Journal of FISH BIOLOGY
Published for the Fisheries Society of the British Isles

Received: 8 September, 2012
IOTC-2012-WPEB08-INF15

Journal of Fish Biology (2012) **80**, 1870–1894
doi:10.1111/j.1095-8649.2012.03238.x, available online at wileyonlinelibrary.com

Identification of factors influencing shark catch and mortality in the Marshall Islands tuna longline fishery and management implications

D. Bromhead*†, S. Clarke*, S. Hoyle*, B. Muller‡, P. Sharples* and S. Harley*

**Oceanic Fisheries Programme, Secretariat of the Pacific Community, BP D5, Noumea 98848, New Caledonia and ‡Marshall Islands Marine Resources Authority, P. O. Box 860, Majuro 96960, Marshall Islands*

Recent average annual catches of sharks by tuna longline vessels fishing in the Republic of the Marshall Islands (RMI) are estimated to be between 1583 and 2274 t. Although 22 shark species have been recorded by the observer programme for this fishery, 80% of the annual catch comprises only five species: blue shark *Prionace glauca*, silky shark *Carcharhinus falciformis*, bigeye thresher shark *Alopias superciliosus*, pelagic thresher shark *Alopias pelagicus* and oceanic whitetip shark *Carcharhinus longimanus*. Wire leaders (*i.e.* branch lines or traces) were also used by nearly all observed vessels. Generalized additive model (GAM)-based analyses of catch rates indicated that *P. glauca* and *A. superciliosus* are caught in higher numbers when vessels fish in relatively cooler waters, at night, close to the full moon, when the 27° C thermocline is close to the surface and during El Niño conditions. In contrast, *C. falciformis*, *A. pelagicus* and *C. longimanus* are caught in higher numbers when shark lines are used (all three species) or hooks are set at a shallow depth (*A. pelagicus* and *C. longimanus* and, also, *P. glauca*). These findings are generally consistent with current knowledge of these species' habitat preferences, movement and distribution. The results of these analyses were combined with information pertaining to shark condition and fate upon capture to compare the likely effectiveness of a range of potential measures for reducing shark mortality in the longline fishery. Of the options considered, the most effective would be to combine measures that reduce the catch rate (*e.g.* restrictions on the use of wire leaders, shark baits and shark lines) with measures that increase survival rates after post-capture release (*e.g.* finning bans).

Key words: catch rates; fishing methods; fishing mortality; generalized additive model; oceanography; targeting.

INTRODUCTION

Global concern about the impact of fishing upon the status of shark stocks is well documented (Baum *et al*., 2003; Camhi *et al*., 2008). The relatively low biological productivity of many stocks and relatively high susceptibility to capture makes them vulnerable to overexploitation (Cortés *et al*., 2010) and a growing number of studies

†Author to whom correspondence should be addressed: Tel.: +61 2 61663657; email: donbromhead@gmail.com

have linked fishing pressure to significant declines in shark communities in different parts of the world (Baum *et al*., 2004; Sibert *et al*., 2006; Polovina *et al*., 2009; Ferretti *et al*., 2010).

There have been few quantitative assessments of the impact of fishing on shark populations in the western and central Pacific Ocean (WCPO), despite this region supporting the world's largest industrial tuna fishery (>2·4 million t year^{-1} of tuna since 2009) (Williams & Terawasi, 2011). Due to under-reporting of sharks in commercial fishing vessel logbooks, WCPO shark catches can only be estimated from limited observer sampling, but it is clear that the majority of pelagic sharks are captured by longline gear (Lawson, 2011). The longline fishery comprises vessels that specifically target sharks, vessels which engage in 'mixed targeting' (methods that aim to catch shark and tuna species simultaneously) and vessels which target only tuna (or other non-shark species) and take sharks purely as by-catch. In the latter instance, even when sharks are brought to the vessel alive and then discarded, survival is often low due to the practice of finning or rough handling during gear retrieval. Total catches of sharks in this fishery are estimated at *c*. 60 000 t year^{-1} (2006 estimate), of which 65% were the blue shark *Prionace glauca* (L. 1758) (SPC, 2008).

With the listing of two WCPO shark species by the International Union for the Conservation of Nature (IUCN) Red List as globally endangered, and another 16 WCPO shark species as globally vulnerable, many Pacific Island countries (PICs) are becoming increasingly aware of the effects of fishing upon shark populations. Many PICs also recognize the intense regional fishing effort and the large catches of sharks that are taken by longline fisheries. The PICs are amongst the signatories to many of the most important treaties, conventions and agreements governing international fisheries and fish trade, including the United Nations Convention on the Law of the Sea, the United Nations Fish Stocks Agreement, the Convention on International Trade in Endangered Species (CITES) and the Convention on Migratory Species (CMS), and are considering options for reducing the effects of fishing on shark populations both regionally (*via* the Western and Central Pacific Fisheries Commission, WCPFC) and within their own national waters.

At the regional level, these concerns have resulted in the development of a Pacific Islands Regional Plan of Action (RPOA) for sharks and the adoption by the WCPFC of a shark conservation and management measure. This measure includes prohibition of finning, mandatory provision of shark catch data and initiation of a shark research plan. With regard to the prohibition of finning, it should be noted that the measure was implemented immediately (in February 2007) for high sea areas within the WCPF Convention Area, but it requires commission members and cooperating non-members to implement this measure or alternative measures in national waters. The measure also designates 13 key shark species (Clarke & Harley, 2010; Clarke *et al*., 2011): *P. glauca*, great hammerhead *Sphyrna mokarran* (Rüppell 1837), scalloped hammerhead *Sphyrna lewini* (Griffith & Smith 1834), smooth hammerhead *Sphyrna zygaena* L. 1758, winghead shark *Eusphyra blochii* (Cuvier 1817), shortfin mako *Isurus oxyrinchus* Rafinesque 1810, longfin mako *Isurus paucus* Guitart Manday 1966, silky shark *Carcharhinus falciformis* (Bibron 1839), oceanic whitetip shark *Carcharhinus longimanus* (Poey 1861), porbeagle shark *Lamna nasus* (Bonnaterre 1788), bigeye thresher *Alopias superciliosus* (Lowe 1839), common thresher *Alopias vulpinus* (Bonnaterre 1788) and pelagic thresher *Alopias pelagicus* (Nakamura 1935).

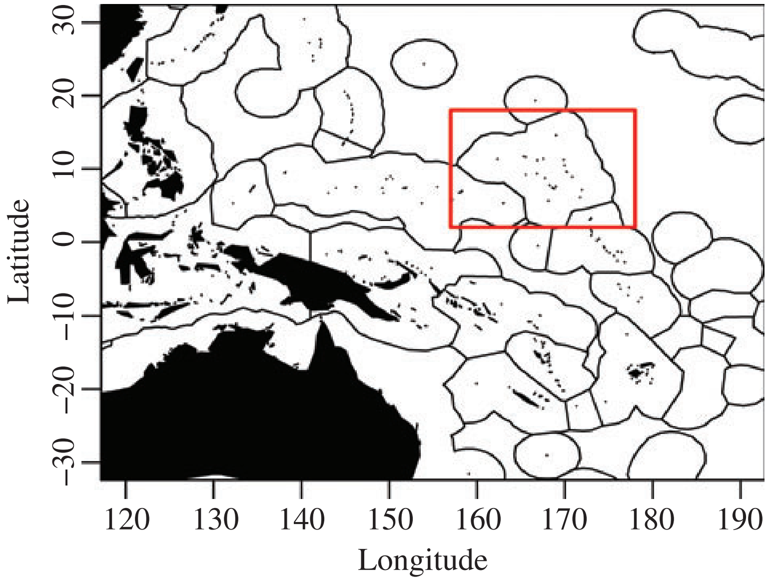

FIG. 1. Map of the western and central Pacific Ocean region showing the location of the Exclusive Economic Zone (EEZ) of the Republic of the Marshall Islands (□).

At the national level, some PICs are looking for additional information and advice which can assist them in determining what, if any, management measures they might implement to reduce the level of shark mortality occurring as a result of the tuna fisheries operating in their Exclusive Economic Zones (EEZs). Limited understanding of the biology and environmental preferences of pelagic shark species, the fishing methods used by longline vessels and how these factors interact to influence catch rates and fishing mortality of sharks in their waters complicates the consideration of different management options. The PICs struggle against resource limitations to implement and maintain data collection programmes required for scientific assessments of tuna, sharks and other species and to justify this spending in the face of other important national needs such as health and education programmes.

The Republic of the Marshall Islands (RMI) (Fig. 1) represents one PIC which has successfully implemented comprehensive data collection programmes in its tuna fisheries over the past 15 years and is now using these data to consider how it might manage interactions between its tuna fisheries and shark populations. This article presents the RMI situation as an example of how fisheries managers can enhance their understanding of interactions between sharks, the environment and the fishery, of shark targeting practices and of the relative effectiveness of different management options for reducing shark mortality.

In this study, data from observer, port sampling and logbook data collection programmes were used to estimate the level and nature of longline fishery interactions with sharks in RMI, to profile shark targeting methods and to identify environmental and fishing method factors which significantly influence shark catch rates. These analyses were then used to assess the relative effectiveness of a suite of management options for reducing shark mortality levels in the RMI fishery.

MATERIALS AND METHODS

DATA SOURCES

The RMI government has implemented several tuna fishery data collection programmes including observer, port sampling and logsheet data collection programmes. Data from each programme are compiled and sent to the Oceanic Fisheries Programme at the Secretariat of the Pacific Community (SPC) in Nouméa, New Caledonia, where they are incorporated into larger regional databases by the SPC. For most of the analyses in this article, complete annual time series were available up to 2009, representing the fishing activities of vessels flagged to China, the Federated States of Micronesia (FSM), Japan, RMI and Taiwan.

