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Socio-ecological change in estuaries of the Western Indian Ocean

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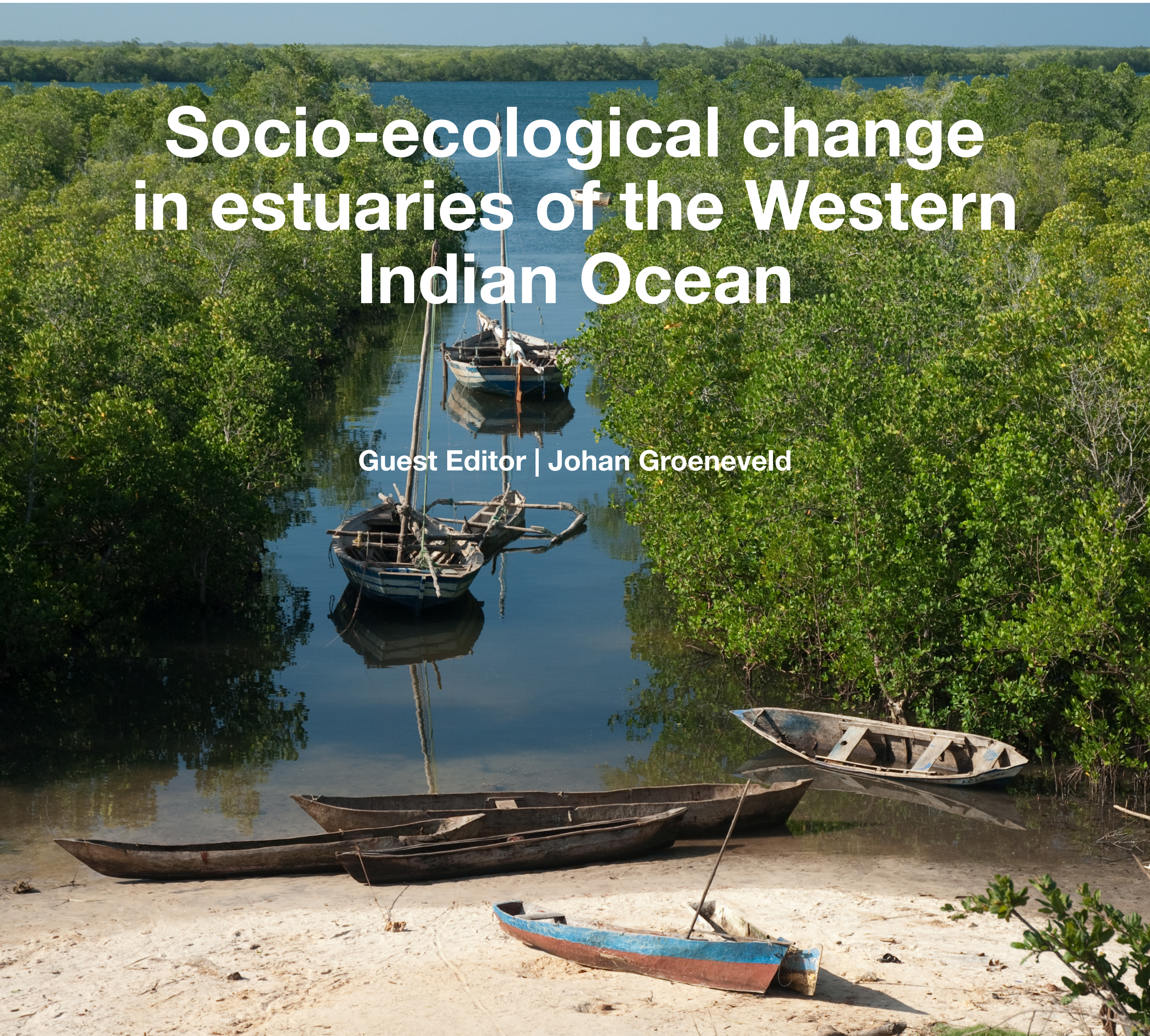

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Cover image: The Rovuma Estuary creeks near Quionga in Mozambique. © José Paula, 2007

Small-scale fisheries of the Bons Sinais Estuary in Mozambique with emphasis on utilization of unselective gear

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Abstract
Small-scale fisheries in estuaries of the Western Indian Ocean form a key component of socio-ecological systems (SES) and food security, yet they remain poorly understood. This study describes the estuarine fisheries of the Bons Sinais Estuary in Mozambique based on fisheries and biological data collected by monitors between 2007 and 2016. Multiple gears were used, including beach seines (78 % of sampled fish), chicocota nets (12 %), gillnets (5 %), and hook and line (4 %). Landings were dominated by small pelagic fishes (Engraulidae 29 %, Pristigasteridae 16 %, Clupeidae 11 %) and prawns (Penaeidae 29 %). Monthly averaged fishing effort, landings and catch per unit effort of beach seine and chicocota nets peaked during the dry season, in April and July to October. The proportion of penaeid prawns in landings increased moderately at the end of the wet season, between January and March. The species and size composition selected by beach seine and chicocota nets overlapped, with chicocota nets also retaining marginally smaller individuals. Both gears exploited low trophic level species near the base of the food web, with low trophic values of 2.8 for chicocota and 3.0 for beach seine nets. The small-scale fishery in the Bons Sinais Estuary followed a 'balanced harvest' approach in which unselective fishing gear is used to exploit a mix of species and sizes proportional to natural productivity and relative abundance.

Keywords: chicocota net, balanced harvest, multi-gear fishery, multi-species fishery, estuarine fisheries, trophic dynamics

Introduction
Small-scale fisheries contribute 75-80 % of the total landings of marine species in Mozambique (Jacquet *et al*., 2010; Doherty *et al*., 2015) and are critically important to coastal communities for food security, nutrition, livelihoods and employment (Benkenstein, 2013; Blythe, 2014; Blythe *et al*., 2014). Monitoring of small-scale fisheries is logistically complex because landing sites are scattered over large geographical areas and fishing is often informal, using multiple gear types to catch a mix of species. In the absence of accurate quantitative data (Cardinale *et al*., 2014), a reconstruction of marine catches estimated that landings were 6.2 times greater than indicated by official statistics, and that the numbers of small-scale fishers had quadrupled over the last four decades (Jacquet *et al*., 2010).

Most fisheries research in the Western Indian Ocean (WIO) region has focussed on coastal waters over the shelf, for example fisheries on Sofala Bank in Mozambique (Mualeque and Santos, 2011; Hoguane and Armando, 2015), Ungwana Bay in Kenya (Fulanda *et al*., 2011; Munga *et al*., 2013, 2014a) and Thukela Bank in eastern South Africa (Turpie and Lamberth, 2010). In

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contrast, estuarine fisheries have received scant attention (Kuguru *et al*., 2019; Costa *et al*., 2020; Dzoga *et al*., 2020; Manyenze *et al*., 2021). Estuarine fisheries are unique from several perspectives: they are influenced by a highly dynamic salinity gradient; affected by daily tides and seasonal freshwater runoff; rely on marine, brackish and freshwater species; include juveniles of many species in nursery habitats; and contribute to livelihoods that rely on fish-based farming systems (Blaber, 2013; Blythe *et al*., 2014; Hamerlynck *et al*., 2020; Mwamlavya *et al*., 2021). The flexibility of estuarine socio-ecological systems (SES) that include fisheries strengthens the capacity of communities to adapt to fluctuations in resource availability (Hamerlynck *et al*., 2010, 2020; Blythe, 2014; Blythe *et al*., 2014).

