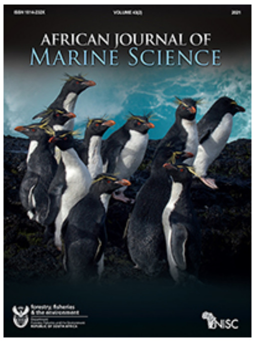

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African Journal of Marine Science

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tams20

Evaluating Kenya's coastal gillnet fishery: trade-offs in recommended mesh-size regulations

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To cite this article: K Osuka, JA Kawaka & MA Samoilys (2021) Evaluating Kenya's coastal gillnet fishery: trade-offs in recommended mesh-size regulations, African Journal of Marine Science, 43:2, 275-276, DOI: 10.2989/1814232X.2021.1945798

To link to this article: https://doi.org/10.2989/1814232X.2021.1945798

African Journal of Marine Science 2021, 43(2): 275–276
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AFRICAN JOURNAL OF MARINE SCIENCE
ISSN 1814-232X EISSN 1814-2338
https://doi.org/10.2989/1814232X.2021.1945798

Addendum

Evaluating Kenya's coastal gillnet fishery: trade-offs in recommended mesh-size regulations

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In the original accepted manuscript by Osuka et al. [K Osuka, JA Kawaka, MA Samoilys. 2021. Evaluating Kenya's coastal gillnet fishery: trade-offs in recommended mesh-size regulations, *African Journal of Marine Science* 43(1), 15–29; doi: 10.2989/1814232X.2020.1857836] (accepted in 2020) the authors used IUCN Red List categories according to IUCN (2018). Subsequent to publication of the article, the authors wish to update some of the IUCN Red List categories for some of the species mentioned using the updated IUCN Red List assessments (IUCN 2021). These changes likewise affect the categories as listed in the online supplemenarty material.

Detailed revisions of the text are as follows:

On p 15, Abstract, the sentence—

> Catches with small mesh tended to be species categorised as Least Concern on the IUCN Red List, in contrast to catches with large mesh which tended to be Near Threatened or Vulnerable species.

is revised as:

> Catches with small mesh tended to be species categorised as Least Concern on the IUCN Red List, in contrast to catches with large mesh which tended to be Vulnerable, Endangered or Critically Endangered species.

On pp 21–22, *Species composition*, the sentences—

> Large mesh sizes were broadly dominated by elasmobranchs, including species listed as Near Threatened or Vulnerable on the IUCN Red List of Threatened Species (IUCN 2018). Near Threatened species included *C. melanopterus, A. narinari* and *T. lymma*, while Vulnerable species comprised *Himantura uarnak*, giant manta ray *Manta birostris* and giant guitarfish *Rhynchobatus djiddensis* (Supplementary Table S1). Only one individual of the Endangered scalloped hammerhead *Sphyrna lewini* was caught in a medium mesh-size gillnet. The majority (30–34%) of threatened species (those listed as Endangered or Vulnerable) were found in large-mesh gillnets, followed by in medium-mesh (13–15%) and small-mesh (0–6%) gillnets (Figure 3).

are revised as:

> Large mesh sizes were broadly dominated by elasmobranchs, including species listed on the IUCN Red List of Threatened Species (IUCN 2021) as Critically Endangered (e.g. whitespotted wedgefish *Rhynchobatus djiddensis*), Endangered (e.g. giant manta ray *Mobula birostris*) and Vulnerable (e.g. whitetip reef shark *Triaenodon obesus, C. melanopterus, H. uarnak* and *A. ocellatus*). Critically Endangered species caught in medium mesh sizes included *R. djiddensis* and scalloped hammerhead *Sphyrna lewini*, while the only Endangered species was *M. birostris*. The majority (50–64%) of threatened species (those listed as Critically Endangered, Endangered or Vulnerable) were found in large-mesh gillnets, followed by in medium-mesh (23–30%) and small-mesh (3–9%) gillnets (Figure 3).

On p 27, ***Policy recommendations for Kenya's gillnet fishery***, the sentence—

> The capture of Vulnerable and Near Threatened species by large mesh sizes controverts their general recommendation for offshore fishing.

is revised as:

> The capture of Critically Endangered, Endangered and Vulnerable species by large mesh sizes controverts their general recommendation for offshore fishing.

In the next paragraph of the same section, the sentence—

> In summary, sustainable management of the coastal gillnet fishery in Kenya requires a trade-off between fishery returns (e.g. CPUE) versus the ecological impact of different mesh sizes in terms of juvenile retention and the capture of Near Threatened, Vulnerable or Endangered species.

is revised as:

> In summary, sustainable management of the coastal gillnet fishery in Kenya requires a trade-off between fishery returns (e.g. CPUE) versus the ecological impact of different mesh sizes in terms of juvenile retention and the capture of Vulnerable, Endangered or Critically Endangered species.

Lastly, Figure 3, p 23, is revised below to include the category Critically Endangered based on the updated IUCN Red List assessments (IUCN 2021):

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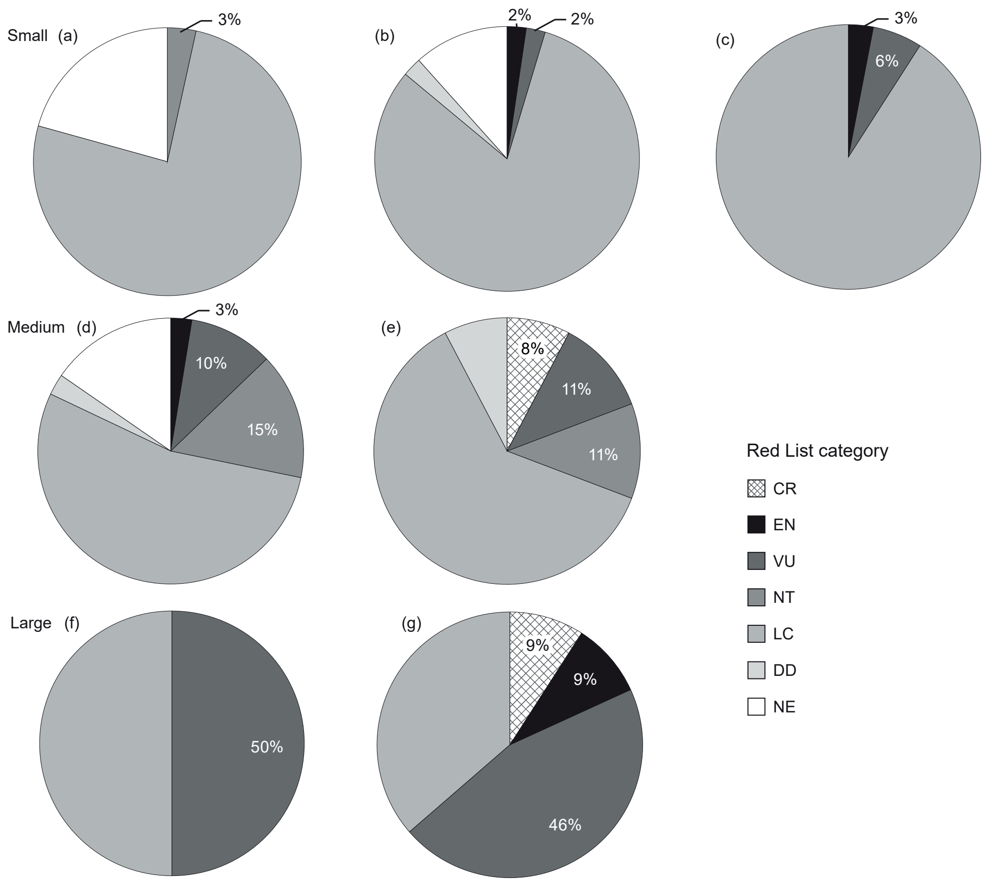

Figure 3: Pie charts showing the composition of the fish catches, as represented by their IUCN Red List categories, in gillnets of different mesh sizes: (a) 1.3 cm; (b) 5.1 cm; (c) 7.6 cm; (d) 10.2 cm; (e) 15.2 cm; (f) 20.3 cm; (g) 25.4 cm. Percentages are labeled only for categories considered threatened. IUCN Red List categories: CR = Critically Endangered; EN = Endangered; VU = Vulnerable; NT = Near Threatened; LC = Least Concern; DD = Data Deficient; NE = Not Evaluated

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Reference

IUCN (International Union for Conservation of Nature). 2021. The IUCN Red List of Threatened Species, version 2021-1. Available at http://www.iucnredlist.org [accessed March 2021].

African Journal of Marine Science 2020, 43(2): 277

AFRICAN JOURNAL OF MARINE SCIENCE
ISSN 1814-232X EISSN 1814-2338
https://doi.org/10.2989/1814232X.2021.1938384

CORRIGENDUM

K Osuka, JA Kawaka, MA Samoilys. 2021. Evaluating Kenya's coastal gillnet fishery: trade-offs in recommended mesh-size regulations, *African Journal of Marine Science* 43(1), 15–29; doi: 10.2989/1814232X.2020.1857836

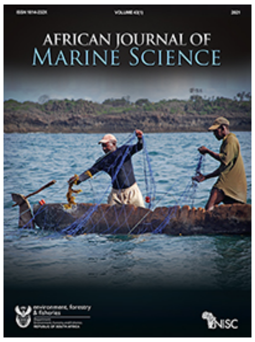
In the original article the following names of fishes should be changed throughout to reflect the correct, current nomenclature:

- genus *Manta* should be *Mobula* (hence, *Mobula birostris*);
- genus *Makaira* should be *Istiompax* (hence, *Istiompax indica*);
- *Valamugil seheli* should be *Crenimugil seheli*.

In addition, the spotted eagle ray was incorrectly referred to as *Aetobatus narinari* (which is restricted to the Atlantic Ocean) and instead is identified as *Aetobatus ocellatus* (which is the species that occurs in the Indo-Pacific).

In Supplementary Table S1, other changes to species names include the following:

- *Liza vaigiensis* should be *Ellochelon vaigiensis*;
- *Thysanophrys arenicola* should be *Sunagocia arenicola;*
- *Thysanophrys otaitensis* should be *Sunagocia otaitensis;* and
- V*alamugil seheli* should be *Crenimugil seheli*.



