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Nutrient capture and sustainable yield maximized by a gear modification in artisanal fishing traps

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Abstract

Coral reef artisanal fisheries are an important source of nutrition and economic wellbeing for coastal communities, but their management is subject to conflicts and tradeoffs between short-term food security benefits and long-term ecological function. One potential tradeoff is between nutrient capture and fish yields, where targeting small, nutrient-dense species may be more valuable for food security than maximizing fish yields, which is more closely aligned with supporting biodiversity and ecological function. We explored these potential tradeoffs by comparing two similar gears: traditional African basket traps and traps modified with an escape gap. Traps without escape gaps captured a higher frequency of fish with body sizes below their estimated lengths at maximum sustainable yield than gated traps. Estimates of nutrient yields for six micronutrients among the 208 captured species indicated high hump-shaped relationships for gated traps and low and linear positive relationships for traditional traps. Maximum nutrients in gated traps frequently corresponded to body sizes at maximum sustainable yield. Daily capture rates of nutrients were above daily needs more often in gated than traditional traps, but calcium values were low in both trap designs. Gated traps were more likely to capture species with unique and potentially important functional traits, including browsing herbivores, which could have negative effects on ecological functions and reef recovery. However, gated traps also catch fewer immature fish and fewer predators. Our results indicate that nutrient yields can be maximized while using a gear that captures larger and more sustainable body sizes in coral reef artisanal fisheries. Preferential targeting of nutrient-dense fishes is only one of many metrics for evaluating a nutrition-centered management strategy and may only be a management target in specific contexts.

1. Introduction

Fisheries are increasingly being recognized as an important source of food that can achieve environmental sustainability, reduce greenhouse gas emissions, and increase the availability of micronutrients to people (e.g. Willett *et al* 2019, Koehn *et al* 2022). However, not all environments, fish species, and fish body sizes provide equal nutrition (Hicks *et al* 2019, Beal and Ortenzi 2022). Moreover, fish play different ecological roles and functions that may change with different fisheries practices. For example, smaller individuals and species are generally more nutrient dense than larger ones (Hicks *et al* 2019, Beal and Ortenzi 2022), so a nutrition-centered approach to fisheries management might target small fish to maximize nutrient production (Kawarazuka and Béné 2011, Golden *et al* 2021). However, targeting small species could lead to recruitment limitations and declines in biomass and associated yields and ecological functions (McClanahan 2018). This is especially relevant in multispecies fisheries using