FLEET OPERATION AND DATA COVERAGE

Logsheet and observer data were used to characterize the fishing strategies employed by each of the major longline fleets (categorized by flag) that have operated in RMI since the mid-1990s. The observer data were used to estimate the median number of hooks per set, the number of hooks between mainline floats (*i.e.* a proxy for relative fishing depth) and time of day of the set. Total observed fishing effort (in hooks) by year and fleet was divided by total estimated fishing effort (in hooks) derived from logsheets to determine the estimated coverage rate of the observer data for each fleet.

CATCH ESTIMATES

High and low estimates of the average annual catch of sharks (in t), including both retained and discarded sharks, were derived for the period 2005–2009 using two methods. The low estimate was determined by multiplying the mean observed catch rate by species and fleet (flag) and year for the period 2005–2009 by the mean estimated fishing effort (in hooks), derived from logsheets, by fleet and by year. The resulting estimate of the mean number of sharks caught per year for each species was then multiplied by estimates of mean sizes (in kg) for each shark species based on observer data to produce an estimate of mean annual catch for each species. Species-specific catch estimates were summed to produce a total shark catch estimate. This estimate assumes that the observed catches are representative of the catch rates and species composition in the fishery overall. This may underestimate total catch, however, as three of the fleets (Japan, Taiwan and RMI) have had very little observer coverage, and at least two of these fleets (Japan and Taiwan) are amongst the countries reporting the greatest amount of shark catches in the Pacific Ocean in recent years (FISHSTAT, 2011). The average shark catch per unit effort (CPUE) of the limited observer data for these fisheries was lower than the average of other observer data.

The second estimation method assumes that the fleets with low observer coverage (Japan, RMI and Taiwan) catch all shark species observed in the fleets with high observer coverage (China and FSM), at a rate equivalent to the observed fleet with the highest catch rate. Under this assumption, the highest catch rate of each species from the fleets with high observer coverage in each year was applied to fishing effort (in hooks) from the fleets with low observer coverage. This method may overestimate the level of shark catch in the fishery, but is designed to be considered alongside the first estimate as an alternative estimate of the true value.

TARGETING INDICATORS

It should be noted that for the purposes of this article, targeting can refer to either deliberate targeting, whereby the gear is deliberately set to catch sharks, or effective (accidental) targeting where the gear might fish in a way which effectively targets sharks (*i.e.* in a time, place and depth where many sharks happen to occur), but is not necessarily intended to. Without clear evidence of specific shark targeting methods (*e.g.* shark baits and lines), it is often not possible to determine if apparent targeting is deliberate or accidental.

Observers collect a broad range of information on fishing operations, including data that can indicate whether shark targeting might have occurred. In this analysis, the following factors are considered to be indicators of shark targeting: 1) bait type, longline operations targeting tuna typically use small fishes and squid as bait, whereas longline operations targeting sharks typically use pieces of fish meat cut from by-catch species or tuna. Observers record the bait types used on each set (not each hook) thereby allowing sets to be identified in which at least one of the target species groups was sharks. In most cases where shark baits are listed, tuna baits are also listed, indicating mixed targeting sets; 2) shark line use (lines deployed off the mainline floats), one practice used to target sharks in sets otherwise mainly aimed at catching tuna, is to attach baited lines directly to the mainline floats. This ensures that the hooks stay in shallow water where the likelihood of catching *C. falciformis*, *C. longimanus* and other shallow habitat species is higher; 3) shark specified as the primary target by observer, observers are also required to determine and report the primary target species of each set. They do this by direct observation of the gear setup or by asking the crew or captain.

The use of wire leaders was also considered as an indicator of shark targeting as it is known to significantly increase the retention of sharks (Ward *et al.*, 2008). It is also recognized, however, that wire leaders may be used for reasons other than shark targeting, for example, increasing retention of other species taking the hook. The data were also screened for sets and trips where shark catch rates were very high and the majority of catch was sharks.

Operational-level logsheet data from five longline vessels licensed to fish for sharks in RMI during 2002–2003 were used to estimate the mean CPUE and species composition levels for these vessels. Catch rates from these vessels were intended to be used as reference indicators to identify potential shark targeting activities in other longline vessels not licensed to fish for sharks.

Estimates of shark CPUE and shark proportions (proportion of the total catch comprising shark species) were estimated for each set, and separately, for each fishing trip recorded in both logsheet and observer datasets. These two variables were selected because targeting of sharks can take different forms: a vessel may make shark targeted sets occasionally, predominantly target shark on all sets within a trip or use a mixed strategy, targeting both tuna and sharks simultaneously (*e.g.* through the use of shark lines and shark bait on some hooks). On the basis of the analyses of regional observer data which suggested that the likelihood of a tuna longline vessel never encountering sharks is extremely low (SPC, 2011), data were screened to exclude vessels with no history of reporting shark catches.

FACTORS INFLUENCING CATCH RATES

Observer data were analysed using generalized additive models (GAMs) to identify which environmental and fishing method factors most strongly influence catch rates of each of these species in RMI. These analyses were restricted to the two fleets with high observer coverage (China and FSM). Analyses were conducted using the statistical software R (version 9.1; www.r-project.org) and the package mgcv for generalized additive modelling.

The analyses of observer data applied two separate GAM models to each species: a time-area model and a causative factors model. This two-model approach was designed to minimize the identification of coincidental relationships and significant confounding between terms. The time-area model does not attempt to explain why catch rates vary, but simply identifies where and when they vary. The time-area models assess the relationship between catch rates and the time of year (season), year, area and El Niño Southern Oscillation (ENSO) period. The causative factor models exclude time and area factors (which are typically confounded with environmental and fishing method factors). A wide range of environmental and method-related data were available, but factors were only considered if there was a reasonable hypothesis to suggest that they might influence shark catch rates (Table I).

The GAM time-area and causative factor models took three forms: a full model using ln(catch + 0·5) as the response variable, log(effort) as an offset and an assumed Gaussian error distribution, a Poisson count model which included only those fishing operations which caught at least one shark and a binomial 'presence or absence' model which applied effort as an offset and assessed factors associated with whether or not sharks are caught. Given

TABLE I. Description of the fishing method and environmental variables considered within the causative factor generalized additive models (GAMs) used to assess what factors influence catch rates of common pelagic shark species caught by longline fishing in the Republic of the Marshall Islands Exclusive Economic Zone

Variable category	Variable name	Description
Fishing method: shark targeting	Bait	Indicator (yes or no) of whether baits used to catch sharks were used in the set
	Shk_line	Indicator (yes or no) of whether shark lines were deployed off the mainline floats
	Target	Indicator (yes or no) of whether the observer reported sharks as a target
Fishing methods: general	Set time	Time of day at which the longline is first deployed
	HooksBF	The number of hooks deployed between each pair of mainline floats. This is considered a proxy for the mean relative fishing depth of the hooks
Environmental	SST	The mean monthly sea surface temperature in the 1° cell in which each fishing operation occurred
	SST_Range	The range in sea surface temperatures (SST) occurring in the 2° area surrounding the location at which the longline set was deployed. A large range in SST can indicate the presence of oceanic fronts (*e.g*. convergence zones)
	Depth27C	The depth (in m) from the surface, at which the 27° C thermocline occurs is a proxy for the depth of warmer surface habitat
	Land_Distance	Distance (in nautical miles; 1 nautical mile = 1·852 km) of the start of the set to the nearest land
	Depth	Mean depth (in m) from surface to the seafloor for the 1° cell in which the set was initiated
	Moon phase	The phase of the moon on the date at which the longline set is initiated
	NOSM	The number of seamounts within 120 nautical miles (222·24 km) of the set start location
	Dist_Seamount	The distance (in nautical miles) of the set start point to the summit of the nearest known seamount

the consistency in the results from the three models, only the results from the full model are presented here.

RESULTS

FLEET OPERATION

The analyses of operational-level logsheet and observer data revealed a major shift in the fishing strategy employed by most fleets operating in the RMI EEZ in 2004. The median number of hooks set per fishing operation almost doubled (to around 2000 hooks per set) for China, FSM and RMI flagged vessels. The number of hooks between floats (HBF) also increased significantly (from 5–15 HBF pre-2004 to 20–25 HBF post-2004), indicating a switch to deeper setting. Consistent with this observation, anecdotal evidence indicates a switch in the main target species from yellowfin tuna *Thunnus albacares* (Bonnaterre 1788) to bigeye tuna *Thunnus obesus* (Lowe 1839) around that period. Such changes in fishing strategy would have the potential to impact shark by-catch rates but were accounted for in the causative factor models through the inclusion of the hooks between floats factors and by using the number of hooks as an offset in the model.

DATA COVERAGE

A review of the longline logsheet data from RMI revealed that 28·7% of longline trips in RMI had not reported any retained or discarded catch of sharks. This contrasts with regional observer data in which only 6% of longline trips caught no sharks.

A review of RMI observer data indicated that the main longline fleets (China and FSM) have averaged 5·3 and 6·3% observer coverage per year, respectively, over the period 2004–2008, with the spatial distribution of observed effort being consistent with the overall fishing effort distribution of those fleets. These observer data are not, however, representative of the Japanese and Taiwanese fleets which had no observer coverage, nor of the RMI fleet, which had observer coverage of only 0·7%. The majority of fishing effort in RMI is, however, by the two observed fleets of China and RMI.

ESTIMATES OF TOTAL CATCHES

Estimates of total annual longline catches of sharks in RMI over the period 2005–2009 were calculated using two methods. Estimates ranged from1583 to 2274 t year^{-1}.

SPECIES COMPOSITION, CONDITION, FATE, SEX AND SIZE

Observer data indicate that at least 22 species of sharks, skates and rays have been caught in the longline fishery (Table II). These are predominantly pelagic species with *P. glauca* (30% of observed shark catches), *C. falciformis* (27%), *Alopias* spp. (13%), pelagic stingray *Dasyatis violacea* (Bonaparte 1832) (4%) and *C. longimanus* (8%) the most commonly caught species.

