Sustainable-use marine protected areas to improve human nutrition

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Sustainable-use marine protected areas to improve human nutrition

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Summary

Coral reef fisheries are a vital source of nutrients for thousands of nutritionally vulnerable coastal communities around the world. Here, we evaluated the potential effects of expanding sustainable-use marine protected areas (MPAs) to improve the nutrition of coastal communities. Using information from underwater visual surveys from 2,518 sites located in 53 countries, we developed a Bayesian hierarchical model to estimate the average effect of existing sustainable-use MPAs reef fish biomass and explored how that may alter fish catch, and the nutrients supplied to local communities. We then estimated the potential nutritional benefits of expanding sustainable-use MPAs to all non-MPA coral reefs globally. We found that existing sustainable use MPAs have on average 15% more biomass than open access reefs. Translating this into catch, we estimated that expanding sustainable-use MPAs could increase

catch potential by 0-20%, which could prevent 0.53-1.95 million cases of inadequate micronutrient intake globally, a fraction of the people who would continue to be sustained by this foundation of coastal food systems. Our study estimates the potential nutritional benefits of expanding sustainable-use MPAs and pinpoints locations with the greatest potential to reduce inadequate micronutrient intake levels, critical knowledge given the strong international movement to cover 30% of our oceans with MPAs by 2030.

Main text

Over 2 billion people are unable to access safe, nutritious and sufficient supplies of food, which threatens human health globally[1]. Coastal residents of tropical developing countries, where coral reef systems are a vital source of critical micronutrients, vitamins, and fatty acids for millions of people[2,3], are particularly vulnerable to nutritional deficiencies[4–6]. Yet, coral reefs around the world are being severely degraded by pollution, overfishing, and climate change, imperiling marine biodiversity and the health of millions of people[7]. Policies governing coral reefs that attempt to address these threats not only shape the future of these ecosystems but also the health of those who depend upon them.

One important management tool rapidly being implemented globally as a measure to recover coral reef ecosystems and associated fisheries from depletion is marine protected areas (MPAs)[8]. MPAs are areas of the ocean with specific rules and restrictions designed to protect marine ecosystems from anthropogenic threats [9,10]. MPAs can be broadly categorized into “no-take” areas where fishing is prohibited and sustainable-use areas where different forms of fishing restrictions are in place (referred to here as “sustainable-use MPAs”). Both MPA types generally have significant positive effects on the biomass of fish within their boundaries compared to neighboring non-MPA areas[11]. Currently, there are about seventeen thousand MPAs worldwide, covering about 7.7% of the ocean (MPAtlas, 2021). Despite failing to reach the globally agreed target of 10% MPA coverage by 2020 (CBD 2011), there is strong international momentum to set a new target to cover 30% of our oceans with MPAs and other effective area-based conservation measures (OECMs) by 2030[12–14].

Here, we quantified the potential human nutritional benefits that can arise from increased access to rehabilitated seafood stocks from sustainable-use MPA implementation. For this, we compiled information on coral reef fish populations and social and environmental conditions from 2,518 reef sites in 53 countries, 804 of which were in sustainable-use MPAs, to estimate the effect of these areas on standing reef fish biomass and the potential nutrient availability for tropical coastal communities. Our analyses were based on a Bayesian hierarchical model that estimated the expected standing reef fish biomass under non-MPA and sustainable-use MPAs conditions, accounting for other social (e.g., human population, market distance, fisheries governance, human development index) and environmental (e.g., productivity, depth, temperature, wave exposure; see Supplement for details) variables. We then used the model to estimate: 1) the effect of sustainable-use MPAs on standing reef fish biomass, 2) expected biomass and catch for existing sustainable-use MPAs, and 3) potential changes in nutritional inadequacies associated with an expansion of sustainable-use MPAs to all non-MPA reefs.

Sustainable-use MPAs increase biomass

We estimated the potential net conservation benefits of sustainable-use MPA establishment by examining the estimated effect size of sustainable-use MPAs on reef fish biomass (Figure 1A). Globally, we found that sustainable-use MPAs have on average 15% more biomass than non-MPA sites (Figure 1A), although percentage increases were dependent on associated variability in physical, environmental, and social conditions in the model and the effectiveness of fisheries management[15] (Figures 1B and 1C). Locations with effective fisheries management were expected to have lower effect sizes because the difference between open access and sustainable-use MPA biomass is likely small. In comparison, locations with low management effectiveness were expected to have greater biomass gains in sustainable-use MPAs. Other known drivers of variation in MPA biomass include variability in MPA design, MPA size and age, and starting conditions, among others[11,16,17].