Fishing gear used in WIO estuaries are diverse and largely made locally from natural forest products or low-cost synthetic materials (Samoilys *et al*., 2011). Dugout canoes and larger planked canoes are typical fishing craft, but fishing areas in estuaries are often accessible by foot. Larger dhows and motorized boats are primarily used in bays or offshore fishing grounds. Fishing gear comprises of beach seine nets, gillnets, hook-and-line and traditional gear such as self-made traps, sticks and spears (Jiddawi and Öhman, 2002; Samoilys *et al*., 2011; Wilson, 2012; Munga *et al*., 2014b; Manyenze *et al*., 2021) and so-called 'chicocota' nets (described below; Costa *et al*., 2020), although utilization of these gear differ among estuaries. Fine-mesh mosquito netting (< 3 mm mesh size) originally distributed to combat malaria in developing countries are used as cod-ends in seine and chicocota nets or are deployed in other ways (Short *et al*., 2018; Jones and Unsworth, 2019). Beach seine and chicocota nets contribute the greatest percentage to landings of small-scale fishers in the Bons Sinais Estuary in central Mozambique (IIP, 2018).

Beach seines have been present in Mozambique since the 1940s and are a widespread and popular gear for catching small pelagic and demersal fishes and crustaceans for local markets (Wilson, 2012). They typically have a head rope of 100 – 225 m long, are deployed by a paddled canoe and hauled back to the beach by teams of up to 14 fishers. Mesh sizes range from 63 mm in the wings to 12 mm in the central panels and they are mounted with or without a 3 mm mosquito net in the cod-end. Mini-beach seines are about half the size of standard nets, are faster to deploy with a smaller crew and are less expensive. Beach seines are considered a destructive gear in several WIO countries, and their use is prohibited in some areas (McClanahan and Mangi, 2001). Compliance with a minimum mesh size of 38 mm (set at a central government level) has been as low as 10 % of inspected nets in Mozambique (Wilson, 2012), because of the perception of fishers that compliance would drastically reduce catch volumes (Darkey and Turatsinze, 2014). Local management measures such as voluntary closed seasons apply in some districts but are not consistently enforced.

Chicocota nets are made of old shrimp trawl nets with a cone-shaped cod-end of fine-mesh mosquito net (Short *et al*., 2018; Costa *et al*., 2020). The top of the net is kept afloat by buoys or recycled empty plastic bottles, flip flops or pieces of Styrofoam, and the bottom is weighted down with pieces of rock or other anchors. Chicocota nets are fixed gear set in the middle of estuary channels and anchored to stakes or vegetation on estuary banks. Net sizes vary depending on space available in estuary channels and the investment capacity of fishers but can be as large as shrimp trawl gear. Fisher dependency on chicocota nets is high in some areas - up to 100 % of gear deployed at sites in Beira, central Mozambique (Darkey and Turatsinze, 2014). As with beach seines, chicocota nets with small mesh sizes capture juveniles of many species, potentially reducing adult cohorts of target stocks. The use of chicocota nets is illegal in Mozambique, although the ban is not enforced and they are commonly used in estuaries (IIP, 2018).

The aims of this study were to: describe the estuarine fisheries of the Bons Sinais Estuary in Mozambique based on fisheries and biological data collected by monitors between 2007 and 2016; estimate the species and size selectivity of the most-used gears (beach seine and chicocota nets); and infer the harvest strategy adopted by estuarine fishers based on the trophic levels exploited, seasonal trends and location in the estuary.

Materials and methods

Study area

The Bons Sinais Estuary discharges into the Southwest Indian Ocean at 18°01' S; 36°58' E and extends ~ 30 km inland to the city of Quelimane where a seaport is located (Fig. 1). The geographical setting, history of settlement, ecosystems and socio-ecological importance of the estuary were summarized by Groeneveld *et al.* (2021). Hoguane *et al.* (2020; 2021) described estuarine circulation patterns, and Furaca *et al.* (2021) used remote sensing maps to infer changes in land use and land cover adjacent to the estuary over the past 27 years, including the growth of Quelimane city and its intrusion into the estuarine functional zone.

Data handling

Fisheries data were extracted from the IIP's PescART database (see IIP, 2006; Vølstad *et al.*, 2014) at two geographical scales; by district and landing site. Aggregated statistics on fishing effort, catch and catch per unit effort (CPUE) were available for Quelimane district (northern bank of the estuary) for the 2007 – 2015 period. Fisheries and biological data of key fish and crustacean species were extracted for four landing sites between the estuary mouth and upper reaches for the 2008 – 2016 period. The four sites were Marrubune (at the estuary mouth where the channel has broadened); Gazelas (lower estuary); Icidua (upper estuary in an urban area of Quelimane); and Chuabo Dembe (upper estuary where the channel has narrowed). The Icidua and Chuabo Dembe landing sites were located within the Quelimane district, but Marrubune and Gazelas were outside the district, but also on the northern bank of the estuary.

Routine sampling of landing sites by IIP monitors took place every month during the fishing season (April-December), on fixed sampling days according to the IIP sampling plan (two days per month per landing site) covering all gear types used. Chicocota nets were first recognized by IIP and sampled as a unique fishing gear after 2011. Fishing effort was determined by counting the number of gears in use during each outing and expressed as the number of active gears (i.e., number of beach seine hauls or chicocota nets sampled per outing). Landings were sorted and identified to species level based on Fischer *et al.* (1990) and weighed by species and gear type. Random samples of 13 commercially important species were selected and the total length (TL ± 1 cm) of specimens measured, with maximum sample size of 100 individuals/species. The selected species have been prioritized for data collection by IIP based on their perceived importance to small-scale fisheries in the region and account for more than 70 % of recorded landings (Daniel Oliveira pers. com., IIP – Zambezia).

