Ocean warming may alter pristine reef ecosystem structure

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Supplementary methods & materials_2

This section deals with the modelling part with the Ecosim module associated with simulations of fish biomass under the increase in sea water temperature.

1.1 Fitting model to fish time series

The model fitting was performed using an automated stepwise fitting procedure (Scott et al. 2016) to define the the vulnerability values of the trophic interactions function that improve the statistical fit of predicted/observed data using the weighted sum of squared differences (SS) and the Akaike Information Criterion (AIC). The formula used for the AIC is defined as:

$$AIC = n * \log(minSS/n) + 2K \quad (1)$$

where n is calculated by the fitting procedure as the total number of observations, or time series values, from the loaded fish biomass times series. minSS is the minimum sum of squares calculated by the algorithm, and K is the number of parameters estimated. In addition the procedure also calculates the AICc, to address small sample size. The AICc is defined as:

$$AICc = AIC + 2K \cdot (K - 1) / (n - K - 1) \quad (2)$$

All the alternative iterations that may describe the observation data in equal measure and the 'best-fit' model are shown in Table S1. Fitted vulnerabilities values are shown in Table S2 and time series biomass dynamics fitted by the food web model are shown in Fig. S1.

Table S1. Comparison across selected stepwise fitting interactions and the model baseline iteration, showing the number of total parameters estimated (Vulnerabilities (Vs), the model sum of squares (SS), the Akaike Information Criterion (AIC) and AICc with a correction for small sample sizes. In bold the best fitted model.

Model iteration	Vs	SS	AIC	AICc
Baseline	0	13.71	-192.74	-192.74
Baseline and 1v	1	13.35	-193.25	-193.25
Baseline and 2v	2	11.88	-202.62	-202.57
Baseline and 3v	3	11.35	-204.94	-204.81
Baseline and 4v	**4**	**11.03**	**-205.58**	**-205.33**
Baseline and 5v	5	11.01	-203.56	-203.12
Baseline and 6v	6	10.74	-203.74	-203.08
Baseline and 7v	7	10.69	-201.80	-200.86
Baseline and 8v	8	10.32	-202.88	-201.62
Baseline and 9v	9	10.32	-200.47	-198.83
Baseline and 10v	10	10.21	-199.06	-196.99
Baseline and 11v	11	10.21	-196.53	-193.97
Baseline and 12v	12	10.20	-194.05	-190.94
Baseline and 13v	13	10.02	-193.06	-189.34

