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# Downscaling global reference points to assess the sustainability of local fisheries

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## Abstract

Multispecies coral reef fisheries are typically managed by local communities who often lack research and monitoring capacity, which prevents estimation of well-defined sustainable reference points to perform locally relevant fishery assessments. Recent research modeling coral reef fisheries globally has estimated multispecies sustainable reference points (i.e., the maximum reef fish yields that can be harvested sustainably and the corresponding reef fish standing biomass at which those are expected to be achieved) based on environmental indicators. These global reference points are a promising tool for assessing data-poor reef fisheries but need to be downscaled to be relevant to resource practitioners. Using a small-scale multispecies reef fishery in Papua New Guinea, we estimated sustainable reference points and assessed the sustainability of the fishery by integrating global-scale analyses with local-scale environmental conditions (i.e., coral cover, sea surface temperature, ocean productivity, and whether the reef is an atoll), reef area, fish catch and standing biomass estimates, and fishers' perceptions. Local-scale relevant data were obtained from a combination of remote sensing products, underwater visual censuses, catch surveys, and household structured social surveys. Our sustainability assessment based on downscaled estimated sustainable reference points was consistent with local fishers' perceptions. Specifically, our downscaled results suggested that the fishing community was overfishing their reef fish stocks and stocks were below biomass levels that maximize production, making the overall reef fishery unsustainable. These results were consistent with fisher perceptions that reef fish stocks were declining in abundance and mean fish length and that fishers had to spend more time finding fish. Our downscaled site-level assessment revealed severe local resource exploitation, the dynamics of which were masked in national-scale assessments, emphasizing the importance of matching assessments to the scale of management. Overall, we show how global reference points can be applied locally when long-term data are not available, providing baseline assessments for sustainably managing previously unassessed multispecies reef fisheries around the globe.

**KEYWORDS**
coral reefs, fishers' perceptions, MMSY, Papua New Guinea, scale mismatch, small-scale fisheries, stock assessment

## INTRODUCTION

Multispecies coral reef fisheries are a major source of food and nutrients for many tropical coastal communities around the globe. Yet, the sustainability of many of these fisheries remains unassessed at scales relevant for fisheries management, mainly due to a lack of clearly defined, locally relevant sustainable reference points (i.e., management targets or limits) against which fishery performance can be assessed (Branch et al., 2011). Estimating sustainable reference points—such as multispecies maximum sustainable yield (MMSY) or standing biomass at which MMSY is achieved ($B_{\mathrm{MMSY}}$)—for a given location usually requires reliable fisheries statistics obtained from long-term monitoring (Worm et al., 2009) and information on how fish populations naturally recover (McClanahan, 2018). However, multispecies coral reef fisheries are typically data poor and predominantly managed locally (e.g., local communities), where monitoring and management capacity may be lacking (Darling & D'Agata, 2017; Mora et al., 2009; Samoilys et al., 2017; Worm & Branch, 2012). Thus, for such a fishery, using only locally available data can severely limit the extent to which relevant sustainable reference points can be estimated.

Recent findings from global analyses of coral reef fisheries can provide additional information that, along with local data, may facilitate the estimation of sustainability benchmarks and assessments at local management scales. The compilation of large global data sets of reef fish biomass (i.e., fisheries-independent surveys) (e.g., Cinner et al., 2020; Graham et al., 2017; McClanahan et al., 2011) has enabled estimation of sustainable reference points for multispecies coral reef fisheries based on local environmental conditions (e.g., Zamborain-Mason et al., 2023). These global analyses provide key parameters, such as unfished biomass (i.e., metric tons of reef fish per square kilometer expected in the absence of fishing), how unfished biomass is expected to change with coral cover, sea surface temperature (SST), ocean productivity, and whether the reef is an atoll, and the community growth rate (i.e., how the multispecies reef fish assemblage is expected to grow towards unfished biomass), which are used to estimate how much reef fish biomass could theoretically be extracted sustainably. These, together with reconstructed fish landings (Zeller et al., 2016) and reef area estimates (UNEP-WCMC et al., 2010), have allowed the assessment of multispecies coral reef fisheries over relatively large geographical scales (e.g., country assessments). Yet, large-scale assessments alone are inadequate to effectively inform resource practitioners at the scales of reef fisheries management (e.g., Cash & Moser, 2000). Uncertainty about fishery status for a given nation (e.g., Zamborain-Mason et al., 2023); spatial heterogeneity in reference points, catch, and standing biomass within national borders (e.g., Karisa et al., 2020; Zeller et al., 2016); and local exploitation context all affect local sustainability (Kerr et al., 2017; McClanahan & Kosgei, 2023). Taking advantage of global information requires the scale of assessment to match the scale of management (Cash & Moser, 2000; Hibbard & Janetos, 2013; McClanahan & Kosgei, 2023).

By integrating global model outputs (Zamborain-Mason et al., 2023) with local-scale environmental and fisheries information, we sought to demonstrate how recent global reference points for coral reef fish stocks can be downscaled to inform local fisheries management when local fisheries-relevant data are insufficient by themselves for a sustainability assessment (e.g., no fish population recovery data). Using a previously unassessed small-scale multispecies coral reef fishery from Papua New Guinea, we estimated local MMSY sustainable reference points for the fishery; assessed the status of local reef fish stocks relative to these key reference points; quantified how much the long-term food-provisioning potential of local reefs could increase if stocks were managed sustainably and how long it would take to reach such a state; and compared assessment results with local fishers' perceptions. To define locally relevant sustainable reference points, we combined global model parameters with local coral cover, ocean productivity, and SST estimates and used these and local-scale estimates of standing reef fish biomass and annual catch to assess the status of the multispecies reef fishery at the local scale. We sought to show how global reef fisheries benchmarks can be applied locally, thus providing a tool to assess and sustainably manage unassessed reef fisheries around the globe at a scale relevant to management.

