Nutrition contributions of coral reef fisheries not enhanced by capture of small fish

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License

Abstract

Recent policy recommendations have highlighted the nutritional benefits of fisheries that capture small finfish species. Small fish, particularly those that feed in the pelagic zone, tend to be more nutrient dense than larger species, with increased concentrations of calcium, zinc, and omega-3 fatty acids. However, capturing fish below some recommended size limit (i.e., length at first maturity = L_{mat}) in coral reefs is frequently considered to be unsustainable and associated with reduced yields and losses of ecosystem functions. To evaluate the potential effects of fish body size, we analyzed nutrient concentrations of 424 demersal and pelagic finfish species reported from Western Indian Ocean artisanal fisheries. We found that length and food source are associated with only small differences in nutrient density in the artisanal catches of this region (≤ 7% of a child's daily requirement in most cases). We also analyzed 20 years of catch monitoring data from Kenya, where many of the common species have L_{mat} ~20–25 cm, to test the potential benefits and tradeoffs of capturing small fishes. Small capture sizes were associated with low yields and sexually immature catches with a mean length of 15 cm resulting in 38% lower catch per unit effort, 37% lower nutrient yield, and a 22% lower maturity index compared to a mean body length of 30 cm. Catches of undersized fish were not associated with substantial increases or decreases in nutrient content relative to human nutritional requirements. Thus, coral reef artisanal fisheries should target moderate to large fishes (> 20 cm) to maximize overall yield, nutrient yield, and sustainability.

Keywords: fisheries, sustainability, nutrition, food security, coral reef

1. Introduction

Strategies for food production in the context of global environmental change should be oriented towards achieving sufficiency, nutritional quality, and sustainability (Mustafa et al., 2021). Fisheries are no exception, and recent policy guidance from academic and intergovernmental organizations has increasingly attempted to take these three goals into account (e.g. Andrachuk et al., 2022; FAO, 2021; HLPE, 2014; Kawarazuka et al., 2023).

However, the policy and science supporting it are relatively new, and significant disagreements remain about how best to maximize the quantity, quality, and sustainability of food produced by capture fisheries (Jones and Unsworth, 2020; Tilley et al., 2020; Zhou et al., 2019). Here, we show using catch data from the Western Indian Ocean (WIO) that an emerging policy recommendation to increase the consumption and capture of small fishes does not achieve food system goals in unselective coral reef artisanal fisheries and should not be considered a universal recommendation.

The nutritional benefits of small fish are celebrated in several recent policy publications (Ahern et al., 2021; Bavinck et al., 2023; FAO et al., 2023; HLPE, 2014; Kolding et al., 2019). Small fish are nutritionally valuable because (1) their muscle tissue tends to be more nutrient dense (Hicks et al., 2019; Mills et al., 2023); and (2) they are often consumed whole (Bavinck et al., 2023; HLPE, 2014; Kawarazuka and Béné, 2011). However, oversimplified summary statements and a variety in the definitions of 'small fish' might lead to a false impression that increasing the capture and consumption of small fish is a recommended policy in many or all contexts. For example, the Food and Agriculture Organization (FAO) of the United Nations observes that "the most nutrient-rich functional groups for both inland and marine fish catches are those that include small (< 25 cm total length), frequently pelagic species" (Mills et al., 2023, p. 151). This observation is then used to inform flexible policy recommendations that can be responsibly applied in different contexts (Mills et al., 2023, p. 148). Despite this nuance, however, the headline statement the FAO highlights in the executive summary of the same report is simply that "small fish are especially nutritious" (FAO et al., 2023, p. xxxv). Similarly, Kawarazuka and Béné review literature on fish consumption in poor households and conclude that "small fish species that are consumed whole with bones, heads, and viscera play a critical role in micronutrient intakes" (2011, p. 1931). They do not define 'small fish,' but they do recommend that "a sustainable supply of these species should be prioritized" (Kawarazuka and Béné, 2011, p. 1936). More recently, an FAO technical paper explicitly addressed the definitional challenge, but nonetheless recommended "substantially increasing fishing pressure on small fish," including in multispecies fisheries (Bavinck et al., 2023, p. 152).

The wide diversity of approaches to, and definitions of, small fish risks a misalignment between science and policy. From the perspective of nutrition-sensitive harvest strategies, capturing small fishes raises two primary concerns. First, capturing juveniles of larger species could jeopardize production and sustainability in unselective multispecies fisheries (Ben-Hasan et al., 2021; Sun et al., 2023). Unselective fishing methods that capture small individuals can cause both recruitment and growth overfishing and potentially provoke fisheries collapse and losses of nutritious seafood and biodiversity (Hicks and McClanahan, 2012; McClanahan, 2022; Myers and Mertz, 1998; Zamborain-Mason et al., 2023). Second, simple headline statements, such as "small fish are especially nutritious" (FAO et al., 2023, p. xxxv), risk obscuring the variability that is found across taxa, habitats, life histories, and management strategies (Hicks et al., 2019; Robinson et al., 2022d, 2023). There is a need to disarticulate these taxonomic, diet, and sustainability concerns to nuance and improve existing advice (Mustafa et al., 2021).