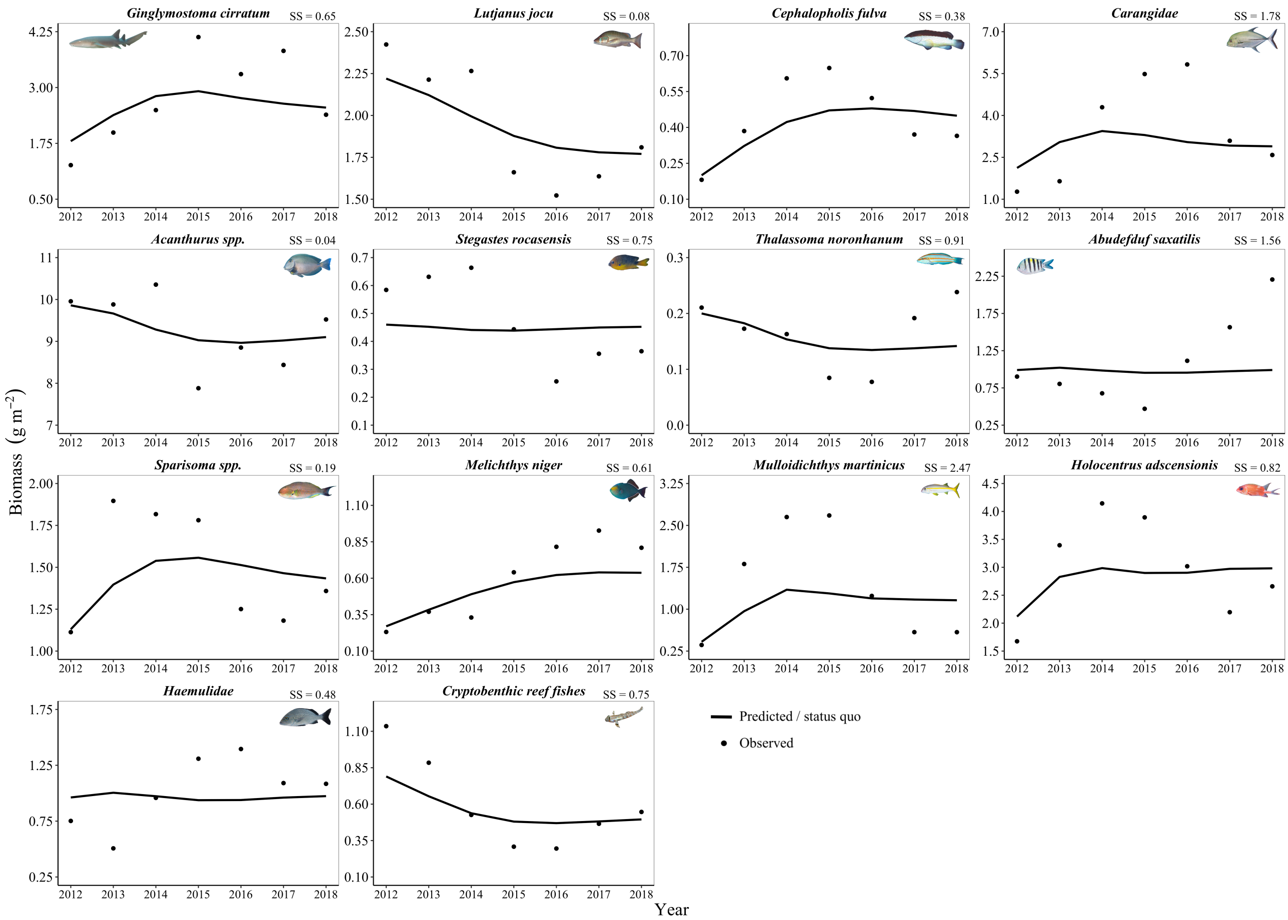

Fig. S1. Observed (dots) and predicted (lines) relative biomass (g·m^{-2}) trends for fish functional groups with fitted estimated biomass data in the Rocas Atoll ecosystem model (2012-2018). The sum of squares is noted next to each fish functional group name.

Table S2. Vulnerability matrix providing the best fit to data and used in the biomass dynamics projections with Ecosim module.

Group number	Prey \ predator	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	Sea birds	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
2	*Negaprion brevirostris*	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
3	*Ginglymostoma cirratum*	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
4	*Lutjanus jocu*	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
5	*Cephalopholis fulva*	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
6	Carangidae	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
7	*Acanthurus* spp.	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
8	*Stegastes rocasensis*	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
9	*Thalassoma noronhanum*	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
10	*Abudefduf saxatilis*	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
11	*Sparisoma spp.*	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
12	*Melichthys niger*	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
13	*Kyphosus spp.*	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
14	*Mulloidichthys martinicus*	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
15	*Holocentrus adscensionis*	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
16	Haemulidae	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
17	Cryptobenthic reef fishes	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
18	Turtles	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
19	Cephalopoda	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
20	*Panulirus* spp.	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2

Group number	Prey \ predator	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
21	Benthic macroinvertebrates	2	2	2	2	10.1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
22	Benthic microinvertebrates	2	2	2	2	2	2	2	2	2	2	2	2	2	5.22	2	2	2	2	2	2	2	2	2	2
23	Siderastrea stellata	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
24	Zooplankton	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
25	Phytoplankton	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
26	*Digenea simplex*	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
27	Other algal turf	2	2	2	2	2	2	2	2	2	2	2	10.5	2	2	2	2	2	2	2	2	2	2	2	2
28	Detritus	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	10.5	2	2	2	2	2	2	2

1.2 Fish biomass dynamics projections under ocean warming

Future sea surface temperature projections were extracted from the Royal Netherlands Meteorological Institute Climate Explorer portal (http://climexp.knmi.nl) within the study area rectangle from the climate changing multi-model ensemble means (RCP2.6, RCP4.5 and RCP8.5 scenarios, Fig. S2). Thirty-two model outputs, sourced from the Coupled Model Intercomparison Project phase 5 (CMIP5), were extracted for the study area with temperatures fluctuating around their mean.

