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Towards process-oriented management of tropical reefs in the anthropocene

Supplementary materials

Towards process-oriented management of tropical reefs in the Anthropocene

Description of covariates : In order to evaluate the influence of environmental and socio-economic factors on the management classes, we identified a suite of covariates at reef, site and country scales. Descriptions, data sources and rationale for all used covariate are described below.

Environmental drivers

*Net primary production (NPP units of mg C / m**2 / day)* is a product from a Vertically Generalized Production Model algorithm at 10km resolution. For each site we averaged the mean NPP observed from 2014 to 2019. (http://orca.science.oregonstate.edu/2160.by.4320.monthly.hdf.vgpm.m.chl.m.sst.php). We included this variable given its importance on trophic-structure and biomass through bottom-up enrichment or pelagic subsidies, and therefore fish standing biomass and biomass production [1–6]. In the absence of fine-scale data at a global scale, we chose to match our UVC data with this remote sensing data, however this ignores fine-scale variation and biases related to albedo or measurement capacity.

Mean sea surface temperature: For each site, we extracted the mean daily sea surface temperature from 2014 to 2019 from NOAA Coral Reef Watch Daily 5km Satellite Coral Bleaching Heat Stress Monitoring, https://coralreefwatch.noaa.gov/product/5km/index.php. Similarly to *Net Primary Production*, this variable ignores fine-scale variation.

Degree Heating Weeks is a satellite-derived measure that incorporates both the magnitude and duration of anomalous warm temperatures [7,8] with 1 DHW defined as 1 °C above the long-term sea surface temperature for the warmest month at a given locality [9]. In other words, the Degree Heating Weeks is the cumulative sum of degrees above the long-term sea surface temperature for the warmest month, averaged between 2014 to 2019. Since Marine Heatwaves disrupt fish communities, including variation in abundance and changes in age structure, size, growth, and energy content of species, we expected a negative impact of this variable on both biomass and biomass production [10].

Depth: Depth of the transect was noted by the divers performing surveys, and represents the mean depth of the transect. Surveys included in the analysis were performed at depths ranging from 0.1 to 42 meters (mean 7 +/- 3.7 meters).

Socio-economic drivers

Gravity: We applied the concept of human gravity [11,12]. Gravity is an indicator of potential interactions between human activities and fish communities, accounting for both the size of the human population and surrogate for distance: travel time. Within 500km buffers around each site the population estimate of the nearest settlement was divided by the squared 'least-cost' travel time (minutes) between the population and the reef site. We gathered population estimates for every 1-by-1 km populated cell within a 500km radius of each reef site using the LandScanTM 2011 database. To compute travel time we used a cost-distance algorithm that computes the least 'cost' (in minutes) of traveling to the reef site. Cost was based on a raster grid of land cover, road networks, and shorelines data and estimated travel time over different surfaces. A 500 km buffer was chosen as the maximum distance any fishing or land use activities could influence tropical reef ecosystems.

MPA Effectiveness: For each site site, we determined if it was: i) unfished- whether it fell within the borders of a high compliance fully protected Marine Protected Area (MPA); ii) restricted - active restrictions on gears (such as bans on the use of nets, spearguns, or traps) or fishing effort (which could have included areas under customary tenure, where 'outsiders' were effectively excluded, as well as inside marine parks that were not necessarily no take); or iii) openly fished - regularly fished without effective restrictions. To determine these classifications, we used the expert opinion of the data providers, and triangulated this with a global database of MPA boundaries [13]. This variable is a proxy of fishing effort in protected areas but also of the number of illegal fishers that negatively impact fish communities [14].

Marine Ecosystem Dependency: The integrated human dependence on marine ecosystems is a standardized score which corresponds to the mean of nutritional dependence, economic dependence and coastal protection [15]. For each site we assigned the marine ecosystem dependency score of its sovereign state. http://info.worldbank.org/governance/wgi/. We expected that the dependency on natural marine resources of a given country will have a negative impact on fish biomass [16].

Human Development Index (HDI) is a synthetic measure capturing elements of life expectancy, education and wealth. We used HDI values for the year 2018 from the Human Development Indicators and Indices published by the United Nations of Development program (UNDP). We assigned for each site the HDI value of the country the cell belongs to.

We chose this variable given the increasingly recognized link between human development and coral reef ecosystems, which may impact factors such as coral reef fisheries or the budget allocated to conservation and fisheries management and in turn impact standing biomass and biomass production [17–21].

NGO: the number of recorded environmental NGOs per country. For each site we assigned the number of NGOs present in its sovereign state. We expected that a high density of NGOs can make a difference in conservation and fisheries management with a positive impact on fish biomass [22].

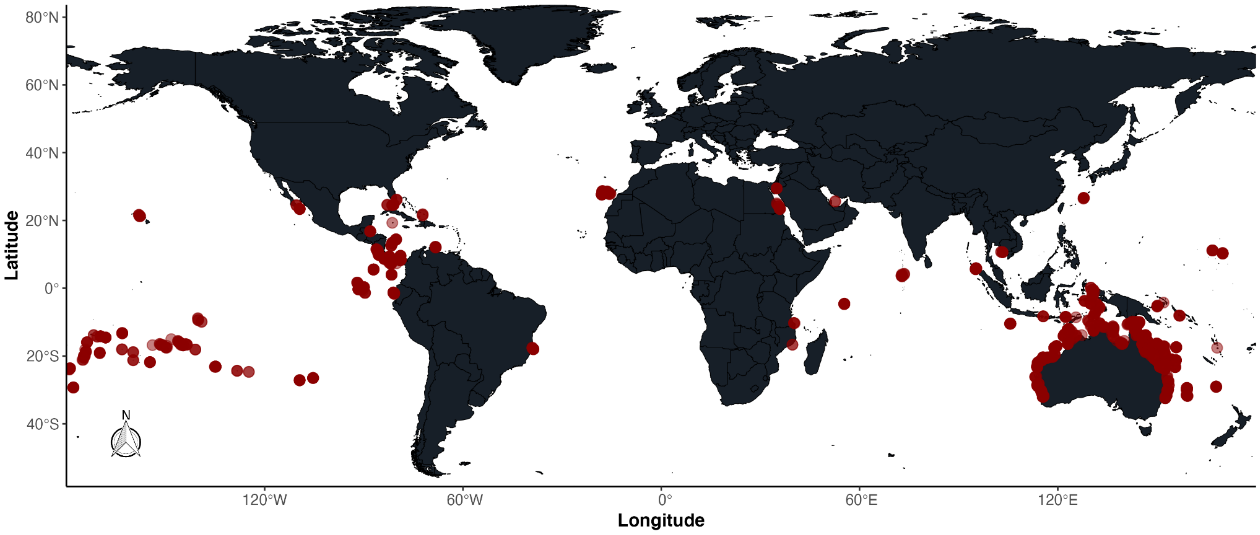
Freedom of expression: The citizen freedom of expression is represented by the Voice and Accountability indicator from the Worldwide Governance Indicators of the World Bank. It reflects perceptions of the extent to which a country's citizens are able to participate in choosing their government, as well as freedom of expression, freedom of association, and free media. For each site we assigned the freedom of expression value of its sovereign state. http://info.worldbank.org/governance/wgi/. Human rights and environmental protection are interdependent. Because the exercise of human rights supports better environmental policymaking, we expected a positive relationship between freedom of expression and fish biomass [23].