Of the more commonly caught species, *P. glauca* (19·6%), *C. falciformis* (26·5%), *C. longimanus* (30·6%) and *D. violacea* (18·5%) have the lowest reported percentages of being dead on hauling or unlikely to survive if released (Table II). Other rays also have low mortality rates at the point of hauling. In contrast, the proportion that are dead or unlikely to survive if released is much higher for *A. superciliosus* (50·0%), *A. pelagicus* (63·8%), *I. oxyrinchus* (50·3%) and *I. paucus* (53·6%), which are also common by-catch species (Table II).

Of the more commonly caught species, only *C. falciformis* (37·7% discarded) and *C. longimanus* (40·3% discarded) are commonly retained as a whole (*i.e.* the trunks are retained, including fins) in the longline fishery in RMI waters (Table II). Most species have trunk discarding rates between 90 and 100%. Of the commonly caught

TABLE II. Summary of key statistics of observed catches of sharks and rays by longline gear in the Republic of the Marshall Islands EEZ including the number of sharks observed caught, the per cent of discarded sharks which were finned, the per cent of sharks caught (total) which were discarded, the per cent of sharks caught which were judged to be dead or unlikely to survive after release and the mean catch rate per set. The data were restricted to and aggregated across the two fleets for which observer coverage is more likely to be representative of those fleets' fishing operations, *i.e.* the Chinese and FSM fleets

Common name	Scientific name	Number observed	Per cent discards (finned)	Per cent discards	Per cent dead	CPUE (fish per 1000 hooks)
Blue shark	*Prionace glauca*	3452	98·9	92·6	19·6	1·0931
Silky shark	*Carcharhinus falciformis*	3242	96·3	37·7	26·5	1·0266
Bigeye thresher	*Alopias superciliosus*	1636	98·9	95·2	50·0	0·5181
Pelagic thresher	*Alopias pelagicus*	1353	98·4	92·9	63·8	0·4284
Oceanic whitetip shark	*Carcharhinus longimanus*	917	97·4	40·3	30·6	0·2904
Pelagic stingray	*Dasyatis violacea*	501	0·0	98·8	18·5	0·1586
Shortfin mako	*Isurus oxyrinchus*	171	100·0	93·0	50·3	0·0541
Longfin mako	*Isurus paucus*	151	99·3	97·4	53·6	0·0478
Crocodile shark	*Pseudocarcharias kamoharai*	139	16·9	75·5	38·7	0·0440
Common thresher	*Alopias vulpinus*	87	94·3	100·0	52·9	0·0275
Silvertip shark	*Carcharhinus albimarginatus*	20	100·0	50·0	15·0	0·0063
Bronze whaler shark	*Carcharhinus brachyurus*	19	84·2	100·0	5·6	0·0060
Blacktip shark	*Carcharhinus limbatus*	10	77·1	70·0	60·0	0·0032
Galapagos shark	*Carcharhinus galapagensis*	8	0·0	0·0	25·0	0·0025
Scalloped hammerhead shark	*Sphyrna lewini*	5	100·0	100·0	60·0	0·0016
Tiger shark	*Galeocerdo cuvier*	5	100·0	80·0	60·0	0·0016
Grey reef shark	*Carcharhinus amblyrhynchos*	4	100·0	75·0	50·0	0·0013
Great hammerhead shark	*Sphyrna mokarran*	3	66·7	100·0	100·0	0·0009
Bigeye sand tiger shark	*Odontaspis noronhai*	1	0·0	100·0	100·0	0·0003
Giant manta	*Manta birostris*	1	0·0	100·0	0·0	0·0003
Sandbar shark	*Carcharhinus plumbeus*	1	100·0	100·0	0·0	0·0003

CPUE, catch per unit effort.

true shark species (*i.e.* excluding rays) discarded, however, 94–100% of each of these have been observed to be finned first.

NOMINAL CATCH RATES

Observed longline catch rates (Table II), averaged for 2005–2009, in the two fleets with the highest observer coverage operating in RMI (China and FSM), were highest for *P. glauca* (1·09 per 1000 hooks), *C. falciformis* (1·02), *A. superciliosus* (0·51), *A. pelagicus* (0·43), *C. longimanus* (0·29) and *D. violacea* (0·16). Note that none of the observed vessels were licensed to fish for sharks. *Prionace glauca* and *C. falciformis* each occurred in at least 50% of observed longline sets in the Chinese and FSM fleets.

TARGETING INDICATORS

Logsheet data provided by longline vessels licensed to fish for shark in RMI (in 2002 and 2003) indicate that the majority of the sets by these vessels have reported only shark catches (shark proportions close to 1) and had catch rates varying between 10 and 100 sharks per 1000 hooks (Fig. 2). At a trip level, CPUE for these vessels averaged between 7 and 34 sharks per 1000 hooks and species proportions were typically >85% sharks. Logsheet data provided by longline vessels licensed to fish for tuna indicate that the reported catch rates and species proportions matched or exceeded these levels only rarely. Similarly, aggregate trip level data for these vessels indicate a small number of trips with high shark CPUE and species proportions similar to those of vessels licensed to fish for sharks (Fig. 2).

None of the observed trips were on vessels licensed to fish for shark. During the period 2005–2008, however, observers classified 19% of observed Chinese longline trips and 9·7% of FSM longline trips as having shark as the primary target species group. A smaller percentage of trips were reported to have used shark baits, and 28 and 23% of the Chinese and FSM observed trips, respectively, used shark lines (Table III). It is worth noting that in the most recent year (2009) observers did not report any use of shark baits or shark lines, and sharks were never reported as the primary target. The number of observed sets was, however, much lower in 2009, and since 2006, all sets used wire leaders. Spatially, shark lines were used throughout the fishery, while shark bait use is less commonly observed in the northernmost region (Fig. 3). Frequency histograms of total shark CPUE indicate that sets using either shark baits or shark lines, or where observers have listed shark as the target species, more frequently achieve higher catch rates of sharks (Fig. 4).

A comparison of observed catch rates and the proportion of sharks comprising the total catch (by discarded and retained numbers) at both set and trip levels demonstrates that some observed Chinese longline sets resulted in very high catch rates (*e.g.* >10 sharks per 1000 hooks) and proportion of sharks in the catch (*e.g.* >75%; Fig. 5). The highest CPUE was just over 40 sharks per 1000 hooks and a number of high CPUE sets reported only sharks in the catch. These figures are comparable to catch rates and shark proportions reported on logsheets by the vessels licensed to fish for sharks in 2002–2003. Regardless of whether the observed high catch rate sets were deliberately targeting sharks, it is clear that they fished in a manner which effectively targeted sharks. Very high trip level catch rates and shark proportions were not as evident for the FSM-flagged vessels.

FACTORS INFLUENCING CATCH RATES

The GAM time-area models indicate significant spatial and temporal variability in catch rates of different shark species in RMI (Table IV and Figs 6 and 7). *Prionace glauca* and *A. superciliosus* catch rates were estimated to be significantly higher

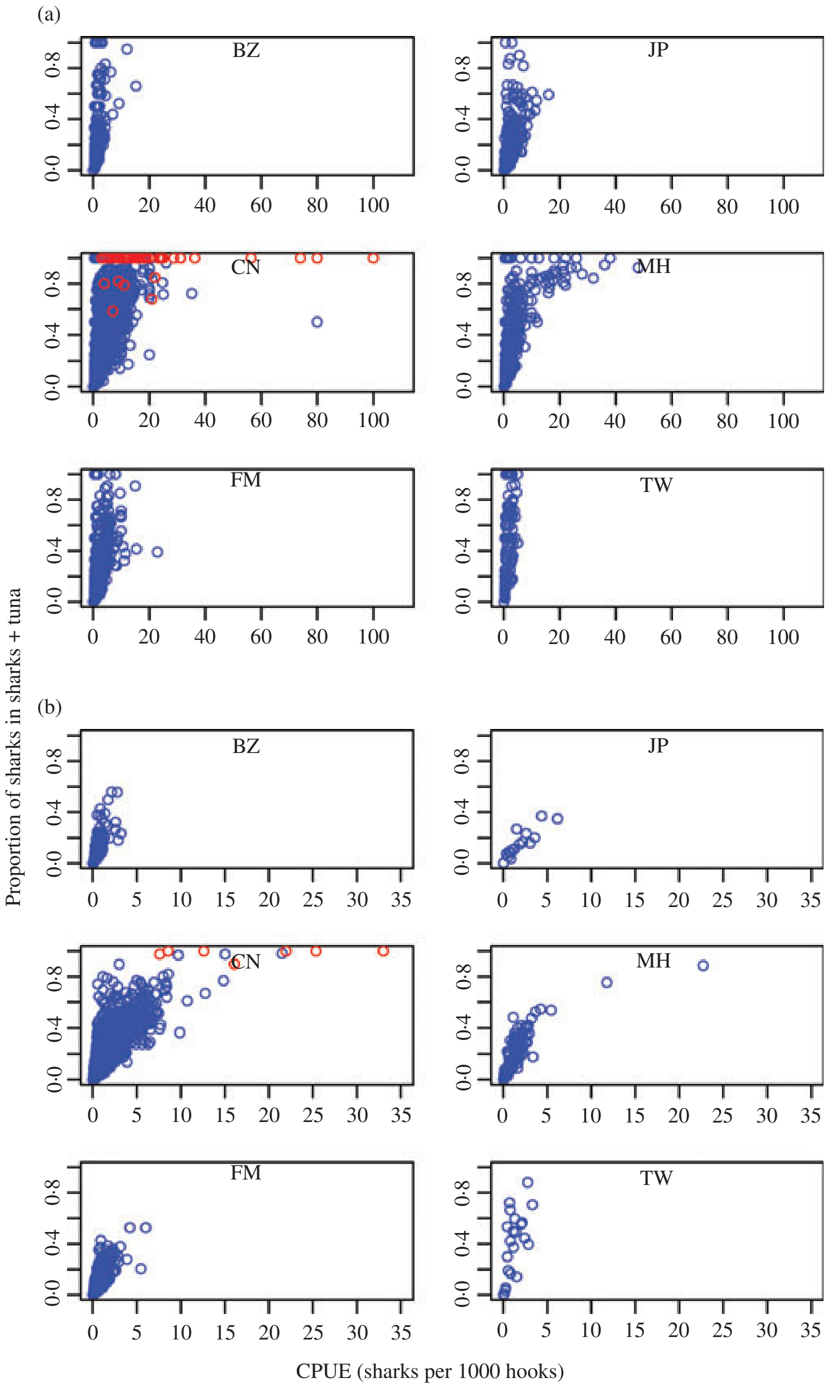

FIG. 2. Reported total shark catch per unit effort (CPUE) and proportion of sharks (of sharks + tuna) as reported on logsheets for longline fishing by (a) sets and (b) trips, for vessels licensed to fish for sharks (O) and vessels not licensed to fish for sharks (O) inside the Republic of the Marshall Islands (RMI) EEZ since 2000. BZ, Belize; CN, China; JP, Japan; FM, Federated States of Micronesia; MH, Marshall Islands; TW, Taiwan.

