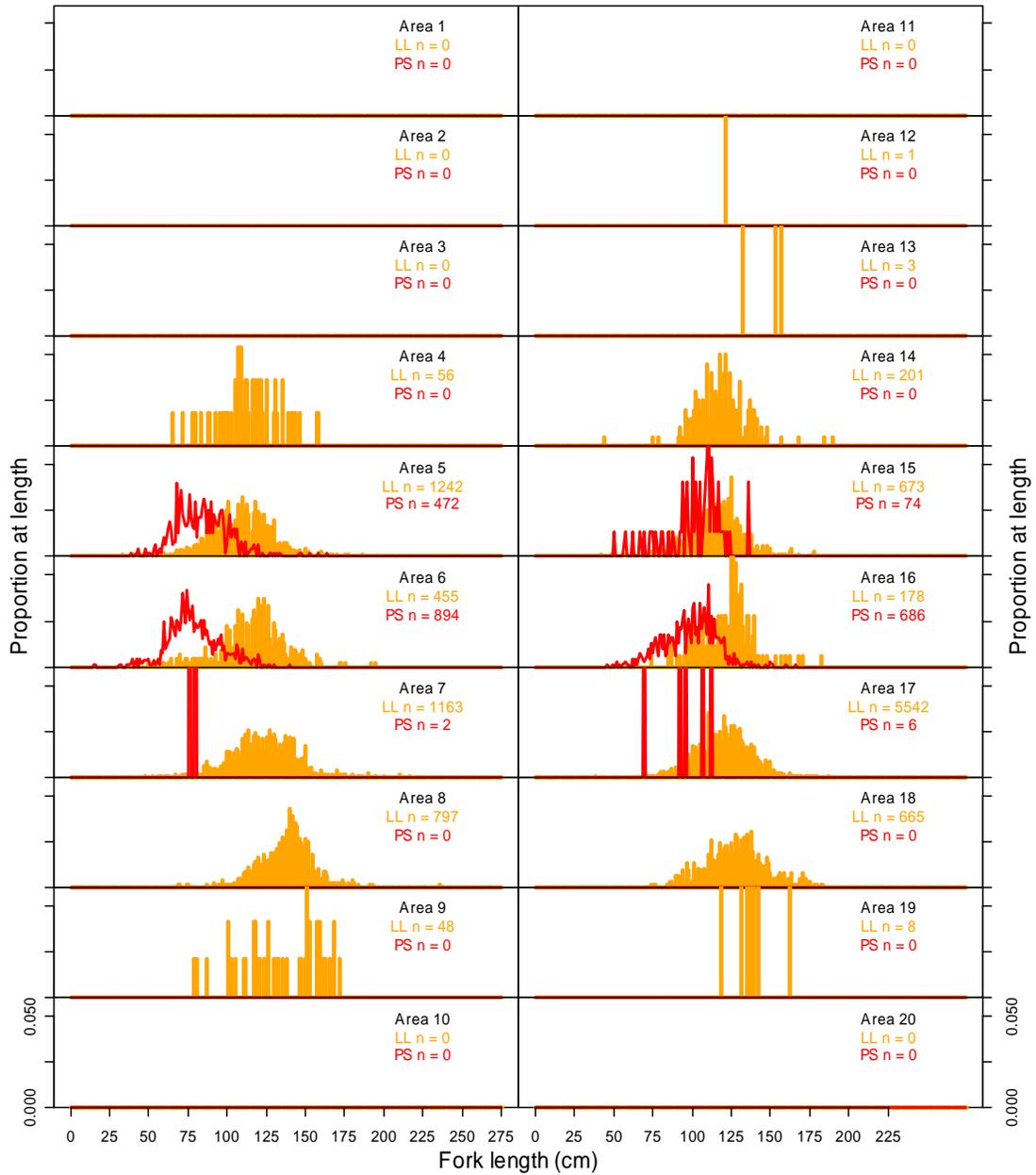
Figure 58. Length-frequency distributions of wahoo pooled into 10º latitude bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as fork lengths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively.
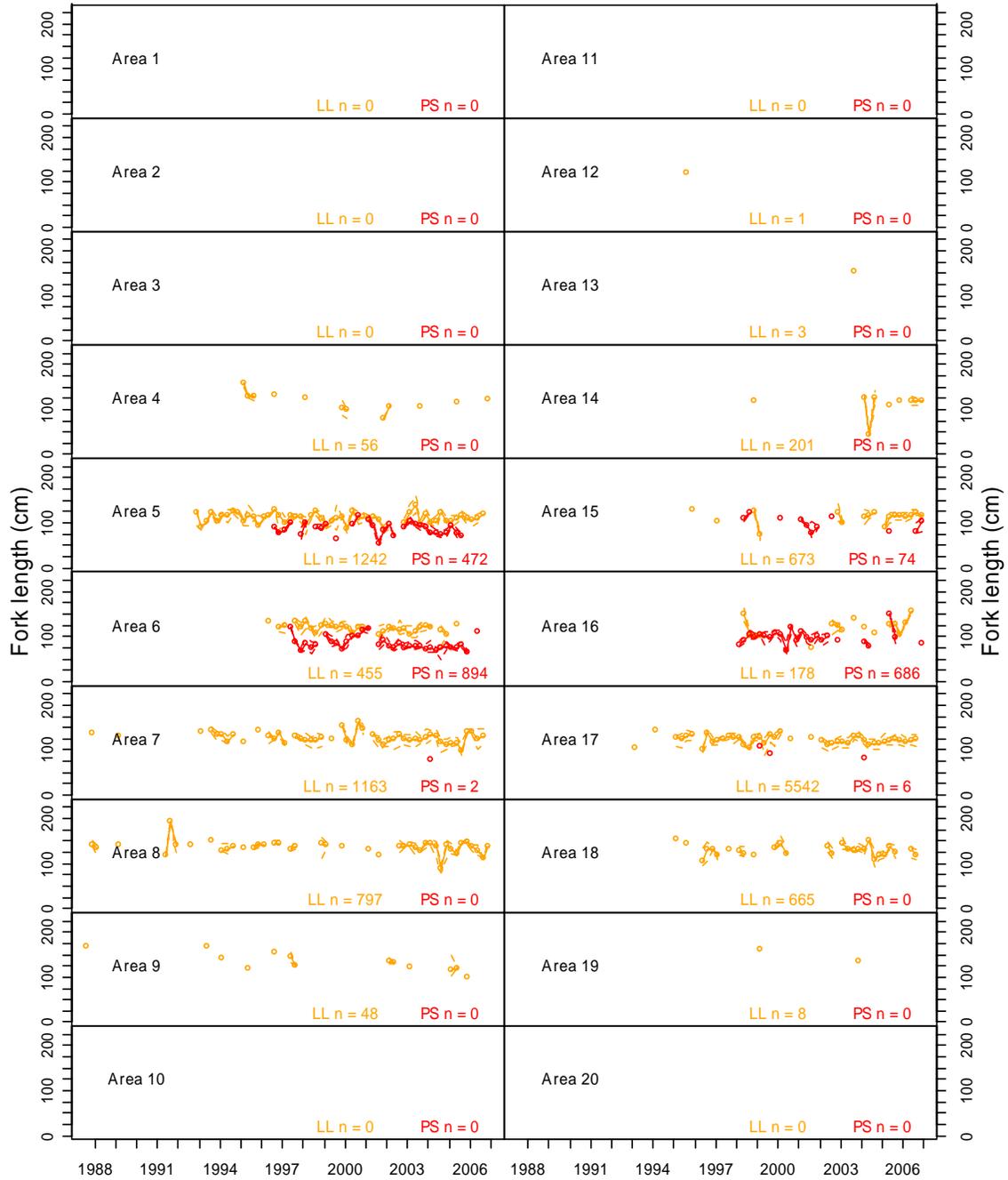
Figure 59. Trends in median size of wahoo pooled into 10º latitudinal bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as fork lengths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively. Points represent median size and dotted lines represent 25th and 75th quartiles of each data series.
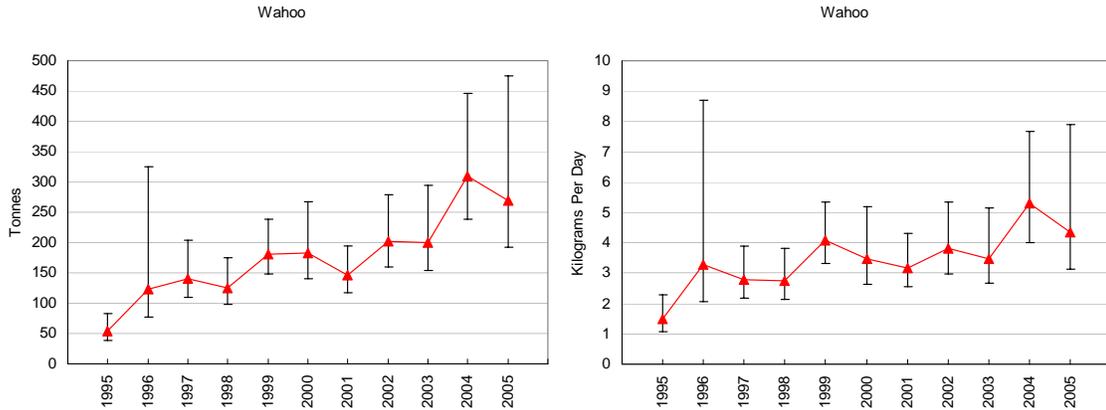
Figure 60. Catches and catch rates of wahoo by purse-seine vessels in the WCPFC Statistical Area (excluding the domestic fleets of Indonesia and the Philippines). Points represent median values of 1,000 random samples from the posterior distributions; error bars represent 95% confidence intervals from 1,000 random samples from the posterior distributions. Source, OFP (2007).
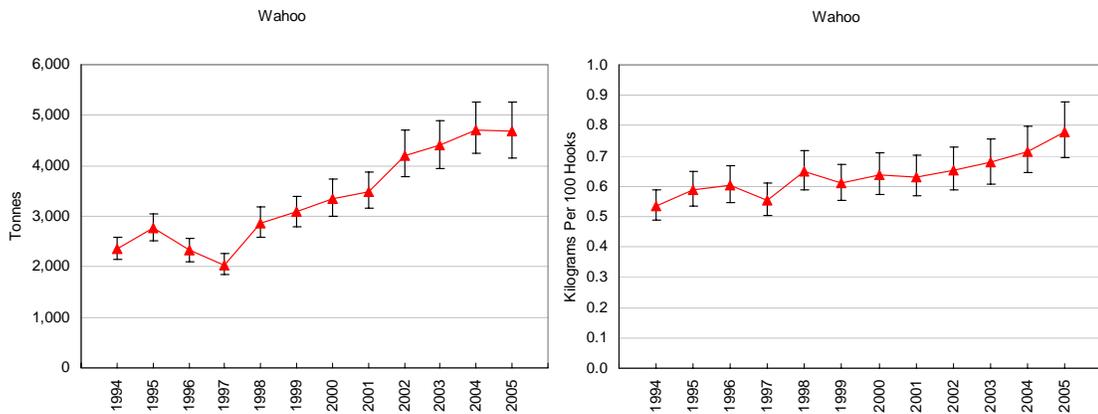
Figure 61. Catches and catch rates of wahoo by longline vessels in the WCPFC Statistical Area (excluding the domestic fleets of Indonesia, the Philippines and Chinese Taipei). Points represent median values of 1,000 random samples from the posterior distributions; error bars represent 95% confidence intervals from 1,000 random samples from the posterior distributions. Source, OFP (2007).

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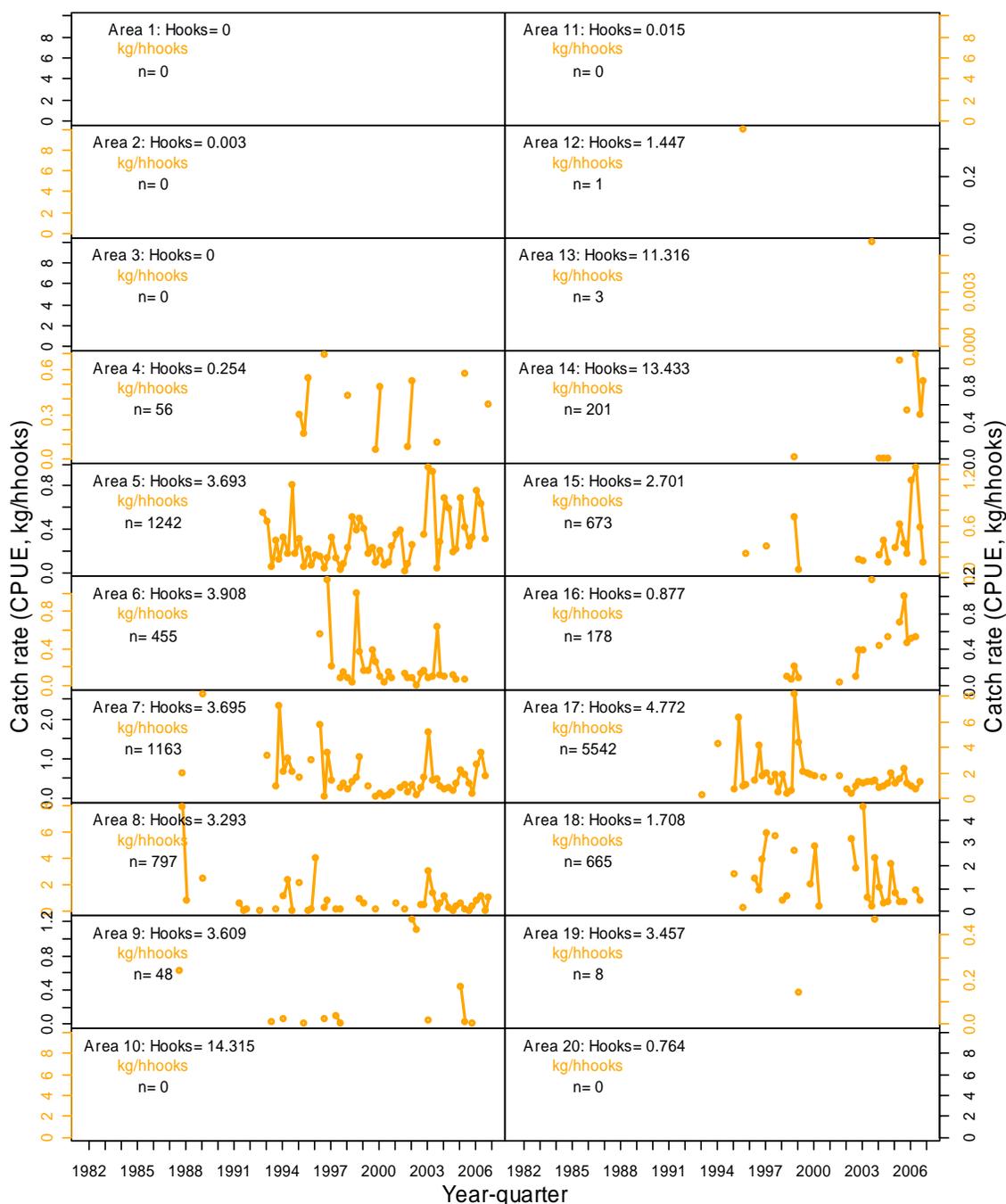
Figure 62. Quarterly catch rates (kg.hhooks^{-1}) of wahoo reported by observers pooled into 10º latitudinal bands (Areas) in the WCPO, 1982–2006. Source, SPC observer data base. Hooks, is the total number of observed hooks (millions) in each Area; n, represents the total number of individuals from each method-fishery within each Area. Scales of the y-axes vary among Areas. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively. Length-weight relationship: whole weight (kg) = (0.0025 x FL$^{3.19}$)/1000 (Torres 1991).
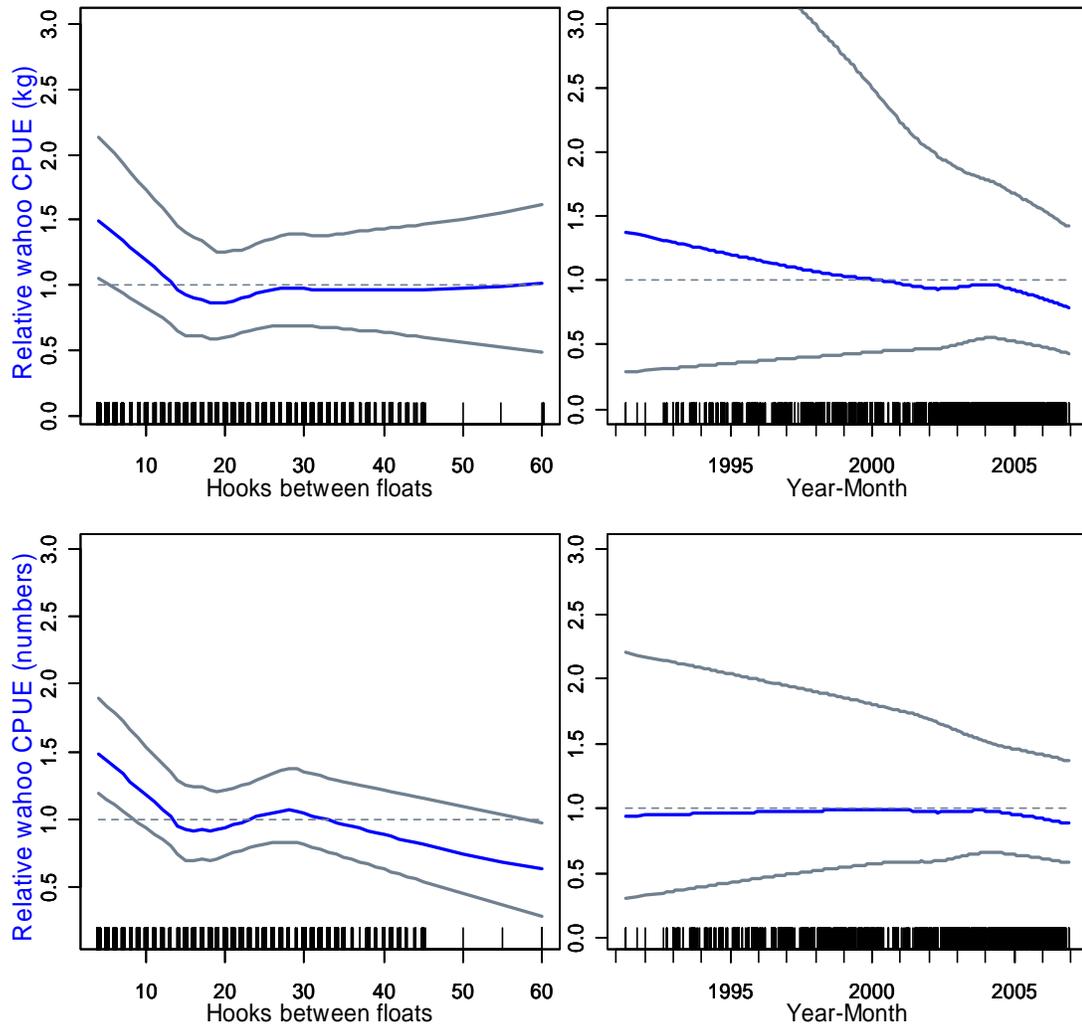
Figure 63. Changes in relative monthly wahoo longline catch rates (blue lines; upper figure, number/hhooks; lower figure, kg/hhooks) for the WCPO under the influence of longitude, latitude, hooks between floats and time period (year-month) as predicted by GLMs, 1991–2006. Sources, observer data held at SPC. Grey lines represent 95% confidence levels. The 'rug' plot along the inside of each x-axis displays the data density along the range of each variable. Weight: $r^2 = 0.200$, adjusted $r^2 = 0.059$; Numbers: $r^2 = 0.234$, adjusted $r^2 = 0.100$.

13. Opah (*Lampris guttatus*)
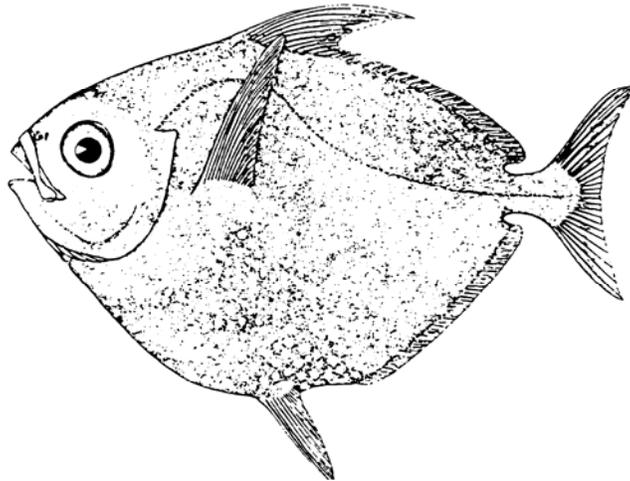
13.1 Description

A large distinctive pelagic fish found in all major oceans. Opah are almost round in profile and are highly laterally compressed. Fins are bright red with body surfaces grading from dark blue on dorsal surfaces to light-silver blue on ventral surfaces. The entire body, except the head, is covered in distinct white spots. Opah are unlikely to be misidentified with any other species.

13.2 Distribution

Opah are widespread in all oceans of the world (Parin and Kukuyev 1983). This species is commonly captured in tropical and sub-tropical longline fisheries in the WCPO, on deeper set gear in the equatorial regions and in the sub-tropical albacore fisheries (Langley et al. 2008). From observer data, opah are more commonly captured in sub-tropical fisheries in the WCPO, suggesting a higher abundance at higher latitudes, at least in the southern WCPO. A second, rarer species, *L. immaculatus*, is found in middle and higher latitudes of the southern hemisphere (south of 40ºS) in the Pacific (Parin and Kukuyev 1983) and Atlantic (Jackson et al. 2000) Oceans.

13.3 Biology

13.3.1 Age and growth

Limited information is available on age and growth of opah. Opah have been aged by examining cross-sections of dorsal fin rays in Hawai'i (www.soest.hawaii.edu/PFRP/progress_rpts/seki_opah04.pdf) and New Zealand (services.fish.govt.nz/fishresourcespublic/Plenary2007/MOO_07.pdf), as otolith microstructure was not suitable for ageing purposes. Initial results suggest that opah live up to seven years (Hawai'i) or 20 years (New Zealand) with similar, rapid growth rates for both sexes. Most opah captured off Hawai'i weigh 44–50 kg, with a maximum weight of 90 kg. (Hawn et al. 2002).

13.3.2 Reproduction

Male and female fish can be identified by differences in the pectoral keel; in males, this keel is thick, bright red and concave; in females the keel is narrow and convex and lacks the bright colouring (Hawn et al. 2002, S. Fukofuka pers. comm.). Spawning is suspected to occur during Spring around Hawai'i, but this was based on the examination of a single ripe female (Hawn et al. 2002). Little is know about the maturity schedule for this species, although opah larger than 80 cm FL are likely to be mature in New Zealand waters (services.fish.govt.nz/fishresourcespublic/Plenary2007/MOO_07.pdf). This corresponds to 4–5 years of age.

13.3.3   Recruitment

In the WCPO, opah start being captured by longline gears at a size of approximately 50 cm FL (Figure 65) (around one year of age). Opah appear fully recruited to longline gears in the WCPO at approximately 100 cm FL. Few opah greater than 125 cm FL are reported by observers in longline fisheries of the WCPO.

13.3.4   Mortality

There are no estimates of natural mortality rate of opah. However, assuming a maximum age of seven years (Hawn et al. 2002) and that only a small proportion survive to this age (5%), the estimated total mortality rate is 0.43 year^{-1} using Hoenig's equation (M = -ln(proportion)/maximum observed age). However, this estimate is very preliminary and uncertain. From New Zealand waters, the best estimate of M for opah was estimated at 0.20–0.25 year^{-1} (services.fish.govt.nz/fishresourcespublic/ Plenary2007/MOO_07.pdf).

13.4 Ecology

13.4.1   Habitat preference

Opah are frequently captured on longline gears in tropical and subtropical waters of the WCPO and other oceans although catch rates are relatively low. Anecdotal evidence suggests that opah are likely to be captured in pairs within a single longline set (S. Fukofuka pers. comm.), suggesting that opah may maintain male and female pairs. The highest catch rates of opah in the WCPO are reported from the subtropical albacore longline fishery and deep sets targeting bigeye tuna in the tropical WCPO. Opah were also reported from Asian driftnet fisheries in the high seas of the Pacific Ocean, suggesting that opah prefer cooler temperatures, having a shallower vertical distribution in higher latitudes. High catch rates of opah from small-scale fisheries around California suggest that opah may also spend time in shallow waters during certain periods (Hawn et al. 2002).

Kerstetter et al. (2003) tagged a single opah with a PSAT tag that was tracked for 23 days before being predated upon by a shark. During this period, the opah moved between 32 m and 456 m from the surface (mean: 222 m) in water temperatures between 8ºC and 25.6ºC (mean 16.7 ºC). However, the data did not allow details about day and night-time periods to be compared. Hawn et al. (2002) concluded that opah are more abundant at depths greater than 300 m, associated with bigeye and albacore habitats, although opah are rarely recorded in some surface fisheries. Hawn et al. (2002) indicated that more than 99% of opah captured in the Hawaiian longline fishery are taken from deep sets targeting bigeye tuna.

Around Hawai'i, opah are regularly hooked in close proximity to seamounts, where it is assumed that they move from deeper waters up the sides of seamounts in order to feed (www.state.hi.us/dbedt/seafood/opah.html).

13.4.2   Movements and migration

Details of movement of opah are poorly understood. This is due to the difficulties in successfully tagging this deep living species. One of the two opahs tagged by Hawn et al. (2002) died shortly after release. The single tagged opah of Kerstetter et al. (2003) moved a total of 330 km from the site of tagging during a 34 day tagged period. However, it was concluded that the opah suffered mortality on day 24. Hawn et al. (2002) suggested that catch rates of opah were highest during the last quarter of each year in the Hawaiian longline fishery, suggesting southern movement from higher latitudes during autumn and winter.

13.4.3   Diet

Diet information for opah are limited. However, it is likely that mesopelagic microneckton are an important component of the diet (Hawn et al. 2002). Additionally, fish and squid may also make up a considerable proportion of the diet due to capture on longline hooks using these baits.

13.5 Details of stocks in the WCPO

13.5.1 Stock structure and size

No details are available for the stock structure of opah from any area. From observer data, the highest proportions of small opah (less than 60 cm FL) are found south of 40ºS in the WCPO (Figure 66), although small opah are also reported between the equator and 20ºS. Small individuals are also reported from the north-east of the WCPO, away from the equator. This suggests the potential for the existence of northern and southern stocks in the WCPO.

There are no details available for the stock size of opah from any areas. From the frequency of occurrence information summarised by Langley et al. (2006b), the stock size of opah is likely to be much smaller than the main tuna species and blue sharks in the sub-equatorial albacore and deep tropical longline fisheries of the WCPO.

13.5.2   Recent stock assessments and status

There are no details available for the stock assessments for opah from any area and thus the stock status is unknown. The median size of opah captured by longline vessels in the WCPO has been relatively stable of increasing at most latitudes since the early 1990s (Figure 67). Overall, the median size of opah captured by WCPO longline fisheries has shown a steady increase since the late 1980s, albeit with (apparently) seasonal fluctuations (Figure 65). Estimated total catches steadily increased from approximately 4,000 mt in 1994, to almost 10,000 mt in 2003, before a recent decline to 6,000 mt (Figure 64). In addition, catch rates in most areas have remained relatively stable, albeit low, since 1994 (Figure 64).

Overall, due to the lack of biological data and uncertainties around catch estimates, the stock status of opah in the WCPO is uncertain and a precautionary approach to further exploitation is recommended.

13.6 Fisheries

13.6.1   Major fisheries and occurrence

Opah are almost exclusively captured by longline fisheries in the WCPO, although some catches by Asian drift nets and coastal fleets was recorded from the EPO (Hawn et al. 2002). There is one observer record of two opah being captured by within a single purse-seine set in the WCPO. Opah was the fifth most frequently captured species in the sub-tropical albacore longline fishery on the WCPO, 1999–2003, representing approximately 5% of the total catch in numbers (Langley et al. 2008). Opah were the 15th most commonly captured species from the tropical deep longline fishery of the WCPO, 1999–2003) but represented less than 1% of the total catch in numbers (Langley et al. 2008). Estimates of median total catches in the WCPO have varied between 4,000 mt and 10,000 mt per year (Figure 64), with some decline estimated since 2003. No catches of opah have been reported by purse-seine fleets in the WCPO.

13.6.2   Artisanal fishery value

Interactions between opah and artisanal fisheries in the WCPO are unlikely to be high, due to the depth preference of opah, being beyond the reach of most artisanal gears.

13.6.3   Sport and recreational fishery value

The gamefish value of opah is likely to be low. Opah have recently received attention as a gamefish species, mainly due to their large size. Around Hawai'i, opah are captured by deep sea jigging on vertical lines down to depths of 500 m, particularly around seamounts (www.konadeepsea.com/charters/bottom.htm).
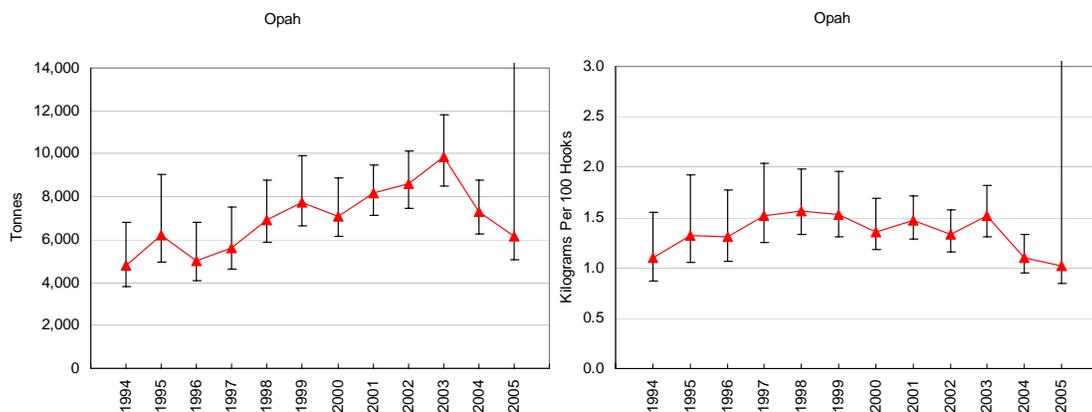
Figure 64. Catches and catch rates of opah by longline vessels in the WCPFC Statistical Area (excluding the domestic fleets of Indonesia, the Philippines and Chinese Taipei). Points represent median values of 1,000 random samples from the posterior distributions; error bars represent 95% confidence intervals from 1,000 random samples from the posterior distributions. Source, OFP (2007).
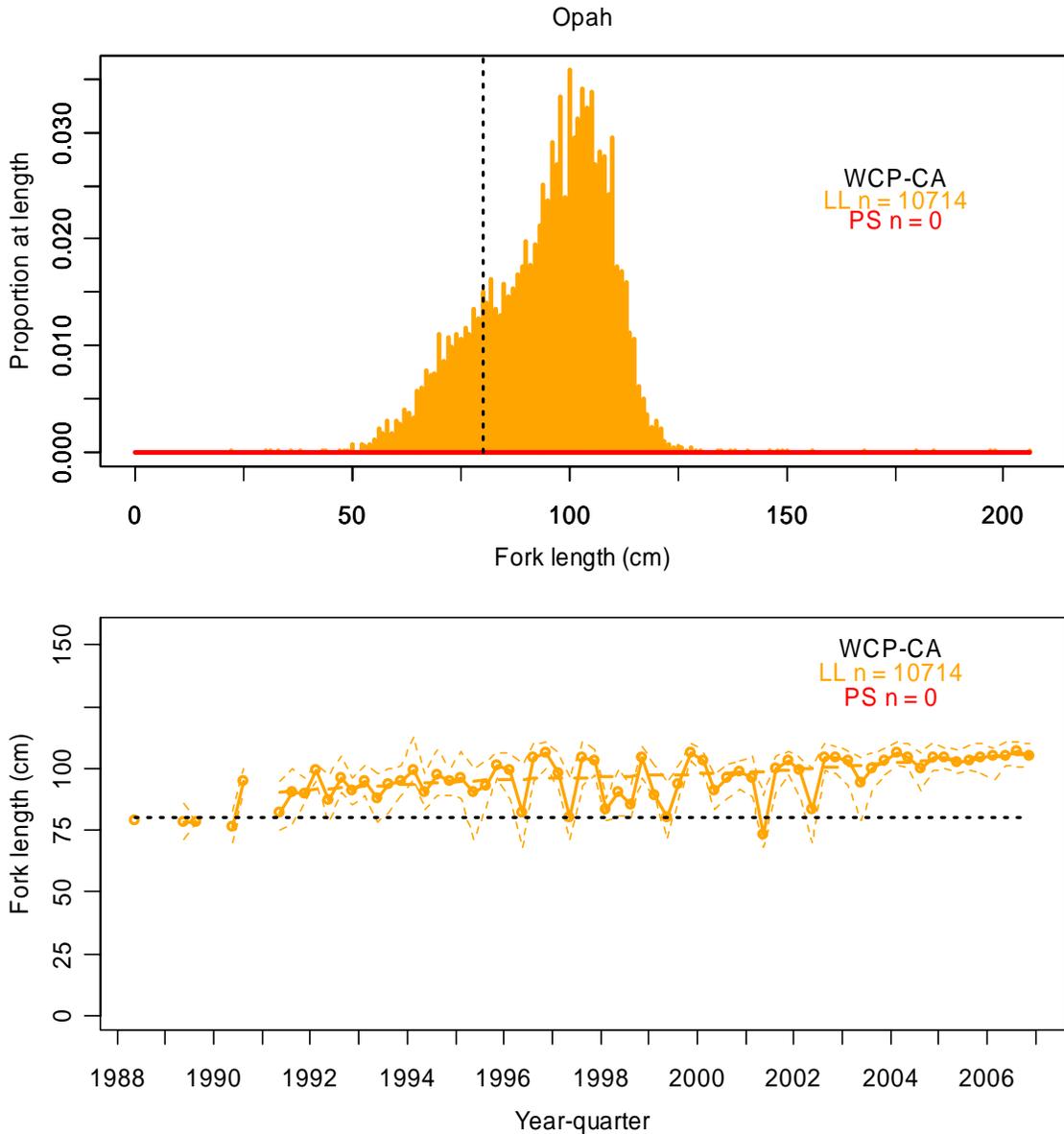
Figure 65. Combined length-frequency distributions (upper figure) and trends in quarterly median size (lower figure) of opah reported by observers in longline and purse-seine vessels in the WCPO, 1988–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery. Thin dashed lines represent the 25th and 75th quartiles of the size data. Heavy dashed lines represent lowess fits to the median size data. Dotted lines represent estimates of size at maturity for opah (both sexes, 80 cm FL) and males (grey, 185 cm FL) (from services.fish.govt.nz/fishresourcespublic/Plenary2006/MOO_07.pdf) from New Zealand.
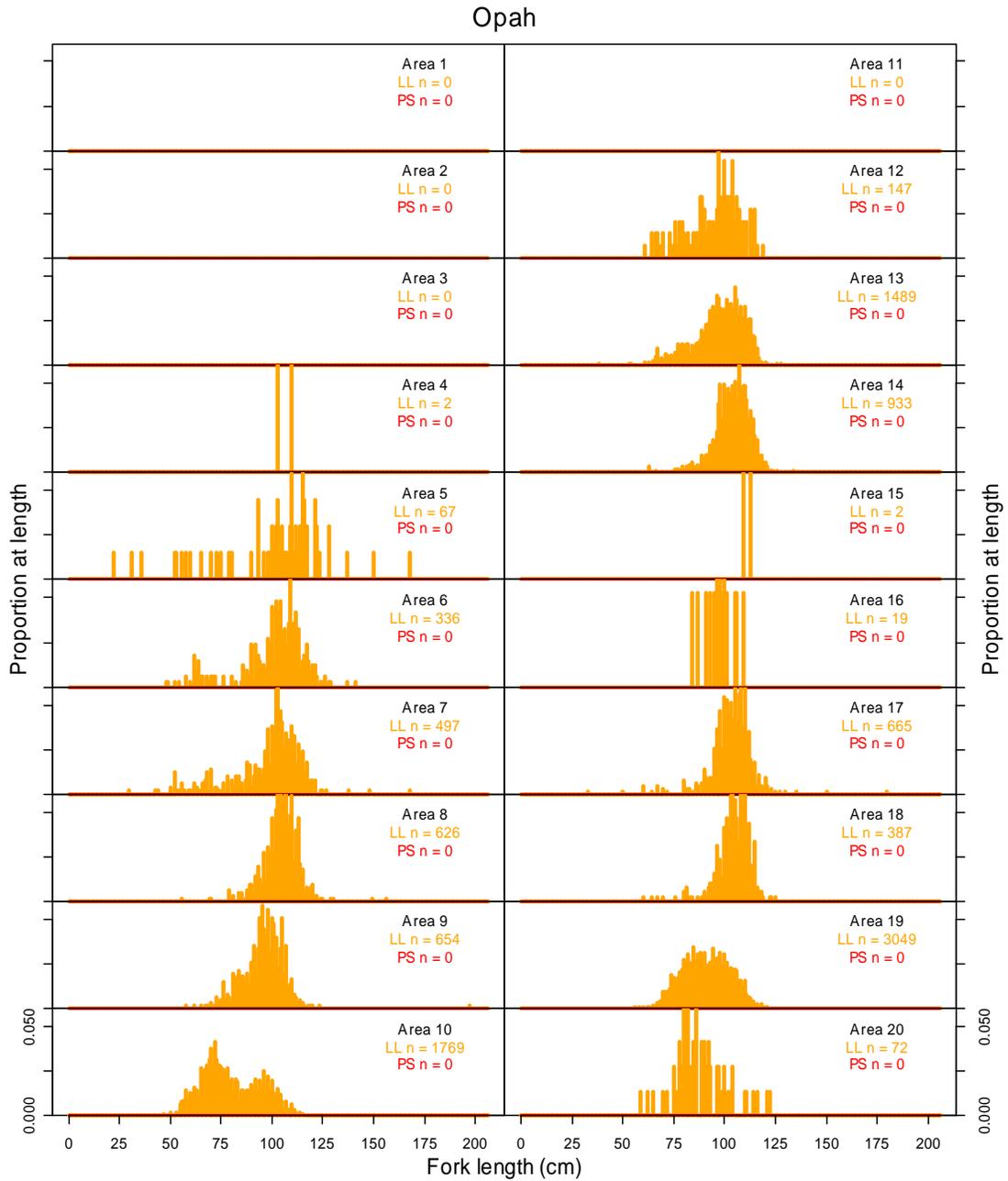
Figure 66. Length-frequency distributions of opah pooled into 10º latitude bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as fork lengths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively.
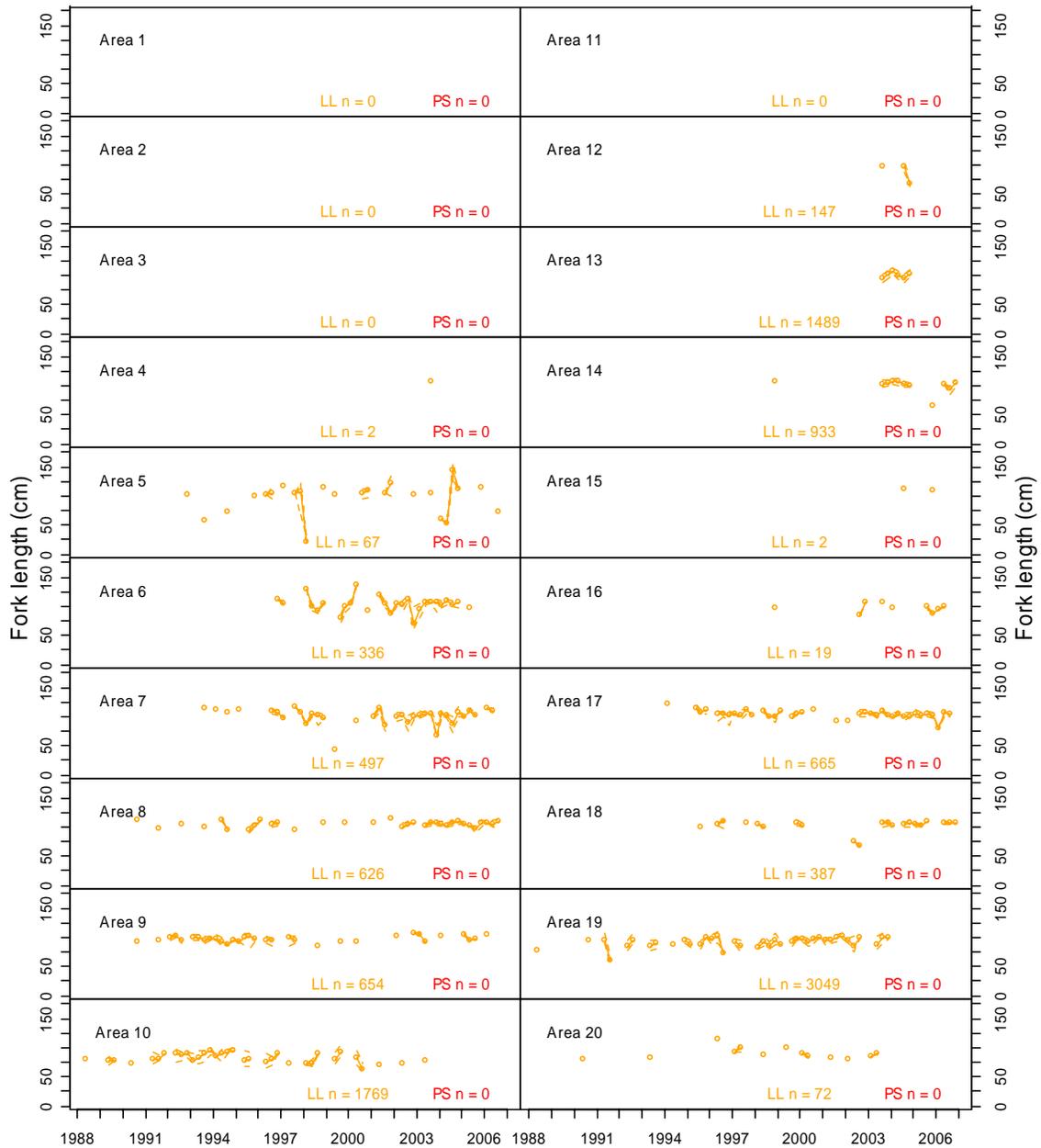
Figure 67. Trends in median size of opah pooled into 10º latitudinal bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as fork lengths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively. Dotted lines represent 25th and 75th quartiles of each data series.