Control of Corruption captures perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as "capture" of the state by elites and private interests. For each site we assigned the marine ecosystem dependency score of its sovereign state. http://info.worldbank.org/governance/wgi/.

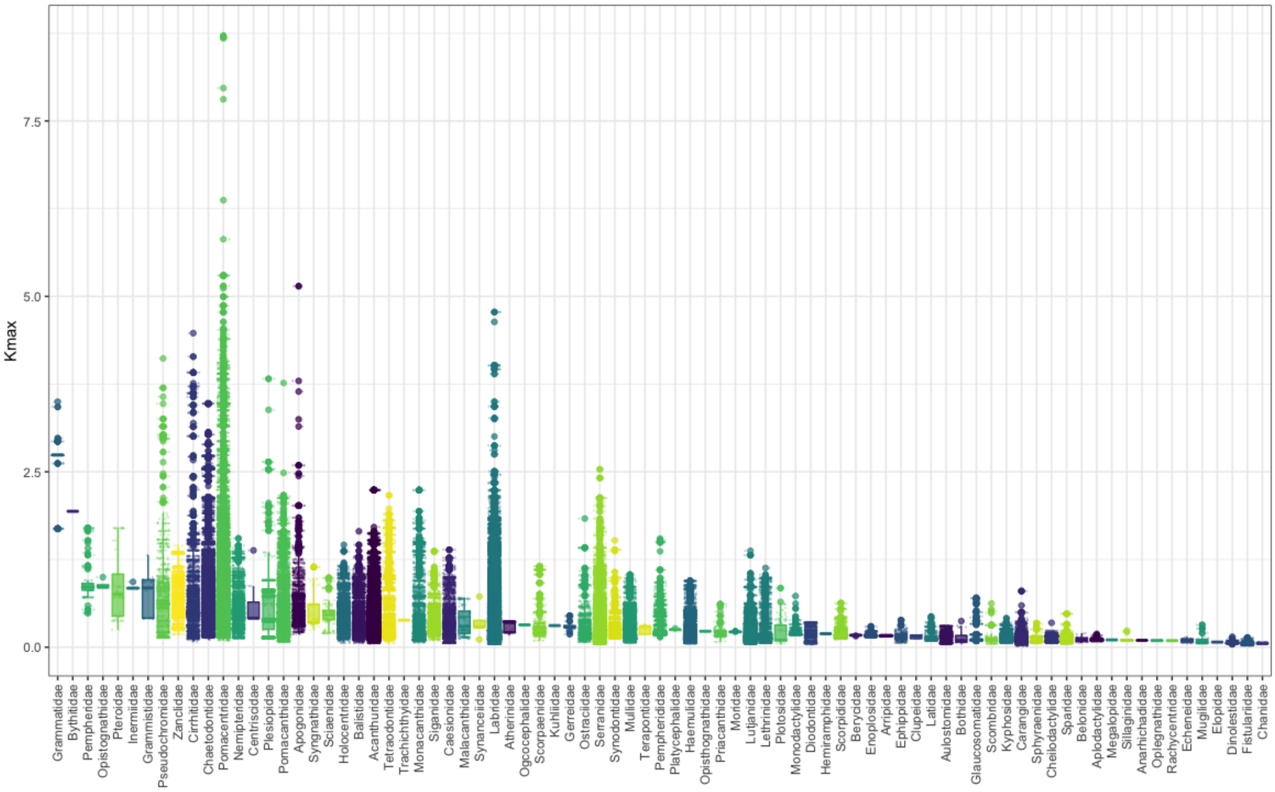
Corruption provides a way for fishers to sustain illegalities and avoid penalties and thus impact fish biomass.

No violence: Political Stability and Absence of Violence/Terrorism measures perceptions of the likelihood of political instability and/or politically motivated violence, including terrorism. For each site we assigned the "no violence" index of its sovereign state. Political instability or violence limit the fight against illegal, unreported and unregulated fishing activities, impacting fish communities [24].

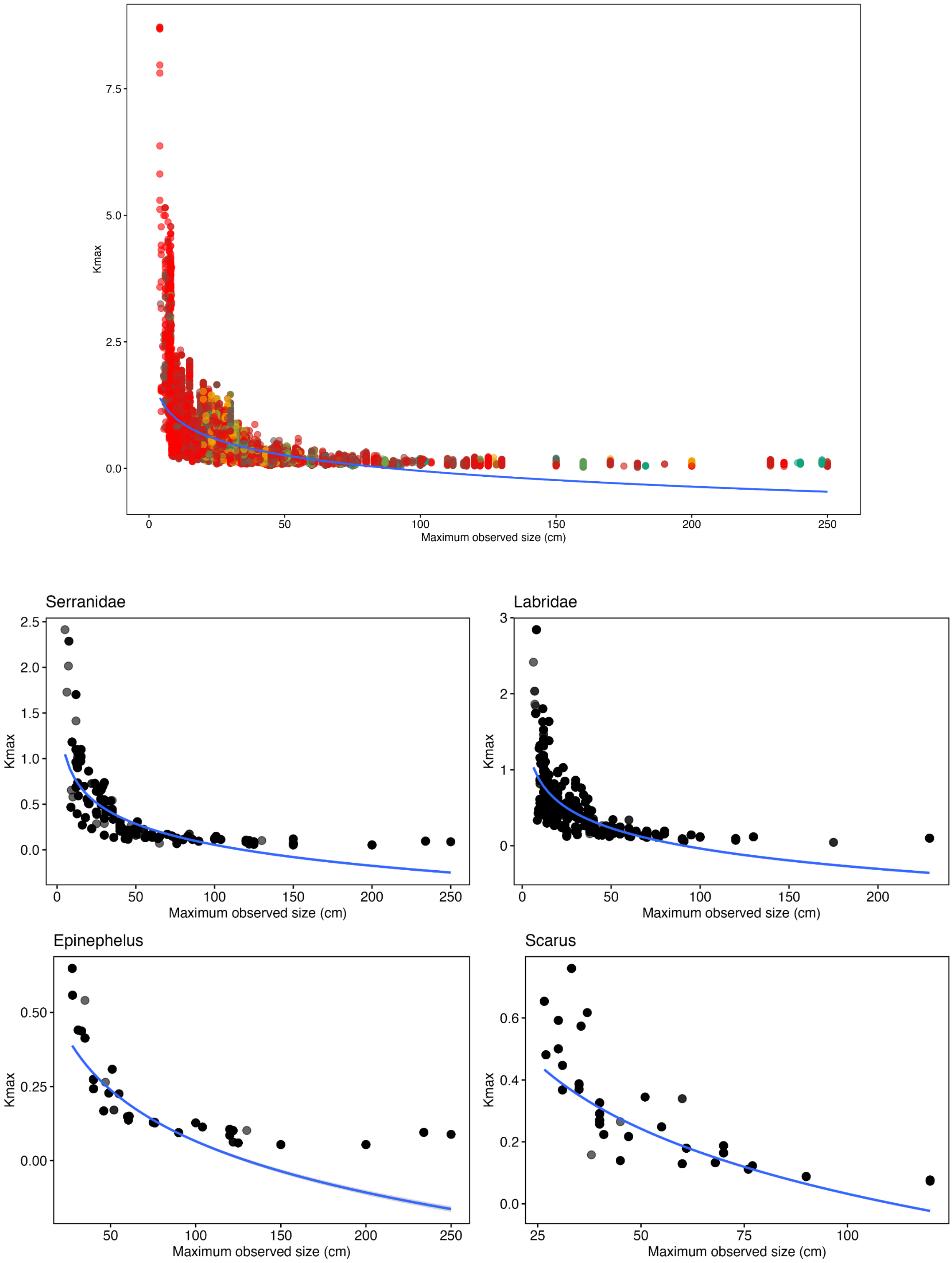
We looked for collinearity among our covariates using bivariate correlations, which led to the exclusion of several covariates related to the HDI: No violence ($R = 0.75$), Control of Corruption ($R = 0.95$) and Freedom of Expression ($R = 0.92$).