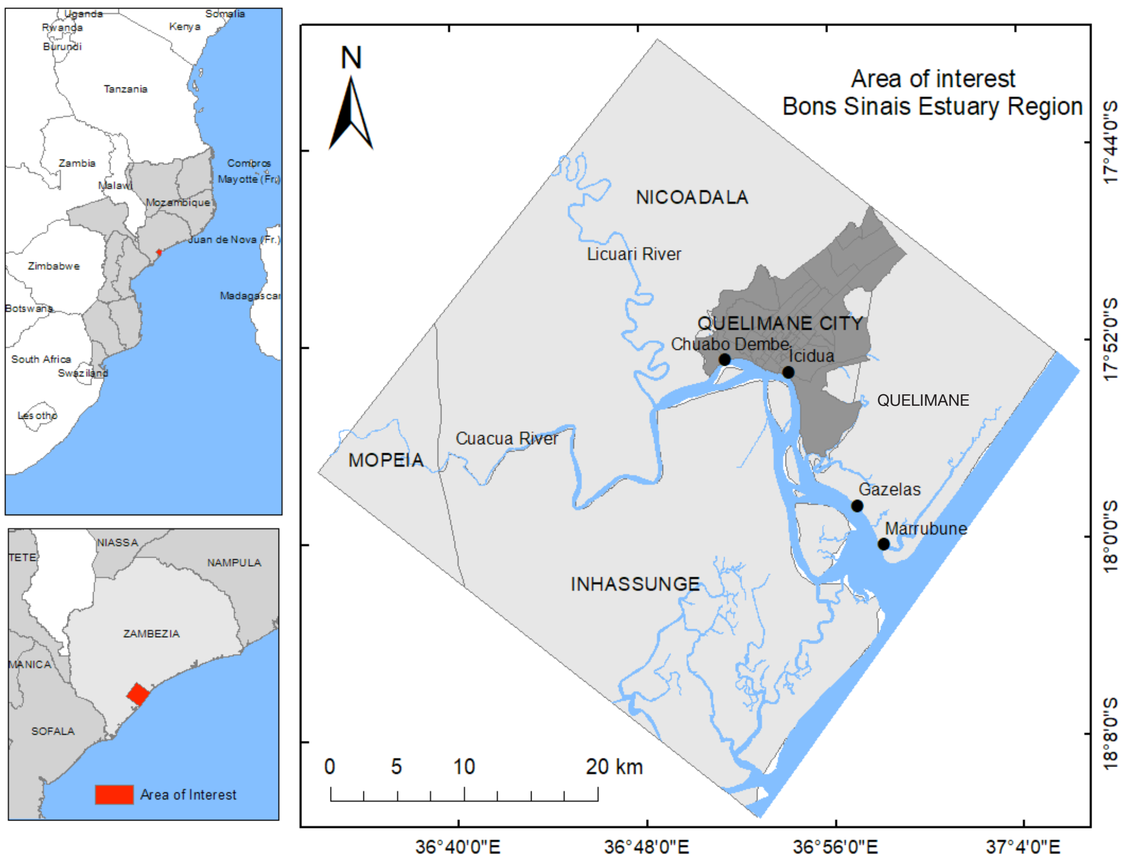

Figure 1. The Bons Sinais Estuary along the central Mozambique coast showing the locations of the four landing sites of Quelimane District sampled.

Table 1. Sampling effort measured as the numbers of fish and prawns measured per landing site and gear type.

	Marrubune	Gazelas	Icidua	Chuabo Dembe	All
Beach Seines	*1697*	2323	1790	1744	*7554*
Chicocota		75	217	847	1139
Gillnet (mono)	81	96	95	230	502
Handline	56	183	20	98	357
Seine Net	29	21	22		72
Longline	1	26		13	40
All	1864	2724	2144	2932	9664

Data were cleaned by removing anomalous records with clearly incorrect or mismatched species names or length measurements. Penaeid prawns were grouped as a single category to eliminate species identification errors of small juveniles. Records with length measurements smaller than 2 cm and larger than 20 cm were considered outliers and removed for three small pelagic fish species (*Hilsa kelee*, *Thryssa vitrirostris*, *Pellona ditchela*) and penaeid prawns (*Penaeus* spp.) prior to length-based analysis.

Data were stratified by landing site as described above, gear type and season. Gear types considered were beach seines, chicocota nets, monofilament gillnets, handline, longline and other seine nets (Table 1). No data were available for traps or other traditional gears such as spears or sharpened sticks – although they are used in the estuary (pers. obs.). Two seasons were considered: a dry season between April and October with average monthly precipitation of < 75 mm; and a wet season between November and March with average monthly precipitation of 75 – 250 mm. Freshwater inflow from rainfall in distant catchment areas was not considered because the historical connection with the Zambezi River (which fed into the upper Bons Sinais Estuary via smaller channels) had been lost after construction of large dams in the upper Zambezi catchment area (Beilfuss and dos Santos, 2001).

Relative abundance was calculated by dividing the number of individuals per species by the sum of individuals of all species combined per landing site. The length composition of small pelagic fishes and penaeid prawns caught by beach seine and chicocota nets at each landing site were compared using 1 cm length categories, and mean lengths were compared using one-way ANOVA followed by post hoc Tukey HSD tests.

Selectivity analysis

Chicocota nets caught a broader range of sizes than beach seines and were assumed to sample the fish assemblage unselectively. The selection curve of beach seines was therefore calculated relative to the size distribution recovered from chicocota nets. Similar fishing power, fishing effort and sampling effort between gears was not assumed (Millar and Fryer, 1999), and therefore the two profiles were compared in relative units, where $f_l=n_l/\sum n$ is the fraction of individuals of length l (total length, cm) in one gear. The ratio f_{BS}/f_{CC} (where BS refers to beach seine and CC to chicocota nets) was calculated for each length class and re-scaled to a maximum ratio of 0.999. Beta-regression of fractional data requires input values in the range]0,1[. The logistic retention curve was calculated using a logit link and the maximum likelihood method with the package betareg in R (Zeileis *et al.*, 2010) and the data and script are shown in Appendix 1. In addition to the l_{50}, the l_{25} and l_{75} points on the curve were determined to define the selection range of beach seine nets.

The trophic level of the catch in a given gear was calculated as $TLc = \sum n_{il}.w_{il}.TL_i / \sum n_{il}.w_{il}$, where w_{il} is the weight of species i at length l, and TL_i is the trophic level of that species (Trites, 2001). The trophic level of the gear g itself is defined as $TLg = 1 + TLc$. Local or regional data on weight-length relationships (Kaka *et al.*, 2019; Costa *et al.*, 2020) and diet composition (Blaber, 1979; Mavuti *et al.*, 2004; de Abreu *et al.*, 2017; Mwijage *et al.*, 2017) of the four main species in the catch were utilized. An average TL_i was utilized per species because no clear ontogenic shifts in diet were specified in the studies above, or these were obscured by spatial differences. *Thryssa vitrirostris*, however, showed a trend towards high piscivory in the size ranges observed, but this ontogenic change was not

