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Marine megafauna catch in southwestern Indian Ocean small-scale fisheries from landings data

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ABSTRACT

The measurable impacts of small-scale fisheries on coastal marine ecosystems and vulnerable megafauna species (elasmobranchs, marine mammals and sea turtles) within them are largely unknown, particularly in developing countries. This study assesses megafauna catch and composition in handline, longline, bottom-set and drift gillnet fisheries of the southwestern Indian Ocean. Observers monitored 21 landing sites across Kenya, Zanzibar and northern Madagascar for 12 months in 2016–17. Landings (n = 4666) identified 59 species, including three sea turtles, two small cetaceans and one sirenian (*Dugong dugon*). Primary gear threats to investigated taxa were identified as bottom-set gillnets (marine mammals, sea turtles and batoids), drift gillnets (marine mammals, batoids and sharks) and longlines (sharks). Overall, catch was dominated by small and moderately sized coastal requiem sharks (Carcharhiniformes) and whiprays (Dasyatidae). Larger coastal and oceanic elasmobranchs were also recorded in substantial numbers as were a number of deeper-water species. The diversity of catch demonstrates the potential for small-scale fisheries to have impacts across a number of ecosystems. From the observed catch rates we calculated annual regional elasmobranch landings to be 35,445 (95%CI 30,478–40,412) tonnes, 72.6% more than officially reported in 2016 and 129.2% more than the 10-year average (2006–16), constituting 2.48 (95%CI 2.20–2.66) million individuals. Productivity-Susceptibility Analyses indicate that small and moderately sized elasmobranchs are most vulnerable in the small-scale fisheries. The study demonstrates substantial underreporting of catches in small-scale fisheries and highlights the need to expand efforts globally to assess the extent and impact of small-scale fisheries on vulnerable marine species and their respective ecosystems.

1. Introduction

Fisheries present the greatest short to medium-term anthropogenic threat to the survival of numerous marine vertebrates. This is particularly true for those species predominantly displaying classic k-selected life history traits (long-life, high natural survivorship, slow growth, late maturity and low fecundity), such as elasmobranchs (sharks and batoids), marine mammals and sea turtles (e.g. Dulvy et al., 2014; Lewison et al., 2004; Wallace et al., 2010; Žydelis et al., 2009). In industrial fisheries elasmobranchs, marine mammals and sea turtles (herein referred to as marine megafauna) are usually considered as bycatch, whereas in many small-scale fisheries (SSF) these taxa may constitute target or by-product species. SSF are herein defined broadly as those as those fisheries operating either for subsistence or for income generation (artisanal) but not as part of a commercial company, generally < 10 m sailing or outboard powered vessels. SSF account for > 95% of fishers at the global level (Pauly, 2006) and 32% of fisheries catch (Pauly and Zeller, 2015). Despite this, SSF have received disproportionately little attention (Molina and Cooke, 2012), especially in developing countries where SSF are most prevalent. Losses of elasmobranchs, marine mammals and sea turtles may have implications for the structure, function and productivity of ecosystems (e.g. Aragones et al., 2006; Heithaus et al., 2008; Kiszka et al., 2015). These implications are especially concerning in SSF dominated regions, as it is there that coastal communities rely most heavily upon near-shore environments for their survival and livelihoods, with limited adaptive capacity to

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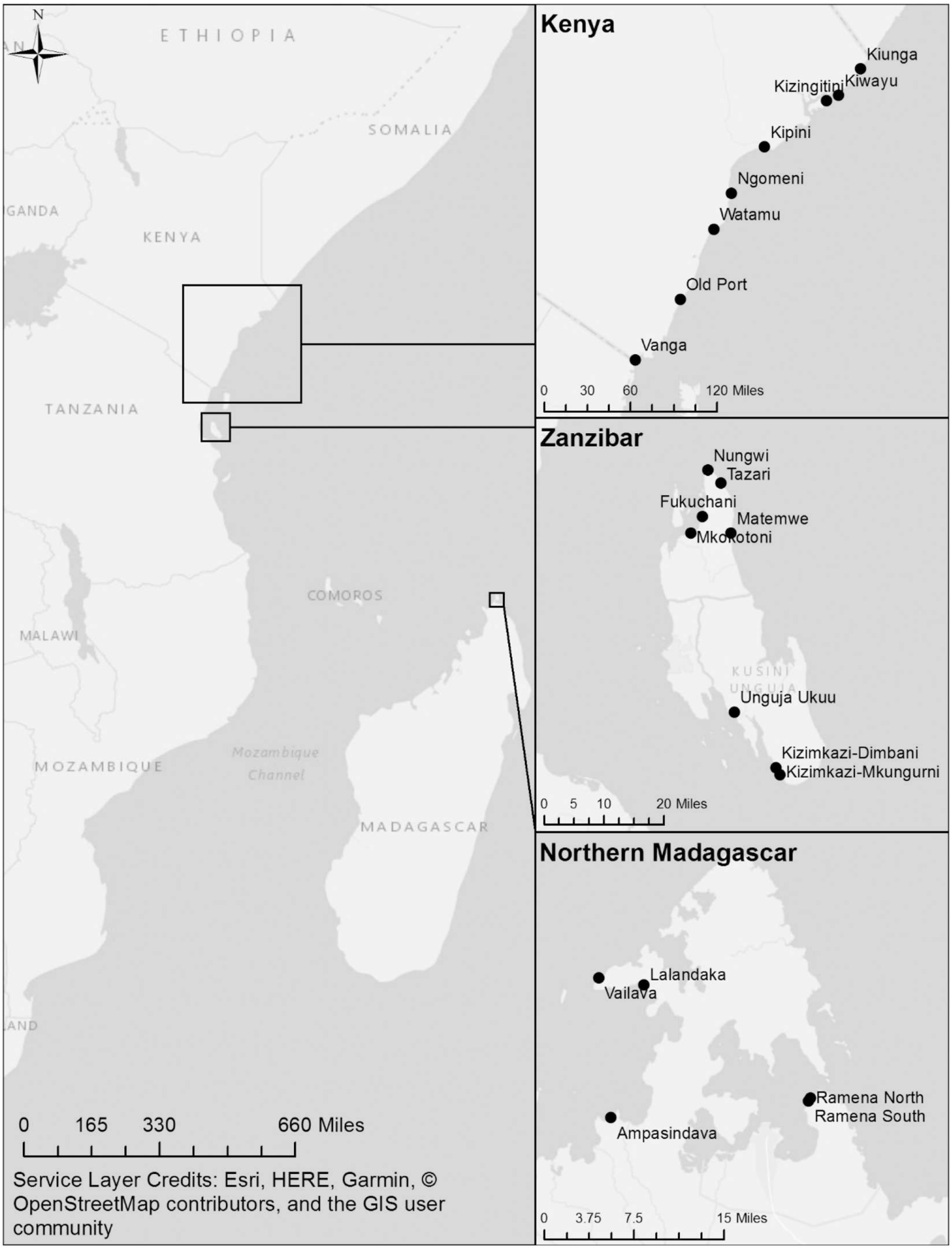

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Fig. 1. Locations of landing sites in the southwestern Indian Ocean monitored for marine megafauna catch between June 2016 and June 2017.

respond to ecosystem change.