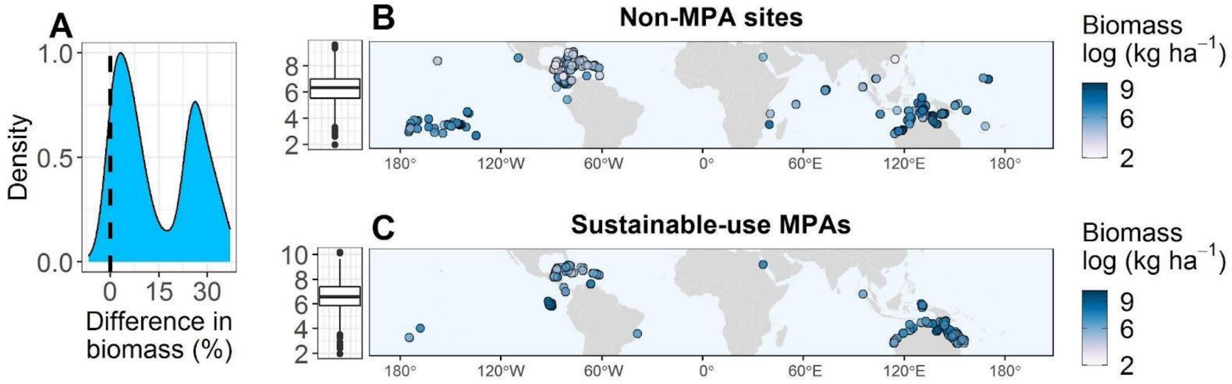

Figure 1 - Biomass in sustainable-use Marine Protected Areas (MPAs), highlighting A) Distribution of percent differences in biomass of sustainable-use MPAs compared to non-MPA sites, B) observed biomass in non-MPA sites (n=1,117), and C) observed biomass in sustainable-use MPA sites (n=804). The distributions of both values are indicated as box plots on the left-hand side of panels A and B.

Expected catch benefits from existing MPAs

We estimated the potential changes in fisheries catch that could result from increases in biomass in existing sustainable-use MPAs. To do so, we used 804 existing coral reef sustainable-use MPAs distributed in 32 countries. Overlaying MPA boundary data from MPAtlas[18] with reef polygons[19], we found that 37% of all coral reefs in the world are within sustainable-use MPAs, 11% are within no-take MPAs and 51% are non-MPA reefs (Figure S1). We then used our Bayesian model to predict the potential biomass density in existing sustainable-use MPAs compared to predicted non-MPA conditions while accounting for local social and environmental conditions.

To estimate the association between standing reef fish biomass and catch within these coral reef MPAs, we used a simple Graham-Schaefer surplus production model, where the sustainable harvest rate was dependent on the predicted reef fish biomass and an estimated population-level intrinsic growth rate for fish of 0.23[20]. We then assessed the expected benefits in catch from existing sustainable-use MPAs compared to non-MPA conditions and found a mean predicted increase in catch of 12%, ranging from 0 - 20 % (Figure 2). Expected catch benefits should be interpreted as the potential sustainable catch benefits derived from existing MPAs.

Based on the risk of inadequate nutrient supply in countries' overall food systems[6], many existing MPAs are in areas with large coastal populations at high risk of inadequate nutritional intake such as Indonesia, Philippines and Haiti and where expected change in catch is the highest (Figure 2). Inadequate intake values range from 0% to 100% and should be considered as a risk of nutritional inadequacies, with higher values representing larger population prevalence predicted to experience inadequate micronutrient intake[21]. We calculated inadequate intake by comparing per capita nutrient supply of overall food systems in each country against age- and sex- specific nutrient demands (see Methods).