Coral reefs and associated ecosystems support complex multispecies fisheries that supply nutrition to many poor and subsistence stakeholders in the Global South. Therefore, we explore the potential benefits and trade-offs of capturing small fish from coral reefs based on (1) nutrient composition data of tropical finfish and (2) catch data from Western Indian Ocean (WIO) nearshore artisanal fisheries. In the unselective reef fisheries of the WIO, we define 'small fish' as < 20 cm, as this size class falls below the length at first maturity (L_{mat}) of the most frequently captured species and will thus include a mix of mature individuals of smaller species and juvenile individuals of larger species (Tuda et al., 2016). Artisanal fisheries in the WIO target a diversity of species, including small pelagic and demersal fishes, and often reserve smaller fishes for home consumption (Cartmill et al., 2022; van der Elst et al., 2005; Wamukota and McClanahan, 2017). Specifically, we asked (1) how nutrient densities of WIO small pelagic fishes compared to human dietary requirements, (2) whether targeting small body sizes in these predominantly mixed species fisheries would increase the nutrient content of fish catches, and (3) how the mean length of fish catches affects yield and sustainability indicators, including nutrient yield. We do not address the nutritional benefits of whole fish consumption or targeted (selective) small pelagic fisheries, such as those that capture herring, sardines, and anchovy.

2. Methods

To address the above questions, we combined nutrition information from publicly available databases, landings reported in 10 Western Indian Ocean (WIO) fishing jurisdictions, and long-term continuous catch monitoring data collected in Kenya by the Wildlife Conservation Society (WCS) (Froese and Pauly, 2023; McClanahan and Azali, 2020; Thorson et al., 2023). From these data we explored the nutrient content, yield, and sustainability implications of targeting small fishes.

2.1. WIO fish species nutrient concentrations

We compiled a list of fish species captured by WIO artisanal fisheries from national catch statistics, published studies, and governments' and NGOs' monitoring data (Tables S1–2). This produced 480 species of which 34 had no nutrient estimates in FishBase and were therefore removed. We also removed an additional 22 species reported to reach maturity (L_{mat}) at > 100 cm in length. These species are outliers, rarely caught in these nearshore fisheries, and detract from the focus on small fish. We considered the 424 remaining species representatives of the WIO artisanal catch as they accounted for 99.3% of all landings by weight observed in the 20-year Kenyan dataset. Using a species list rather than landings data allowed us to separate mature, small-bodied species from juvenile, large-bodied species and specifically test for species-level effects of body size and food source.

Densities of calcium, iron, omega-3, selenium, vitamin A, and zinc for each species (per 100 g) were obtained from FishBase using the *rfishbase* package (Boettiger et al., 2012; Froese and Pauly, 2023). FishBase values are estimates produced by a hierarchical Bayesian model that uses the functional traits of finfish species to estimate nutrient concentrations (Hicks et al., 2019). The predictive model includes tropical covariates such as temperature and latitude and is revised annually as nutrient data for new species are added (Froese and Pauly, 2023). One limitation of the FishBase nutrient values is that they assume no variability within species regardless of habitat or life stage (Froese and Pauly, 2023; Robinson et al., 2022b). Nevertheless, FishBase is the largest fish nutrient dataset available and is the most appropriate for large studies with many taxa (e.g., Cheung et al., 2023; Hicks et al., 2019; Maire et al., 2021; Robinson et al., 2022c, 2023).

All analyses were conducted in R (R Core Team, 2022). We tested the relationships between body lengths and food source (benthic or pelagic) on nutrient densities for all 424 WIO species using linear mixed models. Length at maturity estimates (L_{mat}) were obtained from the *FishLife* R package (Thorson et al., 2023). For each nutrient, we modeled L_{mat} and food source as interacting effects using the model structure $\log Nutrient\ Density \sim L_{mat} \times Food\ Source$. We first implemented mixed models for each nutrient in the *glmmTMB* R package and evaluated residuals and outliers using the *DHARMa* package (Brooks et al., 2017; Hartig, 2022). We evaluated quantile-quantile plots of residuals for over- and underdispersion and heteroscedasticity and used the *DHARMa* package's built-in outlier test to determine whether model predictions were overly influenced by extreme values (Hartig, 2022). For nutrients that failed one or more of these tests, we implemented a version of the same model using the *rlm* function from the *MASS* package in R, which generates model predictions that are robust to outliers and non-normal distributions using an M estimator (Venables et al., 2002). Vitamin A and zinc met the assumptions for linear regression, but all other nutrients required robust models as implemented in the *MASS* R package.

2.2. Kenya catch monitoring

Catch monitoring was conducted at 22 landing sites from 2001–2021. Observers recorded 1,163 fishing trips with a mean catch per unit effort (CPUE) of 1.78 kg fisher^{-1} day^{-1} (± 0.06 SE). Fishers captured a total of 249 species ranging in size from a 1 cm marbled parrotfish (*Leptoscarus vaigiensis*) caught with a beach seine to a 121 cm pompano dolphinfish (*Coryphaena equiselis*) caught with a handline. Captured fish were identified to the species level and their total lengths were measured (total length, cm). The gear used and number of fishers per crew were also recorded. Individual fish weights were then calculated using the length-weight relationships in FishBase, which were accessed using the *rfishbase* package in R (Boettiger et al., 2012; Froese and Pauly, 2023). Finally, we combined catch monitoring data with estimates of nutrient densities and lengths at maturity (L_{mat}) for each captured fish as described in section 2.1, with the added procedure of using genus-level mean nutrient values where no estimates were available for an observed species. We used the ratio of length at capture to length at maturity (L/L_{mat}) as an indicator of stock sustainability (Froese, 2004). Using catch monitoring data allowed us to assemble a more accurate picture of the mix of mature and immature fishes captured by this unselective fishery when small lengths predominate in the catch (Tuda et al., 2016).