The southwestern Indian Ocean (SWIO), consisting of East Africa and the associated islands, represents a SSF dominated developing region, where catch of marine megafauna is common (for review see Temple et al., 2018). The SWIO has upwards of 0.5 million SSF fishers (Temple et al., 2018) contributing around 66.4% of the annual catch (Pauly and Zeller, 2015). The region is undergoing rapid population growth, with the human population expected to double to 357 million by 2050 (WB, 2016), and migration from rural inland areas to coastal regions. Thus, increasingly pressure is placed on marine resources for food and income generation. Indeed, fish proteins (marine and freshwater) range from 7.3–49.7% of animal protein and 1.9–23.1% of total protein consumed (FAO, 2017), with means of 20.7% and 3.6% respectively across the region, once population size is accounted for. Traditionally marine megafauna in the SWIO has been used for both subsistence and commercially marketed as food and bait (e.g. Barrowclift et al., 2017; Humber et al., 2011; Razafindrakoto et al., 2008). Elasmobranchs may be targeted (particularly for fins and meat), but are mostly considered as by-product species and are commonly caught in gillnet and longline gears (Kiszka and van der Elst, 2015; Temple et al., 2018). Little in the way of management exists for elasmobranchs in the SWIO region, though National Plans of Action are either in place or under development throughout the region, suggesting widespread recognition of the potential threat to elasmobranchs (Temple et al., 2018). Conversely, as prohibited species sea turtles and marine mammals are rarely targeted, but are frequently captured in gillnets throughout the region (Bourjea et al., 2008; Kiszka et al., 2009; Muir and Kiszka, 2012). However, a burgeoning range of ecotourism activities focused around marine megafauna species are present across the region (Gallagher and Hammerschlag, 2011; O'Connor et al., 2009; O'Malley et al., 2013) and may incentivise increasingly non-consumptive uses for these species for livelihoods in future.

Despite the prevalence of marine megafauna in SWIO SSF, there is limited understanding of catch and composition in these fisheries (Temple et al., 2018). Official catch statistics show systemic under-reporting and are often inconsistent. Elasmobranchs are primarily reported under generalised categories with limited species level information (FAO, 2018; Temple et al., 2018). Moreover, limited independent data are available, with the majority being geographically restricted case studies (Temple et al., 2018). Data for sea turtles and marine mammals are generally lacking (FAO, 2018). Yet, there is evidence of sea turtle captures in several countries across the SWIO (e.g. Humber et al., 2011; Okemwa et al., 2004; Pusineri and Quillard, 2008) and for marine mammals wherever they encounter fisheries (Kiszka et al., 2009).

Improving fisheries catch and composition data, paired with fishing effort data, are essential in informing robust evidence-based management strategies to safeguard the future sustainability of marine megafauna fisheries and those communities whose livelihoods are dependent upon them. Further, such data act as first-steps towards understanding fisheries and thus form a baseline for future stock assessment and management. In this study, we aim to provide detailed, multi-country cross-sectional data on the scale and composition of SWIO SSF marine megafauna landings in high-risk gears, specifically, gillnets (bottom-set and drift) and longlines, as well as those of the numerically dominant handlines. SSF are herein defined broadly as those as those fisheries operating either for subsistence or for income generation (artisanal) but not as part of a commercial company, generally < 10 m sailing or outboard powered vessels. Further, we analyse the fisheries effort, patterns and drivers and use this to predict total annual landings of marine megafauna in SWIO SSF both at select national scales and estimate landings at the regional level.

2. Methods

2.1. Data collection

Trained land-based observers recorded landings of marine megafauna (elasmobranchs, marine mammals and sea turtles) from select fisheries gears at landings sites in Kenya (n = 8), Zanzibar (n = 8) and northern Madagascar (n = 5) (Figure 1) for a period of 12 months between June 2016 and June 2017. Gears monitored were drift and bottom-set gillnets, longlines (demersal and pelagic) and handlines (including rod and reel gears). However, within each gear category there is variability in specifications (e.g. mesh size, net length, hook size, number of hooks etc.), the impacts of which are not considered in this study. Observers at each site collected data for 147 simultaneous sampling days. Sampling days were selected using a stratified-random approach: the year was divided into lunar months which were subdivided into four lunar phases (new moon, first quarter, full moon, third quarter) and three sampling days randomly generated within each lunar phase. This sampling regime ensured that the study accounted for potential lunar-driven patterns in fishing effort and species availability to the fishery (e.g. variability in vertically migrating species), and subsequent effects on catches. Landing sites were selected accounting for three major factors: prevalence of longline and gillnet gears (maximising representation), geographic spread (maximising geographic coverage and potential links to species availability) and logistical constraints (e.g. sites needed to be accessible by road).

Observers recorded data for landed marine megafauna including photographs for species identification, morphometric data (fork length, disc width and weight), sex, vessel primary gear used and local species name. Observers also recorded fishing effort as total number of vessels active per day by primary gear type, fishing trips were < 24 h and a single vessel may make more than one trip per day, multiple trips are not counted separately for the purpose of this monitoring fishing activity. In the event of vessels also employing a secondary gear type, catch was assigned to the primary gear type used by the vessels, secondary gears were rarely employed.

In order to validate landings observations, fishers (n = 521) at each site were independently asked to give an anonymous opinion on the efficacy of observers. Specifically, fishers gave an estimate, for each recorded megafauna taxon, of the average proportion of landings, if any, that were not recorded by the landings observer on any given day. Fishers' declarations indicate the potential magnitude of catch underestimate in the study.

2.2. Analysis

Patterns in fisheries effort data by gear type were assessed using a Generalised Additive Mixed Modelling (GAMM) approach, with landing site as a random-effect variable. This meant that cross-sectional patterns in fisheries effort could be drawn across the whole study area whilst also accounting for landing site-specific patterns when using the GAMM to predict effort for days where sampling did not occur. Independent variables input to the GAMM model included daily data on precipitation, wind speed, wind direction, temperature, maximum tidal height (as a proxy for lunar phase) and month. Environmental data were extracted from the NCEP/NCAR Reanalysis database (ESRL, 2017). Cyclical variables (e.g. wind direction, month) were fitted with cyclic splines. Where independent variables showed evidence of colinearity ($r > 0.2$ or < -0.2), those with least explanatory power were removed from the model for subsequent iterations.