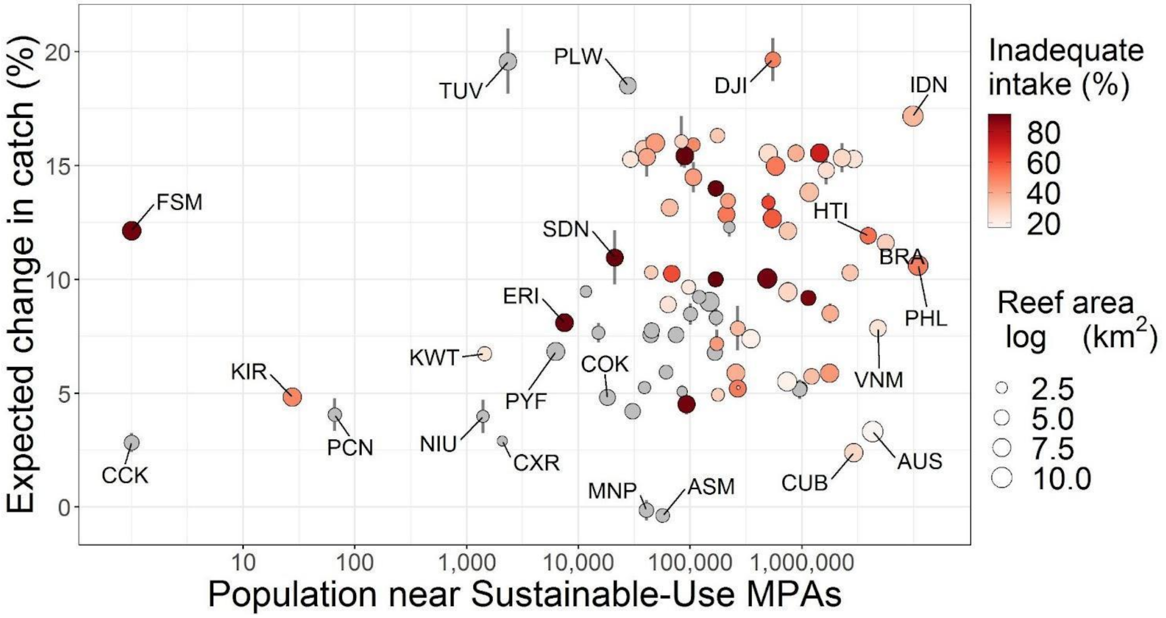

Figure 2 – **Expected catch benefits from existing sustainable-use MPAs to support coastal populations' nutrient intake.** Expected catch effects in all existing sustainable-use MPAs relative to expected catch under non-MPA conditions, plotted on a log-scale for country populations within 10km of an MPA. Error lines represent uncertainty around estimates of change in catch. Inadequate nutrient intake is the average prevalence across key nutrients found in aquatic species in 2017 (iron, EPA+DHA, calcium, zinc, and vitamins A and B_{12}). Points in gray represent countries with no data on prevalence of nutrient intake.

Expanding sustainable-use MPAs to reduce nutritional inadequacies

We predicted the potential nutritional gains of expanding sustainable-use MPAs to all non-MPA reefs (total area of 70,003 km^2, Figure 3A), by (i) calculating the estimated total number of people nutritionally supported by existing and future MPAs, and (ii) calculating the potential change in the prevalence of inadequate nutrient intake with MPA expansion. First, we defined nutritional support from MPAs as the provision of at least 5% of aquatic animal source food intake from coral reef catch (see Figure S8 for sensitivity analysis). We then summed the population near reefs above this threshold to estimate the total number of people supported by MPAs.

Next, we calculated the potential change in nutrient supply attributed to changes in catch from MPA expansion (Figure 3B). To account for geographical differences in reef catch composition from environmental conditions and human behavior, we used the Sea Around Us (SAU) database[22] to assign species catch composition proportions based on their reported data from 2017. This portfolio of species caught were then cross-referenced with the Aquatic Food Composition Database[6] to assign nutrient composition to each species, and to estimate overall nutrient supply from the potential catch. Differences in nutrient supply attributed to predicted changes in catch were then added to the overall diets of populations living within a 10km buffer around reefs (see supplement for sensitivity analysis) to predict the potential changes in inadequate nutrient intake from sustainable-use MPA establishment. In addition, we calculated the total number of people nutritionally supported by MPAs.

We found that expanding sustainable-use MPAs to non-MPA locations could increase catch in many nutritionally vulnerable countries (inadequate intake higher than 25%), with potential positive impacts on human nutrition and health. On average, catch could increase by 12% when considering all countries or 15 % (from 2-20%) if we only consider nutritionally vulnerable countries. Globally, the expansion of sustainable-use MPAs could lead to reductions in inadequate intake across all assessed nutrients for 0.53 - 1.95 million individuals (reduction of 0.2-0.9 million vitamin B_{12}, 0.1-0.5 million calcium, 0.07-0.2 million iron, 0.06-0.2 million vitamin A, 0.05-0.15 million omega-3 long-chain polyunsaturated fatty acids (specifically DHA+EPA), and 0.02-0.08 million zinc inadequate intakes). Beyond preventing nutritional deficiencies, sustainable-use MPAs could also maintain the support of nutritional needs for 2.8 to 30 million people by substantially contributing to overall aquatic animal-source food intake. Countries such as Madagascar, Mozambique, Kiribati, Yemen, and Solomon Islands have the highest potential reductions of inadequate intake following implementation of effective sustainable-use MPAs (Figure 3F). Other countries, including Seychelles and Sudan, have high potential changes in per capita seafood consumption but cannot be modeled in terms of inadequate intake because of a lack of catch or baseline nutrient supply data.

Four major factors drive the extent of potential nutritional impacts of sustainable-use MPA expansion in our study, (i) non-MPA reef area (Figure 3A), (ii) population size near non-MPA coral reefs (Figure 3C), (iii) the prevalence of inadequate intake within coastal communities (Figure 3E), and (iv) the efficacy of fisheries management. First, the larger the area of non-MPA reef (Figure 4A), the larger the potential for MPA expansion to provide nutritional benefits. Second, the size of the local population around reefs (Figure 4C) determines the per capita consumption estimate for reef-caught seafood (Figure 3D). While large local populations will lead to low per capita impacts, but potentially high numbers of people impacted, small populations can have high per capita impacts. Third, increasing catches in coastal communities with high levels of inadequate intake (Figure 4E) has the greatest potential to decrease nutritional risks. On the other hand, increasing catch in communities that already have adequate nutrient intake will have minimal impact on nutritional status. Lastly, the data supported the addition of an interaction between sustainable-use MPA and the national efficacy of fisheries management in the model (Figure S2), reflecting those potential changes in catch following MPA establishment will be different across countries depending on their efficacy of fisheries management (Mora et al 2012). This reflects the fact that locations with high fisheries management efficacy, which may have high biomass outside of MPAs, have little potential for MPAs to provide net biomass increases. Because of uncertainty around all these factors, the absolute number of people impacted by MPA expansion is also uncertain (from 0.4 to 1.8 million people; See Figure S8 for sensitivity analysis). Yet, our results suggest that MPAs can benefit human nutrition, and the general geographical patterns appear robust to a large range of conditions.