Opah
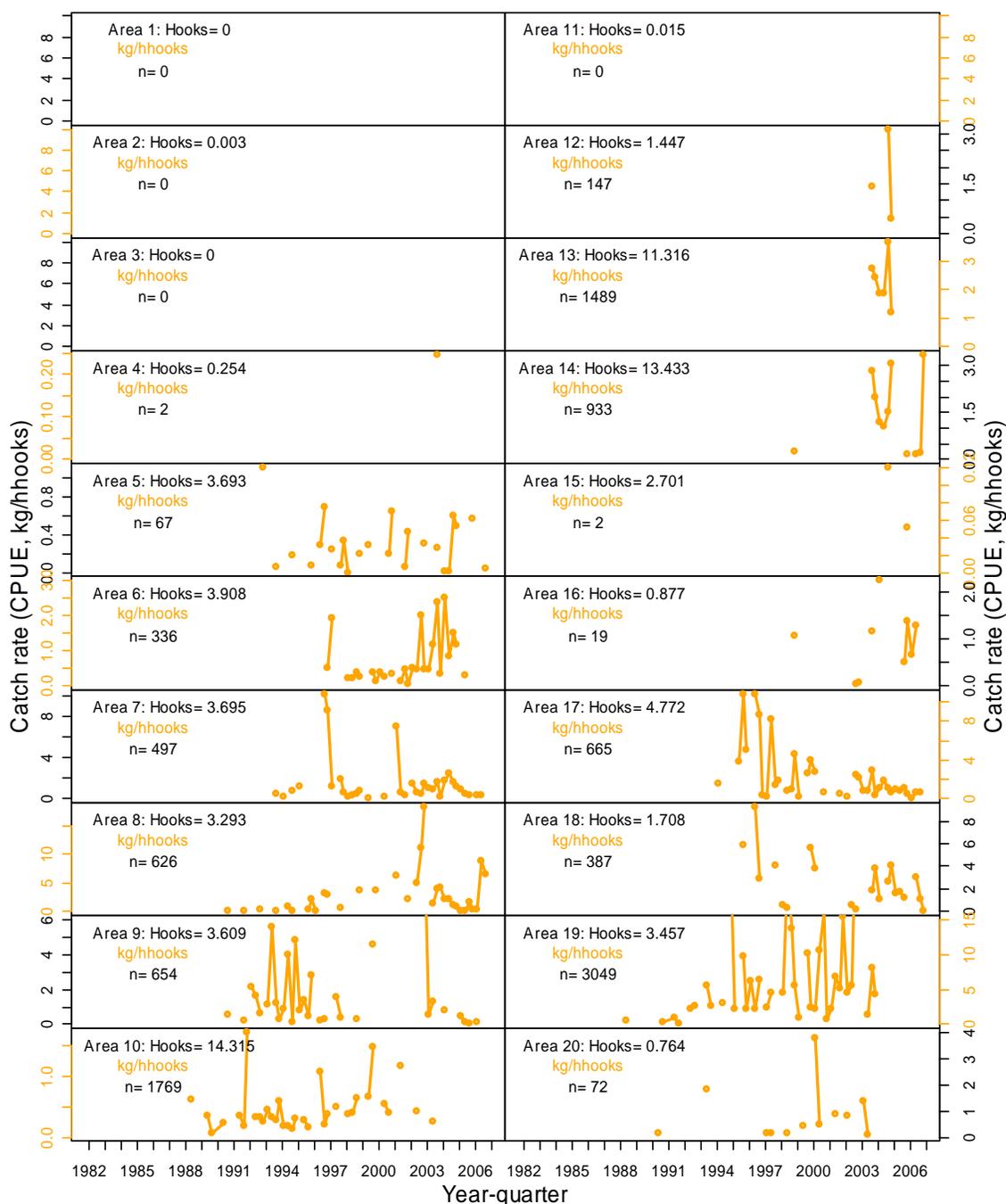
Figure 68. Quarterly catch rates (kg.hhooks⁻¹) of opah reported by observers pooled into 10º latitudinal bands (Areas) in the WCPO, 1982–2006. Source, SPC observer data base. Hooks, is the total number of observed hooks (millions) in each Area; n, represents the total number of individuals from each method-fishery within each Area. Scales of the y-axes vary among Areas. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively. Length-weight relationship: whole weight (kg) = (0.0390 x (FL/1.143)³)/1000 (www.fishbase.org).
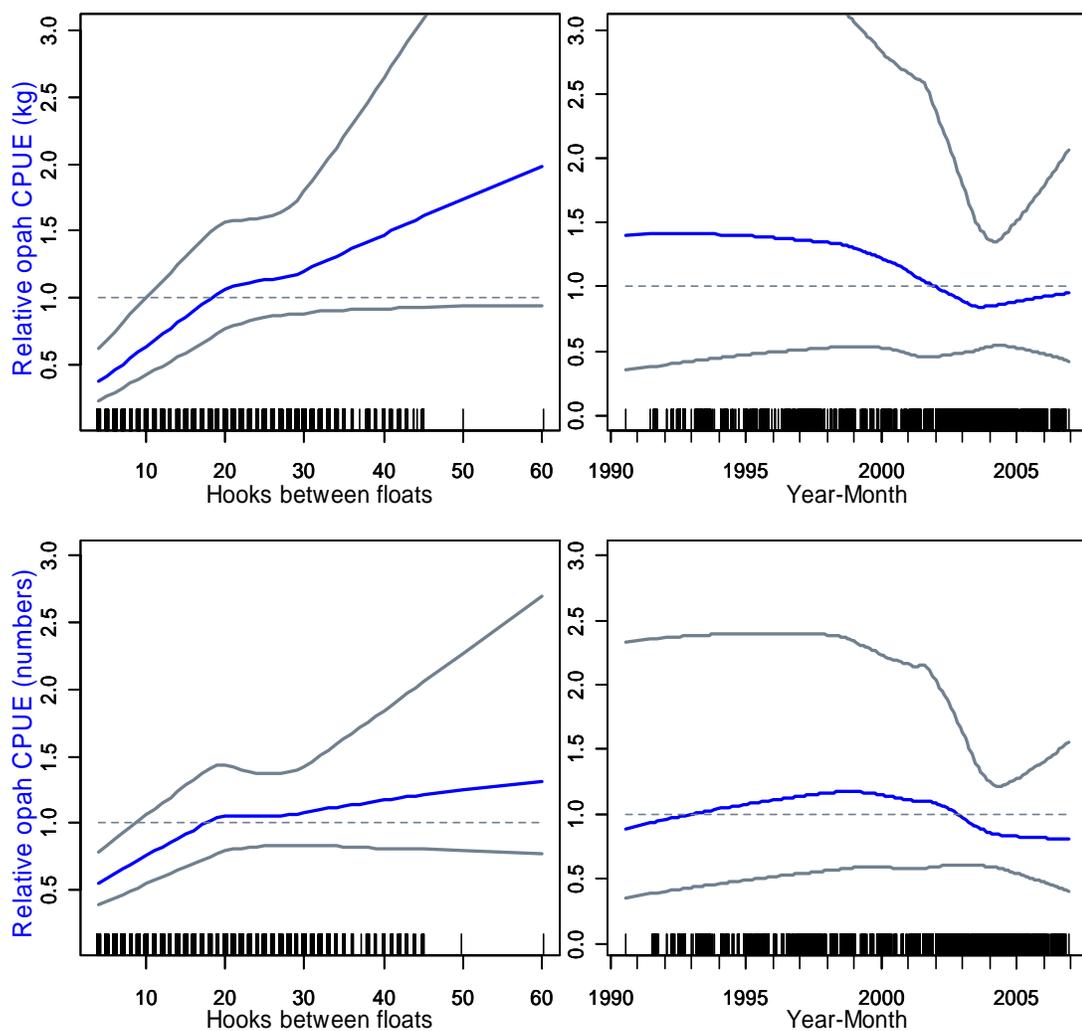
Figure 69. Changes in relative monthly opah longline catch rates (blue lines; upper figure, number/hhooks; lower figure, kg/hhooks) for the WCPO under the influence of longitude, latitude, hooks between floats and time period (year-month) as predicted by GLMs, 1991–2006. Sources, observer data held at SPC. Grey lines represent 95% confidence levels. The 'rug' plot along the inside of each x-axis displays the data density along the range of each variable. Weight: $r^2 = 0.273$, adjusted $r^2 = 0.150$; Numbers: $r^2 = 0.288$, adjusted $r^2 = 0.169$.

14. Mahimahi (*Coryphaena hippurus*)
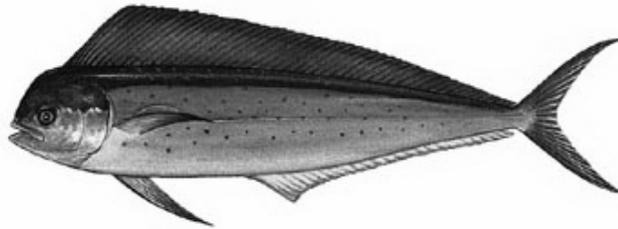
14.1 Description

Mahimahi are a common, high speed surface species of pelagic fish (Arocha et al. 1999). The dorsal fin is continuous along the length of the body. Dorsal colouration is blue , merging to yellow-gold along the sides and pale underneath, often with irregular blue flecks along the body. The forehead of males is pronounced. Mahimahi are unlikely to be misidentified with any other species.

14.2 Distribution

Mahimahi are common in all waters of the world, between approximately 45º and 40ºS. They are most commonly reported from shallow (0–85 m) tropical and sub-tropical waters, with temperatures above 21º (Lasso and Zapata 1999).

14.3 Biology

14.3.1   Age and growth

Mahimahi display one of the highest growth rates of all pelagic fish. Age and growth of mahimahi have relied on length-frequency analyses, scale increments, increments in whole otoliths and increments in section otoliths. Recently, Massuti et al. (1999) validated daily deposition of otolith increments and concluded that other methods over-estimated ages and under-estimated growth rates. In their study, the maximum age recorded was approximately one-year for an individual approximately 120 cm FL. Thus growth rates are extremely high. Mahon and Oxenford (1999) estimated longevity of mahimahi at 12–18 months, with most workers concluding that longevity is less than two years (Oxenford 1999). However, Massuti and Morales-Nin (1995) estimated longevity up to three years of this species, although this was prior to validation of the ageing.

Three studies since the early 1980s using otolith increments estimated growth rates between 3.31 and 4.71 mm SL per day for mahimahi collected within central western Atlantic Ocean. This resulted in estimates of the growth parameter (k) in the VBGF of 2.87–3.13 year^{-1} (Rivera and Appeldoorn 2000). In comparison, Massuti et al. (1999) reported k varying between 1.56 and 2.5 year^{-1} for fish sampled in the western Mediterranean Sea. In the Caribbean, Mahon and Oxenford (1999) estimated K to be approximately 3.49 year^{-1}. This broadly equates to a growth rate of 10 cm/month in the first year. Highest growth rates were estimated for fish living waters of 28ºC or greater (Mahon and Oxenford 1999).

Very rapid growth of mahimahi have also been demonstrated in aquaculture grow-out situations. For example, Schaleger and Ostrowski (1995) fed juvenile mahimahi (60 days old)

to satiation for up to 240 days, with fish reaching 1.0 kg within 150 days and 2.3 kg by 240 days. Males were typically 15- 35% heavier than females.

Maximum size (L∞) varied between males and females and geographic locations. From all fish combined in their study, Rivera and Appeldoorn (2001) estimated a pooled L∞ of approximately 146 cm FL. Estimated L∞'s for adult fish from the Massuti et al. (1999) study ranged between 99 cm FL (males) and 110 cm FL (females).

14.3.2 Reproduction

Females dominate mahimahi populations in most areas (Oxenford 1999), especially in fish smaller than 100 cm FL (Arocha et al. 1999). This may be due to the more voracious feeding of males, and therefore the higher vulnerability of males to fishing, reducing the numbers of males in many populations.

Mahimahi can spawn year-round when surface water temperatures are greater than 27ºC (Lasso and Zaoata 1999) in highly productive areas (Arocha et al. 1999). This is evidenced by the reporting of ripe females, spent fish and larvae throughout the year in some areas (Oxenford 1999). Two peaks in spawning were reported in April and September for mahimahi captured near Taiwan (Wang 1979), with larvae present year-round in waters adjacent to Hsing-Kang (north-eastern Taiwan).

Mahimahi are batch spawners and individual fish are likely to spawn at least 2–3 times per season in the central Atlantic (Oxenford 1999). Batch fecundity from a range of areas in the western and central Atlantic varied 50,000–1,500,000 (Oxenford 1999), with size-fecundity estimate varying among populations. Typically three size modes of eggs are present within an ovary at any time (Oxenford 1999).

In the western central Atlantic, mature females as small as 35 cm FL have been reported, with 50% maturity of females at 45 cm FL and approximately 100 % mature at 55 cm FL. Males are slightly larger before they mature, with the smallest mature male reported at approximately 43 cm FL (Oxenford 1999). However, there is a high degree of variability across small spatial scales. For example, from summarised data presented for the western and central Atlantic (Florida current, US Virgin Islands, Puerto Rico, Gulf of Mexico, Barbados), Oxenford (1999) reported a wide range of size at first maturity for males (43–80 cm FL) and females (35–67 cm FL). In Barbados, Oxenford (1999) concluded that females mature at a smaller size than males (61 cm FL compared to 74 cm FL), but at a similar ages (108–112 days of age).

Laboratory studies have reported maturity at 6.5 months of age in a 56 cm FL fish of 2.5 kg (Schekter 1982 in Oxenford 1999).

14.3.3 Recruitment

From observer records, mahimahi start to recruit to longline fisheries of the WCPO at approximately 50 cm FL (Figure 72), at or above the estimated size at first maturity from other populations. Mahimahi are fully recruited to longline gears in the WCPO by approximately 100 cm FL.

Mahimahi recruit to purse-seine fisheries at approximately 25 cm FL or age, below the estimated size at first maturity (Figure 72). This is similar to the recruitment of mahimahi to fisheries in the Caribbean Sea, which also occurs at sizes below that the estimated size at first maturity (Mahon and Oxenford 1999). Mahimahi are fully recruited to purse-seine fisheries of the CPO by approximately 50–60 cm FL (Figure 72).

14.3.4 Mortality

Due to their short life-span and fast growth rates, mortality rates of mahimahi are expected to be relatively high. Natural mortality of mahimahi was originally estimated at 0.87 year^{-1} (Murray 1985). However, this was prior to the validated age estimates which indicated that mahimahi grow faster and have a lower longevity (maximum about one year) than originally estimated (Massuti et al. 1999). Assuming the short lifespan, Honeig's estimate of total mortality (Z) is 4.2–4.6 year^{-1}, while length based methods suggest a Z of more than 2.0 year^{-1}. Fishing mortalities as high as 3.53 year^{-1} have also been estimated (Murray 1985), although this may be an under-estimate due to the use of relative age data only.

A recent review by Mahon and Oxenford (1999) presented estimates of natural mortality (M) between 0.66 and 8.7 year^{-1} for different populations and scenarios. They concluded that a M of 2.56 year^{-1} (~0.21 month^{-1}) for Caribbean mahimahi was most realistic. However, the range of estimates are likely to be partially due to the complicated stock structure of this species in the region (i.e. many small stocks).

14.4 Ecology

14.4.1 Habitat preference

Mahimahi have a preference for warm, surface waters with temperatures greater than approximately 20ºC and a preference for water temperatures above 27ºC (Oxenford 1999). Massuti and Morales-Nin (1995) described a relationship where catches peaked approximately 1–2 months after the peak in water temperatures above 20ºC. About 70% of total Taiwanese coastal longline catches of mahimahi were taken from surface waters with temperatures of 26–27ºC (Wang 1979). Lasso and Zapata (1999) demonstrated the low food conversion of mahimahi at temperatures below 23ºC and concluded that mahimahi are likely to move in order to remain in waters above 27 ºC (i.e. equatorial areas), to support their high metabolic rate.

Smaller individuals may be closely associated with flotsam lines and floating objects (Rose and Hassler 1974), with observers reporting high catch rates from purse-seine sets around floating objects. Mahimahi may also be closely associated with shallow seamounts (Arocha et al. 1999).

14.4.2 Movements and migration

From catch rate data and limited tagging data, Oxenford (1999), proposed "migration circuits" for mahimahi in the central Atlantic Ocean, north and south of the equatorial regions. Mahimahi would move towards equatorial regions during cooler (winter) months, with their range expanding to high latitudes during warmer months (summer), as sea surface temperatures increased in areas away from the equator. The expansion and contraction of the range of mahimahi followed the main currents, resulting in "migration circuits". This seasonal

movement may be related to reproduction, where adults move to warmer, tropical areas of the central-western Atlantic to spawn (Lasso and Zapata 1999). There was a similar seasonal pattern of movement by mahimahi reported from the north-western Pacific (Wang 1979).

Longer term movement patterns have also been proposed. For example, Lasso and Zapata (1999) proposed that mahimahi 'migrate' southward during strong *El Niño* periods, resulting increases in abundances in areas off northern Peru in the eastern Pacific Ocean. While similar relationships are likely to exists in the WCPO, details of movement of mahimahi are currently limited.

14.4.3   Diet

Mahimahi from the western Atlantic Ocean consumed mainly epipelaic fish prey, including Exocoetidae (flying fishes), scombrids, carangids, and balistids. Mahaimahi are also reported to consume smaller individuals of their own species (i.e. cannibalism) (Rose and Hassler 1974).

In the WCPO, fish of a wide range of species made up more than 90% of the diets of mahimahi by weight or number of food items, with most prey classified as pelagic or epipelagic species (Allain 2003). Similarly, fish dominate the diet of mahimahi from the central eastern Pacific for most of the year (Lasso and Zapata 1999). Cephalopods, other molluscs and crustaceans account for a small proportion of overall diets of mahimahi from the WCPO (Allain 2003).

14.5 Details of stocks in the WCPO

14.5.1 Stock structure and size

The stock structure of mahimahi is likely to be complicated (Rivera and Appeldoorn 2000) due to short-life span, ability to undertake relatively long-distance movements and being seasonally abundant in may areas (Oxenford 1999). Differences in length-weight relationships and sex ratios over small spatial scales (e.g. between the Pacific coasts of central Mexico and Baja California, a distance of 500–1,000 km) (Madrid and Beltran Pimienta 2001) support the highly complex stock structure. For example, at least two (north and south) (Oxenford 1999) or more (Mahon and Oxenford 1999) stocks of mahimahi are thought to exist in the Caribbean Sea based on fishery data, size data, biological characteristics and allele frequencies. Patterson and Martinez (1991) concluded that there were likely to be several stocks in the in the Pacific Ocean of the central-eastern Americas. It is likely that many sub-stocks exist in the WCPO.

Similar length-frequency distributions are reported in the WCPO between 20ºN and 20ºS (Figure 73). At high latitudes, strong bimodal distributions are observed, with modes at approximately 50–75 cm FL and 100-125 cm FL. The length-frequency data does not lend support to any hypothesised stock structure of mahimahi at the WCPO, especially given the complex structure found in other areas over relatively small spatial scales. The strong modes of small fish at higher latitudes in the southern WCPO (30–40ºS) suggests a the possibility of more than one stock of mahimahi in the WCPO.

The stock of mahimahi in the WCPO is likely to be relatively high given the occurrence of mahimahi in the top 20 species (by weight) in all three longline fisheries and all four purse-seine fisheries in the WCPO (Langley et al. 2008).

14.5.2 Recent stock assessments and status

Stock assessments for this species are rare, likely due to the complexity of defining stocks. Mahon and Oxenford (1999) produced a stock assessment for Caribbean Sea mahimahi. The biological attributes of mahimahi (e.g. rapid growth, young age at first maturity, batch spawner, year-round reproduction in tropical areas, high natural mortality rates) suggested that the species would be robust to exploitation. However, the marketable size of mahimahi in some areas is well below the size at first maturity (Mahon and Oxenford 1999). Further, mahimahi are exploited throughout their range, aggregate around floating objects and are captured by industrialised longline and purse-seine fisheries (e.g. Figure 72), and catches are likely to be increasing (Mahon and Oxenford 1999).

Further, there have been some recorded declines in CPUE in the Caribbean Sea in recent years, suggesting that abundances are declining. The declining in CPUE may be due to the high inter-annual variability in the timing and strength of seasonal mahimahi fisheries, a result of variations in oceanographic conditions. The high inter-annual variability in availability is suggested to make the species vulnerable to over-exploitation as high-levels of effort during several consecutive poor years may result in the stock being locally depleted or over-exploited (Mahon and Oxenford 1999).

In the WCPO, the median size of mahimahi from the longline fisheries has been relatively stable, both overall (Figure 72) and within 10º bands of latitude (Figure 74). Overall median size of mahimahi has fluctuated around a median length of approximately 100 cm FL since at least 1988. However, some seasonality is observed from Areas where relatively high levels of data are available (Figure 74).

From the purse-seine fishery, the median size increased between 1996 and 200, declined until 2004 and has been stable around a length of 75 cm FL since 2004 (Figure 72). Median size for purse-seine fisheries have been relatively stable in most areas (Figure 74). Estimated median total catches and catch rates of mahimahi from the WCPO have shown increasing trends in the longline (Figure 70) and purse-seine fisheries (Figure 71).

Overall, while the biological and fishery data suggest that mahimahi are likely to be robust to exploitation, the lack of region-specific information suggests a precautionary approach to exploitation until more robust information become available.

14.6 Fisheries

14.6.1 Major fisheries and occurrence

Mahimahi support large catches for a wide range of fisheries throughout their distribution, especially as part of the retained catch for longline fisheries, including swordfish longline fisheries (Massuti and Morales-Nin 1995). Mahimahi are a significant proportion of the retained catches in many longline fisheries with median estimates of total catches of 2,000–7,000 mt per year captured in WCPO longline fisheries since 1994 (Figure 70). Largest catches are reported in the tropical shallow and south Pacific albacore longline fisheries

(Langley et al. 2006). Significant quantities are also captured as bycatch in purse-seine fisheries (Massuti and Morales-Nin 1995), with 200–900 mt per year estimated from purse-seine fisheries of the WCPO, 1994-2005 (Figure 71). Mahimahi are frequently captured in all set-types, with the highest rates reported from sets on logs and drifting FADs. From more than 13,000 observed purse-seine sets from which mahimahi were reported, approximately 98% were associated sets (i.e. logs, FADs, animals).

Catches of mahimahi are likely to be greatly under-estimated due to issues of under-reporting and discarding. For example, Chang et al. (2005) estimated mahimahi catches from coastal Taiwanese fleets to be approximately 10,000 mt per year, exceeding the estimates of catches by the industrial longline and purse-seine fleets of the WCPO (Figure 71). In addition, mahimahi are targeted by longline fisheries in some PICTs at certain times of the year.

14.6.2   Artisanal fishery value

Artisanal catches of mahimahi are likely to be very large throughout its distribution due to the shallow distribution and high abundance of this species (Massuti and Morales-Nin, 1995). For example, in Ecuador in 1991, more than 680 artisanal vessels were reported as targeting mahimahi for supply to local markets (Patterson and Martinez 1991). It is likely that significant quantities of mahimahi are also captured by artisanal fishers throughout the WCPO, although no estimates are available.

14.6.3   Sport and recreational fishery value

Mahimahi are a prized sportfishing species throughout their range (Whitelaw 2001). Males are especially prized due to their larger size and fighting strength. However, estimates of recreational catches are currently unavailable.
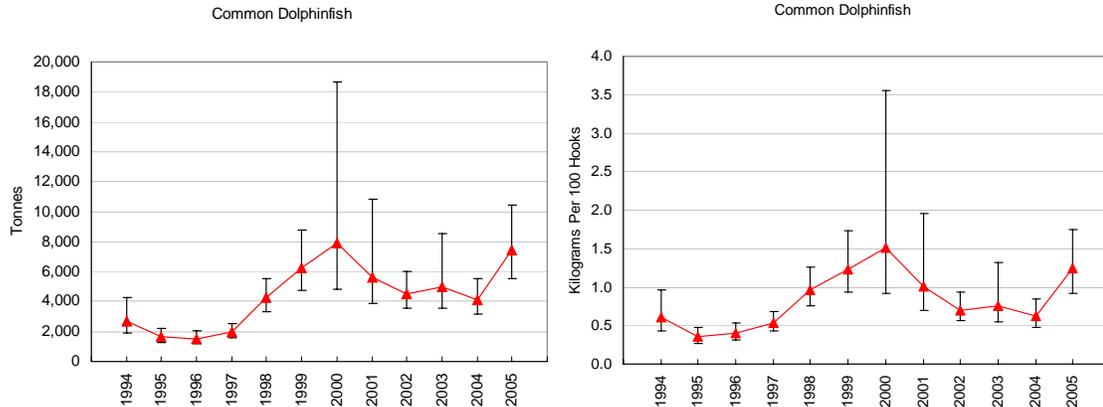
Figure 70. Catches and catch rates of mahimahi by longline vessels in the WCPFC Statistical Area (excluding the domestic fleets of Indonesia, the Philippines and Chinese Taipei). Points represent median values of 1,000 random samples from the posterior distributions; error bars represent 95% confidence intervals from 1,000 random samples from the posterior distributions. Source, OFP (2007).
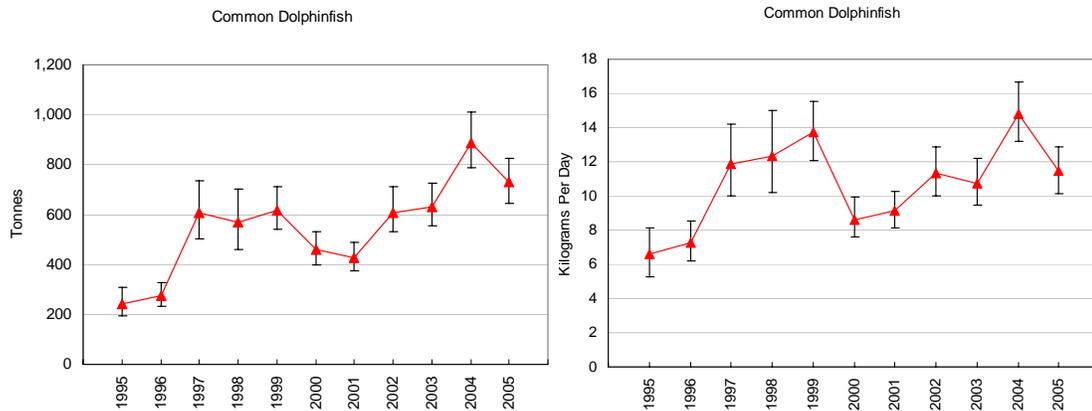
Figure 71. Catches and catch rates of wahoo by purse-seine vessels in the WCPFC Statistical Area (excluding the domestic fleets of Indonesia and the Philippines). Points represent median values of 1,000 random samples from the posterior distributions; error bars represent 95% confidence intervals from 1,000 random samples from the posterior distributions. Source, OFP (2007).