African Journal of Marine Science

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tams20

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African Journal of Marine Science 2021, 43(1): 15–29
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AFRICAN JOURNAL OF
MARINE SCIENCE
ISSN 1814-232X EISSN 1814-2338
https://doi.org/10.2989/1814232X.2020.1857836

Evaluating Kenya's coastal gillnet fishery: trade-offs in recommended mesh-size regulations

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Gillnets are a widely used fishing gear in Kenya's artisanal fisheries, yet their mesh sizes are inadequately monitored or regulated. This study evaluated the impacts of gillnets of seven stretched-mesh sizes, through comparative analysis of species-related metrics and catch per unit effort (CPUE), to inform Kenya's small-scale fisheries regulations. Data were collected from June 2014 to May 2015. Three mesh-size groups were identified from catch composition data using non-metric multidimensional scaling and comprised small (1.3, 5.1 and 7.6 cm), medium (10.2 and 15.2 cm) and large (20.3 and 25.4 cm) mesh. The dominant species (and their mean lengths) that were caught in the small, medium and large mesh sizes, respectively, were whitespotted rabbitfish *Siganus sutor* (21.7 cm [SD 5.3]), mackerel tuna *Euthynnus affinis* (40.8 cm [SD 9.1]) and honeycomb stingray *Himantura uarnak* (87.3 cm [SD 37.4]). Values of length at first capture (L_{50}) for *S. sutor* and *E. affinis* caught with the small and medium mesh sizes were below length at maturity (L_m). Catches of juveniles were proportionately high in the small meshes (61.3–74.2%) and lower in the medium (38.3–50.9%) and large (9.1–36.2%) mesh sizes. Catches with small mesh tended to be species categorised as Least Concern on the IUCN Red List, in contrast to catches with large mesh which tended to be Near Threatened or Vulnerable species. Biomass CPUE differed between mesh-size groups, with the small sizes recording low CPUE. The medium sizes caught mid- to high-trophic-level species with high-income returns, displayed moderate CPUE, and had the lowest juvenile retention and capture of threatened species. Medium mesh sizes are therefore recommended for artisanal fisheries, given low trade-offs between ecological impact and fishery returns.

Keywords: adaptive co-management, artisanal fisheries, conservation status, juvenile capture, multispecies catches, size selectivity, small-scale fisheries

Online supplementary material: The total number of fish examined, the number of juveniles in the sample, and the proportion of juvenile fish for each species caught in each of seven gillnet mesh-size categories are provided in Table S1. The IUCN Red List status and the contribution of each species to the catch in each of the gillnet mesh-size categories are provided in Table S2. The Supplementary tables are available at https://doi.org/10.2989/1814232X.2020.1857836.

Introduction

Small-scale coastal fisheries provide valuable food security and livelihoods for ~20 million coastal people living in eastern Africa (Bell et al. 2017). However, excessive dependence on fishing coupled with high population growth, poor regulation of fishing and destructive gears have caused overharvesting and habitat damage (Wells et al. 2007; Samoilys et al. 2015). Kenya's small-scale fisheries generate approximately $7.95 million per year (Obura et al. 2017) and produce 90% of the total annual marine landings of 24 000 tonnes (Government of Kenya 2016a). The sector also supports more than 13 400 fishers and their dependents through providing income and animal protein to up to 80% of rural households living on the coast (McClanahan et al. 2013). The artisanal fishery, which encompasses small-scale traditional fishing carried out for subsistence or commercial purposes, mostly operates inshore in lagoons or creeks, with a capacity for offshore fishing limited by initial capital investment (Mangi et al. 2007). Nevertheless, the use of destructive, illegal and inadequately regulated fishing gears is widespread in both inshore and offshore waters, leading to a decline in fish yields (Samoilys et al. 2017) and alteration of marine habitats (Mangi and Roberts 2006; McClanahan et al. 2008).

More than 13 different artisanal fishing gear types are used within 12 nautical miles of the Kenyan shoreline (Samoilys et al. 2011, 2017). While gear diversity is considered high, only five gears dominate in usage: basket-trap, gillnet, handline, speargun and beach-seine (McClanahan and Mangi 2004; Samoilys et al. 2017), although the last two gears are prohibited (Government of Kenya 2016b). Gillnets are one of the most widely used gears among marine artisanal fishers in all coastal counties of Kenya, with a total of 3 835 gillnet pieces of varying mesh sizes, lengths, and heights recorded in 2016, increasing by 15% from 2014 (Government of Kenya 2016c). The artisanal marine gillnets are highly diverse, used either as active seine nets or passive setnets, with their stretched-mesh sizes ranging from <6.4 cm (2.5″) to >25.4 cm (10.0″), though the 15.2-cm (6.0″) mesh size is the most common (Government of Kenya 2016c). Interestingly, fishers in Kenya categorise gillnets into eight subtypes that are identifiable by local names and mesh sizes: (i) *soni* 10–15 cm (3.9–5.9″); (ii) *shuhuri* 18 cm (7.1″); (iii) *oban* 20 cm (7.9″); (iv) *sinia nusu* ~23 cm (~9.0″); (v) *lasha* 30–36 cm (11.8–14.2″); (vi) *sinia kubwa* 46 cm (18.1″); (vii) *jarife/nyavu ya kueleza/nyavu ya kuogelesha* 5–12 cm (2.0–4.7″); and (viii) *nyavu ya tafi/mpweke* 2.5–11 cm (1.0–4.3″) (Samoilys et al. 2011, 2017). This classification of gillnets by fishers differs from what is recorded by government fisheries frame surveys, which involve censuses of fishers, gears, crafts, landing-site facilities and services operating at the coast (Government of Kenya 2016c). Despite this, all fisheries research to date aggregates all gillnets as one gear type, largely because national research projects and landings data have not distinguished between different gillnets (e.g. Kaunda-Arara et al. 2003; McClanahan and Mangi 2004; Tuda et al. 2016; Samoilys et al. 2017). As a result, knowledge of the impacts of fishing with various types of gillnets is minimal. More importantly, there is a general concern over the use of gillnets as they are associated with bycatch of threatened species, such as sea turtles, sharks, rays and marine mammals (Kiszka et al. 2009). In addition, landings from Kenya's coral reef and seagrass habitats are mainly composed of undersized fish, likely driven by the use of gillnets of small mesh sizes (McClanahan and Mangi 2004; Mangi and Roberts 2006; Hicks and McClanahan 2012).

The Kenyan Fisheries Management and Development Act No. 35 of 2016 prohibits fishing practices such as the use of explosives, poison, spearguns and beach-seines (Government of Kenya 2016b) because of their negative impacts on target species and juvenile fish populations as well as habitat damage. Restrictions on the use of particular gillnet mesh sizes in the marine environment are not clear, though there are restrictions specific to fishing in rivers or bodies of water forming parts of riverine systems (Government of Kenya 2016b). In this regard, mesh sizes of <4.5 cm are not allowed and neither are monofilament nylon gillnets. Prohibitions on monofilaments are due to their non-biodegradable nature and the possibility of 'ghost fishing' when discarded or lost (Samoilys et al. 2011; Government of Kenya 2016b). For a gear type that is used in many coastal and marine habitats, targeting a wide range of species, the existing laws that regulate the use of gillnets are inadequate in promoting sustainable fishing with minimal destruction to the marine ecosystem (Hicks and McClanahan 2012).

Gillnet mesh-size-selective properties determine the species composition and size structure of the catch (Ramírez-Amaro and Galván-Magaña 2019), which are in turn influenced by habitat type. Therefore, consistent deployment of particular mesh sizes in shallow habitats such as coral reefs and seagrass beds can alter the size structure of fish stocks (Dalzell 1996; Argent and Kimmel 2005). Finding an optimum mesh size for a multispecies artisanal fishery is a challenge (Ramírez-Amaro and Galván-Magaña 2019), and thus research providing practical management recommendations pertaining to gillnet mesh sizes is needed to support Kenya's fisheries regulations. This is one of only a few studies that seek to understand the effects of fishing with gillnets in an artisanal tropical fishery by evaluating catch composition, juvenile retention, the trophic level of fish captured, and the catch per unit effort (CPUE) of different mesh sizes. The study provides policy recommendations on mesh sizes, by seeking to achieve a balance between minimising negative impacts of the gear on the marine ecosystem and ensuring sustainable and profitable fishing.

Materials and methods

Study sites

The study was conducted at eight fish-landing sites distributed across two counties (Kilifi and Kwale) in Kenya, from June 2014 to May 2015 (Figure 1). A total of 77 and 70 fishing trips were undertaken in the dry northeast monsoon season (NEM; October to March) and the wet southeast monsoon season (SEM; April to September), respectively. The landing sites were variously situated adjacent to coral fringing reefs and lagoons (Watamu, Mnarani, Gazi, Mkunguni), along creeks (Sita, Uyombo), and on offshore sandbanks in waters of >40 m depth (Ras Ngomeni, Ras Ngoi). In this study, creeks refer to non-estuarine small inlets or bays, whereas lagoons are seagrass marine habitats separated from the sea by a reef. The landing sites of Watamu and Ngomeni consisted of two or three smaller gazetted landing sites that were combined into a single landings dataset. Sites were pre-selected based on prior knowledge of gillnet use and the results of a biannual fisheries frame survey conducted by the State Department for Fisheries and Blue Economy (Government of Kenya 2016a).

