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**Supporting Information for**
Protection efforts have resulted in ~10% of existing fish biomass on coral reefs.

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**Other supporting materials for this manuscript include the following:**
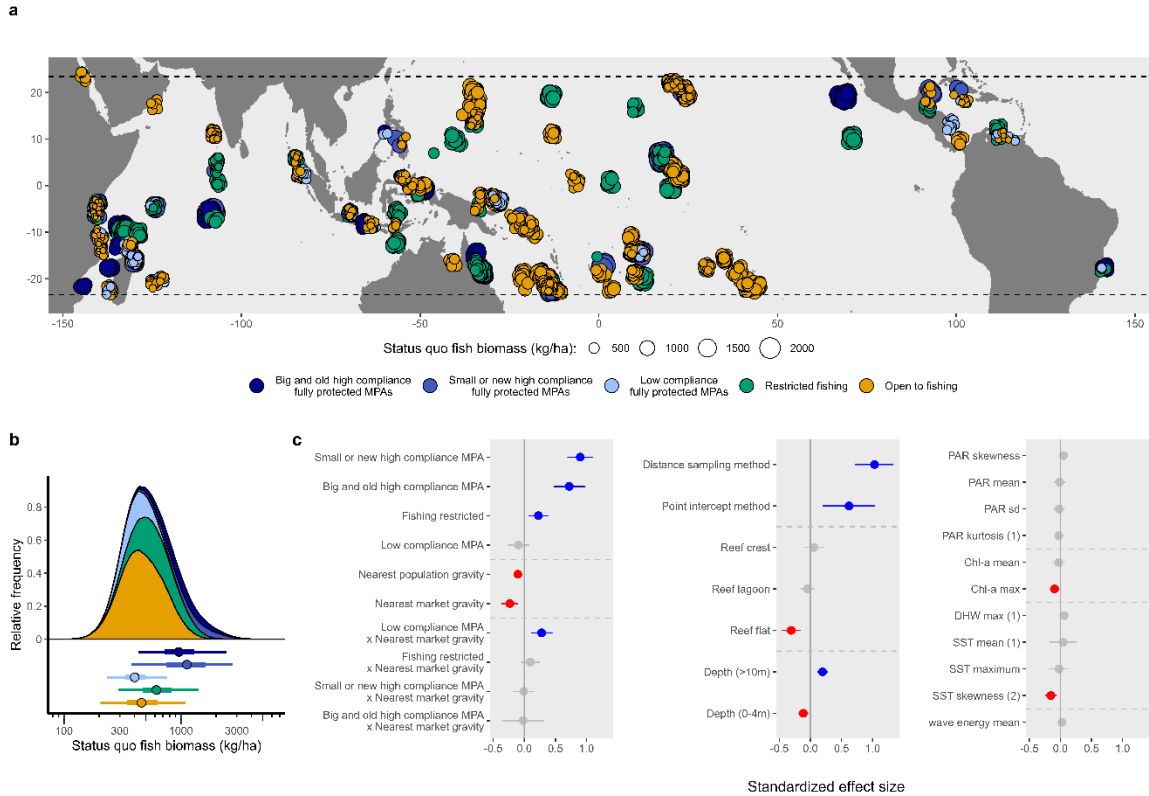
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**Fig. S1. Coral reef fish biomass predicted by socio-ecological context. a,b**, Locations and stacked frequency distribution plot showing fish biomass (>10 cm within 22 fish families) from 2,599 tropical surveyed locations, standardized by survey method, habitat, and depth (i.e. status quo fish biomass). Points on the map are sized to represent biomass, colored by protection status, and jittered to allow for visualization of overlapping reef sites. Dashed lines in the map indicate the latitudinal extent of tropical locations. Shown below the stacked frequency distributions are medians (points), 50% quantiles (thick lines) and 95% quantiles (thin lines) for each management category. **c**, Effect sizes of all fixed covariates in the most predictive spatial GLMMs, with management type, gravity, and their interaction in the leftmost