TABLE III. The number of sets by year in which wire leaders, shark baits or shark lines were used, or where the primary target species was listed as shark. Note that the total number of observed sets during this period is 1499, with 0·5% of these lacking data for baits and target species reporting, and 7·4% lacking data pertaining to whether or not wire leaders were used. Shark line use was reported for all sets

	Bait use		Shark listed as target		Shark lines		Wire trace used	
Year	Sets	%	Sets	%	Sets	%	Sets	%
2005	242	8	242	9	242	9	177	90
2006	621	3	621	9	621	19	581	99
2007	472	7	472	33	472	44	452	100
2008	90	0	90	26	90	58	90	100
2009	74	0	74	0	74	0	74	100

under El Niño climate conditions than under neutral conditions. Also, for *P. glauca*, catch rates were estimated to be significantly higher under El Niño climate conditions than under La Niña climate conditions. Strong seasonal (monthly) trends in catch rates were evident for *P. glauca* and *A. superciliosus*, with *P. glauca* catch rates higher in the period November to February, during which time *A. superciliosus* catch rates were relatively low.

The two most common species showed opposing spatial trends in catch rates. *Prionace glauca* catch rates were highest in the northern area of the fishery (latitudes 8–10° N), whereas *C. falciformis* catch rates were lowest in that area and higher in the central and southern areas (latitudes 2–9° N). *Alopias superciliosus* catch rates were highest around the northern Ratak Chain (*c*. 10° N; 172° E) and lowest closer to the equator (2–4° N), whereas *A. pelagicus* catch rates were highest between 4 and 10° N. *Carcharhinus longimanus* catch rates show significant spatial variation within the RMI EEZ. All five species show temporal trends in mean catch rates with observed catch rates increasing significantly for all species between 2005 and 2008, except for *A. superciliosus*. *Carcharhinus falciformis* and *C. longimanus* catch rates both dropped significantly in 2009.

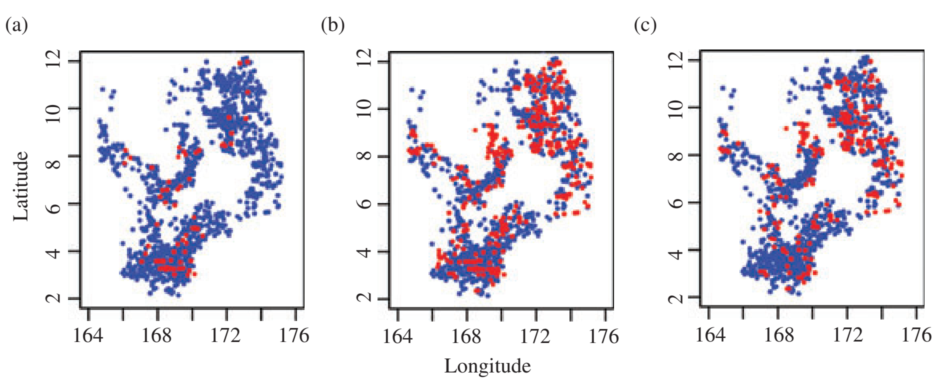

FIG. 3. Spatial distribution of sets (●) utilizing (a) shark baits, (b) shark lines or (c) where sharks were listed as the target species, 2005 to 2010. ●, sets not using these methods, and plotted 'under' ●.

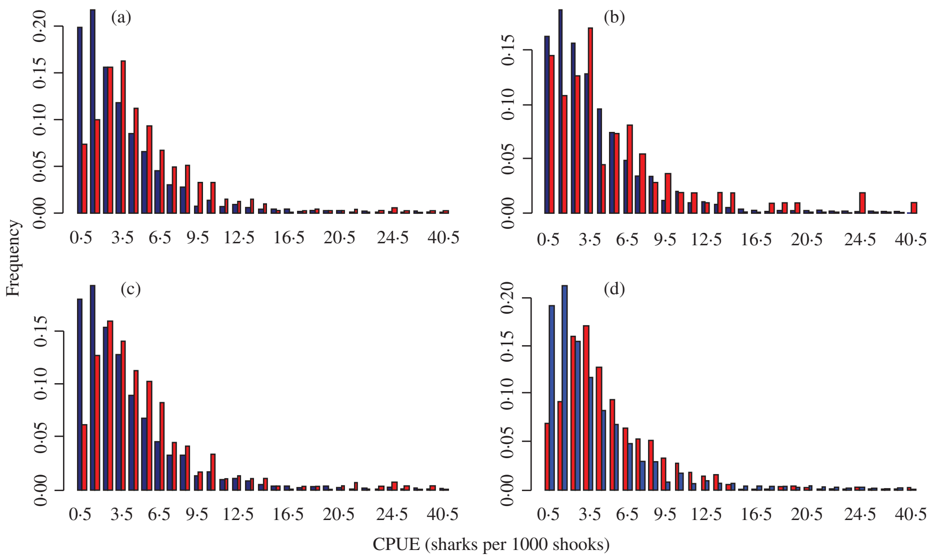

FIG. 4. Frequency distribution of catch per unit effort (CPUE) for observed longline sets where (a) at least one of the following shark targeting factors were recorded by the observer (shark baits, shark lines used or sharks listed as the primary target species), (b) shark baits were used (c) sharks were listed by the observer as the target species and (d) shark lines were used (■, the relative frequency of sets utilizing the specified shark targeting gear or method; ■, relative frequency of sets which did not utilize the specified shark targeting gear or method, *i.e.* sets that were not partly or fully targeting sharks).

Results from the causative factor models are presented in two parts. The statistical significance of each term (parameter) tested is summarized in Table V. Graphical descriptions of these relationships are provided in Fig. 8.

A statistically significant relationship was observed between catch rates of each species and numerous explanatory variables that were included in the causative factor models. The set of significant variables varied between species as did the nature of the relationships (Table V).

The *P. glauca* model [Table V and Fig. 8(a)] explained 29·8% of model deviance and indicated that *P. glauca* catch rates were highest when the sea surface temperature (SST) was relatively cool (*c*. 28° C), the 27° C thermocline was shallow, water depth was between 3500 and 5000 m, hooks were set very shallow (HBF < 10), fishing occurred close to the full moon and sets were made at night. Targeting factors (including shark lines and baits) were not significant.

The *C. falciformis* model [Table V and Fig. 8(b)] explained 23·5% of model deviance and indicated that *C. falciformis* catch rates were highest when the range of SST values in the fished area was high, the 27° C thermocline was shallow, hooks were set at shallower depths (*i.e.* HBF < 10), hooks were set at night and shark lines were used. A number of other factors were also significant (Table V).

The *A. superciliosus* model [Table V and Fig. 8(c)] explained 27·7% of model deviance and indicated that *A. superciliosus* catch rates were highest when SST was cooler (*c*. 27° C), the 27° C thermocline was shallow (*c*. 80 m), hooks were set during the period close to the full moon and SST range was low. A number of other factors were also significantly related to catch rates but the shape of those

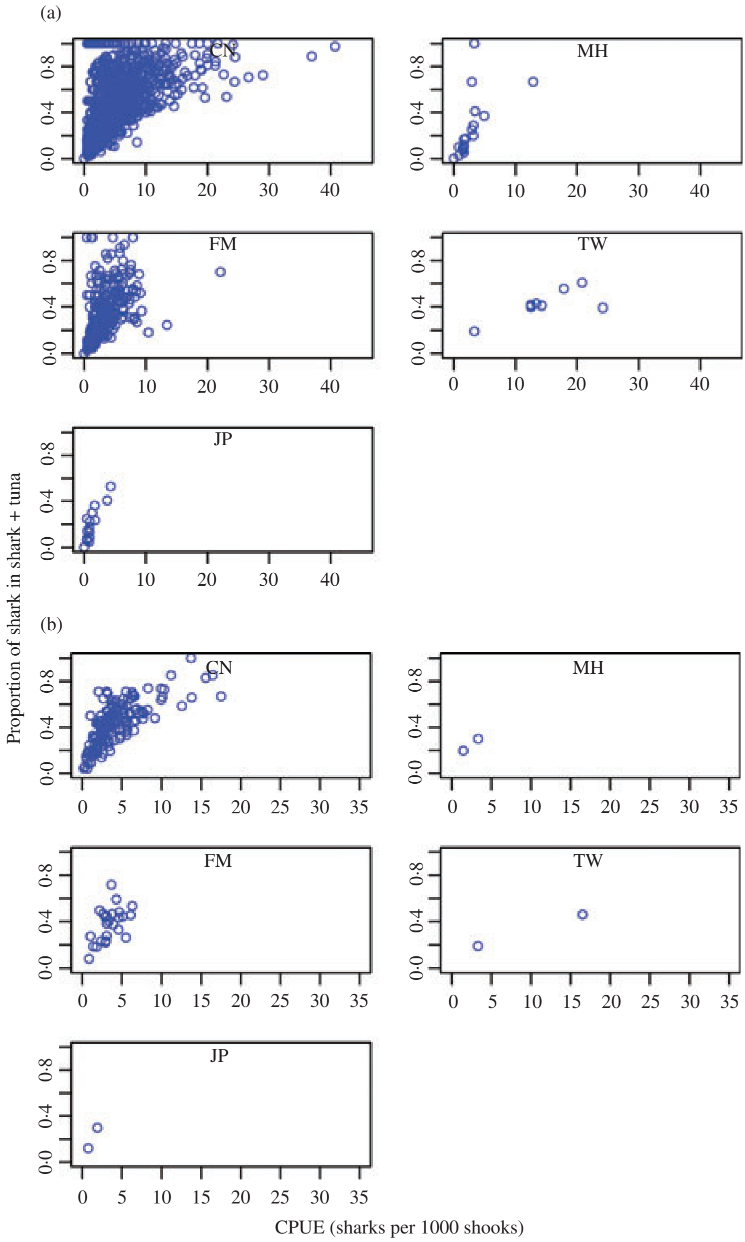

FIG. 5. Comparisons of total observed shark catch rates and observed proportion of sharks (of sharks + tuna) by flag for (a) set level and (b) trip level. CN, China; JP, Japan; FM, Federated States of Micronesia; MH, Marshall Islands; TW, Taiwan.

relationships [Fig. 8(c)] were typically more complex. None of the targeting factors were found to be significantly related to catch rates for this species.