An annual weighted mean Catch Per Unit effort (CPUE) was calculated, as the number of individuals caught per active vessel, for sharks and batoids separately, by gear type, across landing sites for each country. This was achieved by first calculating respective CPUEs at each site and subsequently weighting CPUEs based on the total predicted effort for each site (sourced from the GAMM model) as this was considered the best estimate of their relative contribution to the overall fisheries effort in their respective country. Where data were missing for either megafauna group or the gear type in which an animal was caught, missing data were retrospectively assigned proportional to known catches, on a site-by-site basis. The weighted mean CPUE was then multiplied by the total predicted effort to create estimates of total catch across sites within each country. This catch was subsequently scaled to the national level for Zanzibar and Kenya. This scaling was achieved by dividing the total predicted catch across sites by the total number of vessels of respective gear type present and multiplying this by the total number of vessels of each gear in the respective country. Vessel by gear type data was sourced from existing frame survey data (KMALF, 2017; ZDFD, 2018) as these data represent the best estimates currently available.

An estimate of total catch weight was also produced for both sharks and batoids. Substantial error is likely in the weight data collected, this is primarily the result of much of the catch being landed in partially dressed states (e.g. organs and/or fins removed) and potential biases in the size of animals that could be successfully weighed (e.g. larger animals are more difficult to weigh). In order to address this, weight-fork length and weight-disc width relationships were modelled for sharks and batoids respectively. For the purpose of estimating weights, guitarfish and wedgefish (Rhyncobatidae) were included with the shark data. Weights for specimens which were known to be in a partially dressed state were excluded from the analysis. A linear model was used to assess weight-fork length/disc width relationships, after data were logN transformed. Cook's distance was used to identify data outliers which exerted undue influence on the linear model, likely a result of measurement and/or data entry errors, and these outliers were removed. The linear models were then re-run and the relationship described (Fig. A1). The model was used to predict the weight for all specimens with a known fork length or disc width as appropriate, back-transformation of weights was done using Sprugel's correction factor method (Sprugel, 1983). The revised weight dataset was assumed to be representative of the weight distributions of species in respective sites and gear types. Mean weight for each elasmobranch taxa for each gear type was calculated and subsequently multiplied by the total estimated megafauna catch to produce a total catch weight by gear for each elasmobranch taxa at each site.

An estimate for SSF elasmobranch landings across the SWIO was also generated. This estimate was calculated by dividing the sum total of predicted catch across all 21 sites by both the number of vessels across all sites and the number of gears across all sites for respective gear types, generating two new CPUE values. CPUE values were scaled using existing SSF fleet data for total vessel counts by gear and/or gear counts, as available, for all SWIO countries to create a regional estimate (Chacate and Mutombene, 2016; IOTC, 2018; Kiszka et al., 2009; KMALF, 2017; MFR, 2010; SFA, 2015; UDC, 2017; URT, 2017; WIOFish, 2018; ZDFD, 2018). Bottom-set and drift gillnets are combined into a singular category in the fisheries statistics of a number of SWIO nations. Thus it is assumed that the proportion of drift and bottom-set gillnets monitored in this study is representative of these gears at the SWIO level.

Landings composition by country and gear type was achieved through species identification from photographs taken by observers, to species or nearest taxonomic level where possible. Local species names were also recorded. Where local names corresponded to specific species groups they were used to identify non-photographed individuals to genus level or higher, with the majority being to family level, minimising the risk of wrongful identification.

Lastly, in order to identify priority species and gear-species interactions for future research, a series Productivity-Susceptibility Analysis (PSA) (Hobday et al., 2011), confined within the context of SWIO SSF, were carried out for gear types in isolation and combination. Species were included in the assessment only if 10 or more individuals were identified in the catch. The PSA (Table 1) was based on existing MRAG and NOAA designs (Patrick et al., 2009; Rosenberg et al., 2009). Categories were excluded, added or modified where they were either irrelevant, required adaptation to be applicable or were needed to better address the classically k-selected life history, biological and ecological characteristics of the species considered in this study. When carrying out the PSA across gear types the "Gear Interaction Risk" attribute was excluded. Further, "Management Strategy" and "Management Regulation" attributes were ultimately removed from all PSA assessments as there was no variability in these attributes among species, a result of the limited monitoring and regulation of elasmobranch catch throughout SWIO SSF (Temple et al., 2018). Attributes were scored on a scale of 1 (Low) to 3 (High) with intervals of 0.5 allowed. Attributes originating from available quantitative data were scored by scaling the data between one and three. In cases where data were skewed by outlier values (e.g. extreme size) these were first logN transformed before scaling. Quality of the data used for each combination of attribute and species, was represented by assigning a confidence scores between 1 (Low) and 3 (High) with intervals of 0.5 allowed. PSA scoring was carried out independently by three of the authors and the mean values of these scores were taken. Weightings reflecting relative importance of attributes as indicators of the respective vulnerability aspect (productivity or susceptibility) were sought independently from a range of experts (with nine respondents, four of whom are authors) with backgrounds in fisheries modelling, fisheries social science and fisheries-marine megafauna interactions. Weightings were combined to calculate mean (± 95% CI) values for productivity and susceptibility as well as confidence in the data used. Mean values are plotted and the overall vulnerability calculated as the Euclidean distance from the origin. Some attributes used in the PSA are unlikely equable measures of vulnerability aspects across taxa, e.g. maximum size (Juan-Jordá et al., 2015). Thus, direct comparisons should be made between sharks and batoids with caution.

All analyses and data visualisations were carried out and produced using the R statistical software, version x64 3.4.0 (R Core Team, 2017). Ethical approval for this project was sought from, and approved by, Newcastle University's animal welfare ethics review board (ID 426).

3. Results

3.1. Fisheries effort

After co-linear independent variables were iteratively excluded, GAMM analyses showed significant effects ($p < 0.05$) of three independent variables on fishing effort: maximum tidal height, month and wind direction. Month significantly influenced bottom-set, driftnet, handline and longline fishing effort (χ^2 = 1453.10, 42.45, 161.48, 380.62, respectively; $p < 0.05$). Tidal height significantly influenced

Table 1
Attributes and scoring used in the Productivity-Susceptibility Analysis, confined within the southwestern Indian Ocean small-scale fisheries context.