panel, methodological covariates in the middle panel, and environmental covariates in the rightmost panel (with groups of covariates separated by grey horizontal dashed lines). Points represent multi-model mean standardized beta coefficients, and horizontal error bars represent the combined propagated uncertainties within and across the four selected spatial GLMMs (95% confidence intervals). Grey dots and lines indicate that 95% confidence intervals overlap 0, while blue and red dots/lines indicate positive and negative associations with fish biomass, respectively. Covariates with numbers in brackets were only retained in a subset of the best models (with numbers indicating the number of models in which they were included).
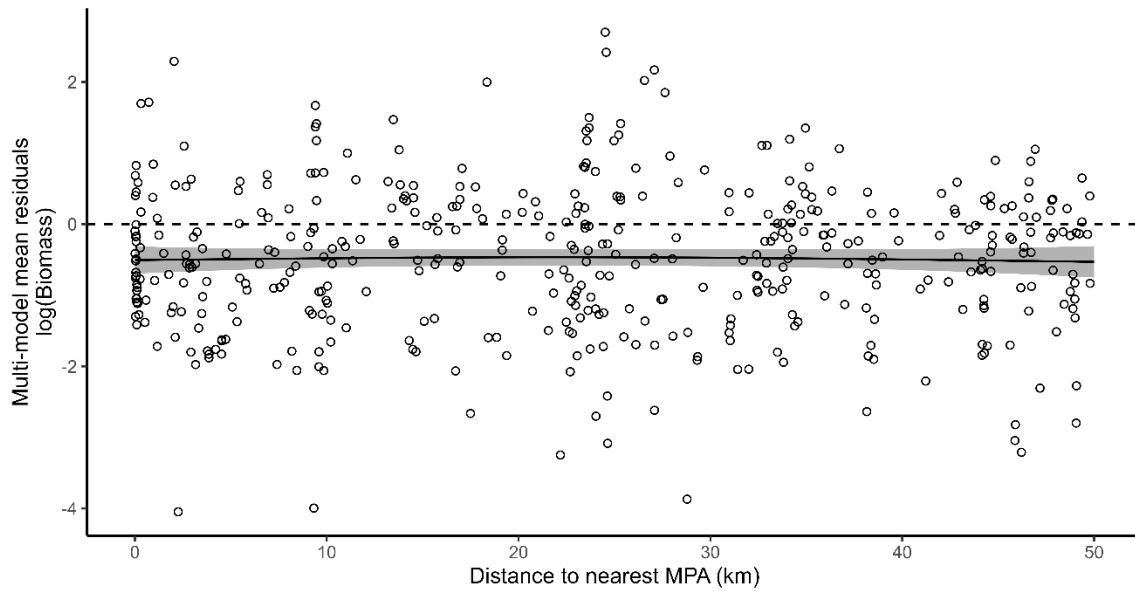
**Fig. S2. Sensitivity test examining how multi-model mean residuals from predictions of log(biomass) vary with distance from an MPA (from four selected spatial GLMMs).** For each survey location that was open to fishing we calculated the distance to the closest fully protected MPA in the World Database on Protected Areas (1). Using a generalized additive model (with mean and 95% confidence limits of the fitted relationship shown as the black