2.3. Analyses of Kenya catch data

Once catch monitoring data were supplemented with nutrition and sustainability indicators, the data were pooled by fishing trip, defined as the total landings per crew per day. This allowed the calculation of catch per unit effort (CPUE) and nutrient yields. Nutrient yields were calculated by developing a combined nutrient density score and multiplying this value by the number of 100 g portions caught per fisher per day (Maire et al., 2021). Other catch parameters included here (nutrient content, length, and L/L_{mat}) are reported as the biomass-weighted mean value per trip. Using the biomass-weighted mean for L/L_{mat} is likely to overestimate the maturity of fish catches by assigning lower weights to small, immature fishes. However, this approach is also more conservative in the context of our hypothesis and more likely to favor a recommendation to capture small fish.

We tested the effect of fish length on nutrient densities in the Kenyan artisanal catch using linear models. We initially included site as a random effect to account for differences in species assemblages at different locations, but minimal amounts of variance were attributed to the random effect. We thus used a model structure of $\log Nutrient\ Density \sim Length\ at\ Capture$ for all nutrients except zinc, which did not need to be log transformed. As described in section 2.1, we implemented an outlier test and examined quantile-quantile plots of residuals to test for over- and under-dispersion and heteroscedasticity (Hartig, 2022). Outliers were dominated by a few extremely high nutrient densities that do not represent the more typical catches and were therefore removed.

The effects of length on overall yield, nutrient yield, and maturity (L/L_{mat}) were also tested using linear models. For overall yield and nutrient yield, we used an initial model structure that included site and fishing gear as random effects. The initial model structure for maturity included only site as a random effect. Fishing gear was included for the yield indicators because gears are associated with different yields in this fishery (Hicks and McClanahan, 2012; McClanahan and Kosgei, 2018). However, similar to the nutrient concentration models, neither random effect was informative, and removing them did not improve residual diagnostics. Examination of quantile-quantile plots found no signs of over- or underdispersion or heteroscedasticity, but outlier tests for all models were significant ($p < 0.05$). We thus implemented robust linear models as described in section 2.1 using the *MASS* package in R (Venables et al., 2002).

3. Results

3.1. Nutrient densities of Western Indian Ocean fishes

Nutrient concentrations were negatively correlated with body lengths for calcium, iron, and zinc, but not for omega-3, selenium, or vitamin A. Significance was strong because of the large sample sizes, but effect sizes were small relative to human nutritional requirements (Table 1; Fig. 1). For example, a species of fish reaching maturity at 10 cm contains around 2.6 times the calcium concentration of a fish reaching maturity at 40 cm, but a 100 g portion of the comparatively nutritious smaller fish still contains only ~9% of the recommended daily allowance for a child 1–3 years old (Fig. 1A). Omega-3 and selenium densities had no relationship with length at maturity, but both were slightly higher in pelagic than in demersal species (Figs. 1C, D; Table 1). Again, however, differences were small, with a 100 g serving of a pelagic fish only providing an additional 8% of a child's adequate intake of omega-3, and both food sources providing 175–200% of a child's RDA for selenium (Fig. 1C, D). Vitamin A densities did not respond to length or food source (Table 1).