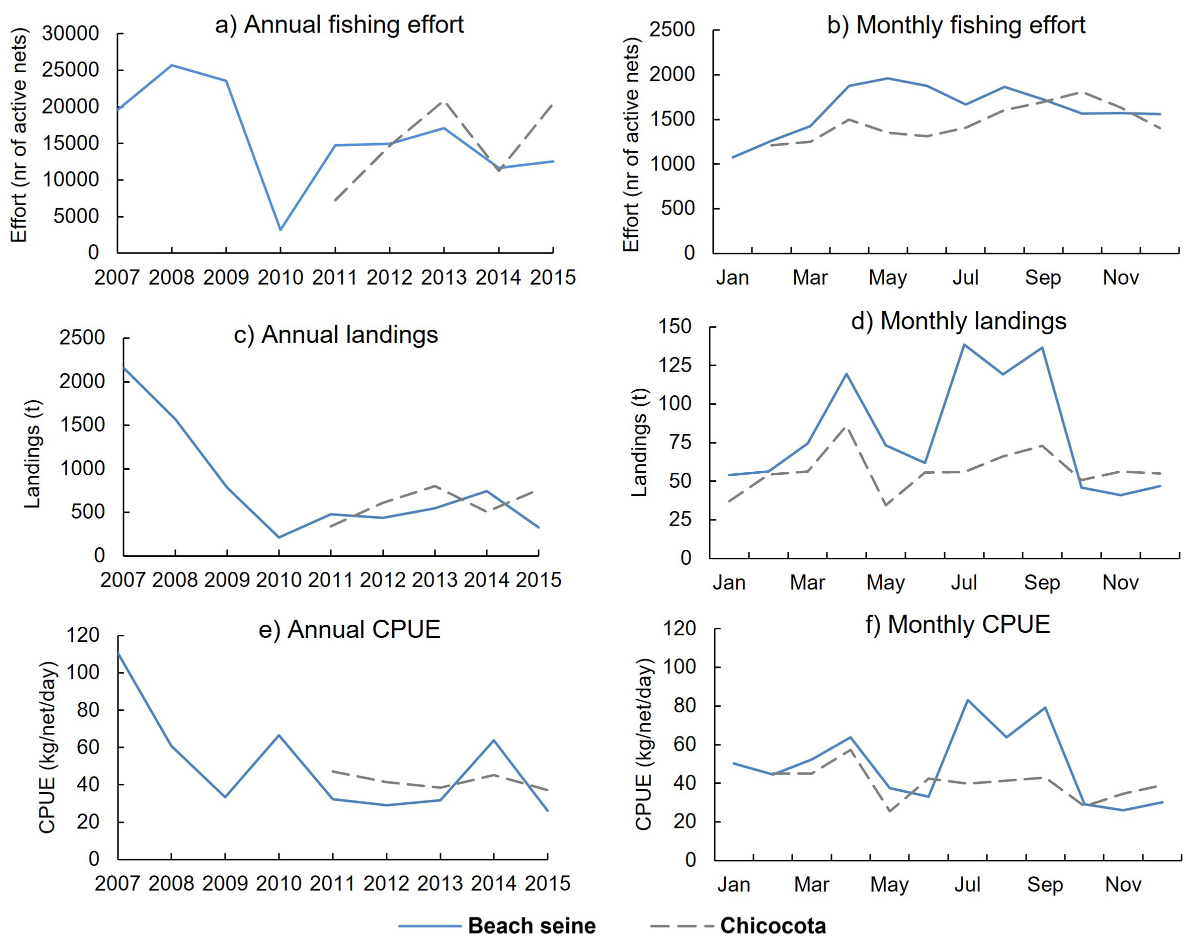

Figure 2. Trends in fishing effort (numbers of active nets observed), landings (tonnes) and CPUE (kg/net/day) for beach seine (line) and chicocota nets (dashed line) in the Quelimane District (central Mozambique) based on the PescART database compiled by the National Institute of Fisheries Research of Mozambique (IIP). Monthly values are averages for the period between 2007 and 2015.

accounted for. The trophic levels for *H. kelee* and *Penaeus* spp. were set at 2.5, for *P. ditchela* at 3.0 and for *T. vitrirostris* at 3.5. (Appendix 1).

Results

Effort, landings and CPUE

Data on fishing effort (number of active nets) and landings (tons) made by beach seines in Quelimane district were available on the IIP's PescArt database for the 2007 – 2015 period, but data for chicocota nets were restricted to 2011 – 2015 (Fig. 2a). Beach seine effort peaked at >25 000 active nets per year in 2007 to 2009 but decreased to ~ 15 000 per year between 2011 and 2015. Chicocota effort increased steeply from 7 000 active sets in 2011 to 20 000 in 2013, when it exceeded beach seine effort.

The average monthly fishing effort for both gear types was lowest between January and March (Fig. 2b). Beach seine effort increased to 1 500 to 2 000 hauls per month between April and December. Chicocota effort first peaked at 1 500 sets in April and then increased steadily to a maximum number of 1 800 sets in October.

Beach seine landings for Quelimane district declined from >2 000 t in 2007 to <750 t per year between 2011 and 2015 (Fig. 2c). Chicocota landings fluctuated between 350 t and 800 t per year between 2011 and 2015. The average monthly landings of beach seines peaked at >120 t in April and July to September but declined to ~ 50 t per month between October and February (Fig. 2d). Chicocota landings had a similar seasonal pattern peaking at 90 t in April and 75 t in September, with less pronounced monthly variability than beach seines.

Nominal CPUE of beach seines declined from 111 kg/net.day^{-1} in 2007 to ~ 40 kg/net.day^{-1} between 2009 and 2015, with smaller peaks at ~ 60 kg/net.day^{-1} in 2010 and 2014 (Fig. 2e). Chicocota CPUE remained stable at 37 – 47 kg/net.day^{-1} between 2011 and 2015.

Table 2. Percentage by family and species of sampled catches in the Bons Sinais Estuary between 2008 and 2016 (n = 9563).

Family	Species	Percentage	
Penaeidae		29	
	Penaeus indicus		21
	Penaeus monodon		6
	Metapenaeus monoceros		1
	Mierspenaeopsis sculptilis		1
Engraulidae		29	
	Thryssa vitrirostris		25
	Thryssa setrirostris		4
Pristigasteridae		16	
	Pellona ditchela		16
Clupeidae		11	
	Hilsa kelee		6
	Sardinella albella		5
Haemulidae		7	
	Pomadasys kaakan		5
	Pomadasys maculatus		1
Sillaginidae		5	
	Sillago sihama		5
Sciaenidae		2	
	Otolithes ruber		2

The average monthly CPUE of both gear types was highest in April, and again between July and September (Fig. 2f).

Overall, the Quelimane district data showed a seasonal trend of lower fishing effort, landings and CPUE during the wet season which was more pronounced for beach seine than chicocota nets. Trends in fishing effort and landings suggested a partial conversion of the fishery, from using beach seines only to using both gears, after 2011. There was no significant difference between the CPUE (mean ± SD) of beach seine (51 ± 28 kg/net.day^{-1}) and chicocota nets (41 ± 4 kg/net.day^{-1}) (Student's t-test; p = 0.45).

Biological characteristics and species composition of landings

Sampling effort (numbers of fish and prawns sampled) was distributed evenly across four landing sites (19 to 29 % of total effort per site) but by gear, the bulk of sampling effort was expended on beach seine (79 %) and chicocota nets (12 %) (Table 1). Table 2 shows the landings composition (all gear combined) comprised of seven families and 13 species. By family, samples were dominated by Penaeidae (29 %), Engraulidae (29 %), Pristigasteridae (16 %) and Clupeidae (11 %), and by species *Thryssa vitrirostris* (25 %), *Penaeus indicus* (21 %) and *Pellona ditchela* (16 %) were most frequently sampled. *Penaeus monodon* (6 %), *Hilsa kelee* (6 %), *Sillago sihama* (5 %) and *Sardinella albella* (5 %) contributed similar quantities to samples, and species with larger body sizes, such as *Otolithes ruber* and *Pomadasys* spp. combined made up approximately 8 % of landings.