## METHODS

### Study site and fishery context

We conducted fieldwork in Ahus Island, a coastal island of approximately 950 people, who are highly dependent on reef resources (Barnes et al., 2022), in Manus Province, Papua New Guinea (Figure 1). Historically, islanders managed their reefs through customary systems (Cinner et al., 2005): clan leaders and individuals with sea tenure rights applied temporary fishing closures and had rights to certain fishing practices (e.g., gears) and specific operating times (i.e., night fishing). However, in recent years, the customary system has eroded and compliance with customary restrictions has faded as the population increased (Lau et al., 2020). The reef fishery lacks MMSY sustainable reference points, has not been assessed against locally specific benchmarks, and has no current fisheries management measures in place.

As with many tropical small-scale reef fisheries (e.g., Grantham et al., 2021), fishing patterns (e.g., catch volumes, composition, and locations) in Ahus are driven by seasonal weather cycles, namely, the windy and the nonwindy season. Ahus's reef fisheries are opportunistic and multispecies. Fishers use a range of gears, such as spear guns, trolling lines, hand lines, nets, and hand spears. Some households own or rent motorized vessels to target pelagic fishes, such as tuna. However, most male fishers use hand-paddled canoes and target reef-associated fishes. Motorized vessels are sometimes used to fish reef-associated species, for instance, for cultural ceremonies. Gleaning is predominantly undertaken by women and

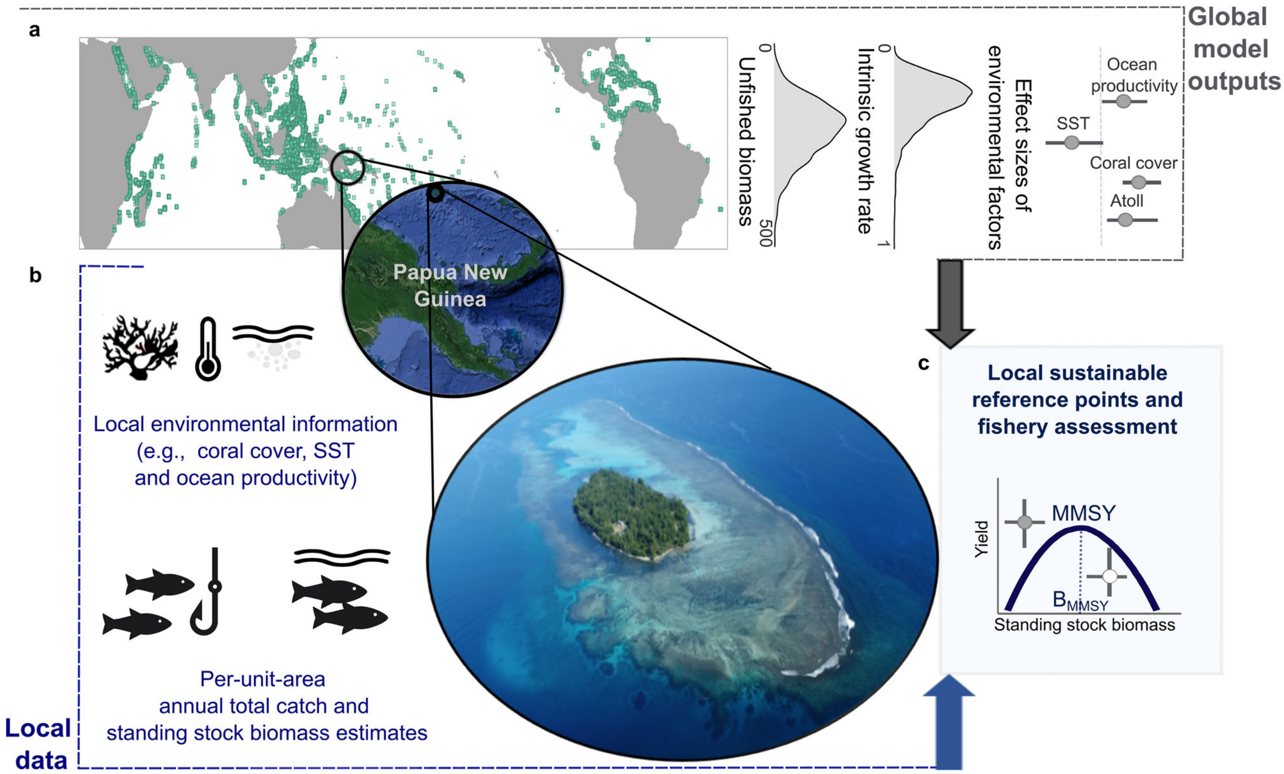


**FIGURE 1** (a) Global map of tropical coral reefs (UNEP-WCMC et al., 2010) showing our study site and reef area as well as example distributions of posteriors from global model outputs (Zamborain-Mason et al., 2023) used to apply to local context (unfished biomass of reef fish: posterior median = 115.6 t/km$^2$, 90% posterior uncertainty interval 97.5–140.6; community growth rate: 0.14 year$^{-1}$, 90% posterior uncertainty interval 0.08–0.31; effect sizes [i.e., slopes in a linear model] of environmental covariates on log unfished biomass: coral cover = 0.69, 90% posterior uncertainty interval 0.41–0.97; ocean productivity = 0.43, 90% posterior uncertainty interval 0.09–0.75; sea surface temperature [SST] = −0.35, 90% posterior uncertainty interval −0.74 to 0.08; atoll = 0.49, 90% posterior uncertainty interval 0.14–0.81), (b) type of local-scale information collected to downscale global estimates (local environmental information to estimate sustainable reference points and per-unit-area standing stock biomass and annual catch estimates to assess the status of stocks), and (c) example of outputs from downscaling global models to local context to perform fishery assessments (e.g., local surplus production and reference points combined with 2 examples of estimates of standing biomass and yield [i.e., total annual catch]: catch below surplus and biomass above the biomass at which yields are expected to be maximized [$B_{\mathrm{MMSY}}$] [i.e., sustainable, white circle] and catch above estimated surplus and biomass below $B_{\mathrm{MMSY}}$ [i.e., unsustainable, gray circle]). Photo by Dean Miller.

children and is focused on lagoon and backreef areas, where invertebrates and reef fishes are targeted.