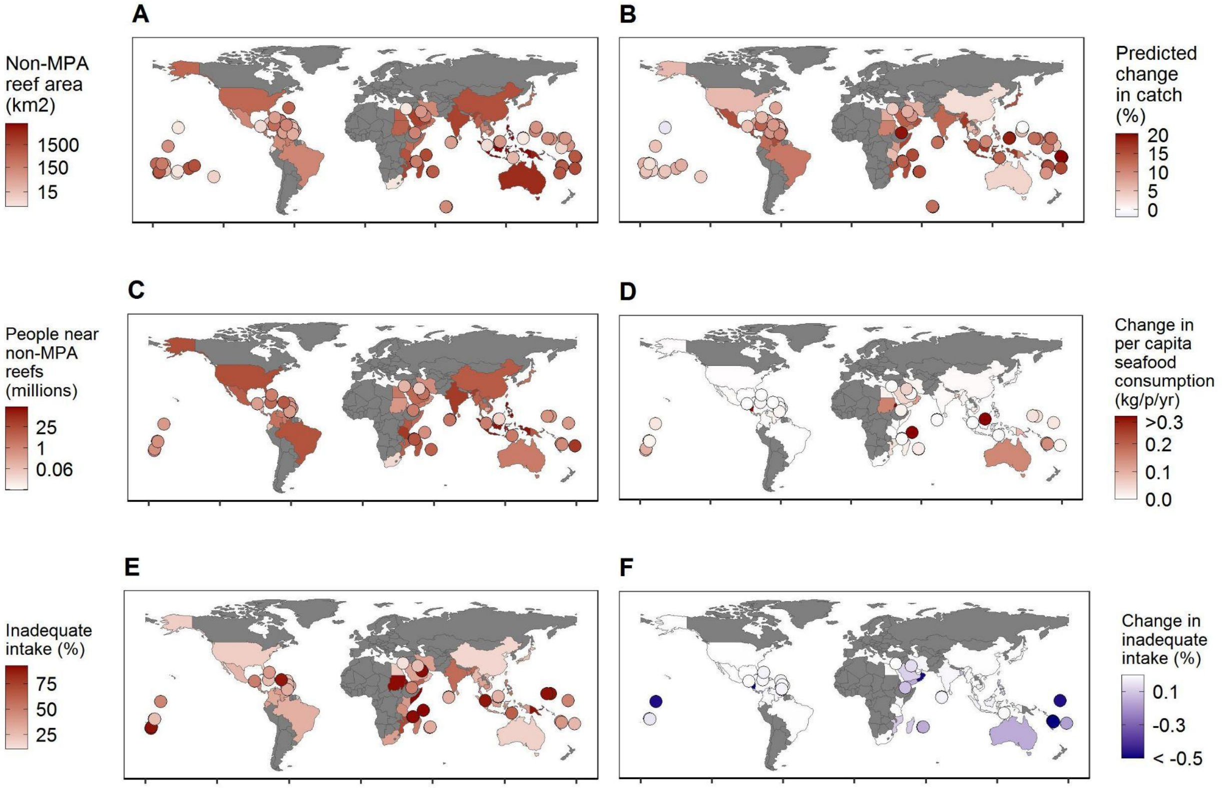

Figure 3 – Nutritional impacts of expanding sustainable-use MPAs into unprotected reefs (A) non-MPA reef area within each country based on the overlap between MPA and reef areas; (B) predicted change in catch in a hypothetical sustainable-use MPA expansion into non-MPA reefs; (C) total number of people within a 10km buffer around non-MPA reefs; (D) predicted change in per capita consumption of seafood for the population around non-MPA reefs; (E) prevalence of present inadequate intake across countries (from Golden et al 2021); and (F) predicted average change in inadequate intake for coral reef coastal populations across all assessed nutrients (iron, EPA+DHA, calcium, zinc, and vitamins A and B_{12}). Countries smaller than 25,000 km^2 are illustrated as points.

Nutritional targeting of vulnerable populations with marine conservation

Because each country has different inadequacies among nutrients, sustainable-MPAs can be strategically implemented to reduce specific nutritional inadequacies in coastal populations (Figure 4). For example, strategically creating sustainable-use MPAs in Yemen and Madagascar has the potential to reduce inadequate intake risks of omega-3 long-chain polyunsaturated fatty acids (DHA+EPA). Increased intake of DHA+EPA can promote brain and eye health and is associated with reduced risk of heart disease[23]. India and Bangladesh could particularly benefit from increased supply of vitamin B_{12}, where inadequacy is more than twice the global average. Vitamin B_{12} deficiency is associated with increased risk of heart disease and cognitive decline[24]. Mozambique and Cambodia could benefit from increased supply of iron, which is particularly important for healthy brain development and growth in children[25], and can prevent maternal mortality[26]. Sustainable-use MPAs in Nicaragua and Madagascar have the potential to reduce inadequate intake of zinc, which supports immunity and is particularly important for children and pregnant women[27]. In contrast, Kuwait and Indonesia could benefit mostly from increased supply of calcium, which supports bone health and blood pressure[28]. Lastly, Oman and Kiribati could benefit from increased vitamin A supply, which supports eye health and cell growth[29].

