Ocean warming may alter pristine reef ecosystem structure

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Supplementary methods & materials_1

This section presents the bibliographic references used to parameterize the Ecopath model of the Rocas atoll ecosystem (reference year 2012). In addition, tables are provided with the basic estimates for the balanced Ecopath model (reference year 2012) and the diet matrix for each species present in the model.

1.1 Indirect estimates of production rates for fish functional groups

Production rate (P/B) in Ecopath is assumed to be equal to total mortality *Z* (Allen 1971), which can be estimated as *Z= F+M2+M0* where Z is total mortality, F – fishing mortality, M2 – natural mortality due to predation, and M0 – natural mortality due to old age, deceases, etc. Natural mortality rate (M) of fish was estimated from an empirical relationship linking M, the parameters of the von Bertalanffy Growth Function (VBGF), to mean environmental temperature (Pauly 1980) as follow:

$$M = (K^{0.65}\,L_{inf}) - \left(0.279\,T_c^{0.463}\right) \qquad (1)$$

where M is the natural mortality ($year^{-1}$), K is the curvature parameter of the VBGF ($year^{-1}$), L_{inf} is the asymptotic length in cm, Tc is the mean ambient temperature, in °C. A life-history routine (FishBase - Froese & Pauly 2019) was used to estimate M, L_{inf} being assumed to equal L_{max}. K was determined using known relationships between L_{inf} and K within the FishBase life-history routine. Ambient temperature was assumed to be the average temperature of the Rocas Atoll Ecosystem (27°C) for the reference year 2012. When functional groups are composed of several species, the group P/B is estimated as a weighted mean (weighted by each species biomass B) of the species P/Bs.

1.2 Indirect estimates of consumption rates for fish functional groups

Consumption rates (Q/B) of fish species were estimated from empirical formulae implemented in the life-history routine of FishBase (Froese and Pauly 2019). Two such formulae were derived by Palomares and Pauly (1998):

$$\log QB = 5.847 + (0.28 \log Z) - (0.152 \log W_{inf}) - (1.36T') + (0.062A) + (0.51h) + (0.39d) \qquad (2)$$

where Z is total mortality, W_{inf} is the asymptotic weight (g), T' is the mean annual temperature (expressed using T' = 1,000/Kelvin (Kelvin = °C + 273.15), A is the aspect ratio (height^2 (cm)/surface area (cm) of the caudal fin), h is a dummy variable expressing food type (1 for herbivores, and 0 for detritivores and carnivores), and d is a dummy variable also expressing food type (1 for detritivores, and 0 for herbivores and carnivores). For cases where Z is not available, the following relation may be used:

$$\log QB = 7.964 + (0.204 \log W_{inf}) - (1.965T') + (0.083A) + (0.532h) + (0.398d) \qquad (3)$$

Table S1. Characterisation of each functional group in the Rocas Atoll Ecopath model and the data sources for parameters for each functional group. Biomass is reported in t·km^{-2} or as the same in g·m^{-2}. P/B is the production to biomass ratio, Q/B is the consumption to biomass ratio.