## Overview of approach

To estimate locally relevant MMSY reference points for our study region, we combined global model parameter outputs with local environmental estimates (i.e., coral cover, ocean productivity, SST, and the nonatoll nature of our study location). To assess the status of the multispecies reef fish assemblage, we used the local MMSY reference points and contrasted these with estimates of standing stock reef fish biomass (i.e., metric tons per square kilometer standardized as per global models) and total annual catch estimates per unit area (i.e., metric tons per square kilometer per year). Global parameters were estimated using the information of 2053 reef sites worldwide, 150 of which were high-compliance marine reserves of different ages or remote uninhabited reefs that were critical to infer the unfished biomass for reef fish assemblages; how the unfished biomass varies with environmental context (i.e., coral cover, ocean productivity, SST, and whether the reef is an atoll); and how reef fish populations grow in the absence of fishing toward unfished biomass (i.e., community growth rate) (Zamborain-Mason et al., 2023). The remaining global reefs informed sampling parameters (i.e., related to census method, sampling area, habitat type, and depth of survey), and their biomass in combination with jurisdiction-level annual estimates of catch was used to assess the status of stocks (e.g., contrasting the biomass per unit area and annual catch per unit area to the estimated reference points [Zamborain-Mason et al., 2023]). We used the global dataset to standardize local biomass and environmental estimates. Next, we used global parameters in combination with standardized local environmental values to estimate locally relevant reference points. Finally, we contrasted local reference points with annual catch and standardized local biomass estimates to assess the status of stocks at a local scale (Figure 1). To estimate sustainable reference points and assess the sustainability status of the multispecies reef fishery with global model outputs, we combined 3 types of local information: environmental characteristics (i.e., coral cover, ocean productivity, SST, and whether the location was an atoll); per-unit-area estimates of standing reef fish biomass; and per-unit-area estimates of annual reef fish catch.

## Environmental context

We sampled 12 reef sites spanning depths of 3–10 m in slope and lagoon reef habitats across 4 different years (2009, 2012, 2016, 2018). Overall, estimates of coral cover, SST, and ocean productivity were obtained by averaging site and year-specific measurements or estimates. Our study location was not an atoll. Live hard coral cover at each site was recorded using replicate 4 × 50 m (2009) or 6 × 30 m (2012, 2016, and 2018) point intercept methods. Transects were laid parallel to the reef crest, and the substrate directly beneath the transect tape was surveyed every 0.5 m (2009, 2012, and 2016) or 1 m (2018) across all transects. No corrections were undertaken for different sampling intervals (i.e., 0.5 and 1 m) because sample intervals provide similar mean coral cover results. Remotely sensed monthly net primary production (i.e., ocean productivity [Behrenfeld & Falkowski, 1997]) and SST estimates (Huang et al., 2017) for each site were annually averaged.

## Per-unit-area standing reef fish biomass

Reef fish biomass estimates were recorded through underwater visual census (UVC) at the same sites as coral cover with belt transects. Consistent with the data used to develop global models (i.e., Zamborain-Mason et al., 2023), diurnally active, noncryptic reef fishes above 10 cm length from families resident on the reef (Appendix S1) were counted, were identified to species level, and had their total length estimated. Total observed biomass of fishes on each transect was calculated using published species-specific length–length and length–weight relationships (http://fishbase.org; Boettiger et al., 2012; Froese & Pauly, 2010). When parameters were not available for specific species, we used parameters for a closely related and similar sized species. Site-specific per-unit-area biomass for each year was estimated by summing the observed biomass from all transects within a site and dividing by the number of transects performed. To make site-specific biomass ($B$) data comparable to the global models, observed site biomass ($B_{obs}$) data were corrected for sampling and methodological effects with the median posterior effect sizes from the global models (i.e., standardizing our site's depth [$depth_{local}$], sampled area [$samplingarea_{local}$)], and habitat when lagoon [$habitat_{lagoon,local}$] to global transformed average conditions (i.e., 6.7 and 518 $m^2$ and slopes) and subtracting or adding the median effects of depth [$\beta_{depth,\ global}$], sampling area [$\beta_{samplingarea,global}$], and lagoon reefs when applicable [$\beta_{lagoon\ global}$] to observed biomass values;Zamborain-Mason et al., 2023) (Figure 1):

$$depth_{stand} = \frac{sqrt(depth_{local}) - 2.607}{2 \times 0.872}, \tag{1}$$

$$samplingarea_{stand} = \frac{\log(samplingarea_{local}) - 6.252}{2 \times 0.497}, \tag{2}$$

$$B = \exp\left(^{\log}(B_{obs}) - \left(\beta_{depth,\ global} \times depth_{stand} + \beta_{samplingarea,global} \times samplingarea_{stand} + \beta_{habitat\_lagoon\ global} \times habitat_{lagoon,\ local}\right)\right), \tag{3}$$

where 2.607, 0.872, 6.252, and 0.497 are the mean and standard deviation, respectively, from the global data for depth (square-root transformed) and sampling area (log transformed).