The *A. pelagicus* model [Table V and Fig. 8(d)] explained 23·3% of model deviance and indicated that *A. pelagicus* catch rates were highest when SST was

TABLE IV. Model summary statistics derived from the generalized additive time-area models used to identify spatial and temporal factors influencing catch rates of the five most common shark species caught in the Republic of the Marshall Islands (RMI) longline fishery (*Prionace glauca*, *Carcharhinus falciformis*, *Alopias superciliosus*, *Alopias pelagicus* and *Carcharhinus longimanus*)

	P. glauca		*C. falciformis*		*A. superciliosus*		*A. pelagicus*		*C. longimanus*	
	F	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Month	6·4	<0·001	2·2	<0·05	8·8	<0·001	4·5	<0·001	4	<0·001
Year	4·1	<0·001	17	<0·001	4·9	<0·001	13·8	<0·001	8·6	<0·001
Latitude × longitude	14·2	<0·001	3·7	<0·001	10	<0·001	7·9	<0·001	2·7	<0·001
SOI (2+)	22·3	<0·001	3·9	<0·001	4·3	<0·001	6·4	<0·001	1·5	>0·05

SOI, Southern Oscillation Index.

relatively cool (*c*. 27° C), hooks were set shallow (<10 HBF), shark lines were used, fishing occurred relatively close to islands, atolls or other land features (<100 nm, <185·2 km) and SST range was high. A number of other factors were also significantly related to catch rates but the nature of those relationships [Fig. 8(d)] appears more complicated. For example, the significant moon phase effect suggests multiple high or low catch rate periods at different phases of the moon.

The *C. longimanus* model [Table V and Fig. 8(e)] explained 38·5% of model deviance and indicated that catch rates were highest when hooks were set shallow (<10 HBF), shark lines were used and the depth of the 27° C thermocline was relatively shallow. Other factors were more weakly significant, including SST, distance to nearest seamount and the number of seamounts in the area (Table V).

Model diagnostics suggested that the model outputs for the two least commonly caught species (*C. longimanus* and *A. pelagicus*) should be interpreted with more caution, and further exploration of these models is suggested.

DISCUSSION

DATA COVERAGE

When developing fisheries advice, the data used must be representative of the processes that the managers wish to understand and control. The results presented here indicate that logsheet reporting of shark catches by longline vessels in RMI has been inconsistent and inaccurate across a substantial proportion of the fleet. This problem is common across WCPO tuna fisheries, and many factors can contribute to it, including fishers' inability to distinguish between shark species, lack of requirement for reporting in licensing agreements and fishers simply not prioritizing non-target catch reporting, for economic or logistical reasons (Nakano & Clarke, 2006). Reporting should improve, however, if RMI and other Commission members are able to implement the mandatory reporting of shark catches and discards that was recently approved (see http://www.wcpfc.int/doc/data-01/scientific-data-be-provided-commission-revised-wcpfc4-wcpfc6/).

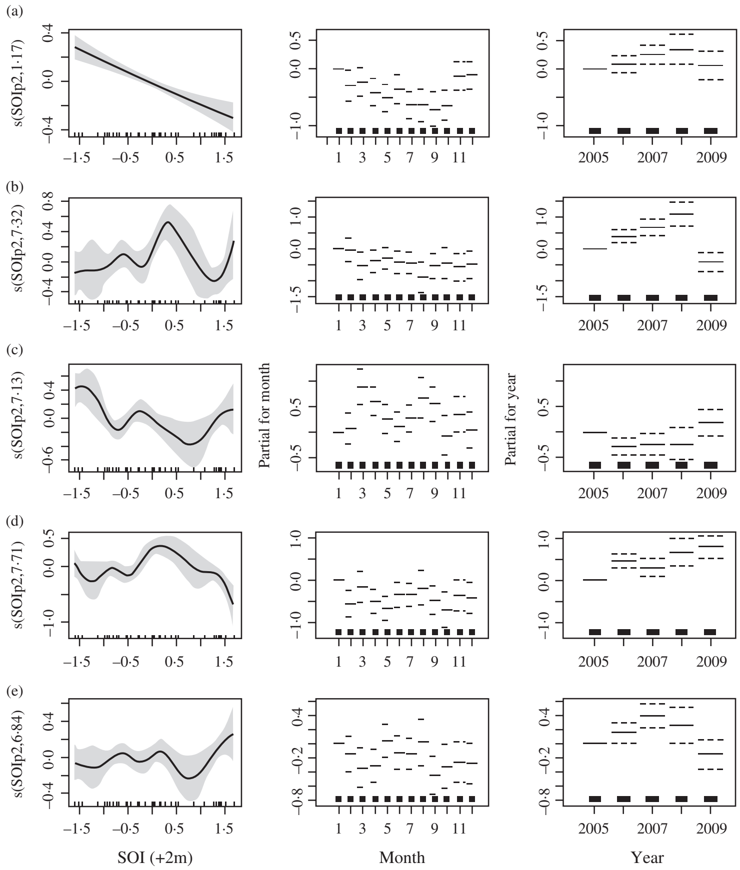

FIG. 6. The relative effect of climate state (proxied by the Southern Oscillation Index, SOI), month and year upon catch rates of each of five shark species: (a) *Prionace glauca*, (b) *Carcharhinus falciformis*, (c) *Alopias superciliosus*, (d) *Alopias pelagicus* and (e) *Carcharhinus longimanus* as estimated by generalized additive models (GAMs). The GAMs are based on longline catch per unit effort data as recorded by observers within the RMI EEZ. The relative influence of climate state is indexed by a 2 month phase shifted SOI with SOI values <1 approximating El Niño conditions and >1 approximating La Niña conditions. The shaded region represents twice the point-wise asymptotic standard errors (2 S.E.) of the estimated curve. For categorical variables, parameters are estimated relative to the first category. The relative density of data points is shown by the 'rug' on the *x*-axis. The *x*-axis of each plot is labelled with the covariate name (*e.g.* month year or SOI), while the *y*-axis label includes the covariate name followed by a number indicating the estimated d.f. of the smooth. The smoothed plots allow the nature of the relative relationship between each covariate and shark catch rates to be visualized.

Due to the inability to rely on logsheet data, this study has focused predominantly on observer data. Coverage rates have averaged 5–6% on two of the main longline fleets (China and FSM) in recent years but have been at or near zero on the other longline fleets, meaning that shark interactions in the latter fleets remain virtually unknown. Future placement of observers on these fleets (ideally to the minimum 5% level mandated by the Commission before June 2012) will be required to validate catches and to assess the effects of the longline fishery on shark populations.

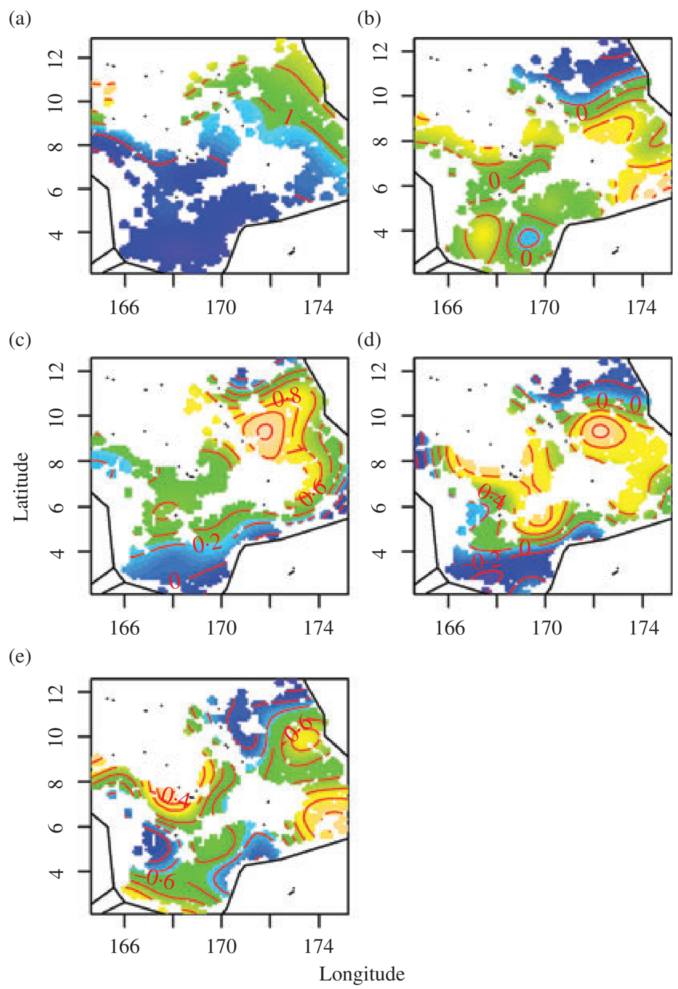

FIG. 7. The relative relationship between latitude and longitude with catch rates of (a) *Prionace glauca*, (b) *Carcharhinus falciformis*, (c) *Alopias superciliosus*, (d) *Alopias pelagicus* and (e) *Carcharhinus longimanus* caught by Chinese and Federated States of Micronesia (FSM) longliners in the Republic of the Marshall Islands (RMI) EEZ, as estimated by generalized additive models (GAMs) utilizing observer data collected in RMI between 2005 and 2010. Relative catch rates are shown: ■, the areas with highest catch rates; ■ the areas with the lowest catch rates; ■, intermediate catch rate areas. Note that the spatial variance in catch rates is estimated independently for each species and hence the colours plotted above cannot be meaningfully compared between species.