line and gray ribbon), we then tested for any relationship between the multi-model mean residuals and distances to the nearest MPAs for the 436 survey locations that were within 50km of a no-take MPA (open points). The fitted generalized additive model (GAM) had 9 basis functions (k) and explained only 0.192% of the deviance.
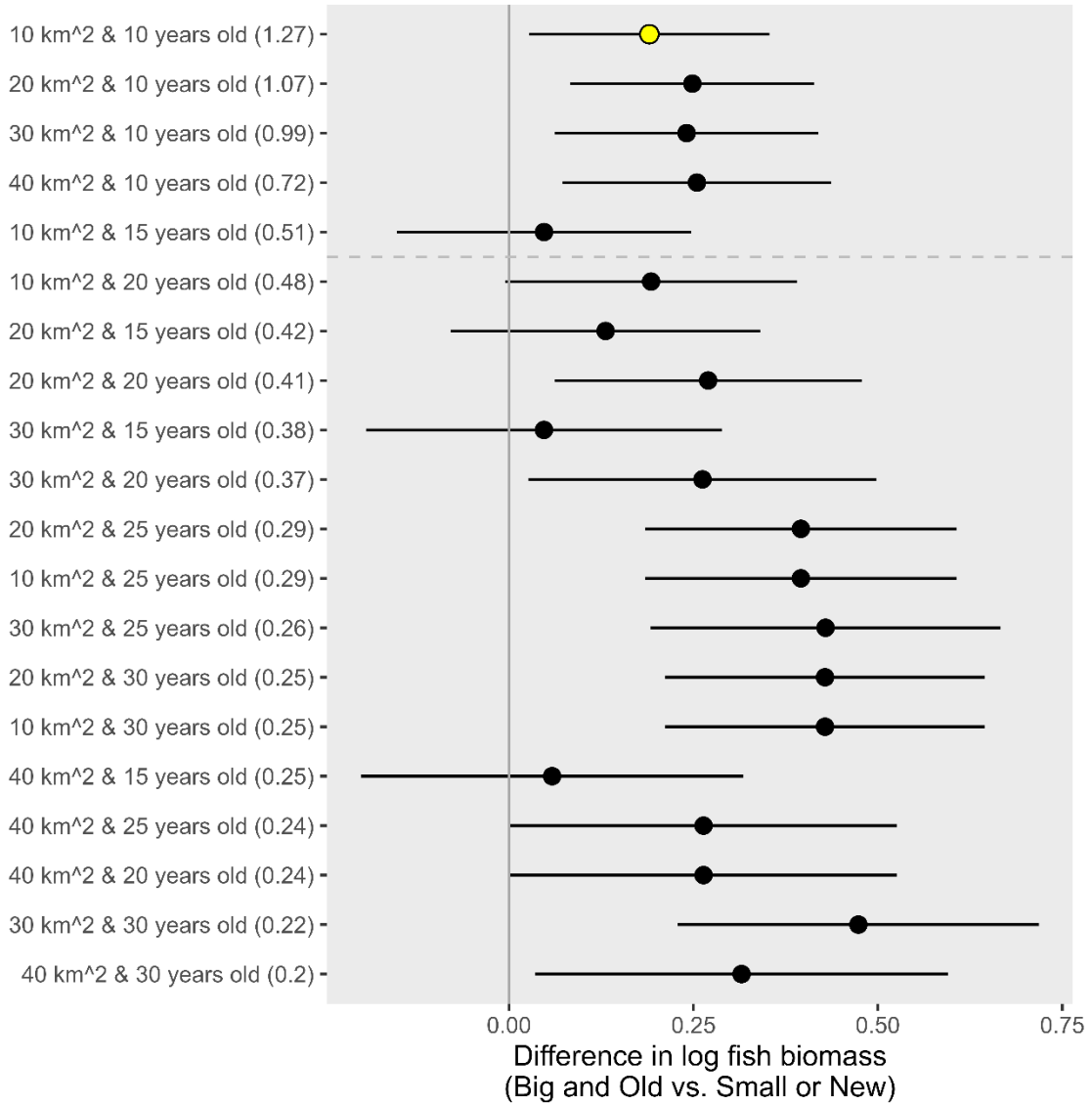
**Fig. S3. Test of age and size breakpoints to differentiate high compliance fully protected MPAs into two categories: big and old vs. small or new.** Points are the means and horizontal error bars are conditional standard error estimates representing the difference in coefficient estimates between the two categories (big and old – small or new) from a spatial mixed effects model (spaMM) predicting coral reef fish biomass. These models included three other fixed effects (habitat, depth, and census method), a nested random effect to account for regional differences (marine ecoregion within marine province), and a Matérn autocorrelation function. Numbers in brackets are the ratios of sample sizes between the two categories, given the size and age splits (i.e. # big and old sites/ # small or new sites).
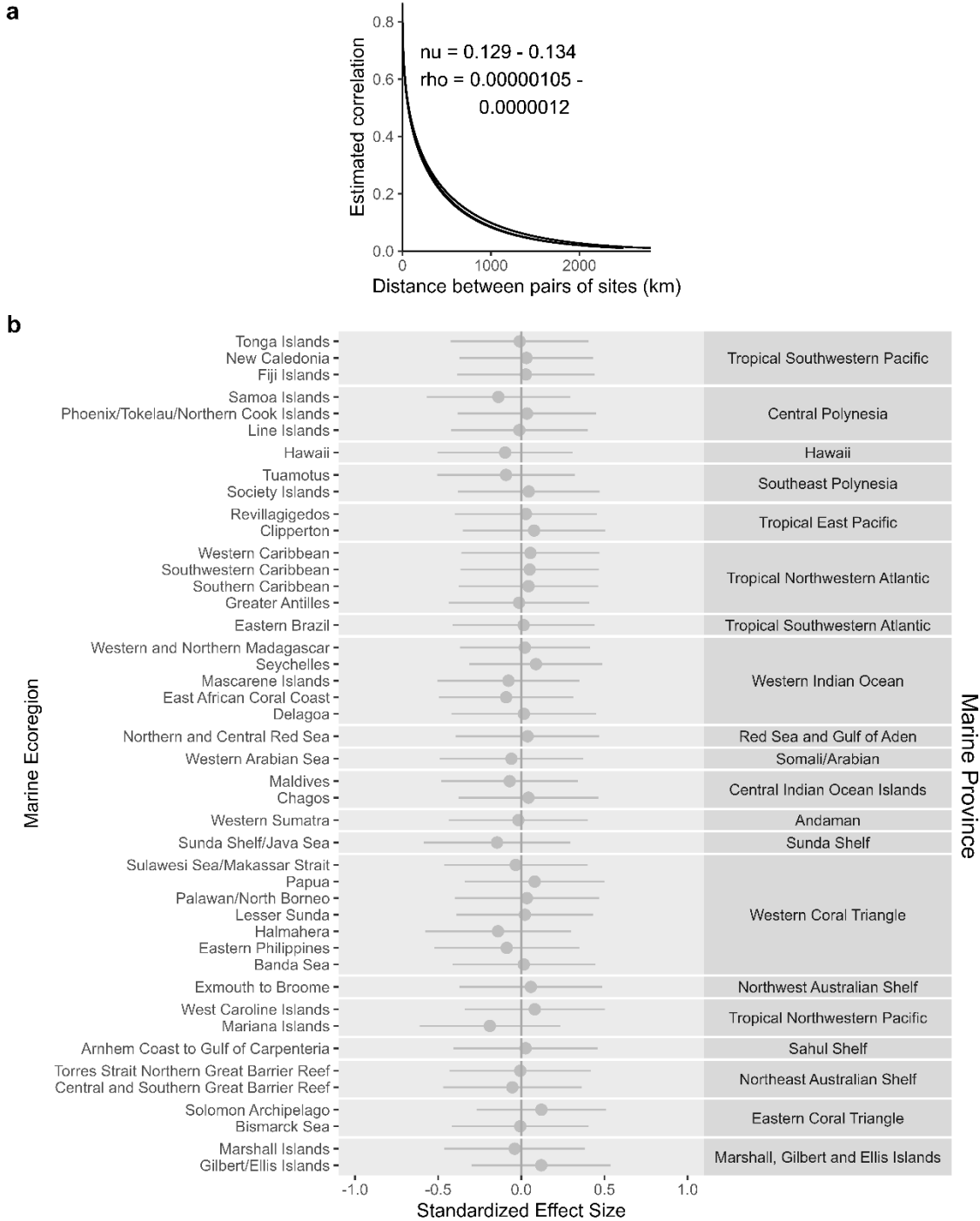
**a**