Because sampled sites varied among years and seasons, we used the entire distribution of standing stock biomass estimates from all sites and years ($n = 26$) and estimated the median standing stock and associated 95% adjusted confidence intervals based on nonparametric bootstrapping with replacement for 4000 iterations (Canty, 2002; Davison & Hinkley, 1997).

## Per-unit-area annual catch

Catch per unit area for our study location was obtained by dividing annual reef catch estimates by reef area. Total reef area used by local fishers (~9 $km^2$) was estimated using the Millennium Mapping project data set (IMaRS-USF, IRD, 2005). Annual reef fish catch estimates were obtained by combining catch surveys collected in 2 points in time representing different seasons (May–June 2018 and February 2019) and household structured social surveys collected in May 2018.

Catch surveys (Appendix S2) were performed at landing sites (i.e., approaching fishers as they returned from fishing activities), individual households (e.g., if a fisher had recently returned from fishing), and at local markets. All catch surveys involved photographing the catch against a size scale (Cinner & McClanahan, 2006), recording the gear used, boat type, number of fishers, their biological sex, effective time spent fishing or effort (i.e., fishing trip hours minus the traveling time where the gear was not deployed), destination of the catch, and fishing grounds (i.e., fishers were presented with a map of the study site and asked to identify where the catch came from), and questions about long-term effort (answered only once by each recorded individual fisher who had time to answer the long-term questions). We typically observed fishers while they were fishing, corroborating their reported fishing grounds. We also made sure fish were not double counted by obtaining fishing trip details at the start of all catch surveys (i.e., fisher, start and end time of fishing trip, and hours that gears were employed). Catch photographs were analyzed to identify individual fish to the lowest taxonomic level possible and measure their standard length. Biomass was estimated as outlined above for the standing stock biomass based on published species-specific length–length and length–weight relationships (Froese & Pauly, 2010). Some of the photographs were of processed fish (e.g., smoked or fried). Cooking tends to decrease the length and weight of a fish. Although the effect on overall catch biomass is likely negligible, catch estimates from such photographs may have led to small downward biases in some cases.

A total of 428 fishing trips, 203 individual fishers, and 5 different gears (handline, spear gun, trolling line, simple spear, and gillnet) were recorded during our surveys. Catch composition included reef-associated fish, invertebrates, sea turtles, and other fish (e.g., tuna and sharks). Because we were interested in reef assemblages and wanted to make estimates comparable to global reference points, for the catch and effort estimates we used only surveys with reef-associated fish families (Appendix S1), where individual fish total length was above 10 cm and fish were caught in designated reef areas ($n = 340$). This ensured that reef area, reef fish catch, and biomass per unit reef area were all estimated consistently and over the same geographical area. Fisher-specific catch was estimated by dividing the total catch by the number of fishers on the fishing trip. For fishing trips that included a mix of target groups (e.g., pelagic and reef-associated fish) and where overall fishing grounds overlapped with the designated reef area, we estimated the proportion of reef fish in the catch and assumed effort was proportional. This allowed us to estimate fisher-specific reef fish catch per unit effort (CPUE) distributions for each season. Median annual catch per fisher (and 95% adjusted confidence intervals) was estimated from fisher-specific CPUE and season-specific effort distributions based on nonparametric bootstrapping with 4000 iterations (i.e., allowing for different subsample sizes). We kept the data structure (i.e., distributions of different sample sizes across sex categories) and estimated the median CPUE and median hours fishing for each season (i.e., windy and nonwindy) and the median total annual catch per fisher (dividing the year into the two 6-month seasons). To examine potential bias in our fish catch sampling, we compared CPUE distributions from fishers who responded to the long-term questions and those who did not (we did not detect any differences [Appendix S3]; Kolmogorov–Smirnov $D = -0.09, p = 0.85$) and compared the CPUE distributions from fishers whose landings were observed more than once with fishers who were only recorded once (results were similar [Appendix S3]; $D = -0.109$, $p = 0.27$). Informally, fishers reported that catch and effort during the survey period were typical for the season.

Household structured social surveys were used to extrapolate fisher-specific median total annual catch to total community annual catch estimates. We surveyed household heads ($n = 138$ out of 140 households) and recorded the livelihood activities of all members of the household, including fishing and gleaning, and the specific fishing gears used. This yielded a total of 152 male fishers and 131 female gleaners in the community. To estimate annual reef fish catch, we excluded 3 male fishers who reported using only trolling line as their gear because trolling generally targets pelagic fish away from reef areas. Therefore, a total of 149 male and 131 female fishers targeting reef fishes were estimated for this study location. We multiplied sex-specific total annual catch by the number of fishers in each sex category to get annual catch estimates for our study location and calculated catch per unit area by dividing the total annual catch by the estimated reef area.

## Estimating local sustainable reference points from global models

Whole assemblage multispecies maximum sustainable reference points (i.e., MMSY and $B_{MMSY}$) for our study location were obtained using local coral cover ($coral_{local}$), ocean productivity ($prod_{local}$), SST ($SST_{local}$), and the nonatoll nature of the location (i.e., not using the atoll parameters) standardized to global conditions, in combination with posterior multispecies unfished biomass ($B_{0,global}$), community biomass growth rate ($r_{global}$), and effect sizes of environmental factors on unfished biomass from global models for SST ($\beta_{SST,\ global}$), ocean productivity ($\beta_{prod,\ global}$), and coral cover ($\beta_{coral,\ global}$) (Zamborain-Mason et al., 2023) (Figure 1):

$$coral_{stand} = \frac{sqrt(coral_{local}) - 5.136}{2 \times 1.80}, \quad (4)$$

$$prod_{stand} = \frac{\log(prod_{local}) - 5.666}{2 \times 0.503}, \quad (5)$$

$$SST_{stand} = \frac{SST_{local} - 27.531}{2 \times 1.423}, \quad (6)$$

$$B_{0,local} = \exp\left(\log\left(B_{0,global}\right) + \beta_{sst,\ global} \times SST_{stand} + \beta_{prod,\ global} \times prod_{stand} + \beta_{coral,\ global} \times coral_{stand}\right), \quad (7)$$

$$MMSY = \frac{B_{0,local} \times r_{global}}{4}, \quad (8)$$

$$B_{MMSY} = \frac{B_{0,local}}{2}, \quad (9)$$

where 5.136, 1.80, 5.666, 0.503, 27.531, and 1.423 are the mean and standard deviation, respectively, from the global data for coral cover (square-root transformed), ocean productivity (log transformed), and SST.