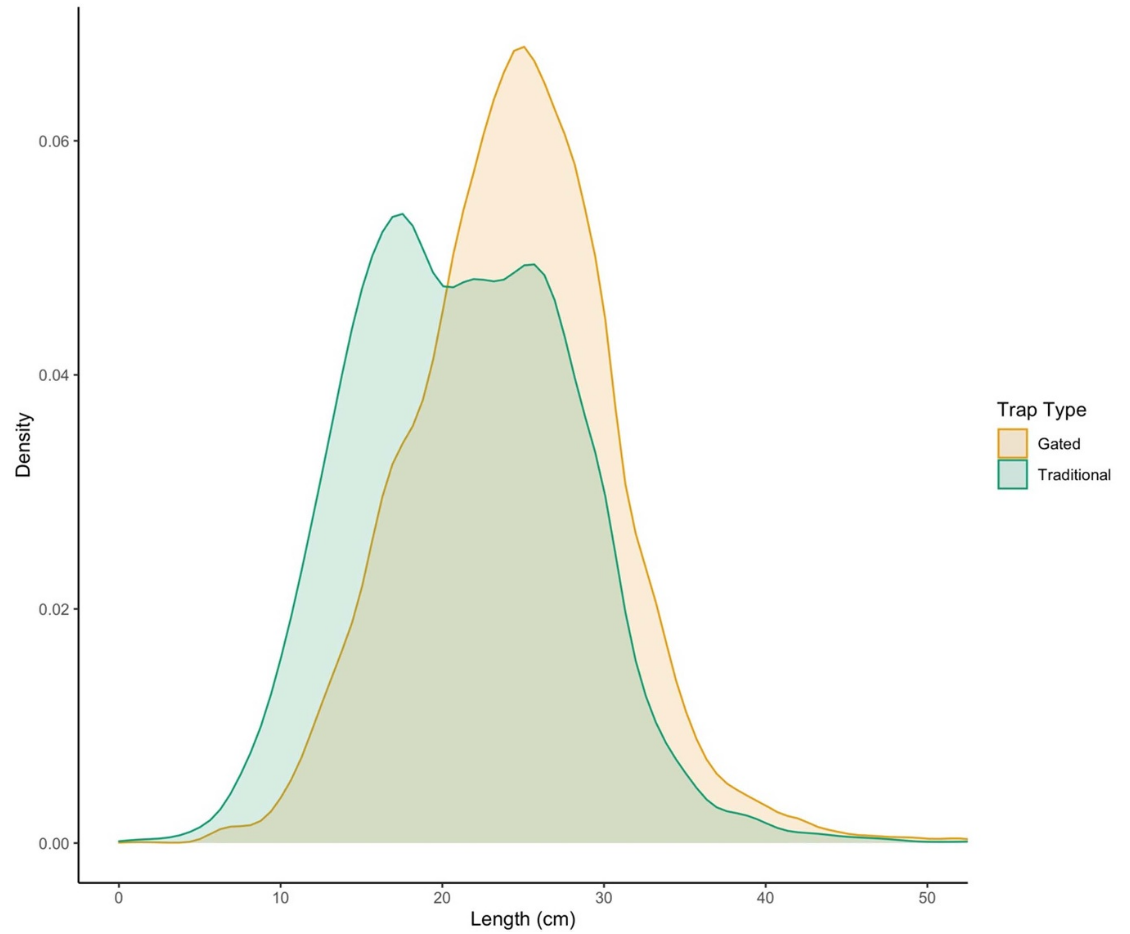

Figure 1. Length density distribution of fish captured by gated and traditional traps for all individual fishes ($n = 25\,789$).

unselective gears, where there may be differences in nutrient composition among captured taxa and where capture of small fishes implies the capture of immature individuals of larger species. These conflicts create challenging, context-specific tradeoffs between nutrition-centered and ecological function-centered approaches to management (Hixon *et al* 2014, Jones and Unsworth 2020).

Artisanal coral reef fisheries often take place in contexts of poverty and food insecurity (Johnson *et al* 2013). This is true in most tropical nearshore fisheries, where overexploitation is common and nutritious food, including protein and micronutrients, is limited (McClanahan *et al* 2015). As a result, the importance of measuring the nutrition provided by these fisheries is increasingly being recognized (Hicks *et al* 2019). Nutrients obtained from capture fisheries can be presented as a nutrient density measure per fish biomass (quality), or as the total yield of nutrients in the whole catch (quantity), and these two measures are not always related (Hicks *et al* 2019, Robinson *et al* 2022b). Thus, the issue of nutrient quality versus quantity may require fisheries-specific evaluations to determine if there are trade-offs. This has raised questions as to whether targeting small fish with high productivity and nutrient density is an acceptable form of fishing among poor fishers in open access multispecies fisheries like those supported by coral reefs and associated ecosystems in Africa (Jones and Unsworth 2020, Tilley *et al* 2020). In this context, the use of gears that capture small fish, such as seine and mosquito nets, are seen by some as a problem for sustainability, profits, and ecological function, while others see it as providing high production and nutrition (Jones and Unsworth 2020, Tilley *et al* 2020). While small pelagic species can often provide high, sustainable, and nutrient-dense catches, targeting small fishes in multispecies fisheries is more complex. Differences in how nutrients are measured (quantity versus quality) and conflicting management priorities contribute to this conflict. The consequences of these tradeoffs for human nutrition and ecological function have not been well examined.

Coral reef artisanal trap fisheries provide an opportunity to examine the potential tradeoffs between a nutrition-centered versus an ecological function-centered approach to fisheries management. A relatively simple management intervention involves adding escape gaps to traditional traps to limit the capture of small fish. Traps with escape gaps (‘gated traps’) catch larger fish than traditional traps (figure 1), and this is widely thought to be a more sustainable alternative because it reduces the likelihood of recruitment overfishing for species with large body sizes (Munro *et al* 2003, Johnson 2010, Mbaru and McClanahan 2013, Gomes *et al* 2014). However, gated traps may also shift the catch composition away from small, nutrient-dense species towards larger, more mature, and less nutritious species. Therefore, the general question we ask is if the loss of small fish will reduce the nutrient content of the captured fish when viewed across the whole daily catch with variable species and sizes. Specifically, we ask (a) if targeting larger fish compromises food security and nutrition, and (b) how this gear modification affects food and nutritional security as well as long-term ecological function outcomes.

2. Methods

2.1. Experimental design

The Kenyan coast is characterized by fringing coral reefs, seagrass beds, and sandy lagoons. Artisanal fisheries target a wide diversity of fishes and octopus using a variety of gears, including basket traps (McClanahan and Mangi 2004, Samoilys *et al* 2017). The basket trap is a traditional fishing gear normally deployed in protected lagoons on or near coral reefs and seagrass beds and is favored by fishers because of its low entry cost and live catch, resulting in a high-quality product (Samoilys *et al* 2011). Historically, traps were constructed from shrub branches and bamboo but are now more frequently constructed from iron rebar and nylon netting.

Traps with escape gaps (‘gated traps’) for undersize fish were introduced at 13 landing sites on the south coast of Kenya beginning in 2010. Escape gap sizes ranged from 2–4 cm, with most gaps measuring 3 cm. Landings from traditional and gated traps were then monitored by trained observers, who identified individual fish to the species, measured total length to the nearest centimeter, and weighed each fish to the nearest 0.1 g. Fish prices (Kenya Shillings per kg) were collected and confirmed locally with fish dealers. Sampling effort was not uniform across sites and years because gated traps were studied as part of a regular monitoring program (Mbaru and McClanahan 2013, Gomes *et al* 2014, Condy *et al* 2015, McClanahan and Kosgei 2018). The most intense sampling took place in 2011 (13 site-days per month), 2014 (15 site-days per month), and September 2016—February 2017 (22 site-days per month). For the entire study period (October 2010—June 2019), mean sampling effort was 8.1 (±1.2 SE) site-days per month.