Beach seine, chicocota and gill nets were unselective and caught similar species groups, but relative proportions differed (Fig. 3). Penaeid prawns made up 22 % of beach seine and chicocota landings respectively, but only 8 % of gill net samples. Handlines were more selective, with samples comprising of *Pomadasys* spp., *O. ruber* and *S. sihama*. Data from handlines, seine nets and longlines were not analysed further because

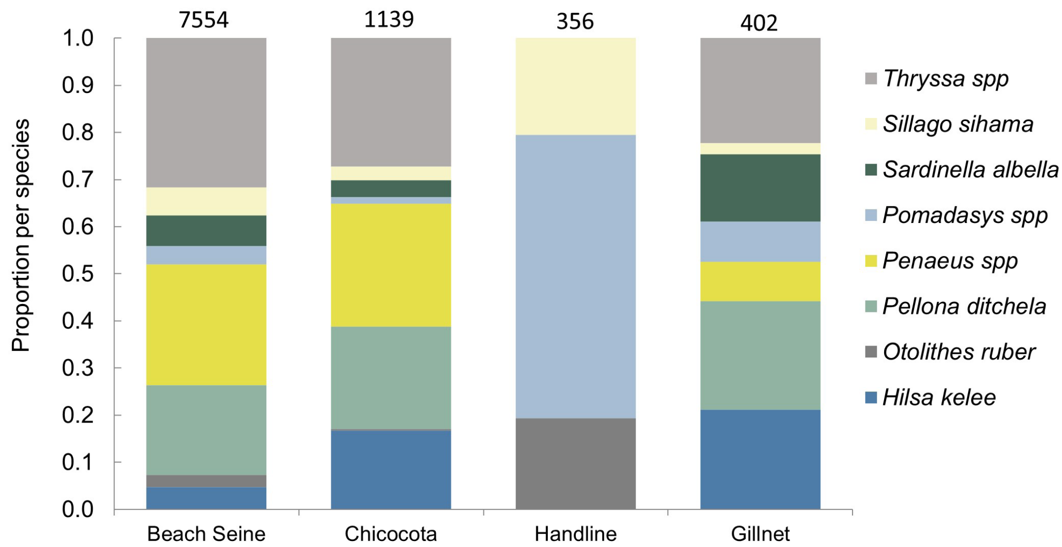

Figure 3. Proportion per species in samples collected with four gear types at all landing sites combined in the Bons Sinais Estuary (2008 - 2016). Sample size per gear type shown on top of bars. Data from longlines and seine nets not shown because of small sample sizes.

of small sample sizes. The seasonal composition of landings (beach seine and chicocota combined) was similar with a moderate increase in the importance of penaeid prawns (+5 %) and concomitant decrease of *P. ditchela* (-4 %) during the wet season in November to March (Fig. 4).

Penaeid prawns and *Thryssa* spp. dominated samples at all four landing sites, irrespective of gear sampled (beach seine or chicocota nets) (Fig. 5). No chicocota samples were available for Marrubune at the estuary mouth, where the channel widens making operation of the net impractical. Beach seine landings at the four sites were proportionally similar, except for *Hilsa kelee* which was absent at Marrubune but increased in importance at upstream sites, to 6 % at Icidua and 8 % at Chuabo Dembe. Like beach seines, the importance of *H. kelee* in chicocota nets increased at Icidua (19 %) and Chuabo Dembe (14 %). Chicocota samples at Gazelas were dominated by penaeids (67 %) based on a small sample (n = 75).

The size composition of *H. kelee*, *T. vitrirostris*, *P. ditchela* and penaeid prawns indicated that chicocota nets retained smaller individuals than beach seine nets (Fig. 6) except for prawns with a TL > 15 cm. The 15 cm plus-group comprised of large prawn samples for both beach seine (n = 124) and chicocota nets (n = 60) and the trend is therefore not considered to be artefactual of small sample sizes.

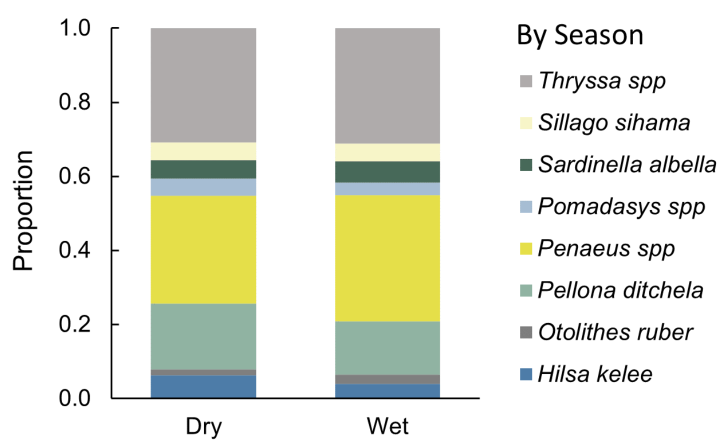

Figure 4. Catch composition during dry (April to October) and wet (November to March) seasons for beach seine and chicocota nets combined.

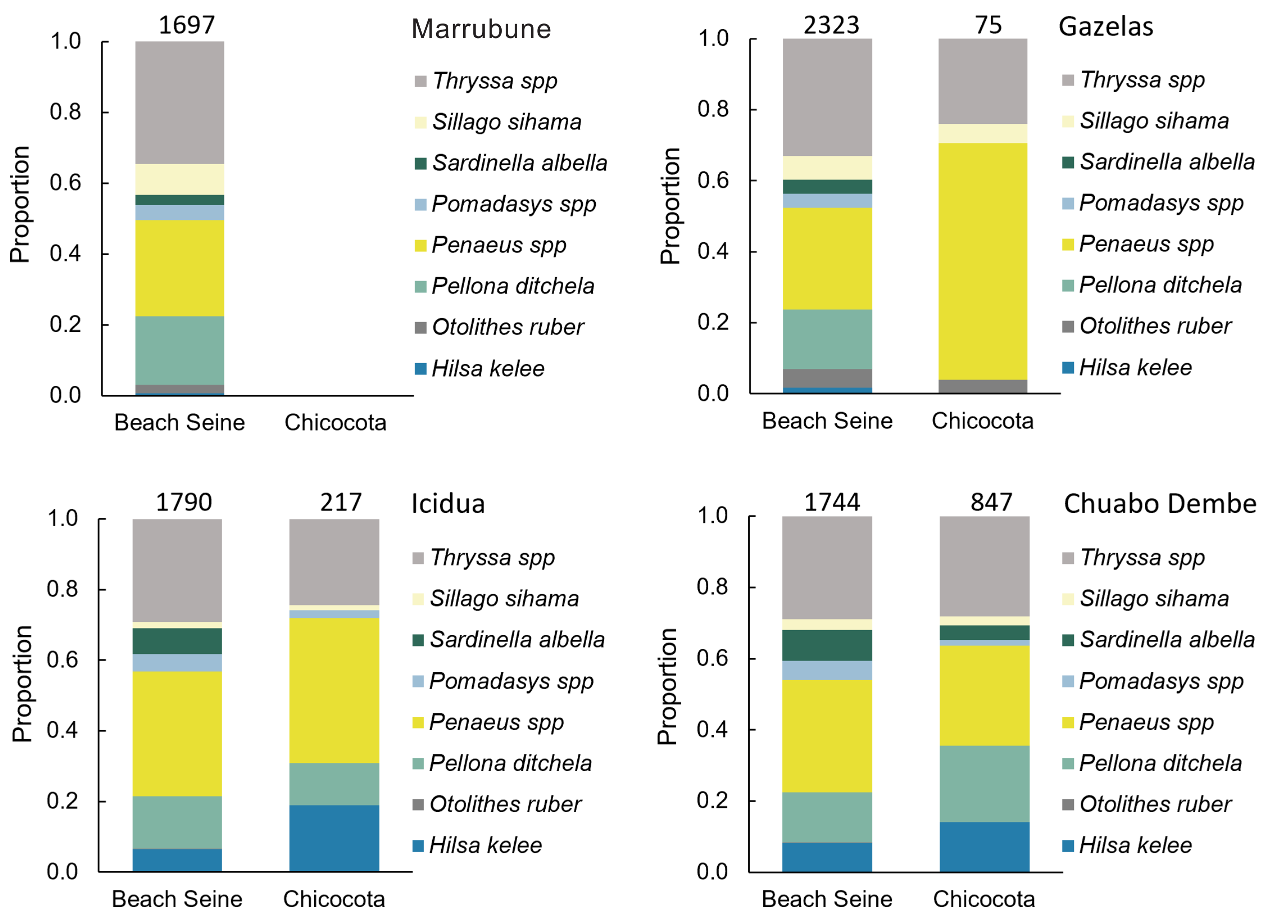

Figure 5. Proportional catch composition of beach seine and chicocota nets at four landing sites in the Bons Sinais Estuary. Chicocota nets were not sampled in Marrubune. The number of fish sampled per gear and site is indicated on the bars.