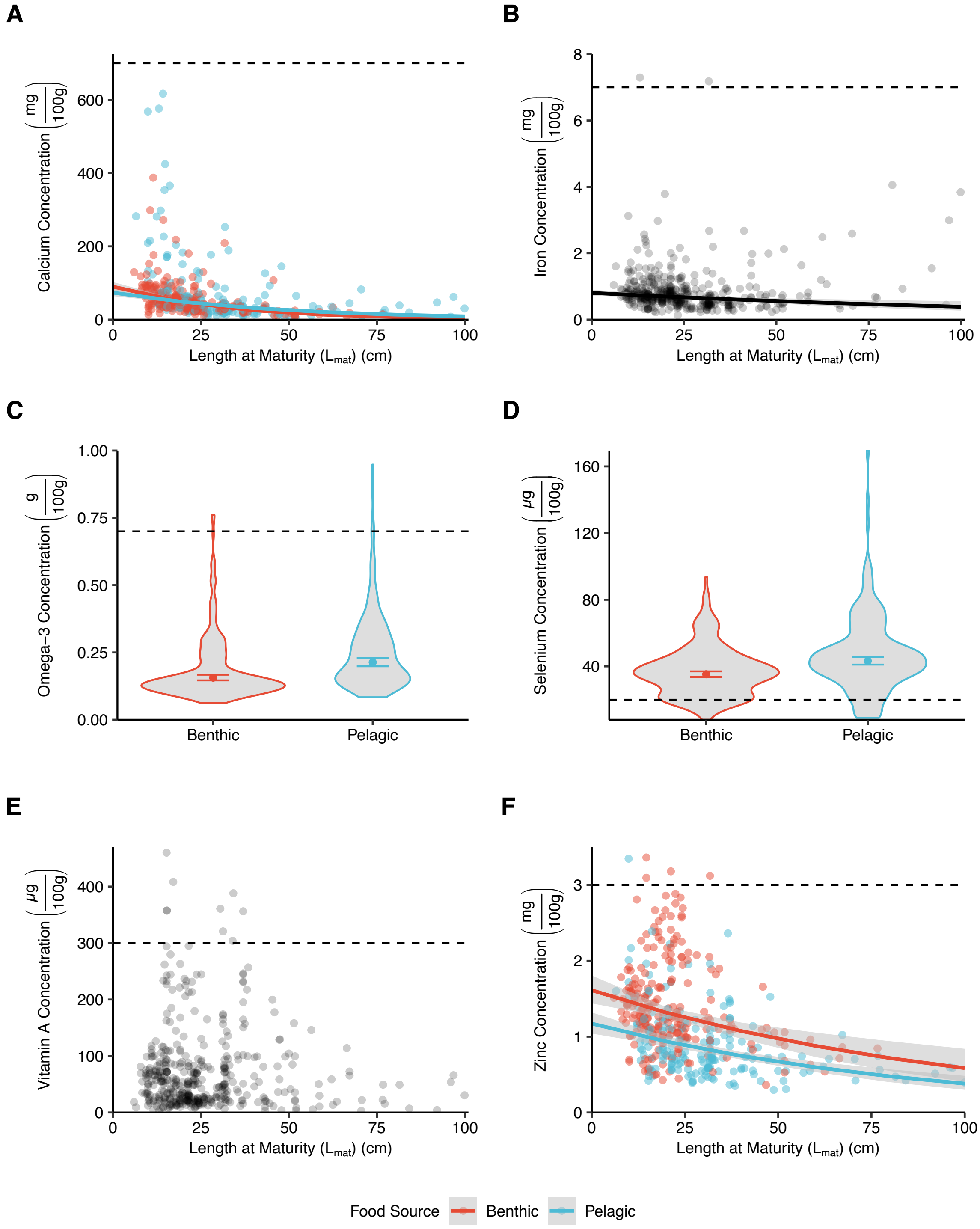

Figure 1 Scatter plots and linear regressions for length at maturity (L_{mat}) and nutrient concentration of 424 species reported in nearshore artisanal fish catches of the Western Indian Ocean. Model best-fit predictions for food source (benthic or pelagic) and length are only displayed if they reached a significance threshold of $p < 0.01$. Dashed horizontal lines indicate the dietary reference intake for each nutrient for a child 1–3 years old (Fig. 2C, F).

3.2. Nutrient densities in the Kenyan artisanal catch

Most species had combined nutrient densities slightly above 200% (out of 600%) of a child's recommended allowance of six nutrients in a 100 g daily portion (Fig. 1). Four species—*Siganus sutor*, *Strongylura incisa*, *Leptoscarus vaigiensis*, and *Lethrinus harak*—accounted for 41% of the catch by mass and ranged in nutrient density from 197–265% (Fig. 1B). Over 71% of all landings and 12 of the top 15 species were benthic feeders (Fig. 1B). The mean length at first maturity (L_{mat}) for all species was 23.5 cm (± 0.98 SE) and the smallest of the top four species was *L. vaigiensis*, which accounted for 7% of the catch and had an estimated L_{mat} of 18.7 cm (Thorson et al., 2023). For all small fish captured (< 20 cm), 67% by mass were sexually mature and 11% of these were pelagic in this predominantly benthic fishery. The mean length at capture was 21.4 cm (± 0.08 SE) and most fish were captured just above their length at first maturity, with a mean maturity index of 1.05 L/L_{mat} (± 3.5×10^{-3} SE).