nu = 0.129 - 0.134
rho = 0.00000105 - 0.0000012

**b**

**Fig. S4. Random effects in the four selected spatial GLMMs used to predict coral reef fish biomass. a**, Spatial autocorrelation between pairs of survey sites based on a fitted Matérn correlation function, with ranges in smoothness (nu) and scale (rho) parameters for the four selected models. The spatial term in the spaMM models used to predict coral reef fish biomass is a multivariate normal distribution with a mean vector of 0 and a covariance matrix given by the Matérn function, with two parameters estimated from the data: nu (control smoothness, smaller values means lower smoothness) and rho (control rate of decay, smaller value means faster decay). **b**, Multi-model standardized effect sizes (model coefficients) +/- propagated uncertainties

(95% confidence intervals) for marine ecoregions within provinces (included in model as nested random effects).
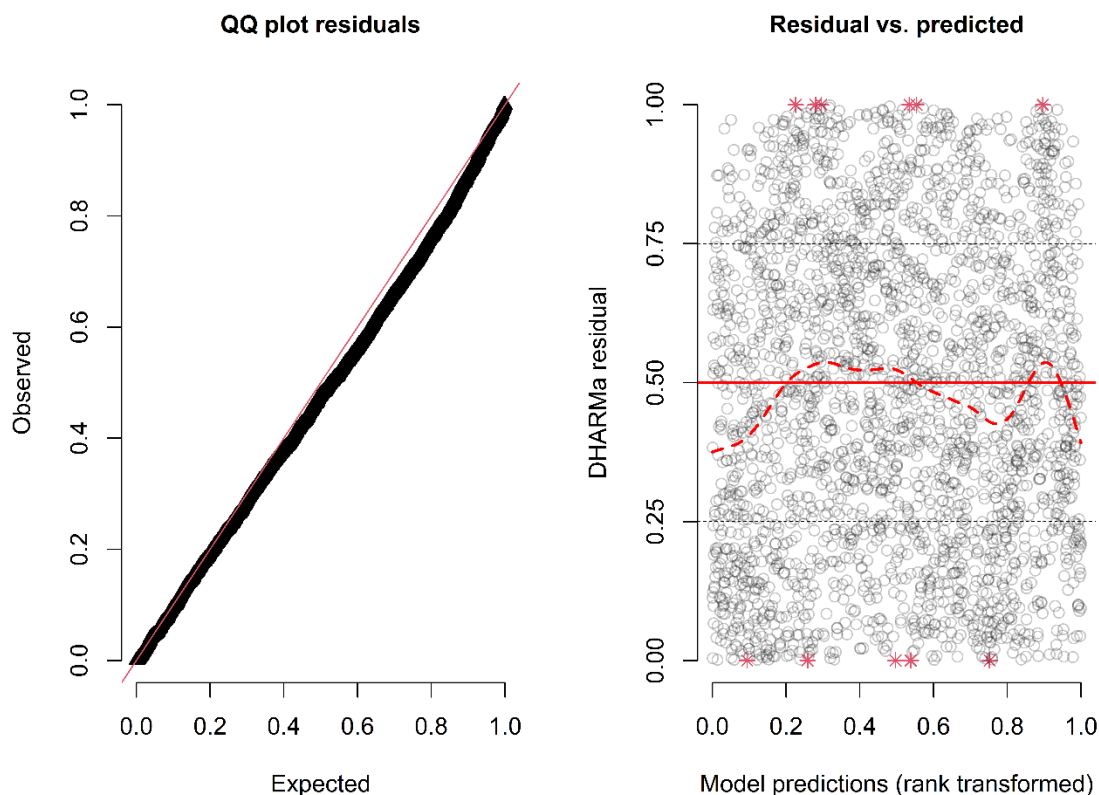
**QQ plot residuals**

**Residual vs. predicted**

**Fig. S5. Model diagnostic plots using the multi-model mean scaled residuals from the four spatial GLMMs selected to predict coral reef fish biomass.** The left panel is a quantile-quantile plot (qq plot) that compares the scaled residuals of the model (in this case the multi-model mean scaled residuals), with an expected distribution indicated by the red line (uniform in the case of scaled residuals). The right panel is a plot of the scaled residuals against simulated responses (in this case both multi-model mean values), with red stars indicating simulation outliers. Both plots were created using the DHARMa R package (2), by first simulating residuals for each model (using the simulateResiduals function) then calculating the multi-model means for the resulting scaled residuals and simulated responses. Those multi-model means were then used to create the two plots (using plotQQunif and plotResiduals functions).
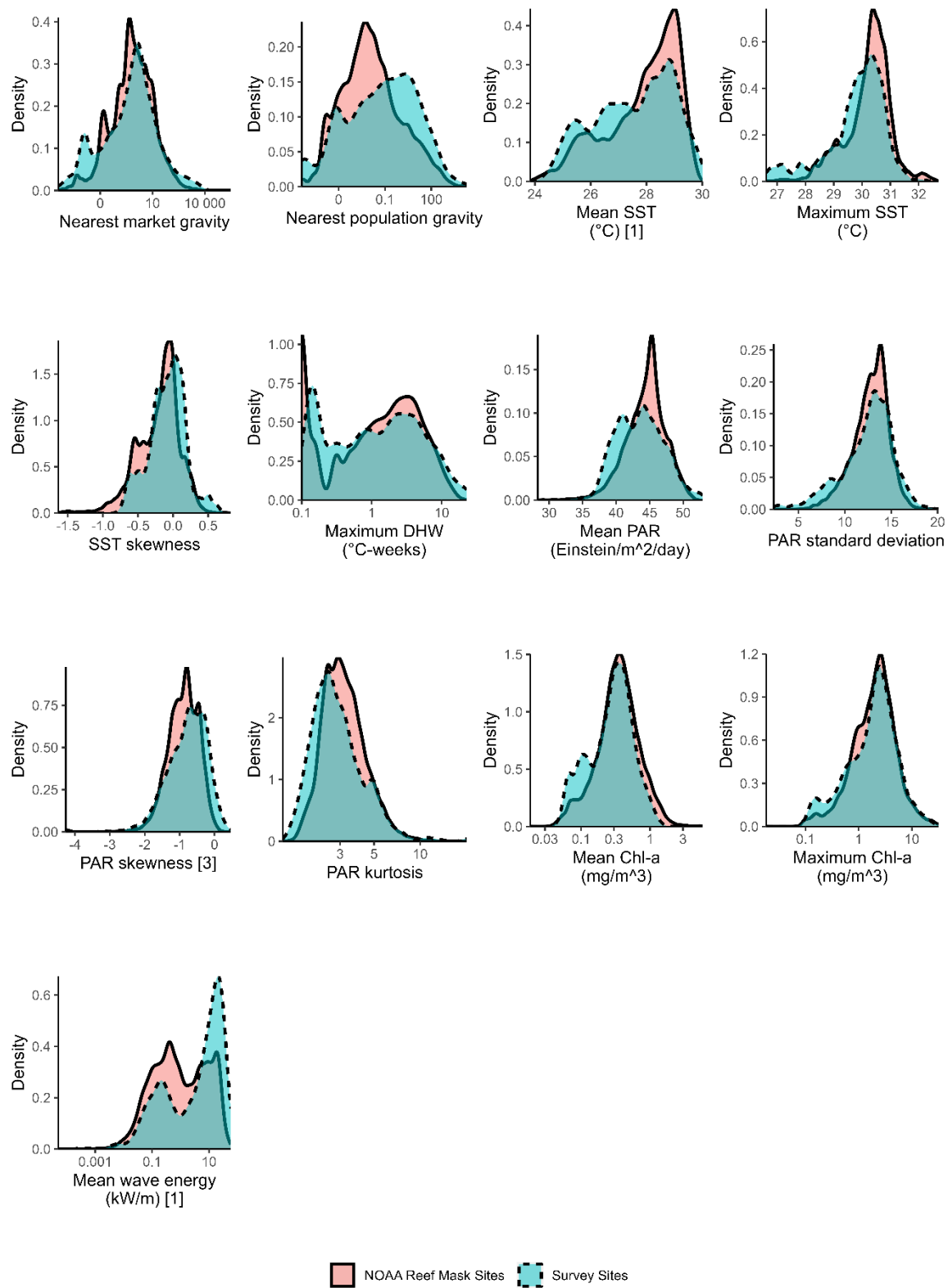
**Fig. S6. Representativeness of the social and environmental predictors retained in at least one of the four selected spaMMs, ordered by absolute effect size (see Fig. S1c).** Density