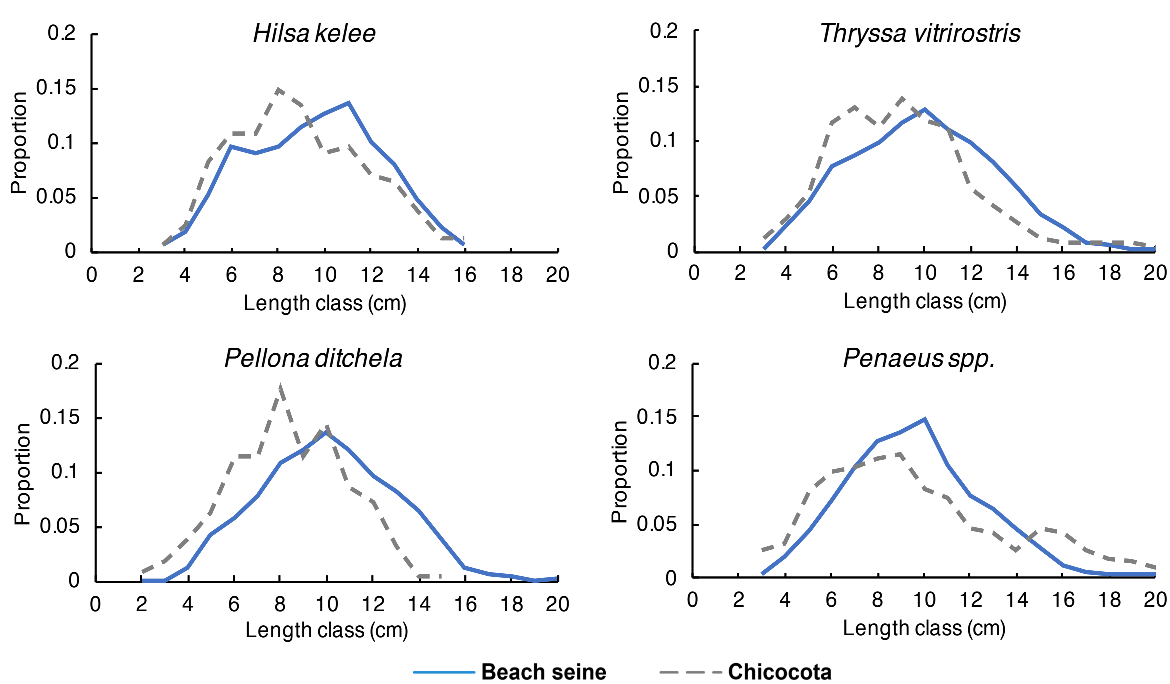

Figure 6. Length composition (TL, cm) of *Hilsa kelee*, *Thryssa vitrirostris*, *Pellona ditchela* and *Penaeus* spp. caught with beach seine and chicocota nets respectively.

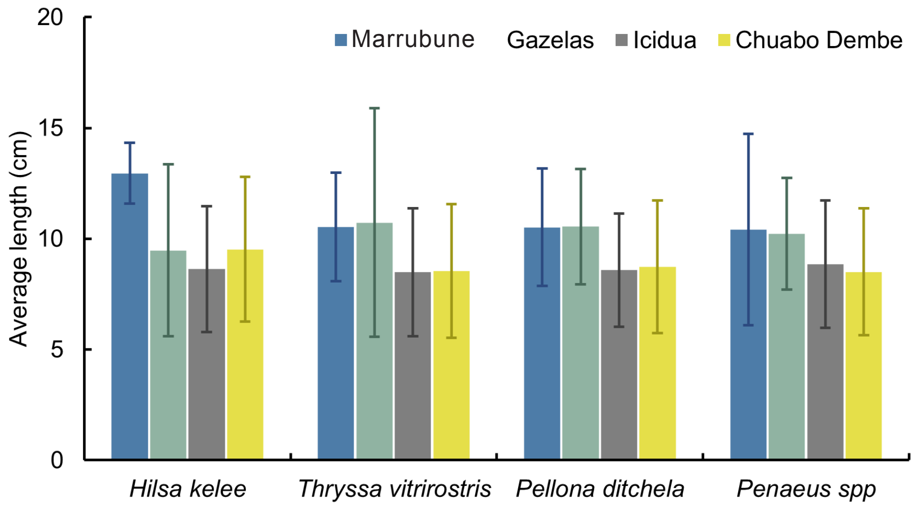

Figure 7. Average total length (TL, cm) by landing site across landing sites for *Hilsa kelee, Thryssa vitrirostris, Pellona ditchela* and *Penaeus* spp. for beach seine and chicocota nets combined.

Single-factor ANOVA indicated that the mean TL of individual species differed among landing sites (Fig. 7; $p < 0.05$ for each of the four species individually). *H. kelee* caught at Marrubune reached a mean TL of 13 cm, significantly larger than at any of the other sites, where means were < 10 cm (Tukey HSD test; $p < 0.05$ in all cases). The mean size of *Thryssa vitrirostris* caught at Marrubune and Gazelas (both sites near the estuary mouth) did not differ from each other significantly but was significantly larger than those caught at the upstream sites at Icidua and Chuabo Dembe (Tukey HSD test; $p < 0.05$ for pairwise comparisons of Marrubune with Icidua and Chuabo Dembe, and of Gazelas with Icidua and Chuabo Dembe). The mean TL of *P. ditchela* and *Penaeus* spp., respectively, differed significantly among sites (ANOVA, $p < 0.05$ in both cases) but pairwise differences between sites were not significant. Even so, declines in mean size between the estuary mouth and upper stations were apparent from Fig. 7.