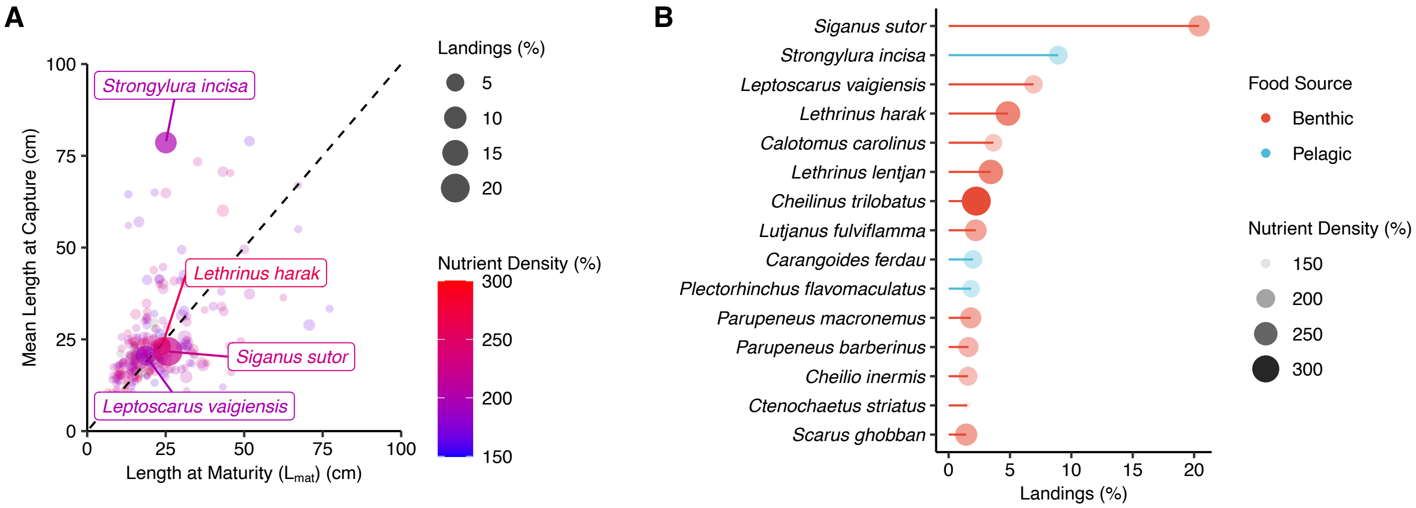

Figure 2 Summary of catch data from Kenya's nearshore artisanal fisheries 2001–2021. (A) Length at maturity (L_{mat}) and mean length at capture for 249 species. Point size represents the percent of landings by mass accounted for by each species, with the top four species labeled. Point color represents the nutrient density of each species for the six nutrients included here, with a possible range of 0–600%. (B) Landings accounted for (% by mass) by the 15 most captured species. Point color represents food source (benthic or pelagic) while point size and darkness indicate nutrient density with a possible range of 0–600%.

The biomass-weighted mean length at capture was significantly correlated with nutrient densities for all nutrients except vitamin A in the Kenyan artisanal catch. Again, however, the effect sizes were small relative to human nutritional requirements (0.3–5.7% of a child's daily requirement between 15–30 cm), and the sign of the correlation varied among nutrients (Fig. 3; Table 2). Small capture sizes (15 cm) were associated with slightly higher densities of calcium, iron, and zinc, amounting to ≤ 5% of a child's daily requirement in a 100 g portion, and lower densities of omega-3 and selenium, amounting to ≤ 6% of a child's daily requirement when compared with larger catch sizes (30 cm) (Fig. 3). For selenium, all nutrient predictions were well above the RDA of 20 μg day^{-1} (Fig. 3D). The mean omega-3 concentration was 0.37 g 100g^{-1} (± 8.7 x 10^{-3} SE), and the mean zinc concentration was 1.6 mg 100g^{-1} (± 3.1 x 10^{-2} SE), both of which fell just above half the daily requirement for a child 1–3 years old.