<table>
<tr><th>Attribute</th><th colspan="2">Low (1)</th><th colspan="2">Medium (2)</th><th colspan="2">High (3)</th></tr>
<tr><td colspan="7"><i>Productivity</i></td></tr>
<tr><td>Maximum size</td><td colspan="6">Scaled LogN transformation of fork length OR disc width as appropriate. Larger size = lower score.</td></tr>
<tr><td>Fecundity</td><td colspan="6">Scaled LogN transformation of offspring per annum. Higher fecundity = higher score.</td></tr>
<tr><td>Mode of reproduction</td><td colspan="2">Viviparous</td><td colspan="2">-</td><td colspan="2">Ovoviviparous</td></tr>
<tr><td>Size at maturity</td><td colspan="6">Scaled size at maturity as a percentage of maximum size. Higher proportion = lower score.</td></tr>
<tr><td colspan="7"><i>Susceptibility</i></td></tr>
<tr><td>Geographic spread</td><td colspan="2">Regional</td><td colspan="2">Sub-regional</td><td colspan="2">Endemic</td></tr>
<tr><td>Overlap with small-scale fisheries</td><td>Oceanic exclusive</td><td colspan="2">Semi-Oceanic</td><td colspan="2">Coastal</td><td>Shallow water restricted</td></tr>
<tr><td>Gear interaction risk</td><td colspan="2">Low risk of gear interaction (e.g. pelagic species and demersal gear)</td><td colspan="2">Moderate risk of gear interaction</td><td colspan="2">High risk of gear interaction (e.g. pelagic species and pelagic gear)</td></tr>
<tr><td>Desirability of catch for consumption or sale</td><td colspan="2">Low value</td><td colspan="2">Moderate value</td><td colspan="2">High value</td></tr>
<tr><td>Management strategy</td><td colspan="2">Appropriate monitoring</td><td colspan="2">Limited monitoring</td><td colspan="2">No monitoring</td></tr>
<tr><td>Management regulations</td><td colspan="2">Regulated</td><td colspan="2">Partially regulated</td><td colspan="2">No Regulation</td></tr>
<tr><td>Catch relative to productivity</td><td colspan="6">Scaled LogN transformation of catch relative to productivity score. Observed catch was divided by the exponential of the mean productivity score, high productivity species are assumed to sustain much higher catch rates. Higher rate = higher score.</td></tr>
<tr><td>Female mortality</td><td colspan="6">Scaled proportion of captures that are female. Higher proportion = higher score</td></tr>
</table>

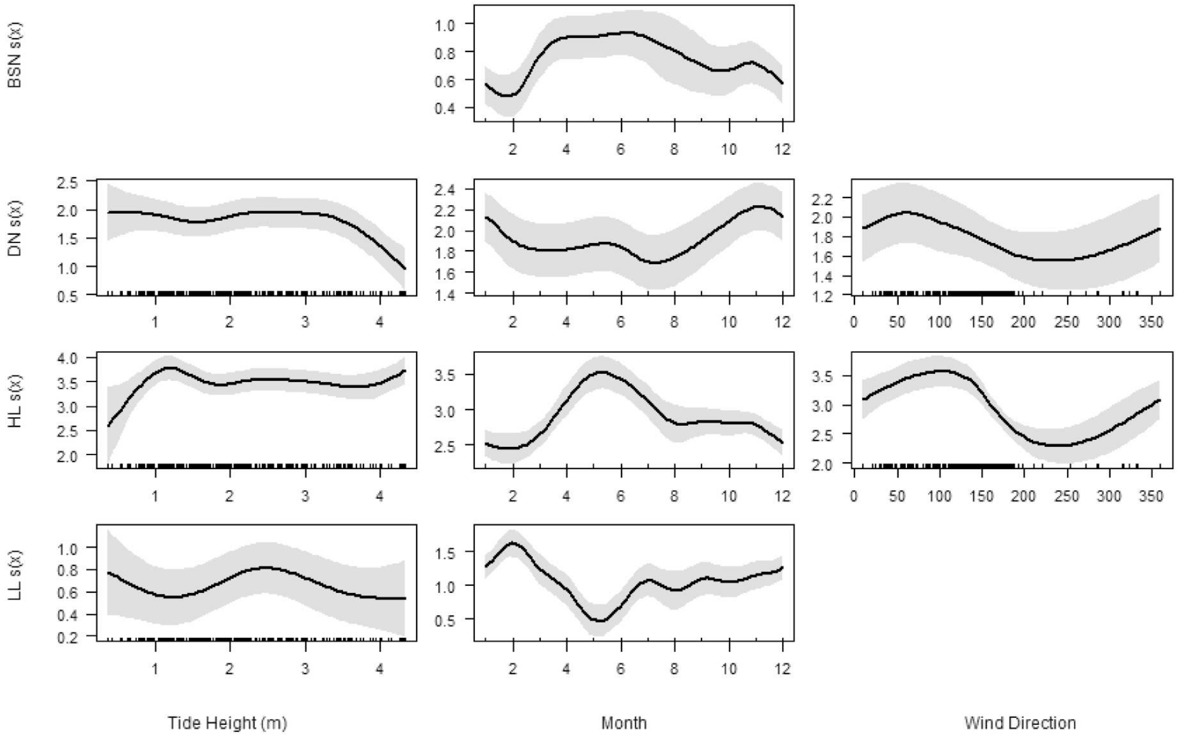

Fig. 2. Smooths (± 95% CI) from a series of generalised additive mixed models describing the cross-sectional relationship between tidal height, month and wind direction (degrees from North) with fishing effort of bottom-set gillnet (BSN), drift gillnets (DN), handline (HL) and longline (LL) small-scale fisheries across Kenya, Zanzibar and northern Madagascar between June 2016–June 2017.

driftnet, handline and longline fishing effort (χ^2 = 41.65, 33.12, 9.76, respectively, $p < 0.05$). Wind direction significantly influenced driftnet and handline fishing effort (χ^2 = 14.57, 175.12, respectively; $p < 0.05$). Wind speed was not found to affect fishing effort for any gear type, despite being expected to impact sea conditions. The models explained 75.0%, 54.2%, 82.2% and 54.9% of the deviance for bottom-set net, driftnet, handline and longline fishery effort, respectively (Figure 2).

Patterns of fisheries effort across gears show intra-annual variability and are suggestive of inverse relationships between efforts from bottom-set gillnet and handline gears with those of drift gillnet and longline gears. Fishers often operate multiple gear types over the course of the year and inverse effort relationships likely reflect fishers transitioning between gears to maximise yield as influenced by external factors. The peaks in longline and drift gillnet use correspond closely to the seasonal monsoons in the SWIO region. SWIO SSF catches are highest during the north-east monsoon (November–March) (Jury et al., 2010; Lan et al., 2013; McClanahan, 1988). This seasonality coincides with increases in coastal availability of migratory oceanic species, such as yellowfin tuna (Lan et al., 2013), which are often target species for longline and drift gillnet gears. Similarly, anecdotal evidence from fishers suggesting a reduction in drift gillnet use during the brightest phases of the moon, because “the fish can see the nets”, is supported and similar patterns may also be emerging in longline gear. Handline gear usage follows an inverse pattern, further reflecting the multi-gear nature of the SSF.