	Group name	Species aggregation (in descending order of abundance)	Biomass (g·m^{-2})	P/B (year^{-1})	Q/B (year^{-1})	Diet
1	Sea birds	*Sula dactylatra*; *Sula leucogaster*; *Sula sula*; *Onychoprion fuscatus*; *Anous stolidus*; *Anous minutus; Fregata magnificens.* (Almeida et al. 2000)	From an other model. (Freire et al. 2008)	From an other model (Freire et al. 2008).	From an other model (Freire et al. 2008).	From another Ecopath model(Christensen et al. 2015)
2	*Negaprion brevirostris*	- - -	*In situ* estimate.	Empirical relationship (Pauly 1980)	Empirical relationship (Palomares and Pauly 1998).	(Cortés and Gruber 1990; Froese and Pauly 2019)
3	*Ginglymostoma cirratum*	- - -	*In situ* estimate.	Empirical relationship (Pauly 1980)	Empirical relationship (Palomares and Pauly 1998).	(Matott et al. 2005; Froese and Pauly 2019)
4	*Lutjanus jocu*	- - -	*In situ* estimate.	Empirical relationship (Pauly 1980)	Empirical relationship (Palomares and Pauly 1998).	Stomach content and isotope analysis (Andrades 2018; Froese and Pauly 2019).
5	*Cephalopholis fulva*	- - -	*In situ* estimate.	Empirical relationship (Pauly 1980).	Empirical relationship (Palomares and Pauly 1998).	Stomach content and isotope analysis (Coelho et al. 2012; Andrades 2018; Froese and Pauly 2019)
6	Carangidae	*Carangoides bartholomaei; Caranx ruber; C. crysos; C. latus; C. lugubris*	*In situ* estimate.	Empirical relationship (Pauly 1980).	Empirical relationship (Palomares and Pauly 1998).	(Silvano 2001; Sley et al. 2009; Froese and Pauly 2019)
7	*Acanthurus* spp.	*A. coeruleus; A. chirurgus; A. bahianus*	*In situ* estimate.	Empirical relationship (Pauly 1980).	Empirical relationship (Palomares and Pauly 1998).	Stomach content and isotope analysis (Longo et al. 2015; Andrades 2018; Froese and Pauly 2019).
8	*Stegastes rocasensis*	- - -	*In situ* estimate.	Empirical relationship (Pauly 1980).	Empirical relationship (Palomares and Pauly 1998).	Stomach content and isotope analysis (Souza et al. 2011; Andrades 2018).

	Group name	Species aggregation (in descending order of abundance)	Biomass ($g \cdot m^{-2}$)	P/B ($year^{-1}$)	Q/B ($year^{-1}$)	Diet
9	*Thalassoma noronhanum*	- - -	*In situ* estimate.	Empirical relationship (Pauly 1980)	Empirical relationship (Palomares and Pauly 1998)	Stomach content and isotope analysis (Andrades 2018; Froese and Pauly 2019)
10	*Abudefduf saxatilis*	- - -	*In situ* estimate.	Empirical relationship (Pauly 1980)	Empirical relationship (Palomares and Pauly 1998)	Stomach content and isotope analysis (Andrades 2018; Froese and Pauly 2019)
11	*Sparisoma* spp.	*S. amplum; S. axillare; S. frondosum*	*In situ* estimate.	Empirical relationship (Pauly 1980)	Empirical relationship (Palomares and Pauly 1998)	Stomach content and isotope analysis (Andrades 2018; Froese and Pauly 2019)
12	*Melichthys niger*	- - -	*In situ* estimate.	Empirical relationship (Pauly 1980)	Empirical relationship (Palomares and Pauly 1998)	(Turingan et al. 1995; Mendes et al. 2019; Froese and Pauly 2019)
13	*Kyphosus* spp.	- - -	*In situ* estimate.	Empirical relationship (Pauly 1980)	Empirical relationship (Palomares and Pauly 1998)	(Silvano and Güth 2006; Froese and Pauly 2019)
14	*Mulloidichthys martinicus*	- - -	*In situ* estimate.	Empirical relationship (Pauly 1980)	Empirical relationship (Palomares and Pauly 1998)	(Krajewski et al. 2006; Froese and Pauly 2019).
15	*Holocentrus adscensionis*	- - -	*In situ* estimate.	Empirical relationship (Pauly 1980)	Empirical relationship (Palomares and Pauly 1998)	Stomach content and isotope analysis (Andrades 2018; Froese and Pauly 2019).
16	Haemulidae	*Haemulon chrysargyreum*; *H. parra*; *Anisotremus surinamensis*; *Orthopristis ruber*	*In situ* estimate.	Empirical relationship (Pauly 1980)	Empirical relationship (Palomares and Pauly 1998)	(Pereira et al. 2015; Froese and Pauly 2019).