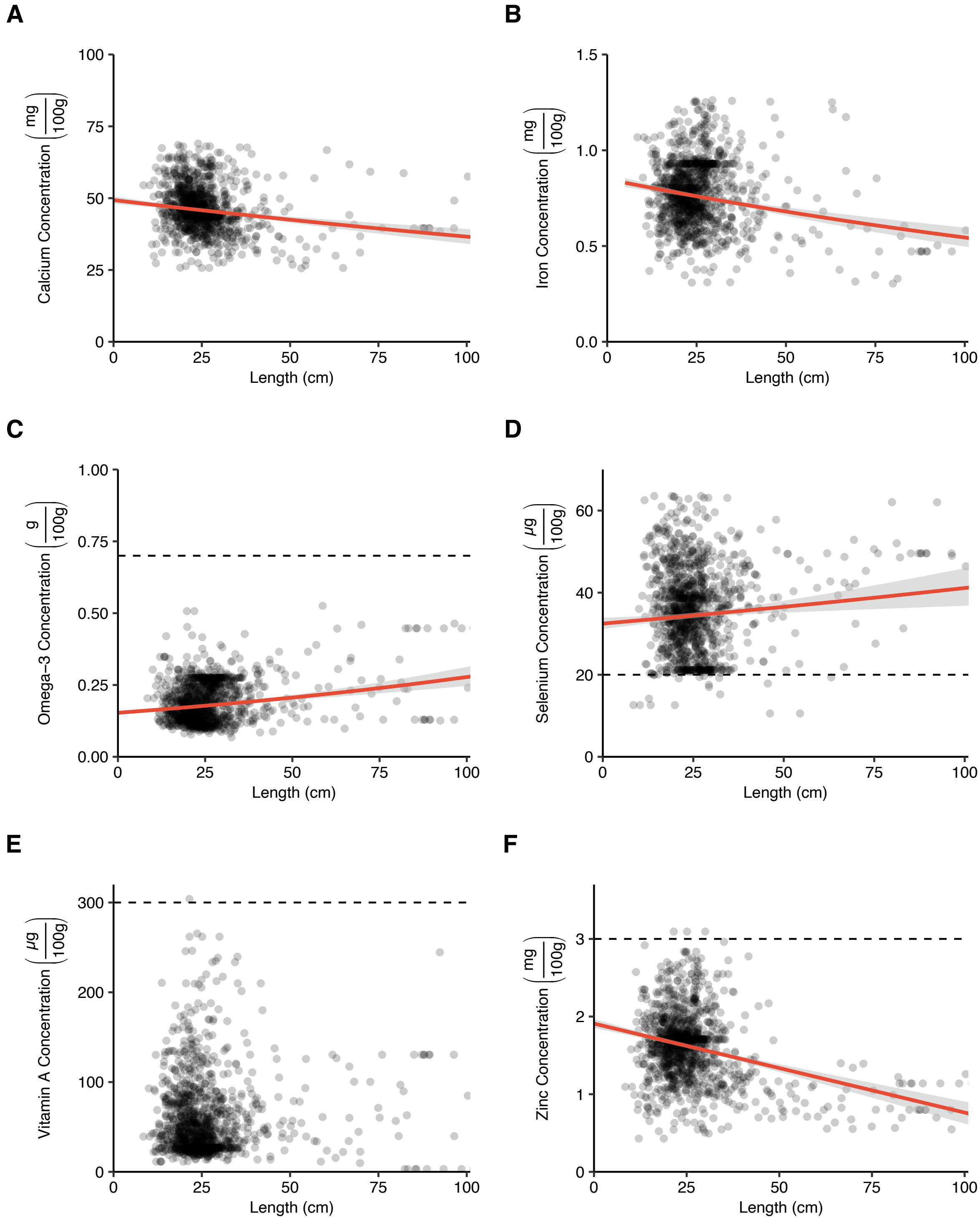

Figure 3 Scatter plots and linear regressions for nutrient densities and biomass-weighted mean length per trip based on 1,163 artisanal fishing trips recorded in Kenya from 2001–2021. Model and best-fit predictions are only displayed if they reached a significance threshold of $p < 0.01$. Dashed horizontal lines indicate the dietary reference intake of each

nutrient for a child 1–3 years old. Dietary reference intakes are not displayed for panels A and B because they are well above the range of observed data and model predictions. A child's recommended daily allowance (RDA) for calcium is 700 mg day^{-1} and the RDA for iron is 7 mg day^{-1} (Institute of Medicine (IOM), 2011, 2006).

3.3 Yield and sustainability indicators

Biomass-weighted mean length was positively correlated with all three yield and sustainability indicators (Table 3; Fig. 4). Small capture sizes were associated with low yields and sexually immature catches, with a mean length of 15 cm generating 38% lower catch per unit effort, 37% lower nutrient yield, and a 22% lower maturity index compared to a mean length of 30 cm (Table 3; Fig. 4). Our linear model predicts that the maturity threshold of 1.0 (biomass-weighted mean L/L_{mat} per trip) is achieved with a capture length averaging 15 cm (0.99, 1.02 95% CI) (Fig. 4C).

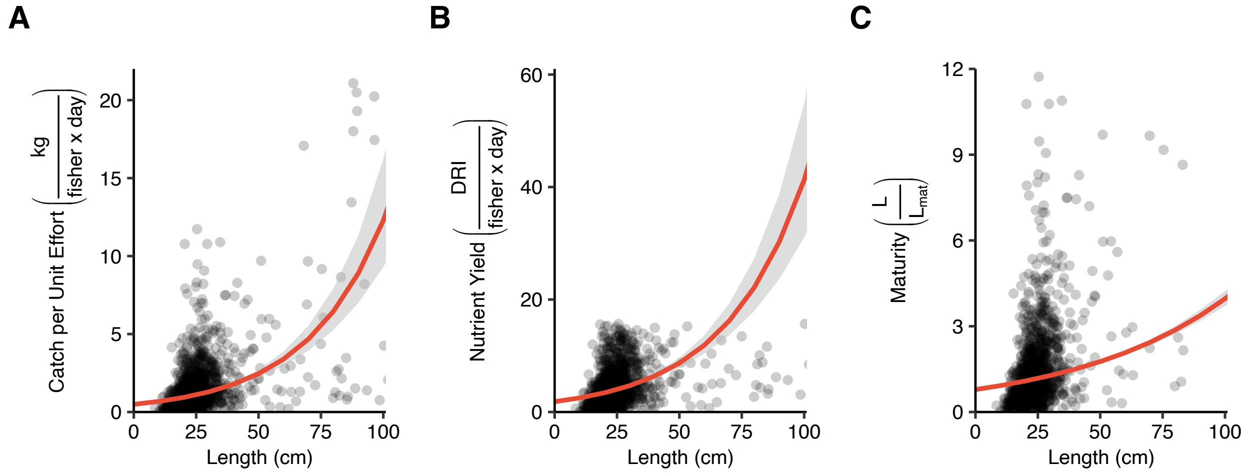

Figure 4 Scatter plots and linear regressions for sustainability and yield indicators and biomass-weighted mean length per trip based on 1,163 artisanal fishing trips observed in Kenya from 2001–2021. All model best-fit predictions reached a significance threshold of $p < 0.01$. (A) Catch per unit effort is expressed in kilograms per fisher per day. (B) Nutrient yield is expressed as the number of complete servings of all six studied nutrients per fisher per day. (C) Maturity is the sexual maturity of the catch, evaluated as the biomass-weighted mean ratio of length at capture to length at maturity (L/L_{mat}) per trip.