2.2. Ecological function and food security indicators

Ecological function indicators (table 1) were designed to evaluate catch performance relative to four common management concerns: functional diversity, trophic structure, climate resilience, and species conservation. Functional diversity, including measures of functional richness, divergence, and evenness in multidimensional trait space (Villéger *et al* 2008), was calculated using the *mFD* package (Magneville *et al* 2022) in R (R Core Team 2022) and trait profiles developed for Kenya’s artisanal coral reef fisheries (Mbaru *et al* 2020). We calculated the mean trophic level of the catch and the proportion of piscivorous fish in the catch by mass based on information found in FishBase (Froese and Pauly 2022), accessed through the *rfishbase* package in R (Boettiger *et al* 2012).

To measure climate resilience, we calculated the mean temperature of the catch (MTC) (°C), which is the biomass-weighted mean of species’ inferred temperature preferences, according to the formula:

$$\mathrm{MTC}_t = \frac{\sum_i^n T_i C_{i,t}}{\sum_i^n C_{i,t}}$$

where $C_{i,t}$ is the catch of species i on fishing trip t, T_i is the mean temperature preference of species i, and n is the total number of species (Cheung *et al* 2013). Species’ temperature preferences were obtained from FishBase (Boettiger *et al* 2012, Froese and Pauly 2022). The temperature preferences in FishBase are model estimates inferred from each species’ modeled distribution based on catch and temperature data (Cheung *et al* 2013). These estimates were available for all 208 species included in our analyses. Proportions of browsing, scraping, and grazing herbivores in the catch were also included. Mean vulnerability of the catch was calculated using vulnerability estimates derived from FishBase (Boettiger *et al* 2012, Froese and Pauly 2022), which range from 0 to 100, are based on species’ life histories, and are preferable to International Union for the Conservation of Nature (IUCN) classifications for multispecies studies (Strona 2014).

Food security is increasingly understood as having six dimensions: availability, access, utilization, stability, agency, and sustainability (Clapp *et al* 2021, FAO *et al* 2022). For this study, we developed five catch-based indicators that provided measures for four of these dimensions (table 1), excluding utilization, which addresses household food and sanitation practices, and agency, which prioritizes human autonomy and participatory governance (Clapp *et al* 2021, FAO *et al* 2022). These dimensions fell outside the scope of this study. Availability, which is concerned with the quantity and quality of food (FAO *et al* 2022), was measured by catch per unit effort (CPUE) (kg/trap), the concentrations of key nutrients (omega-3 polyunsaturated fatty acids, calcium, iron, vitamin A, selenium, and zinc) in the catch (g, mg, or μg per 100 g), and nutrient yields (g, mg,

Table 1. Indicators for ecological function and food security performance based on catch data.

Domain	Concern	Indicator
Ecological function	Functional diversity	Functional richness
		Functional evenness
		Functional divergence
	Trophic structure	Mean trophic level
		Proportion of piscivores by mass
	Climate resilience	Mean temperature of the catch
		Proportion of scraping herbivores by mass
		Proportion of browsing herbivores by mass
		Proportion of grazing herbivores by mass
	Species conservation	Mean species vulnerability
Food security	Availability	Catch per unit effort
		Nutrient concentrations
		Nutrient yields
	Access	Value per unit effort
	Stability	Catch variation
	Sustainability	Mean $\frac{L}{L_{mat}}$

or μg per trap). Nutrient concentrations for each species were obtained from FishBase (Boettiger *et al* 2012, Froese and Pauly 2022). The values in FishBase were estimates derived from Bayesian hierarchical models that predict nutrient concentrations of finfish species based on traits related to their diet, energetic demand, and thermal regime (Hicks *et al* 2019). Where trait data were missing for particular species (3 species of 208 total), or where only the genus of a captured individual was available, nutrient concentrations were estimated based on the average concentrations of other local species in the missing taxon's genus or family.

Access, which is concerned with people's ability to acquire available food (FAO *et al* 2022), was assessed by calculating the monetary value of the catch. Stability, which is concerned with food systems' ability to reliably provide availability and access to food on daily, seasonal, and interannual timescales (FAO *et al* 2022), was represented by the proportional distance of one trip's CPUE from the mean CPUE for each combination of site and trap type, so that:

$$C_{var,\,i} = \frac{\left|\overline{X_{c,t,s}} - C_i\right|}{\overline{X_{c,t,s}}}$$

where $C_{var,\,i}$ is the catch variation of fishing trip i, $\overline{X_{c,t,s}}$ is the mean CPUE for trap type t and site s, and C_i is the CPUE of fishing trip i. Sustainability, which estimates whether a food system is using ecosystem services faster than they can be replenished (Clapp *et al* 2021, FAO *et al* 2022), was represented by the mean ratio of the length of fishes caught to each species' length at first maturity $\left(\frac{L}{L_{mat}}\right)$. If this ratio is less than 1, recruitment overfishing is likely taking place, at least at the level of the multispecies stock (Froese 2004). Species-level estimates for length at first maturity (L_{mat}) were obtained from the *FishLife* package in R (Thorson *et al* 2017, Thorson 2020), which uses a Bayesian modeling approach to predict life history parameters for all known fish species based on data found in FishBase (Froese and Pauly 2022) and the RAM Legacy Stock Assessment Database (Ricard *et al* 2012).