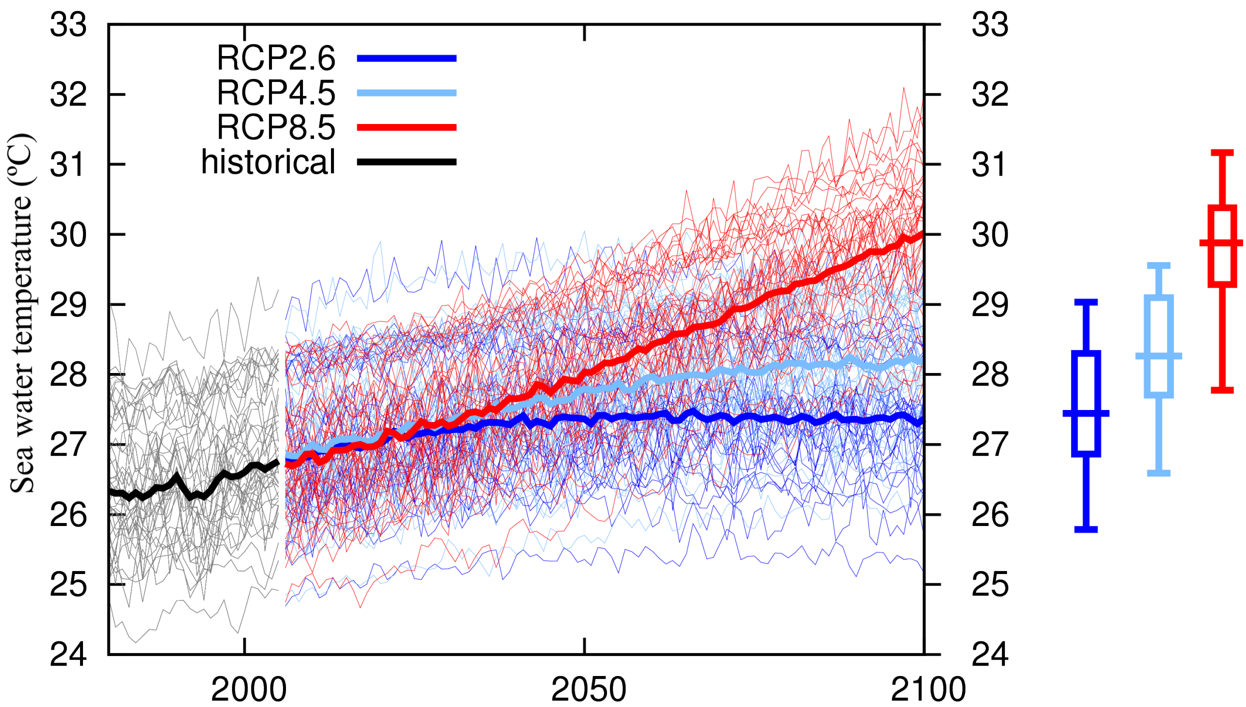

Fig. S2. Future Sea Surface Water Temperature projections (1980-2100) for the Rocas Atoll reef ecosystem (03°50'S, 33°49'W, 7.5 km^2) from the climate changing multi-model ensemble means (RCP 2.6, RCP 4.5 and RCP 8.5 greenhouse gas emissions scenarios). Box plots represents means (solid lines), the lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles) and the length of the whiskers as multiple 1.5 of Inter Quartile Range.

Optimum temperature and tolerance ranges for Rocas Atoll ecosystem functional groups were taken from AquaMaps (Kaschner et al., 2016) (Fig. S3). Temperature ranges for functional groups with multiple species were prorated by species contribution to the group's biomass.