4. Discussion

In the WIO and Kenyan nearshore catch, there was little or no apparent nutritional benefit associated with capturing small fish. Given the high numbers of species and the functional traits examined, these results are likely to apply to coral reefs more broadly. Coral reef fishes share a diversity of key functional traits that drive nutrient content (Hicks et al., 2019; McLean et al., 2021). This analysis also indicates that small pelagic fishes captured around reefs and associated nearshore ecosystems are not particularly nutrient dense, with the potential exception of specific targeted fisheries not studied here, such as the small pelagic fishery of the Pemba Channel in Tanzania (Sekadende et al., 2020). Small pelagic species are an important dietary resource in developing countries, and sometimes provide a win-win for nutrition and sustainability, but small fish cannot be said to provide a generally applicable and sustainable solution to malnutrition (Robinson et al., 2022a, 2022c; Wessels et al., 2023). Current recommendations seem to be based on differences in nutrient content among a few selected fish species (e.g., anchovies) and not on patterns seen across larger numbers of species or ecosystems. Coral reef fisheries are a particularly important case in point as they directly or indirectly support approximately 13% of the global population (Sing Wong et al., 2022).

Correlations between fish size, yield, and sustainability indicators (Fig. 3) confirm recommended best practices for coral reef fishery management (Hilborn et al., 2020; McClanahan, 2021). Moreover, that nutrient yield is critical for feeding people and is of greater importance than nutrient density in some contexts (Galligan et al., 2022; Robinson et al., 2022d). The conventional approach to reef fishery management recommended here includes a combination of spatial closures, gear restrictions, and effort reductions that would protect both juveniles and large spawners from overexploitation (MacNeil et al., 2015; McClanahan, 2021, 2018; Samoilys et al., 2017). The theory behind this approach is based on community surplus production curves, which have been used to predict biomass and yields in the WIO and globally (McClanahan and Azali, 2020; Zamborain-Mason et al., 2023). In coral reef artisanal fisheries, gear restrictions that limit the capture of small, sexually immature fishes are associated with increased yields and biomass (Hicks and McClanahan, 2012; McClanahan, 2021; Prince et al., 2015). Conversely, biomass depletion is correlated with truncated size and trophic structures, resulting in catches dominated by small body sizes (McClanahan, 2018; Zamborain-Mason et al., 2023).

One proposed alternative to conventional management is the concept of balanced harvest (BH), which recommends moderate fishing mortality distributed across species, sizes, and ecological functions in proportion to their productivity (Zhou et al., 2019). Advocates for BH argue that removing minimum size restrictions could provide coastal communities with increased access to highly nutritious small fish without compromising overall yields or depleting biomass (Bavinck et al., 2023; Garcia et al., 2012). Its critics argue that BH would lead to overfishing, that it relies on unrealistic ecosystem modeling, and that the empirical evidence supporting it is questionable (Froese et al., 2016; Zhou et al., 2019). While BH has not been explored in coral reef artisanal fisheries, some authors have observed that these fisheries tend to approximate BH naturally in the absence of regulations and market dynamics based on consumer preferences for large fish (Ranaivomanana et al., 2023; Ratusinski, 2023; Tuda et al., 2016). In light of the nutritional benefits of consuming small fish whole (Bavinck et al., 2023; Kawarazuka and Béné, 2011), facilitating increased access to small fish from coral reefs by relaxing minimum size restrictions according to BH might be a legitimate management strategy. However, doing so at current levels of effort would lead to reductions in species richness, maximum yield, nutrient yield, and fisher income (Galligan et al., 2022; Hicks and McClanahan, 2012; McClanahan, 2022; Zamborain-Mason et al., 2023).

We believe policy advice and headline statements should move beyond an oversimplified focus on the nutritional quality of fished species to consider optimizing long-term yields. Distinguishing nutrient density and nutrient yield as well as consistently incorporating recommended nutrient intakes are critical to improving recommendations. Most importantly, recommendations to increase the capture of small fish in unselective fisheries should be met with caution (Bavinck et al., 2023). The losses of income from these policies can be considerable, and they undermine the profitability and sustainability of fishing (McClanahan et al., 2023). Larger capture sizes were associated with increased nutrient yield even when size and nutrient concentration were unrelated (Figs. 2, 3B). While we found no conflict between yield and nutrient objectives here, stronger tradeoffs may exist in other systems (Galligan et al., 2022; Robinson et al., 2022d). As a result, maximizing the nutrient content of fish catches may seldom be a universally desirable goal. Rather, it is more likely to apply only to rare or local circumstances. While nutrient density is an important metric from a consumption perspective, it must be evaluated in the context of other goals such as total production, sustainability, and ecological resilience (Galligan et al., 2022; Maire et al., 2021; Mustafa et al., 2021; Robinson et al., 2022d).

Capturing larger, sexually mature fishes leads to increased yields and more sustainable catches and does not compromise nutrient capture in coral reef artisanal fisheries. Nonetheless, some fisheries may have the potential for increasing nutrient densities (Maire et al., 2021). However, increasing the capture of small fishes in coral reef fisheries is expected to undermine the production of an important source of dietary nutrients. Instead, the many people who rely on coral reefs for their nutrition should focus on sustaining high production of moderate sized fishes.