3.2. Fisheries catch

Weighted mean CPUE and individual weight is presented by gear for sharks and batoids for Kenya, northern Madagascar and Zanzibar (Table A1). Using weighted mean CPUEs combined with fishing effort, annual catch was estimated across gear types for Kenya and Zanzibar at the country level (Table 2). An annual estimate for Madagascar is not calculated as the sampling sites are not considered representative of the country as a whole. Further, reliable data for fishing effort metrics (i.e. number of vessels by gear type) was not available for the provinces covered. A total estimate for SWIO level catch was also calculated (Table 2).

Fisher estimates of observer efficacy in recording elasmobranch catch suggest a weighted mean underreporting rate across sites of 21.1% and 33.9% in Kenya, 23.3% and 19.2% in Zanzibar and 17.3% and 19.1% in Madagascar, for batoids and sharks respectively.

3.3. Species composition and vulnerability

Landings compositions (frequency of occurrence) for both batoids and sharks are presented by country and gear type (Fig. 3). Composition is presented at the genus or family levels depending on the level at which catch could be identified. Additionally, in Kenya, bottom-set nets landed one loggerhead (*Caretta caretta*), 24 green (*Chelonia mydas*), 43 hawksbill (*Eretmochelys imbricata*) and one unidentified sea turtle; drift gillnets landed one spinner dolphin (*Stenella longirostris*); and handlines landed four *C. mydas* and one *E. imbricata*. In Zanzibar, bottom-set gillnets landed two *C. mydas*, two *E. imbricata*, two unidentified sea turtles and one unidentified dolphin; and drift gillnets landed one *E. imbricata*, two unidentified sea turtles, one Indo-Pacific bottlenose dolphin (*Tursiops aduncus*) and one unidentified dolphin. In Madagascar, one unidentified sea turtle was landed from a longline. Whilst most fishers declined to declare the subsequent use of landed sea turtles and dolphins, at least seven of the turtles were sold for human consumption and two of the dolphins for use as fisheries bait, indicating an existing market for these species. The full list of species caught is available (Table A2).

Batoid landings (Fig. 3) across the three countries were primarily dominated by whiprays (Dasyatidae). The largest contributors were small and moderately sized, benthic, coastal species such as the bluespotted maskray (*Neotrygon caeruleopunctata*), bluespotted fantail ray (*Taeniura lymma*), leopard whipray (*Himantura leoparda*) and Baraka's whipray (*Maculabatis ambigua*). The whiprays were commonly captured

Table 2

Estimates (± 95% CI) for total individuals and weight of elasmobranchs landed from handline, longline, bottom-set and drift gillnet gears in Kenya, Zanzibar and in the southwestern Indian Ocean (SWIO) between June 2016–June 2017.

Scale	Type	Individuals	Weight (tonnes)
Kenya	Batoids	17,393 (13,680–21,106)	264.9 (184.8–344.9)
	Sharks	34,354 (22,436–46,273)	327.0 (222.0–432.9)
	Elasmobranchs	51,748 (39,265–64,231)	591.8 (459.8–723.8)
Zanzibar	Batoids	134,384 (110,646–158,122)	1512.5 (900.1–2124.9)
	Sharks	52,575 (48,247–56,903)	414.9 (246.2–583.5)
	Elasmobranchs	186,959 (162,830–211,089)	1927.4 (1292.2–2562.6)
SWIO	Batoids	1,148,467 (1,016,745–1,280,189)	17,040.3 (12,567.7–21,512.8)
	Sharks	1,332,971 (1,210,680–1,455,261)	18,404.8 (16,244.7–20,565.0)
	Elasmobranchs	2,481,437 (2,301,700–2,661,175)	35,445.1 (30,478.3–40,412.0)

across the four gear types of interest, presumably reflecting higher abundance and availability in inshore waters relative to other batoids. There was also notable landings of spotted eagle rays (*Aetobatus ocellatus*), shorttail cownose rays (*Rhinoptera jayakari*) and various mobulids (*Mobula* spp.), which were predominantly (68.1%) bentfin devilrays (*Mobula thurstoni*). These pelagic batoids were most commonly caught in drift gillnets, particularly in Zanzibar at sites with access to adjacent deeper waters. Conversely, none of these pelagic batoids were caught in drift gillnets in northern Madagascar, although these species did appear in both bottom-set gillnet and longline landings. Drift gillnet catches in northern Madagascar were almost entirely comprised of benthic species, suggesting that unlike other areas drift gillnets in northern Madagascan sites operated primarily in shallow water environments. Various species of guitarfish and wedgefish were also landed.

Shark landings (Fig. 3) across the three sampled countries were dominated by ground sharks (Carcharhiniformes), within which requiem (Carcharhinidae), hammerhead (Sphyrnidae) and hound (Triakidae) sharks were most common. The largest contributors were small and moderately sized species occurring in a range of coastal, oceanic and deep-sea habitats, particularly smoothhounds (*Mustelus* spp.), sliteye (*Loxodon macrorhinus*), spurdog (*Squalus* spp.), hardnose (*Carcharhinus macloti*), grey reef (*Carcharhinus amblyrhynchos*) and spottail (*Carcharhinus sorrah*) sharks. Scalloped hammerheads (*Sphyrna lewini*) were also common. Larger species, such as bull (*Carcharhinus leucas*) and tiger (*Galeocerdo cuvier*) sharks, were recorded in limited numbers. Oceanic and deep-water species, including shortfin mako (*Isurus oxyrinchus*), silky (*Carcharhinus falciformis*), thresher (*Alopias* spp.) and bigeye sixgill (*Hexanchus nakamurai*) were recorded in relatively low numbers. Other landings of note included a 5.7 m male whale shark (*Rhincodon typus*) caught in a bottom-set gillnet in Kenya, and a large female white shark (*Carcharodon carcharias*) in a drift gillnet in Zanzibar, one of few records in East Africa (Cliff et al., 2000). Both *Rhincodon typus* and *Carcharodon carcharias* appear rare in the catch, and the magnitude of SSF impacts on these species in the SWIO is likely to be limited.