Fortunately, with the majority of recent longline effort in RMI attributable to China and FSM vessels, the analyses of observer data from these fleets are highly relevant to the management of the fishery as a whole.

FLEET OPERATION

The main recent change in fleet operation was the shift from shallow night sets to deeper day sets targeting *T. obesus*. This was evidenced by the virtual doubling of the

TABLE V. Model summary statistics derived from generalized additive causative factor (see Table I) models used to identify factors influencing catch rates of the five most common shark species caught in the RMI longline fishery (*Prionace glauca*, *Carcharhinus falciformis*, *Alopias superciliosus*, *Alopias pelagicus* and *Carcharhinus longimanus*)

	P. glauca		*C. falciformis*		*A. superciliosus*		*A. pelagicus*		*C. longimanus*	
	F	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Bait	−1·7	>0·05	1·5	>0·05	−0·2	>0·05	1·45	>0·05	1·1	>0·05
Shk_line	0·6	>0·05	4·6	<0·001	−0·2	>0·05	3·88	<0·001	10·7	<0·001
Target	1·2	>0·05	3	<0·001	−0·2	>0·05	−2·9	<0·01	1·3	>0·05
SST	11	<0·001	—	—	38·15	<0·001	31·4	<0·001	3·49	<0·001
SST_Range	—	—	12	<0·001	9·6	<0·001	3·8	<0·001	0·02	>0·05
Depth27C	6·1	<0·001	4·3	<0·001	13	<0·001	3·7	<0·001	7·6	<0·001
Land_Distance	—	—	—	—	4·5	<0·001	5·4	<0·01	2	>0·05
Set time	2·7	<0·05	4·3	<0·001	—	—	—	—	2·2	>0·05
Depth	4·5	<0·001	4·3	<0·001	4·1	<0·001	2·8	<0·01	3·6	<0·05
Moon Phase	14·9	<0·001	4·2	<0·001	12·2	<0·001	12·4	<0·001	1·9	>0·05
NOSM	1·6	>0·05	3·2	0·001	2·8	<0·01	1·4	>0·05	3·3	<0·01
HooksBF	8·8	<0·001	3·1	<0·01	7	<0·001	6·2	<0·001	31·9	<0·001
Dist_seamount	—	—	—	—	—	—	—	—	5·7	<0·05

median number of hooks per set and the median number of hooks between mainline floats, the switch to morning sets after 2004 in most of the major fleets, anecdotal reports (*i.e.* from observers) and target tuna species catch composition changes. As discussed below, such major changes in fishing strategy might be expected to affect catch rates of sharks, depending on the vertical habitat range of each species.

CATCH CHARACTERIZATION

Total annual shark catch by the longline fishery in RMI remains uncertain due to the data reporting and coverage issues mentioned above. Two alternative estimates were calculated to include all sharks caught, whether retained or discarded. These estimates should thus represent estimates of the effective biomass removal from the shark populations. A separate analysis of catches taken by the purse seine fishery in RMI indicated that catches by that sector comprise 98% *C. falciformis*, but constitute only *c.* 11 t year^{-1} (SPC, 2011). This suggests that management actions to reduce overall fishing mortality on pelagic sharks in RMI will be most effective if focused on the longline fishery.

Observers have identified 22 species of sharks and rays caught in the longline fishery in the RMI EEZ. Given the relatively low coverage of the observer data, this is likely to be an underestimate, with rarer species less likely to have been observed. Most of the 13 species currently listed as ‘key species’ by the WCPFC (Clarke *et al.*, 2011) were, however, caught in RMI. Two species caught in RMI (*S. lewini* and *S. mokarran*) are listed as endangered by the IUCN and seven more [*A. superciliosus*, *A. pelagicus*, *C. longimanus*, *I. oxyrinchus*, *I. paucus*, *A. vulpinus* and sandbar shark *Carcharhinus plumbeus* (Nardo 1827)] as vulnerable. Whale sharks *Rhincodon typus* Smith 1828, caught in the purse seine fishery, are listed under CITES and CMS. WCPO assessments do not exist for any of these species, but some are planned

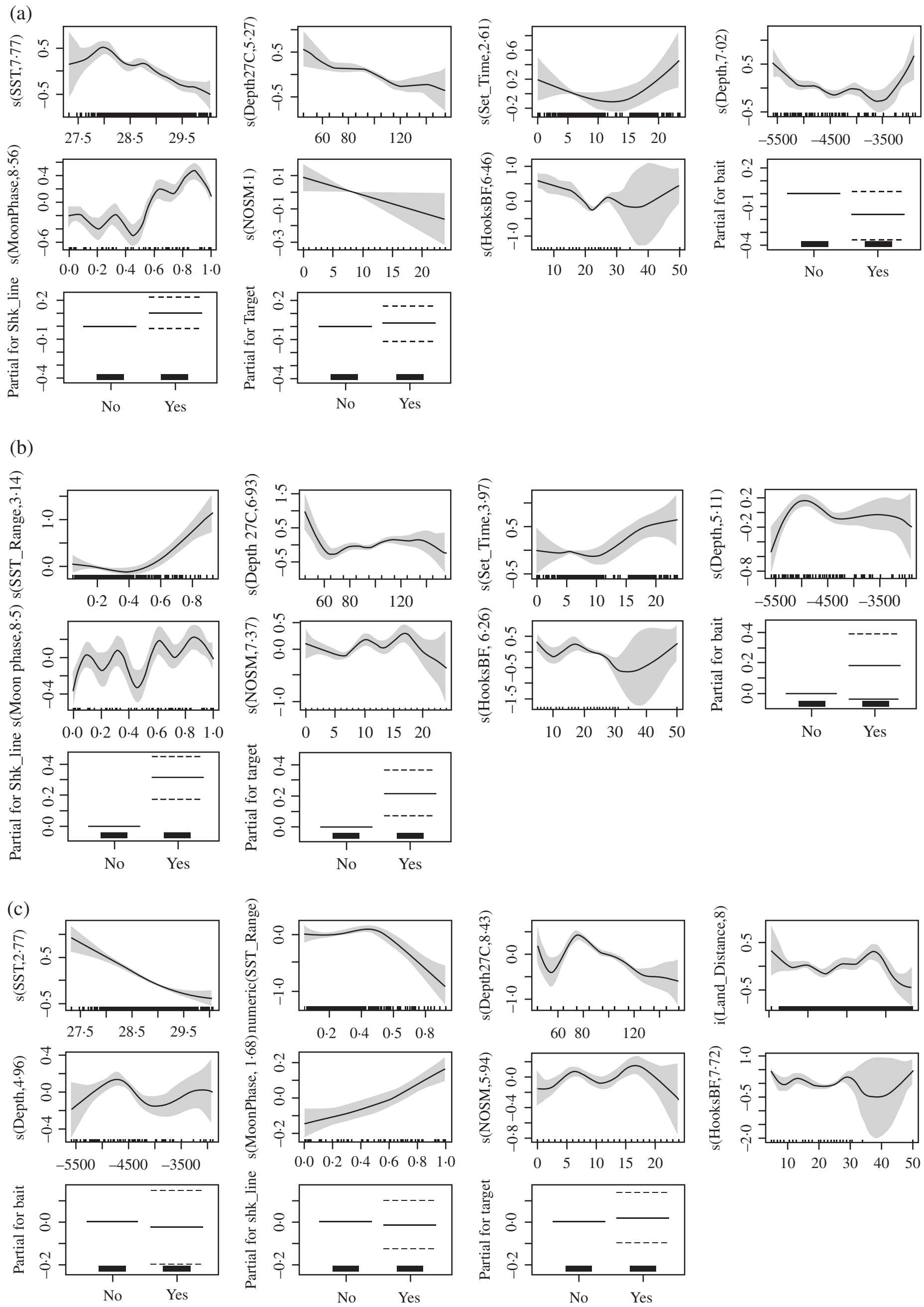

FIG. 8. The relative effect of environmental and fishing method factors (see Tables I and V) upon catch rates of (a) *Prionace glauca* (b) *Carcharhinus falciformis*, (c) *Alopias superciliosus*, (d) *Alopias pelagicus* and (e) *Carcharhinus longimanus* as estimated by generalized additive models (GAM). The shaded region represents twice the point-wise asymptotic standard errors (2 S.E.) of the estimated curve. For categorical variables, parameters are estimated relative to the first category. The relative density of data points is shown by the 'rug' on the *x*-axis. The *y*-axis label includes the covariate name (see Table I) followed by a number indicating the estimated d.f. of the smooth (for continuous variables).