The overall size profiles of landings by beach seine and chicocota nets (including all catches of the four main species at all four landing sites) overlapped. Length frequencies of chicocota landings peaked in the 7-9 cm TL class, probably reflecting availability in the estuary, whereas beach seine landings peaked in the 9-11 cm TL class, suggesting a more selective retention pattern. The retention curve was calculated for the 2-15 cm size range, resulting in an overall L_{50} of 9 cm for the four species combined for beach-seine nets, and a selection range ($L_{25} – L_{75}$) of about 6-12 cm (Fig. 8). Beach seine and chicocota nets exploited the

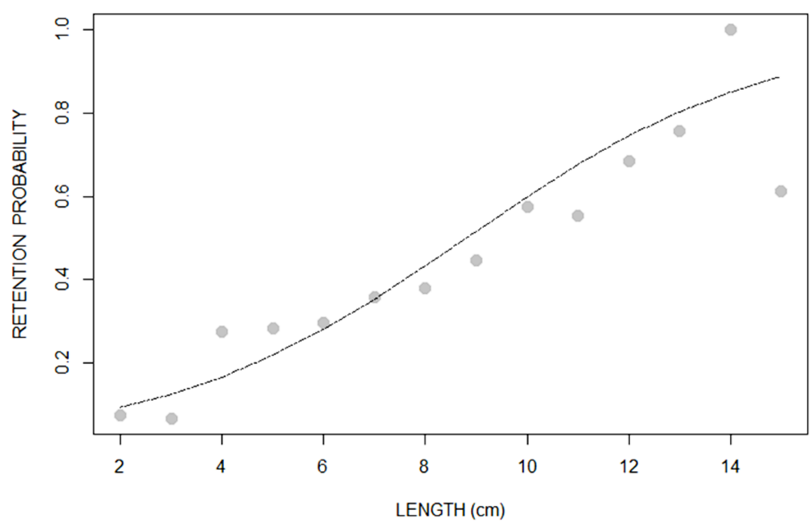

Figure 8. Selectivity curve of the beach seines for the four species combined, with length measured as total length.

estuarine ecosystem at marginally different trophic levels, near the base of the food web. The trophic level of catches made by beach seines (TL*c*) was estimated at 3.0 (TLg=4.0) and that of chicocota nets at 2.8 (TLg=3.8). Chicocota nets caught proportionally more detritivores and planktivores, like *H. kelee* and *Penaeus* spp., and beach seines caught more zooplanktivorous and piscivorous fish like *P. ditchela* and *T. vitrirostris.*

Discussion

Small-scale fisheries are critically important as a source of food security, nutrition, livelihoods and employment in coastal Mozambique, yet quantitative information on fishing effort and catch composition remains sparse (Jacquet *et al.*, 2010; Benkenstein, 2013). This is especially so for estuarine fisheries, which are widespread, informal and difficult to monitor. Therefore, this study on the small-scale fisheries of the Bons Sinais Estuary is considered representative of similar data-poor estuarine fisheries along the central Mozambique coast, and potentially the wider WIO region.

The data obtained from the IIP onshore data collection programme in Quelimane focuses on selected (mainly marine) species perceived to have commercial importance (IIP, 2018). Several key estuarine (e.g., sea catfish *Arius africanus*) and freshwater species (e.g., Mozambique tilapia *Oreochromis mossambicus;* sharptooth catfish *Clarias gariepinus*) were absent from the data, because they were not sampled by monitors at landing sites, even when present in landings (pers. com. IIP; Costa *et al.*, 2020). No data were available for landings by traditional gear types (spears, homemade traps) or hand-collected species, such as clams (pers. obs.) and not all landing sites along the length of the estuary were sampled. Quantitative data on fishing effort and landings by species were therefore incomplete (see Jacquet *et al.*, 2010) and the assumptions of random sampling could not always be met. The limitations of the data affected the scope of the study, and the findings must be seen within the context of data-poor systems.

Fine-mesh mosquito netting is commonly used in the centre panels or cod-ends of beach seine and chicocota nets in the Bons Sinais fisheries and explained the predominantly small size of organisms caught (Wilson, 2012; Short *et al.*, 2018; Costa *et al.*, 2020). Both gears were unselective, with chicocota nets catching a broader size range, assumed to reflect both the availability of fish and retention properties of the gear (Millar and Freyer, 1999). Beach seines were relatively more selective, with a selection range of 6 – 12 cm (L_{50} = 9 cm TL). Beach seines are active gears dragged horizontally through the water whereas chicocota nets are stationary and spanned across channels. The mode of operation and different habitats targeted by the two gear types plausibly explained the difference in selectivity, even when both were fitted with mosquito net cod-ends (Karama *et al.*, 2017). Beach seines are commonly used in different littoral environments in the WIO (Wilson, 2012) making their properties a convenient benchmark for evaluating the selectivity of alternative gears, by using a relative selectivity measure as demonstrated here.

Landings comprised mainly of small pelagic fishes and penaeid prawns, confirming the findings of previous studies on small-scale fisheries in coastal Mozambique (Gjosaeter and Sousa, 1983; Mualeque and Santos, 2011; Wilson, 2012; Cardinale *et al.*, 2014; Hoguane and Armando, 2015). Similar taxa were caught by beach seine and chicocota nets at the estuary mouth and upper estuary (~ 30 km upstream) consistent with a well-mixed marine dominated system (Hoguane *et al.*, 2020; 2021). The marine dominance stems from reduced river runoff following the construction of the Kariba- (1955) and Cahora Bassa dams (1974) in the upper Zambezi River (Beilfuss and dos Santos, 2001). The absence of clear seasonality in the species composition of landings (Fig. 4) presumably reflects reduced seasonal freshwater flooding – hence the estuary remains predominantly marine throughout the year, with salinity levels too high for some freshwater species to tolerate (Whitfield, 2015). Alternatively, the absence of freshwater species in the data was an artefact of the selective sampling strategy, which focussed on marine species.

The average size of small pelagic fishes and penaeid prawns declined between the estuary mouth and upper estuary, supporting the hypothesis that the upper estuary is a nursery area. Surveys by the research vessel (RV) Dr Fridtjof Nansen have shown large aggregations of clupeid and engraulid fishes offshore over the Sofala Bank from where they approach the coast seasonally and enter estuaries to spawn (Gislason and Sousa, 1985; Mualeque and Santos, 2011; Krakstad *et al.*, 2017); for example *T. vitrirostris* (Blaber, 1979) and *H. kelee* (Gjøsaeter and Sousa, 1983). Penaeid prawns spawn on the Sofala Bank near river mouths (Malauene *et al.*, 2021) and larvae drift into bays or estuaries as nursery areas before migrating back to the offshore banks as larger juveniles (Brito and Pena, 2007).

The observed size increase of small pelagic fishes and penaeid prawns between the upper estuary and mouth therefore fits well with a seaward migration of larger juveniles from upstream nursery areas to adult habitats in nearshore waters (Blaber, 2013).

Species captured by beach seine and chicocota nets were predominantly detritivores (prawns) or planktivorous (small pelagics). Low trophic values (TLc) of 2.8 for chicocota nets and 3.0 for beach seines confirmed that they exploited low trophic level species near the base of the food web. Chicocota nets caught proportionally more detritivores and planktivores (*Penaeus* spp and *H. kelee*) whereas beach seines caught more zooplanktivores and piscivores (*P. ditchela* and *T. vitrirostris*), explaining the difference in trophic values. Larger species were also caught and utilized, but in general, beach seine and chicocota nets exploited the most productive components of the ecosystem, often with generation times < 1.5 years, high resilience, and low vulnerability (www.fishbase.org). Handlines and longlines caught larger species (*Pomadasys* spp. and *Otolithes ruber*) at higher trophic levels, often at the mouth of the estuary where larger marine fish enter.

