Abundance or artefact? Explaining anomalies in long-term CPUE indices of sharks retained by pelagic longline fisheries (#21432)

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Abundance or artefact? Explaining anomalies in long-term CPUE indices of sharks retained by pelagic longline fisheries

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Pelagic longline fisheries directed mainly at tunas and swordfish frequently catch sharks, which can be retained and reported along with primary target species, or discarded overboard, mostly unreported. The assumption of a proportional relationship between catch-per-unit-effort (CPUE) data based on retained sharks, and shark abundance on fishing grounds, is therefore tenuous. We asked whether known changes in retention practices, resulting from regulatory changes and operational decisions, would be visible as anomalies in CPUE indices constructed from commercial logbook data. As a case study, we analysed data obtained from South African local and foreign-flagged longline fleets operating in the Southeast (SE) Atlantic and Southwest (SW) Indian Oceans between 2000 and 2015. A generalized linear mixed modelling (GLMM) framework was used to construct standardized CPUE indices for blue sharks *Prionace glauca* and shortfin makos *Isurus oxyrinchus* reported by the two fleets, accounting for the random effects of individual vessels (gear and fishing method), subregion and season. Shark catch rates were much higher for local- than foreign-flagged vessels, blue sharks were more abundant than shortfin makos, and both species were more abundant in the SE Atlantic than the SW Indian Ocean. A steep increase in the shortfin mako CPUE index in 2004 was ascribed to expanding fishing grounds and higher retention rates, to supply increased demand after 2003, rather than higher abundance. A second steep increase in shortfin mako and blue shark indices in 2011 coincided with a restructuring of the fishing sector, bringing formerly shark-directed vessels into the local pelagic longline fleet. Standardized CPUE indices based on retained sharks were not reliable indices of abundance, but could clearly identify increases in shark retention rates in a post hoc correlation with known operational and regulatory changes.

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Abstract

Pelagic longline fisheries directed mainly at tunas and swordfish frequently catch sharks, which can be retained and reported along with primary target species, or discarded overboard, mostly unreported. The assumption of a proportional relationship between catch-per-unit-effort (CPUE) data based on retained sharks, and shark abundance on fishing grounds, is therefore tenuous. We asked whether known changes in retention practices, resulting from regulatory changes and operational decisions, would be visible as anomalies in CPUE indices constructed from commercial logbook data. As a case study, we analysed data obtained from South African local and foreign-flagged longline fleets operating in the Southeast (SE) Atlantic and Southwest (SW) Indian Oceans between 2000 and 2015. A generalized linear mixed modelling (GLMM) framework was used to construct standardized CPUE indices for blue sharks *Prionace glauca* and shortfin makos *Isurus oxyrinchus* reported by the two fleets, accounting for the random effects of individual vessels (gear and fishing method), subregion and season. Shark catch rates were much higher for local- than foreign-flagged vessels, blue sharks were ~~more abundant~~ than shortfin makos, and both species were ~~more abundant~~ in the SE Atlantic than the SW Indian Ocean. A steep increase in the shortfin mako CPUE index in 2004 was ascribed to expanding fishing grounds and higher retention rates, to supply increased demand after 2003, rather than higher abundance. A second steep increase in shortfin mako and blue shark indices in 2011 coincided with a restructuring of the fishing sector, bringing formerly shark-directed vessels into the local pelagic longline fleet. Standardized CPUE indices based on retained sharks were not reliable indices of abundance, but could clearly identify increases in shark retention rates in a post hoc correlation with known operational and regulatory changes.

Key words: Fishery management; ICCAT; IOTC; Pelagic longline; Pelagic sharks; Reporting; Retained bycatch

1. Introduction

Pelagic (drifting) longline fisheries directed mainly at tunas and swordfish typically have high shark bycatch ratios (Oliver et al., 2015). The captured sharks are either discarded at sea, mostly unreported, or are retained and processed for their meat and fins. Drivers of retention are primarily the species of shark, as a proxy for economic value, and the regulatory environment within which a fishery operates (James et al., 2016). Commonly retained sharks with high quality meat and marketable fins include shortfin makos *Isurus oxyrinchus*, whereas blue sharks *Prionace glauca* are less valuable, and are more often discarded.

Pelagic sharks are vulnerable to fishing pressure, because of their life history traits and behaviour patterns (Dulvy et al., 2008). As a group, they have lower productivity than teleosts, are long-lived and slow-growing, and produce few offspring which mature late (Musick, 1999). Pelagic sharks are predatory animals, and some species are found in association with other target species of longline gear, on which they prey or compete with for food (Mejuto et al., 2008). Inevitably, these sharks are caught in large numbers in areas of intensive longline fishing (Campana, 2016). Pelagic sharks migrate freely and widely over their range, often across international boundaries (Kohler et al., 2002; Block et al., 2011, Campana, 2016), thus making them vulnerable to high seas fishing fleets.

Blue sharks dominate the bycatch of pelagic longline fisheries in subtropical and temperate waters worldwide (Oliver et al., 2015), and in some areas, they exceed the catches of tuna and swordfish target species (Campana et al., 2009). They are faster-growing and relatively more productive than most other shark species, and are considered less vulnerable to fishing pressure (Smith et al., 1998; Aires-da-Silva and Gallucci, 2007). Shortfin makos make up a large proportion of retained bycatch of longline fisheries, and in some cases form the target of shark-directed fisheries (Francis et al., 2001; Campana et al., 2005; Petersen et al., 2009; Bustamante and Bennett, 2013). Makos are characterized by low rates of population increase and are considered to be more vulnerable to overfishing than blue sharks (Dulvy et al., 2008). Neither species are considered to be in imminent danger of collapse, although populations of one or both might be overexploited (Campana et al., 2005; Campana, 2016). For example, North Atlantic stocks of shortfin makos appear to be overfished and undergoing overfishing, whereas the status of South Atlantic stocks are highly uncertain (ICCAT, 2017a).

The track record for shark management worldwide has been poor, and the IUCN Red List recently reported that 17% of the species were considered threatened with extinction (critically endangered, endangered or vulnerable) (Dulvy et al., 2014). Shark landings reported to the FAO peaked in 2003, and in the decade since then have declined by almost 20% - a reflection of overfishing, rather than good management (Davidson et al., 2016). Average shark exploitation rates exceed rebound rates for many shark populations (Worm et al., 2013). Campana (2016) highlighted the risks associated with ineffective fisheries management structures, unmonitored fishing mortality (particularly of discarded sharks), and the scarcity of basic information on the status of populations. Importantly, species-specific patterns and information gaps, by ocean region and individual fishery, have been identified as a critical weakness, in terms of global conservation and improved fisheries management efforts (Oliver et al., 2015).

Standardized catch-per-unit effort (CPUE) trends based on fisher's logbook data of catch and effort are widely used in fisheries management, under the assumption that they provide measures that are proportional to abundance. Potentially important biases can, however, arise from catchability fluctuations by area and season, and also as a result of changes in fishing methods and gear. Maunder and Punt (2004) reviewed methods to standardize catch and effort data, to remove the impacts of these factors from inter-annual trends. Nominal CPUE data are, however, also affected by under-reporting; in longline fisheries, sharks that are discarded overboard are infrequently reported in logbooks, and landing statistics therefore underrepresent the actual numbers of sharks caught during a fishing trip (Campana, 2016). Hence, there remains considerable uncertainty about the relationship between shark abundance, CPUE time series and total catches over the past decades (IOTC, 2016). Nevertheless, standardized CPUE trends remain an important relative measure of the abundance of sharks caught by longline gear, including for national fleets and fisheries managed by Regional Fisheries Management Organizations (RFMOs), such as the Indian Ocean Tuna Commission (IOTC) and the International Commission for the Conservation of Atlantic Tunas (ICCAT) (Francis et al., 2001; Su et al., 2008; Petersen et al., 2009; Cortés, 2013; ICCAT, 2016; IOTC, 2016). Some of these studies have used auxiliary information collected by fisheries observers at sea to assess the levels of discarding or misreporting in logbooks (Cortés, 2013).