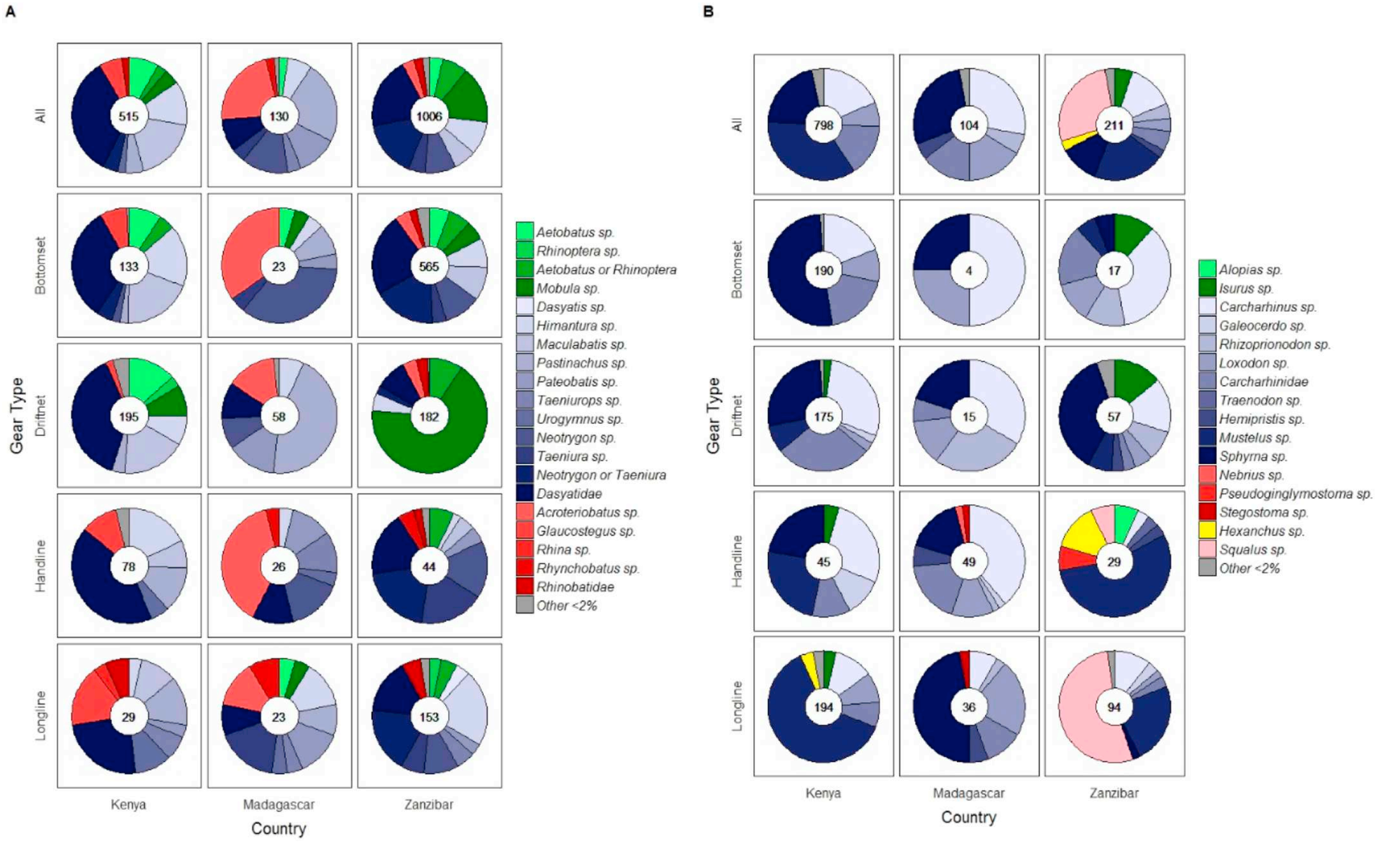

Fig. 3. Elasmobranch frequency of occurrence at the genus and family level displayed by country and gear type for A) batoids and B) sharks respectively. Sample size is displayed in the centre of each chart.