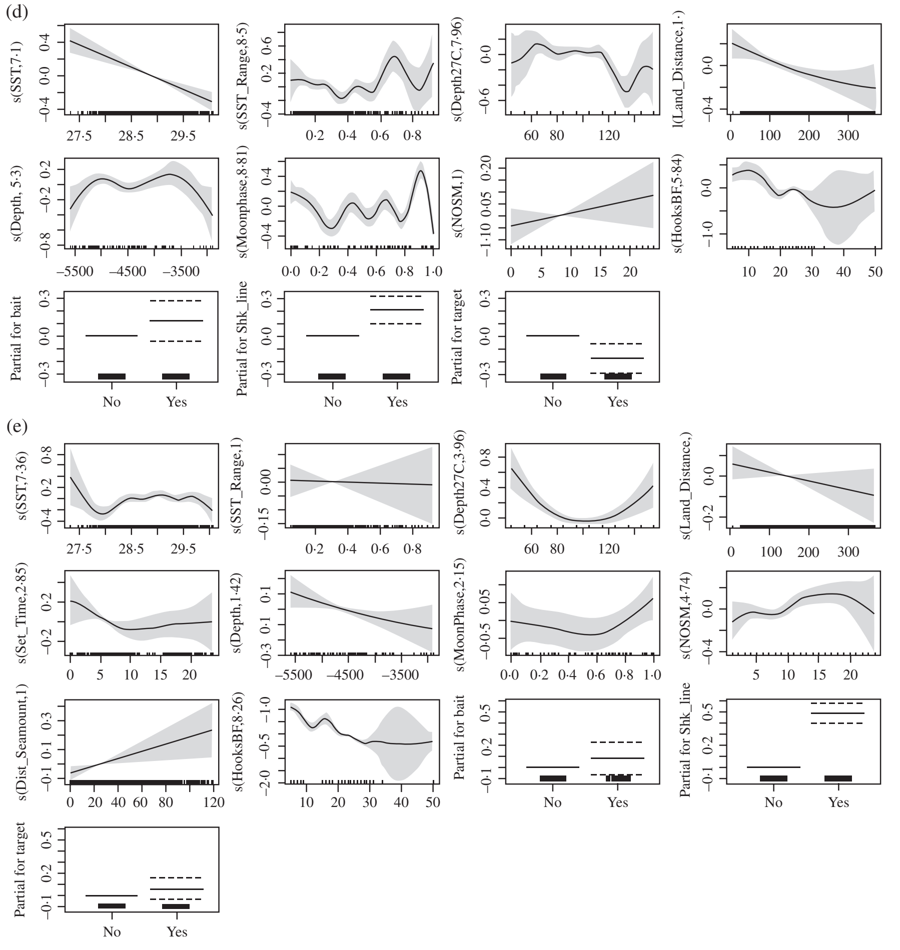

FIG. 8. Continued

to commence soon under the new WCPFC Shark Research Programme (Clarke & Harley, 2010).

A key consideration in the management of sharks is the condition (life status) and fate (*i.e.* retained, finned or discarded whole) of each of the species caught. Observer data indicate substantial interspecific variability in the percentage of sharks alive when hauled onto the deck, although the uncertainty associated with those statistics may be high for the less common species, given the relatively low sample size. Only two of the common species (*C. falciformis* and *C. longimanus*) are usually retained, whereas the remainder of shark species are usually discarded, mostly finned and therefore effectively dead. The implications of these trends for management of shark interactions are discussed below.

TARGETING INDICATORS

In Pacific Island longline fisheries and indeed globally, there is a significant incentive for fishers to target sharks (*via* direct targeting or in conjunction with tuna sets) due to the significant value of and demand for shark fins in Asia, particularly China (Clarke *et al.*, 2007). Accurate estimates of the total level of targeting of sharks by vessels licensed to fish for tuna in RMI during the period examined were not possible, however, due to the poor reporting rates for sharks on logsheets (noted earlier) and the low level of observer coverage, even on the main observed fleets. It may be assumed that vessels are unlikely to report fishing practices contrary to their licenses, or to fish in that manner when observers are present. Those assumptions, however, have been proven to be at least partly incorrect in this particular fishery.

Data on shark catch rates, proportions of sharks to tunas and the use of shark baits and shark lines indicate that some vessels within the longline fleet fishing in RMI have targeted sharks. Few trips achieved shark catch rates and shark proportions similar to those of vessels licensed to fish for sharks, but those that did are likely to have actively targeted sharks. This is because vessels targeting tuna will generally avoid areas where initial sets indicate high shark abundance as it results in lost or damaged tuna catch.

Analysis of observer data identified a number of sets and trips whose catch rates and catch proportions of sharks were similar to those of vessels licensed to target shark. Analysis of gear characteristics also suggested that mixed targeting (targeting both shark and tuna simultaneously through the use of shark baits on some hooks and shark lines) was relatively common until at least 2009. Most observed vessels used wire leaders [which, while used in targeting tuna, also increase shark catch rates (Ward *et al.*, 2008)], while 28, 23 and 5% of China, FSM and RMI observed sets, respectively, used shark lines and a smaller percentage used shark baits. Shark line and bait use percentages dropped to 0% in 2009, but it is uncertain if this only reflects a smaller sample of sets available for analysis or a broader fishery trend.

FACTORS INFLUENCING CATCH RATES

Results from statistical models developed to identify factors influencing the catch rates of shark by longline fisheries in RMI were generally consistent with previous research findings regarding the habitat, biology and behaviour of the five species examined.

The two cooler water species with greater depth ranges (*P. glauca* and *A. pelagicus*), both of which show night time vertical migrations (Nakano *et al.*, 2003, Weng & Block, 2004), are caught in higher numbers when vessels fish in relatively cooler waters at night, close to the full moon and when the 27° C thermocline is close to the surface (bringing cooler water habitat closer to the surface). As cooler surface waters occur in the northern part of the fishery and warmer surface waters in the central and southern parts of the fishery, the results for *P. glauca* and *C. falciformis* from the time-area models are consistent with those of the causative factor models. The higher catch rates of *P. glauca* and *A. superciliosus* predicted under El Niño conditions (when warm pool waters move to the south and east of RMI) are also consistent with the predicted higher catch rates in cooler waters from the causative factor model.

Similarly, results for shallow water species (*C. falciformis*, *A. pelagicus* and *C. longimanus*) show that these species are caught in higher numbers when shark lines are used (all three species) or hooks are set shallow (*A. pelagicus* and *C. longimanus* only). Shallow set hooks were also significantly related to increased catch rates of *P. glauca*, with this likely to be accentuated on night sets when *P. glauca* are closer to the surface or in cooler northern surface waters. It should be noted that shallow and night time sets have been much less common since 2004. The use of shark lines and baits persisted, however, until at least 2008 and wire traces in 2009 also.

Most species were found to have at least one catch rate relationship apparently unique to that species. For example, *P. glauca* catch rates were estimated to be higher in areas without seamounts, *C. falciformis* catch rates are higher when SST range is high (which is suggestive of convergence zones) and *A. pelagicus* catch rates are higher near land features (*e.g.* atolls and islands). Some statistically significant relationships appear more complex and are difficult to explain, such as the relationship between catch rates and bathymetric depth (most species), and for *A. pelagicus*, the relationships between catch rates and SST range, moon phase and HBF. This may indicate that the data were over-dispersed and/or that the models were over-parameterized. Therefore, further work is needed to understand and test the causative mechanisms underlying the identified relationships.

MANAGEMENT IMPLICATIONS

These analyses provide information relevant to the assessment of management options which RMI may consider implementing as a means of reducing shark mortalities in the longline fishery. For example, RMI may consider implementing in its own national waters the WCPFC prohibition on finning as written or it may implement an alternative measure. A key assumption is that the available observer data are representative of the main fleets and of the interaction between the fishery, the sharks and the environment. Furthermore, as not all fleets had observer coverage, this discussion assumes that the fleets which were observed are similar to those which were not. Ideally, observer coverage rates for all fleets would be higher in order to increase confidence regarding the representativeness of the data.

Time and area options

The five main shark species differed in the times and areas of their fisheries interactions. For example, the two most commonly encountered species, *P. glauca* and *C. falciformis*, have almost directly opposing spatial catch rate patterns, with *P. glauca* catch rates highest in the northern area and *C. falciformis* catch rates highest in the central and southern areas of the fishery. It may therefore be impractical to use time-area closures to reduce mortalities for all shark species without closing very large areas of the fishery. Large closures would restrict fleet access to preferred tuna fishing grounds and increase competition in areas which are not closed. Under such a scenario, lower catches of one or more shark species would likely be offset by increased catches of other species, due to the redistribution of fishing effort and differing distributions of the shark species (*e.g. C. falciformis* and *P. glauca*). Such measures might be more practical if they were designed to reduce catches for a single species or a sub-set of similar species.

Finning ban

Most *C. falciformis* and *C. longimanus* are retained by longliners in RMI, but the other shark species are generally finned and discarded. Under the assumption that the desirability of retaining sharks for reasons other than for their fins remains low, banning the practice of shark finning would probably increase the discard rate. If so, such a ban would probably reduce mortality rates for *P. glauca* in particular because 80% are in a healthy condition when first hauled. A finning ban would have less of an effect on the mortality of *Alopias* spp. as only 36–50% are alive when first hauled to vessel.

No retention

In addition to a finning ban which, as discussed above, already applies in some parts of the WCPFC, a supplemental management measure could involve banning the retention of certain species of sharks either whole or in part. Therefore, the effect of a no retention measure would be expected to increase discard rates beyond those observed under a finning ban alone. As for the finning ban, under this scenario, species which are relatively healthy when first hauled to the side of the vessel will benefit most. These species include *P. glauca* (80% alive at hauling) and *C. falciformis* (70% alive at hauling). Other species, such as *Alopias* spp., which have lower survival rates at hauling (36–50%), would be expected to benefit to a lesser extent. For all management options which potentially act to increase discard rates, the actual reduction in mortality will depend on the post-release survival rates of various species. Some studies of post-release mortality have been conducted (Moyes *et al*., 2006; Campana *et al*., 2009*a*, *b*; Musyl *et al*., 2009), but the results vary widely and more research is required to understand the factors which influence these rates for different species and in different fisheries.