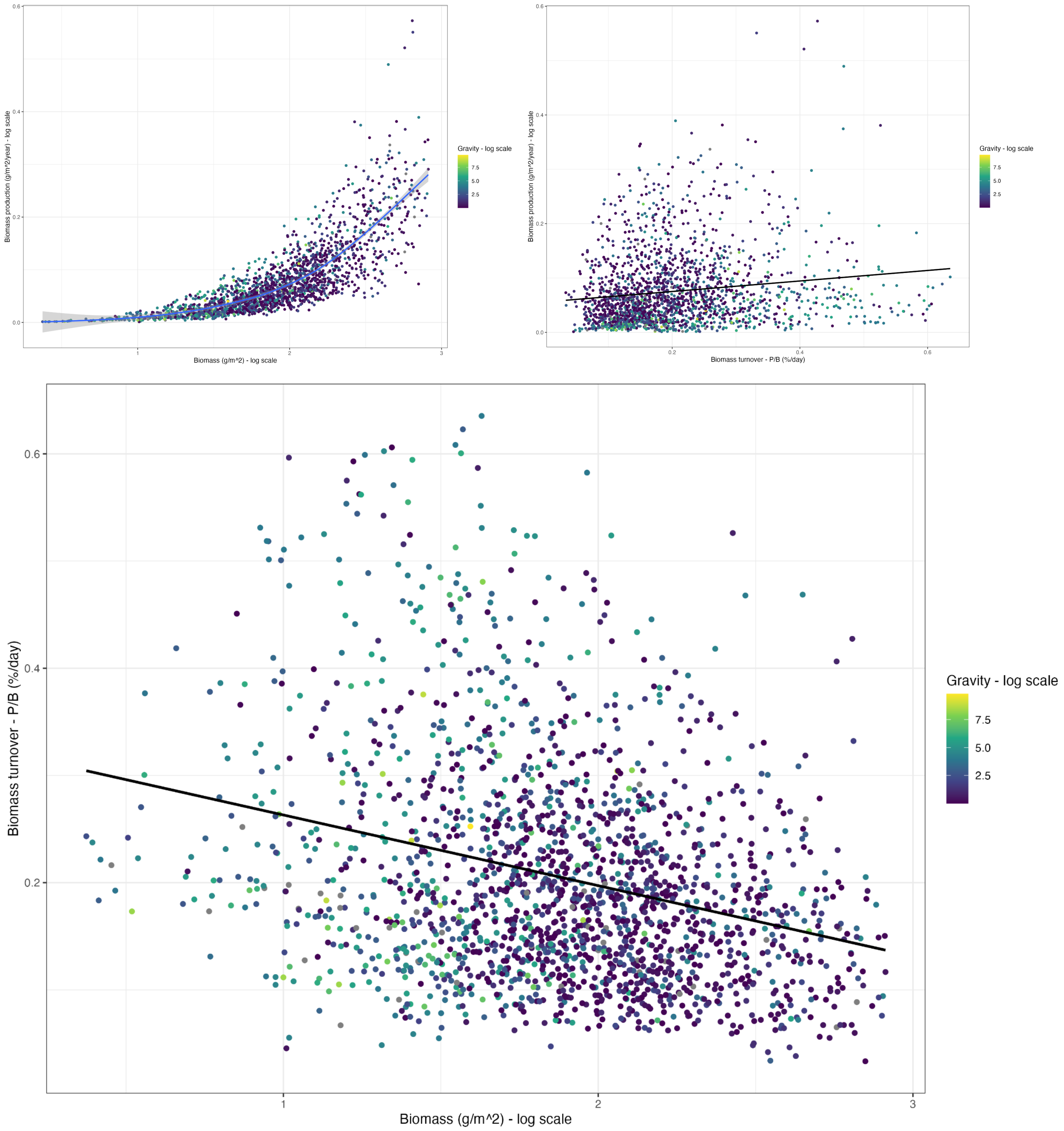
Supplementary Figure 1: Map of the 1,979 sites used in the Reef Life Survey database, comprising 3,666 surveys over 39 countries.