	Group name	Species aggregation (in descending order of abundance)	Biomass (g·m^{-2})	P/B (year^{-1})	Q/B (year^{-1})	Diet
17	Cryptobenthic reef fishes	*Gnatholepis thompsoni*; *Coryphopterus glaucofraenum*; *Elacatinus phthirophagus*; *Labrisomus kalisherae*; *Malacoctenus spp.*; *Ophioblennius atlanticus*; *Ophioblennius trinitatis*; *Pempheris schomburgkii.* We classify reef-fish species as cryptobenthic if they have >10% individuals smaller than 50 mm maximum length. All other species are considered to be large reef fishes. (Brandl et al. 2018)	*In situ* estimate.	Empirical relationship (Pauly 1980)	Empirical relationship (Palomares and Pauly 1998)	Stomach content and isotope analysis (Andrades 2018; Froese and Pauly 2019).
18	Turtles	*Chelonia mydas, Eretmochelys imbricata*	*In situ* estimate (Grossman et al. 2019)	From another Ecopath model (Araújo et al. 2017).	From another Ecopath model (Araújo et al. 2017).	From an other Ecopath model (Araújo et al. 2017).
19	Cephalopoda	*Octopus insularis*, *Octopus vulgaris*	Sampling locally, low precision. Biomass values of 0.27 g·m^{-2} was increased 50% to achieve EwE assumptions. (Bouth et al. 2011)	From another Ecopath model (Freire et al. 2008).	From another Ecopath model (Freire et al. 2008).	Quantitative, detailed, isotope diet composition study (Dantas et al. 2019).
20	*Panulirus* spp.	*Panulirus echinatus, Panulirus argus, Parribacus antarticus*	Sampling locally, low precision. Master thesis. (Gaeta 2014)	From another Ecopath model. (Freire et al. 2008)	From another Ecopath model. (Freire et al. 2008)	Quantitative gut content and isotope diet composition studies (Góes and Lins-Oliveira 2009; Higgs et al. 2016)
21	Benthic macroinvertebrates	Bivalves and gastropods mostly larger than 2 mm. Mostly echinodermes, small crabs, gasteropods, scallops. (Netto et al. 2003)	Estimated by Ecopath routine.	From another Ecopath model. (Araújo et al. 2017)	From another Ecopath model. (Araújo et al. 2017)	Stable isotope analisys (Andrades 2018)
22	Benthic microinvertebrates	Amphipoda; Tanaidacea; Decapoda; Chironomidae; *Lysmata grabhami; Stenopus hispidus.* (Netto et al. 2003)	Estimated by Ecopath routine.	From another Ecopath model. (Araújo et al. 2017)	From another Ecopath model. (Araújo et al. 2017)	From another Ecopath model. (Morato et al. 2016)