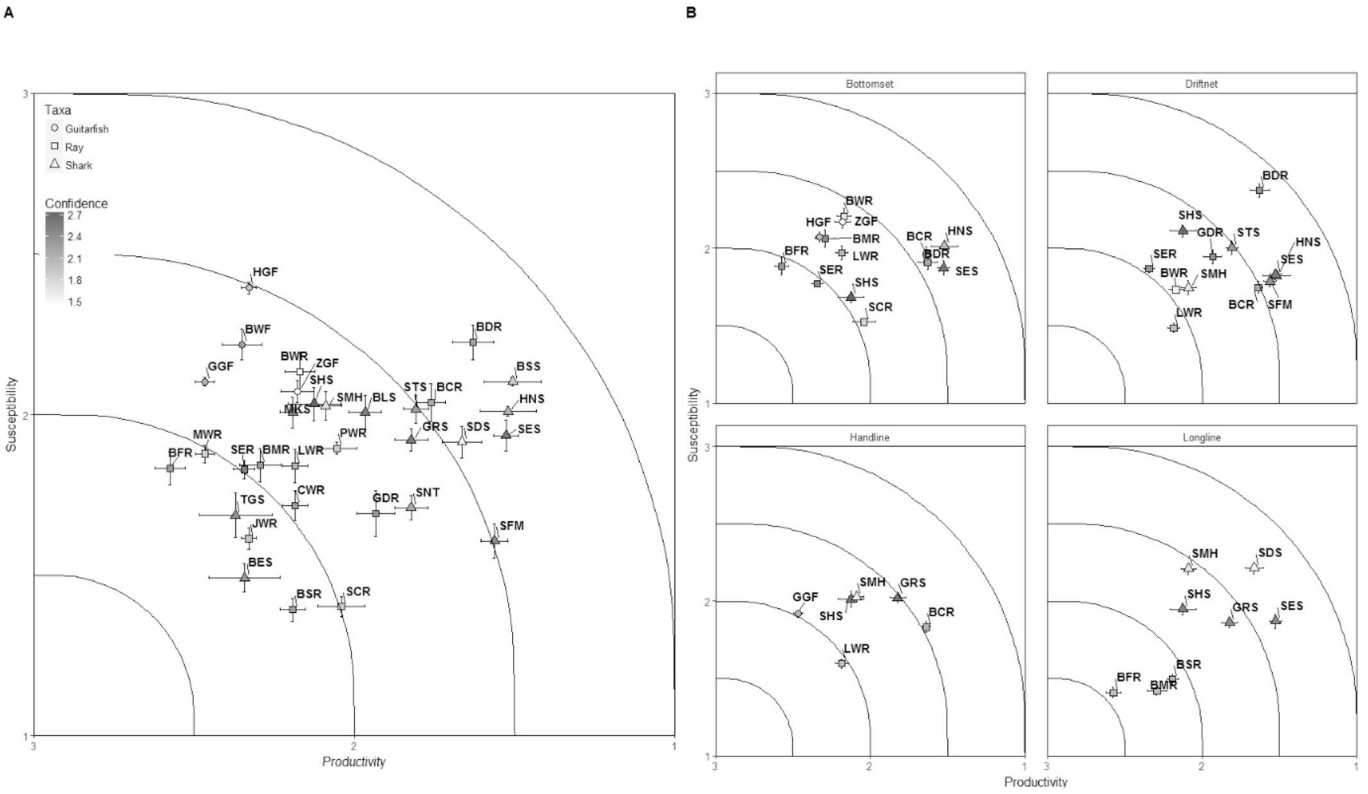

Fig. 4. Productivity-Susceptability Assessments for A) combined fishing gears, and B) individual fishing gears. Guitarfish: BWF, *Rhynchobatus australiae*; GGF, *Acroteriobatus leucospilus*; HGF, *Glaucostegus halavi*; ZGF, *Acroteriobatus zanzibarensis*. Rays: BWR, *Maculabatis ambigua*; BDR, *Mobula thurstoni*; BSR, *Taeniurops meyeni*; BFR, *Taeniura lymma*; BMR, *Neotrygon caeruleopunctata*; BSR, *Pastinachus ater*; CWR, *Himantura uarnak*; GDR, *Mobula mobular*; JWR, *Pateobatis jenkinsii*; LWR, *Himantura leoparda*; MWR, *Urogymnus granulatus*; PWR, *Pateobatis fai*; SCR, *Rhinoptera jayakari*; SER, *Aetobatus ocellatus*. Sharks: BES, *Hexanchus nakamurai*; BLS, *Carcharhinus leucas*; BSS, *Carcharhinus humani;* GRS, *Carcharhinus amblyrhynchos*; HNS, *Carcharhinus macloti*; MKS, *Rhizoprionodon acutus*; SHS, *Sphyrna lewini*; SFM, *Isurus oxyrinchus*; SES, *Loxodon macrorhinus*; SMH, *Mustelus* sp.; SNT, *Hemipristis elongata*; STS, *Carcharhinus sorrah*; SDS, *Squalus* spp.; TGS, *Galeocerdo cuvier*.

The PSA assessments (Fig. 4) for a total of 32 species give initial insight into relative species vulnerability across and within gear type. The overall assessments indicate the most vulnerable batoids to be: *M. thurstoni*, broad cowtail ray (*Pastinachus ater*), halavi guitarfish (*Glaucostegus halavi*), Zanzibar guitarfish (*Acroteriobatus zanzibarensis*) and *M. ambigua*; and the most vulnerable sharks to be *C. macloti*, blackspot (*Carcharhinus humanii*), *L. macrorhinus*, *Squalus* spp. and *C. sorrah*.

4. Discussion

This study presents the first independent estimates of elasmobranch landings in SWIO SSF handline, longline, bottom-set and drift gillnet gears. Despite the study covering only the aforementioned gear types, landings estimates are 72.6% higher than the cumulative total of 20,547 t reported by SWIO nations (which included large-scale fisheries) to the FAO in 2016, 129.2% more than the 10 year average of 15,468 t (2006–16), and 109.4% higher than the 16,928 t estimated in catch reconstructions for SWIO SSF in 2010 (FAO, 2018; Pauly and Zeller, 2015). Further, this estimate does not account for the landings (number of individuals) missed by observers at study sites, which were potentially substantial (weighted means between 17.3 and 33.9%). Overall, the results clearly demonstrate that the landings of elasmobranch species originating from SSF are likely to be substantially underrepresented in fisheries statistics outputs from the SWIO region.

The level of underreporting was variable at the country level. In Kenya, annual elasmobranch landings were estimated at 80.7% higher than their 10 year average of 327.5 t (2006–16) (FAO, 2018). Conversely, landings in Zanzibar are more similar to reported FAO data, with an estimate at 18.1% higher than the 10 year average of 1,631.6 t (2006–16) (FAO, 2018) which falls well within the 95% confidence intervals of the study estimate. Such differences reflect the varied efficacy of official landings data collection programmes among SWIO nations. Identifying and ameliorating low-efficacy observation programs is a clear priority if data derived from them is to be relied upon for evidence-based management, not only of elasmobranch resources but SSF resources as a whole. Other priority countries in the SWIO for such work include Madagascar and Mozambique, given their size and the relative disparity between elasmobranch landing declarations and the size of their SSF fleets (Chacate and Mutombene, 2016; FAO, 2018; WIOFish, 2018).

Previous studies have given some insight into elasmobranch composition of SWIO SSF, but are heavily biased towards the shark component (Temple et al., 2018). These studies suggest that the shark landings were comprised mainly of coastal and coral reef associated species such as *C. amblyrhynchos*, blacktip reef (*Carcharhinus melanopterus*), *T. obesus*, *Sphyrna* spp. and *G. cuvier* (e.g. Cooke, 1997; Kiszka et al., 2010; Maoulida et al., 2009; Robinson and Sauer, 2013). Though, particularly in the oceanic island nations, oceanic species such as blue shark (*Prionace glauca*) and *C. falciformis* also appear to be common (Kiszka et al., 2010; Maoulida et al., 2009; Soilihi, 2014). Pre-existing batoid compositional data often list *Mobula* spp., *Aetobatus* spp., large wedgefish (Rhinidae) and sawfish (*Pristis* spp.) (e.g. Cooke, 1997; Heinrichs et al., 2011; Poonian, 2015). This study, alongside other recent works (Barrowclift et al., 2017; Robinson and Sauer, 2013), clearly demonstrates that much of the pre-existing data is heavily biased by ease of identification and memorability. The vast majority of landings are composed of species that are either not easy to discern for untrained observers from more iconic species (e.g. *C. sorrah* are more numerous in the catch than *C. melanopterus*), or smaller species (e.g. *N. caeruleopunctata*, *T. lymma*, *Mustelus* spp., *Squalus* spp. and *L. macrorhinus*).

Further, the range of species impacted, from coastal, oceanic and deep-sea habitats demonstrate the potential for SSF to have impacts across a wide-range of ecosystems. It is clear that historically data for SWIO SSF elasmobranch catch composition is deficient. Whilst this study contributes substantially to our understanding, further improvement of compositional understanding is a clear priority in facilitating risk-assessment and sustainable management of elasmobranchs.

This study also demonstrates that despite receiving limited attention by SWIO SSF research (Temple et al., 2018), batoids are a significant and sometimes dominant portion of the elasmobranch landings. Batoids represented 43.3%, 30.7% and 74.7% by number, and 45.4%, 38.9% and 82.1% by weight of the landings in Kenya, northern Madagascar and Zanzibar, respectively. Batoids have a particularly high representation in Zanzibar, which may reflect fishing practices, market demand or the suspected decline and partial collapse of shark stocks (Barrowclift et al., 2017; Jiddawi and Shehe, 1999). The high level of batoid landings, combined with limited understanding of the ecology and life history of many of the species recorded, demonstrate a need to allocate research efforts to document life history parameters for this taxa.