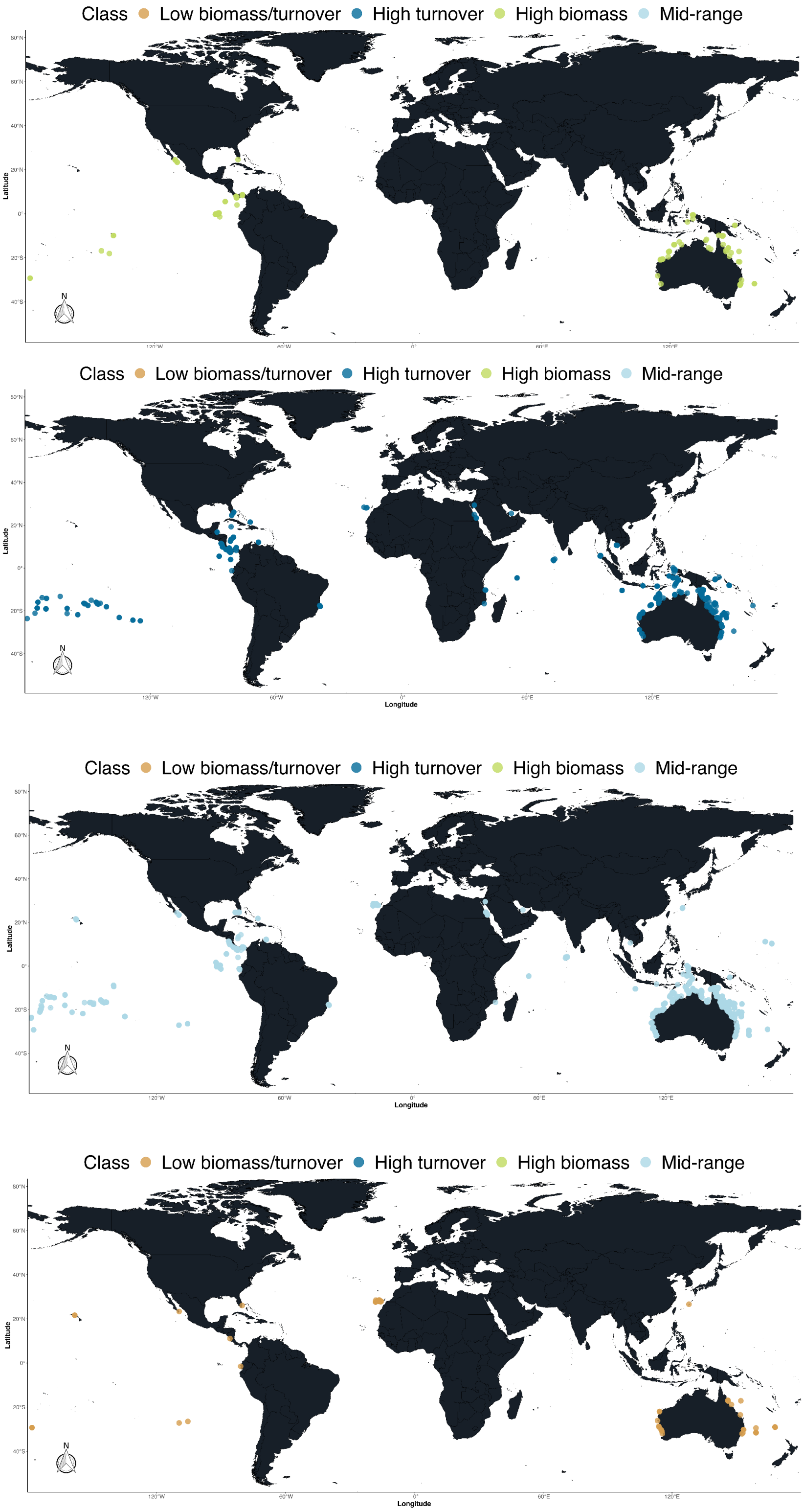
Supplementary Figure 2: Predicted growth coefficients (Kmax) for the 79 families. Each point represents one species, each color one family, the center bar is the median and upper and lower limits are 25 and 75% quantiles.



Supplementary Figure 3: (Top) Maximum observed size according to estimated growth coefficients (Kmax) for 79 families. These estimations are coherent with the theoretical relationship between growth coefficients and maximum size. Blues lines were made using the default loess smoother from the "geom_smooth" function using the *ggplot* package v 3.3.5.. **(Bottom)** Example of the relationship between maximum observed size (cm) according to estimated growth coefficients (Kmax) for two families (Lutjanidae and Labridae) and two genera (Lutjanus and Bodianus). Blues lines were made using the default loess smoother from the "geom_smooth" function using the *ggplot* package v 3.3.5.



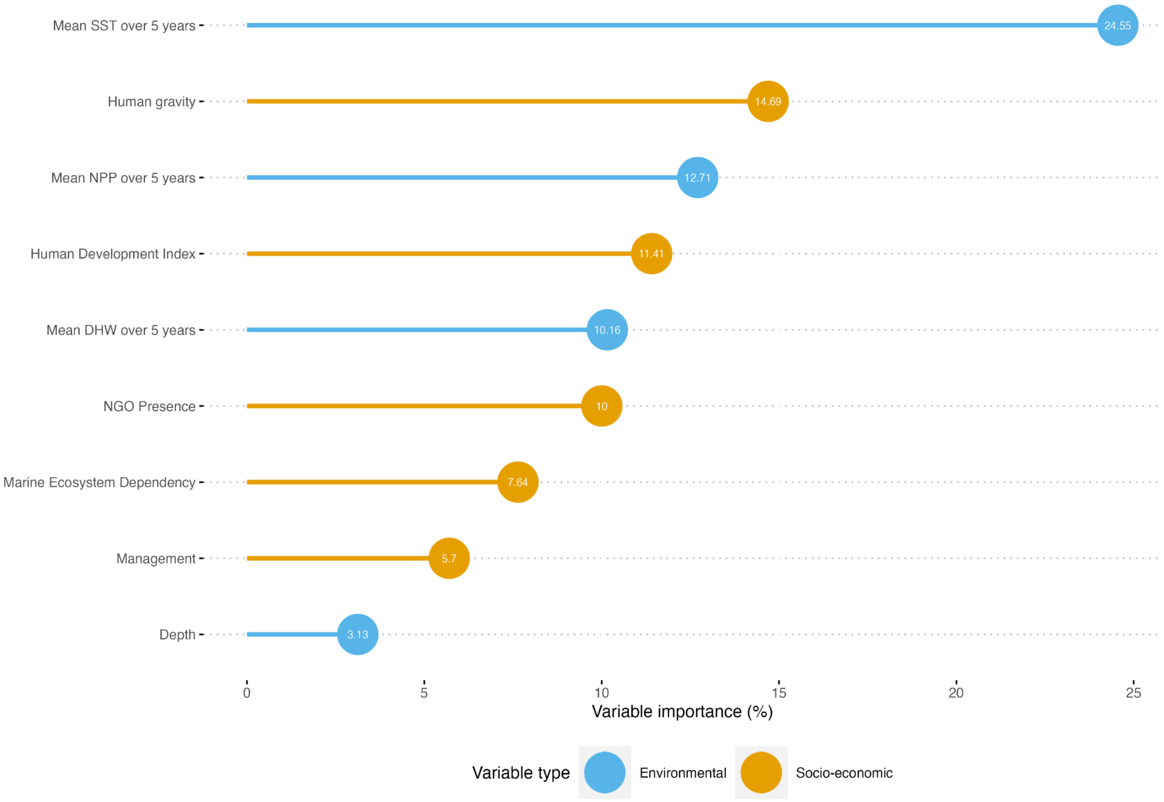
Supplementary Figure 4: Pearson correlation between standing biomass and biomass production (r = 0.76, P < 0.001), biomass production and turnover (P/B ratio, r = -0.15, P<0.001) and turnover and biomass (P/B ratio, r = -0.28, P<0.001).