We used global estimates based on an aggregate Graham–Schaefer surplus growth model in which the whole assemblage is treated as a single stock (e.g., Link, 2017; Mueter & Megrey, 2006), and a symmetric (logistic) population growth curve whose productivity (and thus sustainable yields) peaks at 0.5 of unfished biomass is assumed (Schaefer, 1954). We also estimated sustainable reference points and assessed the fishery with other versions of the Pella–Tomlinson (Pella & Tomlinson, 1969) surplus production models (of which the Graham–Schaefer is one special case): the Gompert–Fox for which production peaks below 0.5 of unfished biomass (Fox, 1970; Tjorve & Tjorve, 2017) and the Pella–Tomlinson with scale parameters of 3 and 4 for which production peaks at >0.5 of unfished biomass (Quinn & Derison, 1999) (Appendix S4). Additionally, we estimated reference points with site-specific environmental estimates for different years but found little variation (Appendix S5).

## Local assessment of reef fish stocks

To provide a baseline assessment of the local multispecies reef fishery, per-unit-area standing biomass and total annual catch were compared with the estimated surplus production curve. Reefs were classified as below $B_{\mathrm{MMSY}}$ if median standing biomass estimates were below the median $B_{\mathrm{MMSY}}$, the biomass at which sustainable yields are expected to be maximized (Garcia et al., 2018), and as undergoing overfishing if median total catch was above the median estimated surplus, given their standing biomass estimates (Hilborn, 2011). The probability of being below $B_{\mathrm{MMSY}}$ and overfishing was also estimated incorporating uncertainty from the surplus production estimates. The fishery sustainability status was categorized following global assessments (Zamborain-Mason et al., 2023) as follows: good condition (not below $B_{\mathrm{MMSY}}$ and not catching above MMSY), unsustainable (below $B_{\mathrm{MMSY}}$ and overfishing), warning (not below $B_{\mathrm{MMSY}}$ and catching above MMSY), or recovering (below $B_{\mathrm{MMSY}}$ and not overfishing). Additionally, we estimated the sustainable yield lost from assemblages below $B_{\mathrm{MMSY}}$ (i.e., potential gains from recovering stocks) as the difference between the whole-assemblage MMSY and the estimated surplus. Minimum required biomass gains for recovery were estimated as the difference between the estimated $B_{\mathrm{MMSY}}$ and current median biomass levels. If uncertainty intervals returned negative values, we reported those values as zero (i.e., no biomass gains required). We repeated the above recovery assessment with a more conservative target, the biomass levels corresponding to pretty good multispecies yields (i.e., $B_{\mathrm{PGMY}}$, biomass levels corresponding to the right-hand side of the surplus production curve that produces 0.8 of MMSY [Hilborn, 2010; Rindorf et al., 2017] and is associated with increased diversity and ecosystem function [Zamborain-Mason et al., 2023]). We then calculated location-specific recovery time frames under a seascape moratorium scenario, assuming a fishing moratorium was imposed on the entire fishery (this estimates the minimum time for recovery to $B_{\mathrm{MMSY}}$ and $B_{\mathrm{PGMY}}$ for the location). These time frames were calculated by combining the posterior community biomass growth rates from global models with the locally estimated standing biomass, unfished biomass, and $B_{\mathrm{MMSY}}$ or $B_{\mathrm{PGMY}}$ estimates. Assuming a logistic growth curve of whole assemblage biomass through time, the recovery time (Rt) is

$$\mathrm{Rt} = \frac{-\log\left(\dfrac{B\times\left(\dfrac{B_{0,\mathrm{local}}}{B_{\mathrm{target}}}-1\right)}{(B_{0,\mathrm{local}}-B)}\right)}{r_{\mathrm{global}}}, \tag{10}$$

where $B$ is the estimated standing biomass, $r_{\mathrm{global}}$ is the posterior community biomass growth rate from global models, $B_{0,\mathrm{local}}$ is the estimated posterior unfished biomass for our study location, and $B_{\mathrm{target}}$ is the biomass benchmark or target to be achieved (i.e., $B_{\mathrm{MMSY}}$ or $B_{\mathrm{PGMY}}$). Similar to required biomass gains, if uncertainty intervals returned negative recovery times, we reported those values as zero. We reported medians and 90% uncertainty intervals and estimated probabilities based on uncertainty results, explicitly acknowledging the importance of propagating uncertainty from global models to local fisheries assessments.

## Fishers' perceptions

To assess how consistent our assessment results were with fishers' perceptions, catch surveys also included a section about perceived reef fish stock status and drivers (Appendix S2), answered once by each recorded individual fisher willing to answer the long-term questions ($n = 77$). Fishers were asked whether, compared with 5 years ago, the amount of reef fish had increased, decreased, or stayed the same; the size of reef fish had increased, decreased, or stayed the same; they had to spend more time traveling to catch reef fish; and they caught the same reef species, and if not, why. Our study design for the survey of fishers was approved by the Human Ethics Research Committee at James Cook University (approvals H6617 and H7261).