Both distant-water pelagic longline fleets and local vessels fish for tunas and swordfish in the Southeast (SE) Atlantic and the Southwest (SW) Indian Oceans, around southern Africa (Petersen et al., 2009; da Silva et al., 2015). A local longline fishery for tunas first developed in South African waters during the 1960s, but it was short-lived because of a weak market for the poor-quality tuna landed by the fleet (Petersen and Goren, 2007). A local shark-directed longline fishery started in 1992, landing mainly blue sharks and shortfin makos (BCLME, 2005). Distant-water fleets, mainly from Japan and Korea, were licensed to fish in South African waters from the early 1990s, where they set deep longline gear to target tunas (Petersen and Goren, 2007). South African vessels re-entered the pelagic longline fishery in 1995, through a joint agreement with a Japanese company. The joint initiative proved to be successful, and by 1997, 30 experimental tuna permits were issued to South African-flagged vessels. This fishery was formalized in 2005, when long-term fishing rights were issued respectively for swordfish- and tuna-directed fisheries, and the shark-directed permits were abolished. Sharks continued to be targeted by some local vessels under a permit exemption, but their licenses were fully amalgamated into the tuna and swordfish fishery in 2011 (da Silva et al., 2015).

Based on data collected by fisheries observers, Petersen et al. (2009) found that blue sharks and shortfin makos were the most common sharks caught in longline gear set around southern Africa, and that local South African swordfish-directed vessels caught more sharks than Asian-flagged tuna-directed vessels. These authors also observed a decline in the standardized CPUE of both shark species over the 2000-2005 period, accompanied by a decline in average shark size. However, data collected by fisheries observers at sea are rarely available for long uninterrupted periods, and therefore long-term indices of abundance must often rely on commercial logbook and landings data – even though these data may be affected by targeting practices and under-reporting.

In the present study, we used logbook data of fishing effort and retained shark catches of two pelagic longline fleets (local and foreign-flagged) for the 2000 to 2015 period, to construct standardized CPUE trends for blue sharks and shortfin makos. The influences of spatio-temporal variables and the characteristics of individual fishing vessels were accounted for within a generalised linear mixed model (Maunder and Punt, 2004). We then asked whether known changes in retention practices, resulting from market demand, changes in the regulatory environment and fleet behaviour, would be visible as anomalies in the CPUE indices. Our study provides a reference framework for the analysis and interpretation of commercial logbook data affected by unreported discards – often the only source of information that fisheries researchers have for assessments.

2. Materials and methods

2.1. Spatio-temporal stratification

The sampling area (South African Exclusive Economic Zone [EEZ] up to 200 nautical miles from the shore and surrounding high seas) was stratified into SE Atlantic (west of 20°E) and SW Indian Ocean regions (east of 20°E; Fig. 1). Along the South African west coast, the SE Atlantic is dominated by cool-temperate waters and highly productive upwelling systems of the northwards flowing Benguela Current (Hutchings et al., 2009). The east coast is influenced by the western boundary Agulhas Current which follows the shelf-edge southwestwards, bringing warmer subtropical waters into this moderately productive part of the SW Indian Ocean (Lutjeharms, 2006a, b; Beal et al., 2011). Cape Agulhas (~20°E) at the southernmost tip of Africa is considered an official dividing line between the Indian and Atlantic Oceans (IHO, 1953), even though the oceanographic boundary zone is dynamic across a broader geographic range, and is affected by water movements.

The SE Atlantic and SW Indian Ocean regions were each divided into two further subregions: West (Namibia border to 33°S; cool temperate, influenced by the Benguela Current), Southwest

(33°S–20°E; dynamic boundary zone, including the western Agulhas Bank), South (20–26°E; influenced by the warming lower Agulhas Current, with a narrow shelf broadening to become the eastern Agulhas Bank) and East (26°E to the Mozambique border; subtropical waters influenced by the upper Agulhas Current) (Fig. 1). This subdivision was similar to one used in a study on pelagic shark bycatches by Petersen et al., (2009).

Seasonal stratification was based on the average sea surface temperature (SST, °C) recorded by skippers in logbooks at the start of each longline set between 2000 and 2015. The "spatial" library of R software (Ripley et al., 2015) and geographic maps available from the "maps" and "mapsdata" libraries (Becker and Wilks, 2016a, b) were used to construct a kriging map of SST around southern Africa (R Development Core Team, 2016). Using 21°C as a reference temperature, we identified two general seasons: a cool season (June–November), when the 21°C isotherm was constrained to the northern parts of the east coast; and a warm season (December–May) when the warmer waters extended further southwards (Fig. 1). Only two seasons were used, to ensure a balanced distribution of observations per category.

2.2. Data and assumptions

Logbook records completed on a set-by-set (daily) basis were obtained from the Department of Agriculture, Forestry and Fisheries (DAFF) for local vessels (South African-flagged vessels) and foreign vessels (mainly Japanese and Korean flagged vessels) licensed to fish for tuna in the South African EEZ, on condition that catches are offloaded in local ports. Logbook records of foreign vessels were available for all years between 2000 and 2015, except 2006, when they did not fish. Records for local vessels were available for all years between 2000 and 2015, for fishing sets targeted at tunas, swordfish and pelagic sharks. The data comprised of daily retained catches by species by numbers, weight (after reconciliation of weights estimated at sea with landed weights, measured by Fisheries Control Officers at offloading points), numbers of hooks set, set and haul positions and times, target species, depth of sets and bait type, and whether a fisheries observer was present or not.

The logbook data were cleaned by removing anomalous records in which setting positions, date, depth, fishing effort (number of hooks), set durations or catch composition or quantities were clearly incorrect or mismatched. Records with setting positions outside the SW Indian Ocean and SE Atlantic region were removed. Data considered to fall within acceptable ranges were dates between 2000 and 2015; 310–3 800 hooks per line; 0–1 200 blue sharks caught per set and 0–801 makos caught per set. Spatio-temporally explicit catch and fishing effort of 29 019 individual sets remained (86% of initial records), which were then aggregated by fishing vessel and month, resulting in 2 488 records for further analysis. Consolidation along time (month) and geographic (region) dimensions improved tractability of the data with standard statistical software and did not corrupt their structure, because individual fishing vessels operated within the same region in any given month.

We assumed that blue sharks and shortfin makos were correctly identified in logbooks – these two species are commonly caught and relatively easy to identify. Longfin makos (*Isurus paucus*) have rarely been reported from the sampling region (Reardon et al., 2006), and hence all makos were assumed to be *I. oxyrinchus*. Other shark species, which made up only a small proportion of the retained catch, were not always identified to species level, and were generally grouped in logbook records, as requiem sharks (mostly *Carcharhinus* spp.), threshers (*Alopias* spp.), hammerheads (*Sphyrna* spp.) or as unidentified sharks.

2.3. Data analysis

Generalized Linear Mixed Models (GLMMs) are an extension of GLMs, and deal better with replicated observations and complex designs in generalized regression (Venables and Dichmont, 2004; Manning, 2007). Variability in blue shark and shortfin mako CPUE (numbers/1 000 hooks) by year, subregion, season, vessel and observer presence (Table 1) was explored using GLMMs in the statistical software package R, version 3.3.2 (R Development Core Team, 2016). The R-libraries "lme4" (Bates et al., 2016) and "lmtest" (Hothorn et al., 2015) were used to run the GLMM procedure. Data from 61 local South African-flagged vessels (16 810 data records) and 49 foreign vessels (12 209 records) were analysed separately, because fleets differed in operational characteristics and in reporting quality.