plots showing overlap between 2,599 surveyed locations (blue dashed distributions) and 49,878 tropical coral reef locations compiled by NOAA (i.e., "reef mask" sites described in (3)) from the same ecoregions (red solid distributions) for covariates included in at least one of the spatial GLMMs selected to predict coral reef fish biomass (see Table S2). Numbers in square brackets indicate the number of models in which the variable was retained (only for those in subsets of the selected models).
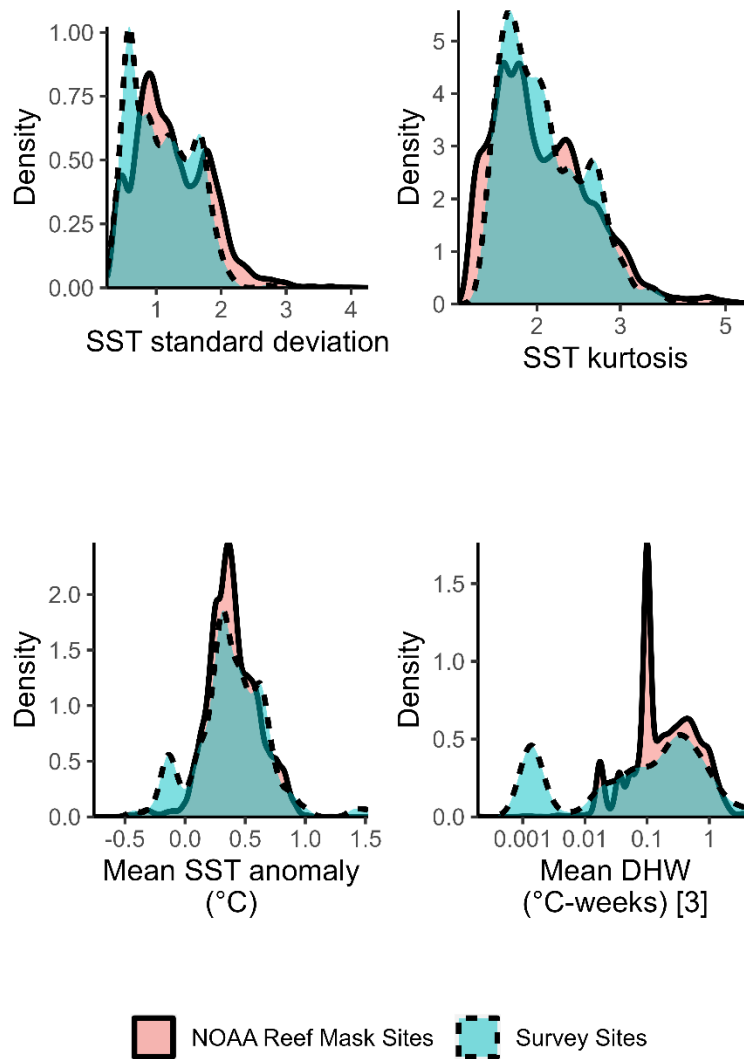
**Fig. S7. Representativeness of social and environmental predictors not included in at least one of the selected spaMMs.** Density plots showing overlap between 2,599 surveyed locations (blue dashed distributions) and 49,878 tropical coral reef locations compiled by NOAA (i.e., "reef mask" sites described in (3)) from the same ecoregions (red solid distributions) for covariates that were included in candidate spatial GLMMs but were not within any of the four spatial GLMMs selected to predict coral reef fish biomass (see Table S2).

**Table S1. Estimates of tropical coral reef area in fully protected Marine Protected Areas (MPAs) by marine province (ordered from most to least protected, then from most to least coral area)**. Using R software, we calculated the "Total Allen Coral Area" as the total area of all polygons identified as "Coral/Algae" in Allen Coral Atlas benthic data within each province (4). We then calculated how much of that area overlapped with fully protected MPA polygons in the World Database of Protected Areas (WDPA) (1) (i.e., MPAs categorized as "All" in the "NO_TK" column or with "NO_TK_AREA" column values equal to "REP_M_AREA" column values). These should be considered sample estimates rather than a census of all coral reefs as we recognize that: 1) the total coral area here is less than other global estimates of total coral area (5), and 2) the WDPA database may contain inaccuracies (e.g., overestimates fully protected MPA area in Ningaloo, Australia), and does not necessarily include all fully protected MPAs (e.g. missing community-based fully protected MPAs in Tonga Islands).