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Table 1 Results of mixed linear regression models for the effect of food source (benthic or pelagic) and length at maturity (L_{mat}) on the nutrient densities of 424 finfish species captured in Western Indian Ocean artisanal fisheries. The first set of three columns contain slope estimates, the second set of columns contains the change in intercept estimates associated with pelagic feeders, and the final set of columns contains the change in slope estimates associated with pelagic feeders. Estimates are not back transformed. Values in italics reached a significance threshold of $p < 0.01$.

	Length at Maturity			Food source (Pelagic)			Length x Food source (Pelagic)		
	Estimate	Std. Error	p-value	Estimate	Std. Error	p-value	Estimate	Std. Error	p-value
Calcium	*–3.2 x 10^{-2}*	*3.1 x 10^{-3}*	*5.4 x 10^{-22}*	–2.0 x 10^{-1}	1.1 x 10^{-1}	7.2 x 10^{-2}	*1.1 x 10^{-2}*	*3.9 x 10^{-3}*	*6.2 x 10^{-3}*
Iron	*–7.3 x 10^{-3}*	*2.7 x 10^{-3}*	*6.2 x 10^{-3}*	3.0 x 10^{-3}	9.5 x 10^{-2}	9.8 x 10^{-1}	3.0 x 10^{-3}	3.3 x 10^{-3}	3.7 x 10^{-1}
Omega-3	3.1 x 10^{-3}	2.7 x 10^{-3}	2.5 x 10^{-1}	*3.0 x 10^{-1}*	*9.7 x 10^{-2}*	*2.0 x 10^{-3}*	3.5 x 10^{-4}	3.4 x 10^{-3}	9.2 x 10^{-1}
Selenium	5.3 x 10^{-3}	2.5 x 10^{-3}	3.2 x 10^{-2}	*2.9 x 10^{-1}*	*8.8 x 10^{-2}*	*9.4 x 10^{-4}*	–3.5 x 10^{-3}	3.1 x 10^{-3}	2.6 x 10^{-1}
Vitamin A	–6.8 x 10^{-3}	5.3 x 10^{-3}	2.0 x 10^{-1}	3.5 x 10^{-1}	1.9 x 10^{-1}	7.0 x 10^{-2}	–3.3 x 10^{-3}	6.6 x 10^{-3}	6.2 x 10^{-1}
Zinc	*–1.0 x 10^{-2}*	*2.3 x 10^{-3}*	*1.4 x 10^{-5}*	*–3.2 x 10^{-1}*	*8.4 x 10^{-2}*	*1.4 x 10^{-4}*	1.1 x 10^{-3}	2.9 x 10^{-3}	7.0 x 10^{-1}

Table 2 Results of linear regression models for the effect of biomass-weighted mean length per trip on nutrient densities for 1,163 fishing trips observed in Kenya from 2001–2021. Estimates and standard errors for regression coefficients of all nutrients except zinc are on a logarithmic scale. All effect sizes are back transformed where necessary and presented in both real terms and as a percent of a child's (1–3 years old) dietary reference intake (DRI) for each nutrient. Effect sizes are presented between 15–30 cm. Rows in italics are statistically significant ($p < 0.01$).

	Estimate	Std. Error	Effect$_{15:30\ \mathrm{cm}}$	p-value
Calcium	-3.0×10^{-3}	4.8×10^{-4}	*–2.1 mg (0.3%)*	6.4×10^{-10}
Iron	-4.4×10^{-3}	6.2×10^{-4}	*–0.05 mg (0.7%)*	1.4×10^{-12}
Omega-3	5.9×10^{-3}	8.1×10^{-4}	*+0.01 g (1.4%)*	5.0×10^{-13}
Selenium	2.4×10^{-3}	7.6×10^{-4}	*+1.2 µg (6%)*	1.8×10^{-3}
Vitamin A	1.1×10^{-3}	1.5×10^{-3}	+0.8 µg (0.3%)	4.5×10^{-1}
Zinc	-1.1×10^{-2}	9.7×10^{-4}	*–0.17 mg (5.7%)*	1.9×10^{-30}

Table 3 Results of linear regression models for the effect of biomass-weighted mean length per trip on yield and sustainability indicators for 1,163 fishing trips observed in Kenya from 2001–2021. Estimates and standard errors for regression coefficients are on a logarithmic scale. Effect sizes are back transformed and presented between 15–30 cm. Catch per unit effort and nutrient yield are expressed in terms of the daily catch per fisher. All relationships displayed strong significance.

	Estimate	Std. Error	$\text{Effect}_{15:30\text{ cm}}$	p-value
Catch per Unit Effort	3.2×10^{-2}	2.1×10^{-3}	+0.49 kg	1.9×10^{-50}
Nutrient Yield	3.1×10^{-2}	2.1×10^{-3}	+1.7 servings	1.1×10^{-46}
Maturity (L/L_{mat})	1.6×10^{-2}	4.9×10^{-4}	+0.28	2.0×10^{-167}