2.3. Data analysis

Catch data and subsequent metrics (Galligan *et al* 2022) were cleaned and pooled at the trip level. We used generalized linear mixed models (GLMMs) to compare nutrient concentrations found in the catches of gated and traditional traps, controlling for site as a random effect. We implemented GLMMs using the *glmmTMB* package in R (Brooks *et al* 2017). We used linear models to test for a relationship between nutrient concentrations and body size, represented by each species' optimal fishing length (L_{opt}) and plotted model predictions with a 95% confidence interval using the *ggeffects* package in R (Lüdecke 2018).

We used generalized additive mixed models (GAMMs) to compare the food security performance of each trap type relative to a traditional indicator of fisheries sustainability. Food security performance of each trap type (the response variable) was represented by nutrient yield (g, mg, or μg per trap) and sustainability (the predictor) was represented by the mean ratio of length to optimum length $\left(\frac{L}{L_{opt}}\right)$ for each trip. Each GAMM followed the same model structure, controlling for site as a random effect. GAMMs were implemented using the *mgcv* package in R (Wood 2017). Two sets of model predictions and corresponding standard errors were plotted for each nutrient: one set for gated traps and one for traditional traps. Model predictions were plotted using the *tidymv* package in R (Coretta *et al* 2022). Alongside the predictions, we included horizontal lines indicating the recommended daily intake (RDI) for each nutrient for children 1–3 years old (IOM 2006, 2011).

Table 2. Nutrient concentrations in gated and traditional traps on a catch per trip basis. Significant results from GLMM ($p < 0.05$) are presented in italics.

Nutrient	Gated trap concentration (100 g^{-1})	±SE	Traditional trap concentration (100 g^{-1})	±SE	GLMM estimate	±SE	Pr(>|z|)
Calcium (mg)	7.52	0.18	7.20	0.17	5.78×10^{-2}	0.27	0.83
Iron (mg)	0.14	3.37×10^{-3}	0.13	2.76×10^{-3}	-7.24×10^{-3}	4.92×10^{-3}	0.14
Omega-3 (g)	3.82×10^{-2}	8.90×10^{-4}	3.47×10^{-2}	7.50×10^{-4}	-1.38×10^{-3}	1.31×10^{-3}	0.29
Vitamin A (µg)	*9.39*	*0.41*	*8.88*	*0.35*	*−2.40*	*0.61*	*<0.001*
Selenium (µg)	*5.78*	*0.15*	*5.81*	*0.14*	*−0.82*	*0.21*	*<0.001*
Zinc (mg)	*0.29*	7.23×10^{-3}	*0.26*	6.00×10^{-3}	-2.28×10^{-2}	1.06×10^{-2}	*0.03*

To visualize each trap type's performance with respect to our entire suite of catch-based food security and ecological function indicators, two principal components analyses (PCA) were conducted: one for food security indicators and one for ecological function indicators. Principal components methods were implemented using the *FactoMineR* and *factoextra* packages in R (Lê *et al* 2008, Kassambara 2017). Only the nutrient yield for calcium and the concentrations of vitamin A and calcium were included in the food security PCA because other nutrient indicators were closely correlated with these values. Dimensions with eigenvalues greater than 1.0 were retained for further analysis (Kaiser 1961, Kassambara 2017). Variables were considered well represented by a dimension where $\cos^2$ was $\geqslant 0.3$. Coordinates of each dimension for both PCAs were then extracted and modeled as dependent variables using linear regression, with trap type (gated or traditional) as the independent variable. Where the PCA did not reduce the dimensionality of the data enough for one dimension to represent multiple variables (i.e. proportion of scraping herbivores in the catch), we modeled the variable independently. The relationship between scraping herbivores and trap type was thus modeled using a GLMM to account for site as a random effect, implemented using the *glmmTMB* package in R (Brooks *et al* 2017).

3. Results

A total of 1853 fishing trips were analyzed for 13 sites between October 2010 and June 2019 (Galligan *et al* 2022). Trip catches from gated and traditional traps had similar concentrations of calcium, iron, omega-3, and zinc (table 2). Vitamin A was more concentrated in the catches of gated traps ($p = 7.17 \times 10^{-5}$) and selenium was more concentrated in traditional traps ($p = 1.09 \times 10^{-4}$). Zinc was marginally more concentrated in gated than traditional trap catches ($p = 0.03$).

Smaller species caught in this artisanal trap fishery had higher concentrations of calcium and zinc, but lower concentrations of selenium (figure 2). Omega-3, iron, and vitamin A did not vary with species' lengths at first maturity (L_{mat}) (figure 2). Catches from trips using gated traps had higher nutrient yields than those using traditional traps for all nutrients, and yields peaked near maximum sustainable yield (MSY) $\left(\frac{L}{L_{opt}} = 1\right)$ for all nutrients except selenium (figure 3). These patterns were different from the patterns of CPUE relative to $\frac{L}{L_{opt}}$, which are linear for both trap types (supplementary figure 1).