The CPUE data contained many records with zero shark catches, and therefore the delta method (Pennington, 1983; Maunder and Punt, 2004; Lauretta et al., 2016) was selected for the analysis. The delta method involves fitting two submodels to the data. In the first submodel, the probability of a non-zero catch was modelled, based on presence/absence information, and assuming a binomial error distribution (Table S1a and b). In the second submodel, the positive catch numbers were modelled using the gamma continuous probability distribution. This distribution was chosen because the relationship between the logarithms of the mean and variance of non-zero CPUE records was close to two (data highly dispersed) (McCullagh and Nelder, 1989; Stefansson, 1996), and the gamma provided better fits than inflated discrete distributions in preliminary tests.

Final models were selected based on a stepwise approach, involving modelling combinations of error structures, link functions and explanatory variables. The most parsimonious models were selected based on the lowest value of the Bayesian Information Criterion (BIC), and visual assessment of residual plots. Error back-calculation and error propagation were calculated using the conservative procedures recommended by Jørgensen and Pedersen (1998), Lindberg (2000) and Tellinghuisen (2001). Standardized CPUE trends by species and year were computed as the product of the probability of catch (binomial model) and positive catch (gamma model) obtained from the model coefficients. The expected values in the final models were the specific CPUE using Year as the fixed (main) effect, as this is the factor of interest with regard to abundance trends of the whole stock (Maunder and Punt, 2004; Venables and Dichmont, 2004). Study of interactions among the random factors proved difficult. Despite the aggregation of the data, the number of realized treatment cells was just a small fraction of the potential interactions (100 vessels × 4 regions × 2 seasons). Indications of the variance of the intercepts of the random effects Region, Season and Vessel are reported (Table S2), as provided in "lme4".

Anomalies in the CPUE index were identified *post hoc*, as sudden increments in the scale of the index that could not be plausibly explained on biological or population dynamics grounds alone. Published and anecdotal information on the history of the fishery, management framework, and market demand were used to identify events that may have influenced the changes in shark retention practices. These were superimposed on the standardized CPUE indices.

3. Results

3.1. Nominal trends in fishing effort and landings

During the period 2000–2015, 52 million hooks were deployed by 110 vessels, 31 million by foreign vessels targeting tuna and 21 million by local vessels targeting mostly swordfish. Fishing effort was greatest in 2011, with a combined total of nearly 6 million hooks set by both fleets combined. Foreign vessels deployed an average of 2.0 ± 1.1 million hooks per year, compared to 1.3 ± 0.4 million set per year by local vessels over the same period. Foreign fishing effort peaked between June and September (Fig. 2a and b), with fishing conducted throughout the South African EEZ and regularly venturing into international waters. Local vessels fished throughout the year, concentrating their effort within the EEZ. The number of hooks per year set by foreign vessels increased from 0.5 million in 2001 to a maximum of 3.9 million in 2011, when 15 vessels were active; thereafter effort declined steeply to 0.8 million hooks by 2015, set by four vessels

(Fig. 2a and b). The number of hooks set by local vessels increased sharply after 2004, and remained at a constant high level of 1.5–1.9 million hooks per year between 2011 and 2015, when the number of active vessels ranged from 15–17 (Fig. 2c and d).

Local vessels fished in all four subregions, but concentrated their effort in the West, Southwest and South subregions (63% of hooks), and in the northern part of the East subregion (37% of hooks; Fig. 3a). The geographical distribution of the local fishing grounds is influenced by distance from fishing harbours along the West Coast (Saldanha Bay), around the Cape Peninsula (Cape Town, Hout Bay), the southern Cape (Mossel Bay, Port Elizabeth) and off northern KwaZulu-Natal (Richards Bay). Foreign vessels concentrated on the SW Indian Ocean, with the bulk of hooks set in the South (58%) and East (33%) subregions, and the remainder (9%) set in the SE Atlantic (Fig. 3b).

A total of 682 084 sharks (10 083 t) were reported as landed by both local and foreign fleets combined between 2000 and 2015 (Fig. 4). Large increments in landings of shortfin makos occurred in 2004 and 2005, with another major year-on-year increment in 2011. Mako landings trended upwards over the last three years of the time series, to the highest level on record in 2015. The numbers of blue sharks in landings increased steeply in 2011, and peaked in 2014 and 2015.

By region, 63 329 (508 t) sharks were reported from the West, 298 114 (3 309 t) from the Southwest, 291 308 (5 623 t) from the South and 29 333 (644 t) from the East subregions, respectively. Sharks contributed 52% by numbers (%N) and 31% by weight (%W) of total landings reported by both fleets. By subregion, sharks contributed high proportions to the total catch, relative to tunas and swordfish, in the Southwest (77% N; 48% W), West (60% N; 22% W), and South (52% N; 42% W) subregions, but a low proportion in the East (11% N; 7% W) (Fig. 3). Local vessels landed the bulk (91% N; 88% W) of all sharks on record, with foreign vessels landing the remainder. Local vessels landed more sharks during the warm than the cool season (58% versus 42% N), whereas the reverse was the case for the foreign fleet (25% versus 75% N).

For the foreign fleet, the annual landings of sharks, as a proportion of their total landings (sharks plus tuna and swordfish), was low (11% N; 8% W on average per year) reaching a maximum in 2008 (19% N; 18% W) (Fig. 5). The local fleet reported similarly low proportions of sharks up to 2003, whereafter annual landings of sharks increased sharply, to roughly half of the total landings made by local vessels (Fig. 5). In the last two years of the time series, the proportion of sharks in landings made by local vessels increased even further (78% N; 63% W in 2014, and 76% N and 64% W in 2015).

3.2. Species composition

Blue sharks dominated the combined shark landings (59% N; 38% W), followed by shortfin makos (40% N; 59% W) and other sharks (1% N; 3% W). ‘Other sharks’ comprised of four groups, which could not be confidently resolved to species level based on the landings data (Fig. 3). Nearly 4 000 sharks were not identified beyond ‘Sharks nei’, 3 500 were grouped as requiem sharks (including several similar-looking Carcharhinid species, but excluding blue sharks), and neither thresher sharks (*Alopias* spp.) nor hammerheads (*Sphyrna* spp.) were identified beyond genus level. Tope sharks (*Galeorhinus galeus*) (included with the requiem shark group) were first identified in landings in 2011. Contrary to the general pattern of shark landings, which is dominated by blue sharks, landings of makos caught in the South subregion exceeded those of blue sharks caught there (see Fig. 3).

3.3. Model outputs

The GLMM with vessel as a random effect consistently provided the lowest BIC, indicating that vessel-to-vessel variation, which incorporates operational characteristics or fishing power, is an important factor (Table S1a and b). Most of the variance could be attributed to the individual vessels, while the remaining random effects, subregion and season, explained a small percentage of the variation in the standardized CPUE (Table S2). The resulting model provided consistently superior fits than the null models, a constant trend for both mako and blue shark models across both local and foreign fleets (Table S2a and b). The standardized CPUE trends confirmed that blue sharks had a much higher catch rate than shortfin makos, irrespective of fleet, and that local vessels had a much higher catch rate of both species, individually, than foreign vessels (Fig. 6a and b). Both these trends were based on retained catches only, and excluded sharks that were caught and discarded overboard during fishing operations, which often went unreported. Hence the standardized CPUE underestimates the actual number of sharks caught per 1 000 hooks.

For blue sharks, the standardized CPUE trend of local vessels indicated a period of low catch rates (1–5 blue sharks/1 000 hooks) between 2000 and 2010, followed by a sudden three-fold increase in 2011, and thereafter consistently high catch rates (15–20 sharks/1 000 hooks) between 2011 and 2015 (Fig. 6a). The standardized CPUE of foreign vessels remained below 4 blue sharks/1 000 hooks over the time series, and stabilized at around 2 sharks/1 000 hooks after 2009.