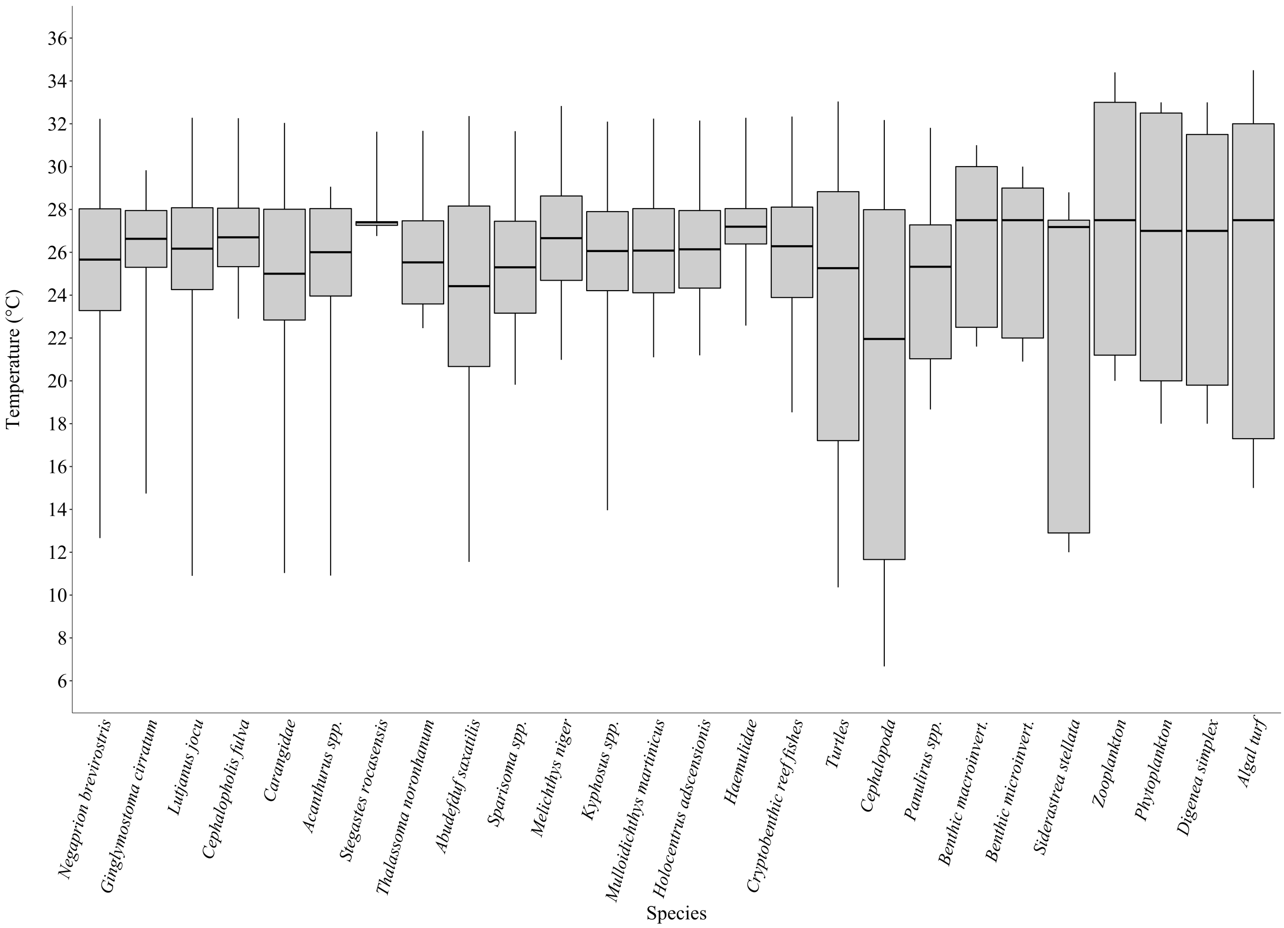

Fig. S3. Temperature ranges for functional groups in the Rocs Atoll reef ecosystem. Box plots represent optimum temperature (bold black line), the lower and upper hinges correspond to the 10th and 90th percentiles and the end of the whiskers as maximum and minimum temperatures for each functional group.

Assessing uncertainty in biomass dynamics under ocean warming

The Monte Carlo routine in Ecosim was used to perform sensitivity analyses for projections of biomass dynamics under ocean warming. This routine tests the sensitivity of Ecosim's output to Ecopath input parameters by drawing input parameters from a uniform distribution centered on the base Ecopath value with the coefficients of variation set to default 0.1 (Christensen and Walters 2004). In this study we set coefficients of variation as 0.1 for P/B, Q/B and Biomass Accumulation parameters. Fish biomass coefficients of variation were defined as the ratio between the standard deviation and the mean of each fish time series (Table S2). We ran 250 Monte Carlo simulations for each scenario based on coefficients of variation to determine the 95% confidence intervals. The mean of the distribution is set as the base Ecopath value of the parameter. CV were used to calculate the upper and lower limits of the distribution (upper limit = mean + 2*CV.*mean; lower limit = mean - 2*CV*mean).

Table S2. Upper and lower biomass coefficients of variations (CV) used for Monte Carlo analysis.

Group number	Group name	CV	Lower limit	Mean	Upper limit
1	Sea birds	0.25	0.01	0.02	0.03
2	*Negaprion brevirostris*	0.15	0.11	0.17	0.22
3	*Ginglymostoma cirratum*	0.15	1.26	1.8	2.34
4	*Lutjanus jocu*	0.05	1,998	2.22	2.44
5	*Cephalopholis fulva*	0.10	0.16	0.2	0.24
6	*Carangidae*	0.15	1.48	2.12	2.75
7	*Acanthurus spp.*	0.1	7.88	9.86	11.83
8	*Stegastes rocasensis*	0.11	0.35	0.46	0.56
9	*Thalassoma noronhanum*	0.15	0.14	0.2	0.26
10	*Abudefduf saxatilis*	0.12	0.75	0.99	1.22
11	*Sparisoma spp.*	0.11	0.88	1.13	1.37
12	*Melichthys niger*	0.13	0.19	0.27	0.34
13	*Kyphosus spp.*	0.05	0.41	0.46	0.51
14	*Mulloidichthys martinicus*	0.2	0.24	0.41	0.58
15	*Holocentrus adscensionis*	0.12	1.61	2.11	2.62
16	Haemulidae	0.15	0.67	0.96	1.25
17	Cryptobenthic reef fishes	0.11	0.61	0.79	0.96
18	Turtles	0.1	0.017	22.0	0.026
19	Cephalopoda	0.25	0.20	0.40	0.60
20	Panulirus spp.	0.25	2.55	5.1	7.65
21	Benthic macroinvertebrates	0.1	12.98	16.23	19.47
22	Benthic microinvertebrates	0.1	19.48	24.35	29.23
23	Siderastrea stellata	0.1	0.56	711	0.85
24	Zooplankton	0.15	0.16	0.23	0.30
25	Phytoplankton	0.05	0.11	0.13	0.14
26	Digenea simplex	0.05	190.47	211.63	232.80
27	Other algal turf	0.05	722.08	802.31	882.54