Vulnerability assessment of the species identified in the study suggest that many of the large elasmobranch species (e.g. *G. cuvier*, *C. leucas*, *Sphyrna* spp., Rhinidae and *Mobula* spp.) achieve only moderate vulnerability scores. Instead many species that have gone unreported in previous works are identified as most vulnerable to SSF impacts. For sharks, highest vulnerability was identified for small coastal and continental shelf species (*C. malcoti*, *C. humanii*, *L. macrorhinus* and *C. sorrah*) and, surprisingly, deeper-water sharks (*Squalus* spp.). High vulnerability scores for sharks were observed in gillnets and longlines, with drift gillnets appearing to also threaten large oceanic species such as *I. oxyrinchus* and *Sphyrna* spp. In batoids, high vulnerability was identified in a number of geographically-restricted coastal species, including *G. halavi*, *A. zanzibarensis*, the recently described *M. ambigua* (Last et al., 2016) and *P. ater*. Unlike sharks, batoids appear primarily threatened by bottom-set gillnets, which dominate the batoid landings as a whole. Additionally, *M. thurstoni* was identified as the most vulnerable batoid, threatened by both bottom-set and drift gillnets. This finding is of particular concern given that *Mobula* spp. are already thought to be in in steep decline in parts of the SWIO (Rohner et al., 2017) and in the Indian Ocean at large (Walls et al., 2016). These unexpected vulnerability outputs further highlight the need to properly assess the catch composition of SSF, rather than relying on declarations of species composition, if catches are to be made sustainable through evidenced-based management in the long-term.

Whilst the study is not able to provide an estimate for the catch of marine mammals and sea turtles in SWIO SSF, it does reinforce the threats presented to both taxa by both bottom-set and drift gillnets across the region. Both species of delphinid (*S. longirostris* and *T. aduncus*) caught during this study have been reported or implicated in gillnet fisheries historically in the region (e.g. Amir et al., 2002; Pusineri and Quillard, 2008; Razafindrakoto et al., 2008), as have both commonly caught species of sea turtle (*E. imbricata* and *C. mydas*) (Okemwa et al., 2004). *E. imbricata* and *C. mydas* are the most common species in the tropical SWIO (Bourjea, 2015) and represented 60.3% and 38.5% of catch in this study, respectively. Bottom-set gillnets dominate sea-turtle captures (90.2%). However, the majority of landings (87.8%) were reported from one site (Watamu, Kenya), biasing the compositional results. Therefore, sea turtle composition presented here may not be representative of composition across SWIO SSF. The high level of reporting from this site is likely a result of the long-term collaboration, and thus trust, between fishers and one of the study partners. Further, in the few cases where usage data for sea turtle and dolphin landings were obtained their respective sales for human consumption and fisheries bait suggest that there continues to be notable markets for these taxa in spite of the illegality of their capture. Additionally, a single dugong (*Dugong dugon*) is known to have been landed during the study period in a drift gillnet in Msambweni, Kenya. Whilst not one of the sites monitored, the incident does highlight the ongoing threat from gillnet gears to the relict populations of this species in the SWIO region (Muir and Kiszka, 2012).

Though this study has begun to address the gap in understanding of marine megafauna catch it is important to acknowledge its limitations. Substantial heterogeneity in composition and catch rates was seen both among countries and among sites within countries. This heterogeneity may result from a large number of factors influencing fishing selectivity and species availability, including variability in gear specifications and fishing methods, exploited habitats and ecosystems and historical exploitation. This suggests that a larger number of sampling sites are required to ensure that outputs are representative. Further, it is important to recognise the likely biases of the methodology. Both marine mammal and sea turtle catch are universally prohibited across the study area (Temple et al., 2018), and so the likelihood of these catches being declared is low, inevitably leading to substantial underestimates of their catch. Identification bias will have an effect on species composition data presented here. This is primarily driven by the variable difficulty in identifying species from images of varying quality. Further, where appropriate we identified some landings by the local names given. Both elements will result in overrepresentation of distinctive species, such as *Sphyrna* spp. and *Mobula* spp., which are easier to identify and often have specific local names. The methodology also likely under-samples smaller elasmobranch species which are often stored and transported mixed with various fish and other landings, making smaller elasmobranchs less likely to be recorded by observers. Lastly, because landings were monitored on a representative sub-sample of days from those available, there is a risk that landings of rare but highly vulnerable species, such as sawfish (*Pristis* spp.), may have been missed. Yet, even limited catches may be highly significant to the long-term sustainability of highly vulnerable species. Conversely, catch discards in SWIO SSF are thought to be relatively low and so likely have limited influence on the overall results. Additionally, none of the sites in this study are known to operate fin-and-discard practices which would lead to underrepresentation of large shark and wedgefish landings.

The outcomes of this study clearly show the potential effects from SSF to a diverse range of coastal, oceanic, and even deep-water marine megafauna species, reinforcing SSFs potential to impact across multiple ecosystems. We provide the first cross-sectional assessment of marine megafauna catch and composition within SWIO SSF and demonstrate the underreporting of catch and the overrepresentation of large, iconic species in most existing assessments. Indeed, in many cases we show that historically under-represented species are likely those at most immediate threat from SSF. Further, we reinforce the cross-taxa threats posed by gillnet gears, and note their particular proclivity for impacting iconic species with implications for the growing ecotourism activities (Gallagher and Hammerschlag, 2011; O'Connor et al., 2009; O'Malley et al., 2013) in this and other regions. However, we recognise that this study represents a limited single-year time scale and, within the context of the SWIO, a limited geographic range. Thus, there is a clear need for further work in other areas and over longer time periods in order to improve assessments at the SWIO scale and inform evidence-based management of SWIO SSF. Similarly, this study focussed primarily on gear types which are thought to pose the greatest threat to marine megafauna and as such may overlook the impacts from other widespread gears such as purse and beach seines, these gears should be considered in future works. However, what is clear is that for the future sustainability of marine megafauna resources, further focus must be placed on the dominant but often overlooked SSF. Researchers and managers must face the challenges of working in SSF head-on, rather than seeking the relative comfort of the industrialised sectors, if touted aims of sustainability are to be met.

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Conflicts of interest

The authors declare no conflicts of interest that would inappropriately influence any aspect of the work carried out.

Role of the funding source and declaration of conflicts of interest

The funders played no part in the study design, analysis, interpretation of data, writing of the paper or decision to submit for publication.

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