For shortfin makos, the standardized CPUE trend of local vessels showed two sudden increases, in 2004 and again in 2011, and a gradual increase after 2013 to the highest level on record in 2015 (Fig. 6b). Standardized CPUE levels fluctuated from 1–2 makos/1 000 hooks between 2000 and 2003, from 3–4.5 makos/1 000 hooks between 2004 and 2010, and increased from 5.5 to 7 makos/1 000 hooks between 2011 and 2015. The standardized CPUE of foreign vessels fluctuated around 1 mako /1 000 hooks over the 16-year time series.

We interpreted the three-fold (2004) and two-fold (2011) increases in shortfin mako standardized CPUE as implausible from biological or population dynamics viewpoints, and hence as a result of increased retention rather than increases in shark abundance. Similarly, the order of magnitude with which blue shark standardized CPUE increased in 2011 was most likely a result of increased retention rates.

4. Discussion

Blue sharks and shortfin makos made up the bulk of shark landings by the local South African- and foreign-flagged pelagic longline fleets operating around southern Africa, confirming a similar finding from fisheries observer data collected prior to 2006 (Petersen et al., 2009). Similarly, pelagic longline fleets from Brazil and Uruguay predominantly caught blue sharks, shortfin makos and porbeagle sharks in the South Atlantic, as bycatch or target species (Hazin et al., 2008). Portuguese longliners caught blue sharks as a main bycatch species in the equatorial Atlantic, with shortfin makos and other sharks also present in catches (Coelho et al., 2012). Fleets in the NW Atlantic (Campana et al., 2005, 2006; Cortés, 2013), NE Atlantic and Mediterranean (Megalofonou et al., 2005; Mejuto et al., 2009), North Pacific (Walsh and Teo, 2012) and South Pacific (Francis et al., 2001) also caught mainly blue sharks and varying quantities of shortfin makos. Silky sharks are sometimes a more common bycatch of pelagic longliners in equatorial regions (Kumar et al., 2015), and they are also more susceptible to purse seine fisheries than blue sharks (Hall and Roman, 2013). Nevertheless, the predominance of blue sharks and shortfin makos in landings from longline fisheries around southern Africa is consistent with trends from most other regions.

Several other shark species made up lesser proportions of the landings, but they were not consistently identified to species level in the data. Requiem sharks (Carcharhinidae) have similar body shape, colour, and overlapping distributions (Compagno, 1999), and large pelagic sharks of the *Carcharhinus* genus, such as dusky- (*C. obscurus*), silky- (*C. falciformes*), and copper sharks (*C. brachyurus*) may have been misidentified (pers. comm. da Silva, DAFF, 2015). Three species of thresher sharks (*Alopias* spp.) look similar, and based on DNA barcoding, Velez-Zuazo et al. (2015), found that common threshers (*A. vulpinus*) were routinely misidentified as pelagic threshers (*A. pelagicus*) in catches from the SW Pacific. Several studies have commented on the misidentification of juvenile hammerheads (*Sphyrna* spp.) in fisheries data (Abercrombie et al., 2005; Barker and Schluessel, 2005). In addition to inconsistent identification of the above taxa, the data available to our study may have been affected by a change in fishing regulations, which prohibited the retention of oceanic whitetip (*C. longimanus*), threshers and hammerhead sharks by South African fisheries since 2011, and silky sharks since 2012 (DAFF, 2014). The coarsely grouped data, combined with near absence of recent (post-2011) landings information on these species, discouraged any attempts at further analysis of species other than blue sharks and shortfin makos.

A key finding of this study was that the standardized CPUE of blue sharks and shortfin makos caught by longlines had increased sharply since 2010, to the highest levels on record between 2011 and 2015. This result is restricted to the local South African-flagged fleet, whereas the standardized CPUE of foreign-flagged vessels remained at low levels throughout the time series. We suggest that three factors, potentially in combination, can explain the observed trends: an increase in the abundance of blue sharks and shortfin makos in the SW Indian Ocean and SE Atlantic; a change in the fishing pattern of local vessels towards targeting and retaining more sharks; and changes to fishing regulations, which affected the reporting of sharks, and hence influenced the standardized CPUE trend.

The hypothesis of an increase in abundance is consistent with the Japanese standardized CPUE series from its longline fleet in the Indian Ocean, which suggests that shortfin mako biomass declined from 1994 to 2003, but has increased since then (Kimoti et al., 2011). Similarly, the time series of shortfin makos caught by the Portuguese longline fleet in the Indian Ocean indicated a declining trend from 1999 to 2004, but increased in more recent years up to 2012 (Coelho et al., 2013). Nevertheless, there is no quantitative stock assessment currently available for shortfin makos in the Indian Ocean, and therefore their status remains uncertain (IOTC, 2016). For blue sharks, reported catches in the Indian Ocean have continued to increase since the early 1990s (IOTC, 2016), although catch estimates are highly uncertain, and probably represent only the sharks that were retained onboard. Standardized CPUE trends were variable and sometimes conflicting among fleets reporting to the IOTC. A first quantitative assessment for the Indian Ocean region in 2015 found blue shark stock status to be close to the maximum sustainable yield, but not yet overfished (IOTC, 2016).

In the South Atlantic, CPUE indices of fleets that report to ICCAT suggest a relative increase in the abundance of shortfin makos, particularly since 2004, although estimates are highly variable between years and fleets (ICCAT, 2017b). Landings of shortfin makos reported to ICCAT by the South African longline fleet increased sharply in recent years, from 250 t in 2013, to 476 t in 2014, and to 613 t in 2015, the highest level on record. CPUE indices for blue sharks were also variable among fleets reporting to ICCAT, but apart from the Brazilian longline fleet, trended generally upwards over the past decade (ICCAT, 2015). An assessment of data up to 2013 showed that the South Atlantic blue shark stock was not overfished, and that overfishing was probably not occurring (ICCAT, 2015). The present stock status information from both the South Atlantic and the SW Indian Ocean can therefore not reject the hypothesis of increasing abundance of blue sharks and shortfin makos in the waters around southern Africa.

Nevertheless, uncertainty remains about the relationship between abundance, CPUE series and total catches (IOTC, 2016), and the assumption that CPUE is proportional to abundance. The standardized CPUE of shortfin makos is most likely a much better reflection of its abundance, compared to the blue sharks, because makos have a higher market value than blue sharks, and are mostly retained (and hence reported in landings data) whenever they are caught (Petersen et al., 2009). Even so, the anomalous increases in standardized CPUE, up to an order of magnitude on a year-on-year basis, are unrealistic from a biological perspective.

The second hypothesis, that a change in fishing pattern (or retention of more sharks) can explain the high standardized CPUE levels of local vessels in recent years, is supported by an increase in the ratio of sharks (by weight) to total landings. In the GLMMs, most of the variance was attributed to the vessel factor, which included properties of fishing operations (e.g., gear configuration) and fishing pattern (e.g., bait type, depth and timing of sets, use of light sticks, and skipper experience). This indicates the high importance of fishing pattern in determining shortfin mako and blue shark catch rates, concurring with the findings of Gilman et al. (2008) and Petersen et al. (2009). In the local fishery, hooks are set near the surface, overnight, and with gear that include lightsticks and squid for bait. Although directed mainly at swordfish, this configuration also contributes to high shark catch rates (Stone and Dixon, 2001; dos Santos et al., 2002; Ward and Myers, 2005; Gilman et al., 2008; Mejuto et al., 2008; Petersen et al., 2009). Swordfish-directed fisheries are often multi-specific (dos Santos et al., 2002; Campana et al., 2016), and may switch their effort towards targeting more pelagic sharks when swordfish are less abundant. Local longline vessels, officially licensed to catch swordfish and tuna, have a long history of also targeting shortfin makos and blue sharks, historically through a now-defunct shark-directed fishery, and permit exemptions (da Silva et al., 2015). The hypothesis of a change in fishing pattern, towards targeting or retaining more shortfin makos and blue sharks, is therefore a likely scenario, based on past performance and an increased ratio of sharks in landings.