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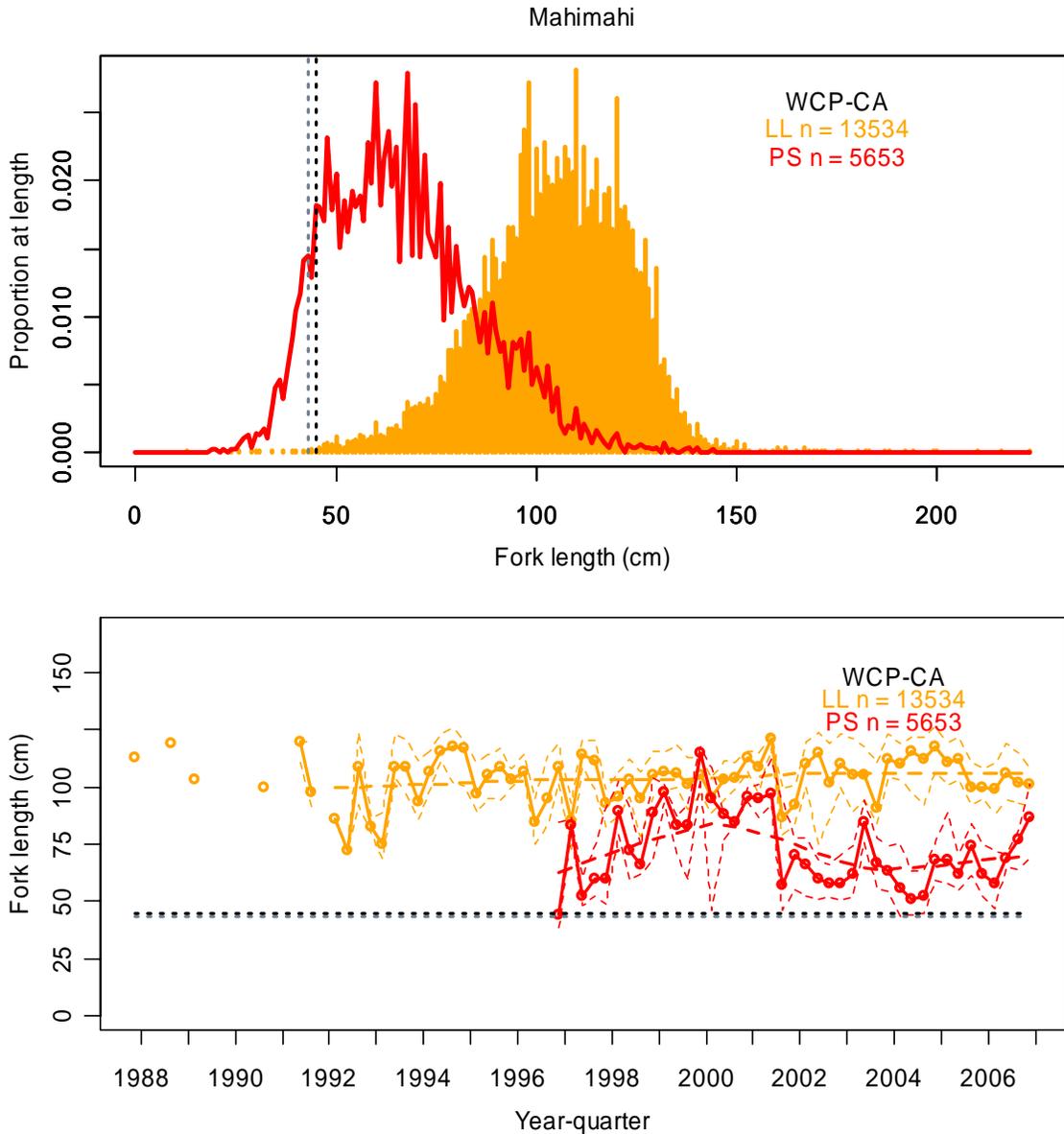
Figure 72. Combined length-frequency distributions (upper figure) and trends in quarterly median size (lower figure) of mahimahi reported by observers in longline and purse-seine vessels in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery. Thin dashed lines represent the 25th and 75th quartiles of the size data. Thick dashed lines represent lowess fits to the median size data. Dotted lines represent estimates of size at 50% maturity for females (black, 45 cm FL) and males (grey, 43 cm FL) (from Oxenford 1999), estimated from the Atlantic Ocean.
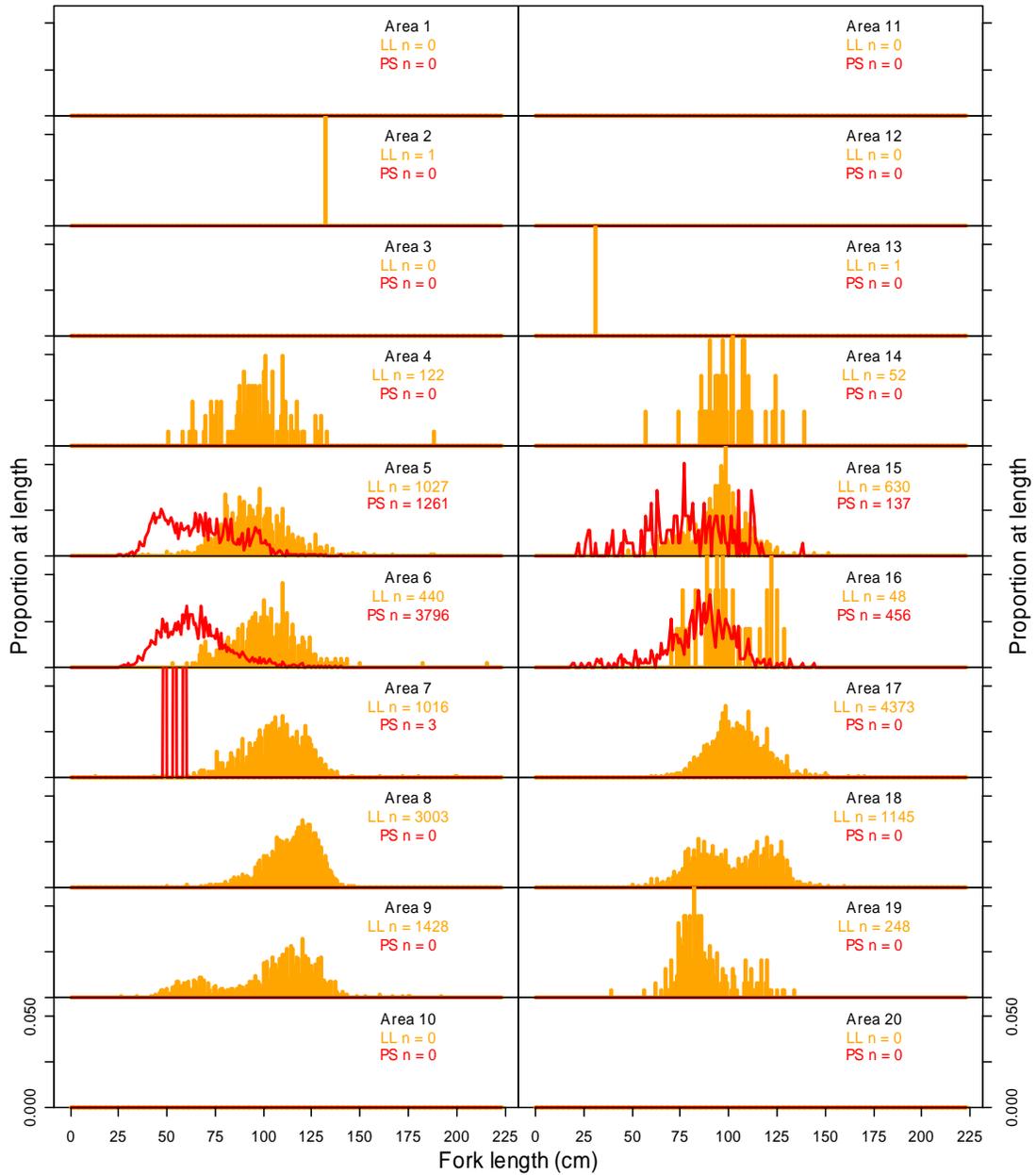
Figure 73. Length-frequency distributions of mahimahi pooled into 10º latitude bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as fork lengths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively.
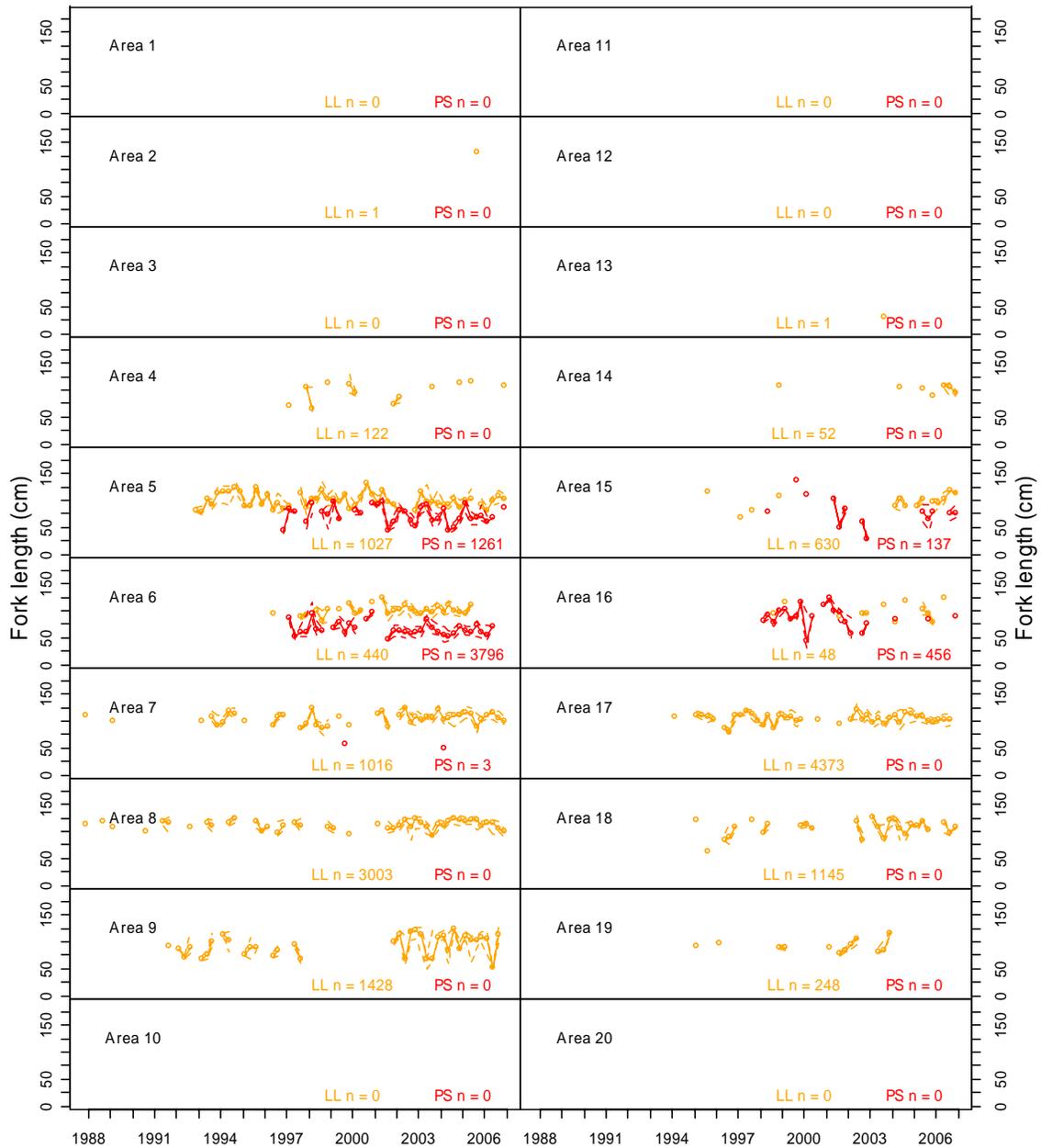
Figure 74. Trends in median size of mahimahi pooled into 10º latitudinal bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as fork lengths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively. Thin dotted lines represent 25th and 75th quartiles of each data series.
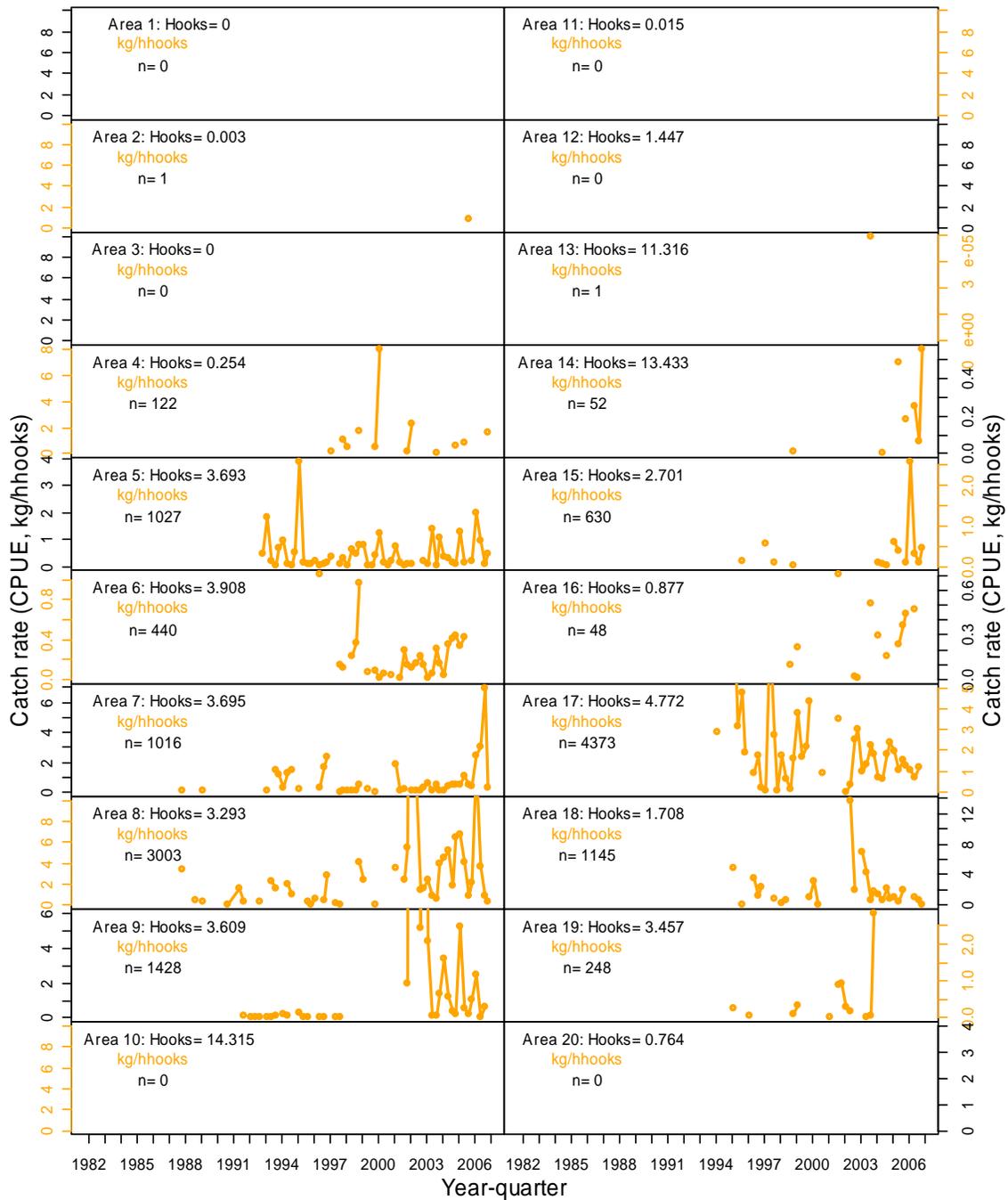
Figure 75. Quarterly catch rates (kg.hhooks^{-1}) of mahimahi reported by observers pooled into 10º latitudinal bands (Areas) in the WCPO, 1982–2006. Source, SPC observer data base. Hooks, is the total number of observed hooks (millions) in each Area; n, represents the total number of individuals from each method-fishery within each Area. Scales of the y-axes vary among Areas. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively. Length-weight relationship: whole weight (kg) = (0.0015 x LJFL$^{3.724}$)/1000.
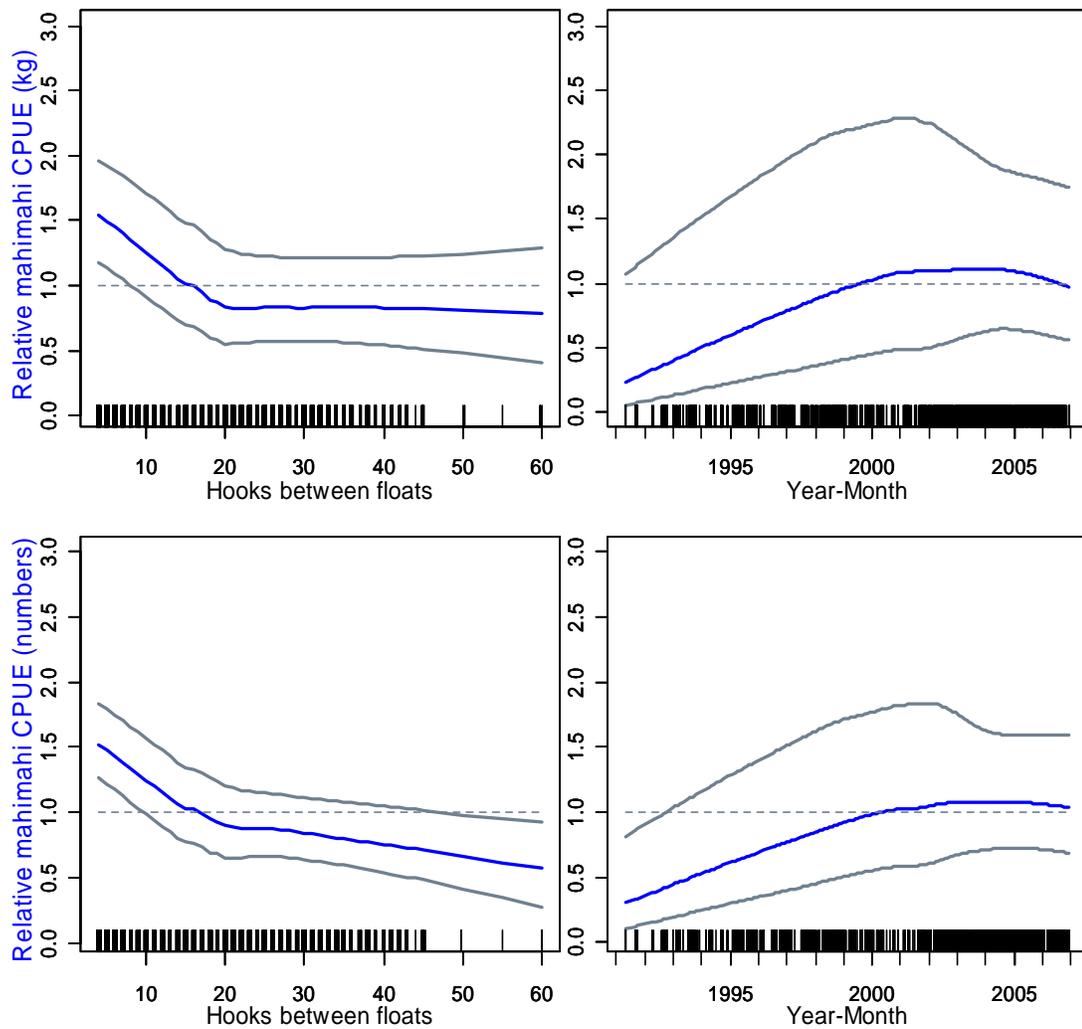
Figure 76. Changes in relative monthly mahimahi longline catch rates (blue lines; upper figure, number/hhooks; lower figure, kg/hhooks) for the WCPO under the influence of longitude, latitude, hooks between floats and time period (year-month) as predicted by GLMs, 1991–2006. Sources, observer data held at SPC. Grey lines represent 95% confidence levels. The 'rug' plot along the inside of each x-axis displays the data density along the range of each variable. Weight: $r^2 = 0.224$, adjusted $r^2 = 0.100$; Numbers: $r^2 = 0.270$, adjusted $r^2 = 0.153$.

15. Blue shark (*Prionace glauca*)
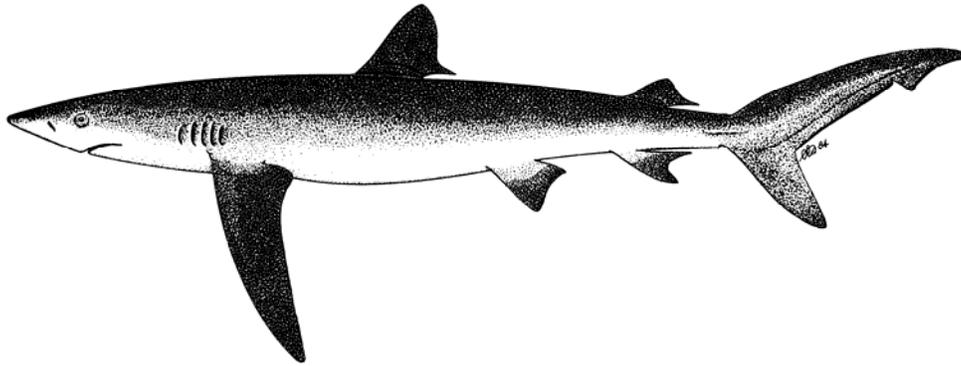
15.1 Description

Blue sharks are a relatively narrow shark with a long snout. They have bright blue sides and a dark blue dorsal surface. Pectoral fins are very long and narrow, with relatively small dorsal fins (Chapman et al. 2006). A weak lateral keel is present at the base of the tail (Compagno 1984a). This species is unlikely to be misidentified due to the strong colouration and morphology.

15.2 Distribution

One of the most widely distributed species of sharks. Blue sharks display a cosmopolitan distribution, being recorded from all oceans between approximately 50ºN and 50ºS (Compagno 1984b). In the Pacific, the highest abundances are recorded between 20º and 50ºN. From catch composition data, blue sharks are the third or fourth most commonly captured species (in weight) by longline fisheries, only exceeded by yellowfin, bigeye and albacore tunas (Langley et al. 2008). Catch rates are highest in equatorial areas, suggesting higher abundances than in sub-tropical areas (Molony 2005a).

15.3 Biology

15.3.1   Age and growth

Blue sharks have been recorded to obtain at least 383 cm TL[6] (315 cm FL) (Last and Stevens 1994), with unconfirmed records of much larger individuals (Compagno 1984a). Blue sharks are born at 35 cm TL (Last and Stevens 1994) to 56.4 cm TL (Lessa et al. 2004) (29–47 cm FL) and reach approximately 90 cm TL (75 cm FL) after the first year (Lessa et al. 2004).

Ageing of blue sharks is generally achieved through the counting of vertebral bands, with each band assumed to represent a year. This annual deposition of growth bands has recently been validated in two tetracycline marked sharks from the north Atlantic Ocean (Skomal and Natanson 2003). Growth is rapid until maturity, which is reached after five years at an average size of 225–228 cm TL (~186 cm FL) for males and females near Brazil (Lessa et al. 2004). The maximum size and age of blue sharks from north-eastern Brazil (Atlantic Ocean)

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[6] The relationship between total length (TL) and fork length (FL) for blue sharks is approximately, FL = 0.827 x TL, and TL = 1.193 x FL
(www.fishbase.org/PopDyn/LLRelationshipList.php?ID=898&GenusName=Prionace&SpeciesName=glauca&fc=11).

were 310 cm TL and 11 years for males, and 283 cm TL and 10 years for females. There was no evidence of sexual dimorphism in growth rates from the central Atlantic Ocean (Lessa et al. 2004), although male growth ceased while female growth was maintained after seven years of age in blue sharks from the North Atlantic (Skomal and Natanson 2003). The maximum estimated longevity for blue sharks is at least 15 years for males and 16 years for females in the North Atlantic (Skomal and Natanson 2003) but only 12 years in the Pacific Ocean (Nakano 1994).

A comparison of growth rates of blue sharks from the Atlantic and Pacific Oceans suggested that sharks in the Pacific reach a maximum of approximately 10 years of age, younger than the North Atlantic stock (maximum age ~ 16 years) (Skomal and Natanson 2002). However, the maximum size of blue sharks from both oceans were similar. In addition, higher growth rates have been reported from the southern hemisphere stock of blue sharks in the Atlantic Ocean (Lessa et al. 2004).

15.3.2   Reproduction

In the north Atlantic Ocean, blue sharks of both sexes are mature at five years of age (Skomal and Natanson 2003) at an average size of 186 cm FL (225–228 cm TL, Lessa et al. 2004). However, blue sharks appear to mature at smaller sizes in the north Pacific (males 130–160 cm TL; females 140–160 cm TL) (Nakano 1994) (105–130 cm FL).

Blue sharks are the most fecund of all shark species. An average litter size of 26 was reported from the north Pacific population, with a maximum litter size of 62 (Nakano 1994). However, litter sizes up to 135 have been reported (Last and Stevens 1994). Details of the frequency of reproduction are limited although it is assumed that each female was only likely to breed every one to three years. However, blue sharks in tropical areas may breed year-round, (Compagno 1984a), although the gestation period has been estimated to be 12 months suggesting that individuals may only produce one litter per year. The presence of pregnant females in tropical areas makes this life-stage vulnerable to industrialised longline fisheries.

15.3.3   Recruitment

Blue sharks are have been reported by observers in the longline fisheries of the WCPO as sizes less than 50 cm FL, with full recruitment by approximately 90 cm FL (Figure 78). Another strong mode appears in the pooled length-frequency data at approximately and 175 cm FL. Blue sharks do not appear vulnerable to purse-seine fisheries of the WCPO, with less than 10 blue sharks reported by observers since the mid 1990s.

15.3.4   Mortality

Limited studies have estimated the mortality rates for blue sharks. Smith et al. (1998) estimated the natural mortality of blue sharks in the Pacific at 0.223 year^{-1} (i.e. 22.3% mortality per year due to natural sources). This compares with the natural mortality of north Atlantic population of blue sharks, estimated by Campana et al. (2006) at 0.23 year^{-1}, with an estimated fishing mortality rate at MSY of 0.18 year^{-1}. Chen and Yuan (2006) estimated the natural mortality rate of female blue sharks in the north Atlantic at 0.196 year^{-1}.

15.4 Ecology

15.4.1   Habitat preference

Blue sharks are truly an oceanic species, although sometimes found close to coasts where the continental shelf is narrow. Blue sharks are rarely encountered in shallow waters and have not been recorded from the Torres Strait and Arafura Sea, between Australia and New Guinea (Last and Stevens 1994). This species has been recorded in surface waters (Compagno 1984a) to depths of at least 350 m (Last and Stevens 1994). Blue sharks are most commonly recorded in waters with temperatures of 14–21ºC in sub-equatorial areas.

Blue sharks are often found in large, loosely organised aggregations close to the surface, particularly in temperate areas (Compagno 1984a).

15.4.2   Movements and migration

Tagging studies have revealed that blue sharks are capable of large-scale movements. In the Atlantic Ocean, the greatest time at liberty was 10.7 years, with 21 blue sharks moving between 4,362 and 7,163 km (Stevens 1990). However, a review of movement of 5,410 recaptured blue sharks in the North Atlantic Ocean revealed that 90% were recorded within 1,500 nmi and 2.5 years of liberty (Kohler et al. 2002). These are similar findings to those of Querioz et al. (2005), who reported that 28 of 34 recaptured blue sharks travelled less than 1,000 km in the north-east Atlantic.

Based on the temporal and spatial patterns of recapture data, Kohler et al. (2002) suggested that blue sharks in the northern Atlantic shown regular movements between the eastern and western Atlantic, following the major currents, navigating by electric and/or magnetic fields. A similar clockwise migratory pattern has been suggested for female blue sharks in the south Atlantic Ocean (Compagno 1984a). The movement patterns are likely to be related to reproductive cycles, reproductive behaviour and size-age segregation, with larger, mature fish captured at higher latitudes (Kohler et al. 2002) and the movement of pregnant females from western areas of the Atlantic, along equatorial current to eastern areas in order to pup (Castro and Mejuto 1995). Nakano (1994) suggested a similar clock-wise movement pattern for the north Pacific stock of blue sharks, although he proposed that pregnant females migrate northward from spring to summer to pup just south of the sub-Arctic boundary.

Acoustic telemetry studies revealed that blue sharks make regular dives from the surface to depths of several hundred metres, with greater depths recorded during the day. At night, blue sharks are generally in surface waters and rarely venture below the thermocline; vertical movement patterns may be a result of feeding and hunting activities (Carey and Scharold 1990). Sciarrotta and Nelson (1977) reported a pattern of migration shoreward by blue sharks each even during summer months, likely in response to the seasonal distribution of prey species.

15.4.3   Diet

Like most sharks, blue sharks are a predator on a wide range of pelagic prey items, mainly fish and cephalopods, with squids being a very important component. However, small sharks, carrion, seabirds and benthic species have all been reported from the guts of blue sharks (Compagno 1984a).

15.5 Details of stocks in the WCPO

15.5.1 Stock structure and size

A single stock of blue shark is assumed in the north Pacific Ocean, with the equator considered as defining the southern extent of the northern stock. In addition, catch rates of blue shark were much higher north of 37ºN in the north Pacific (Nakano 1994) with highest abundances between 20ºN and 50ºN (Compagno 1984a). Thus there are likely to be at least two stocks of blue shark in the Pacific Ocean, with the equator defining the boundary. Nonetheless, limited movement data are available for blue shark in the Pacific Ocean.

Tagging studies in the Atlantic Ocean have revealed few trans-equatorial movements, with only four blue sharks recaptured in the other hemisphere from where they were tagged (nominal cross-equatorial recapture rate of 0.07%), suggesting separate northern and southern stocks in the Atlantic Ocean (Kohler et al. 2002).

Length-frequency data collected by observers in the WCPO reveal that small blue sharks (less than 100 cm FL) are captured by longline fisheries operating in tropical areas (10ºN–10ºS) and temperate areas (30–50ºS) (Figure 79). Larger sharks are typically reported from longline fisheries operating in areas between these latitudes (10–30ºS). However, larger sharks are also reported between 0–20ºN in areas east of 170ºE (Figure 79). Thus the stock structure of blue shark in the Pacific may be more complex than simply north and south of the equator.

Blue sharks are likely to have the largest stock size of any shark in the WCPO, due to their high occurrence in all longline fisheries (Langley et al. 2008). However, their abundance is likely to be much lower than albacore, bigeye or yellowfin tuna.

15.5.2   Recent stock assessments and status

Klieber et al. (2001) presented a preliminary assessment of the north Pacific stock of blue shark and concluded that fishing mortality was well below that estimated under a wide-range of possible scenarios; they concluded that the stock was in a healthy state. Catch rates in the north Pacific have remained high for several decades, supporting the healthy status of the northern stock (Nakano 1994).

Catch rates and catches of blue sharks have reduced since the late 1990s for the tropical longline fisheries of the WCPO (Molony 2005a, Figure 77), potentially suggesting a decline in abundance. However, catch rates and catches have been relatively stable, albeit lower, from the temperate longline fishery of the sub-equatorial WCPO (Molony 2005a).

Since 1997, the median size of all blue sharks captured by longline fisheries in the WCPO has shown strong seasonal fluctuations at approximately 180 cm FL, similar to the average size at maturity (~186 cm FL). Trends in length-frequency data suggest that the median size of blue sharks in many areas of the WCPO appear relatively stable. However, recent declines in median sizes have been reported from the north-eastern areas of the WCPO (Areas 12,13 and 14) and Area 9 of the western WCPO (Figure 80). Median total catches across the WCPO have stabilised at between 40,000 mt and 50, 000 mt per year since 2002 (Figure 77), with catch rates also stabilising at a relatively low level.

The data and trends suggest that the WCPO stock of blue shark may be stable, albeit at a lower level than in the 1990s. However, the stock status is uncertain as uncertainties in

biological and fishery parameters remain. A precautionary approach to further exploitation of this species should be considered until more robust information are available

15.6 Fisheries

15.6.1   Major fisheries and occurrence

Blue sharks are the most common and frequently captured sharks species in the world (Nakano 1994), accounting for more than 99% of all shark catches in the north Atlantic Ocean (Campana et al. 2006).

Nearly all blue sharks in the WCPO are recorded from the longline fisheries, with the tropical Pacific shallow longline fishery recording the highest catches and catch rates (Molony 2005a, Langley et al. 2008). Observers report that most blue sharks are discarded but are likely to be finned. Median total longline catches of blue sharks from the WCPFC-CA were estimated at 40,000–110,000 mt per year between 1994 and 2005 (Figure 77), with a major decline in catches between 1999 and 2002. In recent years catches have been relatively stable at 40,000–50,000 mt per year.

Insignificant catches of blue sharks have been recorded from the purse-seine fishery of the WCPO (Molony 2005a) (Figure 78), with all but one record from associated sets (logs, FADs, animals).

15.6.2   Artisanal fishery value

Given the close proximity to deep waters preferred by blue sharks near many Pacific Islands, and the high catch rates of blue sharks in the WCPO, it is likely that this species may be regularly encountered by artisanal fisheries in some areas .

15.6.3   Sport and recreational fishery value

Sport fisheries for blue sharks exist in some areas of the world. For example, in north-eastern Canada, recreational catches of blue sharks during fishing tournaments have been estimated to have rapidly increased from approximately 4 mt in 1993 to exceed 19 mt in 2002, similar to the estimated commercial catches of blue shark from the Canadian Atlantic (Campana et al. 2006). All recreationally captured blue shark in Canada are released alive. No information for sport fisheries for blue sharks in the WCPO were identified.
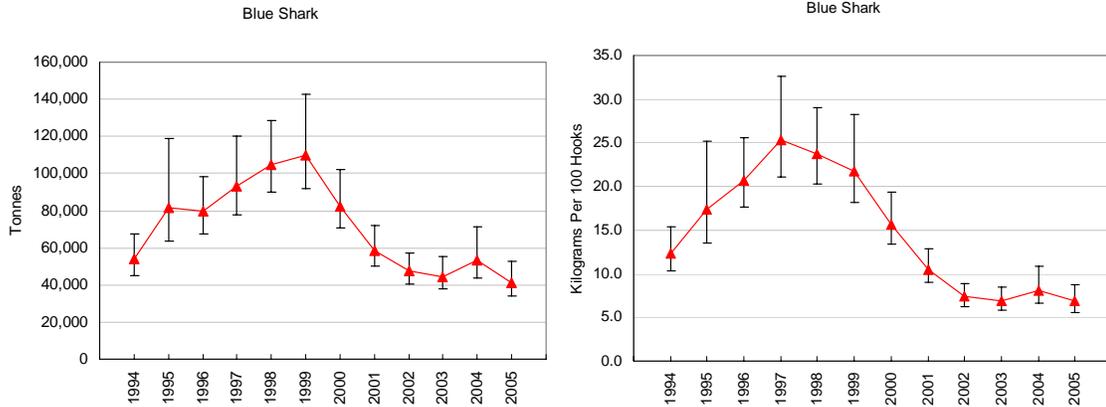
Figure 77. Catches and catch rates of blue sharks by longline vessels in the WCPFC Statistical Area (excluding the domestic fleets of Indonesia, the Philippines and Chinese Taipei). Points represent median values of 1,000 random samples from the posterior distributions; error bars represent 95% confidence intervals from 1,000 random samples from the posterior distributions. Source, OFP (2007).
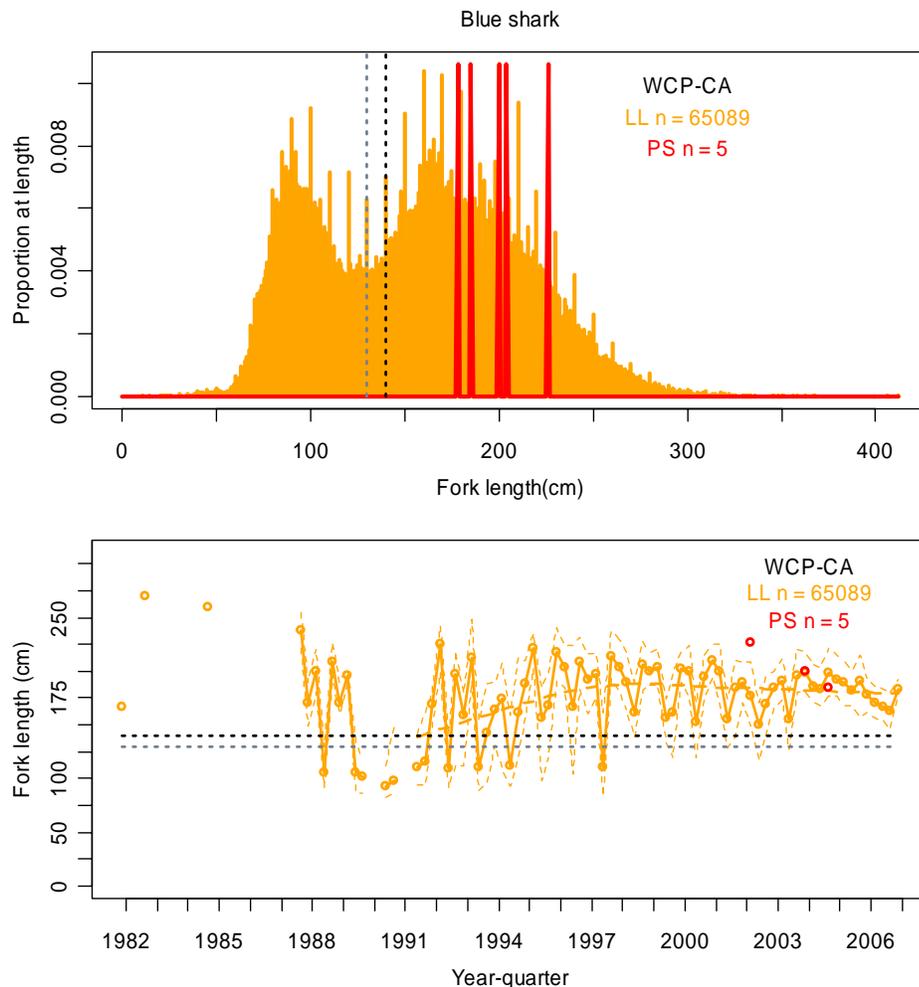
Figure 78. Combined length-frequency distributions (upper figure) and trends in quarterly median size (lower figure) of blue sharks reported by observers in longline and purse-seine vessels in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery. Thin dashed lines represent the 25th and 75th quartiles of the size data. Thick dashed lines represent lowess fits to the median size data. Dotted lines represent estimates of size at first maturity for females (black, 140 cm FL) and males (grey, 130 cm FL) (from Nakano 1994) from the north Pacific.