Based on the size and species distribution of landings, the estuarine fishery followed a 'balanced harvest' approach in which removals were proportional to natural productivity and relative abundance (Garcia *et al.,* 2012; Kolding *et al*., 2016). Beach seine and chicocota nets harvested mainly low trophic level species with high productivity and variable recruitment affected by environmental conditions (Somarakis *et al*., 2019), whereas hand lines harvested smaller numbers of larger species (see Fig. 3). The mosquito net cod-ends of beach seine and chicocota nets also caught juveniles of many species in the estuary, confirming a similar finding by Costa *et al*. (2020). Modelling studies and limited empirical evidence from small-scale fisheries in Africa (Kolding and van Zwieten, 2011) have suggested that balanced harvest strategies can reduce the impact of fishing on ecosystem structure and increase aggregate yield under certain conditions (reviewed by Zhou *et al*., 2019) although the concept has also been criticised (Froese *et al*., 2016). Under the present conditions, fishing effort in the Bons Sinais Estuary is adaptive, largely regulated by natural production, and serves as a 'social security system' (Kolding and van Zwieten, 2011). Enforcing a selective fishing strategy is presently impractical and will undermine the livelihood opportunities and socio-economic role of small-scale fishers. Overall, present analyses suggest the presence of a *de facto* balanced harvest pattern in the Bons Sinais Estuary, based on landings of unselective gear.

Small fish caught by beach seine and chicocota nets are sun-dried (pers. obs.) and either consumed by fisher households or sold locally, as a staple food for nearby communities. Penaeid prawns and larger fish species have a higher market value and are used to generate a cash income. Blythe *et al*. (2014) showed that local fishing communities used different strategies to adapt to livelihood stressors arising from socioeconomic (e.g., disease, theft, food insecurity) and ecological sources (e.g., severe storms or drought). Specialized fishers were organized in fishers' groups with access to fishing assets, and intensified fishing effort when catch rates declined. Poorer fishers diversified into non-fishing work, such as small business, mangrove harvesting, and casual labour. Adaptation to livelihood stressors was heterogenous and influenced by multiple factors. Hamerlynck *et al*. (2020) described fish-based farming systems as a flexible livelihood portfolio along the edges of Africa's water bodies, able to maintain the drivers of ecosystem productivity, and Mwamlavya *et al*. (2021) demonstrated that coastal and upstream communities in the Tana Estuary in Kenya relied on different livelihood strategies (fishing, part-time fishing and farming) and that the strategies were site-specific and seasonal. In the Bons Sinais Estuary, lower fishing effort (and landings) during the wet season potentially reflected more difficult access to fishing areas and a switch to other occupations than fishing. Small-scale fisheries in the Bons Sinais Estuary should therefore be seen as key components of a complex socio-ecological system that supports traditional and more contemporary livelihood strategies, rather than in isolation as 'fisheries to be managed'.

Fisheries in the Bons Sinais Estuary are monitored and managed by a regional fisheries authority located in Quelimane (Zambézia branch of IIP, National Institute of Fisheries Research) reporting to a fisheries ministry at national level (REPMAR, 2003). A minimum mesh size of 38 mm set at national level applies to all beach seine nets in Mozambique. At local level some beach seine fisheries have applied local management measures such as voluntary closed seasons. In a co-management mechanism, Community Fisheries Councils (CCPs) composed of fishers and community leaders mediate compliance with both national fisheries legislation and local measures. Compliance with management measures, including mesh size and closed seasons, is 'extremely low' (Wilson, 2012) and not consistently enforced by CCPs – to a large extent because CCP members do not all agree with the measures. Chicocota nets are illegal gear in Mozambique, but the ban is not enforced. The chicocota fishery is now as important as the beach seine fishery in the estuary, and its landings have been officially monitored by the IIP since 2011.

In conclusion, the role of official fisheries management structures appears to have been marginalized by small-scale fishers in favour of subsisting on a broad range of harvestable resources – including all available sizes and species of fish and invertebrates. The prevalence of beach seine and chicocota nets therefore also reflect a social, rather than an ecological challenge alone, requiring policies that favour diversification of livelihoods in combination with enforcement of regulations (Kolding and van Zwieten, 2011). The *de facto* balanced harvest strategy observed in the small-scale fisheries of the Bons Sinais Estuary relies mainly on low trophic level species and forms an integral part of local socio-ecological systems.

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Appendix

Calculation of trophic levels of the two gears

LENGTH	HK BS	TV BS	PD BS	PEN BS	LENGTH	HK CC	TV CC	PD CC	PEN CC
2	0	0	2	0	2	0	0	2	0
3	2	3	2	9	3	1	3	4	10
4	6	49	17	45	4	4	8	8	12
5	16	93	52	103	5	13	14	13	30
6	30	157	73	166	6	17	30	24	37
7	28	179	98	236	7	17	34	24	39
8	30	202	134	295	8	23	29	37	42
9	35	239	148	315	9	21	36	24	43
10	39	262	169	340	10	14	31	30	31
11	42	228	148	245	11	15	29	18	28
12	31	201	119	176	12	11	15	15	17
13	25	167	103	148	13	10	11	7	16
14	15	117	79	108	14	6	7	1	10
15	7	68	49	63	15	2	3	1	17
16	2	45	15	26	16	2	2	0	16
17	0	16	9	12	17	0	2	0	10
18	0	12	6	9	18	0	2	0	7
19	0	3	2	8	19	0	2	0	6
20	0	5	3	6	20	0	1	0	4
Length-weight relationship a and b					*Length-weight relationship a and b*				
a	-4,821	-5,285	-4,921	0,00000112	a	-4,821	-5,285	-4,921	0,00000112
b	3,014	3,067	2,977	3,32	b	3,014	3,067	2,977	3,32
				biomass B=w x n, (g)					biomass B=w x n, (g)

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LENGTH	HK BS	TV BS	PD BS	PEN BS	LENGTH	HK CC	TV CC	PD CC	PEN CC
2	0	0	0	0	2	0	0	0	0
3	0	0	0	1	3	0	0	1	1
4	3	17	8	11	4	2	3	4	3
5	16	66	46	50	5	13	10	11	15
6	54	194	110	149	6	30	37	36	33
7	80	354	234	353	7	48	67	57	58
8	127	602	477	688	8	98	86	132	98
9	212	1023	748	1085	9	127	154	121	148
10	325	1549	1169	1662	10	117	183	207	152
11	466	1806	1359	1644	11	166	230	165	188
12	447	2079	1416	1576	12	159	155	179	152
13	459	2208	1556	1729	13	184	145	106	187
14	344	1941	1488	1614	14	138	116	19	149
15	198	1394	1133	1184	15	56	62	23	319
16	69	1125	420	605	16	69	50	0	372
17	0	482	302	342	17	0	60	0	285
18	0	430	239	310	18	0	72	0	241
19	0	127	93	329	19	0	85	0	247
20	0	248	163	293	20	0	50	0	195
SUM (g)	2799	15645	10962	13624	SUM (g)	1207	1565	1062	2844
f	0,07	0,36	0,25	0,32	f	0,18	0,23	0,16	0,43
	HK BS	TV BS	PD BS	PEN BS		HK CC	TV CC	PD CC	PEN CC
Trophic level	2,5	3,5	3,0	2,5	Trophic level	2,5	3,5	3,0	2,5