Whilst the occurrence or reporting of sharks, or the decision to target them, could be attributed purely to the individual vessels in the binomial model, the remaining random effects, subregion and season, explained a larger portion of the variation in the gamma model. This trend was consistent, irrespective of fleet. The local fleet operated mainly in the West, Southwest and South subregions (SE Atlantic), from where the bulk of blue shark and shortfin mako landings originated. A far greater abundance of sharks in these subregions, compared to the East (SW Indian Ocean), is supported by the logbook data, and also by data collected by fisheries observers (Petersen et al., 2009). Fewer, but larger-sized shortfin makos, have been caught in the SW Indian Ocean, and the mean fork length (FL) of captured makos decreased from east to west, with the smallest individuals, in much larger numbers, occurring near the Agulhas Bank edge, in June to November (Groeneveld et al., 2014). This suggests that the Agulhas Bank may be a feeding ground for juvenile makos, which would explain the large proportion of mako landings originating from the South and Southwest subregions – i.e., the transition zone between the SE Atlantic and SW Indian Oceans. A similar pattern has been suggested for blue sharks (da Silva et al., 2010) whereby juvenile blue sharks have been caught within the Benguela / Agulhas Current transition filaments, suggesting a parturition and nursery area for blue sharks. This area coincides with the West, Southwest and South subregions in our study, where the bulk of the local fleet operates, and from where most of the landed blue sharks originated.

In our study, local vessels landed far more sharks during the warmer season (December to May), which may reflect a seasonal shift towards retaining more sharks. During this season, foreign vessels follow tuna schools out of the South African EEZ, suggesting a lower availability of tunas in local waters (Zagaglia et al., 2004; Block et al., 2005, 2011). Swordfish are similarly less available over the Agulhas Bank region during the warm season (pers. comm. Vessel Skippers, 2015). Two asynchronous fishing seasons for swordfish and blue sharks have previously been observed in the Portuguese longline fleet in the North Atlantic, where fishing effort shifted towards targeting pelagic sharks during times of low abundance of swordfish (dos Santos et al., 2002). We suggest that a similar seasonal fishing pattern has evolved in the local South African fishery, where vessels land a greater proportion of swordfish and tunas during the cooler months (June to November), switching to blue sharks and shortfin makos during warmer months.

The third hypothesis, that changes to fishing regulations had affected shark landings, and hence influenced the standardized CPUE trend, is supported by two sudden increases in the standardized CPUE, which both coincide with major changes to fishing regulations. For shortfin makos, the standardized CPUE increased steeply in 2004, and again in 2011. For blue sharks, a steep increase was observed in 2011 only. Both increases were too large to be explained by changes in stock status alone. Fisheries management decisions, and their effects on fishing practices and reporting, may explain the abrupt increases in the CPUE better.

The low CPUE prior to 2004 can best be explained by misreporting of data. Fisheries observers found large-scale finning and discarding of carcasses in 2000 and 2001 (25–30% of blue sharks) (Petersen and Goren, 2007) and the landings of the shark-directed fishery were not reported to the IOTC in 2001 and 2002 (IOTC, 2004). The market price for pelagic sharks (especially makos) increased in 2003, leading to more sharks being landed, and an expansion of fishing grounds to the Agulhas Bank, where shortfin makos are more abundant (Smith, 2005). In 2005, the now-defunct shark-directed sector was split into a demersal component, and a large pelagic fish component, as a management attempt to reduce catches of large pelagic sharks (West and

Kerwath, 2015). The pelagic component of the shark fishery was incorporated into long-term commercial fishing rights allocated to 18 swordfish and 26 tuna-directed vessels (da Silva et al., 2015) – with the intention that these vessels would now target swordfish and tunas, instead of sharks. An administrative loophole, however, resulted in permit exemptions, which allowed the shark-directed vessels to continue targeting sharks, up to March 2011. The sudden increase in the standardized CPUE of shortfin makos in 2004 can therefore be explained by an expansion of fishing grounds, and increased shark landings because of higher market prices (DAFF, 2013).

The official incorporation of the shark exemption permit holders into the large pelagic fishery for tunas and swordfish in 2011 was expected to reduce landings of pelagic sharks (West and Smith, 2012), but it had the opposite effect – with steep increases observed in the standardized CPUE of blue sharks and shortfin makos in 2011. A plausible explanation is that the formerly shark-directed vessels actively continued to target sharks, despite having permits for tunas and swordfish. These vessels now reported their landings directly to the pelagic longline fishery. Hence the observed increases in standardized CPUE in 2011 are potentially artefactual, reflecting a change in reporting practices, rather than changes in stock status. As a response, regulatory changes in 2012 included a precautionary upper catch limit of 2 000 tonne dressed weight per year (West and Smith, 2013; Anderson et al., 2015), prohibiting the retention of thresher (*Alopias* spp.), hammerhead (*Sphyrna* spp.), oceanic whitetip, and silky sharks. Shark fins had to be accompanied by trunks, with the total weight of retained fins not exceeding 8% (shortfin makos) and 13% (blue sharks) of landed weight, respectively (West and Smith, 2013). Total shark landings by pelagic longline vessels have remained well below the 2 000 tonne dressed weight in each year since 2012 (da Silva et al., 2015).

5. Conclusion

To conclude, the interpretation of landings data and log-book derived CPUE indices constructed for blue sharks and shortfin makos caught by the local longline fleet in South African waters is complex. The index is an unreliable indicator of shark abundance in the region, but an effective indicator of changes in shark targeting or retention practices. The scale of increments correlating with changes in retention strategies, up to an order of magnitude on a year-on-year basis, was unexpected, and highlights the strong influence of market demand on targeting and retaining sharks in fisheries where they are frequently considered as bycatch, or secondary target species. The regulatory environment within which the fishery operates was unable to reduce targeting and retention of pelagic sharks, and a continued increase in the standardized CPUE index for shortfin makos over the last years of the time series suggested that they are increasingly being targeted and retained. The index proved to be a useful tool for measuring the influence of fisheries management decisions on operational realities of fishing fleets.

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Figure titles:

Fig 1. Average sea surface temperatures (SST C°) for cool (June to November) and warm (December to May) seasons as reported in logbooks. Interpolation performed by kriging. The four subregions are shown in plot a) as W – West, SW – South West, S – South, and E – East. Towns and ports are abbreviated as follows: CT = Cape Town, CA = Cape Agulhas, PE = Port Elizabeth, DBN = Durban, RB = Richards Bay.

Fig 2. Fishing effort (numbers of hooks set) by month and year by foreign- (a & b) and local pelagic longline vessels (c & d) between 2000 and 2015. The distribution of the data by area and season is shown in supplementary Table S3.

Fig 3. Average fishing effort (numbers of hooks set) and landings by weight by subregion for local and foreign pelagic longline fleets, based on DAFF landings data (2000-2015). Bubble size is proportional to the numbers of hooks set. Sharks nei (not elsewhere included) include thresher, hammerhead, requiem, and unknown sharks.

Fig 4. Annual landings (in numbers) of shortfin mako and blue sharks reported by local and foreign pelagic longline fleets.

Fig 5. The ratio of shark landings (blue sharks + shortfin makos) to total landings (all species, including tunas, swordfish, blue sharks and shortfin makos) for local and foreign pelagic longline fleets.

Fig 6. The standardized CPUE (±SE) trends for blue sharks and shortfin makos landed by local and foreign pelagic longline fleets.