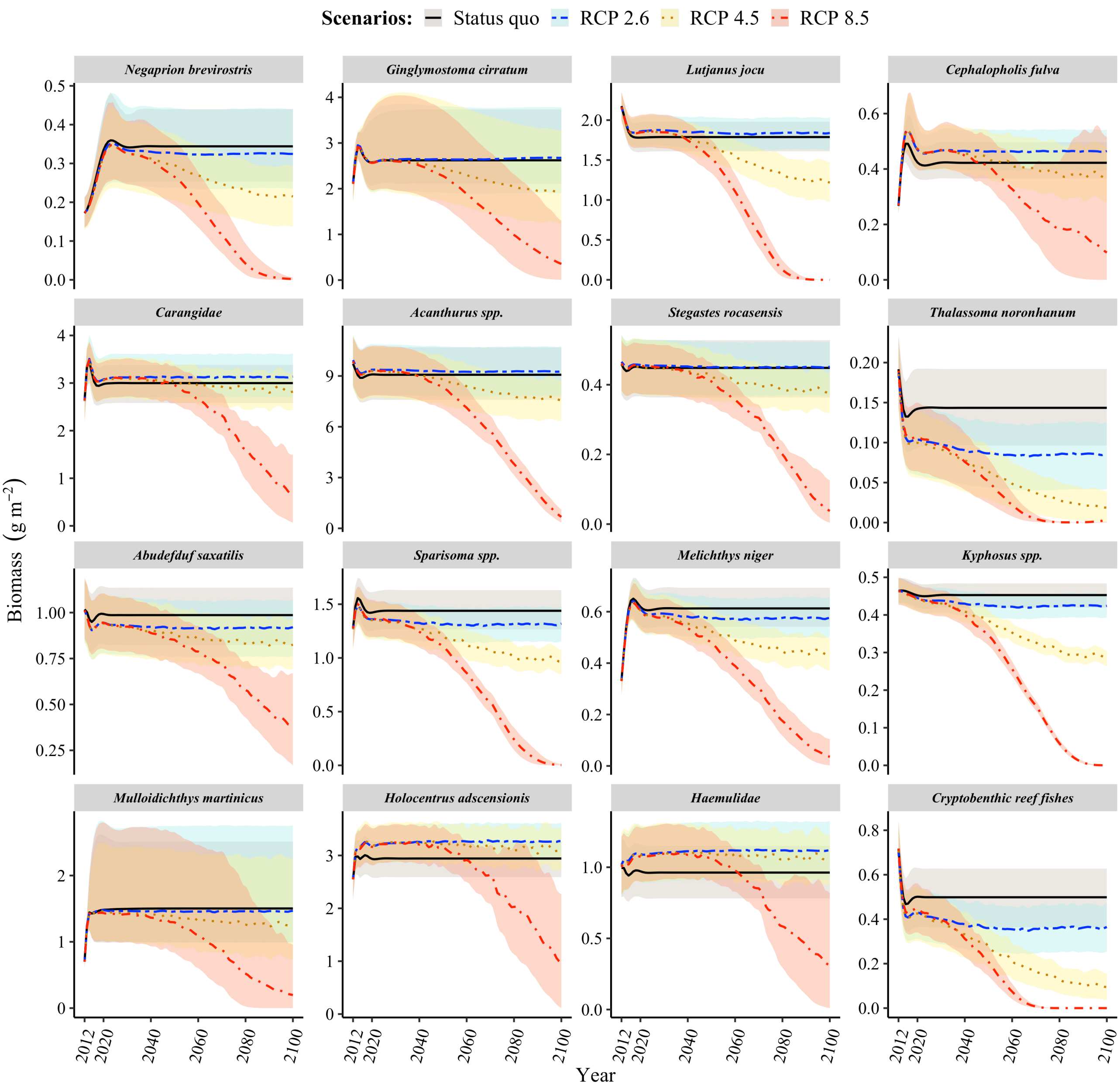

Fig. S4. Projections of fish biomass dynamics in the Rocas Atoll reef ecosystem under climate change scenarios. Shadows represent the 5% and 95% percentiles obtained using the Monte Carlo routine.