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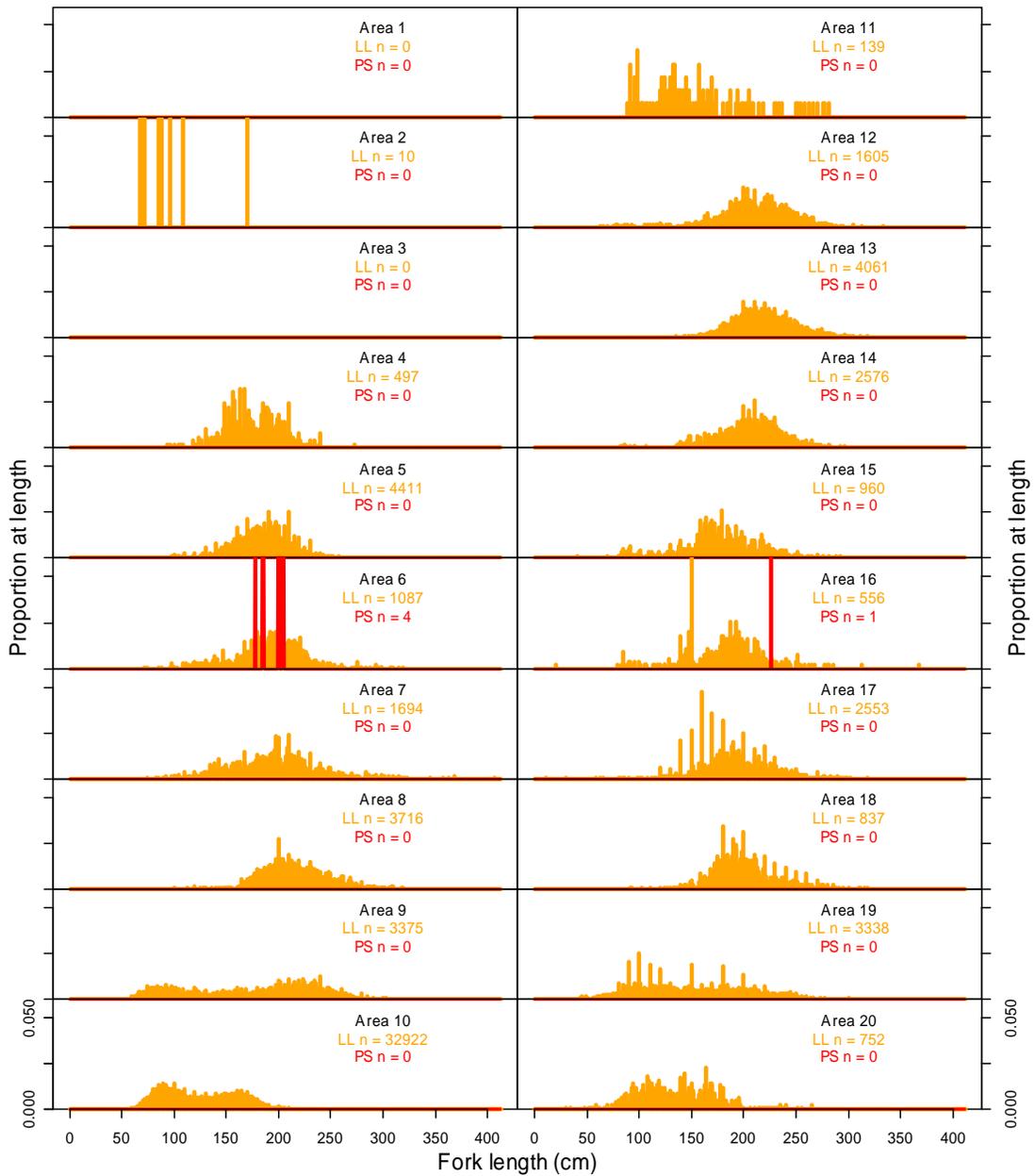
Figure 79. Length-frequency distributions of blue sharks pooled into 10º latitude bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as fork lengths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively.
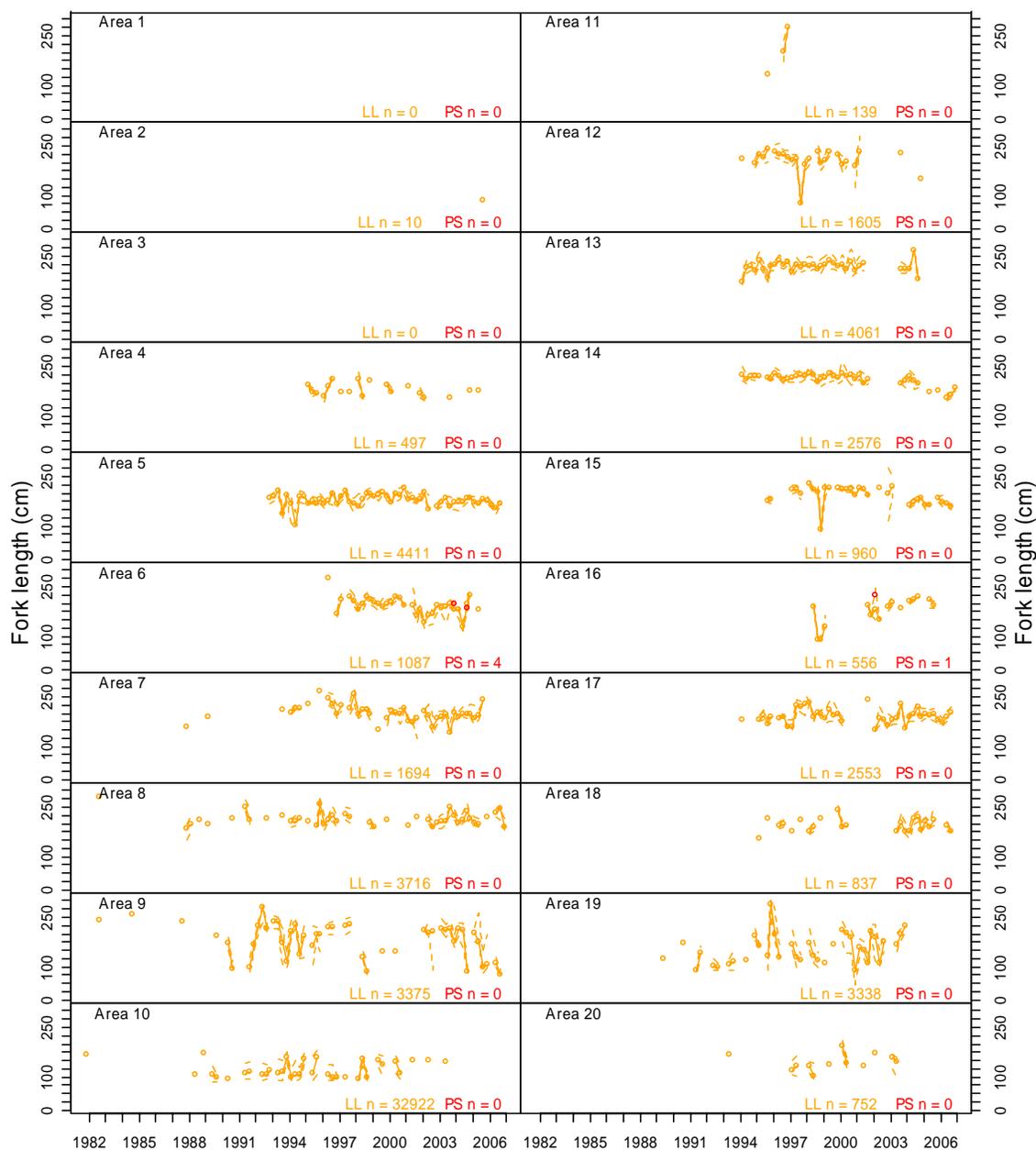
Figure 80. Trends in median size of blue sharks pooled into 10º latitudinal bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as fork lengths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively. Dotted lines represent 25th and 75th quartiles of each data series.

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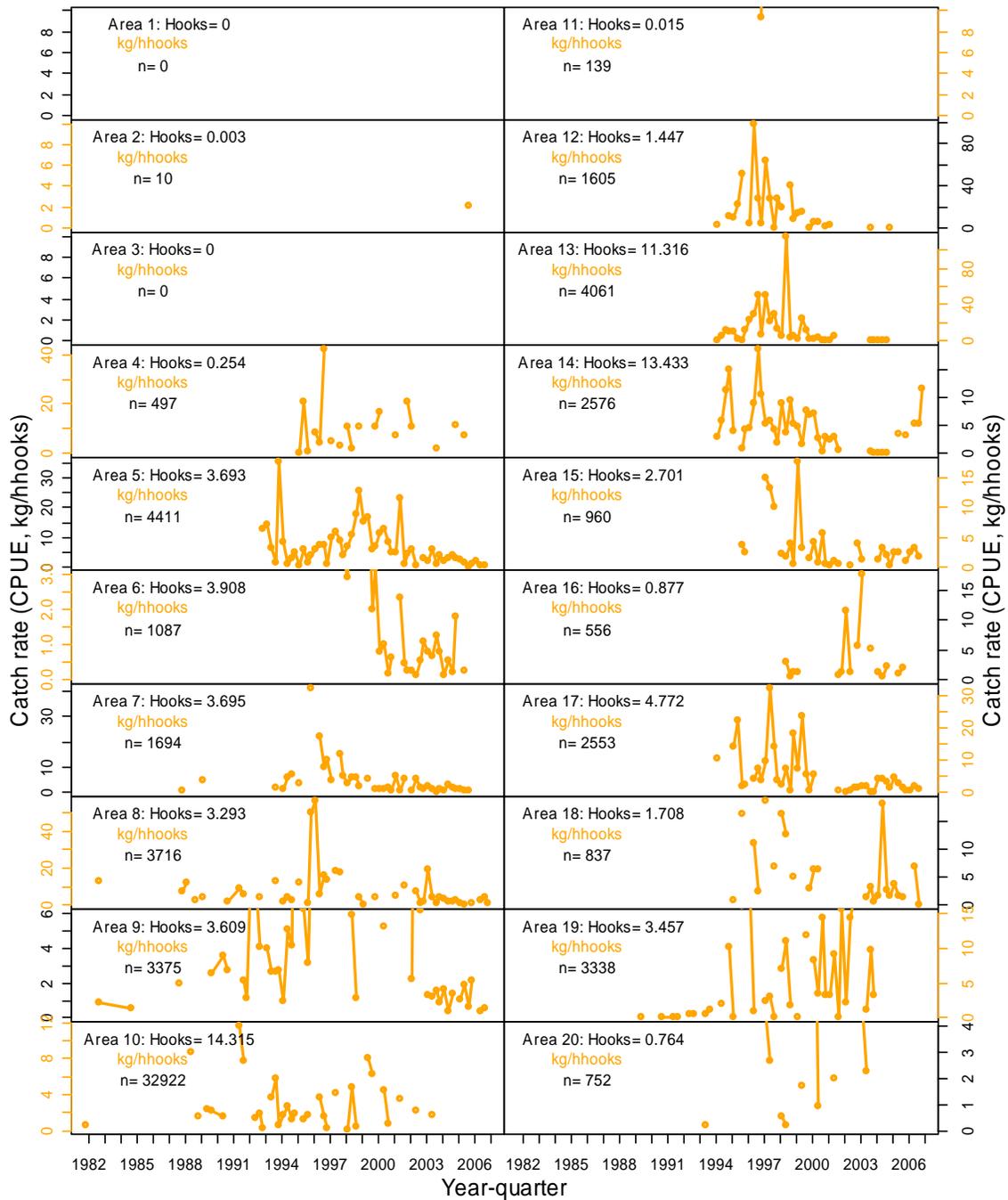
**Figure 81. Quarterly catch rates (kg.hhooks⁻¹) of blue shark reported by observers pooled into 10°
latitudinal bands (Areas) in the WCPO, 1982–2006. Source, SPC observer data base. Hooks, is the total
number of observed hooks (millions) in each Area; n, represents the total number of individuals from
each method-fishery within each Area. Scales of the y-axes vary among Areas. Left-hand figures are west
of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–
10ºS of the equator, respectively. Length-weight relationship: whole weight (kg) = (0.0032 x FL$^{3.131}$)/1000
(Kohler et al. 1995).**
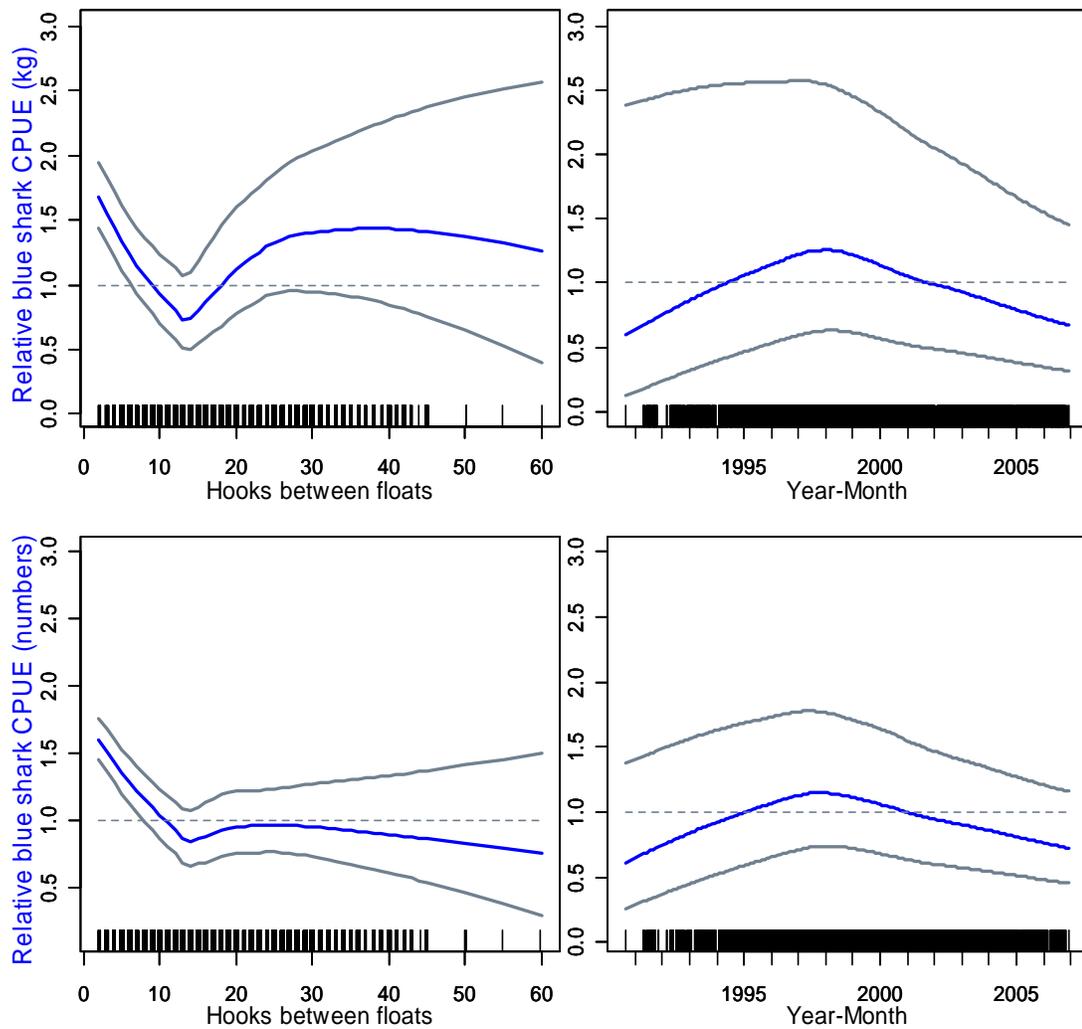
Figure 82. Changes in relative monthly blue shark longline catch rates (blue lines; upper figure, number/hhooks; lower figure, kg/hhooks) for the WCPO under the influence of longitude, latitude, hooks between floats and time period (year-month) as predicted by GLMs, 1991–2006. Sources, observer data held at SPC. Grey lines represent 95% confidence levels. The 'rug' plot along the inside of each x-axis displays the data density along the range of each variable. Weight: $r^2 = 0.333$, adjusted $r^2 = 0.274$; Numbers: $r^2 = 0.267$, adjusted $r^2 = 0.203$.

16. Silky shark (*Carcharhinus falciformis*)
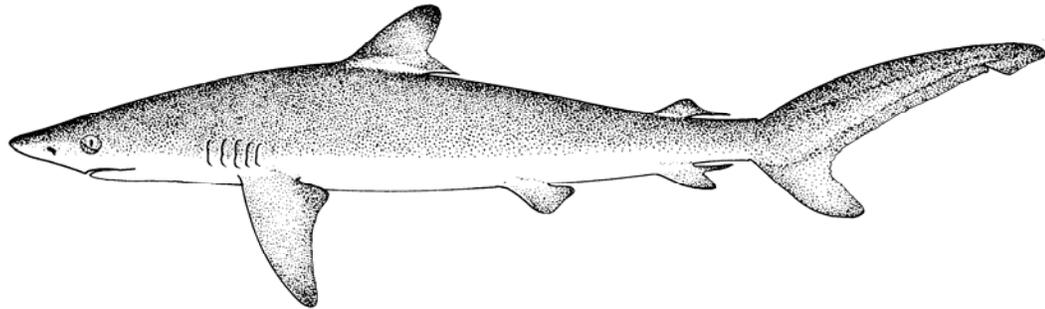
16.1 Description

A large dark grey shark with a long, rounded snout and long, narrow pectoral fins. There are no conspicuous markings on this species of shark (Compagno 1984a). The origin of the first dorsal fin is well behind the posterior base of the pectoral fins (Chapman et al. 2006).

16.2 Distribution

Silky sharks are a pelagic species displaying a patchy distribution in tropical and sub–tropical waters of all oceans, although they are more commonly found in tropical waters (Compagno 1984a). Silky sharks have been recorded from the Pacific, Indian and Atlantic Oceans, and the Mediterranean Sea (Cortés 2000). In the WCPO, silky sharks have been commonly reported from the EEZs of the Marshall Islands, Papua New Guinea, Northern Mariana Islands, New Caledonia, the Philippines, northern New Zealand, Australia and are common in Hawaii.

16.3 Biology

16.3.1   Age and growth

Ageing of silky sharks has been achieved by enumerating bands in thinly sectioned vertebrae. Silky sharks captured around the Yucatan Peninsula (Gulf of Mexico, western Atlantic Ocean), were estimated to have a longevity of more than 22 years for females and more than 20 years for males (Bonfil et al. 1993). A recent study of silky sharks from waters off north-eastern Taiwan (western WCPO) estimated maximum longevities of 36 years for females and 29 years for males (Joung et al. 2008), higher than for sharks from the Gulf of Mexico.

A VBGF model estimated the L∞ of silky sharks in the Gulf of Mexico at 291 cm TL[7] (235 cm FL), with *k* estimated at 0.153.year^{-1} (Branstetter 1987). However, Bonfil et al. (1993) estimated a maximum size of more than 310 cm TL (249 cm FL) from sharks sampled off the Yucatan Peninsula and this species is thought to exceed 330 cm TL (265 cm FL) elsewhere (Compagno 1984a). From the western WCPO, the estimate of L∞ of 332 cm TL was similar to previous, although k was estimated to be much lower (0.0838.year^{-1}) (Joung et al. 2008). The study of Joung et al. (2008) included small sharks with estimated ages of less than one year, although growth rates of young fish is likely to be underestimated. In addition, few

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[7] The relationship between total length (TL) and fork length (FL) for silky sharks is approximately, FL = 0.804 x TL, and TL = 1.224 x FL
(www.fishbase.org/PopDyn/LLRelationshipList.php?ID=868&GenusName=Carcharhinus&SpeciesName=falciformis&fc=11).

large, old shakers were captured in the study, with the maximum age being approximately 14 years. Growth is similar for both sexes (Joung et al. 2008).

16.3.2   Reproduction

Male silky sharks first mature at 187–220 cm TL (150–175 cm FL) and females at 213-230 cm TL (170–185 cm FL) (Compagno 1984a, Branstetter 1987), corresponding to ages of 6–7 years and 7–9 years at first maturity, respectively (Branstetter 1987). However, Bonfil et al. (1993), using alizarin staining techniques of sectioned vertebrae, estimated the ages at first maturity at 10 years for males and more than 12 years for females. Silky sharks from Taiwanese waters have similar sizes at 50% maturity (females: 210–220 cm TL; males: 212 cm TL) but are slightly older due to their slower growth (females: 9-10 years; males: 9 years) (Joung et al. 2008). The sex ratio of silky sharks approximates 1:1 (Joung et al. 2008).

There is also a considerable range in sizes and ages at maturity. For example, Joung et al. (2008) reported that the largest immature male was 230 cm TL (more than 11 years old), while the smallest mature male was 191 cm TL and less than 8 years old.

The gestation period has been estimated as approximately 12 months (Branstetter 1987, Bonfil et al. 1993) although there is no clear breeding season, with individuals of this species birthing year round (Compagno 1984b, Last and Stevens 1994). Size at birth is approximately 70–87 cm TL (55–70 cm FL), although size at birth is slightly smaller for silky sharks in Taiwanese waters (63–76 cm TL) (Joung et al. 2008).

Littler size is variable (2–17 pups) (Compagno 1984a, Last and Stevens 1994, Joung et al. 2008). However, litter sizes of less than five pups may be a result of pups being aborted from one uterus during capture (Beerkircher et al. 2003). Silky sharks appear to birth in offshore nursery grounds (Compagno 1984a, Joung et al. 2008).

16.3.3   Recruitment

Silky sharks are vulnerable to longline fishing from relatively small sizes and ages. Beerkircher et al. (2003) estimated high fishing mortality rates for 0+ year old sharks off the south-eastern United States. From observer records in the WCPO, silky sharks recruit to the longline fisheries at approximately 50 cm FL, and are fully recruited by approximately 125 cm FL (Figure 85), well below the estimated sizes at first maturity.

Silky sharks recruit to the purse-seine fisheries of the WCPO at less than 50 cm FL, and are fully recruited at 80 cm FL, well below the estimated size of first reproduction (Figure 85).

16.3.4   Mortality

Beerkircher et al. (2003) presented total and/or fishing mortality estimates for silky sharks from several sources in a demographic analysis of the species. Estimates of total mortality varied up to 0.486 year^{-1} (48.6% reduction in numbers per year) with fishing mortality ranging between 0.022 year^{-1} and 0.287 year^{-1}. In a base-case scenario, natural mortality was set at 0.329 year^{-1} for all age classes. However, total and fishing mortality rates for this species off the south-east coast of the United States were estimated to be very high for young sharks (less than 3 years old), reducing rapidly with age (e.g. total mortality rates were estimated at less than 0.1 year^{-1} for sharks five years and older in one scenario). Chen and

Yuan (2006), also using a demographic approach, estimated the natural mortality rate for silky sharks off the south-eastern United States as 0.155 year^{-1}.

Smith et al. (1998) estimated the natural mortality of silky sharks in the Pacific at 0.179 year^{-1}.

16.4 Ecology

16.4.1 Habitat preference

Silky sharks are commonly reported near land masses and along drop–offs the near the edges of continental shelves and atolls. They are most common between the surface and at least 500 m deep and in waters above 23 °C (Compagno 1984a, Last and Stevens 1994). Silky sharks are often associated with tuna schools in surface waters (Compagno 1984a), leading to their high catches and catch rates by purse-seine fisheries of the WCPO.

Nominal average annual catch rates of silky sharks from the WCPO were approximately 1.5 sharks per hundred hooks in the tropical shallow longline fishery, 0.1 sharks per hundred hooks in the tropical deep longline fishery and 0.05 sharks per hundred hooks in the sub-equatorial albacore longline fishery (Molony 2005a) highlighting the higher abundance in tropical regions, especially in shallow waters.

Silky sharks are the most commonly shark species reported by observers on purse-seine vessels in the WCPO (Langley et al. 2008). Catch rates of silky sharks from associated sets average an order of magnitude higher than the catch rates from unassociated or school sets (Molony 2005a).

16.4.2 Movements and migration

Movements of silky sharks are poorly known. Oshitani et al. (2003) suggested that there were clear nurseries areas for silky sharks, with adults found further offshore. Unlike blue sharks, there is no evidence to suggest a regular migratory cycle and it is assumed that the low movement rates suspected for silky sharks are why catch rates trends for this species vary between the eastern and western Pacific (i.e. due to differences in local levels of effort and fishing mortality rates). The low movement rates were suspected of contributing to the patchy distribution of this species, resulting in areas of higher and lower abundances (Compagno 1984a).

16.4.3 Diet

Silky sharks mainly feed on pelagic fishes, cephalopods and crabs (Randall et al. 1990, Last and Stevens 1994). As silky sharks are commonly associated with surface tuna schools (Compagno 1984a), it is likely that tuna make up a significant amount of their diet.

16.5 Details of stocks in the WCPO

16.5.1 Stock structure and size

Stock structure is unknown. However, the patchy distribution of this species in the tropical and sub-tropical areas of the WCPO (Compagno 1984a) suggests the potential of there at least

being a number of sub-populations. There is likely to be separate eastern and western Pacific stocks due to major differences in catch rates. Length-frequency analyses of observer data suggests that smaller silky sharks are found in equatorial areas of the WCPO, with larger sharks found at higher latitudes (Figure 86). Few silky sharks have been reported north or south of 30º (Figure 86, Figure 87). This suggest that there is may be a single, patchy, stock of silky sharks in the WCPO, but does not discount the existence of a single Pacific-wide stock.

No information on stock size are available for the WCPO. The distribution of silky sharks in the EPO is more continuous than in the WCPO, suggesting higher relative abundances. Additionally, areas of continuous distribution of silky sharks are found along the tropical and subtropical coasts of Africa and throughout the Gulf of Mexico (Compagno 1984a).

16.5.2   Recent stock assessments and status

Catch rate data (Molony 2005a) suggest that there are considerable fluctuations in local abundances. However, the patchy distribution does not permit CPUEs to be a reliable index of abundance. Median sizes of silky sharks captured by the longline and purse-seine fisheries of the WCPO have been relatively stable since at leats the late 1990s, at 140 cm FL and less than 100 cm FL, respectively (Figure 85). The median size of silky sharks captured in equatorial areas has been relatively stable since the mid 1990s (Figure 87). However, declines in median size of silky sharks have been observed in sub-equatorial areas of the western WCPO (Areas 7 and 8) and Area 14 (10–20ºN, east of 170ºE) (Figure 87). This suggests that some degree of local depletion may be occurring. Purse-seine catches of silky sharks in the WCPO have increased since 1994 (Figure 83), while longline catches have declined since 2000 (Figure 84). This suggest that the longline-vulnerable proportion of the WCPO stock of oceanic whitetip sharks may not be able to sustain the recent levels of longline effort.

Regulations in the EPO have encouraged shark releases and banned finning with subsequent increases in CPUEs in the EPO, but not in the WCPO (Molony 2005 a).

16.6 Fisheries

16.6.1   Major fisheries and occurrence

Silky sharks are captured in industrialised longline and purse-seine fisheries in the WCPO (Langley et al. 2008). Silky sharks are commonly captured by longline and purse-seine fisheries in the WCPO, although they account for a higher proportion of catches in tropical fisheries. Median total longline catches of silky sharks from the WCPFC-CA have varied between 1,500 mt and more than 13,000 mt per year between 1994 and 2005 (Figure 84), with a decline in catches since 2000. Most silky sharks are finned and carcasses discarded if captured by longline fisheries.

Silky sharks are reported from all set types in the purse-seine fisheries of the WCPO, but constitute a higher proportion of overall catches in sets on floating objects (FADs, logs) (Langley et al. 2008). More than 95% of sets in which silky sharks are reported are associated sets (i.e. logs, FADs, animals). Total catches have been estimated to have steadily increased from less than 200 mt in 1994, to exceed 1,000 mt in recent years (Figure 83). Catch rates have also increased.

16.6.2   Artisanal fishery value

Due to the offshore distribution of silky sharks there is unlikely to be much interaction with artisanal fisheries.

16.6.3 Sport and recreational fishery value

There is likely to be little recreational or sporting value for this species, due to the offshore distribution.
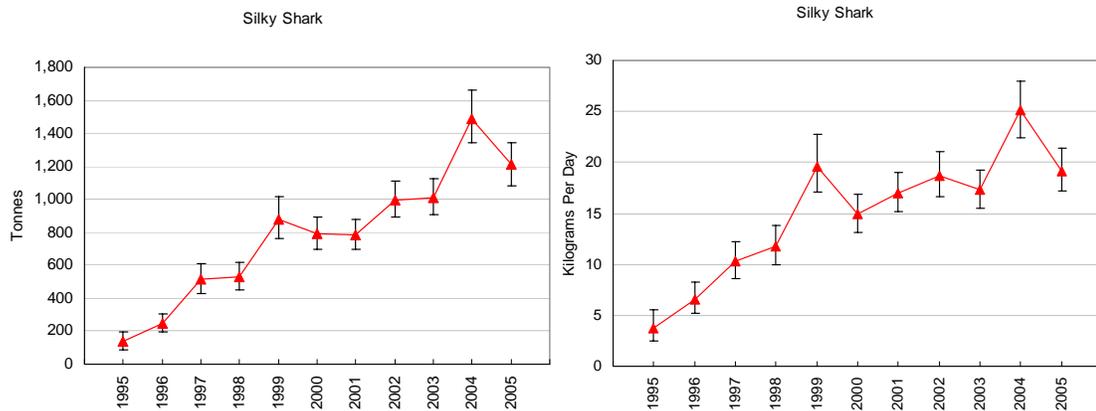
Figure 83. Catches and catch rates of silky sharks by purse-seine vessels in the WCPFC Statistical Area (excluding the domestic fleets of Indonesia and the Philippines). Points represent median values of 1,000 random samples from the posterior distributions; error bars represent 95% confidence intervals from 1,000 random samples from the posterior distributions. Source, OFP (2007).
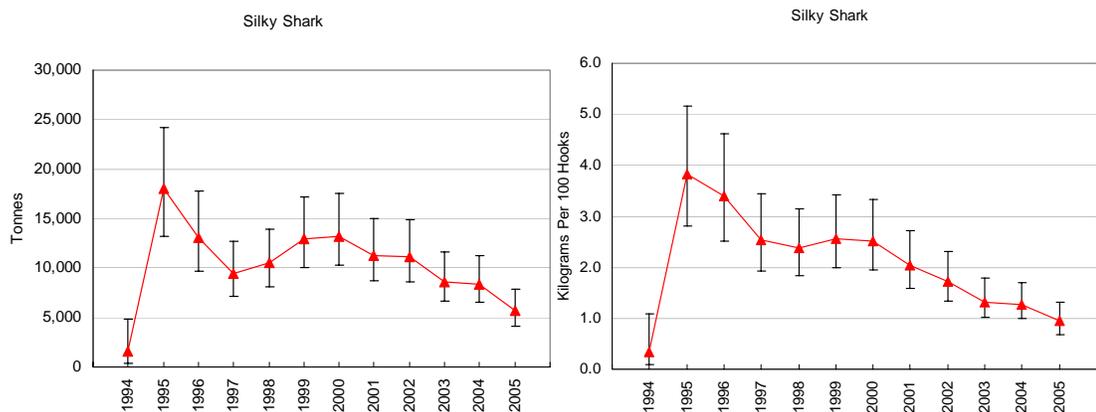
Figure 84. Catches and catch rates of silky sharks by longline vessels in the WCPFC Statistical Area (excluding the domestic fleets of Indonesia, the Philippines and Chinese Taipei). Points represent median values of 1,000 random samples from the posterior distributions; error bars represent 95% confidence intervals from 1,000 random samples from the posterior distributions. Source, OFP (2007).
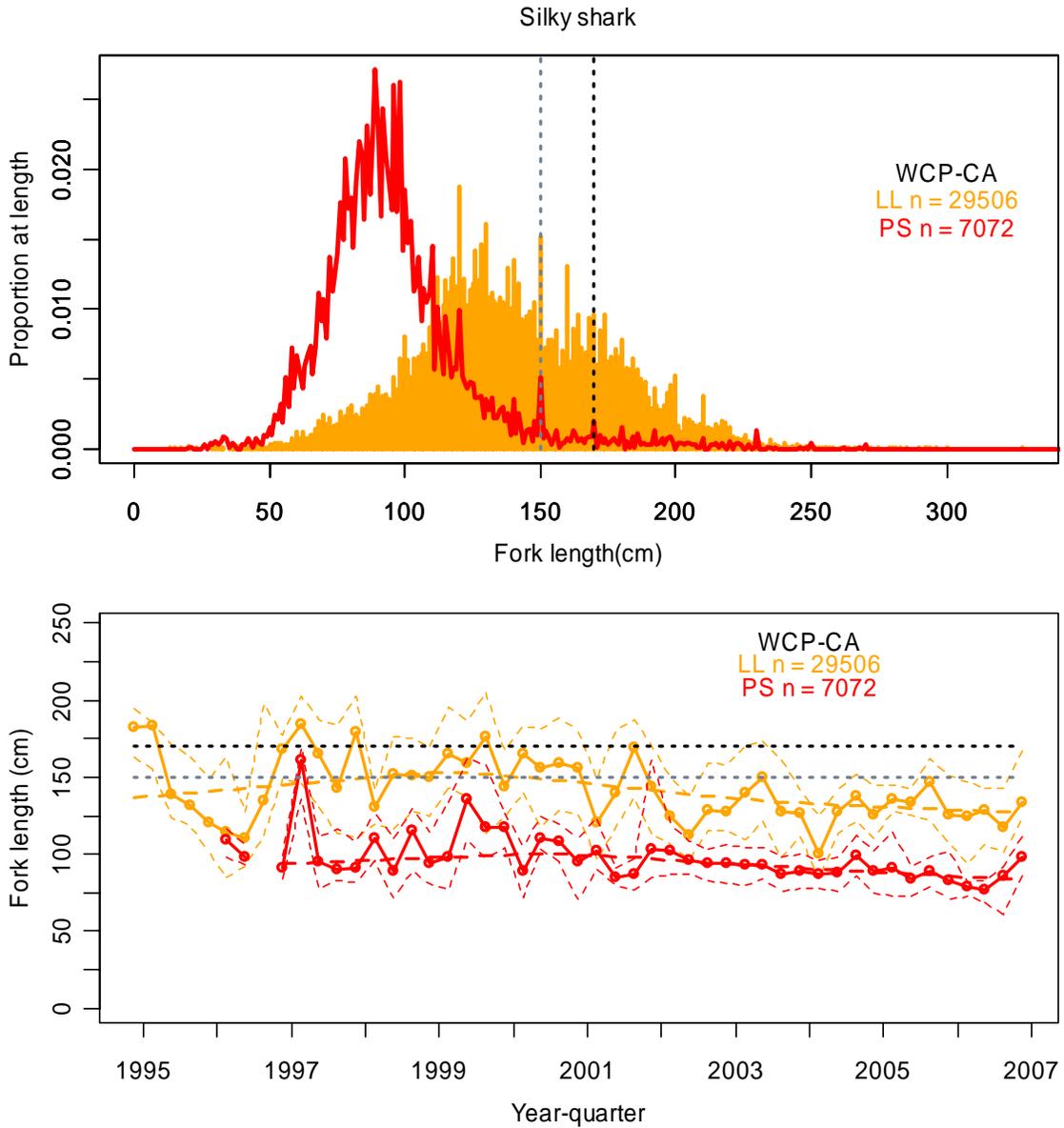
Figure 85. Combined length-frequency distributions (upper figure) and trends in quarterly median size (lower figure) of silky sharks reported by observers in longline and purse-seine vessels in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery. Thin dashed lines represent the 25th and 75th quartiles of the size data. Dashed lines represent lowess fits to the median size data. Dotted lines represent estimates of size at first maturity for females (black, 170 cm FL) and males (grey, 150 cm FL) (from Campagno 1984b, Branstetter 1987 and Joung et al. 2008).
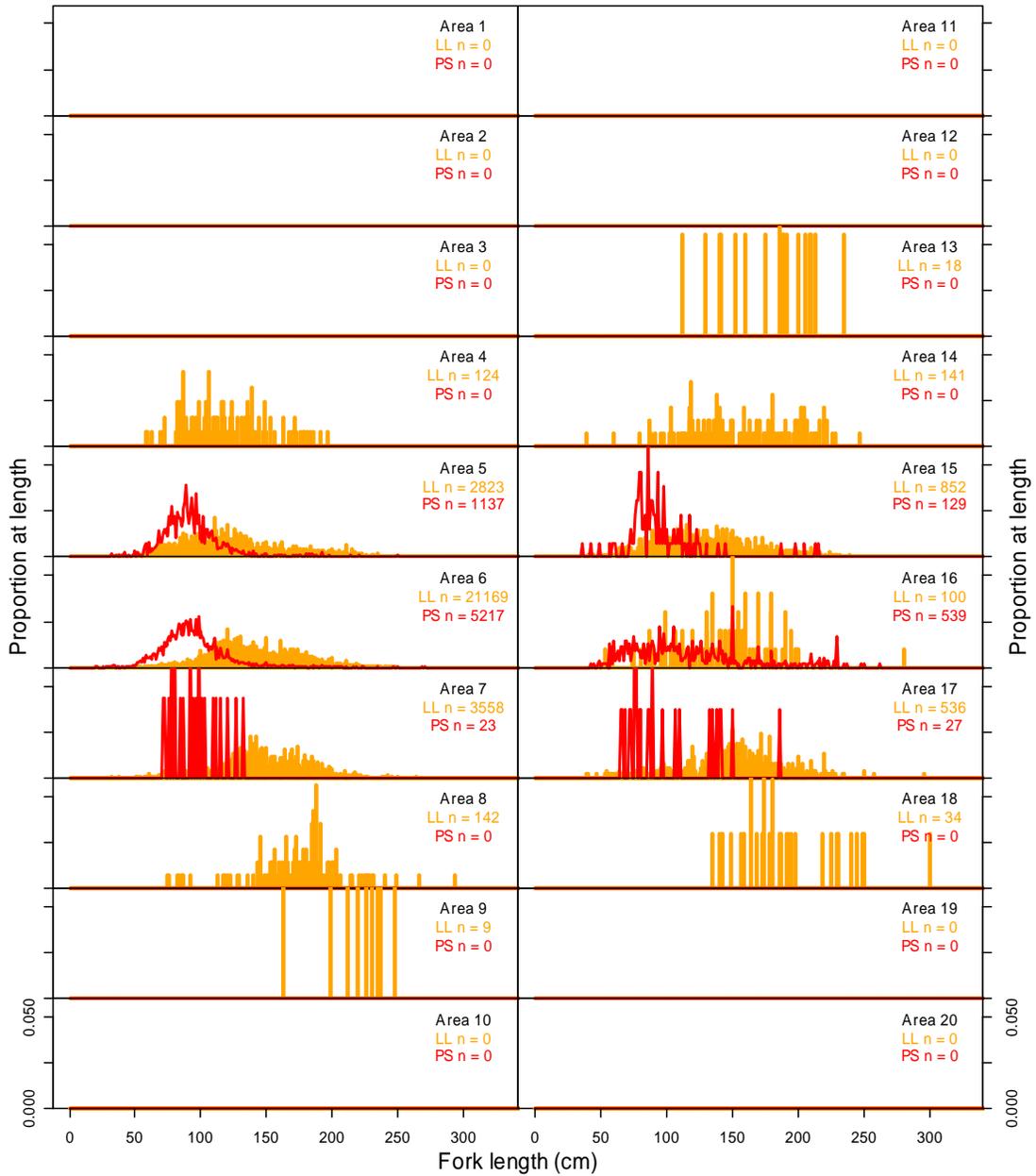
Figure 86. Length-frequency distributions of silky sharks pooled into 10º latitude bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as fork lengths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively.