Figure 1(on next page)

Average sea surface temperatures (SST C°) for cool (June to November) and warm (December to May) seasons as reported in logbooks. Interpolation performed by kriging.

The four subregions are W = West, SW = South West, S = South, and E = East. Towns and ports are abbreviated as follows: CT = Cape Town, CA = Cape Agulhas, PE = Port Elizabeth, DBN = Durban, RB = Richards Bay. Source: DAFF landings data (2000 – 2015).

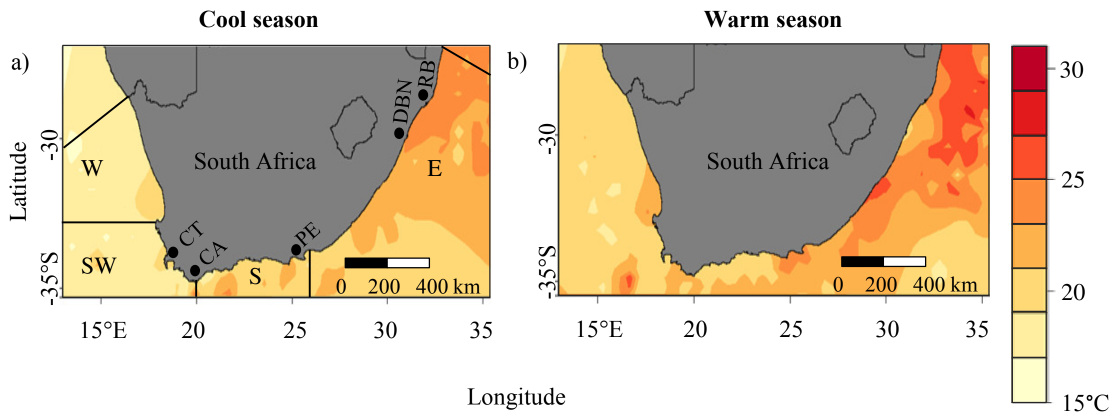
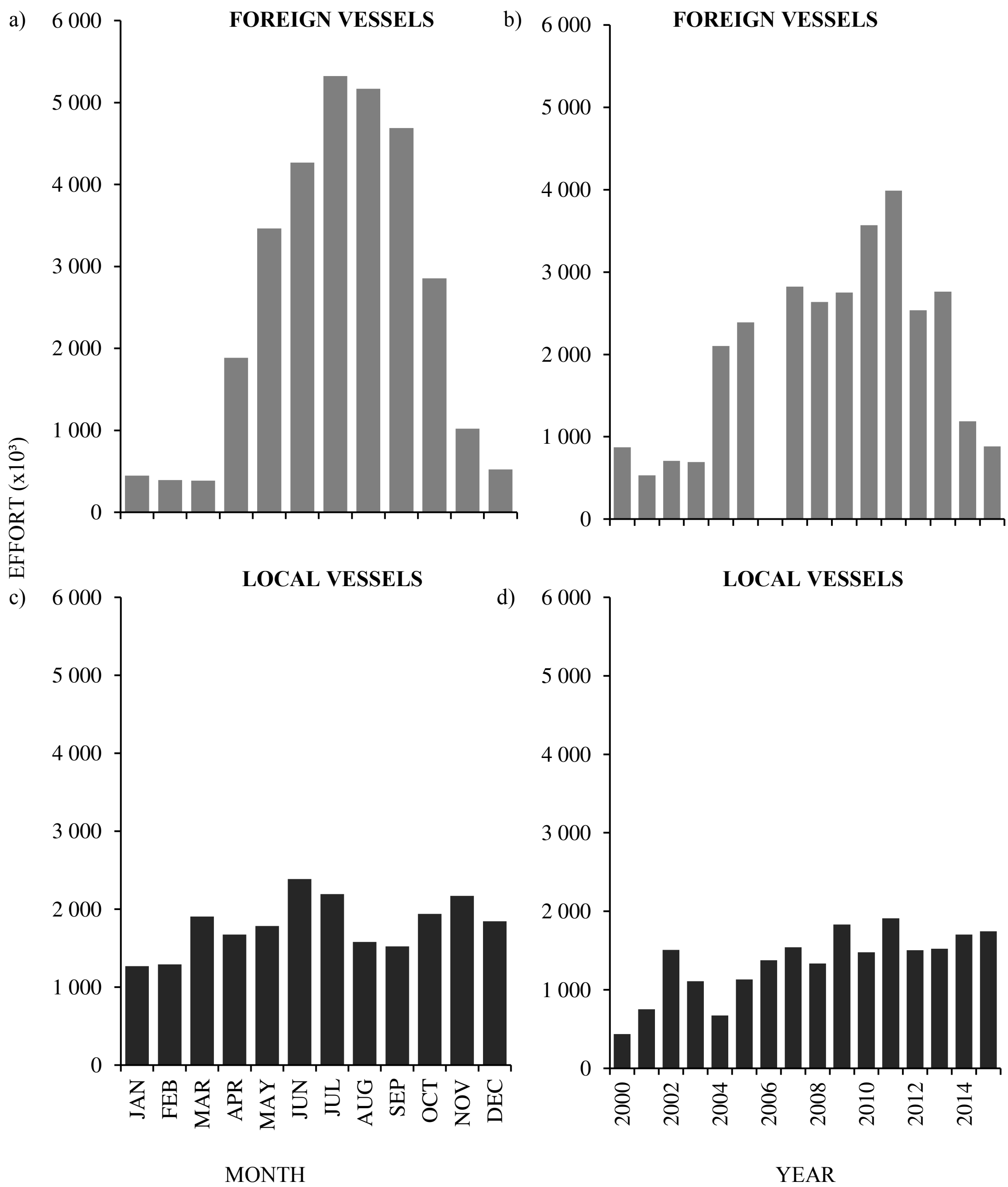

Cool season
Warm season
a)
b)
South Africa
South Africa
W
SW
S
E
CT
CA
PE
DBN
RB
0 200 400 km
0 200 400 km
Latitude
-30
-35°S
15°E
20
25
30
35
Longitude
30
25
20
15°C

Figure 2 (on next page)

Fishing effort (numbers of hooks set) by month and year by foreign- (a & b) and local pelagic longline vessels (c & d) between 2000 and 2015.

The distribution of the data by area and season is shown in supplementary Table S3.



a)
FOREIGN VESSELS
b)
FOREIGN VESSELS
c)
LOCAL VESSELS
d)
LOCAL VESSELS
EFFORT (x10³)
0
1 000
2 000
3 000
4 000
5 000
6 000
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
2000
2002
2004
2006
2008
2010
2012
2014
MONTH
YEAR

Figure 3 (on next page)

Fig 3. Average fishing effort (numbers of hooks set) and landings by weight by subregion for local and foreign pelagic longline fleets, based on DAFF landings data (2000-2015).

Bubble size is proportional to the numbers of hooks set. Sharks nei (not elsewhere included) include thresher, hammerhead, requiem, and unknown sharks.