| Province | Total Mapped Allen Coral Area (km²) | Allen Coral Area in WDPA Fully Protected MPAs (km²) | % Allen Coral Area in WDPA Fully Protected MPAs |
|---|---|---|---|
| Northeast Australian Shelf | 1962 | 468 | 23.9 |
| Northwest Australian Shelf | 1316 | 309 | 23.5 |
| Andaman | 1973 | 201 | 10.2 |
| Central Indian Ocean Islands | 902 | 88.1 | 9.77 |
| Sunda Shelf | 1176 | 92.2 | 7.84 |
| Marshall, Gilbert and Ellis Islands | 1420 | 109 | 7.68 |
| Central Polynesia | 327 | 18.8 | 5.75 |
| Hawaii | 214 | 10.4 | 4.86 |
| Tropical Northwestern Pacific | 441 | 17.4 | 3.95 |

| | | | |
|---|---|---|---|
| Tropical Southwestern Pacific | 4507 | 111 | 2.46 |
| Western Coral Triangle | 16081 | 228 | 1.42 |
| Western Indian Ocean | 4459 | 40.5 | 0.908 |
| Tropical Northwestern Atlantic | 7709 | 43.4 | 0.563 |
| Eastern Coral Triangle | 3121 | 8.01 | 0.257 |
| Tropical Southwestern Atlantic | 127 | 0.242 | 0.191 |
| Java Transitional | 181 | 0.0406 | 0.0224 |
| Sahul Shelf | 4735 | 0.723 | 0.0153 |
| West African Transition | 399 | 0.0362 | 0.00907 |
| Red Sea and Gulf of Aden | 2254 | 0 | 0 |
| Bay of Bengal | 1277 | 0 | 0 |
| South China Sea | 1245 | 0 | 0 |
| Southeast Polynesia | 480 | 0 | 0 |
| Gulf of Guinea | 414 | 0 | 0 |
| Tropical East Pacific | 122 | 0 | 0 |

| | | | |
|---|---|---|---|
| West and South Indian Shelf | 121 | 0 | 0 |
| Galapagos | 85.7 | 0 | 0 |
| South Kuroshio | 46.1 | 0 | 0 |
| Marquesas | 16.0 | 0 | 0 |
| Somali/Arabian | 13.2 | 0 | 0 |
| Warm Temperate Northwest Pacific | 8.11 | 0 | 0 |
| North Brazil Shelf | 0.0102 | 0 | 0 |
| **Total** | **57132** | **1746** | **3.06** |

**Table S2. Social and environmental predictors evaluated in predictive models with their data sources, descriptions and rationale/ support for their inclusion in the model selection process**. In addition to support for relationships between each covariate and fish biomass, the rationale/support column includes support for relationships between covariates and two other metrics (coral cover and fish biodiversity), reasoning that those metrics are both related to fish biomass (6, 7).

| Covariate | Source | Description | Rationale/support |
|---|---|---|---|
| Sea surface temperature (SST): mean, maximum (max), standard deviation (sd), skewness, kurtosis. | NOAA's Coral Reef Watch (8). | Daily 5km satellite-derived nighttime ocean temperatures measured at the surface (CoralTemp SST product). We calculated each summary metric (e.g. mean) for SST, SSTa, and DHW from the nearest data available within 10km of each survey location for the two years prior to the survey year. | -Mean SST linked to reef fish biomass (6), reef fish species richness (9), coral cover (10), coral species richness (11), and coral thermal resistance (12). |
| | | | -Max SST max linked to reef community regimes (13), coral species richness (11), and coral thermal susceptibility (14). |
| | | | -SST variability (e.g. sd) linked to reef fish biomass (6), reef fish occurrence (15), reef community regimes (13), coral bleaching susceptibility (16), and coral cover change (17). |
| | | | -SST skewness linked to coral cover (16, 18) and coral thermal resistance (12). |
| | | | -SST kurtosis linked to coral cover (16), coral species richness (11), coral thermal resistance |

| | | | |
|---|---|---|---|
| | | | (12), and cover of calcifying organisms (18). |
| Sea surface temperature anomalies (mean SSTa). | NOAA's Coral Reef Watch (8) | Difference between daily 5km SST and long-term average SST for each location (ranges from -5 to +5 °C). Calculated as above for SST metrics. | -Mean SSTa linked to coral cover (16, 18). |
| Degree heating weeks (DHW): mean, max. | NOAA's Coral Reef Watch (8) | Accumulated heat stress at a location over the previous 12 weeks, measured as the sum of positive SSTa's more than 1°C above a baseline summer maximum (mean temperature of the warmest month) (19). Calculated as above for SST metrics. | -Mean DHW associated with coral bleaching probability (19–21).  -Max DHW linked to coral abundance (22). |
| Photosynthetically active radiation (PAR): mean, sd, skewness, kurtosis. | GlobColour Project (23) | Daily 4km mean daily photon flux density in the visible range (400 to 700 nm) that can be used for photosynthesis (Einstein/m$^2$/day). We calculated each summary metric (e.g. mean) for PAR and Chl-$a$ from the nearest data available within 10km of each survey location for the | -Mean PAR linked to reef fish biomass through species richness (6) and coral cover (10).  -Median PAR linked to coral cover (18).  -PAR sd linked to reef community regimes (13).  -PAR skewness and kurtosis associated with coral cover (16). |

| | | two years prior to the survey year. | |
|---|---|---|---|
| Chlorophyll-*a* (Chl-*a*): mean, max. | GlobColour Project (23) | Daily 4km chlorophyll-*a* concentration (mg/m$^3$) for waters where the phytoplankton concentration dominates over inorganic particles, using the GSM algorithm for merging single sensor L3 NRRS. The GSM method uses the normalized reflectances at the original sensor wavelengths, without intercalibration, and is commonly used as a proxy for the biomass of phytoplankton (24). | -Mean Chl-*a* linked to reef fish biomass through species richness (6) and coral cover (10). <br><br> -Median Chl-*a* linked to coral cover (18). <br><br> -Max Chl-*a* linked to reef community regimes (13). |
| Wave energy (mean) | Marine Socio-Environmental Covariates (MSEC) (25) | Mean wave energy flux (kW/m) calculated from the significant wave height and peak wave period extracted from the WAVEWATCH III hindcast dataset over a span of 31 years (1979-2009) (25). | -Wave exposure linked to coral abundance (22). <br><br> -Wave height linked to coral cover (26). <br><br> -Wave power linked to live coral cover (10). |