Deployment and catch surveys

Deployment and catch surveys were conducted to collect effort and catch data from gillnet fishing trips. In both types of survey, gillnets were measured in terms of stretched mesh size (in inches), length and height, and the type of material used in manufacturing the nets was recorded. Deployment surveys involved following fishers fishing on foot to observe and record their gillnet deployment process. Effort data were collected by recording the deployment method used (foot or boat), crew size, major habitat at the fishing ground, estimated bottom depth and fishing duration. Fishers using canoes and boats were monitored at a central landing site or on the shore where they beached their boats, and their catch was assessed before it was landed and sold. In Kenya's artisanal fishery, discards are minimal to almost none (Mangi and Roberts 2006), and thus the landings assessed were representative of the actual catches. Where fishers could not be followed, information on deployment was obtained by interviewing the fishing crew, with particular focus on the start and finish times of fishing, major habitat of fishing ground, and bottom depth. It was not possible to determine the method of capture (i.e. gilled or entangled) at the landing sites. Instead, the catch surveys involved assessing all landed individual fish, both gilled and entangled, and recording total weight of catch (kg), species' weight and fork length (cm). Total weight was measured to the nearest 0.5 kg using a spring balance (Nops®). Fish species were identified using published guides (e.g. Lieske and Myers 2002; Anam and Mostarda

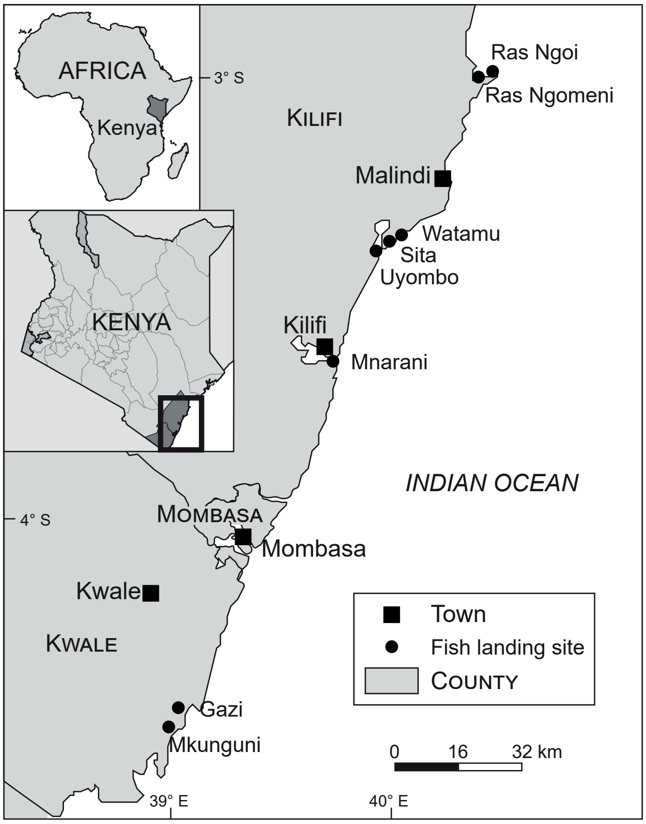

Figure 1: Map of the study area on the Kenyan coast showing landing sites where the gillnet fishery deployment and catch surveys were conducted, from June 2014 to May 2015

2012), and unidentified species were photographed and recorded with their local Swahili names for subsequent identification. Individual weights were measured using an electronic balance to the nearest 10 g, while fork lengths (FL) and disc widths (DW) were measured to the nearest 0.1 cm using a fish-measuring board or tape measure. For small catches, all fish were measured. For large catches (>20 kg), and where the fishers were in a hurry, a random subsample of approximately a quarter of the catch was selected for measurement of individual weights and FL.

Local gillnet dealers operating fishing-gear shops in Mombasa were consulted to provide information on availability and cost of, and fishers' preference for, different gillnet mesh sizes. Furthermore, the distribution of gillnet mesh sizes at a national level was assessed using data published in the biannual marine frame survey of 2016 (Government of Kenya 2016c).

Data analysis

Seven mesh-size categories were defined for analysis: 1.3–3.8 cm (0.5–1.5″), hereafter 1.3 cm; 5.1–6.4 cm (2.0–2.5″), hereafter 5.1 cm; 7.6–8.9 cm (3.0–3.5″), hereafter 7.6 cm; 10.2–12.7 cm (4.0–5.0″), hereafter 10.2 cm; 15.2–17.8 cm (6.0–7.0″), hereafter 15.2 cm; 20.3–22.9 cm (8.0–9.0″), hereafter 20.3 cm; and 25.4–30.5 cm (10.0–12.0″), hereafter 25.4 cm. Grouping of mesh sizes and ensuring a 'mesh-size gap' between the mesh-size categories was undertaken in order to maximise detection of differences in selectivity. Two multinomial logistic regressions were performed, first to determine factors influencing selection by fishers of the gillnet mesh sizes based on deployment information about the location of the landing site (south coast or north coast), material type (multifilament or monofilament) and cost of the gear, and second to determine factors predicting deployment of gillnet mesh sizes based on the habitat type (creek, lagoon, coral reef or offshore sandbanks), nature of deployment (passive or active), time of day (day or night) and depth (shallow or deep, arbitrarily defined as 0–40 m and >40 m, respectively). Data were binary-coded, and where more than two nominal groups existed, a reference class was selected: for example, 1.3 cm for mesh sizes, and coral reefs for habitat type. The cost of the gear was determined by multiplying the cost per metre by length of the net.

Nonparametric tests were used to test significance for difference because the data did not conform to the assumptions applicable to the use of parametric statistics, even after transformation (Zar 1999). The number of fishing trips made by gillnet fishers was compared between day and night, using a Mann–Whitney *U*-test. The number of individuals per species caught during each fishing trip per mesh size was used to test for differences in diversity between the fish species caught by different mesh sizes. Measures of diversity applied included species richness (*S*), Shannon–Weiner diversity index (*H*′), evenness (*J*′) and ecological dominance (*D*). The Kruskal–Wallis nonparametric test was applied to determine differences between mesh sizes. To showcase the similarity and selectivity of species by mesh size, nonmetric multidimensional scaling (nMDS), based on Bray–Curtis similarity, was performed in PRIMER 6 (Clarke and Warwick 2001) on a subset of species-composition data with ≥10 individuals across all seven mesh-size categories. This involved 32 species of the total of 102 species recorded. A one-way SIMPER analysis was performed to identify species that contributed most towards (dis)similarity in the mesh-size groups. Clustering of mesh sizes in the nMDS formed the basis for assessing the gillnet fishery, including the length-frequency distributions of three dominant species. One-way ANOSIM was applied to identify (dis)similarity in species composition across seasons and mesh sizes. Having tested that the differences between seasons were not significant (ANOSIM; $R = 0.032$, $p = 0.465$), data were aggregated across seasons. Length at first capture (L_{50}), which is the mean length at which 50% of the fish are retained, was determined for species with at least 25 individuals per mesh size (*sensu* Ramírez-Amaro and Galván-Magaña 2019), based on methods by Sparre and Venema (1998) and Millar (2000).

Length at first maturity (L_m) per species was obtained from FishBase (Froese and Pauly 2015) and used to determine the proportion of juveniles in catches across the mesh-size categories. Individuals with a FL less than L_m were considered juveniles, and those with a FL equal to or greater than L_m were considered adults. Trophic level is a useful metric for profitability (Neori and Nobre 2012).

Thus, trophic levels of the fish species were obtained from FishBase, with lower trophic groups, such as herbivores, in levels 1–2, and higher trophic groups, such as piscivores, in levels 4–5. The trophic level of the catch for each mesh-size category (k) was calculated using the following formula of Pauly et al. (2001):

$$TL_k = \sum_{i=1}^{m} Y_{ik} TL / \sum Y_{ik}$$

where Y_{ik} is the catch of species i in gear k, and TL is the mean trophic level of species i for m fish. Catch per unit effort (CPUE), expressed as kg^{-1} fisher^{-1} h^{-1} and ind. fisher^{-1} h^{-1}, was calculated for each fishing trip and compared across the different mesh-size categories using a Kruskal–Wallis test followed by a pairwise Mann–Whitney *post hoc* test.

Results

Deployment surveys and interviews/consultations

A total of 147 gillnet fishing trips from eight landing sites were surveyed. The number of trips conducted by fishers was higher during the day than at night (Mann–Whitney $U = 432.5$, $p = 0.03$). Fishing using gillnets was carried out by crews of 2–8 fishers, who deployed gillnets from vessels that included dugout canoes, dhows and motorised boats, and in 6.2% of cases gillnets were deployed on foot.

Gillnet fishing was reported to take place in four major coastal habitats: creeks (5.4%), coral reefs (15.7%), lagoons (19.7%) and offshore sandbanks (59.2%). Particular mesh sizes tended to be deployed in fishing grounds of a certain marine habitat type (Table 1). For example, the smallest mesh sizes, 1.3 cm and 5.1 cm, were widely deployed in lagoons, at 73.3% and 40.9%, respectively, whereas the mesh sizes 10.2 cm and 20.3 cm were mainly deployed on offshore sandbanks, at 96.3% and 100%, respectively. A wide range of mesh sizes, including 5.1 cm, 7.6 cm, 10.2 cm and 15.2 cm, were deployed in coral reef habitats.

The cost per metre of gillnets increased with mesh size: $0.60 for 1.3–7.6 cm, $0.66 for 10.2 cm, and $1.37 for 20.3–25.4 cm (Table 1). The marine artisanal fisheries frame survey report of 2016 showed that the 15.2-cm mesh size was the most widely used gillnet at 41.3%, followed by the mesh sizes 10.2 cm (29.5%) and 7.6 cm (14.0%) (Table 1). The large mesh sizes of 20.3 cm and 25.4 cm were the least common gillnets, together contributing to only 2.6% of the total number of gillnets. Consultations with fishing-gear suppliers and fishers in the present study also revealed 10.2 cm and 15.2 cm to be the most common mesh sizes. Deployed gillnets were constructed from either multifilament (78.6%) or illegal monofilament nylon (21.4%). Multifilament gillnets were common in all mesh-size categories while monofilament nylon gillnets were found only in the 1.3-cm, 5.1-cm and 7.6-cm mesh sizes.

Most of the gillnet fishing trips (67.8%) in the present study were conducted through passive fishing, and 32.2% were through active fishing. In passive fishing, nets were deployed from the vessel as either bottom-set nets that were heavily weighted and negatively buoyant, or as floating surface nets that were lightly weighted and positively buoyant. After a period agreed among the crew, usually 2–3 hours during the day or ~12 hours overnight, the net was hauled into the vessel while the surrounding water was struck with sticks to herd fish into the net. The fish were then separated from the net and the gear was stowed aboard the vessel, as the captain travelled to the next fishing ground for the next deployment. This was generally repeated during the entire ebb tide and part of the flood-tide period. Active gillnet fishing involved deploying the gear from a fishing vessel and dragging the net through the water column, usually in shallow lagoons.