The first two dimensions of the food security PCA had eigenvalues >1 and were retained for analysis. For food security indicators, the first dimension of the PCA (eigenvalue = 2.9) represented economic value ($\cos^2 = 0.88$), calcium yield ($\cos^2 = 0.88$), and CPUE ($\cos^2 = 0.84$), while the second dimension (eigenvalue = 1.7) represented vitamin A concentration ($\cos^2 = 0.70$), calcium concentration ($\cos^2 = 0.47$), and maturity $\left(\frac{L}{L_{mat}}\right)$ ($\cos^2 = 0.43$) (figure 4). Catch variation was not well represented by the PCA. Linear models found that gated traps generated catches with higher economic values, calcium yields, and CPUE ($p = 4.43 \times 10^{-8}$), as well as higher nutrient concentrations and maturity $\left(\frac{L}{L_{mat}}\right)$ ($p = 3.39 \times 10^{-5}$) (supplementary figure 2).

The first three dimensions of the ecological function PCA had eigenvalues >1 and were retained for analysis. The first dimension of the PCA (eigenvalue = 3.0) represented the proportion of browsing herbivores in the catch ($\cos^2 = 0.88$), trophic level ($\cos^2 = 0.84$), temperature (MTC) ($\cos^2 = 0.38$), vulnerability ($\cos^2 = 0.33$), and functional divergence ($\cos^2 = 0.31$) (figure 4). The second dimension of the PCA (eigenvalue = 1.6) represented functional evenness ($\cos^2 = 0.50$), maturity $\left(\frac{L}{L_{mat}}\right)$ ($\cos^2 = 0.49$), and functional richness ($\cos^2 = 0.31$) (figure 4). The third dimension of the PCA (eigenvalue = 1.3) represented only the proportion of scraping herbivores in the catch ($\cos^2 = 0.47$) (figure 4). Proportions of piscivores and grazing herbivores were not well represented by the PCA.

Linear models found that gated traps generated catches with lower trophic levels, temperature, and vulnerability, but increased functional divergence and the proportion of browsing herbivores ($p < 2.0 \times 10^{-16}$) (supplementary figure 3). There is

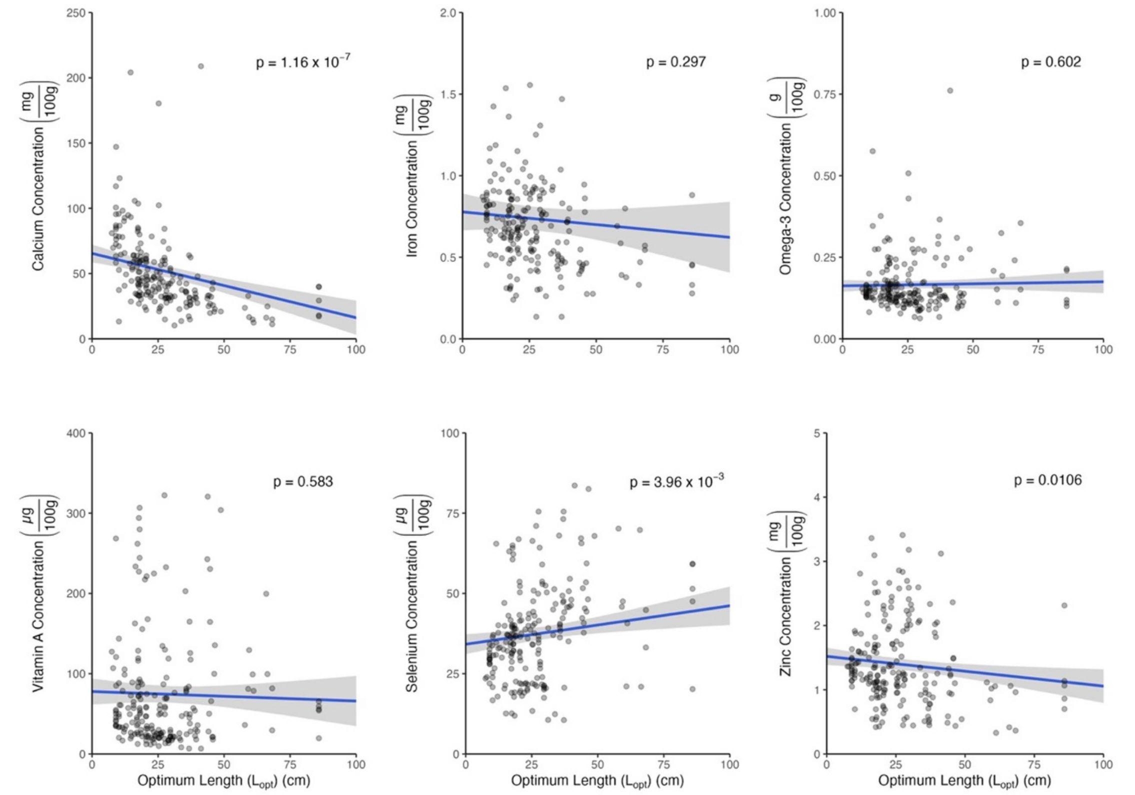

Figure 2. Scatterplots and linear regressions for nutrient concentrations and body lengths of the 208 species caught in artisanal fish traps. Error ribbons indicate 95% CI.