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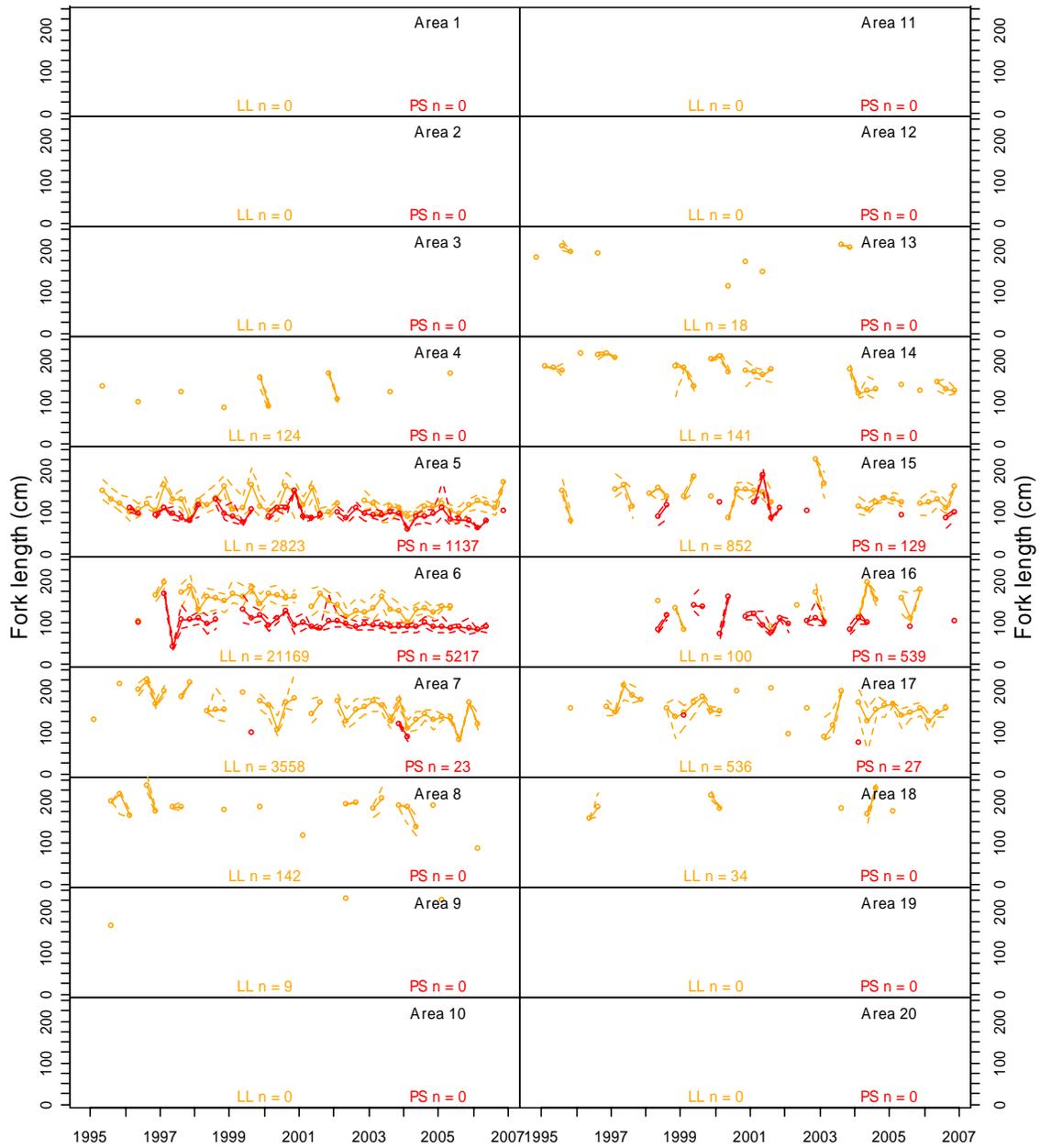
Figure 87. Trends in median size of silky sharks pooled into 10° latitudinal bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as fork lengths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively. Dotted lines represent 25th and 75th quartiles of each data series.
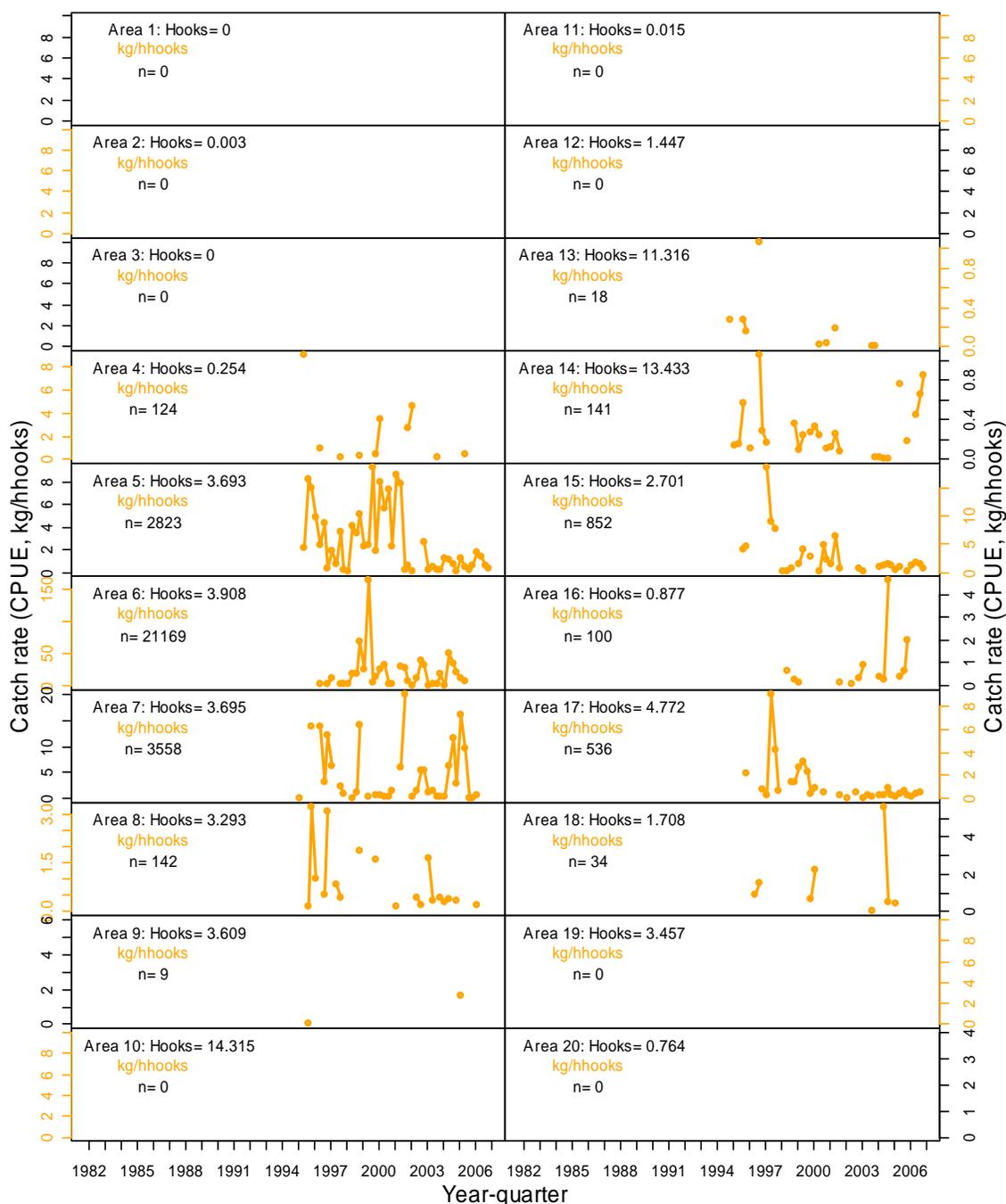
Figure 88. Quarterly catch rates (kg.hhooks⁻¹) of silky shark reported by observers pooled into 10º latitudinal bands (Areas) in the WCPO, 1982–2006. Source, SPC observer data base. Hooks, is the total number of observed hooks (millions) in each Area; n, represents the total number of individuals from each method-fishery within each Area. Scales of the y-axes vary among Areas. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0– 10ºS of the equator, respectively. Length-weight relationship: whole weight (kg) = (0.0154 x FL$^{2.922}$)/1000 (Kohler et al. 1995).
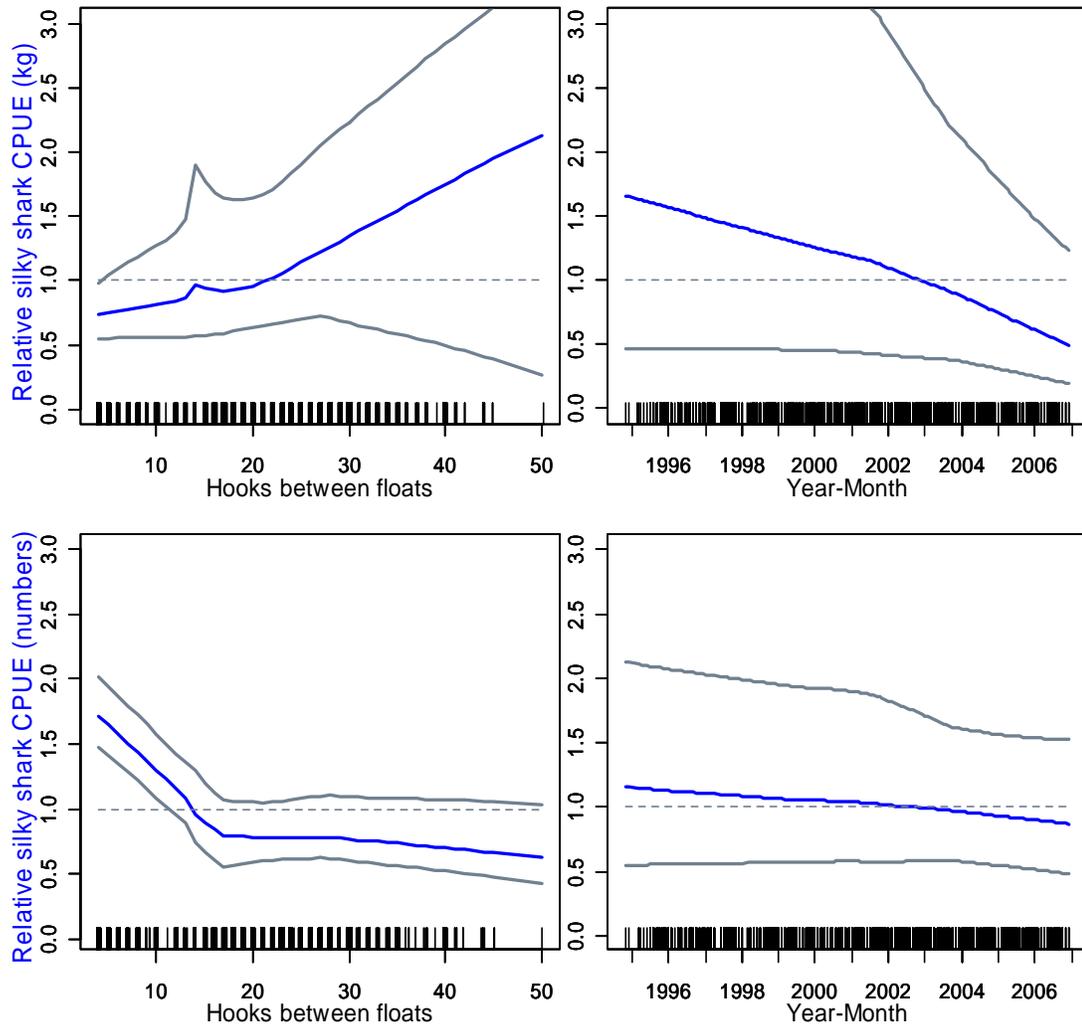
Figure 89. Changes in relative monthly silky shark longline catch rates (blue lines; upper figure, number/hhooks; lower figure, kg/hhooks) for the WCPO under the influence of longitude, latitude, hooks between floats and time period (year-month) as predicted by GLMs, 1991–2006. Sources, observer data held at SPC. Grey lines represent 95% confidence levels. The 'rug' plot along the inside of each x-axis displays the data density along the range of each variable. Weight: $r^2 = 0.227$, adjusted $r^2 = 0.078$; Numbers: $r^2 = 0.335$, adjusted $r^2 = 0.206$.

17. Oceanic whitetip shark (*Carcharhinus longimanus*)
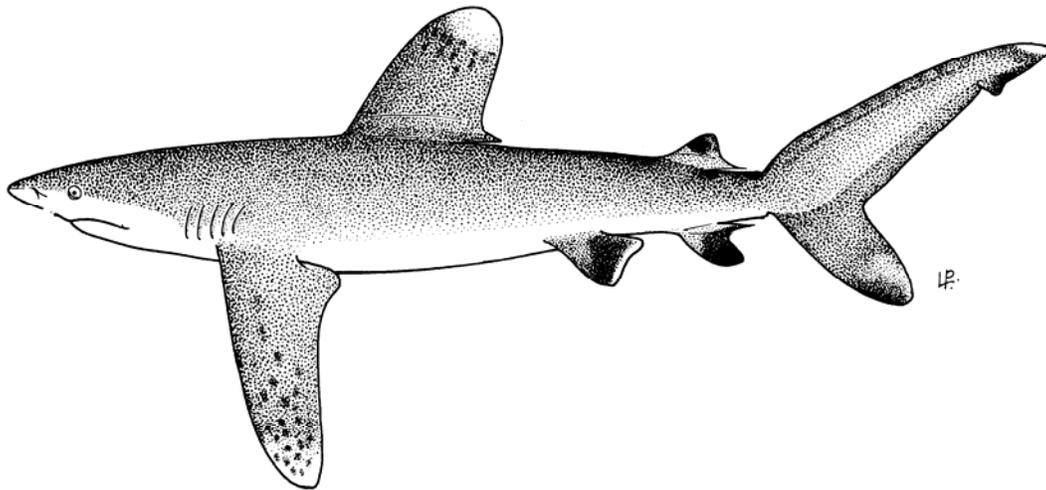
17.1 Description

Oceanic whitetip sharks are easily recognised by the large, broad paddle-shaped pectoral and first dorsal fins with rounded, white ends and white spots (Compagno 1984a, Chapman et al. 2006). The snout of this species is very short (Compagno 1984a). The tail usually has a white tip and other fins may have dark or black markings (Compagno 1984a).

17.2 Distribution

Oceanic white tips are found globally in tropical and warm-temperate waters between approximately 30ºN and 30ºS of the equator. Observer data confirms a similar latitudinal distribution in the WCPO (Figure 93). The latitudinal range of this species is greater in the Atlantic Ocean (Compagno 1984a).

17.3 Biology

17.3.1   Age and growth

Ageing of oceanic whitetip sharks is achieved via sectioning vertebrae and counting bands seen in the sections. The size at birth is approximately 60–75 cm TL[8] (50–62 cm FL) with a maximum size for this species of approximately 270–325 cm TL (Lessa et al. 1999, Cortés 2000). Both sexes follow a similar growth schedule, reaching maturity 180–190 cm TL (150–160 cm FL) by 6–7 years of age in the equatorial Atlantic (Lessa et al. 1999). However, oceanic whitetip sharks may reach maturity at a smaller size (125–135 cm TL, 100–110 cm FL) and younger age (4–5 years) in the Pacific Ocean, corresponding with a smaller maximum size (245 cm TL (Seki et al. 1998)) (200 cm FL).

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[8] The relationship between total length (TL) and fork length (FL) for oceanic whitetip sharks is approximately, FL = 0.822 x TL, and TL = 1.224 x FL
(www.fishbase.org/PopDyn/LLRelationshipList.php?ID=875&GenusName=Carcharhinus&SpeciesName=longimanus&fc=11).

Oceanic whitetip sharks have been aged to 11 years but were estimated to reach 22 years of age in the Pacific Ocean (Seki et al. 1998) and 17 years in the Atlantic Ocean (Lessa et al. 1999), although data are limited (Cortés 2000). The variation is likely to be due to difficulties in estimating age from length as the growth rates reduce significantly after the onset of maturity, resulting in sharks of a similar size being of a wide range of ages (Lessa et al. 1999) (Table 9).

17.3.2   Reproduction

Oceanic whitetip sharks give birth to live young, 60–75 cm TL (50–62 cm FL) in the Atlantic (Lessa et al. 1999, Cortés 2000) and 45–55 cm TL (37–45 cm FL) in the Pacific (Seki et al. 1998) after a 12 month gestation period (Lessa et al. 1999). Litter sizes vary between one and 15 young, with average litter sizes estimated at 6–8 young per litter in the Pacific Ocean (Cortés 2000). Gestation time is estimate at 12 months (Randall et al. 1990).

17.3.3   Recruitment

Oceanic whitetip sharks have been recorded from longline fisheries as small as 70 cm TL (57 cm FL) and are fully recruited into commercial fisheries before they each the size of the onset of maturity (Lessa et al. 1999). Oceanic whitetip sharks have been captured by longline and purse-seine fisheries below 50 cm FL (Figure 92) and appear fully recruited into longline fisheries of the WCPO by approximately 125 cm FL. The median size of oceanic whitetip sharks captured by the longline fishery in the WCPO is approximately 150 cm FL, with much small sharks captured in the purse-seine fishery (Figure 92).

17.3.4   Mortality

Mortality estimates are rare for oceanic whitetip sharks. Smith (1998) estimated natural mortality rate of 0.203 year^{-1} from data collected in the Pacific Ocean by Seki et al. (1998).

17.4 Ecology

17.4.1   Occurrence in pelagic community

Based on catches from industrialised tuna fisheries, oceanic whitetip sharks are one of the three most common species of oceanic sharks in the world (along with blue and silky sharks). They are found in oceanic and pelagic waters, and may be found close to islands and land when the continental shelf is narrow (Compagno 1984a). Oceanic whitetip sharks are reported from all EEZs and international waters of the WCPO. In the WCPO fisheries, oceanic whitetip sharks are the second most commonly captured species of shark by longline and purse-seine fisheries (Langley et al, 2006b).

17.4.2   Habitat preference

Oceanic whitetip sharks are most common between the surface and at least 150 m deep, usually in areas where the water depth is greater than 180 m (Compagno 1984a). They have a preference for warm waters (greater than 18–20°C) and have been captured in waters greater than 28°C (Compagno 1984a). As such, the catch rates of this species are higher from shallow

longline sets in tropical regions than from other longline fisheries of the WCPO (Molony 2005a, Langley et al, 2006b).

17.4.3 Movements and migration

Movement information is limited for this species. However, Lessa et al. (1999) found similar length-frequency distributions for oceanic whitetip sharks captured in the south-western equatorial Atlantic as in samples collected in other locations, suggesting a high degree of mixing and therefore movement. Observer data from the WCPO indicates that larger oceanic whitetip sharks are captured at sub-equatorial latitudes (Figure 93).

17.4.4 Diet

Oceanic whitetip sharks have one of the most varied diets of all sharks, explaining their wide distribution and relatively common occurrence in all oceans. Oceanic whitetip sharks mainly feed on fishes (mainly tunas and mackerels) and cephalopods (Last and Stevens 1994) but also turtles, birds, pelagic crustaceans and marine mammals (Randall et al. 1990). Being aggressive, they are also likely to be responsible for attacks on people after air or sea disasters in the open oceans (Last and Stevens 1994)

17.4.5 Predators

Adult oceanic whitetip sharks are unlikely to have many natural predators. However, smaller sharks may be predated upon by lager sharks (Cox et al. 2002).

17.5 Details of stocks in the WCPO

17.5.1 Stock structure

Few details are know of the stock structure of oceanic whitetip sharks anywhere in the world. Size-frequency data collected by observers in the WCPO reveal that small sharks are typically found in tropical areas, while larger sharks at sub-equatorial latitudes. This suggest that there may be a single stock in the WCPO. However, given the similar size-frequency distributions across many locations in other oceans (Lessa et al. 1999), it is possible that there is a single stock across the WCPO.

17.5.2 Stock size

Unknown for this species.

17.5.3 Recent stock assessments and status

There are no known stock assessments undertaken for this species and the stock status is currently unknown. Analysis of catch rate data from the Atlantic Ocean suggests that the CPUE for oceanic whitetip sharks slightly increased between 1986 and 1997, suggesting that the population may be stable. Molony (2005a) estimated the that nominal catch rates of oceanic whitetip sharks from the tropical deep longline fishery and the sub-tropical albacore fisheries were low and stable since the early 1990s. Catch rates were highly variable for the tropical shallow longline fishery.

Median size data reveals steadily decreasing median sizes of oceanic whitetip sharks from both longline and purse-seine fisheries of the WCPO (Figure 92), with most of the declines in median size in equatorial areas (Areas 5, 6 and 15) and north eastern sub-equatorial areas (Areas 13 and 14) of the WCPO (Figure 94). In addition, longline catches of oceanic whitetip sharks have also declined since 2002 (Figure 90). This suggest that there may be a reduction in the abundance of larger sharks. However, the median size of oceanic whitetip sharks captured by the longline fishery (~150 cm FL) is above the size at maturity estimated for the Pacific Ocean (100–110 cm FL (Seki et al. 1998), although this is based on a few samples. The median size of oceanic whitetip sharks captured by the purse-seine fisheries in the WCPO is less than 100 cm FL, below the size of first maturity (Figure 92).

In addition, overall estimates from the WCPFC longline and purse-seine fisheries reveal a decline in catches and catch rates since the late 1990s (Figure 90, Figure 91). This suggests that the level of effort and catches of this species may be higher than the WCPFC stock can sustain.

17.5.4   Relative stock size and status (c.f. other non–wcpo areas)

Little information on stock sizes of oceanic whitetip sharks are available to allow comparison among areas. As catch rates are similar between the WCPO (Molony 2005a) and Atlantic Oceans (Cramer 2000) stocks sizes may also be similar. In both oceans, catch rates were higher in tropical areas, suggesting higher abundances in warm equatorial waters than in cooler, more-temperate waters. Limited information were available for the Indian Ocean although catches have been reported by observers on longline vessels operating south of 35º near South Africa (Petersen 2005).

17.6 Fisheries

17.6.1   Major fisheries and occurrence

Oceanic whitetip sharks are a bycatch species in longline and purse-seine fisheries throughout their range. Most oceanic whitetip sharks incidentally captured by longline are likely to be finned fined, resulting in a high mortality rate (approximately 65% in the WCPO, Molony 2005a). However, the meat of oceanic whitetip sharks has also been used for human consumption in some areas (Last and Stevens 1994). Higher catch rates and total catches were estimated from the tropical shallow longline fishery of the WCPO than for the tropical deep longline or sub-tropical albacore longline fisheries (Molony 2005a). However, oceanic whitetip sharks are in the top 10 of all species commonly reported by observers from all three longline fisheries (Langley et al 2006b). Median estimated longline catches of oceanic whitetip from the WCPFC were estimated at 3,000–9,000 mt per year between 1994 and 2005, with steadily declining catches since 1998 (Figure 90).

Oceanic whitetip sharks are also captured in purse-seine fisheries in the WCPO (Molony 2005a) and other areas, with 93% of sets capturing oceanic whitetip sharks being associated sets (logs, FADs, animals). Catch rates are much higher from sets on tuna schools associated with drifting FADs (Langley et al 2006b), and from sets associated with anchored FADs and logs than for sets on tuna schools unassociated with floating objects (Molony 2005a). Median total catches have been estimated to be between 30 mt and 270 mt per year for the period 1994–2005, with declining catches estimated since 1999 (Figure 91).

17.6.2 Artisanal fishery value

Interactions of artisanal fisheries with oceanic whitetip sharks are likely to be low due to their preference for oceanic waters.

17.6.3 Sport and recreational fishery value

Oceanic whitetip sharks are unlikely to have a high recreational value. However, there are some anecdotal reports of this species being captured on recreational gears (Compagno 1984a). This may occur during gamefishing operations targeting billfishes.

Table 9. Observed and back calculated lengths-at-age from vertebrae analyses for oceanic whitetip sharks from the south-western Atlantic Ocean. Modified from Lessa et al. (1999). – indicate that no sharks of a particular age class were sampled. The maximum age of a shark examined by Lessa et al. (1999) was estimated at 17 years old and 250 cm TL.

Age (years)	Females: length-at-age		Males: length-at-age	
	Back-calculated	Observed	Back-calculated	Observed
0	71.4	85.7	71.2	71.0
1	90.6	103.2	89.7	95.0
2	108.0	115.8	107.5	114.3
3	124.1	138.4	124.0	136.8
4	138.3	145.7	139.0	-
5	151.7	163.4	153.0	162.3
6	163.4	174.5	166.0	178.0
7	173.7	187.1	177.3	189.0
8	182.9	190.2	187.2	193.8
9	191.5	201.4	196.5	199.7
10	198.8	207.0	208.0	-
11	204.8	200.0	216.9	217.5
12	221.7	-	227.0	-
13	227.9	230.0	233.4	235.5
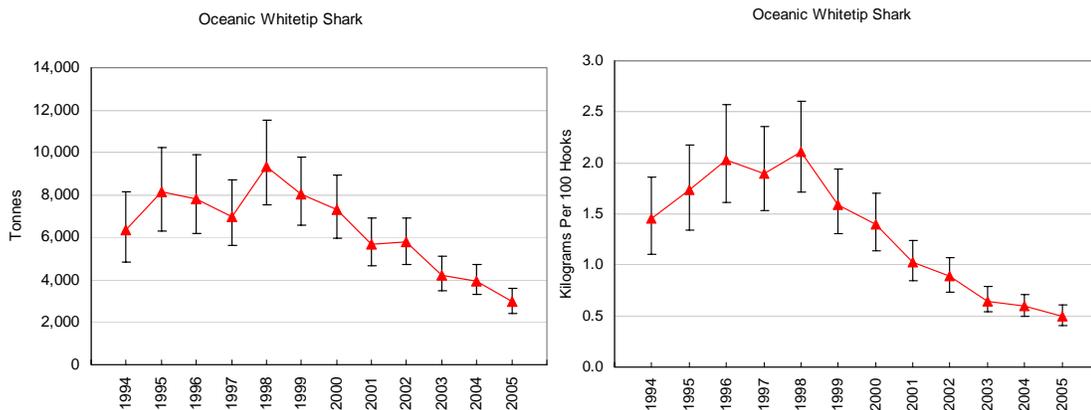
Figure 90. Catches and catch rates of oceanic whitetip sharks by longline vessels in the WCPFC Statistical Area (excluding the domestic fleets of Indonesia, the Philippines and Chinese Taipei). Points represent median values of 1,000 random samples from the posterior distributions; error bars represent 95% confidence intervals from 1,000 random samples from the posterior distributions. Source, OFP (2007).
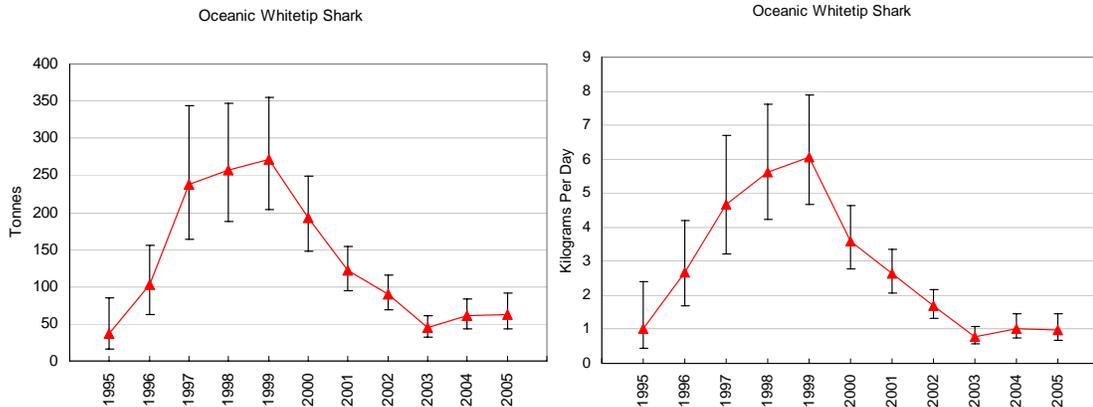
Figure 91. Catches and catch rates of oceanic whitetip sharks by purse-seine vessels in the WCPFC Statistical Area (excluding the domestic fleets of Indonesia and the Philippines). Points represent median values of 1,000 random samples from the posterior distributions; error bars represent 95% confidence intervals from 1,000 random samples from the posterior distributions. Source, OFP (2007).
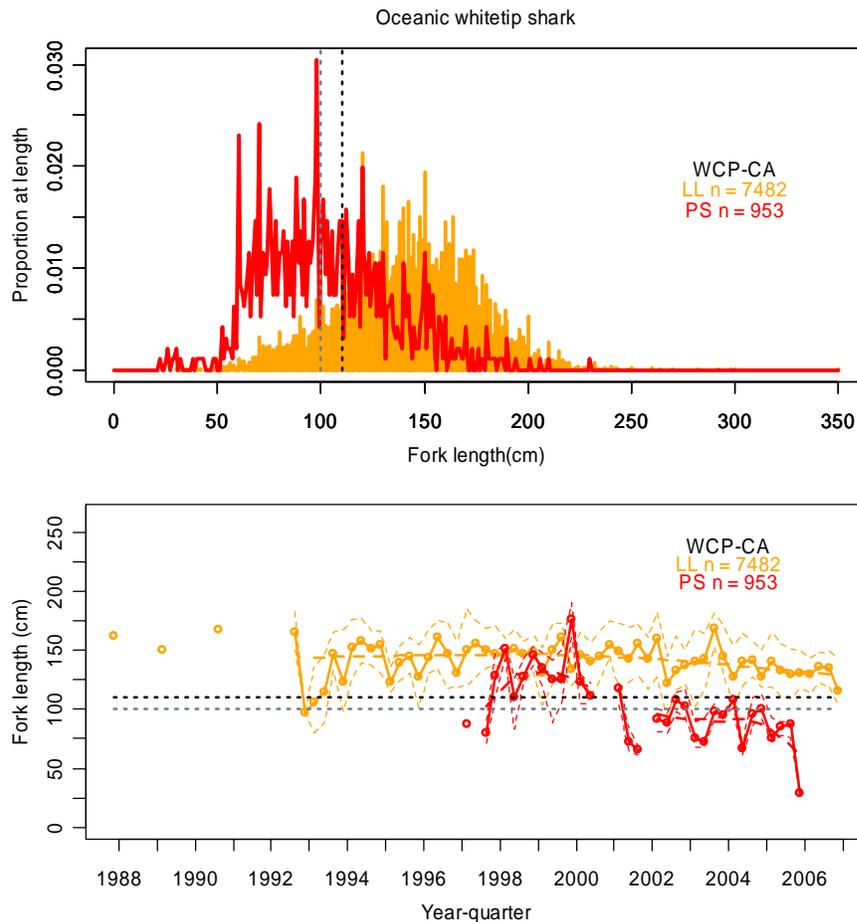
Figure 92. Combined length-frequency distributions (upper figure) and trends in quarterly median size (lower figure) of oceanic whitetip sharks reported by observers in longline and purse-seine vessels in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery. Thin dashed lines represent the 25th and 75th quartiles of the size data. Dashed lines represent lowess fits to the median size data. Dotted lines represent estimates of size at first maturity for females (black, 100 cm FL) and males (grey, 110 cm FL) (from Seki et al. 1998).
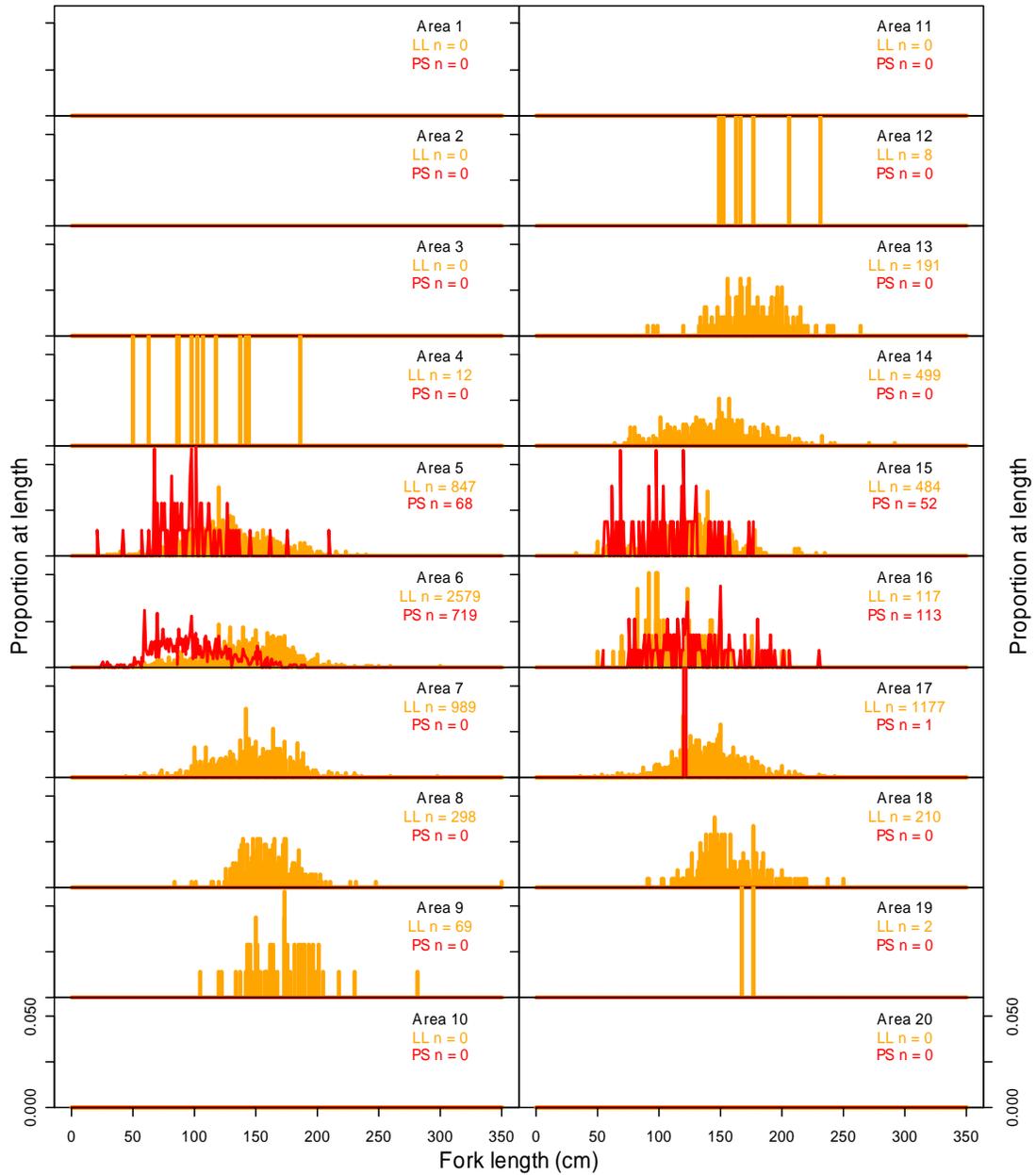
Figure 93. Length-frequency distributions of oceanic whitetip sharks pooled into 10º latitude bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as fork lengths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively.