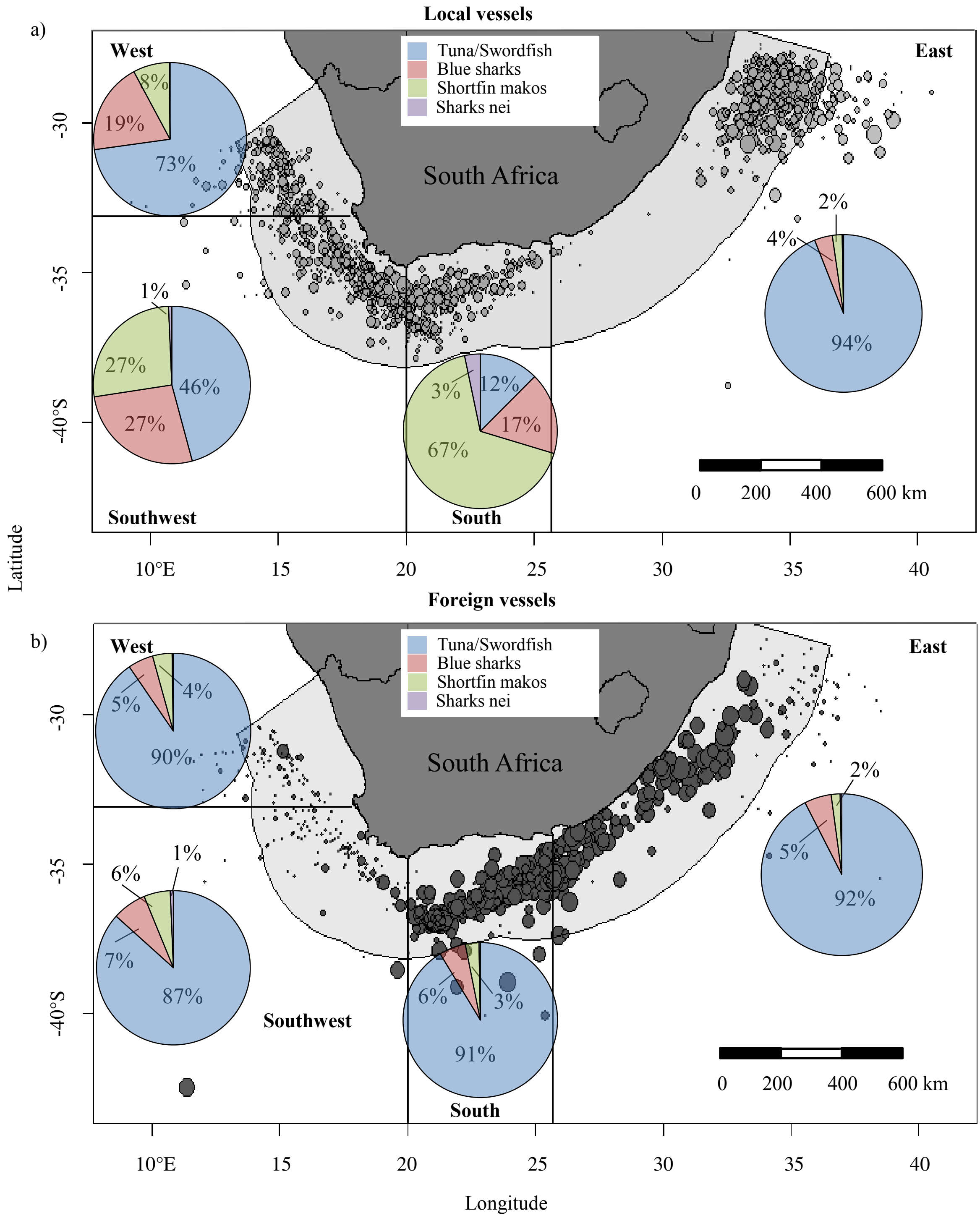

a)
Local vessels
West
East
Southwest
South
Tuna/Swordfish
Blue sharks
Shortfin makos
Sharks nei
South Africa
8%
19%
73%
1%
27%
46%
27%
3%
12%
17%
67%
2%
4%
94%
0 200 400 600 km
-30
-35
-40°S
10°E 15 20 25 30 35 40
Latitude
b)
Foreign vessels
West
East
Southwest
South
Tuna/Swordfish
Blue sharks
Shortfin makos
Sharks nei
South Africa
5%
4%
90%
1%
6%
7%
87%
6%
3%
91%
2%
5%
92%
0 200 400 600 km
-30
-35
-40°S
10°E 15 20 25 30 35 40
Longitude

Figure 4 (on next page)

Annual landings (in numbers) of shortfin mako and blue sharks reported by local and foreign pelagic longline fleets.

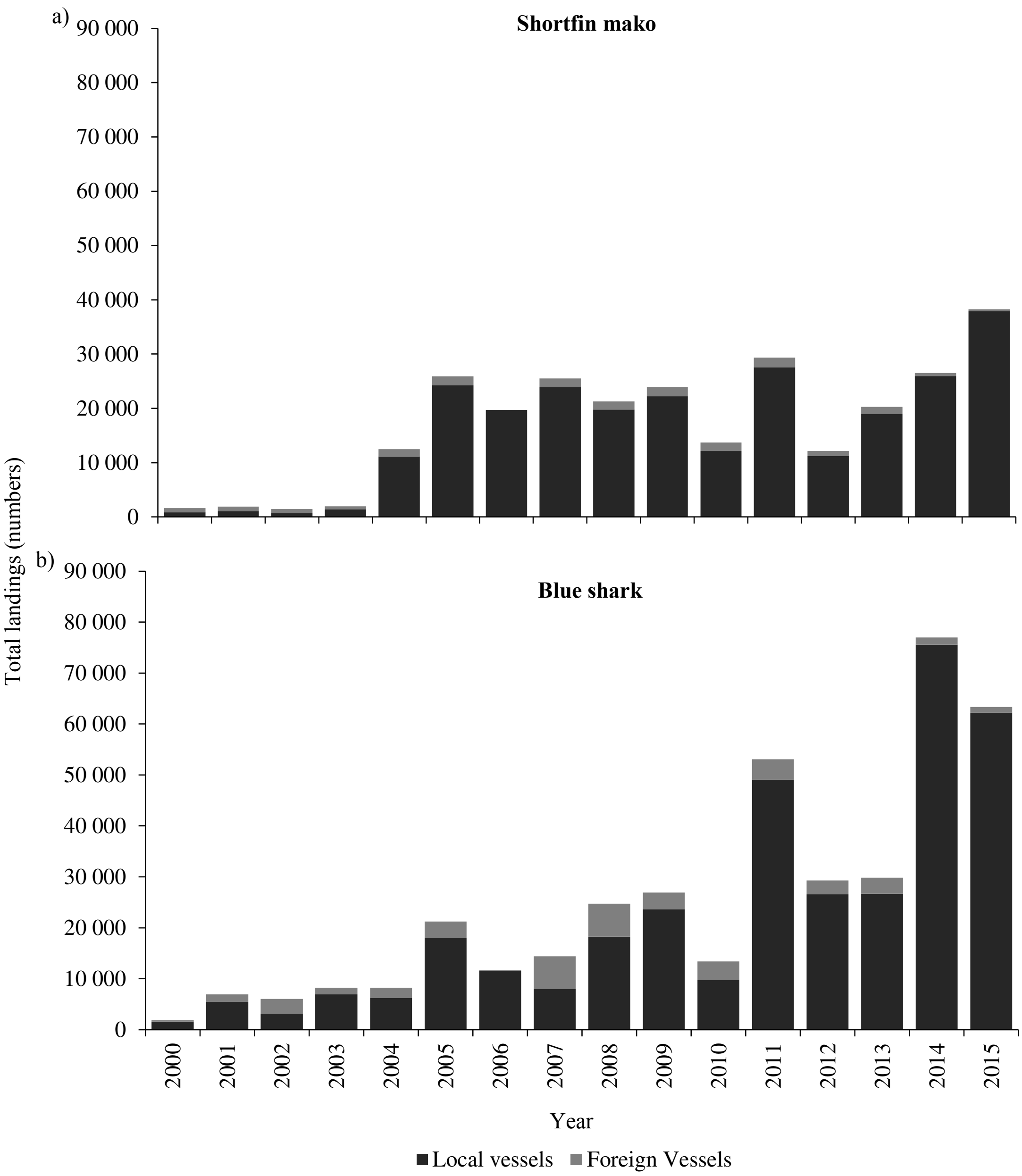

a)
Shortfin mako
b)
Blue shark
Total landings (numbers)
90 000
80 000
70 000
60 000
50 000
40 000
30 000
20 000
10 000
0
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
Year
Local vessels
Foreign Vessels

Figure 5 (on next page)

The ratio of shark landings (blue sharks + shortfin makos) to total landings (all species, including tunas, swordfish, blue sharks and shortfin makos) for local and foreign pelagic longline fleets.