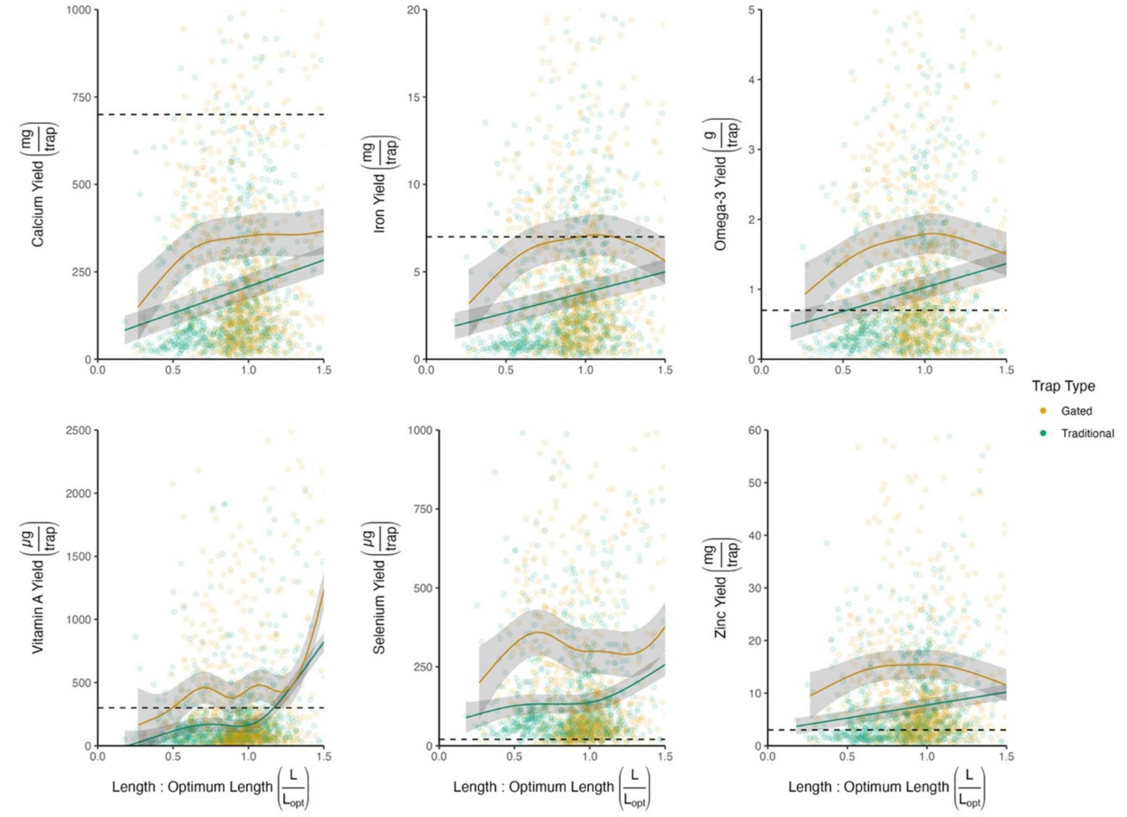

Figure 3. GAMM results for nutrient yields of gated and traditional traps relative to the ratio of length to optimum length (L_{opt}). Error ribbons indicate standard error. Horizontal dotted lines indicate recommended daily intakes (RDI) for children 1–3 years old.