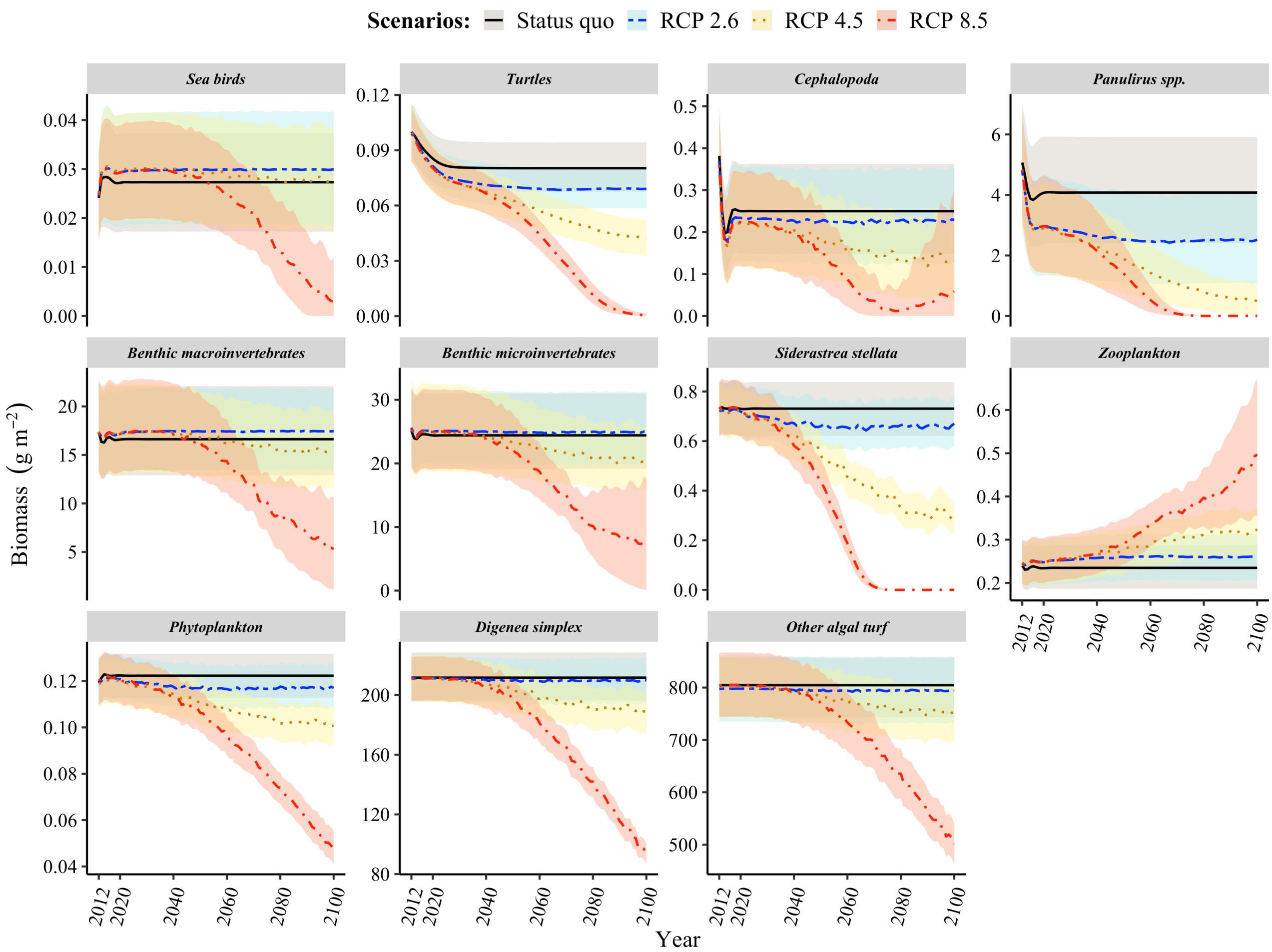

Fig. S5. Projections of no-fish groups biomass dynamics in the Rocas Atoll reef ecosystem under climate change scenarios. Shadows represent the 5% and 95% percentiles obtained using the Monte Carlo routine.