| | | | |
|---|---|---|---|
| Population gravity (nearest) | Calculated based on (27, 28). | Gravity between each reef site and the nearest human settlement (of any population size) is calculated by dividing the population of the human settlement by the squared travel time between the human settlement and the reef site. Travel time was calculated using a cost-distance algorithm that computes the least cost (in minutes) it would take to travel between those two locations, taking into account that the cost of travel differs over water and different land surfaces. | -Nearest population gravity linked to reef fish biomass (28), shark abundance (29), and coral abundance (22). |
| Market gravity (nearest) | Calculated based on (27, 28). | As with population gravity but using the population of the nearest major market (provincial capital city, major population center, landmark city, national capital, or port) and the travel time between that major market and the reef survey location. | -Nearest market gravity linked to reef fish biomass (28), shark abundance (29), and coral abundance (22). |

**Table S3. Predictive and explanatory power of candidate spatial mixed effects models for predicting coral reef fish biomass at 2599 coral reef sites.** Models were compared and ranked through a 20-fold spatially blocked cross-validation process where data outside each fold (training sets) were used to build models. Data within each fold was then used to test the predictive power of that model. Ranks are based on mean RMSE cross-validation scores (across all 20 folds). Asterisks indicate which models were kept - either because they were the best performing (lowest mean RMSE) or their correlation adjusted standard error overlapped with the lowest mean RMSE (see methods). All models included a nested random effect of Marine Ecoregion within Marine Province and a Matérn spatial covariance structure to account for spatial autocorrelation: Matérn(1|Easting + Northing). Bolded variables are those that are shared among all four selected models. The general mathematical equations for these spaMM models are as follows:

$$Y_i \sim \Gamma\left(\mu_i, \phi \cdot \mu_i\right)$$
$$\log(\mu) = X\beta + Z_1 b_1 + Z_2 b_2$$
$$b_1 = b_{\text{province}} + b_{\text{ecoregion[province]}}$$
$$b_{\text{province}} \sim \mathcal{N}(0, \sigma^2_{\text{province}}) \quad \text{and} \quad b_{\text{ecoregion[province]}} \sim \mathcal{N}(0, \sigma^2_{\text{ecoregion}})$$
$$b_2 \sim \mathcal{MVN}(0, \Sigma)$$
$$\Sigma_{ij} = \sigma_s^2 \frac{2^{1-\nu}}{\Gamma(\nu)} \left(\frac{h_{ij}}{\rho}\right)^\nu K_\nu\left(\frac{h}{\rho}\right)$$

Where:
- $Y_i$ is the response variable (fish biomass) for the ith observation, assumed to be Gamma distributed ($\Gamma(\cdot)$) with mean ($\mu_i$) and variance ($\mu_i$ times the dispersion parameter for the Gamma family, $\varphi$).
- The mean ($\mu$) is modelled using a log link function, with $X$ as a vector of fixed effects covariates, $\beta$ as a vector of fixed effect coefficients, $Z_1$ as a vector of non-spatial random effect covariates, $b_1$ as a vector of non-spatial random effects, and $Z_2 b_2$ representing the spatial random effects.
- $b_1$ is composed of the effect of marine province ($b_{\text{province}}$) and nested marine ecoregion within province ($b_{\text{province[ecoregion]}}$), each of which are assumed to be normally distributed [$N(\cdot)$] with a mean of 0 and variances of $\sigma_{\text{province}}^2$ and $\sigma_{\text{ecoregion}}^2$, respectively.
- The spatial random effects ($b_2$) are assumed to be multivariate normally distributed [$MVN(\cdot)$] with mean of 0 and a variance covariance matrix ($\Sigma$) defined by a standard Matérn correlation function with smoothness ($\nu$) and scale ($\rho$) parameters.
- $\Sigma_{ij}$ is element ij of the $\Sigma$ correlation matrix, which is determined by the Matérn correlation function for a given geographic distance between the locations for observations i and j ($h_{ij}$), with fitted smoothness ($\nu$) and scale ($\rho$) parameters.
- $\sigma_s^2$ is the variance parameter for the spatial random effects.
- $K_\nu(\cdot)$ is the modified Bessel function of the second kind and zero order.

| Rank | Model differences<br><br>Common model: Biomass ~ Habitat + Depth + Census Method + Management*log(Nearest Market Gravity) + (1\|Province/Ecoregion) + Matérn(1\|Easting + Northing) + log(Chl-*a* max) + PAR sd... | RMSE cv<br><br>(Mean; log-scale) | *Correlation-adjusted SE*<br>(paired t-test) | Marginal/<br><br>Conditional $R^2$<br>(full model) |
|---|---|---|---|---|
| 1 | …log(DHW max) + **log(Chl-*a* mean)** + **PAR mean** + PAR skewness + **log(mean wave energy)** | 1.006 | 0* | 0.251/0.715 |
| 2 | …log(Nearest Population Gravity) + SST max + SST skewness + **log(Chl-*a* mean)** + **PAR mean** + log(PAR kurtosis) + **log(mean wave energy)** | 1.011 | 0.0117* | 0.251/0.715 |
| 3 | …SST max + log(DHW max) + **log(Chl-*a* mean)** + **PAR mean** + PAR skewness | 1.012 | 0.0034 | 0.241/0.713 |
| 4 | …SST max + log(DHW mean) + **log(Chl-*a* mean)** + **PAR mean** + PAR skewness + **log(mean wave energy)** | 1.013 | 0.0021 | 0.238/0.713 |
| 5 | …log(Nearest Population Gravity) + SST mean + SST max + **log(Chl-*a* mean)** + **PAR mean** + PAR skewness + **log(mean wave energy)** | 1.013 | 0.0070* | 0.240/0.713 |