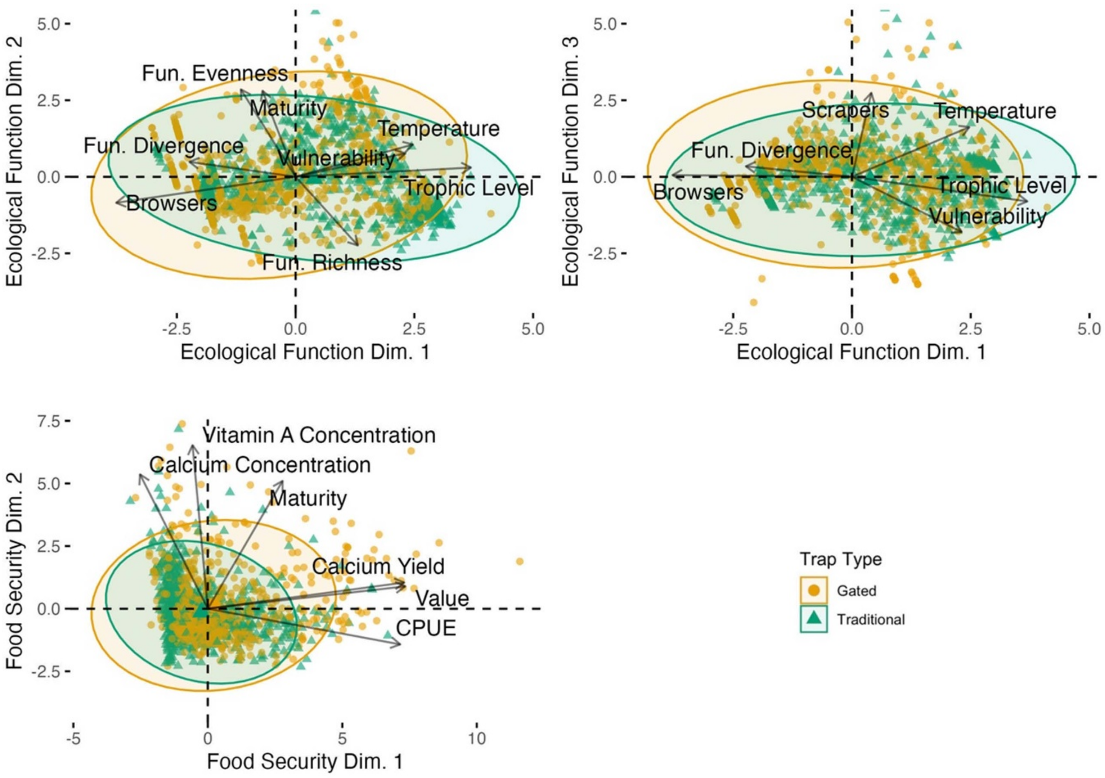

Figure 4. Principal components analyses for ecological function and food security indicators of gated and traditional basket traps in this nearshore artisanal fishery. Dimensions are shown if the eigenvalues were >1.

limited evidence ($p = 0.09$) that gated traps increased functional evenness and decreased functional richness (supplementary figure 3). No significant effect was found on the proportion of scraping herbivores (supplementary figure 3).

4. Discussion

Gated traps were shown to achieve food security, nutrition, and ecological function objectives by simultaneously generating higher nutrient yields and a more sexually mature catch with body sizes that were closer to length-based MSY estimates. These findings highlight the fact that managing coral reef artisanal fisheries for larger, more mature, and sustainable body sizes can address food security objectives without strongly compromising ecological function. Stark tradeoffs between daily nutrition and sustainability were not evident (e.g. Kawarazuka and Béné 2011, Tilley *et al* 2020, Golden *et al* 2021, Beal and Ortenzi 2022). While gated traps did not increase nutrient concentrations in the catch, they did generate higher nutrient yields. Gated traps led to higher overall catches and body sizes that were closer to optimal capture lengths (L_{opt}) than traditional traps. Furthermore, nutrient concentrations in captured fish did not always strongly decline with increased body size at the species level. As a result, total nutrient yields peaked when harvesting fish close to L_{opt} even when CPUE did not.

Gated traps captured more fish closer to L_{opt} and this was associated with maximum nutrient yields. Although the nutrient density (quality) of fish is an important dietary concern (Beal and Ortenzi 2022), it can be compensated by nutrient quantity. In this fishery, targeting small, nutrient-dense fishes does not maximize nutrient yields because doing so strongly limits overall yields. One exception was for vitamin A, which displayed a curvilinear relationship with $\frac{L}{L_{opt}}$ rather than the hump-shaped relationships observed for other nutrient yields. These findings contrast with a modeling study of the North and Baltic seas, which found that fishing for maximum nutrient yield would require overfishing large-bodied predators and exploiting the predicted increase in forage fish (Robinson *et al* 2022b).

Gated traps are expected to reduce the chances of growth and recruitment overfishing (Munro *et al* 2003, Johnson 2010, Gomes *et al* 2014), but their overall ecological performance was mixed. For example, the proportion of scraping herbivores was not reduced in gated trap catches and the proportion of browsing herbivores was higher. The removal of these taxa from the ecosystem could promote erect algae and slow coral recovery after coral mortality events (Cheal *et al* 2010, McClanahan *et al* 2012, Humphries *et al* 2014). Experiments with very large escape gaps (6–8 cm) found that such traps caught fewer scraping herbivores and also generated lower overall catches (Condy *et al* 2015). Consequently, traps with large escape gaps are unlikely to be adopted by subsistence fishers despite their ecological benefits. Given that herbivores are a large portion of the coral reef fish biomass, it is difficult to fully protect them without undermining the high yields needed for food security (McClanahan 1992).

Gated traps' largest effect on functional diversity was to increase functional divergence in the catch. Thus, while gated traps capture fewer functional entities overall (Mbaru *et al* 2020), the functional entities they do capture tend to be more extreme and unique (Schleuter *et al* 2010, Mouillot *et al* 2014). Despite effects on these potentially vulnerable fish functions, gated traps have several attributes associated with a sustainable catch. Specifically, the capture of fewer immature fishes limits the likelihood of recruitment overfishing (Froese 2004), which can pose a threat to reef fisheries sustainability in the absence of marine reserves (McClanahan and Kosgei 2019). The mean sexual maturity of fished individuals was higher in gated traps than in traditional traps for all 208 target and nontarget species (figure 4; supplementary figure 2). This type of tradeoff between ecological function and sustainable yield is a common problem even among the best fisheries management systems when compared to unfished remote wilderness baselines (McClanahan *et al* 2022).