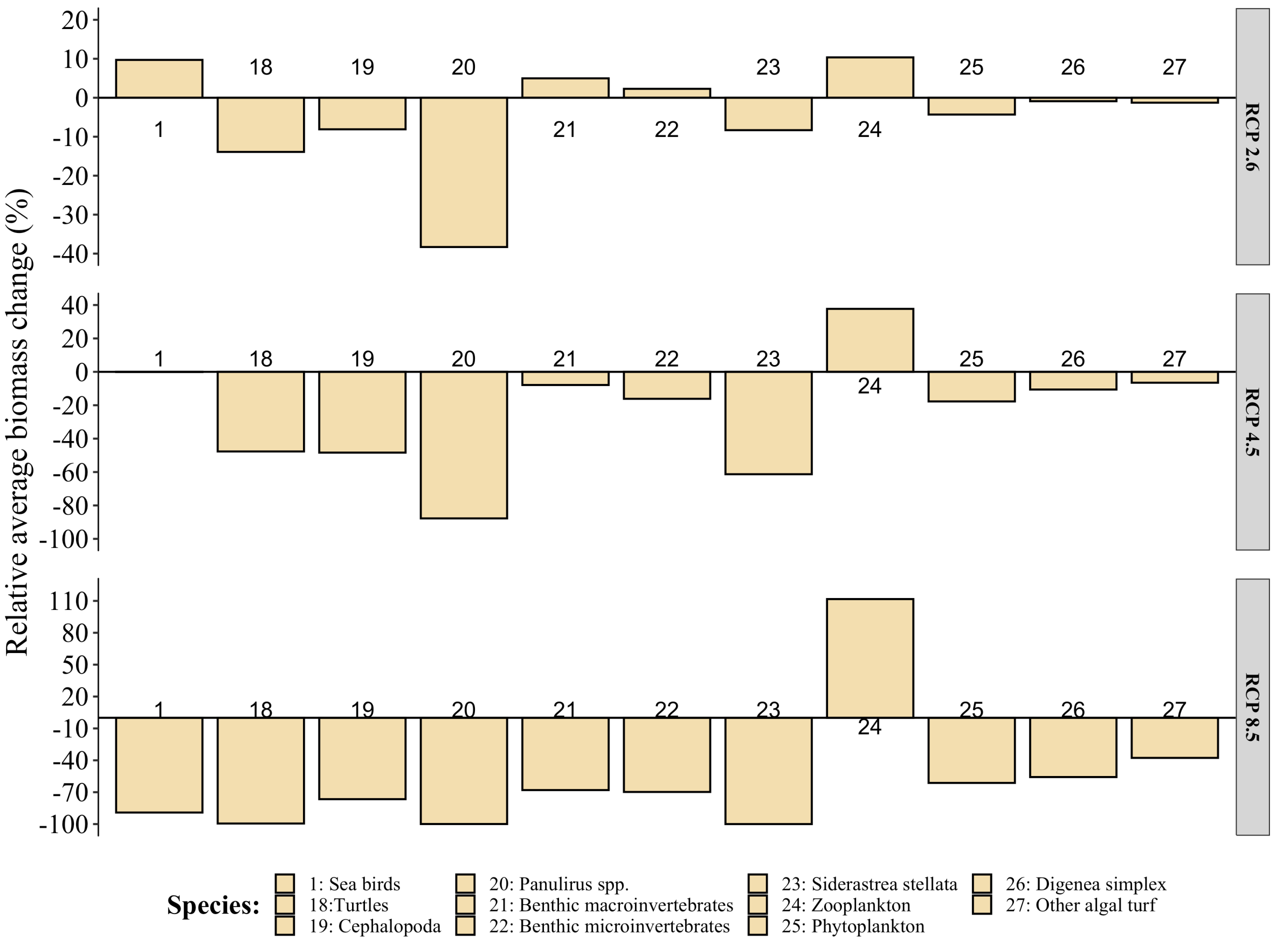

Fig. S6. Model projections for relative biomass change under climate change scenarios for functional groups of the Rocas Atoll ecosystem that are not fish. All changes are expressed as % mean of the 2100 relative to the 2100 Status quo scenario projections.

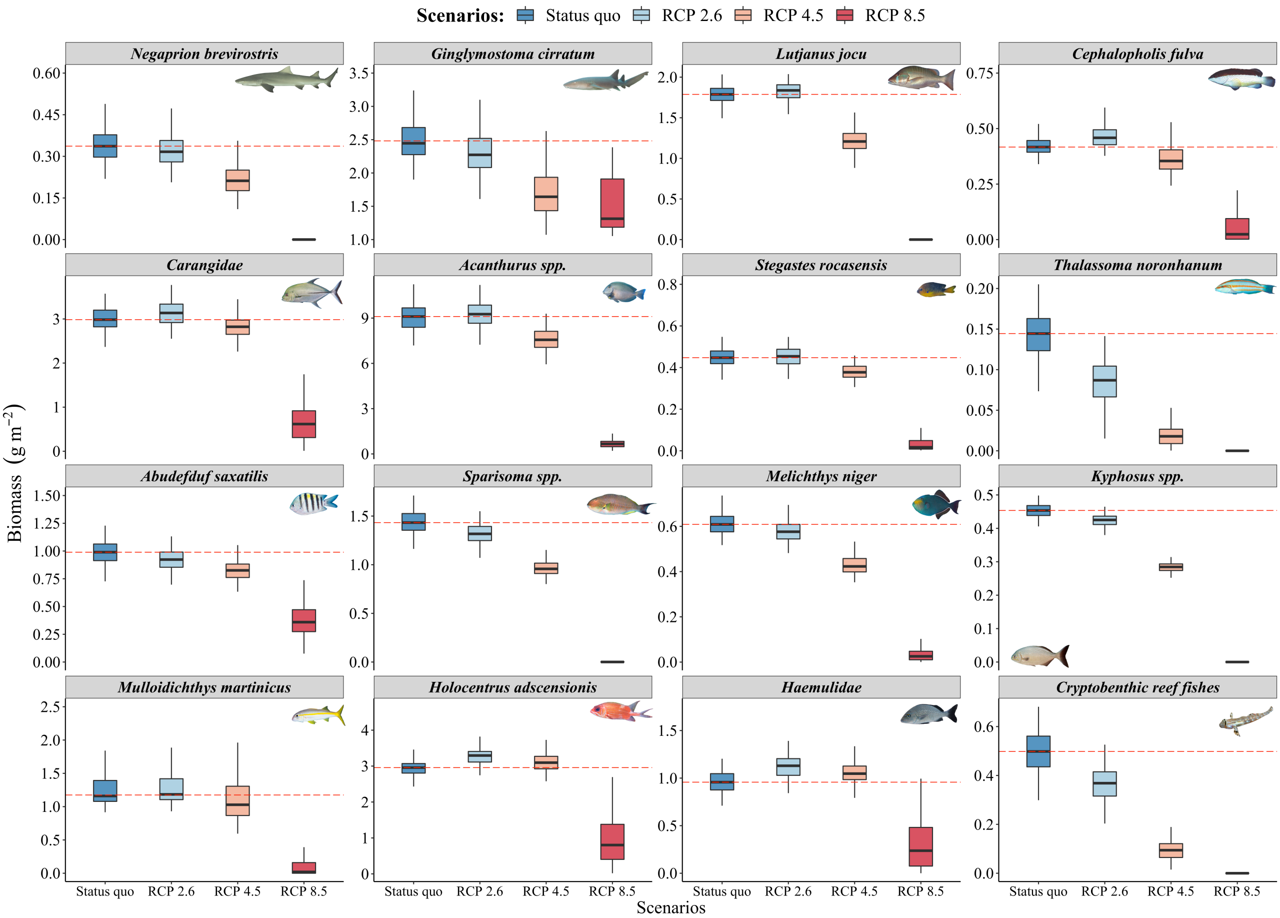

Fig. S7. Projected climate change effect (RCP 2.6, RCP 4.5, RCP 8.5) vs Status quo scenario in 2100 for fish functional groups biomass. Box plots display the median (horizontal line), the lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles). The lower whisker extends from the hinge to the smallest value at most 1.5 * interquartile range of the hinge. The red dotted line represents the Status quo scenario median value for reference.