	Group name	Species aggregation (in descending order of abundance)	Biomass ($g \cdot m^{-2}$)	P/B ($year^{-1}$)	Q/B ($year^{-1}$)	Diet
23	*Siderastrea stellata* (coral)		Sampling locally, low precision. (Pinheiro et al. 2017)	From another Ecopath model. (Tan et al. 2018)	From another Ecopath model. (Tan et al. 2018)	We assumed that this species is mixotrophic, obtaining 40 % of its energy through heterotrophic means. (Leletkin 2000; Ferrier-Pagès et al. 2011)
24	Zooplankton	Tinnines, copepods, foraminifers, heliozoan, crustacean larvae, radiolarian.(Neumann-Leitão et al. 2008; Lira et al. 2014)	Sampling locally, low precision. Value of 0.11 (Lira et al. 2014) was incresed to balance the model	From another Ecopath model. (Christensen et al. 2015)	From another Ecopath model. (Christensen et al. 2015)	General knowledge of related tropical south Atlantic group/ species (Bode and Hernández-León 2018).
25	Phytoplankton	*Prorocentrum balticum*, *P. lima*, *P. compressum*, *Coccolithus* sp., *Pyrophacus* sp., *Ostreopsis ovata*. (Jales 2015)	Average value over ten years 2002-2012. NOAA OceanWatch (https://oceanwatch.pifsc.noaa.gov/)	Similar species, same system, low precision. Value: 10 $\mu g\ C \cdot (L \cdot day)^{-1}$ (Buitenhuis et al. 2013)	- - -	- - -
26	*Digenea simplex*	- - -	Sampling locally, high precision. (Longo et al. 2015)	Same species, same system, high precision (Fonseca 2010; Fonseca et al. 2018). Conversion factor g C : g dw = 40 (Bowie et al. 1985). Conversion factor g dw : g ww = 4.17 (*in situ* personal estimation).	- - -	- - -
27	Algal turf	*Caulerpa verticillata, Canistrocarpus cervicornis, Dictyosphaeria ocellata; Dictyopteris spp.; Gelidiella acerosa; Hydrolithon pachydermum; Padina gymnospora; Sargassum spp.*	Sampling locally, high precision. (Longo et al. 2015)	Same species, same system, high precision (Fonseca et al. 2018). Conversion factor g C : g dw = 40 (Bowie et al. 1985). Conversion factor g dw : g ww = 4.17 (personal observation).	- - -	- - -
28	Detritus	- - -	- - -	- - -	- - -	- - -

Table S2. Functional groups' diet composition used in the Rocas Atoll Ecopath model (reference year 2012), showing final balanced input values. Import is the consumption of preys that are not a part of the Rocas Atoll ecosystem as it is defined (for example for species that spend fractions of the year feeding outside the area of the model).

Functional group number	Functional group	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	*Negaprion brevirostris*																								
3	*Ginglymostoma cirratum*																								
4	*Lutjanus jocu*		0.01	0.01	0.01	0.01																			
5	*Cephalopholis fulva*		0.10																						
6	Carangidae	0.07	0.06																						
7	*Acanthurus* spp.	0.05	0.20	0.01	0.05	0.11	0.05																		
8	*Stegastes rocasensis*		0.05		0.02	0.04																			
9	*Thalassoma noronhanum*					0.04	0.01																		
10	*Abudefduf saxatilis*				0.01	0.01	0.01																		
11	*Sparisoma* spp.		0.05																						
12	*Melichthys niger*		0.04																						
13	*Kyphosus* spp.		0.05																						
14	*Mulloidichthys martinicus*		0.02																						
15	*Holocentrus adscensionis*		0.04	0.01	0.04	0.03	0.01																		
16	Haemulidae	0.03	0.05		0.03	0.02																			
17	Cryptobenthic reef fishes	0.03	0.08		0.01	0.10	0.01																		

18	Turtles		0.01																						
19	Cephalopoda	0.05	0.05	0.10	0.03	0.01	0.04																		
20	*Panulirus* spp.			0.35																					
21	Benthic macroinvertebrates	0.12	0.03	0.29	0.39	0.35	0.19			0.10					0.25	0.70	0.30	0.05	0.35	0.70	0.20	0.05			
22	Benthic microinvertebrates	0.10	0.01	0.15	0.31	0.19	0.40	0.10	0.03	0.15	0.20	0.20	0.10	0.02	0.70	0.25	0.60	0.21	0.25	0.30	0.35	0.20	0.01		
23	*Siderastrea stellata*																								
24	Zooplankton						0.06			0.10	0.20		0.15		0.05	0.05	0.10	0.10						0.40	0.15
25	Phytoplankton										0.10							0.05							0.50
26	Digenea simplex							0.20	0.10	0.05		0.20	0.10	0.88					0.20			0.10			
27	Algal turf							0.40	0.59	0.40	0.40	0.30	0.60	0.10				0.15	0.10				0.10		
28	Detritus						0.11	0.30	0.28	0.20	0.10	0.30	0.05					0.44	0.10		0.45	0.65	0.89		
	Import	0.55	0.14	0.08	0.10	0.08	0.11																		0.35

Table S3. Basic estimates of the Rocas Atoll Ecopath model (reference year 2012). Values in bold were estimated by Ecopath balance routine. TL = trophic level; EE = ecotrophic efficiency; B = biomass (g·m²); P/B =production to biomass ratio ($year^{-1}$) ; Q/B = consumption to biomass ratio ($year^{-1}$); BA= biomass accumulation (g·m²).