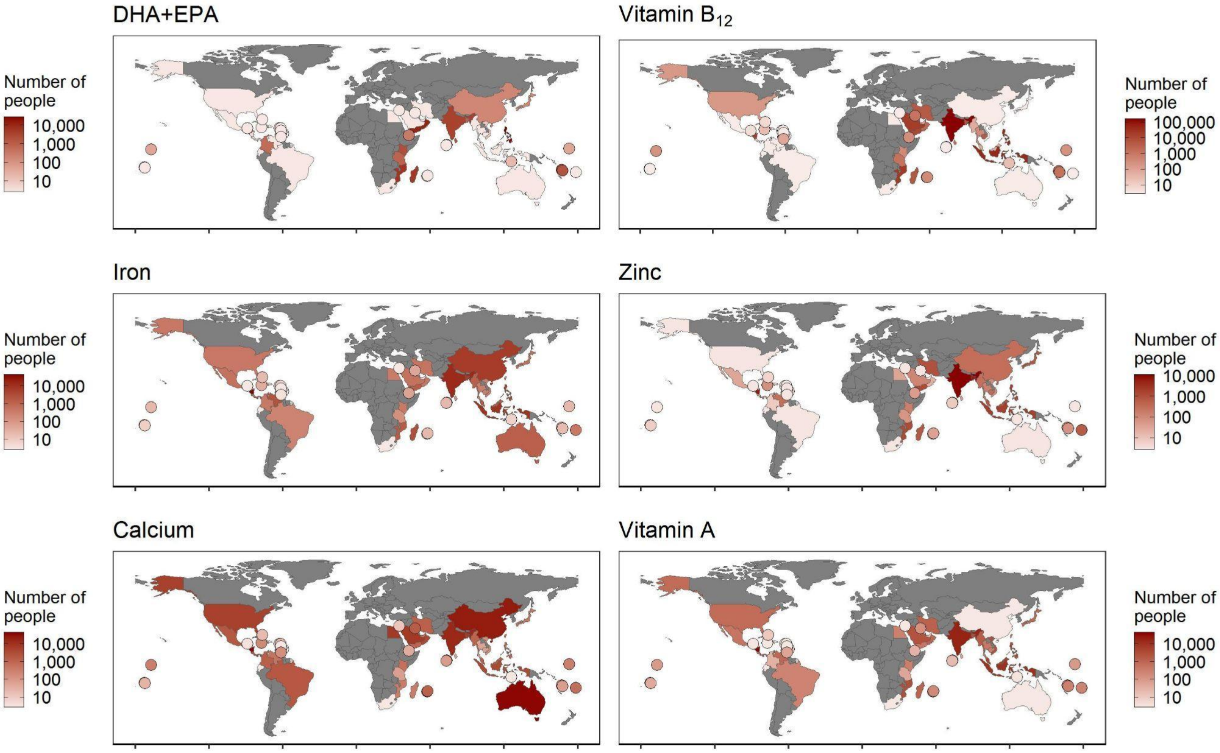

Figure 4 - **Potential nutritional benefits from sustainable-use MPA expansion.** Total reduction in inadequate intake of key nutrients from coral reef sources for coastal human populations from expansion of sustainable-use MPAs relative to non-MPA conditions. Countries smaller than 25,000 km2 are illustrated as points.

Discussion

Our global analysis suggests that effective sustainable-use MPAs have the potential to increase biomass and support nutritional security through increased catches. These benefits are on top of the traditional MPA impacts on livelihoods and marine biodiversity (in essence, co-benefits). We predict that expansion of sustainable-use MPAs to non-MPA reefs can have significant nutritional benefits, both sustaining the nutrition of vulnerable populations and decreasing the prevalence of inadequate intake of vital nutrients. For coastal communities that rely on coral reef resources for key nutrient intake, increasing sustainable supply of nutritious food can have significant positive impacts on their health and well-being. Many factors will affect the magnitude of impacts on a local scale. For example, we show that the quantity of seafood communities will catch (harvest rate) and how many people will consume that seafood (per capita consumption) are particularly important. Other local conditions such as reef area, prevalence of inadequate intake, and the efficacy of fisheries management will also play an important role.

Our model predictions are based on the current performance of sustainable-use MPAs. To restrict catch, these areas use an array of fisheries management tools to support reef management, including gear restrictions, access rights, size limits, temporal closures, bag limits, and more[8]. Some of these sustainable-use MPAs may be zoned for multiple uses, potentially containing small no-take areas within them, which may also benefit fished areas through spillover[30,31]. Because our results depend on actual performance of sustainable-use MPAs, if management of these areas improves (through more investment, management capacity, planning, community participation, etc.), potential biomass and consequential nutritional gains could be even greater. Understanding how close MPAs are to their maximum sustainable yield can provide a better estimate of their true potential to provide nutritional benefits. In addition, for fish stocks below maximum sustainable yield, recovery will likely require a short-term decrease in catch to obtain long-term gains[32,33]. Therefore, it is important to consider potential short-term nutritional costs to achieve predicted long-term nutritional benefits.