Gears used in this fishery show significant overlap in catch composition (McClanahan and Mangi 2004, Hicks and McClanahan 2012, McClanahan and Kosgei 2018). In Kenyan coral reef fisheries, gears that capture small fishes include traps, handlines, gillnets, and beach seines (McClanahan and Mangi 2004, McClanahan and Kosgei 2018). Despite the focus here on a single gear, we expect that managing this fishery for larger and more sustainable body sizes (e.g. increasing gillnet mesh sizes and banning beach seines) will have similar outcomes for other gears. Despite the compositional overlap, the catch compositions of these gears are not identical (McClanahan and Mangi 2004, Tuda *et al* 2016). As a result, it is still possible that managing for larger body sizes may cause unexpected changes in nutrient yields and other food security or ecological function outcomes not recorded for fish traps. For example, pelagic planktivores, which are often rich in omega-3 fatty acids (Hicks *et al* 2019), are caught by nets and handlines but are not well represented in the trap fishery (Mbaru *et al* 2020). Excluding small pelagic species from the catch could decrease omega-3 yields, but this would not be reflected in the trap data. We also acknowledge that not all gears in this fishery target small fishes. Notably, spear guns tend to capture large-bodied piscivores (Mbaru *et al* 2020, Carvalho and Humphries 2022), which are generally rich in protein and poor in micronutrients (Hicks *et al* 2019). Gear restrictions for nets and traps might indirectly affect spear gun catches by increasing reef fish biomass (Campbell *et al* 2018), but it is unclear how this might affect overall nutrient yields from this fishery. There is a need to evaluate the nutrient composition of all gear types and potential modifications, such as mesh sizes, to better understand the consequences of gear composition on nutrition.

Our approach relied primarily on by-species estimates of nutrient concentrations (Hicks *et al* 2019). We acknowledge within-species variation in nutrient concentrations in coral reef fishes that may have affected our conclusions (Robinson *et al* 2022a). Species-level nutrient concentration estimates are a useful contemporary tool, but future nutrient yield work should evaluate both size- and location-specific data when available. Nevertheless, our results still show that species effects on nutrient capture can be strong. Moreover, nutrient yields are likely to be more important than nutrient concentrations in diverse, multi-species fisheries like those frequently found in the tropics. Additionally, the relationship between nutrient bioavailability and MSY may often be hump-shaped because of the sometimes inverse tradeoff between nutrient quality and quantity.

We did not evaluate all aspects of food security because utilization and agency indicators require more than catch data. However, our results still have implications for these aspects of food security. Gated traps increase the economic value of catches (Mbaru and McClanahan 2013), which may pose a challenge for utilization when fishers are forced to decide between selling their catch or taking it home for consumption. Home consumption is an important part of this local subsistence fishery (Wamukota and McClanahan 2017, Cartmill *et al* 2022), and when fishers use traditional traps, the small, low-value fish are often consumed at home (Gomes *et al* 2014). A more valuable catch might increase fishers' spending power, but may not increase household food security, especially if less nutritious foods such as maize meal and rice are purchased in place of fish (Darling 2014, Cartmill *et al* 2022).

The increases in value reported here were the result of low-value fishes exiting the escape gaps before capture. These bycatch species are not normally brought to market (Gomes *et al* 2014), so their absence likely affects fishing households but not the trading community. Conversely, increased catches may cause fish prices to drop as supply-driven price fluctuations are known to occur in this fishery (Degen *et al* 2010). Lower prices might increase the fish consumed in households and reduce competition with the export value chain (Wamukota and McClanahan 2017). In fishing households, women and men take on gendered economic roles so that households with members engaged in both fishing and trading will most benefit from improved catch performance

(McClanahan and Abunge 2017). In non-fishing households, accessing fish can be difficult due to the high cost of fish at markets and shops (Cartmill *et al* 2022). Women experience more barriers to both fishing and profitable trade then men, which could affect their support for gear modification (McClanahan and Abunge 2017, Cartmill *et al* 2022). Gear-based management generally finds high support among small-scale fishers in East Africa (McClanahan *et al* 2005). One reason for this is that gear choices enhance fishers' agency relative to other common government-controlled management options, such as reduced numbers of fishers (i.e. limited licensing), closed fishing seasons, and area closures (McClanahan and Abunge 2020).

In this study, we developed a suite of indicators to evaluate fishery catch performance relative to the objectives of food security and ecological function (table 1). We found that a simple gear-based management intervention—adding escape gaps to traditional African fish traps—helped achieve multiple objectives, although it did not eliminate tradeoffs. We also found that managing coral reef artisanal fisheries for traditional sustainability targets can achieve a variety of food security outcomes, including the enhancement of nutrient yields. There is no single approach capable of balancing nutrient yields, fishery sustainability, and ecological function in every context. Therefore, gear selection and modification, habitat type, and available management interventions should inform strategies for achieving food security and ecological function outcomes. Future efforts to reconcile the objectives of food security and ecological function would benefit from using our indicators and considering the crucial distinction between nutrient yields (quantity) and nutrient concentration (quality).

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.7256316.

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