Multinomial regression on factors thought to drive the selection of mesh sizes (location, material type and cost) showed specific differences based on the estimates of the log-odds, which are an alternate way of expressing probabilities (Table 2). Landing sites located on the south coast relative to the north coast showed increased log-odds (2.20–21.65) (Table 2) of using mesh sizes ≥5.1 cm relative to mesh size 1.3 cm. The increase (0.54) was, however, not significant for mesh size 7.6 cm relative to 1.3 cm. The log-odds for choosing multifilament net relative to monofilament net decreased for 5.1-cm and 7.6-cm mesh relative to 1.3-cm mesh, and it increased for 10.2 cm, 15.2 cm, 20.3 cm and 25.4 cm relative to 1.3 cm. Increase in gear cost significantly increased the log-odds (0.11) of selecting mesh size 5.1 cm relative to 1.3 cm; however,

Table 1: Distribution of gillnet mesh sizes by deployment habitat, and cost per metre of gillnet, in the present study, and national distribution of gillnets by mesh size in 2016. Costs of gillnets were derived through consultation with gear dealers, while numbers of gillnets per mesh size in 2016 were derived from a national frame survey report (Government of Kenya 2016c)

Mesh size range (cm)	1.3–3.8	5.1–6.4	7.6–8.9	10.2–12.7	15.2–17.8	20.3–22.9	25.4–30.5
No. of fishing trips in present study	15	22	19	27	36	10	18
	Deployment habitats (as % of fishing trips per mesh size)						
Creeks	26.7	13.6	5.3	0	0	0	0
Lagoons	73.3	40.9	36.8	0	0	0	11.1
Coral reef	0	27.3	36.8	3.7	25.0	0	0
Offshore sandbanks	0	18.2	21.1	96.3	75.0	100	88.9
Cost per meter ($)	0.60	0.60	0.60	0.66	0.82	1.37	1.37
	National totals in 2016						
No. of gillnets	144	315	514	1 082	1 514	68	27
% of total gillnets	3.9	8.6	14.0	29.5	41.3	1.9	0.7

Table 2: From a survey of Kenya's coastal gillnet fishery, the results of a multinomial logistic regression predicting selection of mesh sizes as a function of location (south coast or north coast), material type (multifilament or monofilament) and gear cost (*n* = 147 gillnet fishing trips). *$p \leq 0.05$; **$p \leq 0.01$; ***$p \leq 0.001$

	(Intercept)		Location		Material type		Gear cost	
Mesh size (cm) (reference class 1.3–3.8)	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE
5.1–6.4	−0.62	0.97	3.10**	1.16	−2.36*	1.01	0.11*	0.06
7.6–8.9	0.20	0.91	0.54	1.39	−2.130*	0.88	0.07	0.06
10.2–12.7	−22.00***	0.38	2.20*	0.89	23.01***	0.38	−0.01	0.06
15.2–17.8	−21.11***	0.40	2.95***	0.90	20.78***	0.40	0.01	0.06
20.3–22.9	−32.70***	0.34	21.65***	0.34	11.46***	0.34	0.13	0.07
25.4–30.5	−21.36***	0.70	4.83***	1.35	17.55***	0.70	0.13	0.07

Table 3: For Kenya's coastal gillnet fishery, the results of a multinomial logistic regression predicting deployment of mesh sizes as a function of habitat type (creek, lagoon, coral reef or offshore sandbank), nature of deployment (passive or active), time of the day (day or night) and bottom depth (shallow or deep) (*n* = 147 gillnet fishing trips). ***$p \leq 0.001$

	Intercept		Creek vs coral reef		Lagoon vs coral reef		Offshore sandbank vs coral reef		Passive vs active		Day vs night		Shallow vs deep	
Mesh size (cm) (reference class = 1.3–3.8)	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE
5.1–6.4	23.88***	1.49	−32.40***	0.89	−14.61***	0.69	−0.54***	1.39	16.72***	0.95	18.25***	1.06	−9.25***	1.47
7.6–8.9	24.10***	1.19	−34.31***	1.05	−15.84***	0.69	−0.42	1.05	17.22***	1.02	18.18***	1.14	−8.88***	1.14
10.2–12.7	25.69***	1.13	−49.87***	0.00	−34.14***	0.00	−1.35	0.91	18.22***	1.19	19.13***	1.23	−12.72***	1.30
15.2–17.8	22.72***	1.17	−62.71***	0.00	−42.44***	0.00	1.37	0.92	18.71***	1.11	19.19***	1.18	−8.02***	0.95
20.3–22.9	−1.91***	0.34	−10.48***	0.00	3.20***	0.00	26.05	0.34	18.10***	0.34	−11.01***	0.00	−23.56***	0.00
25.4–30.5	−71.37***	0.40	−29.51***	0.00	−11.43***	0.00	66.53***	0.40	21.08***	1.46	46.88***	0.97	20.73***	0.88

the log-odds of selecting the other gears relative to 1.3-cm mesh were not significant.

The log-odds of gillnet fishers fishing in either creeks or lagoons relative to coral reef habitats decreased when using mesh sizes ≥5.1 cm relative to 1.3-cm mesh (Table 3). An exception was increased log-odds (3.20) of deploying a mesh size of 20.3 cm relative to 1.3 cm in lagoons relative to coral reefs (Table 3). The log-odds of deploying 5.1-cm mesh relative to 1.3-cm mesh decreased (−0.54) when the habitat was offshore sandbanks relative to coral reefs, whereas that of deploying 25.4-cm mesh relative to 1.3-cm mesh increased (66.53). In terms of deployment method, the log-odds of fishing passively relative to active fishing increased when fishing with mesh sizes ≥5.1 cm relative to 1.3-cm mesh. The log-odds of fishing during the day relative to at night increased for all mesh sizes relative to 1.3-cm mesh, except for a mesh size of 20.3 cm, for which there was a decrease (−11.01). The log-odds of fishing in shallow water (≤40 m) compared with in deep water (>40 m) decreased for all mesh sizes relative to 1.3-cm mesh, except for mesh size 25.4 cm, for which there was an increase (20.73).

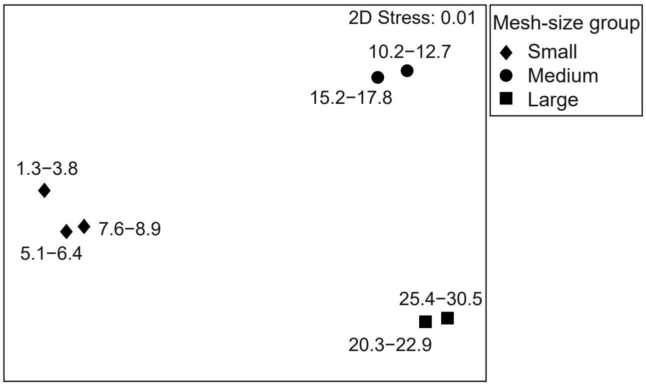

Figure 2: Non-metric multidimensional scaling plot of the species composition of fish catches in gillnets of seven mesh sizes, grouped into small, medium and large meshes, in Kenya's coastal fishery. The data points are labelled with the mesh-size ranges

Catch surveys

Mesh-size selectivity

The nMDS plot identified three main mesh-size groups in terms of species composition of the catches (Figure 2). Mesh sizes ranging from 1.3 to 7.6 cm defined the first group; a second group comprised mesh sizes of 10.2 cm and 15.2 cm; a third group comprised mesh sizes of 20.3 cm and 25.4 cm. ANOSIM results showed significant differences among the mesh-size categories (Global R = 0.925; $p < 0.001$), providing statistical justification for presenting the results based on three mesh-size groups: small (1.3 cm, 5.1 cm and 7.6 cm), medium (10.2 cm and 15.2 cm), and large (20.3 cm and 25.4 cm). Dissimilarity of the mesh-size groups was attributed to dominance of whitespotted rabbitfish

Table 4: Results of one-way SIMPER analyses of fish species contributing approximately 90% of the dissimilarity in abundance (%) in three mesh-size groups in the Kenyan coastal fishery. Small mesh = 1.3 cm, 5.1 cm and 7.6 cm; medium mesh = 10.2 cm and 15.2 cm; large mesh = 20.3 cm and 25.4 cm. Species contributing most to the dissimilarity are shown in bold