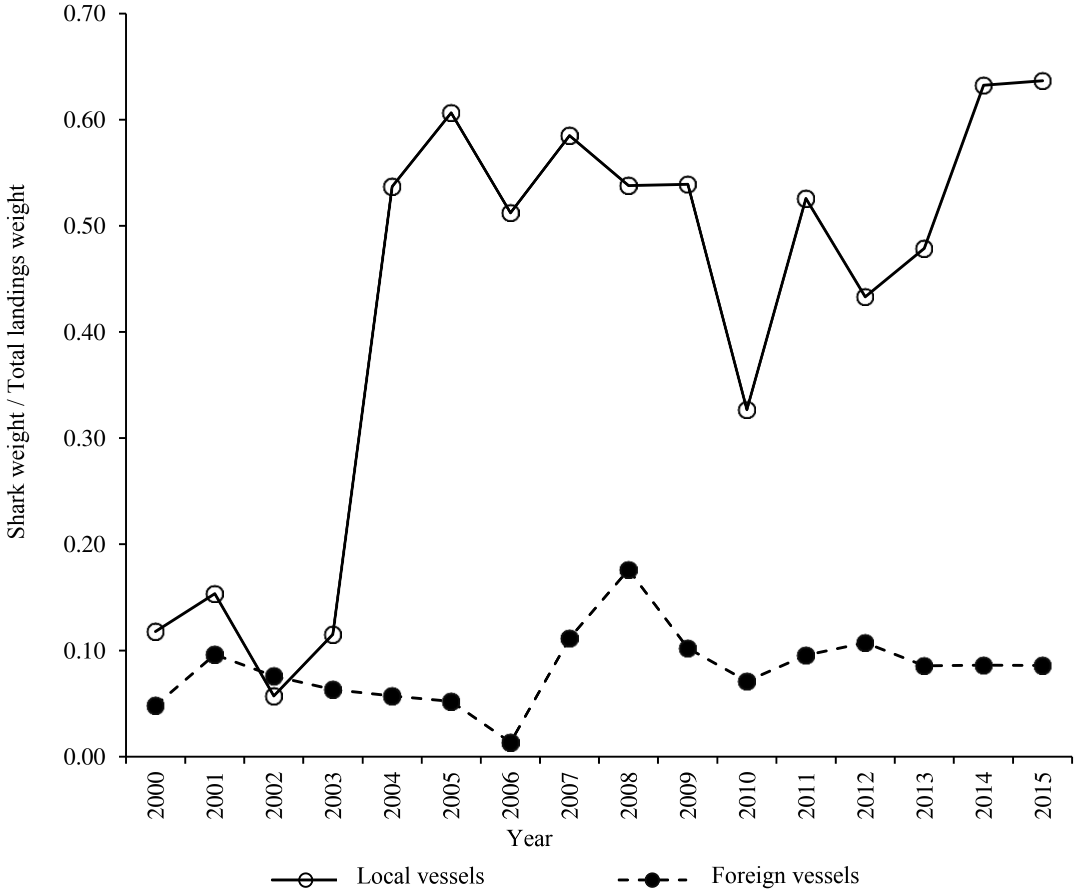

0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Shark weight / Total landings weight
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
Year
Local vessels
Foreign vessels

Figure 6(on next page)

The standardized CPUE (±SE) trends for blue sharks and shortfin makos landed by local and foreign pelagic longline fleets.

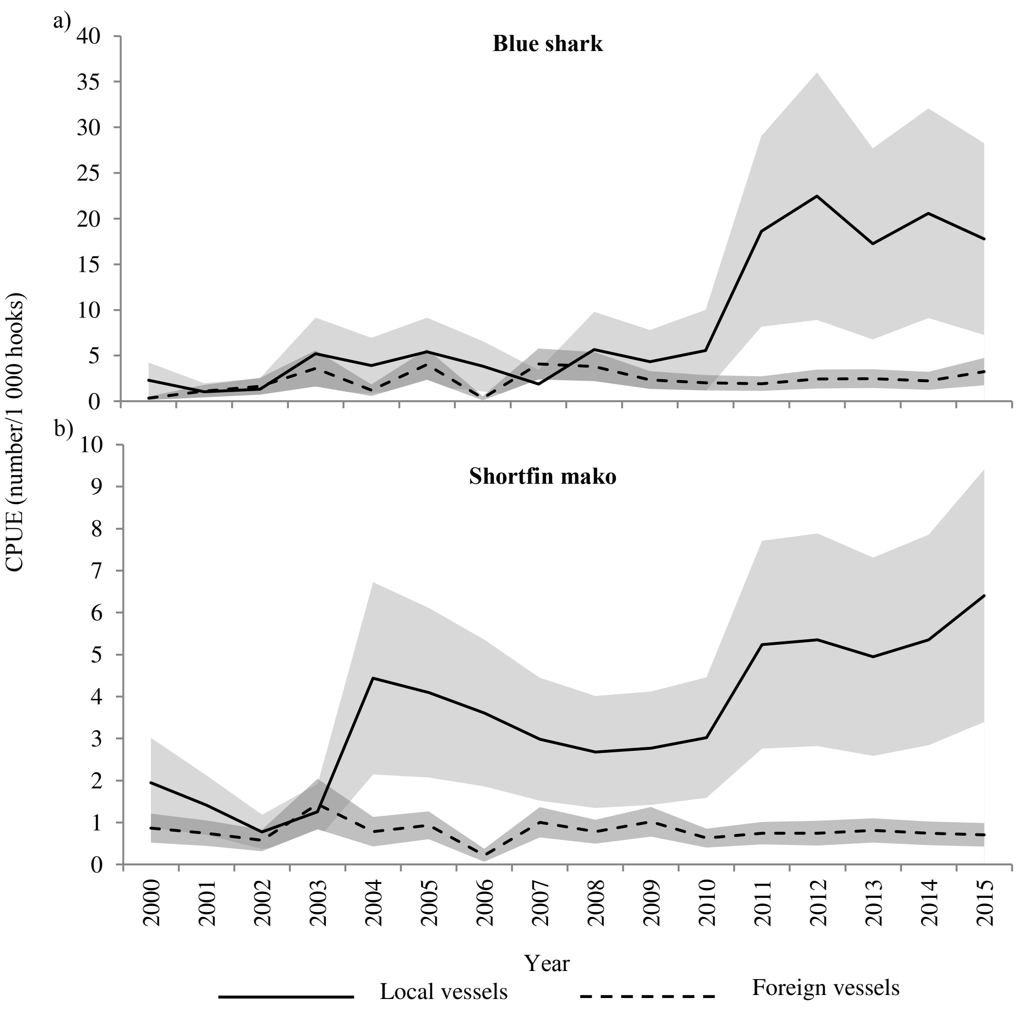

a)
Blue shark
b)
Shortfin mako
CPUE (number/1 000 hooks)
Year
Local vessels
Foreign vessels

Table 1 (on next page)

Explanatory variables hypothesised to affect the CPUE of blue sharks and shortfin makos caught by local and foreign pelagic longline fishing vessels from 2000–2015.

“Year” was the only fixed effect in the model.

Variable	Type	Description
Year	Categorical	2000–2015
Region	Categorical	West, Southwest, South, East
Season	Categorical	Warm = December–May Cool = June–November
Vessel	Categorical	Local: 61 individual vessels represented by 16 810 longline records Foreign: 41 individual vessel represented by 12 209 longline records
Observer present	Categorical	Yes, No