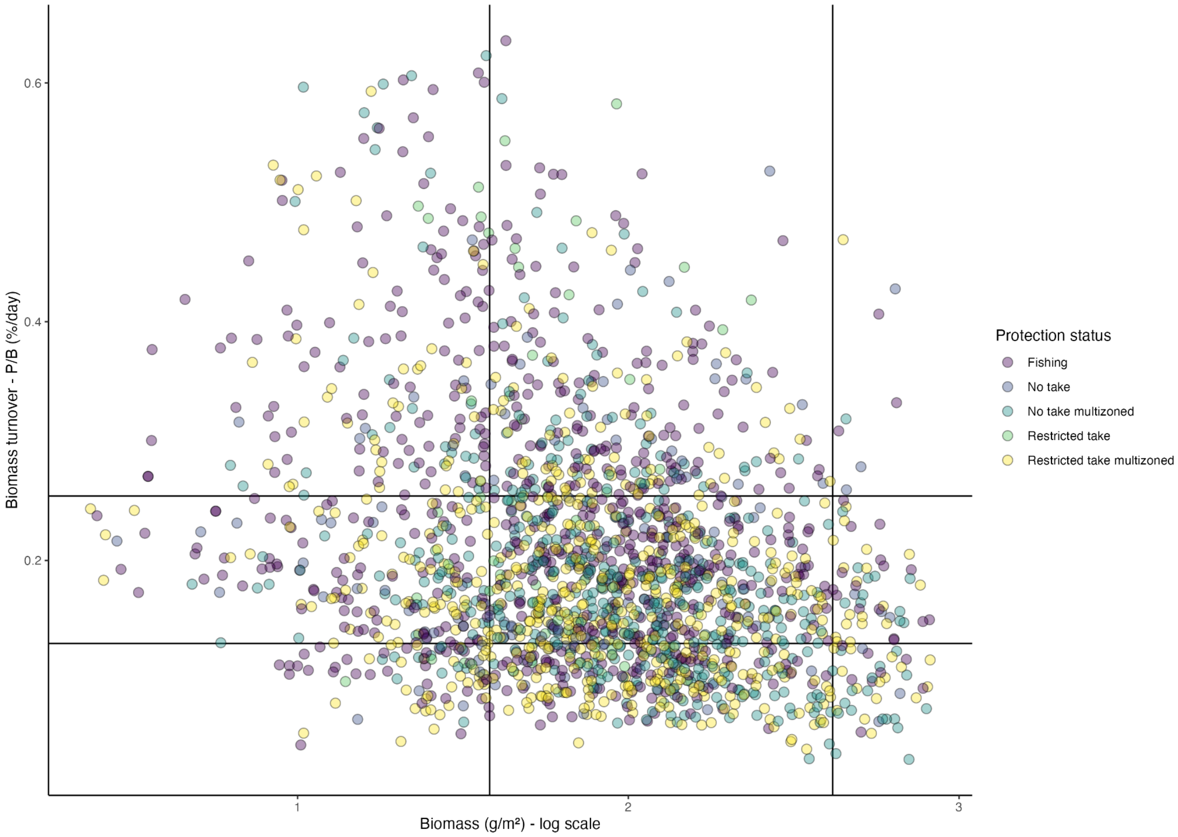
Supplementary Figure 5: World maps of the 91 sites classified as “High biomass”, characterized by high biomass (over 95% of observed values), 495 sites classified as “High turnover”, characterized by high biomass turnover (over 75% of observed values), 90 sites classified as “Low biomass/turnover”, characterized by low biomass and biomass turnover (under 25% of observed values for these two metrics), 1,303 sites classified as “Mid-range”, which fit in neither of the three above categories.

Supplementary Table 1 : Sensitivity analyses for our biomass/biomass turnover thresholds. We ran the model for thresholds at +5%/15% and -5%/15% around the used thresholds in the study. Even though the repartition of sites in the four different classes varied, model performance remained stable across all chosen thresholds.

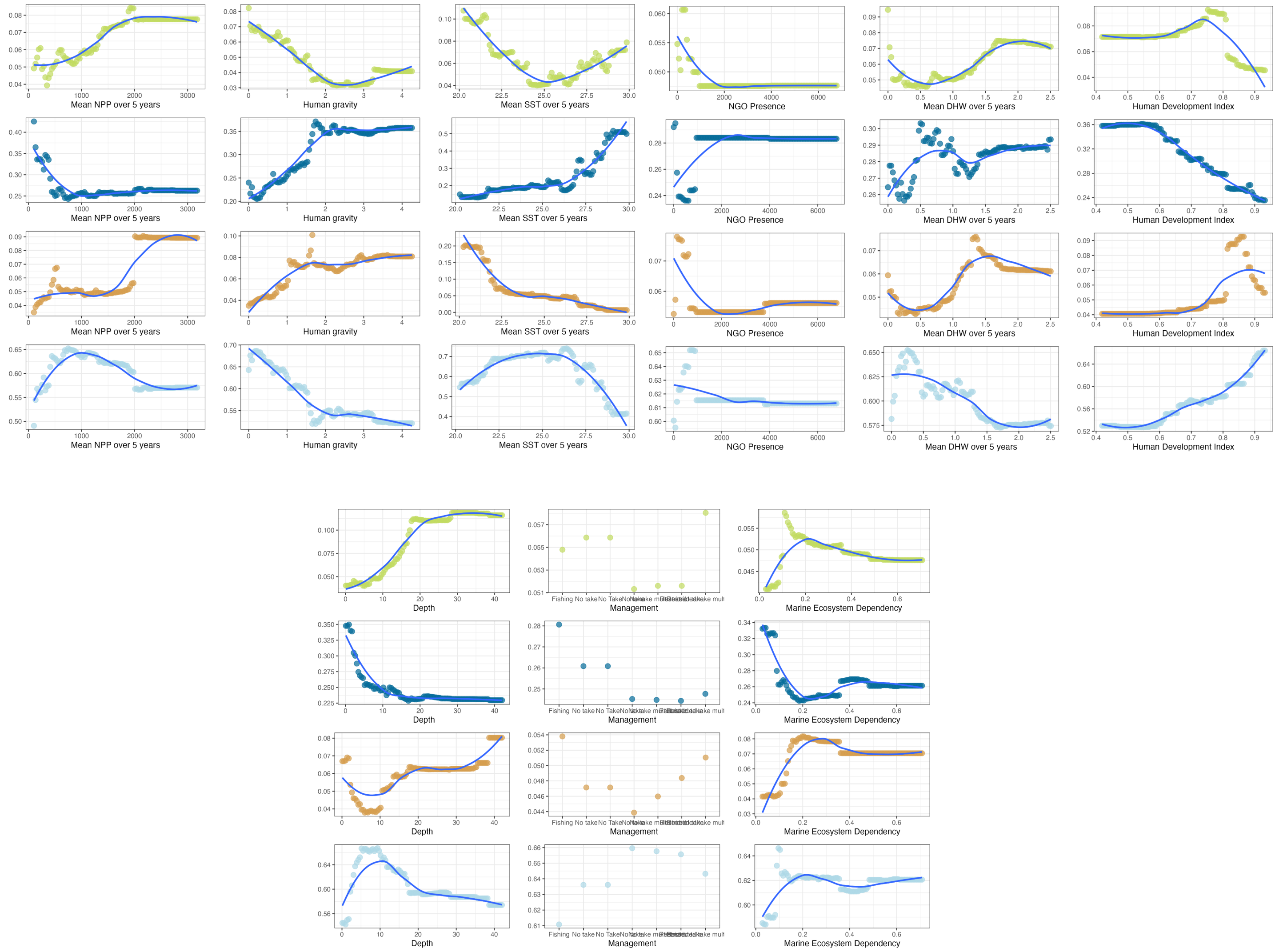
Thresholds	**-15%**	**-5%**	**Used thresholds**	**+5%**	**+15% (99% for biomass)**	**Without large individuals/large schools (95% quantile)**
Model performance (mean accuracy over 100 cross-validation folds)	0.65	0.67	0.73	0.76	0.79	0.72
Percentage of low biomass/low turnover	0.2%	2.5%	4.5%	6.6%	12.3%	4.5%
Percentage of high biomass	15.1%	8.8%	5%	1%	1%	4.5%
Percentage of high turnover	40%	30%	25%	20%	10%	25%
Percentage of mid-range	44.7%	58.6%	75.5%	72.3%	76.7%	66%