Species	Average abundance		Average dissimilarity	Contribution (%)
Average dissimilarity = 88.16	Small mesh	Medium mesh		
Siganus sutor	**4.2**	0.0	7.2	8.2
Euthynus affinis	0.0	**4.0**	7.0	7.9
Hyporhamphus affinis	**2.8**	0.0	4.7	5.4
Scomberomorus commersoni	0.4	**3.0**	4.5	5.2
Lutjanus fulviflamma	**2.8**	0.4	4.1	4.7
Lethrinus lentjan	2.2	0.0	3.8	4.4
Coryphaena hippurus	0.0	2.2	3.7	4.2
Leptoscarus vaigiensis	2.2	0.0	3.5	4.0
Carcharhinus melanopterus	0.0	2.1	3.5	3.9
Thunnus albacares	0.0	1.9	3.4	3.8
Scomberomorus plurilineatus	0.0	1.8	3.3	3.7
Lethrinus harak	2.1	0.4	3.0	3.4
Gerres longirostris	1.7	0.0	2.8	3.2
Scarus psittacus	1.7	0.0	2.8	3.2
Scomberoides commersonianus	0.2	1.9	2.7	3.1
Istiophorus platypterus	0.0	1.5	2.7	3.0
Lethrinus nebulosus	1.7	1.0	2.5	2.8
Himantura uarnak	0.0	1.4	2.3	2.6
Herklotsichthys punctatus	1.3	0.0	2.3	2.6
Parupeneus barberinus	1.2	0.0	1.9	2.2
Mugil cephalus	1.1	0.9	1.8	2.1
Plectorhinchus flavomaculatus	0.8	0.4	1.8	2.0
Rastrelliger kanagurta	1.1	0.0	1.6	1.8
Jenkinsia lamprotaenia	0.9	0.0	1.6	1.8
Sargocentron diadema	0.9	0.0	1.4	1.5
Average dissimilarity = 95.50	Small mesh	Large mesh		
Siganus sutor	**4.2**	0.0	9.5	10.0
Hyporhamphus affinis	**2.8**	0.0	6.2	6.5
Lutjanus fulviflamma	**2.8**	0.0	6.2	6.5
Himantura uarnak	0.0	2.5	5.8	6.1
Lethrinus lentjan	2.2	0.0	5.1	5.4
Carcharhinus melanopterus	0.0	2.2	5.0	5.3
Lethrinus harak	2.1	0.0	4.7	5.0
Leptoscarus vaigiensis	2.2	0.0	4.6	4.8
Taeniura lymma	0.0	1.8	4.2	4.4
Aetobatus narinari	0.0	1.7	3.9	4.1
Gerres longirostris	1.7	0.0	3.7	3.9
Scomberomorus plurilineatus	1.7	0.0	3.7	3.9
Lethrinus nebulosus	1.7	0.0	3.6	3.8
Herklotsichthys punctatus	1.3	0.0	3.1	3.2
Mugil cephalus	1.1	0.0	2.6	2.7
Parupeneus barberinus	1.2	0.0	2.5	2.6
Lutjanus argentimaculatus	0.7	1.0	2.4	2.5
Manta birostris	0.0	1.0	2.3	2.4
Chanos chanos	0.6	1.6	2.2	2.3
Plectorhinchus flavomaculatus	0.8	0.0	2.2	2.3
Jenkinsia lamprotaenia	0.9	0.0	2.1	2.2
Rastrelliger kanagurta	1.1	0.0	2.0	2.1
Average dissimilarity = 65.98	Medium mesh	Large mesh		
Euthynus affinis	**4.0**	0.0	10.4	15.7
Scomberomorus commersoni	**3.0**	0.0	7.7	11.7
Coryphaena hippurus	**2.2**	0.0	5.4	8.2
Thunnus albacares	1.9	0.0	5.1	7.7
Scomberomorus plurilineatus	1.8	0.0	5.0	7.6
Scomberoides commersonianus	1.9	0.0	4.6	7.0
Istiophorus platypterus	1.5	0.7	3.1	4.7
Himantura uarnak	1.4	**2.5**	3.1	4.7
Aetobatus narinari	0.6	1.7	3.1	4.6
Taeniura lymma	0.8	1.8	2.8	4.3
Lutjanus argentimaculatus	1.4	1.0	2.6	4.0
Manta birostris	0.8	1.0	2.6	4.0
Lethrinus nebulosus	1.0	0.0	2.3	3.4
Chanos chanos	0.7	1.6	2.1	3.2

Siganus sutor, tropical halfbeak *Hyporhamphus affinis* and dory snapper *Lutjanus fulviflamma* in small mesh sizes; mackerel tuna *Euthynnus affinis* and common dolphinfish *Coryphaena hippurus* in medium mesh sizes; and honeycomb stingray *Himantura uarnak*, spotted eagle ray *Aetobatus narinari* and bluespotted fantail ray *Taeniura lymma* in large mesh sizes (Table 4).

Common species explaining within-group similarity of the three mesh-size clusters were: *S. sutor*, *L. fulviflamma* and thumbprint emperor *Lethrinus harak* for small mesh sizes; *E. affinis*, narrow-barred Spanish mackerel *Scomberomorus commersoni* and *C. hippurus* for medium mesh sizes; and *H. uarnak*, blacktip reef shark *Carcharhinus melanopterus* and *A. narinari* for large mesh sizes (Table 5).

Species composition

Catch of the gillnet fishery comprised a total of 1 303 individuals representing 102 species (Supplementary Table S1). *Siganus sutor*, *E. affinis* and *Hyporhamphus affinis* formed 30% of the landed fish across all mesh sizes (Supplementary Table S2). The small mesh sizes captured 29–43 species, while the medium and large mesh sizes captured 26–39 and 10–12 species, respectively (Table 6). Large mesh sizes were broadly dominated by elasmobranchs, including species listed as Near Threatened or Vulnerable on the IUCN Red List of Threatened Species (IUCN 2018). Near Threatened species included *C. melanopterus*, *A. narinari* and *T. lymma*, while Vulnerable species comprised *Himantura uarnak*, giant manta ray *Manta birostris* and

Table 5: Results of one-way SIMPER analyses of fish species contributing 90% overall to the within-group similarity in abundance (%) in the mesh-size groups: small (average similarity = 37.1%), medium (average similarity = 46.9%) and large (average similarity = 62.9%), in the Kenyan coastal gillnet fishery

Species	Average abundance	Average similarity	Contribution (%)
Small mesh sizes (1.3 cm, 5.1 cm and 7.6 cm)			
Siganus sutor	4.2	6.9	18.7
Lutjanus fulviflamma	2.8	4.7	12.5
Lethrinus harak	2.1	3.6	9.6
Hyporhamphus affinis	2.8	3.2	8.6
Lethrinus lentjan	2.2	2.8	7.6
Leptoscarus vaigiensis	2.2	2.5	6.6
Gerres longirostris	1.7	1.8	4.8
Parupeneus barberinus	1.2	1.3	3.4
Strongylura incisa	1.2	1.3	3.4
Scarus psittacus	1.7	1.3	3.4
Lethrinus nebulosus	1.7	0.9	2.5
Lutjanus argentimaculatus	0.7	0.6	1.7
Mugil cephalus	1.1	0.6	1.7
Parupeneus macronema	0.9	0.6	1.7
Cheilinus chlorourus	0.8	0.6	1.6
Valamugil seheli	1.1	0.6	1.6
Carangoides ferdau	0.7	0.5	1.3
Medium mesh sizes (10.2 cm and 15.2 cm)			
Euthynnus affinis	4.0	8.2	17.7
Scomberomorus commersoni	3.0	6.3	13.7
Coryphaena hippurus	2.2	3.6	7.8
Carcharhinus melanopterus	2.1	3.1	6.7
Lutjanus argentimaculatus	1.4	3.1	6.7
Plicofollis dussumeiri	1.6	3.1	6.7
Thunnus albacares	1.9	3.1	6.7
Rhynchobatus djiddensis	1.2	2.5	5.3
Scomberoides commersonianus	1.9	2.5	5.3
Carangoides ferdau	0.7	1.6	3.4
Epinephelus fuscoguttatus	0.9	1.6	3.4
Himantura uarnak	1.4	1.6	3.4
Istiophorus platypterus	1.5	1.6	3.4
Lobotes surinamensis	0.9	1.6	3.4
Large mesh sizes (20.3 cm and 25.4 cm)			
Himantura uarnak	2.5	13.3	21.1
Carcharhinus melanopterus	2.2	12.7	20.2
Aetobatus narinari	1.7	9.3	14.8
Taeniura lymma	1.8	9.3	14.8
Chanos chanos	1.6	8.0	12.7
Epinephelus fuscoguttatus	1.1	6.3	10.1

Table 6: From a survey of Kenya's coastal gillnet fishery, mean values (standard error) of community parameters (measures of diversity) for different mesh sizes. The number of fishing trips sampled and the total number of species recorded for each mesh size are also shown

Parameter	Stretched mesh size (cm)						
	1.3–3.8	5.1–6.4	7.6–8.9	10.2–12.7	15.2–17.8	20.3–22.9	25.4–30.5
No. of fishing trips	15	22	17	27	36	10	18
Total no. of species	29	43	36	39	26	10	12
Species richness (*S*)	4.47 (0.98)	4.23 (0.94)	3.37 (0.82)	2.26 (0.41)	2.17 (0.21)	2.00 (0.26)	1.72 (0.11)
Shannon diversity index (*H*′)	0.88 (0.22)	0.85 (0.18)	0.65 (0.20)	0.51 (0.11)	0.55 (0.09)	0.58 (0.12)	0.47 (0.07)
Species evenness (*J*′)	0.84 (0.05)	0.86 (0.03)	0.90 (0.03)	0.95 (0.01)	0.93 (0.02)	0.96 (0.02)	0.97 (0.01)
Dominance (*D*)	0.60 (0.09)	0.59 (0.08)	0.70 (0.09)	0.71 (0.06)	0.67 (0.05)	0.62 (0.07)	0.67 (0.05)

giant guitarfish *Rhynchobatus djiddensis* (Supplementary Table S1). Only one individual of the Endangered scalloped hammerhead *Sphyrna lewini*was was caught in a medium mesh-size gillnet. The majority (30–34%) of threatened species (those listed as Endangered or Vulnerable) were found in large-mesh gillnets, followed by in medium-mesh (13–15%) and small-mesh (0–6%) gillnets (Figure 3).

None of the diversity measures showed significant differences between mesh sizes (Kruskal–Wallis test: species richness S = 5.178, p = 0.459; Shannon–Weiner diversity index H' = 3.887, p = 0.662; evenness J' = 4.457, p = 0.487; and ecological dominance D = 3.032, p = 0.783) (Table 6).

Juvenile retention

The proportion of juveniles pooled across all mesh sizes was 55.6%, slightly higher than the proportions in medium mesh sizes, which ranged from 38.3% to 50.9%. Juvenile retention in the small mesh sizes ranged from 61.3% to 74.2%, and in large mesh sizes it ranged from 9.1% to 36.2% (Table 7). The highest proportions of juvenile capture were in small mesh sizes deployed in creeks (63.9–70.8%), lagoons (59.9–91.7%), and coral reef habitats (65.2–81.0%). Low proportions of juveniles were caught by large mesh sizes deployed on offshore sandbanks (Table 7).

The length-frequency distribution of the three most-abundant species varied across the mesh sizes (Figure 4). The small mesh sizes captured the highest proportion of juveniles of abundant species, and medium mesh sizes caught the least juveniles (see also Supplementary Table S1). Large mesh sizes captured both juveniles and adults of two ray species; however, the smaller mesh (20.3 cm) captured more juveniles of *H. uarnak*, whereas the larger mesh (25.4 cm) captured more juveniles of *A. narinari*. Only two species (*Coryphaena hippurus* and *Carcharhinus melanopterus*) of the nine analysed for length distribution had all their individuals taken as adults (Figure 4).