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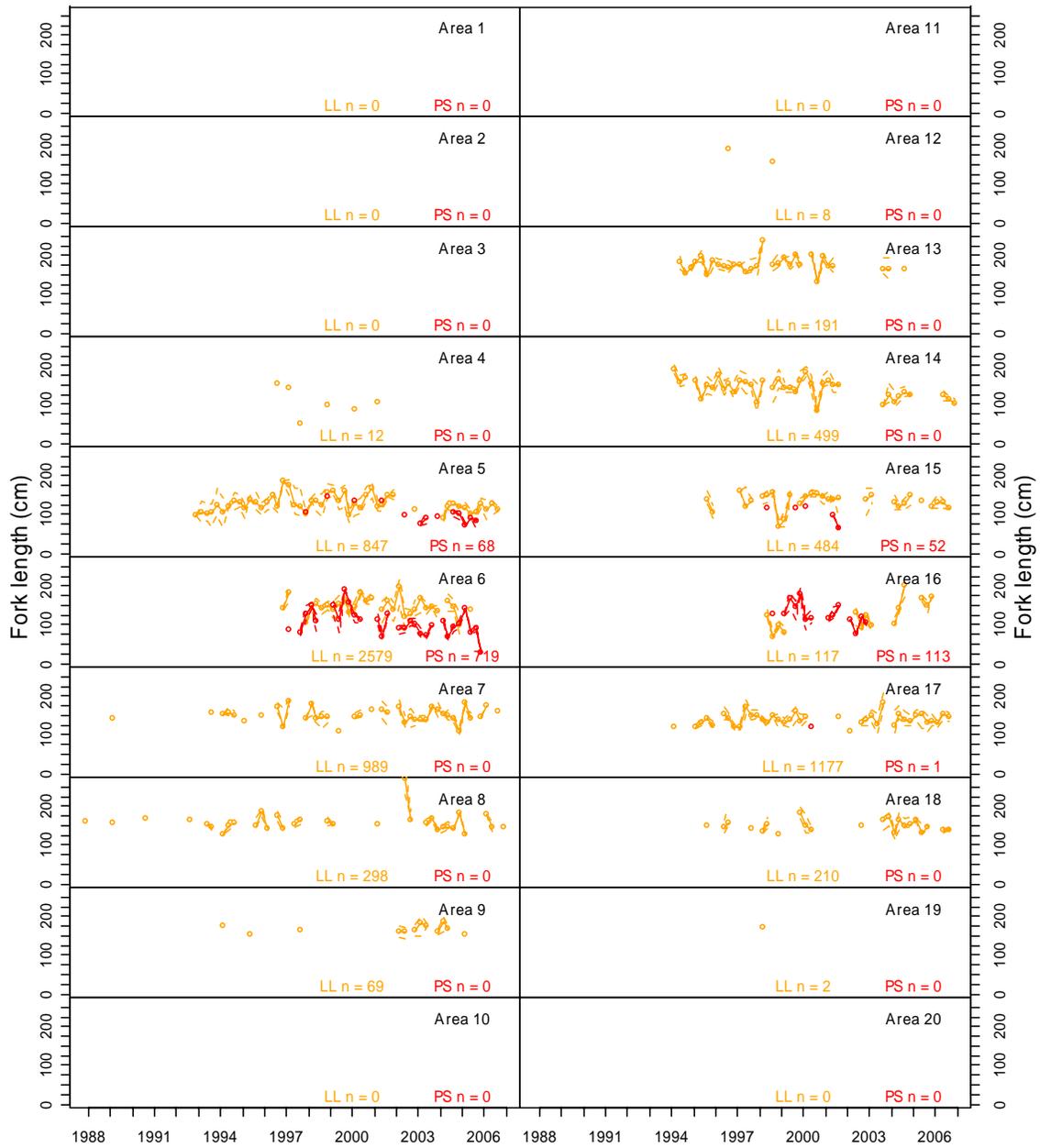
Figure 94. Trends in median size of oceanic whitetip sharks pooled into 10º latitudinal bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as fork lengths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively. Dotted lines represent 25th and 75th quartiles of each data series.
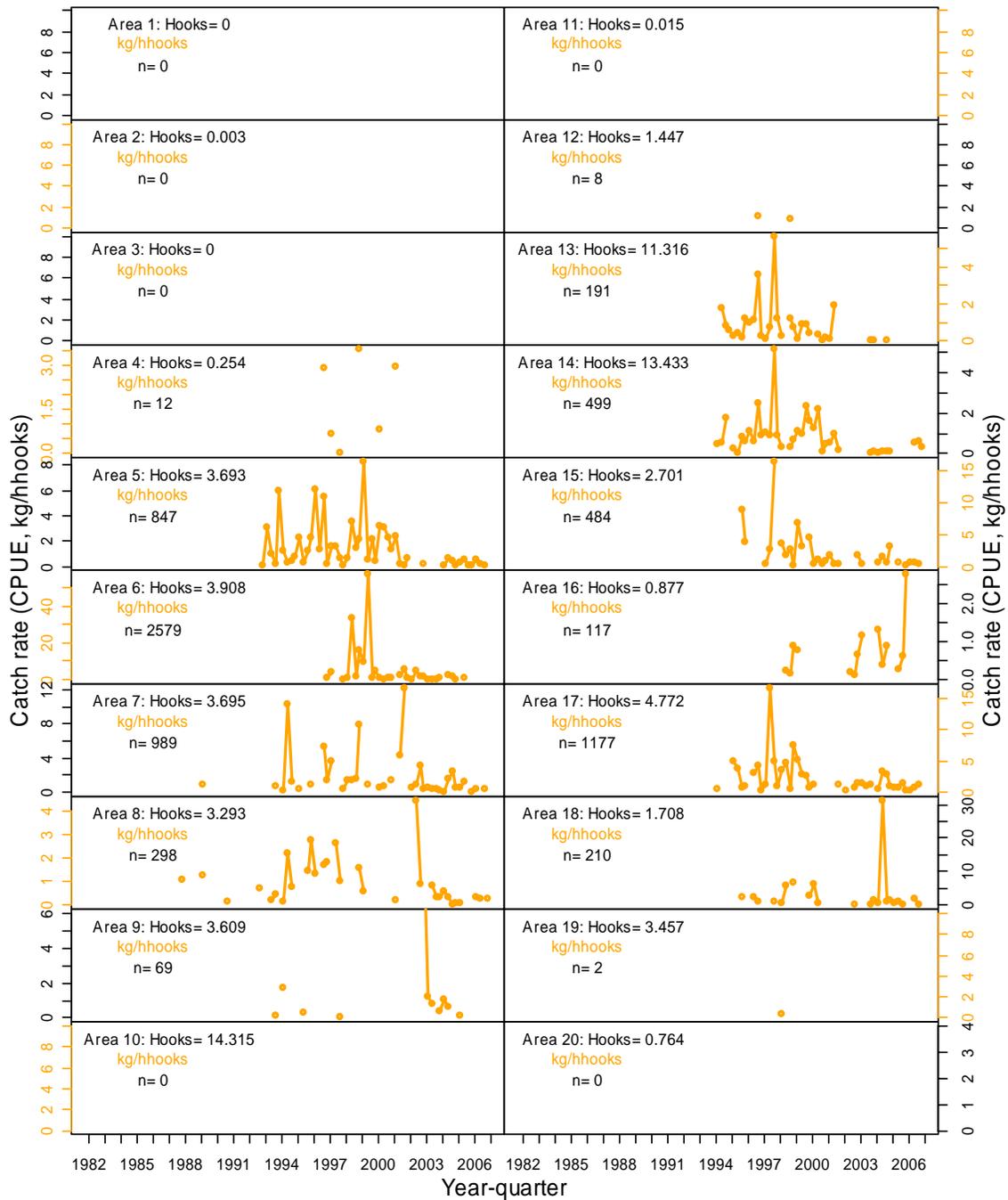
Figure 95. Quarterly catch rates (kg.hhooks⁻¹) of silky shark reported by observers pooled into 10° latitudinal bands (Areas) in the WCPO, 1982–2006. Source, SPC observer data base. Hooks, is the total number of observed hooks (millions) in each Area; n, represents the total number of individuals from each method-fishery within each Area. Scales of the y-axes vary among Areas. Left-hand figures are west of 170°E; right hand figures are east of 170°E. Areas 5 and 15, and 6 and 16 represent the 0–10°N and 0–10°S of the equator, respectively. Length-weight relationship: whole weight (kg) = (0.0170 x FL^{2.98})/1000 (Claro and Garcia-Arteaga 1994, in www.fishbase.org).
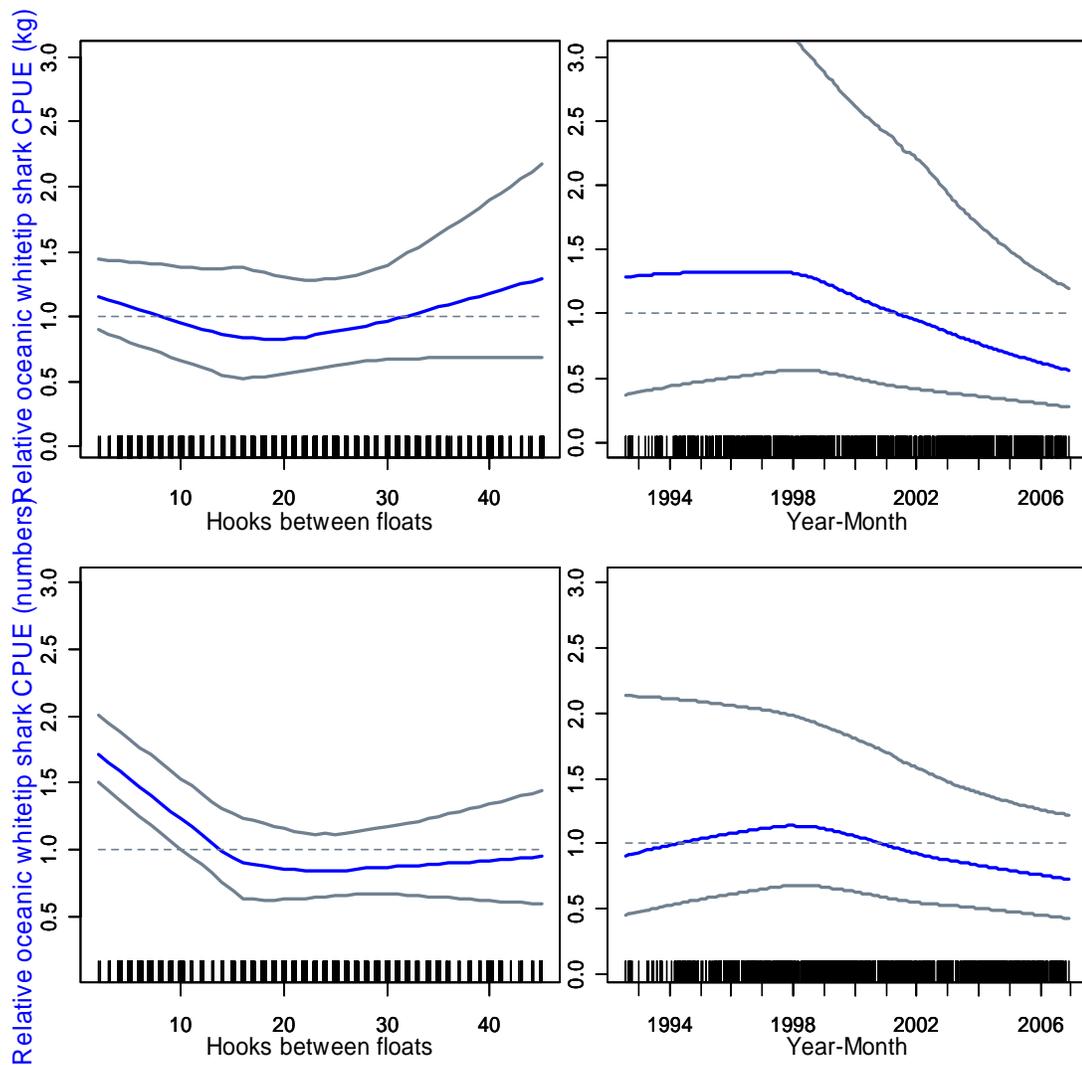
Figure 96. Changes in relative monthly oceanic whitetip longline catch rates (blue lines; upper figure, number/hhooks; lower figure, kg/hhooks) for the WCPO under the influence of longitude, latitude, hooks between floats and time period (year-month) as predicted by GLMs, 1991–2006. Sources, observer data held at SPC. Grey lines represent 95% confidence levels. The 'rug' plot along the inside of each x-axis displays the data density along the range of each variable. Weight: $r^2 = 0.270$, adjusted $r^2 = 0.139$; Numbers: $r^2 = 0.339$, adjusted $r^2 = 0.221$.

18. Shortfin mako (*Isurus oxyrinchus*)
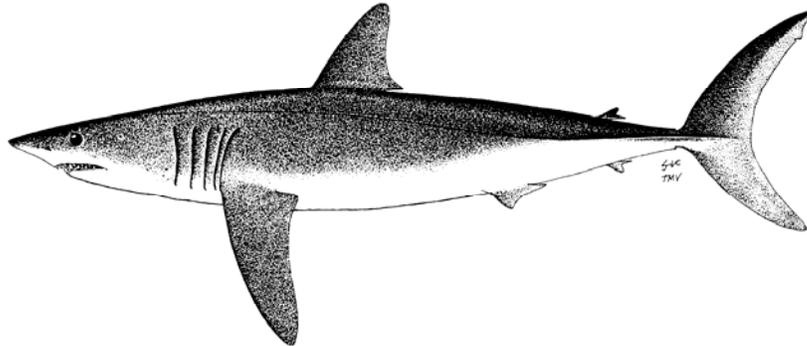
Of the two species of mako sharks that regularly interact with commercialised tuna fisheries of the WCPO, the shortfin mako (*Isurus oxyrinchus*) is most common and wide spread. Less is known about the long-finned make (*Isurus paucus*) and is much less frequently recorded by observers on fishing vessels (Molony 2005a). In addition, observers have reported a large number of sharks classified only as mako (unidentified) (Molony 2005a). It is likely that most of the unidentified mako sharks are in fact short-finned mako sharks. This section will focus on the shortfin mako sharks but information for long finned mako will be presented where appropriate.

18.1 Description

Shortfin mako sharks are identified by their sleek shape and very pointed snout. They have a relatively large first dorsal fin and very small second dorsal and anal fins set well back along the body. There is a strong lateral keel along the caudal peduncle that extends beyond the second dorsal and anal fins. Dorsal surfaces are indigo blue with white ventral surfaces. Teeth protrude from the mouth at all times (Compagno 1984b, Last and Stevens 1994). Longfin mako sharks are easily separated from shortfin mako sharks due to the very large pectoral fins that are greater than the length of the head (Chapman et al. 2006).

18.2 Distribution

Shortfin mako sharks have a worldwide distribution, found in all tropical and temperate waters (Last and Steven 1994, Loeffer et al. 2005). In the WCPO, shortfin mako sharks have been reported between at least 40ºN–40ºS, with a contraction of the their southern range to north of 20ºS in the central Pacific Ocean (between 160ºW and 120ºW) (Compagno 1984b, Last and Stevens 1994).

Long finned mako sharks have a patchy distribution, limited to between approximately 30ºN and 15ºS in the Pacific Ocean (Compagno 1984b). However, the distribution of this species is poorly known.

18.3 Biology

18.3.1   Age and growth

Shortfin mako sharks have generally been aged by enumerating bands visible in sectioned vertebrae (Bishop et al. 2006), validated using marginal increment analysis in samples collected on a monthly basis (Ribot-Carballal et al. 2005). The size at birth is estimated to be

70 cm TL (Ribot-Carballal et al. 2005), and the species attains a maximum size of at least 394 cm TL[9] in Australian waters of the western Pacific (Last and Stevens 1994) but exceeds 410 cm TL in the eastern Pacific Ocean (Ribot-Carballal et al. 2005).

Growth is relatively rapid in the first year, but reduces as sharks increase in age (Natanson et al. 2006, Ardizzone et al. 2006). The growth rate of shortfin mako sharks greater than one year of age is relatively slow compared to other species of sharks (Campana et al. 2005). The growth rate of females remains higher than males, potentially due to the late maturing of females (e.g. males mature after approximately seven–eight years of age; females mature after 18–21 years) (Bishop et al. 2006, Natanson et al. 2006), corresponding to a size at $L\infty$ of 253 cm FL and 366 cm FL for males and females, respectively (Natanson et al. 2006). Estimated maximum ages for this species have ranged from 19 years (Ribot-Carballal et al. 2005) to more than 28 years (Bishop et al. 2006) for both sexes. VBGF growth rates (i.e. k) were estimated at 0.125 year^{-1} and 0.087 year^{-1} for males and females, respectively.

Recent research using bomb-radiocarbon dating methods (Campana et al. 2002, Ardizzone et al. 2006) suggest that the ages of shortfin mako sharks have generally been under-estimated, reducing the estimated growth rates and increasing the estimated longevity of this species. In a recent study, Natanson et al. (2006) estimated longevities at 21 years for male and 38 years for female shortfin mako sharks in the North Atlantic Ocean, from sharks aged up to 29 years (males) and 32 years (females). However, other studies have suggested that the longevity of males (nine years) is significantly shorter than that of females (23 years) (Cope 2006). Typically, catches are dominated by smaller (less than 160 cm TL) and younger (less than five year old) sharks (Ribot-Carballal et al. 2005, Natanson et al. 2006), and thus estimates of longevity are uncertain.

18.3.2 Reproduction

Males mature at significantly smaller sizes and younger ages than female sharks. Ages at maturity vary between sexes and authors. For example, Smith (1998) assumed that females were seven years of age at maturity, Cope (2006) indicated that female shortfin makos were at least 15 year of age at maturity, while (Bishop et al. 2006) concluded that females mature at 19–21 years of age, although age-determination for this species has recently been questioned (Campana et al. 2002) and older estimates may be more realistic. Nonetheless, males mature at significantly smaller sizes (195 cm TL) than females (280 cm TL) (Last and Stevens 1994), corresponding to approximately 7–8 years old and 18+ years old, respectively (Ribot-Carballal et al. 2005). A recent study estimated size and age at 50% maturity of males was 185 cm FL and eight years for males, and 275 cm FL and 18 years for females from the north Atlantic (Natanson et al. 2006).

Shortfin mako sharks are a live bearer, with litters consisting of 2–18 pups (Smith 1998, Cortés 2000), although litters up to 25 pups have been reported (Mollet et al. 2000). The gestation period has been estimated at 15–18 months, with females resting for up to 18 months before the next batch of eggs are fertilised (Mollet et al. 2000). These reproductive characteristics make the shortfin mako shark a relatively un-productive species of shark. Birth

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[9] The relationship between total length (TL) and fork length (FL) for shortfin mako sharks is approximately, FL = 0.929 x TL
(www.fishbase.org/PopDyn/LLRelationshipList.php?ID=752&GenusName=Isurus&SpeciesName=oxyrinchus&fc=9).

size has been estimated to be between 70 cm TL and 80 cm TL (Cortes 2000, Ribot-Carballal et al. 2005) (65–75 cm FL).

18.3.3 Recruitment

Most sharks that are captured by longline fisheries are typically less than seven years of age (Ribot-Carballal et al. 2005), corresponding to less than 200 cm TL (less than approximately ~180 cm FL). However, shortfin mako sharks have been reported as small as 77 cm TL from longline fisheries in the eastern Pacific Ocean (Ribot-Carballal et al. 2005) corresponding to 0+ age fish. Shortfin mako sharks appear to be fully recruited to the fishery in the eastern Pacific Ocean at approximately 100 cm TL or 1+ years of age, well below the size of first reproduction.

From observer data, shortfin mako sharks have been reported from around birth size (less than 70 cm FL) in both the longline and purse-seine fisheries of the WCPO (Figure 98). Most shortfin mako sharks captured in the longline fisheries of the WCPO are less than 175 cm FL.

18.3.4 Mortality

Bishop at al. (2006) estimated the natural mortality of shortfin mako sharks in New Zealand waters at 0.10–0.15. Smith et al. (1998) estimated a natural mortality of 0.160 for shortfin mako sharks using data from several different locations. Applying the VBGF and longevity data from Natanson et al. (2006), the total mortality rates of north Atlantic sharks were estimated to be 0.129–0.219 year^{-1} for males and 0.117–0.194 year^{-1} for females, using Hoenig's and Beverton and Holt's length-based estimates of total mortality (Z).

18.4 Ecology

18.4.1 Habitat preference

Shortfin mako sharks are relatively common in warm, surface waters of the topical and sub-tropical Pacific Ocean. The species is commonly reported by observers in tropical and subtropical longline fisheries (approximately the 10th most commonly reported species between 1999 and 2003 (Langley et al. 2008)). This species is also recorded from the WCPO purse-seine fisheries (Molony 2005a, Langley et al. 2008) (Figure 98).

Shortfin mako sharks are usually restricted to shallow oceanic and pelagic waters (Compango 1984b, Last and Stevens 1994). Most catches of this species are recorded in waters less than 150 m deep and greater than 16ºC (Compango 1984b, Last and Stevens 1994), with a preference for waters of greater than 18ºC (Campana et al. 2005). However, a recent archival tagging study has indicated that a single shortfin mako shark was capable of making (rare) dives to depths of greater than 550 m into waters approximately 10ºC (Loeffer et al. 2005), with deep dives generally recorded during the day (Sepulveda et al. 2004, Loeffer et al. 2005). Nonetheless, short-term (less than 48 hours) tracking studies in the eastern Pacific Ocean revealed that for 80% of the time all sharks remained within 12 m of the surface (Sepulveda et al. 2004). Dives to depths greater than 150 m and low temperatures may be possible due to the heat exchange system of this shark, allowing it to be a functional endotherm and resulting in faster swimming (and movement) rates compared to ectothermic sharks (e.g. blue sharks) (Klimely et al. 2002).

18.4.2   Movements and migration

Shortfin mako sharks are one of the fastest species of sharks (Last and Stevens 1994) and are a highly migratory species, capable of long range (trans-Atlantic) movements (Campana et al. 2005). Thus this species is also likely to be capable of trans-Pacific movements.

A review of extensive tagging data for the Atlantic Ocean revealed that most shortfin mako sharks remained within 500 nm of the site of tagging, with most time was spent in shallow, surface waters in temperatures above 18ºC. This information was collected from more than 600 recaptures, with times at liberty ranging between one day and 12.8 years (Kohler et al. 2002). The shortfin mako shark at liberty for 12.8 years was recaptured less than 300 nmi from the site of tagging. However, a single shortfin mako shark was recaptured more than 2,800 nmi away after 1.4 years of liberty, moving from the north-eastern United States to the western coast of Saharan Africa, although trans-basin movements are rare (Kohler et al. 2002).

Kohler et al. (2002) proposed that there was an annual pattern of migration for north-eastern Atlantic shortfin mako sharks. Shortfin mako sharks appear to display clockwise rotation around the north-eastern Atlantic, moving northwards with the Gulf Stream and north Atlantic Gyre, and inshore onto the continental shelf and Grand Banks. The Grand Banks may be an important juvenile feeding area for the mako population of the north-eastern Atlantic. Shortfin mako sharks move offshore to overwinter in the Gulf Stream and Sargasso Seas, in areas where water temperatures remain above 18ºC. Shortfin mako sharks return to may remain move inshore as water temperatures increase, appearing in the Gulf of Mexico and Florida Straits in Spring. However, female sharks are more commonly captured in deeper waters, further offshore (Mollet et al. 2000). This strategy may result in newly birthed shortfin mako sharks being in areas away from high concentrations of juvenile and male sharks, reducing predation (Kohler et al. 2002). The movement pattern proposed by Kohler et al. (2002) implies that there are separate northern and southern stocks of Atlantic shortfin mako sharks, with limited exchange east and west of the mid-Atlantic Ridge

Movement data from other areas are limited. However, given the experiences in the Atlantic, it is likely that regular, broad-scale movement patterns also exist for shortfin mako sharks in other oceans, including the Pacific.

18.4.4   Diet

The diets of shortfin mako sharks consist mainly of teleost fishes and squids (Last and Stevens 1994). However, larger sharks may show a shift towards larger prey items, including swordfish (Kohler et al. 2002) and small cetaceans (Last and Stevens 1994). There is also evidence of cannibalism of smaller shortfin mako sharks by larger individuals (Kohler et al. 2002).

Archival tagging data suggests that shortfin mako sharks are constantly moving, displaying regular up and down movements across the thermocline (Klimely et al. 2002). This may be to assist in regulating temperature and for feeding. Loeffer et al. (2005) showed that a single shortfin mako shark generally remained within the top 300 m (mean: ~100–150 m) of the surface during the night and at within 500 m (mean: ~150–400 m) of the surface during the day in a 60 day study using an archival tag. This individual generally stayed in waters between 17ºC and 25ºC.

18.5 Details of stocks in the WCPO

18.5.1 Stock structure and size

Stock structure of shortfin mako sharks in the Pacific Ocean has been poorly studied and is currently unknown (Bishop et al. 2006). However, the movement pattern proposed by Kohler et al. (2002) for Atlantic shortfin mako sharks implies that there are separate northern and southern stocks of Atlantic shortfin mako sharks, with limited exchange east and west of the mid-Atlantic Ridge. In addition, there is no evidence of cross-equatorial movement in the Atlantic Ocean (Heist et al. 1996). The existence of two stocks suggests that the northern and southern stocks should be managed as separate management units. However, Campana et al. (2005) proposed that there was a single stock of shortfin mako in the Atlantic. Assuming similar patterns of movement of this species in the Pacific Ocean, there is a likelihood of separate northern and southern stocks, with the equator separating the stocks..

Observers in the WCPO report strong modes of smaller sharks (less than 100 cm FL) from western equatorial waters, with larger modes reported further south. However, a wide size range of shortfin mako sharks are reported at latitudes of 30–40ºS. Limited size data also reports a wide size range of shortfin mako sharks from 30–40ºN, east of 170ºE. This is potentially suggestive of northern and southern stocks in the WCPO, although evidence is limited.

Heist et al. (1996) could not separate eastern Australian, Brazilian and Californian individuals based on analyses of mitochondrial DNA. However, Allendorf and Phelps (1981, in Heist et al. 1996) concluded that only a small number of migrations (1–10 per generation) were needed to prevent genetic drift. Thus, fisheries relevant stocks may exist despite the lack of significant genetic variation.

The stock size of shortfin mako in the Pacific Ocean is currently unknown (Bishop et al. 2006).

18.5.2   Recent stock assessments and status

Limited information of the status of shortfin mako stocks are available. In the WCPO, catches and catch rates of shortfin mako have steadily increased in the tropical deep longline fishery since 1998 (Molony 2005a), while catches and catch rates have shown large inter-annual fluctuation in the tropical shallow fishery. Increasing catches of this species have also been recorded in the sub-equatorial albacore longline fisheries in the WCPO as they develop (Molony 2005a). Estimates from the combined longline fisheries of the WCPFC show a steady decline in catches and catch rates of combined mako sharks (shortfin, longline and unidentified mako sharks) since the late 1990s (Figure 97). This suggest that the recent levels of fishing effort on mako sharks may be high than the stocks can sustain. However, thorough assessments have not been undertaken on shortfin mako in the Pacific Ocean (Francis et al. 2001).

18.6 Fisheries

Shortfin mako sharks have good quality flesh. In addition, oil, fins, hide and teeth are also useful fishery products (Last and Stevens 1994). Shortfin mako sharks are often retained due to their relatively high commercial value (Loeffer et al. 2005).

18.6.1 Major fisheries and occurrence

Shortfin mako sharks are commonly reported from longline fisheries in tropical, sub-equatorial and temperate waters. Originally, most shortfin mako were a discarded but now are a targeted species (Heist et al 1996). The fate of most shortfin mako sharks are unknown, although most appear to be alive at the time of landing and many are likely to be at least finned (Francis et al. 2001). Highest catch rates are reported in shallow set longlines in tropical regions including the WCPO (Molony 2005a). Median estimates of total catches of mako sharks in the WCPO have varied between 5,000 mt and 11,000 mt since 1994, with a decline in catches estimated since 1999 (Figure 97).

Shortfin mako sharks are rarely captured by purse-seine fisheries (Kirby 2006, Figure 98), with the highest occurrence reported in sets on associated sets (Langley et al. 2008). From 207 observed purse-seine sets from which shortfin mako sharks were reported, 200 (97%) were associated sets (i.e. logs, FADs, animals).

18.6.2 Artisanal fishery value

Details of artisanal catches of shortfin mako are unknown. However, given the shallow distribution and the extension of the range of this species over shelf waters, interactions with artisanal fishers are likely to occur.

18.6.3 Sport and recreational fishery value

Shortfin mako sharks are an important recreational species in many parts of the world due to its high-quality meat (Compagno 1984b) and speed and aggression, which make the it a highly prized gamefish species (Heist et al. 1996, Loeffer et al. 2005). Intensive recreational fisheries exist in north eastern United States when shortfin mako sharks move inshore during spring and summer (Natanson 2002). There is also a small but important recreational catch in New Zealand (Francis 1998).

Table 10. Estimated size –at-age for the for short-fin mako sharks from the North Atlantic Ocean . Source: Natanson et al. (2006). Estimates of vertebral size-at-age were derived by applying the published VBGF values for males and females separately. Estimates of size at age from length-frequency data were

only available for the first 3 years of life. Estimated longevity is approximately 21 years (males) and 38 years (females).