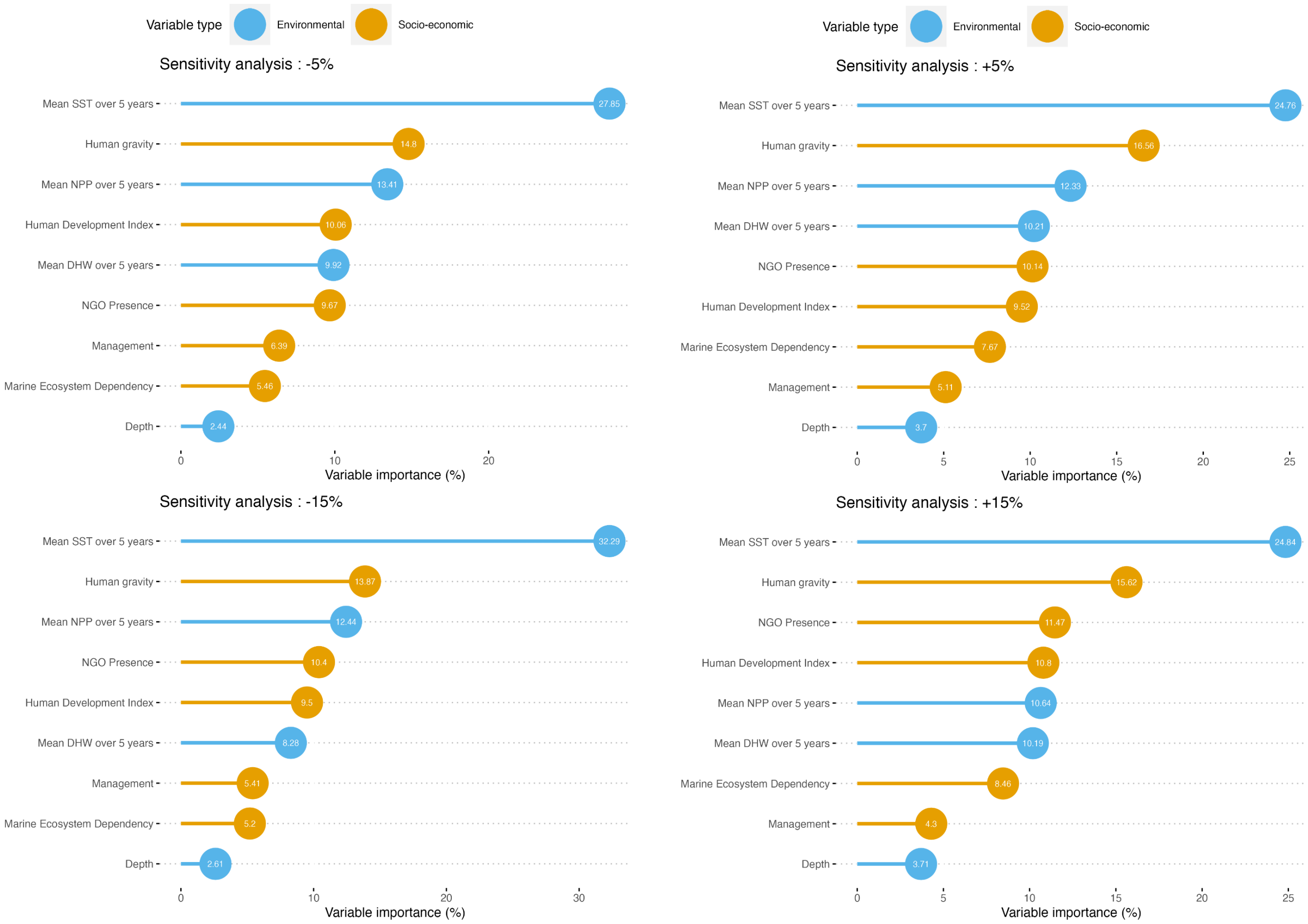
Supplementary Figure 6: Mean relative influence over 100 model iterations of our 9 environmental and socio-economic covariates on management classes using variable permutation. Sea surface temperature, human gravity (a proxy of human impact) and primary productivity had the strongest predictive capacity (relative contribution of 24.55%, 14.69%, 12.71% respectively).



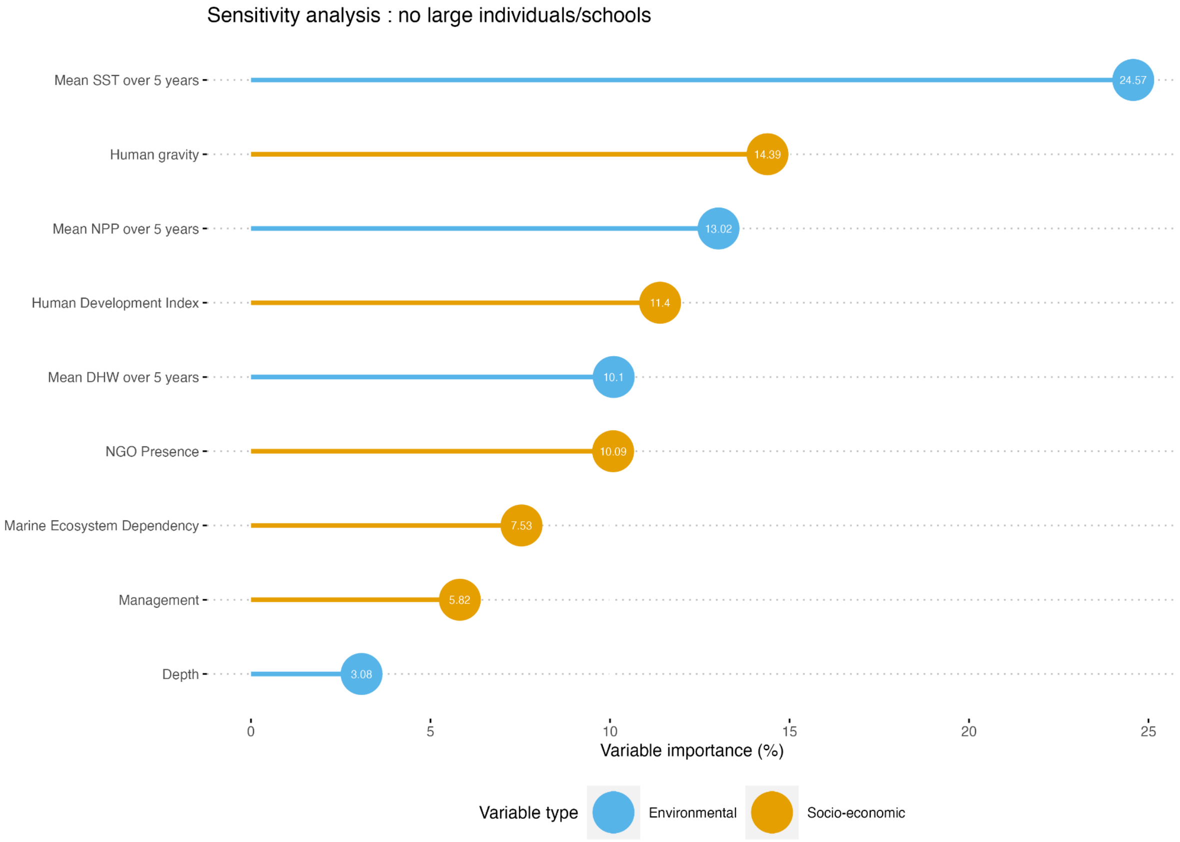
Supplementary Figure 7: Standing biomass and biomasss turnover biplot of the 1,979 sites according to protection status – Fishing area, No-take area, Multizoned no-take area, Restricted take, Multizoned restricted take area. Lines represent Q25 and Q75. The second vertical line is the Q95 of the biomass distribution.