The catches showed a clear relationship between a species' mean length and the mesh size in which it tended to be caught. For example, catches in small mesh sizes were dominated by *Siganus sutor* (21.7 cm FL [SD 5.3]) and *Hyporhamphus affinis* (21.7 cm FL [SD 4.7]). Catches in the medium mesh sizes were dominated by *E. affinis* (40.8 cm FL [SD 9.1]) and *Scomberomorus commersoni* (69.6 cm FL [SD 18.6]). The largest mesh sizes caught *H. uarnak* (87.3 cm DW [SD 37.4]) and other elasmobranchs which spanned 85–193 cm FL or DW. Analyses of length at first capture (L_{50}) were performed on two species: *Siganus sutor* for small mesh sizes, and *E. affinis* for medium mesh sizes. The L_{50} for *S. sutor* caught in small mesh sizes ranged between 15.5 cm and 22.8 cm and was below the length at maturity (L_m) of 26.0 cm. Similarly, the L_{50} of *E. affinis* was ~42.5 cm and was below the L_m of 47.1 cm.

Trophic level

The gillnet mesh sizes caught species across a wide range of trophic levels, from 2.0 to 4.5, but trophic level did not increase linearly with increasing mesh size (Figure 5a). The 7.6-cm mesh captured species with the lowest trophic level (median = 2), mostly herbivores, but did not differ significantly (p = 0.406) from the 5.1-cm mesh, which captured mid-trophic-level species (median = 3.2). The smallest mesh size of 1.3 cm also captured mid-trophic-level species (median = 3.5) and differed significantly from all other mesh sizes, including the largest mesh sizes of 20.3 cm and 25.4 cm (both with a median of 3.6). Both the 10.2-cm and the 15.2-cm mesh sizes captured mid- to high-trophic-level species, largely piscivores, with medians of 4.1 and 4.5, respectively.

Catch per unit effort

Catch per unit effort (CPUE) based on the biomass and abundance of fish caught differed significantly between the gillnet mesh sizes (Figure 5b, c). The lowest biomass CPUE (median = 0.25 kg fisher^{-1} h^{-1}) was recorded in the 1.3-cm and 5.1-cm mesh sizes, while the highest biomass CPUE (median = 17.35 kg fisher^{-1} h^{-1}) was recorded in the 25.4-cm mesh size. The *post hoc* results showed that the large mesh sizes of 20.3 cm and 25.4 cm had significantly higher biomass CPUE than all other mesh sizes. By contrast, CPUE expressed in numbers of individuals caught was higher in the small mesh sizes (median = 4.5 ind. fisher^{-1} h^{-1}) compared with the medium and large mesh sizes.

Discussion

Deployment of gillnets

Medium mesh sizes were deployed in a range of habitats that overlapped those where small and large mesh sizes were used. Medium mesh sizes were used on coral reefs and offshore sandbanks. Small mesh sizes were deployed from creeks to lagoons to coral reefs, whereas large mesh

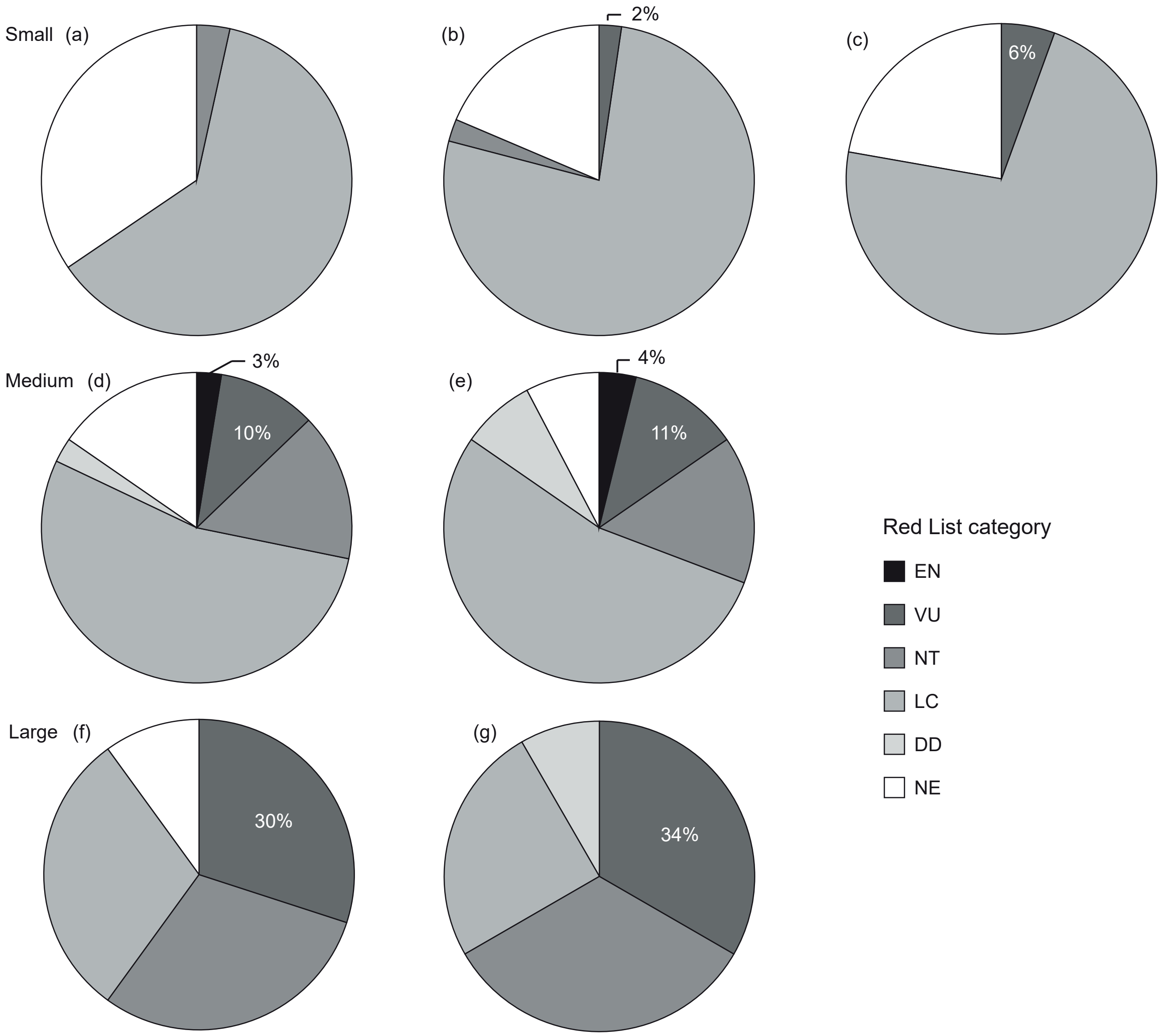

Figure 3: Pie charts showing the composition of the fish catches, as represented by their IUCN Red List categories, in gillnets of different mesh sizes: (a) 1.3 cm; (b) 5.1 cm; (c) 7.6 cm; (d) 10.2 cm; (e) 15.2 cm; (f) 20.3 cm; (g) 25.4 cm. Percentages are labelled only for categories considered threatened. IUCN Red List categories: EN = Endangered; VU = Vulnerable; NT = Near Threatened; LC = Least Concern; DD = Data Deficient; NE = Not Evaluated

Table 7: Percentages of juvenile fish in the catches of seven gillnet mesh sizes (grouped as small, medium and large) in the Kenyan coastal fishery, from June 2014 to May 2015

Mesh-size group	Mesh size (cm)	Juvenile captures (%)	Juvenile captures by habitat (%)			
			Creeks	Lagoons	Coral reef	Offshore sandbanks
Small	1.3–3.8	61.3	63.9	59.9		
	5.1–6.4	64.4	75.7	62.0	65.2	53.8
	7.6–8.9	74.2	70.8	91.7	81.0	53.3
Medium	10.2–12.7	50.9			42.9	51.6
	15.2–17.8	38.3			41.3	36.4
Large	20.3–22.9	9.1				9.1
	25.4–30.5	36.2				36.2