| 6 | …log(Nearest Population Gravity) + SST max + SST skewness + **log(Chl-*a* mean)** + **PAR mean** + PAR skewness + **log(mean wave energy)** | 1.013 | 0.0117* | 0.240/711 |
|---|---|---|---|---|
| 7 | …SST max + SST skewness + SSTa mean + **log(Chl-*a* mean)** + **PAR mean** + PAR skewness + **log(mean wave energy)** | 1.019 | 0.0097 | 0.240/0.712 |
| 8 | …SST max + SST sd + SST skewness + **log(Chl-*a* mean)** + **PAR mean** + PAR skewness + **log(mean wave energy)** | 1.019 | 0.0090 | 0.246/0.711 |
| 9 | …SST mean + SST max + SST skewness + **log(Chl-*a* mean)** + **PAR mean** + log(PAR kurtosis) + **log(mean wave energy)** | 1.020 | 0.0093 | 0.246/0.711 |
| 10 | …log(SST kurtosis) + SST skewness + **log(Chl-*a* mean)** + **PAR mean** + log(PAR kurtosis) + **log(mean wave energy)** | 1.021 | 0.0096 | 0.239/0.711 |
| 11 | …SST max + log(SST kurtosis) + SST skewness + **PAR mean** + PAR skewness + **log(mean wave energy)** | 1.021 | 0.0102 | 0.239/0.710 |
| 12 | …SST mean + SST max + SST skewness + **log(Chl-*a* mean)** + **PAR mean** + PAR skewness + **log(mean wave energy)** | 1.022 | 0.0091 | 0.263/0.712 |

| 13 | …log(SST kurtosis) + SST skewness + **log(Chl-*a* mean)** + **PAR mean** + PAR skewness + **log(mean wave energy)** | 1.022 | 0.0093 | 0.237/0.711 |
|---|---|---|---|---|
| 14 | …SST max + log(SST kurtosis) + **log(Chl-*a* mean)** + **PAR mean** + log(PAR kurtosis) + **log(mean wave energy)** | 1.022 | 0.0079 | 0.240/0.711 |
| 15 | …SST max + log(SST kurtosis) + SST skewness + **log(Chl-*a* mean)** + PAR skewness + **log(mean wave energy)** | 1.023 | 0.0099 | 0.270/0.714 |
| 16 | …SST max + log(SST kurtosis) + **log(Chl-*a* mean)** + **PAR mean** + PAR skewness + **log(mean wave energy)** | 1.023 | 0.0073 | 0.264/0.710 |
| 17 | …SST max + SST sd + SST skewness + SSTa mean + **log(Chl-*a* mean)** + **PAR mean** + PAR skewness | 1.024 | 0.0109 | 0.256/0.706 |
| 18 | …SST max + log(SST kurtosis) + SST skewness + **log(Chl-*a* mean)** + **PAR mean** + log(PAR kurtosis) | 1.024 | 0.0112 | 0.246/0.708 |
| 19 | …SST max + log(SST kurtosis) + SST skewness + **log(Chl-*a* mean)** + **PAR mean** + PAR skewness | 1.025 | 0.0110 | 0.245/0.707 |

**Dataset S1 (separate file: Caldwelletal_RealizedPotentialGains_FishSurveysCovariates.csv).** Coral reef fish survey data with covariates used in the model and figures. File is accessible via GitHub (within the folder https://github.com/ircaldwell/Caldwelletal_RealizedPotentialGains/Data/) or the linked Zenodo repository (30) (https://doi.org/10.5281/zenodo.13363303, within the "Data" folder).

**Dataset S2 (separate file: Caldwelletal_RealizedPotentialGains_BestSpammSummResWithFilenames.csv).** Results and file names for the four selected spaMMs used to predict coral reef fish biomass. File is accessible via GitHub (within the folder https://github.com/ircaldwell/Caldwelletal_RealizedPotentialGains/Data/) or the linked Zenodo repository (30) (https://doi.org/10.5281/zenodo.13363303, within the "Data" folder).

**Dataset S3 (separate file: Caldwelletal_RealizedPotentialGains_ReefMaskCovariates.csv).** Covariates for all reef locations compiled by NOAA (i.e., "reef mask" sites described in (2); used for Fig. S6 and Fig. S7). File is accessible via GitHub (within the folder https://github.com/ircaldwell/Caldwelletal_RealizedPotentialGains/Data/) or the linked Zenodo repository (30) (https://doi.org/10.5281/zenodo.13363303, within the "Data" folder).

**Software S1 (separate file: Caldwelletal_RealizedPotentialGains_SaveBestStandSpammModels.R).** R software code used to run and save the best spaMM models. Needs to be run first as these saved models are used in the other two codes. File is accessible via GitHub (within the folder https://github.com/ircaldwell/Caldwelletal_RealizedPotentialGains/Rcode/) or the linked Zenodo repository (30) (https://doi.org/10.5281/zenodo.13363303, within the "Rcode" folder).

**Software S2 (separate file: Caldwelletal_RealizedPotentialGains_PredictGains.R).** R software code used to predict coral reef fish biomass in counterfactual scenarios and to calculate gains in fish biomass. Software S1 needs to be run first so the saved models can be used in this code. File is accessible via GitHub (within the folder https://github.com/ircaldwell/Caldwelletal_RealizedPotentialGains/Rcode/) or the linked Zenodo repository (30) (https://doi.org/10.5281/zenodo.13363303, within the "Rcode" folder).

**Software S3 (separate file: Caldwelletal_RealizedPotentialGains_AllFigures.R).** R software code used for the analysis and plotting throughout the manuscript. Software S1 and S2 should be run first as S3 code depends on files produced by the other two. File is accessible via GitHub (within the folder https://github.com/ircaldwell/Caldwelletal_RealizedPotentialGains/Rcode/) or the linked Zenodo repository (30) (https://doi.org/10.5281/zenodo.13363303, within the "Rcode" folder).

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