Age (years)	Fork length (FL) cm		
	Length-frequency	Vertebral ageing Males	Vertebral ageing Females
0 (birth)	70 (♂); 88 (♀)	70	88
1	120	92	111
2	155	110	132
3	185	127	152
4		142	170
5		155	186
6		167	201
7		177	215
8		186	227
9		194	239
10		201	250
15		225	291
20		238	317
25			334
30			346
35			353
40			357
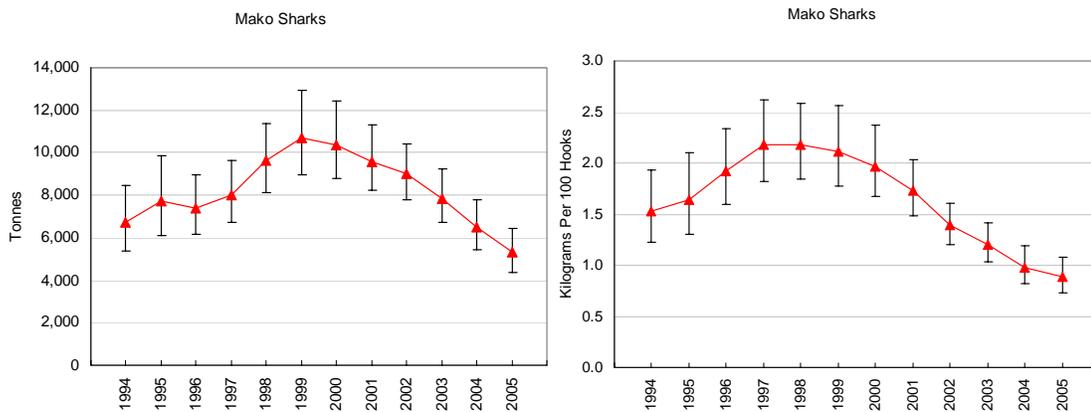
Figure 97. Catches and catch rates of combined mako sharks (shortfin, longfin and unidentified) by longline vessels in the WCPFC Statistical Area (excluding the domestic fleets of Indonesia, the Philippines and Chinese Taipei). Points represent median values of 1,000 random samples from the posterior distributions; error bars represent 95% confidence intervals from 1,000 random samples from the posterior distributions. Source, OFP (2007).
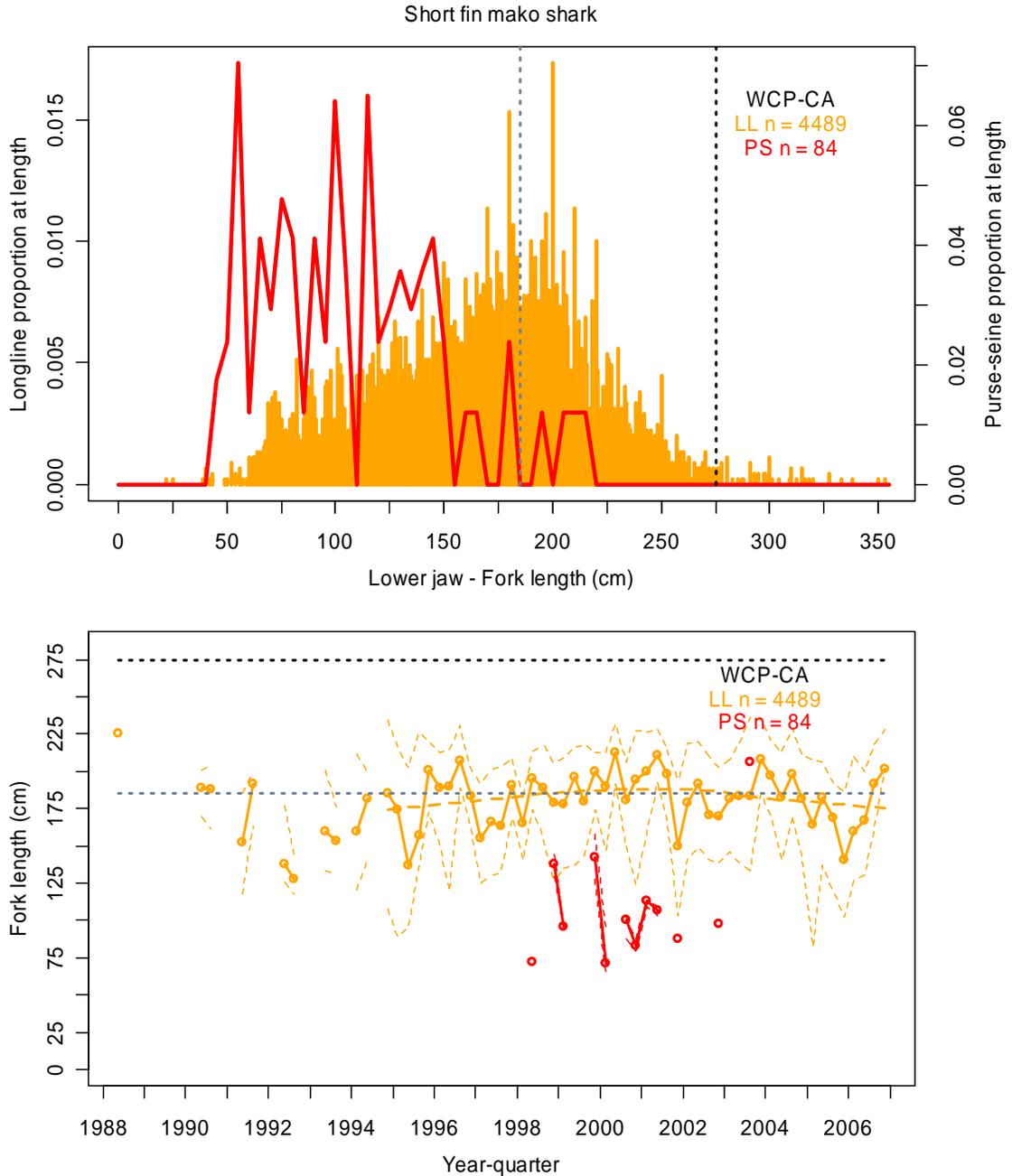
Figure 98. Combined length-frequency distributions (upper figure) and trends in quarterly median size (lower figure) of shortfin mako sharks reported by observers in longline and purse-seine vessels in the WCPO, 1988–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery. Thin dashed lines represent the 25th and 75th quartiles of the size data. Heavy dashed lines represent lowess fits to the median size data. Dotted lines represent estimates of size at first maturity for females (black, 275 cm FL) and males (grey, 185 cm FL) (from Natanson et al. 2006 for the north Atlantic). In the upper figure, 1 cm and 5 cm size class bins were used for fish from the longline fishery and purse-seine fishery, respectively.
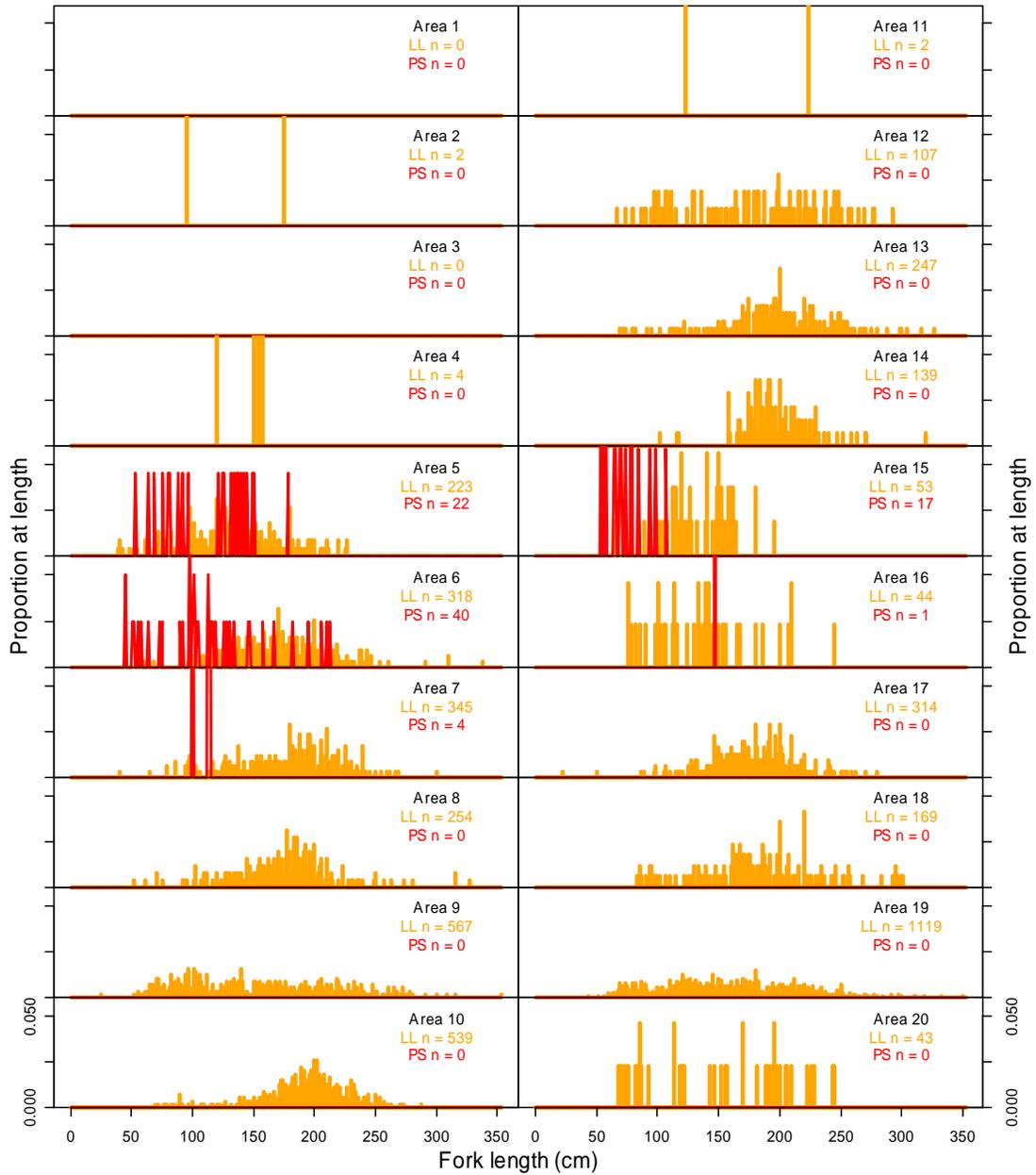
Figure 99. Length-frequency distributions of shortfin mako sharks pooled into 10º latitude bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as fork lengths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively.
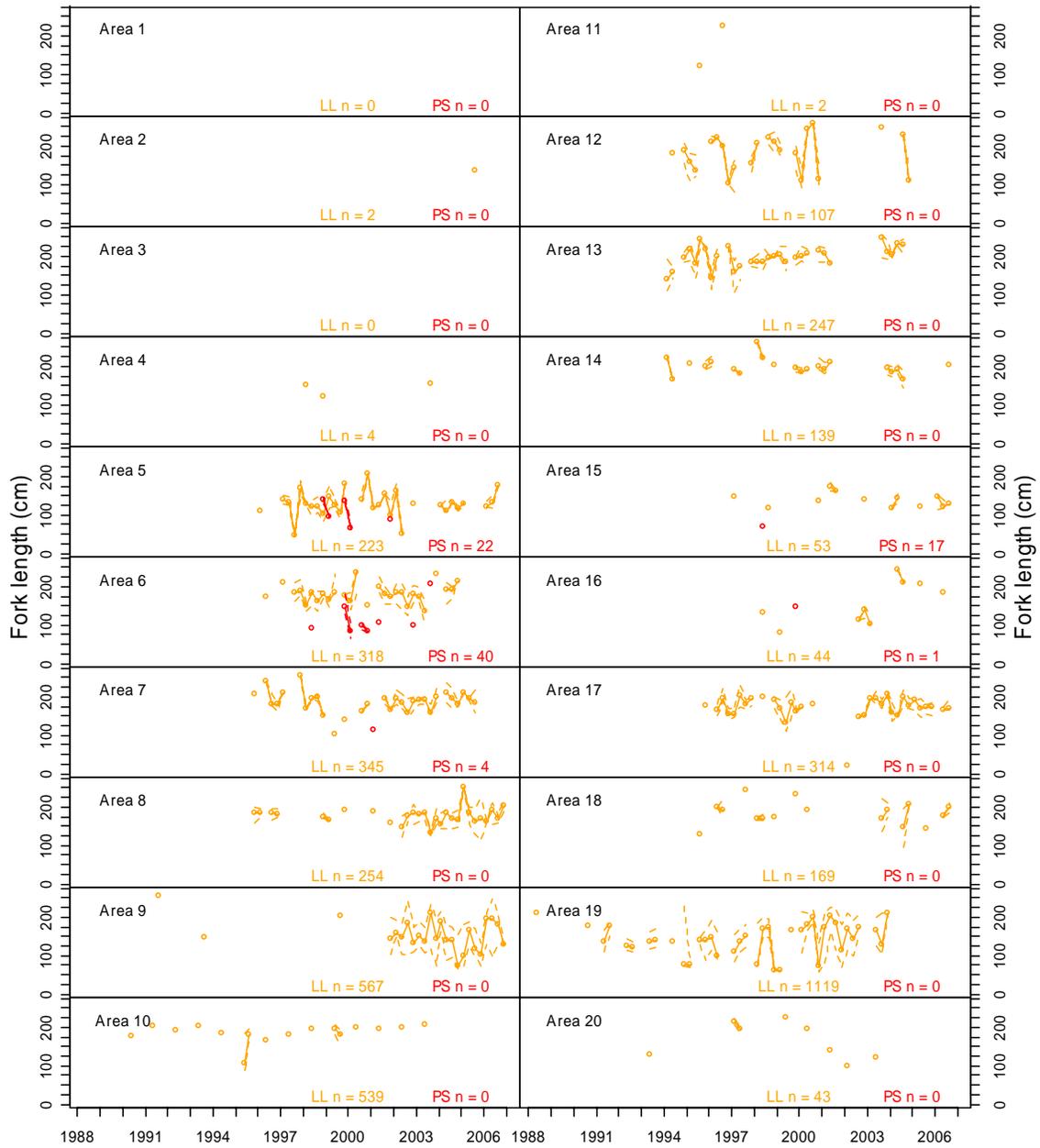
Figure 100. Trends in median size of shortfin mako sharks pooled into 10º latitudinal bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as fork lengths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively. Dotted lines represent 25th and 75th quartiles of each data series.
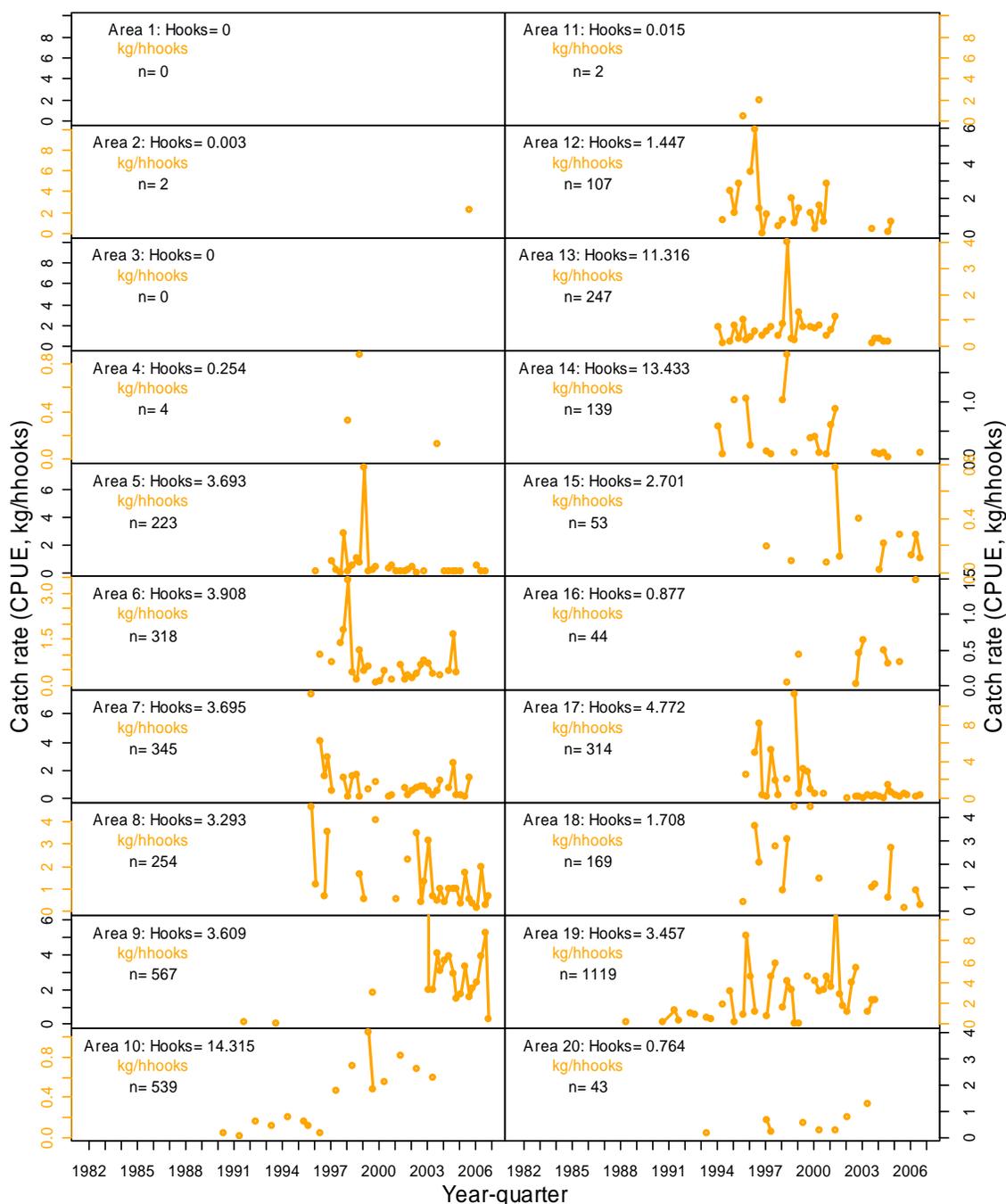
Figure 101. Quarterly catch rates (kg.hhooks⁻¹) of shortfin mako shark reported by observers pooled into 10º latitudinal bands (Areas) in the WCPO, 1982–2006. Source, SPC observer data base. Hooks, is the total number of observed hooks (millions) in each Area; n, represents the total number of individuals from each method-fishery within each Area. Scales of the y-axes vary among Areas. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively. Length-weight relationship: whole weight (kg) = (0.0052 x FL^{3.141})/1000 (Kohler et al. 1995).
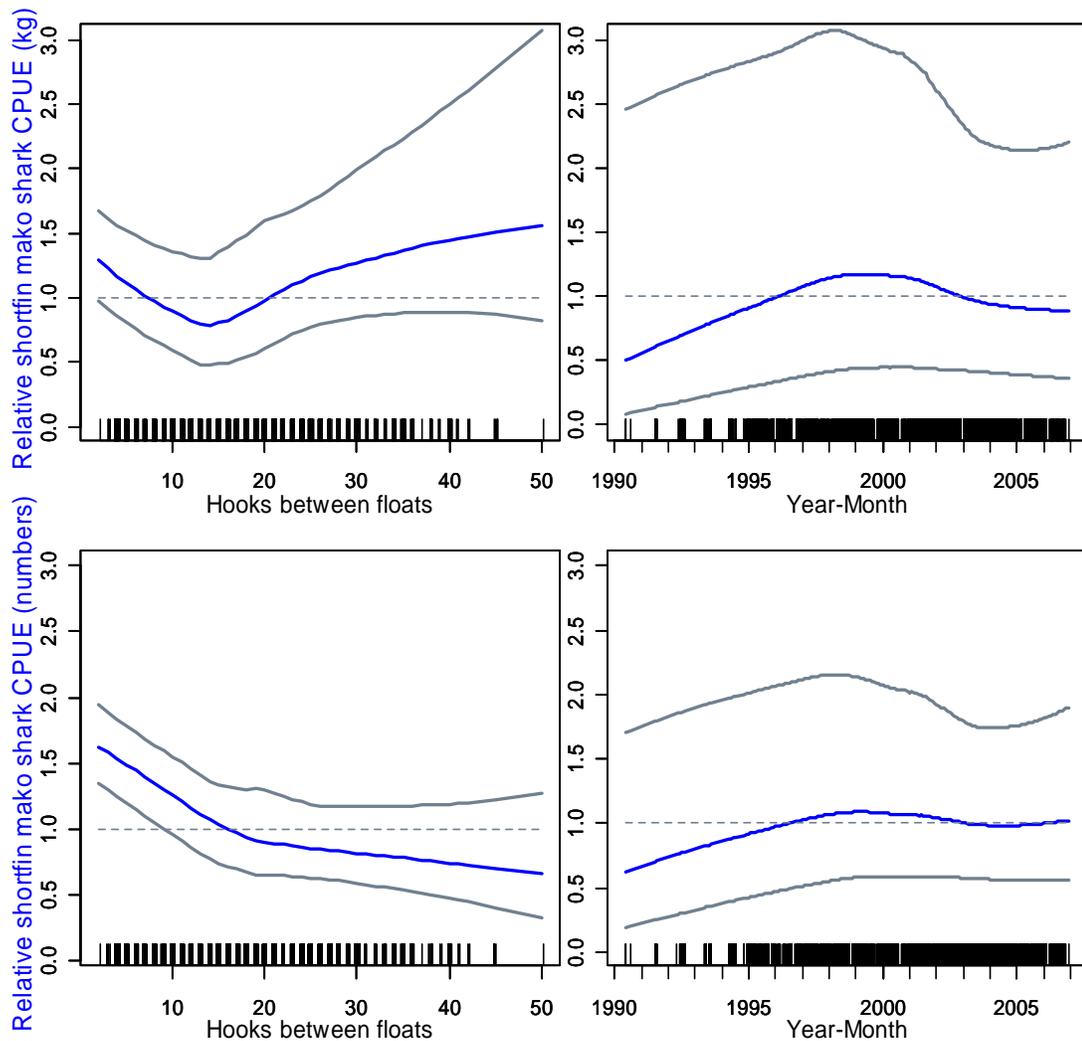
Figure 102. Changes in relative monthly shortfin mako shark longline catch rates (blue lines; upper figure, number/hhooks; lower figure, kg/hhooks) for the WCPO under the influence of longitude, latitude, hooks between floats and time period (year-month) as predicted by GLMs, 1991–2006. Sources, observer data held at SPC. Grey lines represent 95% confidence levels. The 'rug' plot along the inside of each x-axis displays the data density along the range of each variable. Weight: $r^2 = 0.220$, adjusted $r^2 = 0.084$; Numbers: $r^2 = 0.267$, adjusted $r^2 = 0.140$.

19. Pelagic stingray (*Dasyatis violacea*)
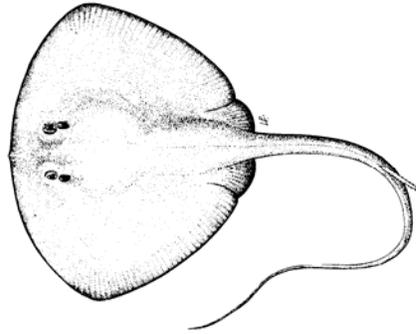
19.1 Description

The pelagic stingray is the only truly pelagic species of stingray in the world. It has an all-black dorsal surface with a rounded snout and a very weak dorsal ridge that runs from the back of the head to the single spine, which is located about a one third along the length of the whip-like tail (Chapman et al. 2006). It is unlikely to be misidentified.

19.2 Distribution

Pelagic stingrays are found nearly universally in all tropical and sub-tropical waters of the world, extending as far as 41ºN in the eastern Pacific Ocean (Mollet 2002). In the WCPO, pelagic stingrays have been reported by observers between 40ºN and 40ºS.

19.3 Biology

19.3.1   Age and growth

Limited growth studies exist for pelagic stingrays. From the Mediterranean Sea, the maximum recorded size was 61 cm disc width (DW) and 6 kg for a female pelagic stingray (Hemida et al. 2003). Mollet et al. (2002) held pelagic stingrays in captivity for more than two years and estimated that pelagic stingrays 40–45 cm DW and 2 kg were approximately two years of age. The largest male reached 68 cm DW and 12 kg and was estimated at seven years of age. Females were larger, exceeding 96 cm DW and 49 kg at nine years of age. Mollet et al. (2002) concluded that the growth of pelagic stingrays was very rapid, with higher growth rates displayed by females (20–30 cm per year) than by males (10–15 cm per year). However, these growth estimates were based on captive stingrays and the estimates of growth rates of wild stingrays may differ. Maximum longevity was estimated at 10 years (Mollet and Caillet 2002). Mollet et al. (2002) also reviewed the growth VBGF parameters for male and female pelagic stingrays (Table 11).

19.3.2   Reproduction

Mature males and females were reported by Mollet et al. (2002) at sizes above 35–40 cm DW and 40–50 cm DW, respectively, with maturity of both sexes at approximately two to three years of age. The period of gestation was estimated to take approximately 4 months, much shorter than many species of sharks, and it is likely that females can produce two litters per year (Hemida et al. 2003). The existence of a twice-yearly reproductive cycle is supported by observations of Mollet et al. (2002) who noted that the food intake of adults was seasonal,

with two periods of high in-take per year. Each litter consist of between two and ten pups. Size at birth is approximately 16–25 cm DW and approximately 0.2 kg (Mollet et al. 2002, Hemida et al. 2003). Birthing is thought to occur in tropical waters of the WCPO, between November and March (Mollet 2002).

19.3.3 Recruitment

Pelagic stingrays are common in tropical and sub-tropical oceans and are the 16th most commonly reported species by observers on longline vessels in the tropical shallow longline fishery in the WCPO (Langley 2005). Pelagic stingrays recruit to the longline fisheries of the WCPO at hatching (less than 25 cm DW) (Figure), and appear to be fully recruited to the fishery by 50 cm DW. The highest proportions of small (less than 25 cm DW) pelagic stingrays are reported between 10ºN and 10ºS, particularly west of 170ºE (Figure).

19.3.4 Mortality

Few estimates of mortality exist for the pelagic stingray. Mollet and Caillet (2002) estimated the natural mortality rate of pelagic stingrays as 0.46 year^{-1}, assuming that 1% of individuals reach 10 years of age. However, Hemida et al. (2003) noted that females significantly out-numbered males in larger size classes, suggesting that the natural mortality rate of adult males is much higher than that for adult females.

19.4 Ecology

19.4.1 Habitat preference

Pelagic stingrays are very common in the epipelagic zone of tropical and sub-tropical oceans (Mollet 2002). In the WCPO, the catch rates (in numbers) of pelagic stingrays declines rapidly with increasing HBF, highlighting their shallow distribution (Figure 107). However, the catch rate in weight peaks at 30 HBF, suggesting that bigger stingrays have a deeper distribution than small stingrays.

From field and aquaria studies, Mollet (2002) suggested that pelagic stingrays prefer water temperatures greater than 20ºC, with mortality reported from aquaria studies when water temperature fell below 13ºC. In the southwest Atlantic, pelagic stingrays appear associated with warm surface waters, with CPUEs being very low for this species when sea surface temperatures are below 20ºC. The southern border of its distribution is around 36ºS, the southern extent of warm sub-tropical waters (Domingo et al. 2005). In the Pacific Ocean, catch records for pelagic stingrays extend between at least as far as 40ºN–40ºS (Mollet 2002).

Most catches of pelagic stingrays are reported within the top 100 m of the surface (Mollet 2002, Ward and Myers 2005a). Pelagic stingrays are more common in open oceanic waters of the epipelagic zones than near coasts and islands.

19.4.2 Movements and migration

Limited information is available examining the potential movement and migrations patterns of this species. From limited field data, females in the eastern tropical Pacific appear to migrate south in winter to birth along the central coast of South America (15–30ºS), before returning to higher latitudes along the Californian coast (~30ºN) (Mollet 2002). Mollet (2002)

also suggested that birth occurs in tropical waters of the WCPO between November and March. Adults may seasonally move to higher latitudes but are limited to areas where water temperatures remain above 20ºC. Most small pelagic stingrays (less than ~25 cm) are reported by observers in the WCPO from the western equatorial regions (10ºN–10ºS), with larger stingrays reported further south (Figure 104). The largest pelagic stingrays from the WCPO are reported south of 40ºS.

19.4.3   Diet

Pelagic stingrays consume a wide range of pelagic jellyfish, squid, crustaceans and fishes (Last and Stevens 1994), although details of their diet are poorly known.

19.5 Details of stocks in the WCPO

19.5.1 Stock structure and size

Stock structure of the pelagic stingray is unknown for the WCPO or any area. Relini et al. (2002) suggested that separate Atlantic and Mediterranean populations of pelagic stingrays existed, based on biological parameters. Given the (limited) movement information (Mollet 2002) which suggests there is limited migration, there is the potential for at least separate WCPO and EPO stocks.

The limited observer data for this species (~900 records) does not provide sufficient information to determine stock structure. However, small stingrays are only reported from western equatorial regions (Figure 104) with large individuals found further south. This is suggestive of a single WCPO stock.

The size of stocks are unknown worldwide. However, given the frequency of occurrence in shallow-set longline fisheries of the Pacific (Molony 2005a) and Atlantic (Domingo et al. 2005) Oceans, the size of stocks are likely to be significant. In some fisheries (e.g. swordfish fisheries in the Lingurian Seas), pelagic stingrays are the most commonly reported species (i.e. more commonly captured than the target species) (Relini et al. 2002). There is some evidence to suggest that abundance of pelagic stingrays has actually increased in the WCPO since the commencement of industrialised longline fishing (Ward and Myers 2005b); however, relative catch rates in terms of weight have displayed a decline since the mid 1990s (Figure 107).

19.5.2   Recent stock assessments and status

Limited assessments of pelagic stingrays have been undertaken. Ward and Myers (2005b) present data that suggests pelagic stingrays in the north-central region of the Pacific Ocean have increased in abundance since the advent of commercial longline fishing. The nominal catch rates of pelagic stingrays have been stable early 1990s from the sub-tropical albacore and the tropical shallow longline fisheries of the WCPO (Molony 2005a). In contrast, the catch rates of pelagic stingrays have showed a steady decline since the mid 1990s in the WCPO deep-setting tropical longline fishery (Molony 2005a). However, a majority of hooks set by this fishery are beyond the preferred depth of pelagic stingrays (less than 100 m) and thus catch rates are expected to be low.

Limited length-frequency data have displayed a relatively stable median size in all areas, at approximately 50 cm DW throughout the time-series of the data (Figure 103). Pooled data (across all times and areas) reveals a similar, stable pattern, with a trend of increasing median size since 2000 (Figure 103). The stable median size of approximately 50 cm DW, which is above the size of first recruitment (Hemida et al. 2003), coupled with the relatively low catch rates of this species, suggests that the impacts of industrialised tuna fisheries on this species in the WCPO are potentially sustainable. However, stock structure remains uncertain.

19.6 Fisheries

19.6.1   Major fisheries and occurrence

Pelagic stingrays are a non-targeted bycatch species, with little or no current commercial value. In the industrialised tuna fisheries of the WCPO, pelagic stingrays are mainly reported from longline fisheries operating south of 10ºN (Figure 104), with virtually no stingrays retained. Highest catch rates are reported from the tropical longline fisheries setting shallow hooks (less than 10 HBF) (Molony 2005a). Pelagic stingrays are the 16th most commonly reported species by observers on longline vessels in the tropical shallow set longline fisheries of the WCPO (Langley et al. 2005a). Catch records suggest that most pelagic stingrays are captured within the top 100 m of the surface of oceanic waters, mainly by tuna and swordfish fisheries (Mollet 2002). Due to their shallow distribution, high catches of pelagic stingrays are likely in fisheries targeting swordfish (Mollet 2002). However, nearly all pelagic stingrays captured by longline fisheries are discarded (Domingo et al. 2005).

Pelagic stingrays are rarely reported from the purse-seine fisheries of the WCPO, with 87% of records reported from associated sets (logs, FADs, animals).

19.6.2   Artisanal fishery value

As pelagic stingrays are rarely found near coasts or islands, artisanal interactions with this species are likely to be insignificant.

19.6.3   Sport and recreational fishery value

It is unlikely that pelagic stingrays have any sport or recreational fishing value.

Table 11. Summary of growth parameters estimated for pelagic stingrays using two growth functions (VBGF, Von Bertalanffy Growth Function; GGF, Gompertz Growth Function). Study 1 comprised of two males and four females held in Monterey Bay Aquarium for 1,175 days; Study 2 comprised of eight males and 45 females held in Monterey Bay Aquarium for between 18 days and 1,175 days. The GGF parameters were concluded to provide a better fit to the size at age data. Source, Mollet et al. (2002).

Study	Males DW∞ (cm)	Maximum longevity (years)	k (year^{-1})	Females DW∞ (cm)	Maximum longevity (years)	k (year^{-1})
1						
VBGF	67 ± 1	6	0.8 ± 0.10	103 ± 5	15	0.32 ± 0.07
GGF	68	7	0.69 ± 0.10	100	11	0.44 ± 0.07
2						
VBGF	74 ± 2	14	0.35 ± 0.03	116 ± 5	24	0.20 ± 0.02
GGF	70	8	0.58 ± 0.04	101	12	0.41 ± 0.02
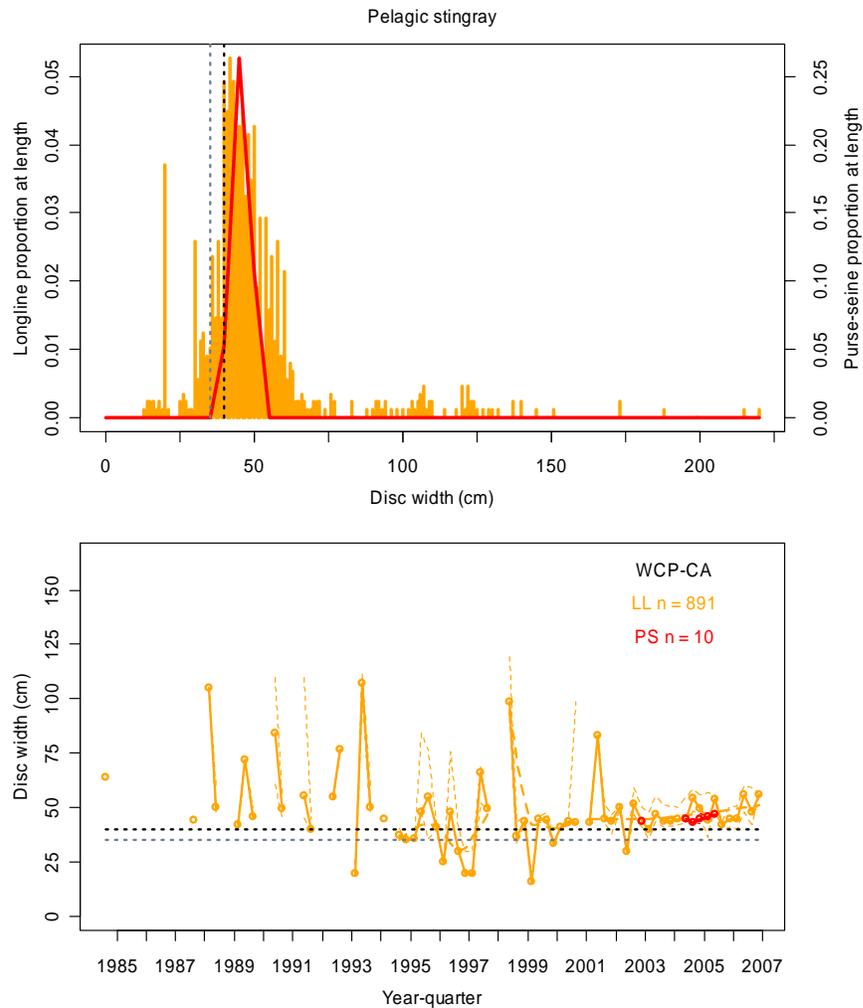
Figure 103. Combined length-frequency distributions (upper figure) and trends in quarterly median size (lower figure) of pelagic stingrays reported by observers in longline and purse-seine vessels in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery. Thin dashed lines represent the 25th and 75th quartiles of the size data. Heavy dashed lines represent lowess fits to the median size data. Dotted lines represent estimates of size at first maturity