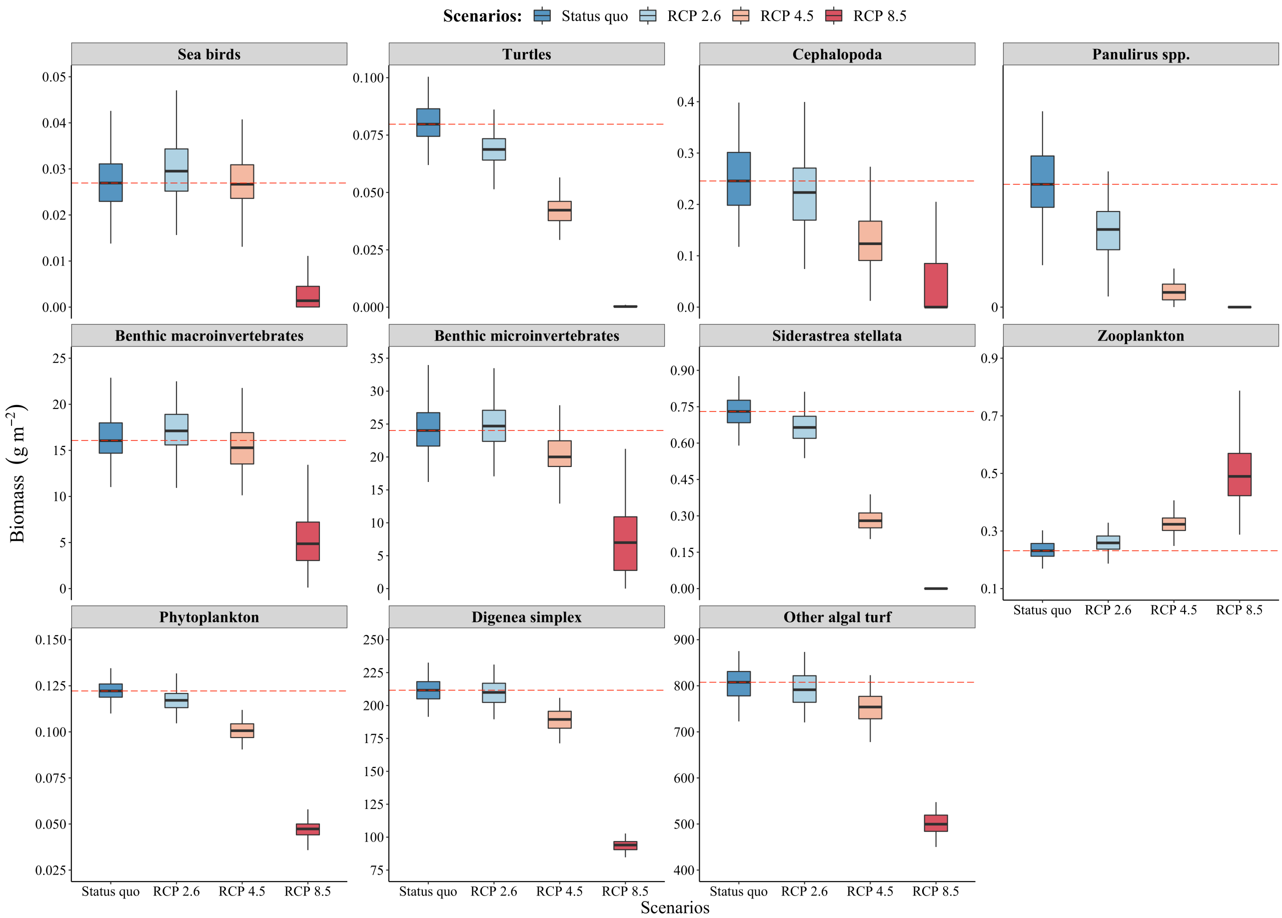

Fig. S8. Projected climate change effect (RCP 2.6, RCP 4.5, RCP 8.5) vs Status quo scenario in 2100 for no fish functional groups biomass. Box plots display the median (horizontal line), the lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles). The lower whisker extends from the hinge to the smallest value at most 1.5 * interquartile range of the hinge. The red dotted line represents the Status quo scenario median value for reference.

References

Scott E, Serpetti N, Steenbeek J, Heymans JJ (2016) A Stepwise Fitting Procedure for automated fitting of Ecopath with Ecosim models. SoftwareX 5:25–30. https://doi.org/10.1016/j.softx.2016.02.002