# RESULTS

Based on the Graham–Schaefer surplus production model, we estimated an 88% chance that reef fishers were catching above MMSY and a 61% chance that stocks were below $B_{\mathrm{MMSY}}$ (Figure 2b), suggesting the multispecies reef fishery is unsustainable and reef fish populations are under ongoing decline. Specifically, estimated MMSY for the coral reef fishery at our study location was 1.9 t/km$^2$/year (0.8–4.3) (median and 90% posterior uncertainty intervals) at standing biomass values or $B_{\mathrm{MMSY}}$ of 18.3 t/km$^2$ (10.2–34.8) (Figure 2a). However, based on the estimated biomass of 15.6 t/km$^2$ (12.6–22.4) (median and 95% adjusted bootstrap confidence intervals), reefs were below $B_{\mathrm{MMSY}}$ ($B < B_{\mathrm{MMSY}}$), so the catch that could be sustained in the long term was 1.6 t/km$^2$/year (0.5–4.3) (e.g., ∼88% of MMSY). Estimated annual catch was 4.6 t/km$^2$/year (1.6–8.7) (median and 95% adjusted bootstrap confidence intervals), more than 2 times the estimated maximum sustainable yields and almost 3 times what was estimated to be sustainable given current biomass levels. Therefore, annual catch estimates

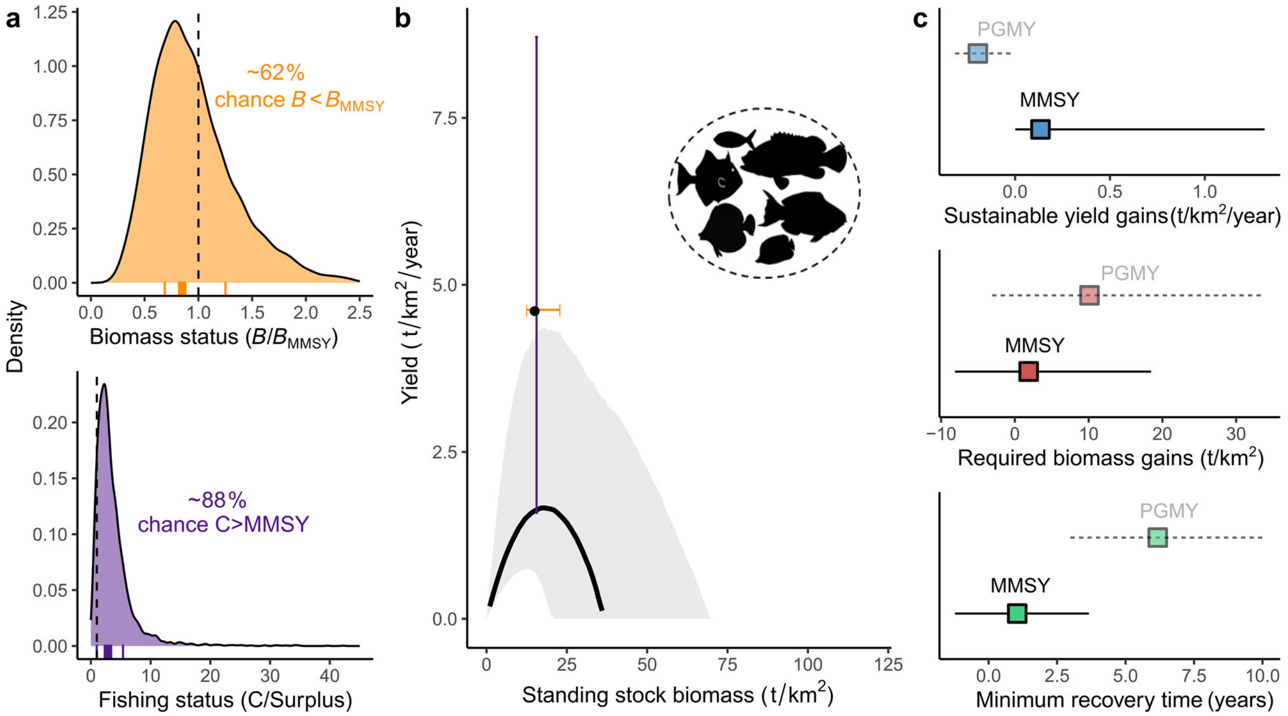


**FIGURE 2** For Ahus Island, Papua New Guinea, the (a) density distributions showing the probability of being below the biomass at which yields are expected to be maximized ($B_{MMSY}$) and of overfishing (accounting for uncertainty in the $B_{MMSY}$ and surplus estimates from the global analysis applied to local conditions and the median biomass estimate) (dashed vertical lines, limit between being below $B_{MMSY}$ and not below $B_{MMSY}$ and between being classified as not overfishing and overfishing, respectively; solid lines, estimated status based on median biomass and 95% adjusted confidence intervals based on bootstrap samples), (b) estimated multispecies maximum surplus production curve and assessment (solid line, median; polygon, 90% uncertainty intervals for the estimated surplus production [t/km$^2$/year] along a gradient of biomass; point, median per-unit-area median standing stock and annual catch estimates; error bars, 95% adjusted bootstrap percentile intervals; orange, standing biomass; purple, annual catch), and (c) potential yield gains, required biomass increases, and minimum time required if reef fish stocks were recovered to $B_{MMSY}$ or $B_{PGMY}$ (biomass at which pretty good multispecies yields are expected to be achieved) levels (points, median; bars, 90% uncertainty intervals).

suggested islanders are overfishing their coral reef fish stocks (catch > surplus). Estimated $B_{MMSY}$ and the probability of being below $B_{MMSY}$ differed when using other surplus production models (Appendix S4). However, these did not affect the overall conclusion that fish stocks were predicted to decline under the estimated level of overfishing.