for females (black, 40 cm DW) and males (grey, 35 cm DW) (from Mollet et al. 2002 from the eastern Pacific).
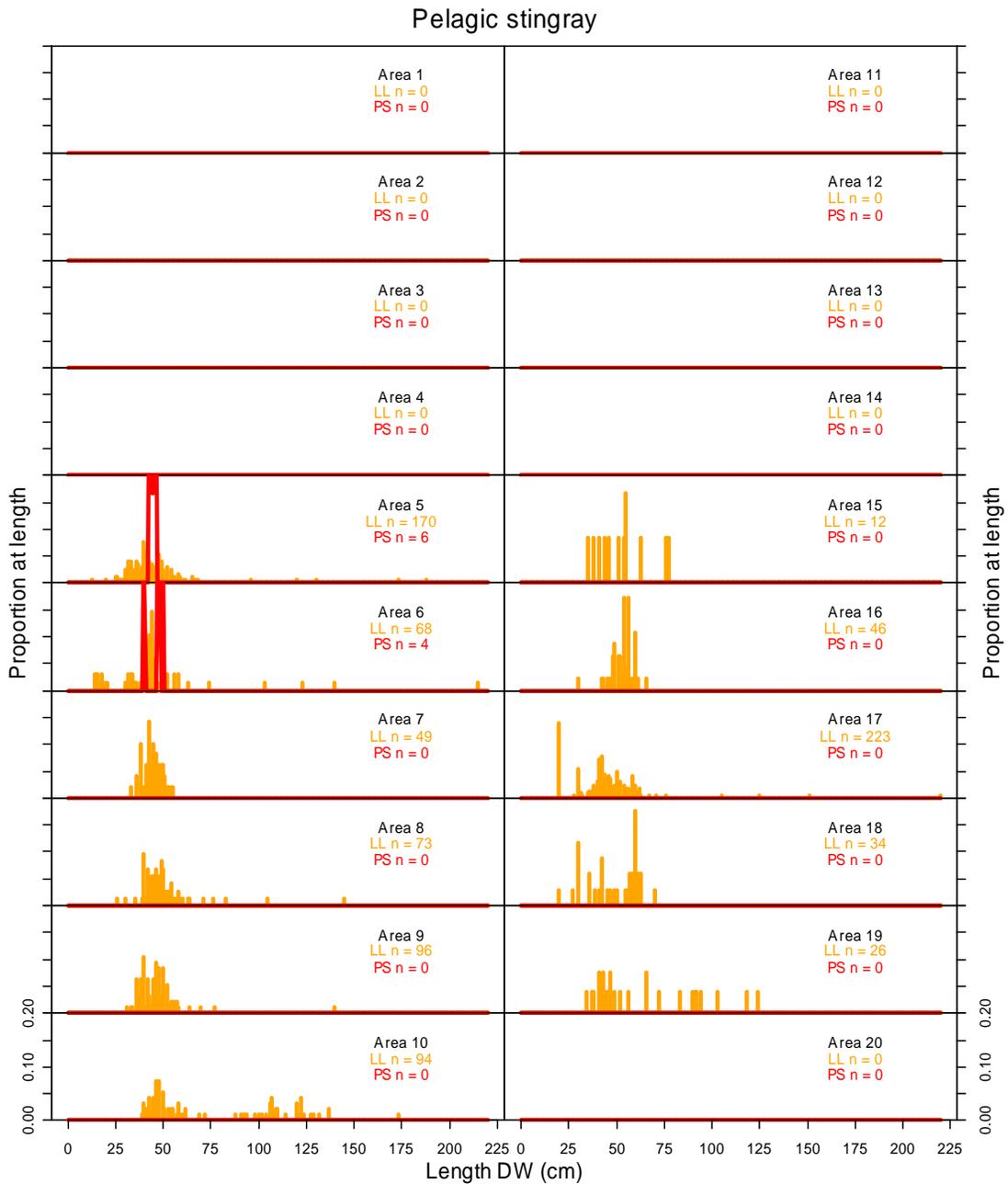
Figure 104. Length-frequency distributions of pelagic stingrays pooled into 10º latitude bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as disc widths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively.
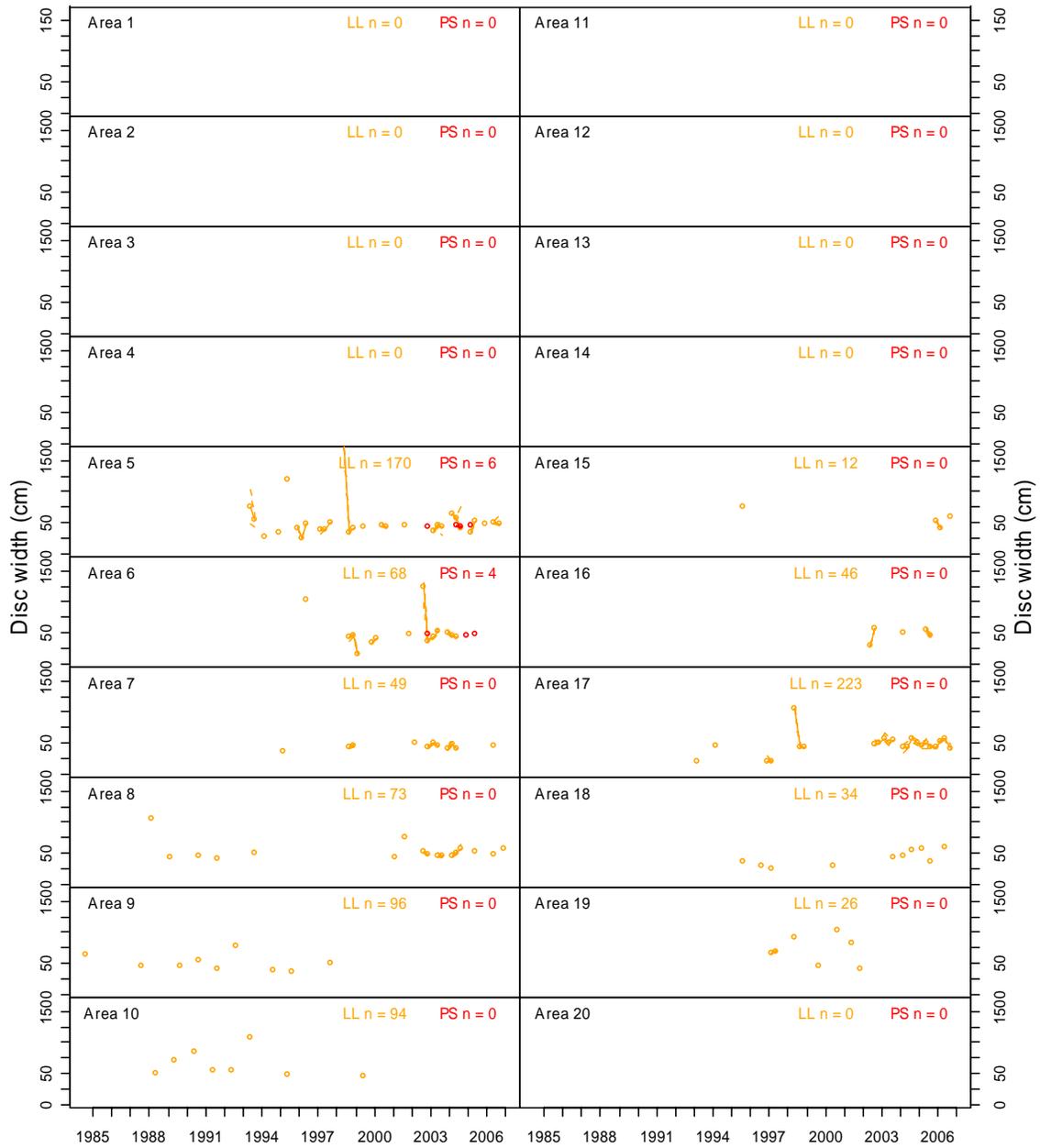
Figure 105. Trends in median size of pelagic stingrays pooled into 10º latitudinal bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as disc widths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively. Dotted lines represent 25th and 75th quartiles of each data series.
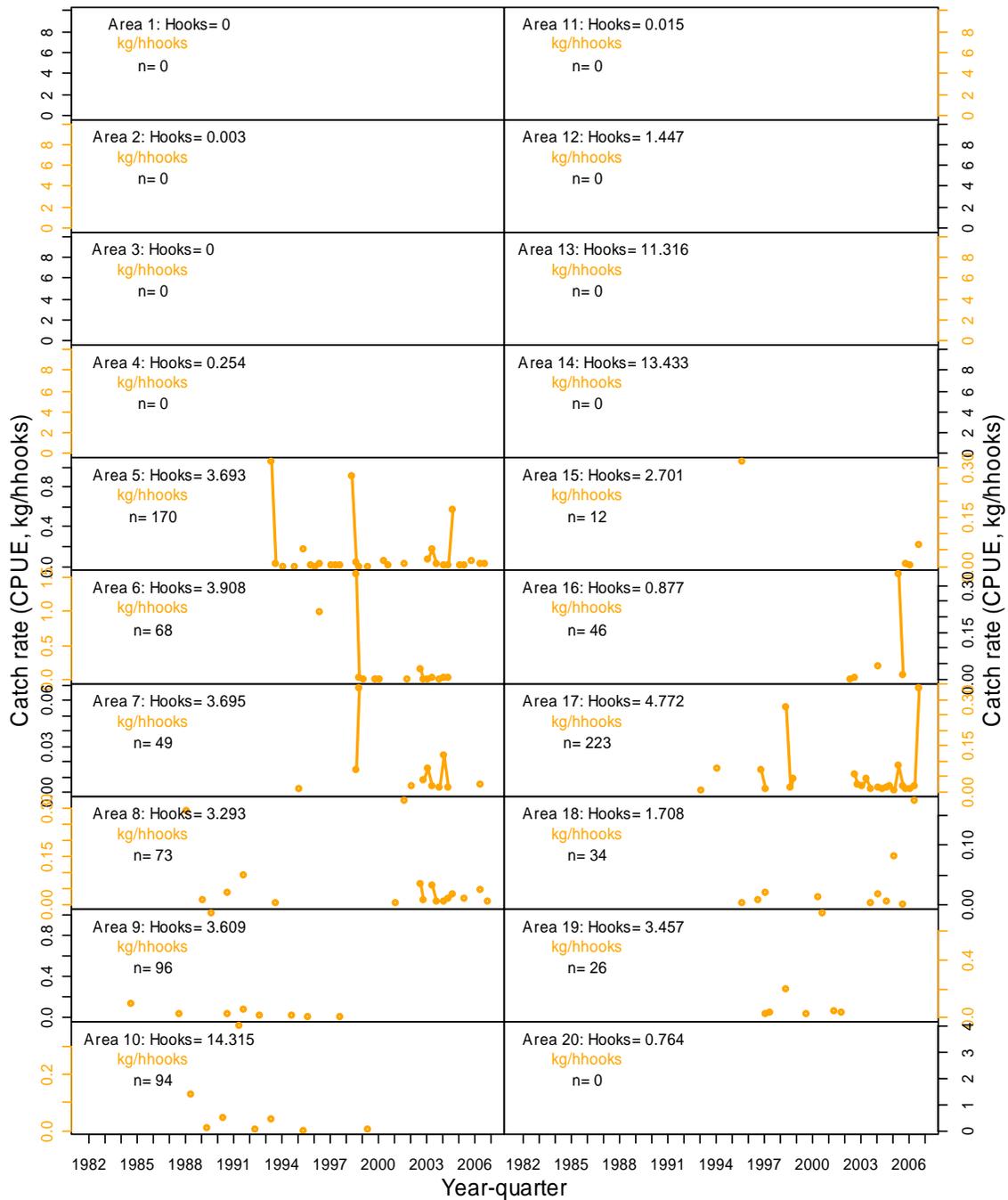
Figure 106. Quarterly catch rates (kg.hhooks^{-1}) of pelagic stingray reported by observers pooled into 10º latitudinal bands (Areas) in the WCPO, 1982–2006. Source, SPC observer data base. Hooks, is the total number of observed hooks (millions) in each Area; n, represents the total number of individuals from each method-fishery within each Area. Scales of the y-axes vary among Areas. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively. Length-weight relationship: whole weight (kg) = (0.0000012 x FL$^{3.810}$) (based on limited data presented in Mollet et al. 2002 and Hemida et al. 2003).
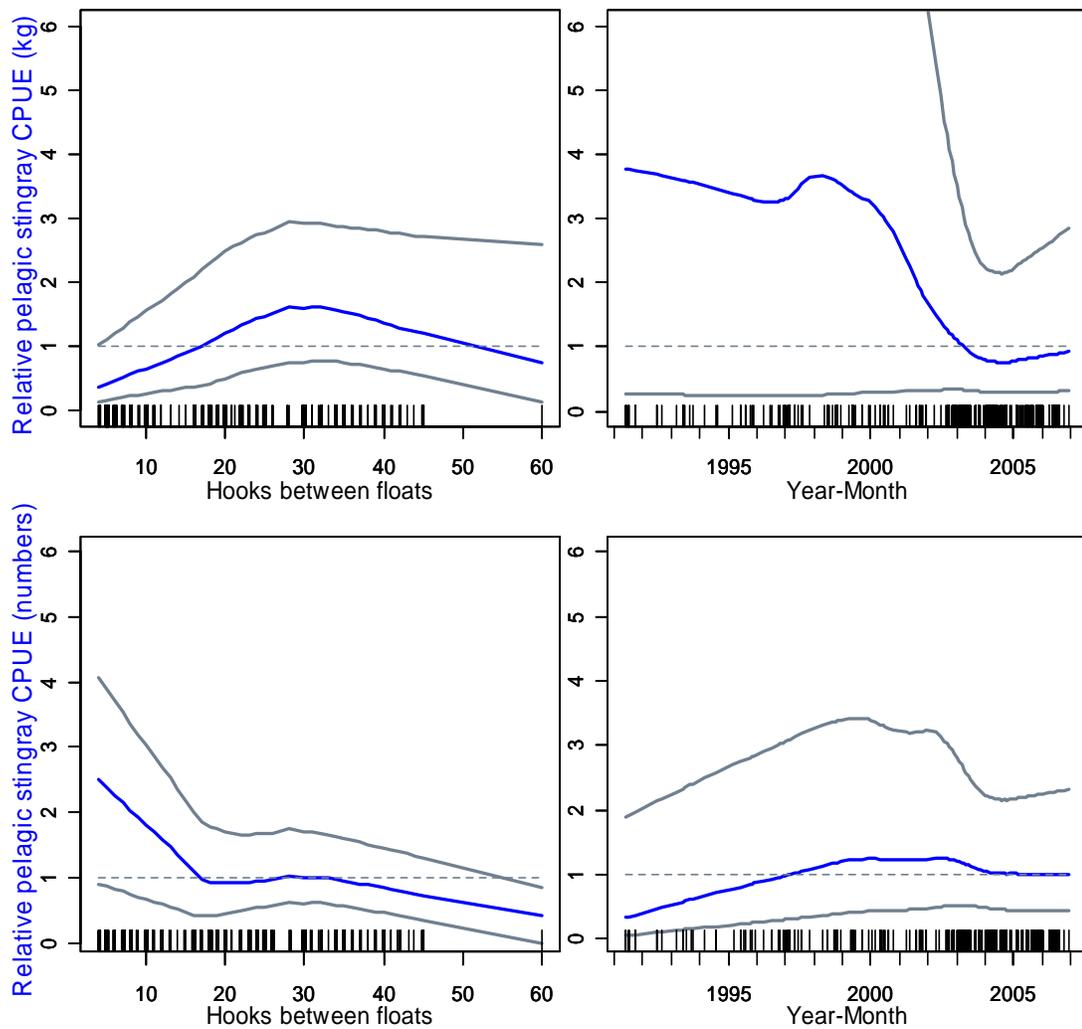
Figure 107. Changes in relative monthly pelagic stingray longline catch rates (blue lines; upper figure, number/hhooks; lower figure, kg/hhooks) for the WCPO under the influence of hooks between floats and time period (year-month) as predicted by GLMs, 1991–2006. Source, observer data held at SPC. Grey lines represent 95% confidence levels. The 'rug' plot along the inside of each x-axis displays the data density along the range of each variable. Weight: $r^2 = 0.669$, adjusted $r^2 = 0.346$; Numbers: $r^2 = 0.639$, adjusted $r^2 = 0.285$.

20. Rainbow runner (*Elagatis bipinnulata*).
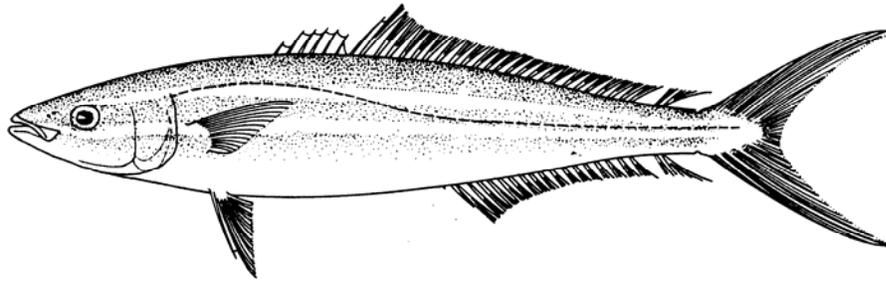
20.1 Description

Dark olive-green to dark-blue on dorsal surfaces with two light blue bands on sides with a yellow band between them. White on ventral surfaces. Most fins are dark coloured, including the relatively large, dark tail. Upper jaw slightly shorter than lower jaw. Maybe confused with yellowtail amberjack as similar colour and shape. However rainbow runners possess small finlets between the end of the second dorsal fin and anal fin and the tail (Chapman et al. 2006).

20.2 Distribution

Rainbow runners are found in tropical and subtropical waters of the WCPO and other Oceans. They appear to be most abundance in equatorial areas.

20.3 Biology

20.3.1   Age and growth

Iwasaki (1991) recorded rainbow runner up to approximately 110 cm FL and more than 7 kg in whole weight. Most rainbow runner reported by observers in the WCPO have been less than 100 cm FL (Figure 109), with very few individuals exceeding 125 cm FL. Age of rainbow runner have been estimated by counting bands on cross sections of vertebrae (Iwasaki 1995). No published accounts of ageing rainbow runner via otoliths were identified.

Iwasaki (1995), based on a total of 219 individuals, estimated the size of rainbow runner from the equatorial western Pacific Ocean at 1, 2, 3, 4 and 5 years of age as approximately 38 cm, 48 cm, 57 cm, 65 cm and 70 cm FL, respectively (Table 6). The growth rate of rainbow runner follows a VBGF for at least ages 2–6, with estimates of L∞ and k being 93.0 cm FL and $0.214.yr^{-1}$ (Iwasaki 1995). These are similar to the estimates of Iwasaki (1991) from the north-west and western equatorial Pacific (L∞ approximately 105 cm FL, and *k* approximately $0.248.year^{-1}$) derived from length-frequency sampling using a Walford plot. Ingles and Pauly (1984), also using length-frequency data, estimated L∞ and *k* at 97.6 cm FL and $0.60.year^{-1}$, respectively, from fish caught coastally in the Philippines, a much higher growth rate than estimated by Iwasaki (1991, 1995).

20.3.2   Reproduction

Size at first maturity of females was estimated at 60–65 cm FL, based on a relatively small number of samples (Iwasaki 1991, 1995, 1998). Iwasaki (1998) identified two annual

spawning peaks in May–June and December-January for rainbow runner from the north-western Pacific, with the largest peak in May–June. However, mature individuals were identified in all months except February and July. It is likely that reproduction occurs year-round, at least in the equatorial regions.

20.3.3   Recruitment

Rainbow runner recruit to the purse-seine fishery of the WCPO at approximately 25 cm FL (Figure 109) and appears fully-recruited to the purse-seine fishery by approximately 35 cm FL, approximately one year of age. This is below the estimated size at first maturity for females.

Recruitment to the longline fishery commences at approximately 40-45 cm FL, and rainbow runner appear to be fully recruited by approximately 75 cm FL (Figure 109), above the estimated size at first reproduction (60-65 cm FL, Iwasaki 1991, 1995, 1998).

20.3.4   Mortality

Estimates of natural mortality for rainbow runner are unavailable. However, using the size data presented in Iwasaki (1991), total mortality was estimated at $0.622–0.658.yr^{-1}$ using several simple length and age based methods (Hoenig's, assuming a maximum age of seven years; Hoenig's assuming that 1% of individual survive to seven years of age; Beverton and Holt's size-based method assuming an L∞ of 100 cm FL).

20.4 Ecology

20.4.1   Habitat preference

Rainbow runner are reported from the western WCPO at least between 40ºN (Iwasaki 1991) and 20–30ºS (Figure 110, Figure 111). However, the higher number of records from equatorial areas suggests that they prefer warm surface waters. The vertical distribution of rainbow runner is likely to be relatively shallow (less than 30 m, Kimura et al. 1998). They are often associated with floating objects, flotsam (Iwasaki 1998, Kimura et al. 1998). Rainbow runner are commonly captured in purse-seine and pole-and-line fisheries of the WCPO (Iwasaki 1991, 1995) highlighting their shallow distribution.

They are the fourth most commonly captured species in all set-types of the purse-seine fishery of the WCPO (Langley et al, 2006b), although they contribute a much higher proportion of catches from associated sets types (especially logs and FADs) than unassociated sets types.

20.4.2   Movements and migration

Iwasaki (1991), using size-frequency data, reported that immature fish were found in inshore waters of Japan (20–40ºN) with adults reported mainly from equatorial regions, suggesting ontogenetic migration. Iwasaki (1991) suggested that small fish move towards the equator at between two and three years of age, typically during the third and fourth quarters of the year. Kimura et al. (1998) also reported an ontogenetic movement pattern, with larval and small rainbow runners in equatorial oceanic waters, with juveniles recruiting to flotsam and other floating objects.

20.4.4   Diet

Rainbow runners prey upon a range of epi-pelagic prey items typically associated with floating logs and other floating objects, especially mackerel scad (*Decapterus macarellus*) (Iwasaki 1998) crustaceans, larval anchovy, and polychaete worms Kimura et al. (1998).

20.5 Details of stocks in the WCPO

20.5.1 Stock structure and size

Details of the stock structure of rainbow runner have rarely been explored. Iwasaki (1998) suggested the existence of ontogenetic migration between sub-equatorial waters (20-40ºN) and equatorial waters, implying a single stock in the north-west Pacific. However, details of the potential east-west movements were not discussed and the extent of sampling was limited. Length-frequency data from observers (Figure 110) reveals that small and large rainbow runner are captured by purse-seine fisheries from equatorial regions of the WCPO, both east and west of 170ºE. Catch rate data from the purse-seine fishery is also similar east and west of 170ºE. While there is the potential for a single stock of rainbow runner at least in equatorial regions of the WCPO, the data does not discount that multiple smaller stocks may also exist.

Purse-seine observer data indicates that rainbow runner are the fourth most commonly reported species in the WCPO purse-seine fisheries (Langley et al. 2008), only exceeded by skipjack, yellowfin and bigeye tuna. The inference is that they may be relatively abundant; less abundant than tunas but more abundant than billfishes, sharks and many other species of teleosts.

20.5.3   Recent stock assessments and status

No formal stock assessments exist for rainbow runner in the WCPO, Pacific or other oceans. Size data reveals a reduction in median size of rainbow runner in pooled purse-seine catches of the WCPO since approximately 2000/01 (Figure 109), from approximately 70 cm FL to less than 50 cm FL. Recent catches are therefore dominated by sub-adult fish. In addition, total catches and catch rates have increased in recent years (Figure 108). While much less size data are available for the longline fisheries of the WCPO, similar downward trends in size (Figure 109, Figure 111) and catch rates (Figure 108) are observed. This may give cause for some concern of the status of this species in the WCPO.

20.6 Fisheries

20.6.1   Major fisheries and occurrence

Rainbow runners are most commonly captured in associated sets by purse-seine fisheries (Sakagawa 1977, Hampton and Bailey 1999, Langely et al. 2006b). Purse-seine catches from the WCPFC-CA have exceeded approximately 10,000 mt per annum in recent years (OFP 2007), although there is a large amount of uncertainty around the estimates (Figure 108). Approximately 97% of all catches recorded by observers are reported from associated sets (logs, FADs, animals). Longline catches have not been estimated.

Rainbow runners are commercially important in other method fisheries in other areas (e.g. trolling and line fisheries of the Colombian Pacific) (Franke and Acero 1993).

20.6.2 Artisanal fishery value

Rainbow runner are likely to contribute to artisanal fisheries in the equatorial Pacific as they are commonly found associated with FADs, logs and flotsam that may be found close to islands and coasts

20.6.3 Sport and recreational fishery value

Rainbow runner is considered a gamefish or recreational species (www.fishbase.org) and small recreational catches are likely to be taking in at least some areas of the WCPO.
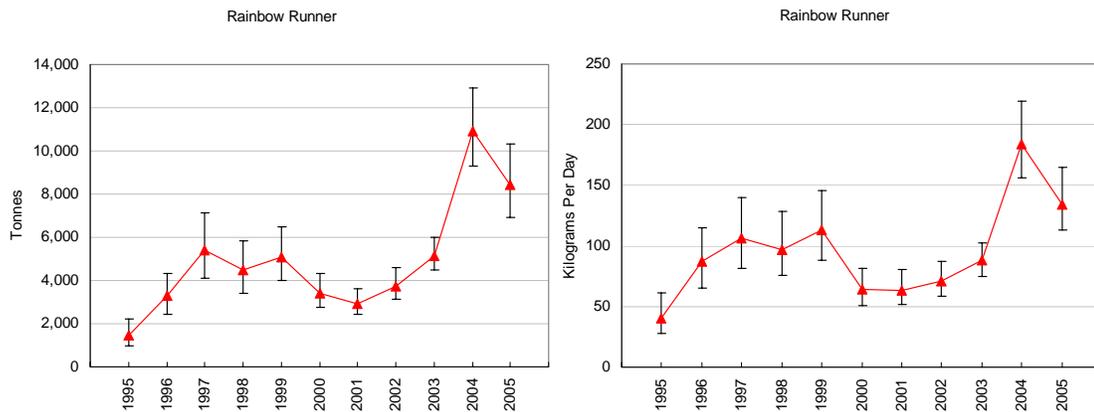
Figure 108. Catches and catch rates of rainbow runner by purse-seine vessels in the WCPFC Statistical Area (excluding the domestic fleets of Indonesia and the Philippines). Points represent median values of 1,000 random samples from the posterior distributions; error bars represent 95% confidence intervals from 1,000 random samples from the posterior distributions. Source, OFP (2007).

Table 12. Size at age of rainbow runner based vertebral ageing (modified from Iwasaki, 1995).

Age (years)	Size (FL, mm)	
	Male	Female
1	377	378
2	484	488
3	574	563
4	659	635
5	714	677

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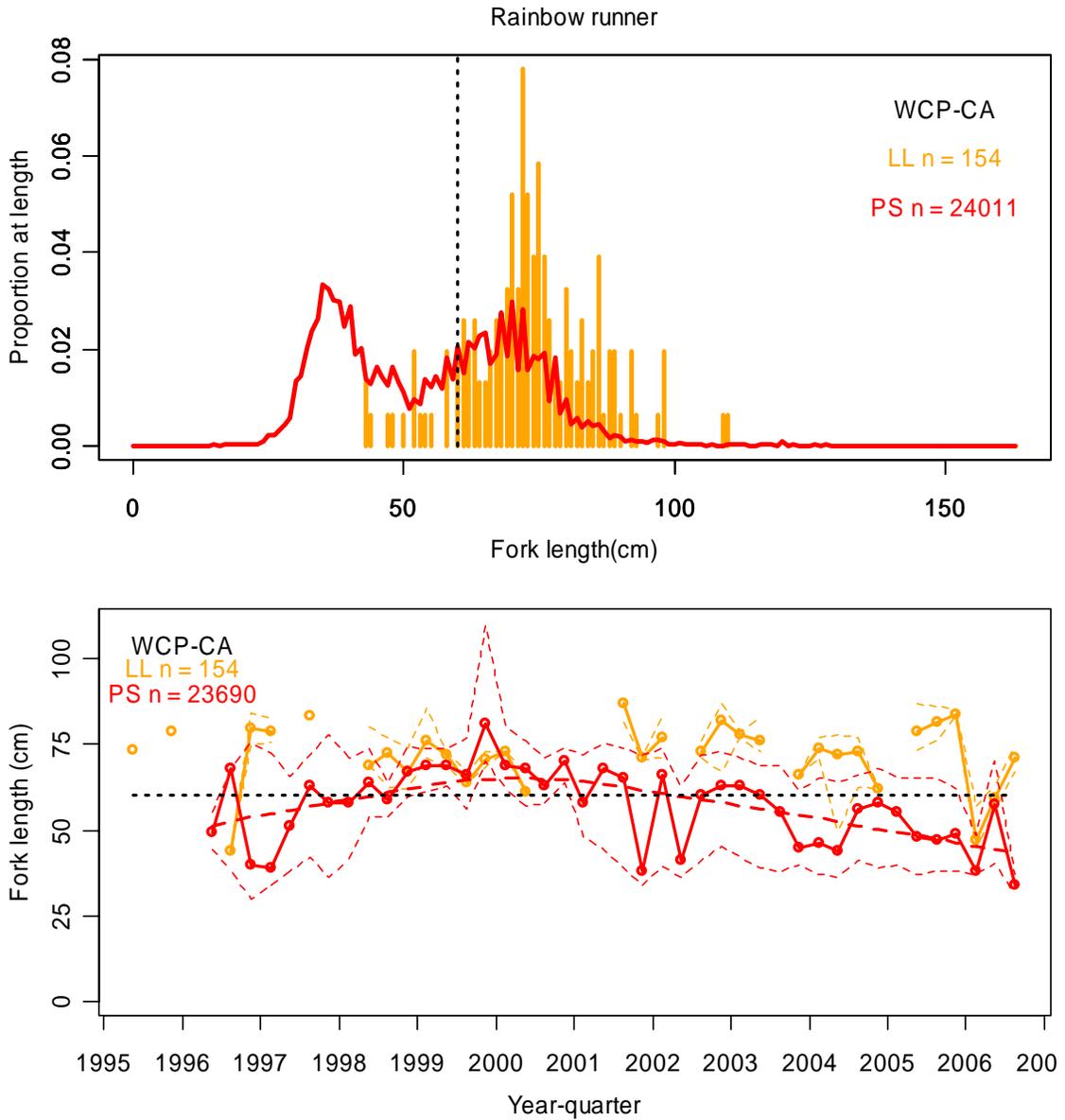
Figure 109. Combined length-frequency distributions (upper figure) and trends in quarterly median size (lower figure) of rainbow runner reported by observers in longline and purse-seine vessels in the WCPO, 1995–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery. Thin dashed lines represent the 25th and 75th quartiles of the size data. Heavy dashed lines represent lowess fits to the median size data. Dotted lines represent estimates of size at first maturity for females (black, 60 cm FL) (from Iwasaki 1991, 1995 and 1998, for north-western Pacific). No size at maturity estimates were identified for male rainbow runner.
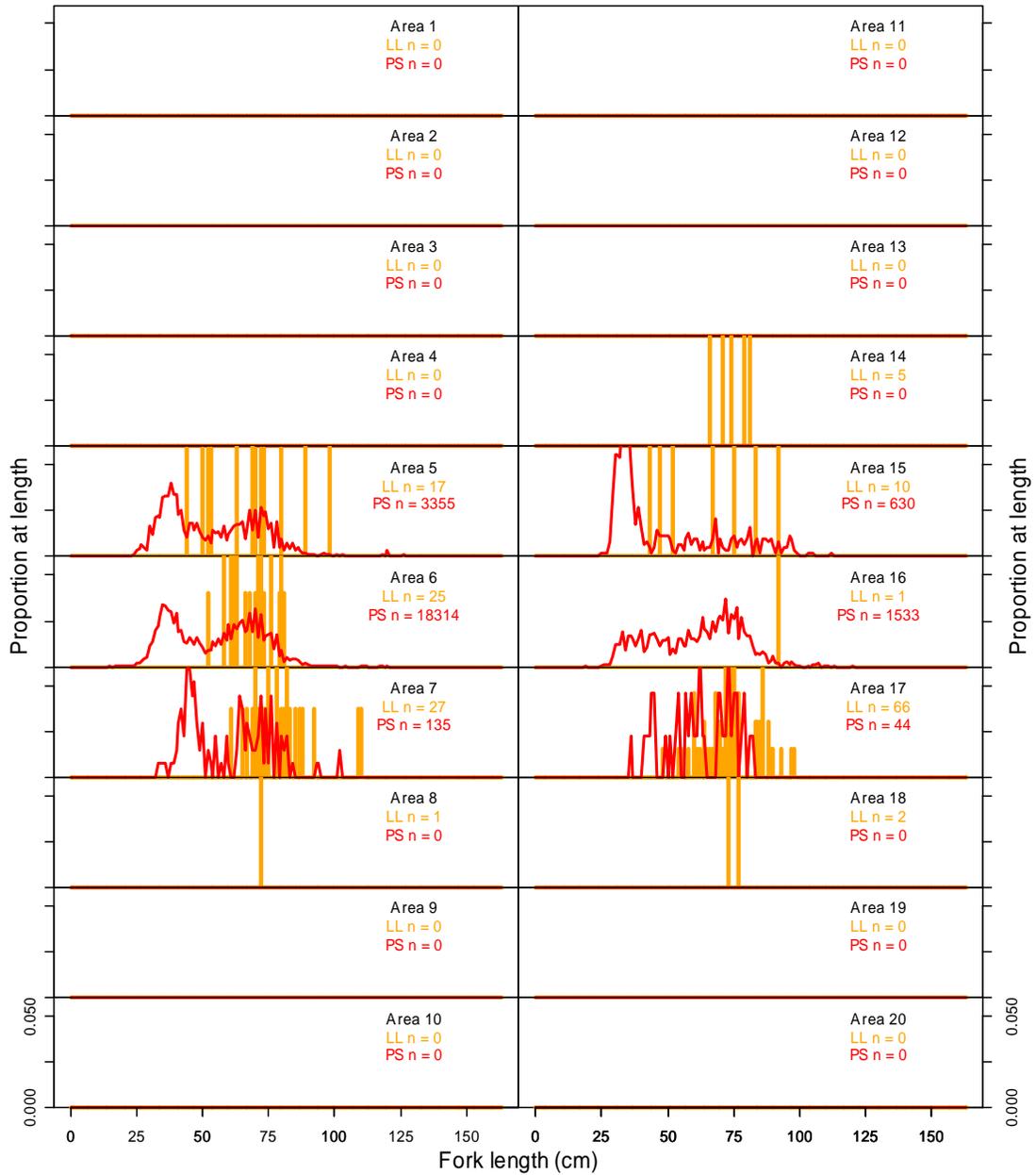
Figure 110. Length-frequency distributions of rainbow runner pooled into 10º latitude bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as fork lengths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively.
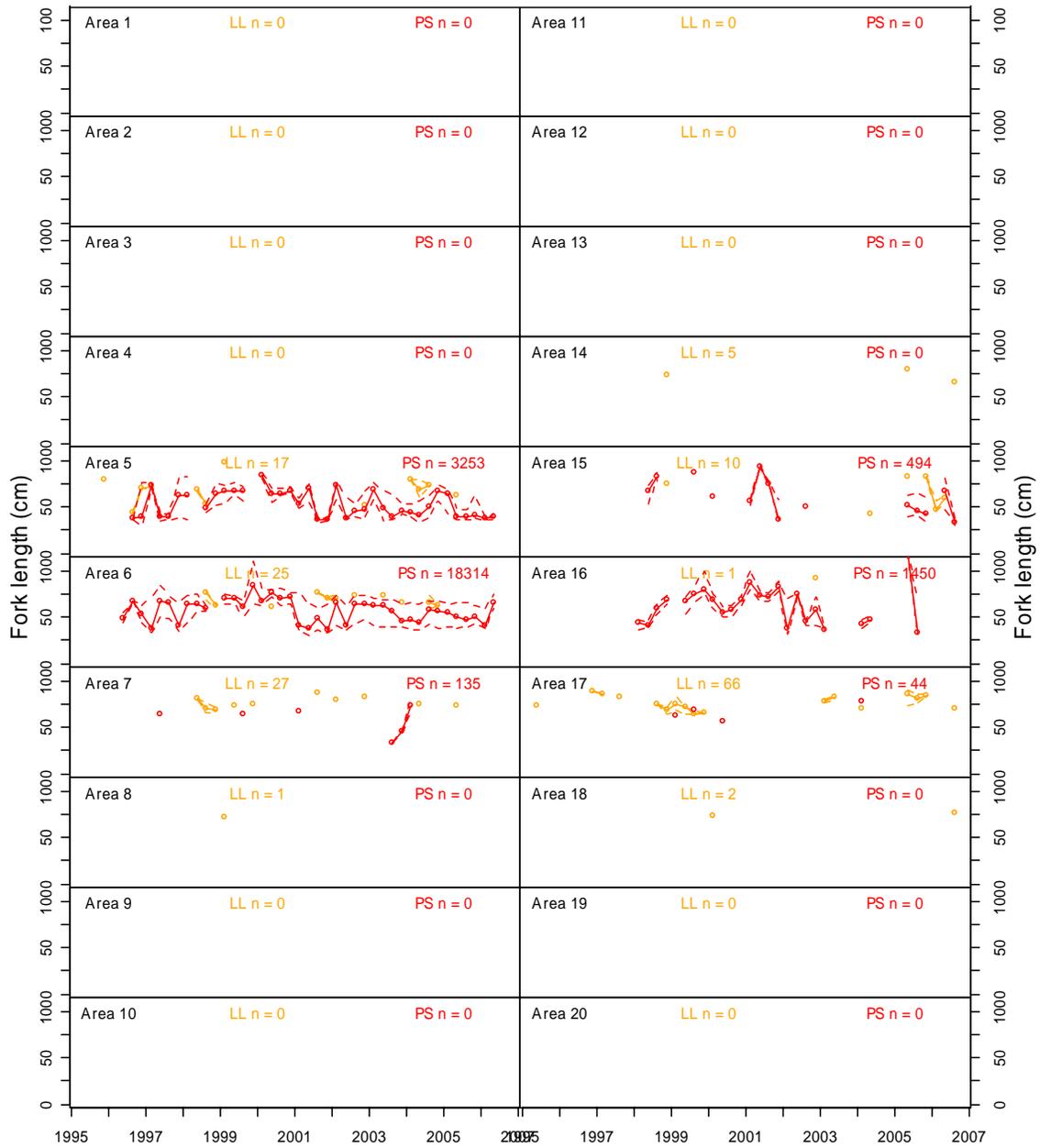
Figure 111. Trends in median size of rainbow runner pooled into 10º latitudinal bands (Areas) in the WCPO, 1984–2006. Source, SPC observer data base. n, represents the total number of individuals from each method-fishery within each Area. All sizes as fork lengths. Left-hand figures are west of 170ºE; right hand figures are east of 170ºE. Areas 5 and 15, and 6 and 16 represent the 0–10ºN and 0–10ºS of the equator, respectively. Points represent median size, dotted lines represent 25th and 75th quartiles, solid lines represent lowess fits to each data series.

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