Supplementary Figure 8: Partial dependence plots showing the relative contribution of the variable on the class probability from the perspective of the model for each environmental and socio-economic covariate, using the partial function from the pdp package, v.0.7.0.9000. Blues lines were made using the default loess smoother from the "geom_smooth" function using the *ggplot* package v 3.3.5.



Supplementary Figure 9: Mean relative influence over 100 model iterations of our 9 environmental and socio-economic covariates on management classes using variable permutation with thresholds at -5 and -15% and at +5 and +15% of thresholds used in the study.



Supplementary Figure 10: Mean relative influence over 100 model iterations of our 9 environmental and socio-economic covariates on management classes using variable permutation without large individuals (bigger than 95% of all other individuals) and large schools (with number of fish higher than 95% of all other schools).

Supplementary Table 2: The 1,979 sites comprised 1400 species, across 79 families and 349 genuses.

Family	Genus
Labridae	Sparisoma
Labridae	Halichoeres
Labridae	Thalassoma
Holocentridae	Holocentrus
Pomacentridae	Stegastes
Haemulidae	Haemulon
Lutjanidae	Lutjanus
Pomacentridae	Abudefduf
Acanthuridae	Acanthurus
Pomacentridae	Microspathodon
Labridae	Scarus
Chaetodontidae	Chaetodon
Pomacentridae	Chromis
Pomacanthidae	Holacanthus
Serranidae	Cephalopholis
Labridae	Bodianus
Ostraciidae	Lactophrys
Pomacanthidae	Pomacanthus
Tetraodontidae	Canthigaster
Haemulidae	Anisotremus
Sphyraenidae	Sphyraena
Labridae	Lachnolaimus
Diodontidae	Diodon
Lutjanidae	Ocyurus
Sciaenidae	Pareques
Serranidae	Epinephelus
Serranidae	Mycteroperca
Carangidae	Carangoides
Serranidae	Serranus
Ostraciidae	Acanthostracion
Kyphosidae	Kyphosus
Mullidae	Pseudupeneus
Aulostomidae	Aulostomus
Serranidae	Hypoplectrus
Ostraciidae	Rhinesomus
Mullidae	Mulloidichthys
Sparidae	Calamus
Ephippidae	Chaetodipterus
Scombridae	Scomberomorus
Synodontidae	Synodus
Sciaenidae	Odontoscion
Serranidae	Rypticus
Echeneidae	Echeneis
Balistidae	Canthidermis
Monacanthidae	Monacanthus
Sparidae	Diplodus
Labridae	Clepticus
Holocentridae	Myripristis
Holocentridae	Neoniphon
Scorpaenidae	Pterois
Grammatidae	Gramma
Gerreidae	Gerres
Balistidae	Melichthys
Inermiidae	Inermia
Priacanthidae	Heteropriacanthus
Balistidae	Balistes
Chaetodontidae	Prognathodes
Fistulariidae	Fistularia
Monacanthidae	Cantherhines
Tetraodontidae	Sphoeroides
Holocentridae	Sargocentron
Pempheridae	Pempheris
Monacanthidae	Aluterus
Mullidae	Parupeneus
Labridae	Coris
Scorpididae	Scorpis
Labridae	Ophthalmolepis
Pomacentridae	Parma
Serranidae	Hypoplectrodes
Cheilodactylidae	Cheilodactylus
Enoplosidae	Enoplosus
Labridae	Notolabrus
Monacanthidae	Meuschenia
Pomacentridae	Mecaenichthys
Acanthuridae	Prionurus
Plesiopidae	Trachinops
Diodontidae	Dicotylichthys
Labridae	Achoerodus
Balistidae	Sufflamen
Labridae	Pseudolabrus

Scorpaenidae	Scorpaena
Zanclidae	Zanclus
Carangidae	Caranx
Aplodactylidae	Aplodactylus
Serranidae	Pseudanthias
Scorpididae	Atypichthys
Serranidae	Acanthistius
Chaetodontidae	Heniochus
Sparidae	Acanthopagrus
Acanthuridae	Paracanthurus
Lutjanidae	Paracaesio
Caesionidae	Caesio
Carangidae	Pseudocaranx
Pomacentridae	Pomacentrus
Caesionidae	Pterocaesio
Siganidae	Siganus
Labridae	Stethojulis
Labridae	Macropharyngodon
Haemulidae	Plectorhinchus
Cirrhitidae	Cirrhitichthys
Moridae	Lotella
Mullidae	Upeneichthys
Monodactylidae	Schuettea
Labridae	Labroides
Labridae	Austrolabrus
Cheilodactylidae	Nemadactylus
Carangidae	Trachurus
Sparidae	Rhabdosargus
Carangidae	Elagatis
Dinolestidae	Dinolestes
Ostraciidae	Anoplocapros
Glaucosomatidae	Glaucosoma
Carangidae	Seriola
Labridae	Olisthops
Acanthuridae	Naso
Pomacentridae	Amphiprion
Pomacanthidae	Centropyge
Apogonidae	Ostorhinchus
Apogonidae	Apogon
Nemipteridae	Scolopsis
Pomacentridae	Dascyllus

Labridae	Cirrhilabrus
Pomacentridae	Chrysiptera
Scorpididae	Microcanthus
Kyphosidae	Girella
Monodactylidae	Monodactylus
Labridae	Pictilabrus
Tetraodontidae	Tetractenos
Monacanthidae	Eubalichthys
Pomacanthidae	Chaetodontoplus
Pomacentridae	Neoglyphidodon
Labridae	Anampses
Labridae	Gomphosus
Serranidae	Trachypoma
Mugilidae	Mugil
Hemiramphidae	Hyporhamphus
Cirrhitidae	Notocirrhitus
Labridae	Suezichthys
Labridae	Eupetrichthys
Plotosidae	Cnidoglanis
Labridae	Hologymnosus
Scorpaenidae	Scorpaenodes
Labridae	Labropsis
Chaetodontidae	Chelmon
Pomacentridae	Amblyglyphidodon
Latidae	Psammoperca
Labridae	Choerodon
Serranidae	Diploprion
Haemulidae	Diagramma
Labridae	Epibulus
Pomacentridae	Dischistodus
Acanthuridae	Ctenochaetus
Labridae	Oxycheilinus
Plesiopidae	Assessor
Serranidae	Plectropomus
Labridae	Labrichthys
Acanthuridae	Zebrasoma
Pomacentridae	Acanthochromis
Pomacentridae	Plectroglyphidodon
Lethrinidae	Monotaxis
Labridae	Chlorurus
Pomacentridae	Neopomacentrus