Gear and method restrictions

Banning the use of shark lines (shallow lines deployed off the mainline floats) would reduce catch rates of shallow habitat shark species, in particular *C. falciformis* and *C. longimanus* and to a lesser extent, *A. pelagicus*. The use of shark baits is less commonly reported by observers, but the models suggest that banning shark bait may assist in reducing *C. falciformis* catch rates in particular. Wire leader usage was almost 100% in this study and so its effect on shark catch rates could not be estimated. Given the evidence, however, that use of wire leaders substantially increases shark catch rates (Ward *et al*., 2008), and its high prevalence in RMI longline fisheries, banning the use of wire leaders may significantly reduce shark catches.

Restricting the use of shark lines is unlikely to affect catch rates for target tunas, whereas restricting the use of shark baits might increase tuna catch rates by increasing the number of hooks baited for tunas. The widespread use of wire leaders throughout the fishery may be due to a belief amongst fishers that it will increase tuna catch rates. If fishers are using wire leaders to target species other than sharks, then a finning ban might decrease the incentive to catch sharks but would be unlikely to result in reduced usage of wire leaders. Ward *et al*. (2008) found no evidence to support increased catch rates of *T. obesus* on hooks using wire leaders.

Other factors relating to longline fishing gear and methods (*e.g.* set depth and time of day) were related to shark catch rates, but the model results were mixed, effects varied between species, and these factors offer less potential for effective management actions without substantially affecting tuna catches.

Combined measures

Overall, the most effective measure for minimizing shark mortalities in the RMI longline fishery would be to combine measures that reduce the interaction rate (*e.g.* restrictions or bans on the use of wire leaders, shark baits and shark lines) with measures that increase the survival rates after capture (finning bans or bans on retention of any part of the shark). Indeed the latter measure by itself might remove incentives to use shark targeted gears (shark baits and shark lines) but is unlikely to remove incentives to use wire leaders in situations where this gear is desirable when fishing for tuna. The overall effectiveness of a combined measure appears to depend to a great extent on the post-release survival of sharks, which is largely unknown, but likely to vary between species.

FUTURE RESEARCH AND MANAGEMENT

The model diagnostics for the two least common species examined here, *C. longimanus* and *A. pelagicus*, were relatively poor due to the large number of zero catch records for these species. As such, results for these two species should be verified in future using more specialized models for zero inflated catch data. In addition, interactions require further investigation. For example, preliminary analyses of *A. superciliosus* indicated that catch rates were highest on shallow night sets and deep day sets consistent with this species' movement pattern of swimming closer to the surface at night than during the day (Nakano *et al*., 2003; Weng & Block, 2004). Seasonal catch rate trends for some species (*e.g. C. falciformis*) differed between areas within the RMI EEZ, which could indicate seasonal shifts in distribution. Finally, the catch estimates could be improved in future once more observer data are collected, once vessels start reporting catches of sharks as required under the recently amended WCPFC data provisions and upon application of a more detailed statistical approach to estimate uncertainty [*e.g.* bootstrapping or techniques developed by Lawson (2011)].

On the basis of existing information and growing concerns about shark management and conservation, the RMI Government plans to incorporate information derived from these analyses into their consideration of stronger regulations aimed at reducing the mortality of sharks in its waters. As of the time of writing, RMI had banned trade in shark fins (Marianas Variety, 2011) and was considering other possible measures, including a permanent legislative ban on shark finning to reduce shark by-catch in the RMI longline fishery (Marshall Islands Journal, 2011).

The authors wish to thank P. Williams, E. Schneiter, S. Caillot, V. Allain and C. Millar for providing data and database assistance and G. Joseph for reviewing a draft of the paper.

References

Baum, J. K. & Myers, R. A. (2004). Shifting baselines and the decline of pelagic sharks in the Gulf of Mexico. *Ecology Letters* **7,** 135–145.

Baum, J. K., Myers, R. A., Kehler, D. G., Worm, B., Harley, S. J. & Doherty, P. A. (2003). Collapse and conservation of shark populations in the Northwest Atlantic. *Science* **299,** 389–392.

Camhi, M. D., Pikitch, E. K. & Babcock, E. A. (2008). *Sharks of the Open Ocean: Biology, Fisheries and Conservation.* Oxford: Blackwell.

Campana, S. E., Joyce, W. & Manning, M. J. (2009*a*). Bycatch and discard mortality in commercially caught blue sharks *Prionace glauca* assessed using archival satellite pop-up tags. *Marine Ecology Progress Series* **387,** 241–253.

Campana, S. E., Joyce, W., Francis, M. P. & Manning, M. J. (2009*b*). Reply Comment: comparability of blue shark mortality estimates for the Atlantic and Pacific longline fisheries. *Marine Ecology Progress Series* **396,** 161–164.

Clarke, S., Milner-Gulland, E. J. & Bjorndal, T. (2007). Social, economic and regulatory drivers of the shark fin trade. *Marine Resource Economics* **22,** 305–327.

Cortés, E., Arocha, F., Beerkircher, L., Carvalho, F., Domingo, A., Heupel, M., Holtzhausen, H., Neves, M., Ribera, M. & Simpfendorfer, C. (2010). Ecological risk assessment of pelagic sharks caught in Atlantic pelagic longline fisheries. *Aquatic Living Resources* **23,** 25–34.

Ferretti, F., Worm, B., Britten, G. L., Heithaus, M. R. & Lotze, H. K. (2010). Patterns and ecosystem consequences of shark declines in the ocean. *Ecology Letters* **13,** 1055–1071.

Moyes, C. D., Fragoso, N., Musyl, M. K. & Brill, R. W. (2006). Predicting postrelease survival in large pelagic fish. *Transactions of the American Fisheries Society* **135,** 1389–1397.

Musyl, M. K., Moyes, C. D., Brill, R. W. & Fragoso, N. M. (2009). Factors influencing mortality estimates in post-release survival studies: comment on Campana *et al*. (2009). *Marine Ecology Progress Series* **396,** 157–159.

Nakano, H. & Clarke, S. (2006). Filtering method for obtaining stock indices by shark species from species-combined logbook data in tuna longline fisheries. *Fisheries Science* **72,** 322–332.

Nakano, H., Matsunaga, H., Okamoto, H. & Okazaki, M. (2003). Acoustic tracking of bigeye thresher shark *Alopias superciliosus* in the eastern Pacific Ocean. *Marine Ecology Progress Series* **265,** 255–261.

Polovina, J. J., Abecassis, M., Howell, E. A. & Woodworth, P. (2009). Increases in the relative abundance of mid-trophic level fishes concurrent with declines in apex predators in the subtropical North Pacific, 1996–2006. *Fisheries Bulletin* **107,** 523–531.

Sibert, J., Hampton, J., Kleiber, P. & Maunder, M. (2006). Biomass, size, and trophic status of top predators in the Pacific Ocean. *Science* **314,** 1773–1776.

SPC (2011). *National Tuna Fishery Status Report for the Republic of the Marshall Islands.* Noumea: Secretariat of the Pacific Community.

Ward, P., Lawrence, E., Darbyshire, R. & Hindmarsh, S. (2008). Large-scale experiment shows that nylon leaders reduce shark bycatch and benefit pelagic longline fishers. *Fisheries Research* **90,** 100–108.

Weng, K. C. & Block, B. A. (2004). Diel vertical migration of the bigeye thresher shark (*Alopias superciliosus*), a species possessing orbital retia mirabilia. *Fishery Bulletin* **102,** 221–229.

Electronic References

Clarke, S. & Harley, S. (2010). *A Proposal for a Research Plan to Determine the Status of the Key Shark Species. WCPFC-SC6-2010/EB-WP-01*. Available at http://www.wcpfc.int/node/2950/ (accessed 14 August 2011).

Clarke, S., Protoy, L., Harley, S. & Williams, P. (2011). *A Progress Report on the Shark Research Plan Including a Summary of the New Shark Tagging Meta-database and the Outlook for the Upcoming Stock Assessments*. *WCPFC-SC7-2011/EB-IP-01*. Available at http://www.wcpfc.int/doc/eb-ip-01/progress-report-shark-research-plan-including-summary-new-shark-tagging-meta-database-a/ (accessed 14 August 2011).

FISHSTAT (2011). *FishStat Plus - Universal Software for Fishery Statistical Time Series*. Rome: FAO Fisheries and Aquaculture Department. Available at http://www.fao.org/fishery/statistics/software/fishstat/en/ (accessed 14 August 2011).

Lawson, T. (2011). *Estimation of Catch Rates and Catches of Key Shark Species in Tuna Fisheries of the Western and Central Pacific Ocean using Observer Data*. *WCPFC-SC7-2011/EB-IP-02*. Available at http://www.wcpfc.int/doc/eb-ip-02/estimation-catch-rates-key-shark-species-tuna-fisheries-western-and-central-pacific-oce/ (accessed 14 August 2011).

Marianas Variety (2011). *Shark Fin, Sea Cucumber Exports Banned in Marshalls.* 4 March 2011. Available at http://www.mvariety.com/2011030334782/local-news/shark-fin-sea-cucumber-exports-banned-in-marshalls.php/ (accessed 14 August 2011).

Marshall Islands Journal (2011). *Shark Finning to be Banned? 10 June 2011*. Available at http://www.marshallislandsjournal.com/Archive%206-10-11-page.html/ (accessed 14 August 2011).

SPC. (2008). *Estimates of Annual Catches in the WCPFC Statistical Area (WCPFC–SC4–2008/ST–IP–1)*. Available at http://www.wcpfc.int/sc4/pdf/SC4-STIP1%20Annual%20Catch%20Estimates.pdf/ (accessed 14 August 2011).

Williams, P. & Terawasi, P. (2011). *Overview of Tuna Fisheries in the Western and Central Pacific Ocean, Including Economic Conditions – 2010. WCPFC-SC7-2011-GN-WP-01.* Available at http://www.wcpfc.int/doc/gn-wp-01/overview-tuna-fisheries-western-and-central-pacific-ocean-including-economic-conditions/