We consider sustainable-use MPAs as all conserved areas included in the MPAtlas where fishing is permitted[9]. In addition to state-managed areas, it encompasses many types of area-based management strategies such as Locally Managed Marine Areas (LMMAs), Environmental Protection Areas (EPAs), and Marine Conservation Areas (MCAs). In many cases, these and other effective area-based conservation measures (OECMs) empower local stakeholders and incentivize resource management, while considering local characteristics of the fishery and cultural traditions of coastal communities[34]. Several studies have shown that when communities are empowered and have secure rights to a fishery, there is greater incentive for successful fisheries management yielding nutritional benefits[35–37]. However, more research is needed to evaluate how different types of sustainable-use MPAs affect biomass, catch and human nutrition. Various other management measures (e.g., individual quotas) could also improve nutrient supply but are not commonly implemented in sustainable-use MPAs in tropical coastal areas.

Expansion of sustainable-use MPAs depends on strong local, national and global commitments and investments. Today, only a small fraction of resources from governments, regional development banks, and multilateral funding agencies are directed to strengthening governance of small-scale fisheries[38]. The lack of adequate capacity to manage MPAs has led to the creation of many “paper parks”, which are designated areas that are not effectively implemented[9], thus having limited potential to provide environmental, economic, and nutritional benefits. In addition, implementation of sustainable-use MPAs are usually not part of the food and nutrition agenda of coral reef countries. Our results suggest that populations who depend on reef systems for nutrition would benefit from funding that is directed to sustainable marine resource management.

Climate change impacts on reef ecosystems creates an uncertain future for millions of people who depend on reef fisheries for nutrition and livelihood. Without actions (such as sustainable-use MPAs) to ensure sustainability of catch into the future, there can be significant loss of nutritional benefits in the coming years, with important implications for public health. Therefore, it is not only the prevention of inadequate intake and the supporting benefits of MPAs that can be important, but also the buffering against the risk of future loss in climate-vulnerable systems. Without conservation action in the present, the risk of future negative nutritional impacts is inevitable in the long-term.

To achieve all United Nation Sustainable Development Goals (SDGs), it is critical to find synergistic strategies whereby coastal marine governance can achieve human health and conservation outcomes, ensuring both sustainable populations of diverse species and the flow of vital nutrients to vulnerable populations. While SDG goals of “zero hunger” and “good health and well-being” are particularly dependent on food availability to vulnerable communities, the goal of “life below water” is particularly dependent on ocean conservation. Here, we show how meeting the “life below water” goal can help support “zero hunger” and other goals. It is essential to analyze tradeoffs between both goals and find win-win solutions that benefit both people and the planet.

Methods

Reef fish underwater surveys

We compiled information of coral reef transects from the Reef Life Survey (RLS) and Atlantic and Gulf Rapid Reef Assessment (AGRRA) databases. Both databases are based on underwater fish counts by size class within a belt transect. We then calculated individual biomass by using length-weight relationships published for all species on Fishbase (Froese and Pauly 2021) and then multiplying individual biomass by the total number of fish within each size class. The final compiled database contained 16,365 surveys from 2,518 tropical coral reef sites (i.e., within 23.5 latitude degrees) distributed across 53 countries. Data collections were conducted from 1997 to 2020. Where data from multiple years were available for a single site, we included only the most recent year. To estimate the “fishable biomass” we retained only fish larger than 10cm[39]. Because underwater fish counts do not accurately capture biomass of large schools of pelagic fish (e.g. Scombrids, Sphyraenids) or large transient fish, we removed all shark and ray species[39,40]. In addition, because of data constraints we only consider reef fish catch as nutrient source, however, invertebrate species and aquatic plants can also be an important source of nutrients in many low-income countries.

We divided all survey sites into three basic categories: non-MPA areas, sustainable-use MPAs and no-take MPAs. Non-MPA areas are all sites outside of marine protected areas, which can be subject to regional or national-level policies (whether enforced or not). In general, these areas are not managed through additional area-based regulations. Sustainable-use MPA sites are all sites within an area-based management system that allows fishing within its borders, including areas such as multiple-use MPAs, Locally Managed Marine Areas (LMMAs) or Environmental Protection Areas (EPAs). No-take MPAs, in contrast, is a term used here to describe areas where no forms of fishing are allowed (also known as fully protected, marine refugia, etc.). These areas may contain other economic activities such as tourism or can be strictly for research and conservation. In total, we had 1,117 non-MPA sites, 804 sustainable-use MPA sites, and 500 no-take MPA sites.

Spatial analysis

For each coral reef polygon, we calculated the total reef area that is within a sustainable-use MPA, no-take MPA, and non-MPA. To do this, we intersected all coral reef polygons[19] with MPA polygons from the MPAtlas[18]. Within the MPAtlas database, each MPA was divided into sustainable-use or no-take MPAs, allowing the calculation of the percentage of reefs falling within each category.

Next, we calculated the population around existing MPAs and non-MPA reefs by intersecting all reef and MPA polygons with the raster of the gridded population of the world in 2019 (CIESIN, 2019). We calculated the population within 5, 10, 20, 25 and 30 kilometers buffers around reefs and MPAs. To avoid double counting coastal populations, all overlapping polygon buffers were aggregated. We used the **sf** package[41] in R statistical software[42] to perform all spatial analysis.