Functional group number	Functional group	Trophic level	Habitat area	B (g·m²)	P/B	Q/B	EE	BA (g·m²)
1	Sea birds	**3.50**	1.00	0.02	5.40	80.00	**0.00**	
2	*Negaprion brevirostris*	**3.58**	1.00	0.17	0.23	3.70	**0.00**	
3	*Ginglymostoma cirratum*	**3.47**	1.00	1.80	0.22	3.60	**0.82**	0.31

Functional group number	Functional group	Trophic level	Habitat area	B (g·m²)	P/B	Q/B	EE	BA (g·m²)
4	*Lutjanus jocu*	**3.27**	1.00	2.22	0.52	6.30	**0.01**	-0.06
5	*Cephalopholis fulva*	**3.28**	1.00	0.20	0.65	5.51	**0.95**	0.54
6	*Carangidae*	**3.04**	1.00	2.12	0.62	13.20	**0.60**	0.44
7	*Acanthurus spp.*	**2.10**	1.00	9.86	0.83	12.90	**0.28**	-0.01
8	*Stegastes rocasensis*	**2.03**	1.00	0.46	1.25	17.10	**0.67**	-0.01
9	*Thalassoma noronhanum*	**2.71**	1.00	0.20	1.19	16.40	**0.79**	0.02
10	*Abudefduf saxatilis*	**2.63**	1.00	0.99	0.89	13.00	**0.45**	0.08
11	*Sparisoma* spp.	**2.20**	1.00	1.13	0.65	7.20	**0.20**	0.25
12	*Melichthys niger*	**2.67**	1.00	0.27	0.76	11.60	**0.52**	0.38
13	*Kyphosus* spp.	**2.02**	1.00	0.46	0.62	24.40	**0.11**	
14	*Mulloidichthys martinicus*	**3.08**	1.00	0.42	0.72	11.10	**0.60**	1.05
15	*Holocentrus adscensionis*	**3.19**	1.00	2.12	0.75	8.30	**0.98**	0.43
16	Haemulidae	**3.09**	1.00	0.96	0.79	11.60	**0.84**	0.09
17	Cryptobenthic reef fishes	**2.38**	1.00	0.79	1.87	10.57	**0.26**	-0.17
18	Turtles	**2.80**	1.00	0.02	0.29	2.35	**0.00**	

Functional group number	Functional group	Trophic level	Habitat area	B (g·m²)	P/B	Q/B	EE	BA (g·m²)
19	Cephalopoda	**3.19**	1.00	0.41	6.40	36.50	**0.95**	
20	*Panulirus* spp.	**2.61**	0.85	5.10	1.28	7.40	**0.36**	
21	Benthic macroinvertebrates	**2.27**	1.00	**16.70**	3.80	10.00	0.90	
22	Benthic microinvertebrates	**2.01**	1.00	**25.69**	4.94	16.69	0.85	
23	*Siderastrea stellata*	**1.76**	0.18	0.71	1.66	9.40	**0.00**	
24	Zooplankton	**2.08**	0.95	0.24	87.00	160.00	**0.94**	
25	Phytoplankton	**1.00**	1.00	0.13	109.50		**0.70**	
26	*Digenea simplex*	**1.00**	0.60	211.64	274.00		**0.00**	
27	Algal turf	**1.00**	0.55	802.31	323.00		**0.00**	
28	Detritus	**1.00**	1.00	1.00			**0.00**	

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