Labridae	Pseudocheilinus
Apogonidae	Cheilodipterus
Pseudochromidae	Ogilbyina
Labridae	Hemigymnus
Balistidae	Balistapus
Labridae	Cheilinus
Cirrhitidae	Paracirrhites
Lethrinidae	Lethrinus
Serranidae	Chromileptes
Monacanthidae	Oxymonacanthus
Labridae	Dotalabrus
Tetraodontidae	Arothron
Ostraciidae	Ostracion
Labridae	Cetoscarus
Labridae	Hipposcarus
Lutjanidae	Macolor
Chaetodontidae	Forcipiger
Monacanthidae	Pervagor
Pseudochromidae	Pseudochromis
Pomacentridae	Hemiglyphidodon
Lutjanidae	Aphareus
Pomacentridae	Premnas
Mugilidae	Crenimugil
Ephippidae	Platax
Labridae	Novaculichthys
Pseudochromidae	Pictichromis
Labridae	Cheilio
Nemipteridae	Pentapodus
Priacanthidae	Priacanthus
Carangidae	Gnathanodon
Carangidae	Trachinotus
Pseudochromidae	Oxycercichthys
Rachycentridae	Rachycentron
Monacanthidae	Cantheschenia
Mullidae	Upeneus
Chaetodontidae	Coradion
Cirrhitidae	Cyprinocirrhites
Carangidae	Decapterus
Synanceiidae	Synanceia
Labridae	Leptojulis
Synanceiidae	Inimicus
Scorpaenidae	Dendrochirus

Labridae	Pteragogus
Lutjanidae	Symphorus
Plotosidae	Paraplotosus
Carangidae	Selaroides
Labridae	Siphonognathus
Plesiopidae	Paraplesiops
Terapontidae	Pelates
Platycephalidae	Cymbacephalus
Pomacanthidae	Pygoplites
Scombridae	Grammatorcynus
Pseudochromidae	Labracinus
Labridae	Heteroscarus
Chaetodontidae	Chelmonops
Kyphosidae	Neatypus
Tetraodontidae	Torquigener
Labridae	Leptoscarus
Diodontidae	Cyclichthys
Nemipteridae	Scaevius
Balistidae	Rhinecanthus
Pomacentridae	Cheiloprion
Bothidae	Bothus
Tetraodontidae	Omegophora
Monacanthidae	Acanthaluteres
Arripidae	Arripis
Serranidae	Epinephelides
Serranidae	Variola
Scorpididae	Tilodon
Serranidae	Gracila
Lutjanidae	Aprion
Labridae	Pseudocoris
Cirrhitidae	Cirrhitus
Lethrinidae	Gnathodentex
Chaetodontidae	Hemitaurichthys
Balistidae	Balistoides
Pomacentridae	Lepidozygus
Labridae	Pseudodax
Chanidae	Chanos
Serranidae	Luzonichthys
Malacanthidae	Malacanthus
Belonidae	Tylosurus
Opisthognathidae	Opistognathus
Chaetodontidae	Parachaetodon

Serranidae	Caesioscorpis
Sillaginidae	Sillaginodes
Atherinidae	Atherinomorus
Serranidae	Othos
Ostraciidae	Aracana
Serranidae	Aethaloperca
Labridae	Calotomus
Labridae	Larabicus
Balistidae	Pseudobalistes
Plesiopidae	Calloplesiops
Monacanthidae	Amanses
Sparidae	Boops
Sparidae	Oblada
Sparidae	Sarpa
Labridae	Centrolabrus
Balistidae	Odonus
Pomacanthidae	Apolemichthys
Scorpaenidae	Scorpaenopsis
Syngnathidae	Corythoichthys
Apogonidae	Pristiapogon
Synodontidae	Saurida
Labridae	Diproctacanthus
Serranidae	Anyperodon
Pomacanthidae	Paracentropyge
Haemulidae	Microlepidotus
Chaetodontidae	Johnrandallia
Serranidae	Paranthias
Serranidae	Dermatolepis
Balistidae	Xanthichthys
Diodontidae	Chilomycterus
Echeneidae	Remora
Carangidae	Uraspis
Kyphosidae	Sectator
Lutjanidae	Hoplopagrus
Serranidae	Alphestes
Elopidae	Elops
Labridae	Iniistius
Scombridae	Euthynnus
Haemulidae	Orthopristis
Pomacentridae	Nexilosus
Haemulidae	Xenocys
Oplegnathidae	Oplegnathus

Labridae	Semicossyphus
Labridae	Nicholsina
Malacanthidae	Caulolatilus
Syngnathidae	Hippocampus
Cirrhitidae	Oxycirrhites
Kuhliidae	Kuhlia
Mugilidae	Neomyxus
Cirrhitidae	Isocirrhitus
Carangidae	Scomberoides
Belonidae	Strongylura
Cirrhitidae	Neocirrhites
Grammistidae	Belonoperca
Pseudochromidae	Cypho
Scombridae	Rastrelliger
Centriscidae	Aeoliscus
Labridae	Bolbometopon
Caesionidae	Gymnocaesio
Cirrhitidae	Amblycirrhitus
Sciaenidae	Equetus
Megalopidae	Megalops
Bythitidae	Stygnobrotula
Scombridae	Sarda
Belonidae	Belone
Haemulidae	Parapristipoma
Mugilidae	Chelon
Labridae	Xyrichtys
Mullidae	Mullus
Atherinidae	Atherina
Chaetodontidae	Amphichaetodon
Labridae	Pseudojuloides
Serranidae	Grammistes
Monacanthidae	Thamnaconus
Berycidae	Centroberyx
Lethrinidae	Gymnocranius
Carangidae	Alectis
Pomacanthidae	Genicanthus
Cirrhitidae	Itycirrhitus
Cheilodactylidae	Goniistius
Cirrhitidae	Cirrhitops
Scorpaenidae	Taenianotus
Monacanthidae	Stephanolepis
Ostraciidae	Lactoria

Scombridae	Gymnosarda
Gerreidae	Eucinostomus
Carangidae	Selar
Monacanthidae	Paraluteres
Serranidae	Aulacocephalus
Sparidae	Spondyliosoma
Haemulidae	Pomadasys
Plotosidae	Plotosus
Serranidae	Serranocirrhitus
Pomacentridae	Pomachromis
Lutjanidae	Symphorichthys
Pseudochromidae	Manonichthys
Anarhichadidae	Anarrhichthys
Scombridae	Thunnus
Clupeidae	Sardinella
Scombridae	Cybiosarda
Pempherididae	Parapriacanthus
Sillaginidae	Sillago
Apogonidae	Rhabdamia

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