Predicting fish biomass

We used a Bayesian model to predict fish biomass (above 10cm) in every coral reef around the world. For all coral reef polygons, we predicted the biomass of reef fish per unit area (kg/ha) under two alternative conditions (non-MPA and sustainable-use MPAs) while accounting for each site's own environmental and social covariates (Figure S2). Site covariates considered in this analysis included chlorophyll concentration, sea surface temperature mean, sea surface temperature range, nitrate concentration, wave exposure, reef area, shore distance, human population, market distance, human development index, and fisheries management effectiveness[39,43]. To account for variability in MPA effectiveness across countries (due to differences in management, staff capacity, state of the reef prior to MPA establishment, etc.), we also considered an interaction term between presence of sustainable-use MPAs and fisheries management effectiveness across nations[15]. In addition, we set ecoregions as a random effect to account for the spatial structure of the data. Collinearity among covariates was examined based on bivariate correlations and variance inflation factors, which led to the exclusion of both environmental variables (pH, salinity, primary productivity, and minimum sea surface temperature) and social variables (land cover, fisher density, and government effectiveness).

We used the **brms** package[44] to construct the model in R statistical software[42]. Models were run using the Hamiltonian Monte Carlo algorithm for 10000 iterations and 4 chains. Posterior estimates were informed by the data alone (weakly informed priors). Convergence was monitored by examining posterior chains and stability and checking if the scale reduction factor was close to 1. Next, we tested a null model with intercepts only and a full model that included all covariates. We compared both models through leave-one-out cross validation information criteria (LOOIC), ensuring that our full model performed better than the null model (elpd_diff = -95.7). In addition, we used LOOIC to test if the model with interaction performed better than the model without the interaction term between MPA and fisheries management effectiveness. To examine model fit and homoscedasticity, we checked residuals against fitted values and conducted posterior predictive checks (Figure S3). In addition, we evaluated the goodness-of-fit of the model using leave-one-out cross-validation (loo_r2 = 0.41). When predicting biomass in reef polygons, we assumed a model with a random intercept since not all ecoregions with reef polygons are represented in our data.

Biomass predictions per unit area (kg/ha) were then multiplied by the area in each reef polygon to estimate the total reef fish biomass on each reef. Implicitly, we thereby assumed equal productivity across each reef polygon. Reef polygons range from about 100 square meters to 9.8 thousand square kilometers, with a median of 6.3 square kilometers. We acknowledge that biomass estimates are affected by (i) our reliance on biomass and social and environmental conditions for reefs within our dataset which may or may not be representative of all reef systems, (ii) potential spatial and temporal imprecision, (iii) other factors not accounted in the model could also drive biomass, (iv) social and environmental conditions can vary over smaller scales than reef polygons considered here, however, data collections enabling to account for local patchiness in productivity would be extremely challenging if not impossible.

Predicting potential changes in catch due to MPA establishment and operation

The potential change in catch from sustainable-use MPAs was estimated by comparing predicted biomass under non-MPA and MPA conditions. To estimate catch from biomass, we used a simple surplus production model (Shafer, 1954). This model assumes that the harvest rate that produces maximum sustainable yield (F_{MSY}) is half of the intrinsic population growth rate (r) of the species. Therefore, species that grow and reproduce faster can sustain higher levels of harvest than slow growing species. Population-level intrinsic growth rates were derived from McClanahan and Graham 2015[45] (r = 0.23). Harvest rate will also depend on the standing biomass in each site relative to the assumed biomass that maximizes yield (B_{MSY}), to reflect the fact that sites with lower biomass should have relatively higher harvest rates than sites with higher biomass. As a proxy for B_{MMSY} we used the 90th biomass quantile of predicted biomass for sustainable-use MPA (544 kg/ha), assuming that these sites are fishing at MMSY or multispecies maximum sustainable yield and within limits of globally proposed BMMSY[43,45] (see Figure S4 for a sensitivity analysis). Sensitivity of results to harvest rate assumptions are shown in Figure S5 (growth rates varying from 0.1 to 0.6). Regional patterns and percent changes in catch are not affected by assumptions of harvest rate. However, total absolute numbers of people affected by MPAs expansion are sensitive to harvest rate assumptions.

Assigning nutritional content to reef fish catch

To assign specific species to the predicted change in reef fish catch, we used the Sea Around Us database (Pauly et al 2020), allocating total catch estimates to species proportions based on the proportion of reef species caught in each country in 2014. We used SAU to account for country-level differences in catch and because our surveys did not cover all countries containing coral reef polygons. To obtain this information from SAU, we first separated production from artisanal and subsistence sectors. Next, we identified reef species as occurring in the following functional groups: “Medium reef assoc. fish (30 - 89 cm)", "Large reef assoc. fish (>=90 cm)" and "Small reef assoc. fish (<30 cm)". In addition, we restricted the data to families that were recorded in the underwater visual surveys.