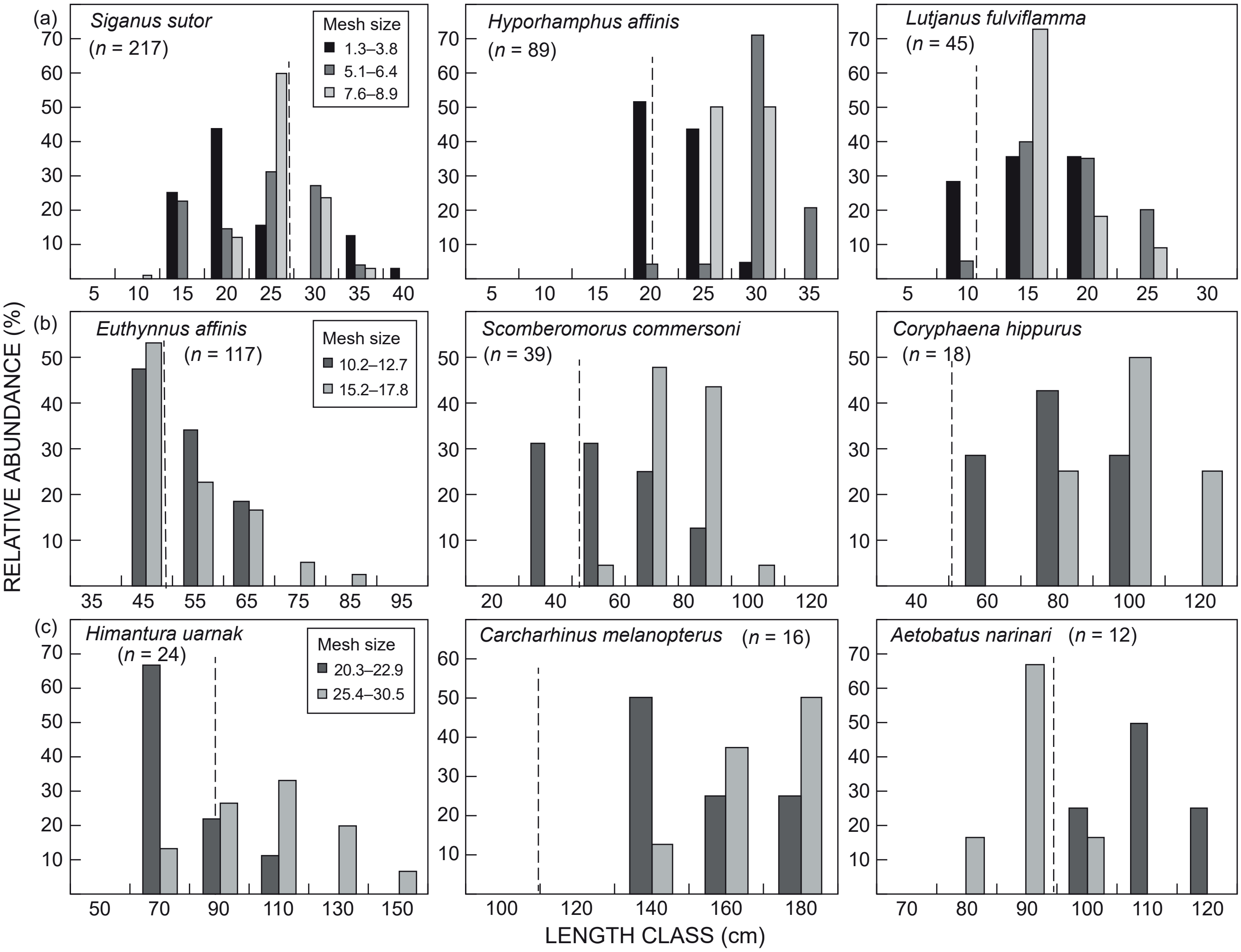

Figure 4: Length-frequency distributions of the three dominant fish species in the gillnet catches in each of the three mesh-size groups: (a) small (1.3 cm, 5.1 cm and 7.6 cm); (b) medium (10.2 cm and 15.2 cm); (c) large (20.3 cm and 25.4 cm). Vertical dashed lines indicate length at first maturity (L_m) (from Froese and Pauly [2015])

sizes were mostly used on offshore sandbanks. The overlap associated with medium mesh sizes provides fishers with a greater choice of areas to fish, because of diverse habitat characteristics, and a wide range of depths and modes of deployment (i.e. passive or active fishing) (Santos et al. 2003; Mangi and Roberts 2006). The spatial distribution of mesh sizes might also be attributable to factors not considered in this study, such as positioning in the water column, skills to use nets of different mesh sizes, and personal preferences, including behavioural rigidity and unwillingness to change (Mangi et al. 2007). The cost of different mesh sizes is likely not a limiting factor preventing fishers from using particular mesh sizes, but rather other running costs associated with the deployment of large mesh sizes, notably fuel and boat maintenance, which are normally taken care of by *tajiris* who are senior fishers who work as fish dealers owning both fishing gears and vessels and often employing young fishers (Fulanda et al. 2009). Availability of the nets, which depends on whether the nets are manufactured locally or imported, would also influence usage. In this study, all nets and mesh sizes were assumed to be equally available. The interplay of these factors makes it difficult to draw firm conclusions about their effects on predicting the deployment of different mesh sizes. Nonetheless, results on deployment show that the gillnet fishery lends itself to location-specific fisheries management and conservation planning (Samoilys et al. 2019).

Facilitating fishers' access to offshore pelagic habitats is likely to reduce overfishing in coral reef and seagrass lagoon habitats and to sustain Kenya's coastal fishery. However, the larger crew size needed for pelagic fishing, coupled with high maintenance costs, might limit the adoption of larger mesh sizes. Moreover, offshore fishing with large mesh sizes would require a consideration of mitigation measures for turtle and cetacean bycatch mortalities (Samoilys et al. 2011), such as installation of low-cost deterrent devices like pingers (Kiszka et al. 2009). Instead, fishing offshore but with gillnets with a medium mesh size could shift targeting to medium-sized pelagic fishes such as tuna species and other scombrids, which

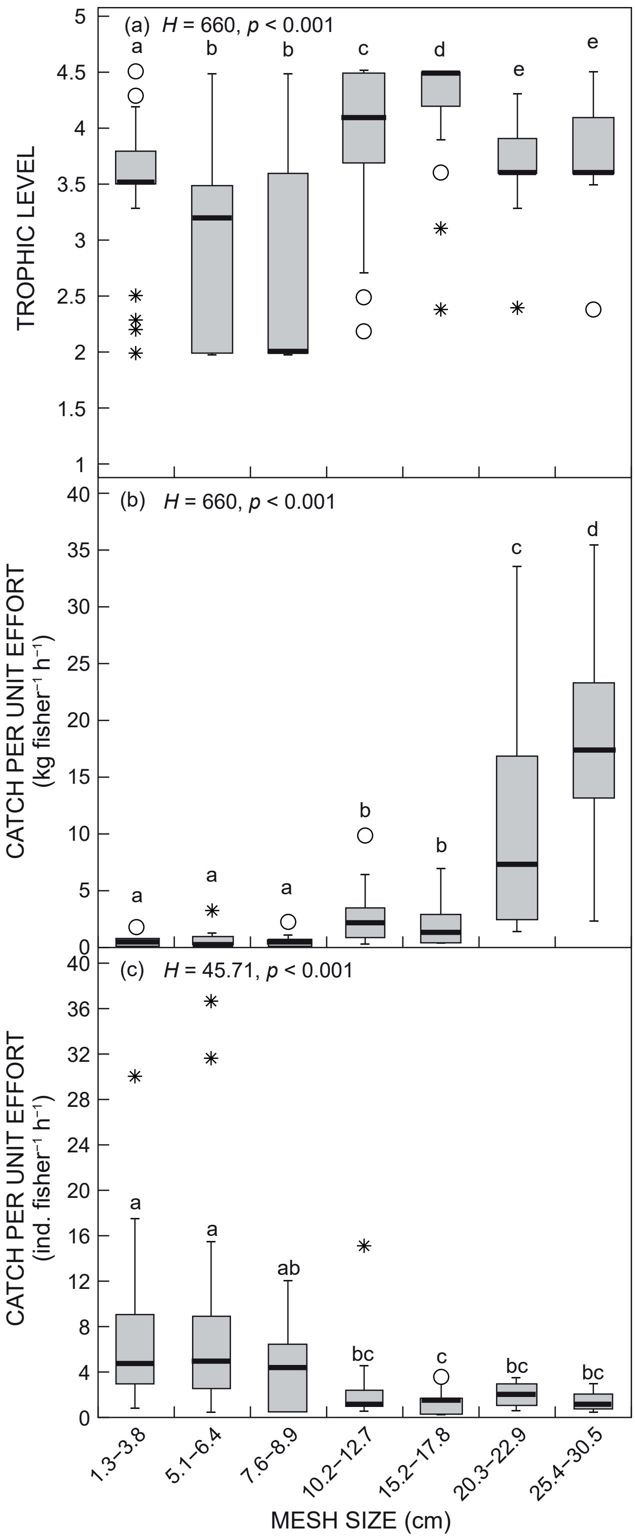

Figure 5: (a) Trophic level of species, (b) biomass catch per unit effort (CPUE), and (c) abundance CPUE of fish caught by gillnets of seven mesh sizes in the Kenyan coastal fishery. Box-plot components represent the upper and lower quartiles (box), the median (solid line within box), 1.5x interquartile range (whiskers), and outliers (circles and asterisks). Mesh sizes (cm) with identical lowercase letters were not significantly different based on a pairwise Mann–Whitney *post hoc* test

are considered underexploited in Kenya (Maina and Osuka 2014; Wekesa 2014).

Gear selectivity and species of special concern

The three mesh-size groups of small, medium and large were identified from the species composition of catches taken in seven gillnet mesh sizes. This implies that the mesh size associated with a particular catch can be ascertained from the species composition and length-frequency distributions of that catch. The smallest mesh size of 1.3 cm captured small pelagic fishes, *Hyporhamphus affinis* and species of *Herklotsichthys*. These seasonally occurring schooling fish are an important part of artisanal fisheries, and fishers have sufficient knowledge of their migration patterns to be able to adjust their mesh sizes to catch certain cohorts (Maina and Osuka 2014). Catches in the other small mesh sizes of 5.1 cm and 7.6 cm were dominated by *Siganus sutor*. This species is targeted widely by other artisanal fishing gears, such as basket traps, beach-seines and spearguns (McClanahan and Mangi 2004; Samoilys et al. 2017), which implies that the species will continue to face considerable fishing pressure (Kaunda-Arara et al. 2003; Samoilys et al. 2011, 2017; Hicks and McClanahan 2012; Tuda et al. 2016). Though it is resilient to heavy fishing pressure owing to a short life span of two years (Grandcourt 2002), efforts are still needed to reduce pressure on the species (Maina et al. 2013), particularly given the increasing number of fishers and gears that target *S. sutor* (Government of Kenya 2016c).

The medium mesh sizes captured *Euthynus affinis*, *Scomberomorus* spp. and *Coryphaena hippurus*, which are moderately large species. They are also fast-growing epipelagic fishes (Ahmed et al. 2015) with a high economic return (Maina and Osuka 2014). As mentioned above, targeting of these species can be considered an option to offset the high fishing pressure on species captured by small mesh sizes (Bell et al. 2016), although high operation costs and long travel times to deeper fishing areas may hinder this option.

Large mesh sizes captured fishes with large body depth and girth, such as *Himantura uarnak* and *Carcharhinus melanopterus*, which are known to feed and rest on sandbank habitats offshore (Froese and Pauly 2015). The general capture of rays by large mesh sizes is associated with their dorso-ventrally flattened body shape, which limits their ability to escape from larger mesh sizes (Ramírez-Amaro and Galván-Magaña 2019). While some fishers in these multispecies fisheries prefer sharks and rays, many other species are vulnerable to capture as well. Indeed, more than 60% of the catches taken with the large mesh sizes were species assessed as Near Threatened or Vulnerable, and therefore widespread use of large-mesh gillnets is of concern.