For the fishery to be sustainable at current biomass levels, catch would have to decrease by about 3 t/km$^2$/year (0–18.6) (median and 90% uncertainty intervals). To maximize sustainable yields (i.e., reach $B_{MMSY}$ from current biomass levels), reef fish biomass would need to increase by 2.0 t/km$^2$ (0–18.6). Such recovery would take, in the most aggressive scenario (i.e., seascape moratorium), ∼1.1 years (0–6.8) (Figure 2c). This would allow sustainable catch to increase by ∼0.2 t/km$^2$/year (0.1–1.3), which was still substantially below current estimated catches because estimated annual catch was above the estimated MMSY. Lower gains (−0.2 t/km$^2$/year [−0.6 to 0.7]), longer time frames (6.2 years [−0.5 to 17.4]), and larger biomass increases (10.1 t/km$^2$ [−3.0 to 33.7]) would be required to reach more conservative targets, such as those that produce pretty good multispecies yields ($B_{PGMY,upper}$) (Figure 2c).

Our status results were consistent with local fishers' perceptions. We found that 83% of fishers perceived that the reef fish quantity and body length had decreased over time and that they spent more time looking for reef fish. Additionally, 67% of fishers reported that the species composition of their catch had changed, which they mostly (74%) attributed to reef fish getting too small or being difficult to find (Figure 3).

## DISCUSSION

Downscaling global models to local context can be a necessary step to sustainably manage and conserve natural resources (Cash & Moser, 2000; McClanahan & Kosgei, 2023), especially for locations with limited long-term monitoring. We constructed a framework to estimate locally relevant sustainable reference points and fishery assessments by integrating the results from global studies on coral reef fisheries when limited local fishery information is available. Our analyses revealed 3 key findings.

First, assessment results from our downscaled procedure were consistent with local fishers' perceptions. Assessment results suggest that the reef fishery is unsustainable in comparison to whole assemblage proposed targets. Our analysis showed that median standing biomass values are currently lower than

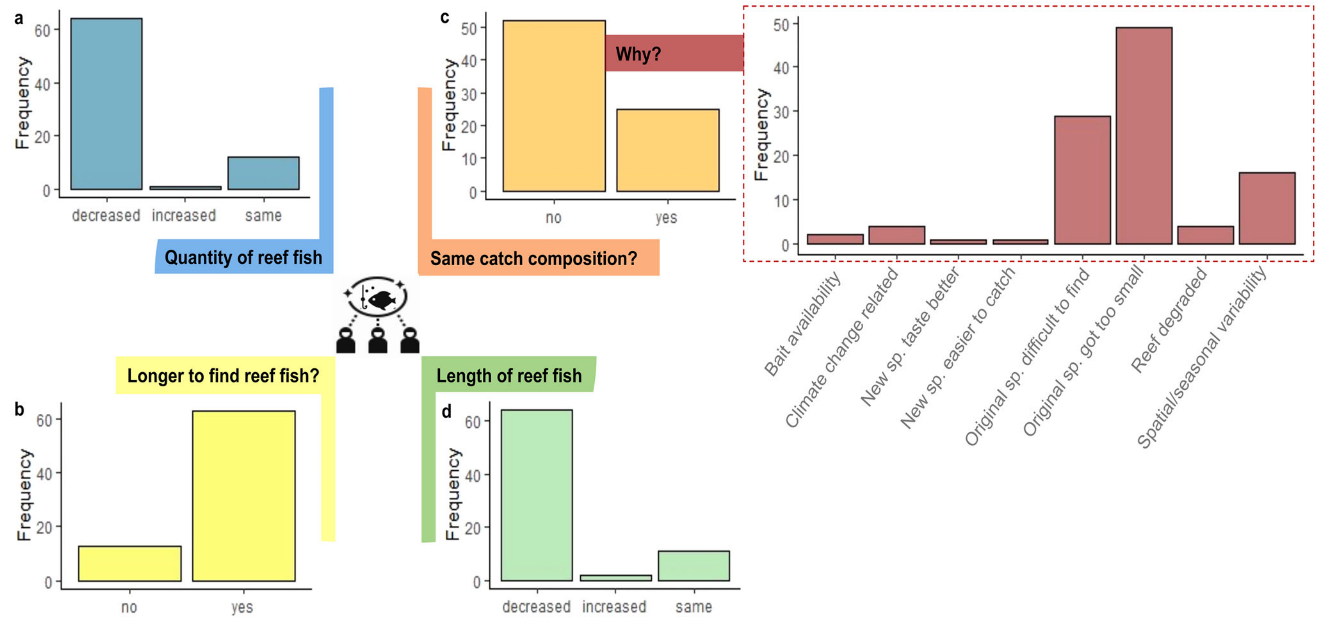


**FIGURE 3** Relative to the previous 5 years, fishers' perceptions of (a) change in the reef fish amount, (b) whether they had to spend more time to find and target reef fish, (c) whether the species composition of catch had changed and the reasons why fishers thought the catch composition had changed, and (d) change in reef fish length.

those needed to maximize yields, indicating that the reef fish assemblage is below levels that maximize production and fishers are overfishing their reef stocks. When overfishing takes place and a fishery becomes unsustainable, biomass is expected to become more depleted (Jackson et al., 2001), fish become more difficult to find and capture (McClanahan et al., 2008), and individual fish length becomes smaller on average (i.e., growth overfishing [Pauly, 1994]). Resource users, who are typically the first to notice and respond to these changes (e.g., by increasing effort or changing fishing locations [Silas et al., 2020]), also reported these changes here, and their perceptions can thus help validate and triangulate global model outputs when integrated to local context (Neiss et al., 1999; Rochet et al., 2008; Ruano-Chamorro et al., 2017).