To assign nutritional content to reef fish species, we used the Aquatic Foods Composition Database (AFCD), a comprehensive database containing 3,750 records of nutrient content from global databases and peer-reviewed literature[6]. We then use a hierarchical approach[6] to match specific species taxonomic information with AFCD and fill nutrient information for species not present in the database. This hierarchy is based on the following order: 1) scientific name, and then the taxa-specific average of 2) genus, 3) family, 4) order, and 5) class. We then matched the following nutrients: iron, zinc, protein, vitamin A, vitamin B_{12} and calcium (Figure S6). These nutrients were chosen because of their high concentration in aquatic species, their importance in human nutrition, and their inadequate intake across many countries[6]. We then multiplied the predicted catch by the edible portion of each species based on AFCD data and multiplied further by nutritional value to obtain the total nutrient supply for each nutrient.

Calculating per capita nutrient supply and catch from MPA expansion

We calculated the per capita nutrient supply by dividing total nutrient supply by the human population around reefs. Although some valuable reef species are traded in international or regional markets, we assumed for simplicity that all extra catch from MPA expansion will be consumed by coastal communities within a 10 km buffer around reefs. At a local scale, the per capita consumption will depend on accessibility: distance of the reef from the community, the size of boats, trade dynamics, etc. For example, a 20 km radius will capture the travel distance that most fishers take in subsistence/artisanal fisheries[46,47]. However, acknowledging the high uncertainty around this value, we tested multiple alternative buffer sizes around reefs to estimate per capita nutrient supply (Figure S7). Larger buffers around reefs increased the number of people impacted, and, thus, lowered per capita nutrient supply. Although the magnitude of impacts changed depending on buffer size, regional patterns were not affected by the assumed population around reefs.

To calculate the number of people supported by sustainable-use MPAs, we first estimated the per capita reef fish catch by dividing the predicted catch in each reef polygon by the population within a buffer around the reef. Next, we estimated the percent contribution of per capita reef catch relative to per capita national average consumption of aquatic animal sourced foods based on the Global Nutrient Database (GND)[48]. The GND used the Food and Agriculture Organization of the United Nations Supply and Utilization Accounts (SUAs) to obtain estimates of apparent per capita consumption of 22 food groups and nutrient supply for 156 nutrients across 195 countries. We considered coral reefs to provide a meaningful contribution when coral reef catch represented at least 5% of aquatic animal food intake (see Figure S8 for sensitivity analysis). We then summed across all reefs that provided a meaningful contribution to calculate the total number of people that could potentially be supported by existing and future sustainable-use MPAs.

Calculating the contribution of MPAs to human nutrition

To calculate potential nutritional effects of MPA expansion, we compared a baseline scenario with a scenario of increased reef fish consumption through an expansion of sustainable-use MPAs. Baseline conditions were calculated using estimates of nutrient consumption in 2017 from Global Nutrient Database (GND)[48]. The MPA expansion scenario was calculated by adding the per capita nutrient supply from MPA expansion to this baseline level of nutrient intake.

We then calculated the prevalence of inadequate intake for current conditions and MPA expansion scenarios to obtain the difference in inadequate intake across both scenarios. Prevalence of inadequate intake was calculated following three main steps. First, we disaggregated country-level mean intakes into age-sex mean intakes using the Global Expanded Nutrient Supply (GENuS) database for all nutrients except DHA+EPA and vitamin B12, which are not included in the GENuS database[49]. Second, using dietary recall data from SPADE (Statistical Program to Assess Habitual Dietary Exposure), we derived habitual dietary intake distributions across age-sex groups and geographies[50]. We used SPADE outputs to describe the shape (gamma or lognormal distribution) of intake distribution for each age–sex group and to derive age–sex mean intakes for DHA+EPA and vitamin B12. Lastly, we calculated the prevalence of inadequate intake using the summary exposure values, or SEVs[6,21]. SEVs estimate the population-level risk related to diets by comparing intake distributions with requirements. The latter are continuous risk curves with values of 1 for low intake, 0 for high intakes and 0.5 for intakes at the Estimated Average Requirement (EAR). These absolute risk curves are then constructed as the cumulative normal distribution function of requirements with a mean at the EAR and a coefficient of variation of 10%[51]. EAR estimates were derived from several sources (FAO, Institute of Medicine), and a coefficient of variation of 25% was used to account for uncertainties regarding recommended intakes. For DHA+EPA, we used the relative risk curves that are associated with ischaemic heart disease and have different values for adolescent and adult subpopulations (with no risk for children)[21]. Estimated prevalence of inadequate intake range from 0% (no risk) to full population-level risk (100%).

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Author contributions

DV, CDG, MM, AZ, and DG conceptualized the research idea, with significant methodological and design input from JZM, AS, CMF, and NK. DV led paper analysis and visualization. DV drafted the original manuscript, and all co-authors edited and revised the writing.

Data Availability

Reef Life Survey data available online (https://reeflifesurvey.com/)
AGRRA data available upon request (https://www.agrra.org/)
Aquatic Food Composition Database available through Harvard dataverse (https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/KI0NYM)
Sea Around Us database is available online (https://www.seaaroundus.org/)

Code Availability

All code used in the analysis is available on GitHub.

Competing interests

MM and AZ are employees of Conservation International, an organization whose mission is to empower societies to care for nature for the well-being of humanity through science, partnerships, and field demonstrations.

Additional Information

- Supplementary Information is available for this paper.
- Correspondence and requests for materials should be addressed to Daniel F. Viana.
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