Fishing is a primary driver of shark and ray population declines worldwide, through both targeted and incidental capture (Dulvy et al. 2000; Worm et al. 2013). The loss of shark and ray populations potentially has severe ecological impacts, such as the inversion of trophic pyramids (Myers et al. 2007; Worm et al. 2013, Hussey et al. 2014; Sandin and Zgliczynski 2015). They are also highly vulnerable to fishing mortality owing to their slow growth and late maturation, and therefore have lesser ability to recover from population decline. Although there is little research published on shark and ray fisheries in Kenya, overexploitation and high demand for shark and ray products are considered the main causes of declines (Samoilys and Kanyange 2008; Oddenyo et al. 2018). They are consumed as meat products that are either sun-dried, salted, frozen or deep-fried. Other products such as shark fins are sold to international markets, while shark liver oils are used for anti-fouling purposes in the artisanal fishery (Oddenyo et al. 2018). Addressing these harvesting and trade challenges will be critical for the recovery of sharks and rays. In Kenya's artisanal fisheries, management and conservation of these fishes is legislated through the Fisheries Management and Development Act 2016 (Government of Kenya 2016b), which also adopts the resolutions of the Indian Ocean Tuna Commission (IOTC) on the conservation, management and transshipment of sharks and rays. However, species conservation and management measures specific to sharks and rays remain minimal. Since large mesh sizes are frequently deployed offshore but frequently capture Vulnerable and Near Threatened sharks and rays, the general recommendation for offshore fishing should be linked with medium mesh sizes.

Juvenile retention among mesh sizes

There were substantial differences in juvenile retention between the three groups of gillnet mesh sizes. Small mesh sizes captured up to twice the proportions of juvenile fish (61–74% of the catch) compared with medium mesh sizes (38–51%), while large mesh sizes caught the lowest proportions (9–36%). This high level of juvenile retention in gillnets in Kenya has been reported previously (Mangi and Roberts 2006; Samoilys et al. 2017) but the mesh sizes were not known. The high proportions of juvenile fishes caught in small mesh sizes are a function of mesh size but also suggest that the habitats fished using these mesh sizes, specifically in seagrass lagoons, creeks and coral reefs, are functioning as nursery grounds for target species (Nagelkerken et al. 2000). Our results corroborate previous studies stating that Kenya's seagrass and coral reef fisheries are heavily exploited (Kaunda-Arara et al. 2003; McClanahan et al. 2008; Hicks and McClanahan 2012; Samoilys et al. 2017) but show specifically that gillnets with mesh sizes of 1.3–7.6 cm are likely to be causing growth overfishing, and that even the 10.2-cm mesh size is problematic, with ~50% juvenile capture.

The dominant species in the small and medium mesh sizes exhibited length at first capture (L_{50}) below length at maturity (L_m). Protection of these species will require L_{50} to be at least more than L_m and this can be achieved by increasing the size of allowed meshes. The medium mesh sizes caught relatively low numbers of juveniles compared with the small mesh sizes, and also captured adults of pelagic species, such as *E. affinis*, *Scomberomorus commersoni* and *Coryphaena hippurus*. These three species are fast-growing and mature early (at 0.5–3 years), and hence are more resilient to overfishing (Froese and Pauly 2015). To counteract their short-lived life history, which makes them vulnerable to environmental perturbations, these species spawn by broadcasting large numbers of eggs and sperm in open water, thereby enhancing recruitment success. However, large mesh sizes also captured two species (*H. uarnak* and *Aetobatus narinari*) with slow growth rates and late maturity (4–9 years). Interestingly, juveniles of *A. narinari* were not captured in the 20.3-cm mesh, suggesting their low likelihood of entanglement in these nets by their tail spine and developing dorsoventrally flattened body, an observation also reported in Mexico (Cuevas-Zimbrón et al. 2011; Ramírez-Amaro and Galván-Magaña 2019). The morphometric characteristics of fish species are therefore important considerations in managing the gillnet fishery. They particularly illustrate that nets with small mesh have a high risk of collapsing stocks of certain fish species (Essington et al. 2015) and should be discouraged.

Trophic level and CPUE

Gillnets of different mesh sizes landed species across a range of trophic levels, reflecting differences in species composition among the mesh sizes. Species of the lowest trophic level were caught in small mesh sizes and those of the highest tophic level in medium mesh sizes. Mid-trophic-level species caught in large mesh sizes included the high proportion of rays (trophic level = 3.6), which feed on invertebrates (Froese and Pauly 2015), whereas the small mesh sizes captured *Hyporhamphus affinis* and *Herklotsichthys punctatus*, the diet of which is composed of zoobenthos and zooplankton (Froese and Pauly 2015). Medium mesh sizes captured mid- to high-trophic-level species belonging to carnivorous or omnivorous families, including the Scombridae and the Coryphaenidae. Species in these families generally have a shorter lifespan than the species of sharks and rays caught in the large-mesh gillnets, and are therefore likely to be more resilient to fishing. In many fisheries, including tropical artisanal fisheries, high-trophic-level groups are preferred because of their high protein content and high economic returns (Neori and Nobre 2012); however, selective removal of high-trophic-level species can lead to alteration of the food web, potentially leading to 'fishing down the food web' (Pauly et al. 1998).

Biomass CPUE and abundance CPUE showed opposite relationships with increasing mesh size. In small mesh sizes, abundance CPUE was highest whereas biomass CPUE was lowest. Biomass CPUE is considered an indicator of profitability to fishers (Carruthers et al. 2011), and a high biomass CPUE is clearly desirable for fishers. The highest biomass CPUE was found in large mesh sizes, but unfortunately large mesh captured a high proportion of sharks and rays that are categorised as Near Threatened or Vulnerable. Moreover, these mesh sizes were not widely popular among fishers (Government of Kenya 2016c; JAK pers. obs.). Medium mesh had moderate biomass CPUE and captured both mid- and high-trophic-level species, and these sizes are therefore suggested as the best gillnets to use. This mesh size would strike a balance between minimal capture of threatened species, which perform critical ecosystem functioning, while maintaining moderately high profitability to fishers.

Policy recommendations for Kenya's gillnet fishery

Deployment of different mesh sizes showed spatial resource partitioning among fishers, which suggests an opportunity for management of the fishery (McClanahan et al. 2008). Changes in use of mesh sizes would require gear-exchange programmes (Maina and Samoilys 2011) that would help fishers acquire and maintain appropriate nets and fishing boats. Successful adoption of appropriate mesh sizes would also depend on appreciation by fishers of the need to change to promote the sustainability of the fishery (McClanahan and Kosgei 2019). Otherwise, the high diversity of gillnets would perpetuate compromised sustainability.

The high juvenile capture and the low biomass CPUE in small mesh sizes indicate they are ecologically destructive and of limited economic value when compared to medium or large mesh sizes. Regulated increases in mesh size have been demonstrated elsewhere to almost double the spawning stock biomass, leading to an increase of ~20% in gillnet catches and hence to better economic returns (Heikinheimo et al. 2006). Optimisation of Kenya's gillnet yield therefore requires an increase in the minimum mesh size (McClanahan and Mangi 2001) to levels that will protect a significant proportion of the stocks of various species prior to reaching maturity; this approach would enable fishers to catch larger fish that attract better income. Expressed differently, prohibition of smaller mesh sizes thus provides protection of juveniles of species targeted as adults by other mesh sizes.

The capture of Vulnerable and Near Threatened species by large mesh sizes controverts their general recommendation for offshore fishing. Thus, phasing out large mesh sizes would reduce the capture of threatened elasmobranchs. This would also lower the incidental capture of marine mammals and turtles, although the extent of the impact of the gillnet fishery on these taxa is still poorly known in Kenyan waters (Kiszka et al. 2009; Temple et al. 2017). However, sharks are a target species for some artisanal fishers, such as on the north coast of Kenya where there has been a shark fishery for centuries, and therefore mitigation measures are likely to be resisted (Samoilys and Kanyange 2008). Consequently, changes in gillnet management need to be preceded by awareness-creation regarding the overall benefits of vulnerable marine species to the ecosystem and the importance of their conservation. It is therefore recommended that offshore fishing with the least-damaging gillnet mesh size of 15.2 cm be promoted as an alternative.

Of the three mesh-size groups identified, medium mesh sizes were associated with the fewest apparent ecological effects and with moderate yields. Adoption of medium mesh sizes has the potential to reduce the current fishing pressure on commonly targeted species, avoid stock collapses, and achieve greater yields in the gillnet fishery. In summary, sustainable management of the coastal gillnet fishery in Kenya requires a trade-off between fishery returns (e.g. CPUE) versus the ecological impact of different mesh sizes in terms of juvenile retention and the capture of Near Threatened, Vulnerable or Endangered species. We recommend the following mesh-size restrictions, which should be applied in conjunction with other management measures under an adaptive and participatory co-management framework with fishers (e.g. Kawaka et al. 2017):

- Temporal and spatial restriction of 1.3-cm mesh size should be implemented to ensure sustainable harvesting of seasonal small pelagic species, such as *Hyporhamphus affinis* and species of *Herklotsichthys*.
- Phase out the mesh sizes of 5.1 cm and 7.6 cm owing to their capture of high numbers of juvenile fish and the low biomass CPUE.
- Promote the use of mesh sizes of 10.2 cm and 15.2 cm, which were characterised by a moderate biomass CPUE of fast-growing and early-maturing species of mid- to high trophic levels, a relatively low juvenile retention, and low catches of Near Threatened, Vulnerable and Endangered sharks and rays.
- Phase out mesh sizes of 20.3 cm and 25.4 cm owing to the high capture of sharks and rays.

Acknowledgements — We are grateful to the United Nations Development Programme–Small Grants Programme (UNDP-SGP) for funding this study. We extend special thanks to the Beach Management Units (BMUs) of Mnarani, Watamu, Mkunguni, Gazi, Uyombo and Ngomeni, as well as to members of the Sita fishing community. We specifically recognise contributions in field-data collection by Michael Murunga, Hashim Omar, Athman Shariff, Michael Gilbert, Steve Trott, Peter Musembi, Farouk Mohamed and Edward Wale. We thank the two anonymous reviewers for their constructive comments, which helped us to improve the manuscript. This study was covered under Research Permit No. NACOSTI/P/18/08032/21763 issued to CORDIO East Africa by the National Commission for Science, Technology and Innovation.

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Manuscript received January 2020 / revised September 2020 / accepted October 2020