Second, local assessment results differ from those conducted at larger scales. Global assessments that use national reconstructed reef fish landings (Zeller et al., 2016) and reef area estimates (Spalding et al., 2001; UNEP-WCMC et al., 2010) suggest overall that reefs in Papua New Guinea tend to be below $B_{MMSY}$, but there is little overfishing, allowing fish populations to recover (Zamborain-Mason et al., 2023) (Appendix S6). However, our results suggest that under current estimated local exploitation levels, the reef fish assemblage in our study location is expected to decline in the long term (i.e., reef fish populations are being exploited above sustainable levels). There are 2 main reasons for this discrepancy. One, spatial variability in environmental conditions, catch, or biomass within nations can affect what can be extracted sustainably, the level of exploitation, and the status of stocks, with average or median conditions (as provided by national-level analyses) not reflecting particular locations (e.g., Karisa et al., 2020; McClanahan & Kosgei, 2023; Zeller et al., 2016). For example, in comparison with national estimates, Ahus had lower MMSY and $B_{MMSY}$ estimates (Appendix S6) due to higher-than-average SST and lower-than-average coral cover. Also, discordance between national and regional analyses could reflect error or bias in jurisdiction-scale estimates, such as representation of sampled reefs and timing, reef area, or catch estimates not being representative of true local conditions. For instance, Ahus had higher estimates of catch per unit area in comparison to those estimated nationally from catch reconstructions (Zeller et al., 2016) and coral cover estimates (Spalding et al., 2001; UNEP-WCMC et al., 2010), making the ratio of catch to MMSY significantly above what is estimated nationally (Appendix S6). This finding emphasizes the importance of integrating local context and downscaling global models at appropriate scales for management.

Third, we found that total annual catch estimates for our study location exceeded not only what can be caught sustainably given the standing biomass (i.e., surplus) but also the estimated MMSY. This could mean one of 3 different things: annual catch estimates for reef fish are not business as usual or biased high (e.g., sampled periods and fisher extrapolation are not representative of annual catch estimates); estimated surplus production is biased low for this location (e.g., global model parameters of unfished biomass, how this changes with environmental context or community growth rate are not representative of this region); or if our baseline assessment is accurate, then the population's demand of reef fish is higher than the reef can provide and reef fish populations are declining.

Accurate and precise annual catch estimates for most locations where reef fisheries operate are difficult to obtain (Russ, 1991), especially if there are no monitoring programs in place

(Teh et al., 2009). We obtained catch samples from different seasons and sexes and then extrapolated these with representative household surveys to get an annual catch estimate for the community. This approach did not discern among other factors such as age or experience, assuming the observed catch distribution for different sexes in different seasons is representative of their respective subpopulations. Changing this assumption if data are available (e.g., doing a weighted mean accounting for experience or fishing frequency) could be incorporated in future analyses that downscale global models to test additional catch estimates.

We used different surplus production models for the whole assemblage to overcome potential uncertainties in the shape of the surplus production curve (e.g., relationship between sustainable catch and standing stock biomass). All supported high probabilities of overfishing (i.e., from 0.86 to 0.88) (Appendix S4). However, the estimated surplus production for the whole assemblage could be biased low for this location if the unfished biomass, the community biomass growth rate, or both (e.g., Figure 1) were biased low (e.g., if the location was an outlier from global coral reefs in terms of how the assemblage responds to coral cover or recovery does not follow the same patterns as those inferred by space-for-time substitution, respectively) or if the location's surplus production does not follow the assumed dynamics (e.g., if species composition and species-specific interactions make the whole-assemblage surplus production different to what current global models infer) (e.g., Fulton et al., 2022). To overcome these in future work, it would be useful to apply global models to additional systems (e.g., that have recovery or validated reference point data), explore species compositional changes and group-specific assessments, and collect species-specific composition and additional temporal data in the study location (e.g., to evaluate whether reef assemblages decline as the assessment suggests).

A possible option, consistent with fishers' perceptions, is that our assessment results are representative of true conditions in which case stocks are expected to decline. Although long-term monitoring will be needed to validate the expected decline in community biomass, the magnitude of the discrepancy between current estimated catch and sustainable reference points suggests that the community is unlikely to be able to meet its current fish demand even if stocks recover to maximum production levels. Thus, communities similar to our study location likely require alternative or diversified livelihoods and food supplies (e.g., mariculture or increased access to offshore fisheries) (Bell et al., 2018) and support mechanisms (e.g., financial help) (Hilborn et al., 2005) to recover their reef fish stocks and return to sustainability. We estimated that stocks would take a median of ∼1.1 years to recover based on a complete seascape moratorium scenario, which would be devastating for communities that depend on reef resources for their daily food and income security. Indeed, in Ahus, completely restricting fishing would have significant impacts on the community and cause severe inequities, particularly for youth who have few skills or alternative livelihood options beyond fishing (Lau et al., 2021).

Most tropical reef fisheries around the globe remain unassessed. Typically, multispecies reef fisheries occur in the developing world, where research and formal management capacity are scarce (Worm & Branch, 2012) and strong institutions to implement effective management measures are lacking (Hilborn et al., 2020). Many communities rely on comanagement initiatives and inputs from nongovernmental organizations to manage their fisheries, but clear reference points and monitoring to manage fisheries sustainably are often absent. Although adequate assessment and effective management of reef resources will require long-term monitoring, validation, and adaptation (Free et al., 2019), we demonstrated how recent global models on reef fisheries can be downscaled to local context providing a pathway to perform baseline multispecies stock assessments for unassessed fisheries around the globe at the scale of fisheries management. This will help provide baseline fishery assessments for unassessed reef fisheries and, in turn, increase understanding of how to update global models to make them more useful for resource practitioners and stakeholders.

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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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