



Gradients in primary production predict trophic strategies of mixotrophic corals across spatial scales

Fox, Michael D.; Williams, Gareth J.; Johnson, Maggie D.; Radice, Veronica Z.; Zgliczynski , Brian J. ; Kelly, Emily L. A.; Rohwer, Forest L.; Sandin, Stuart A. ; Smith, Jennifer E.

Current Biology

DOI:

[10.1016/j.cub.2018.08.057](https://doi.org/10.1016/j.cub.2018.08.057)

Published: 05/11/2018

Peer reviewed version

[Cyswllt i'r cyhoeddiad / Link to publication](#)

Dyfyniad o'r fersiwn a gyhoeddwyd / Citation for published version (APA):

Fox, M. D., Williams, G. J., Johnson, M. D., Radice, V. Z., Zgliczynski , B. J., Kelly, E. L. A., Rohwer, F. L., Sandin, S. A., & Smith, J. E. (2018). Gradients in primary production predict trophic strategies of mixotrophic corals across spatial scales. *Current Biology*, 28(21), 3355-3363. <https://doi.org/10.1016/j.cub.2018.08.057>

Hawliau Cyffredinol / General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal ?

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

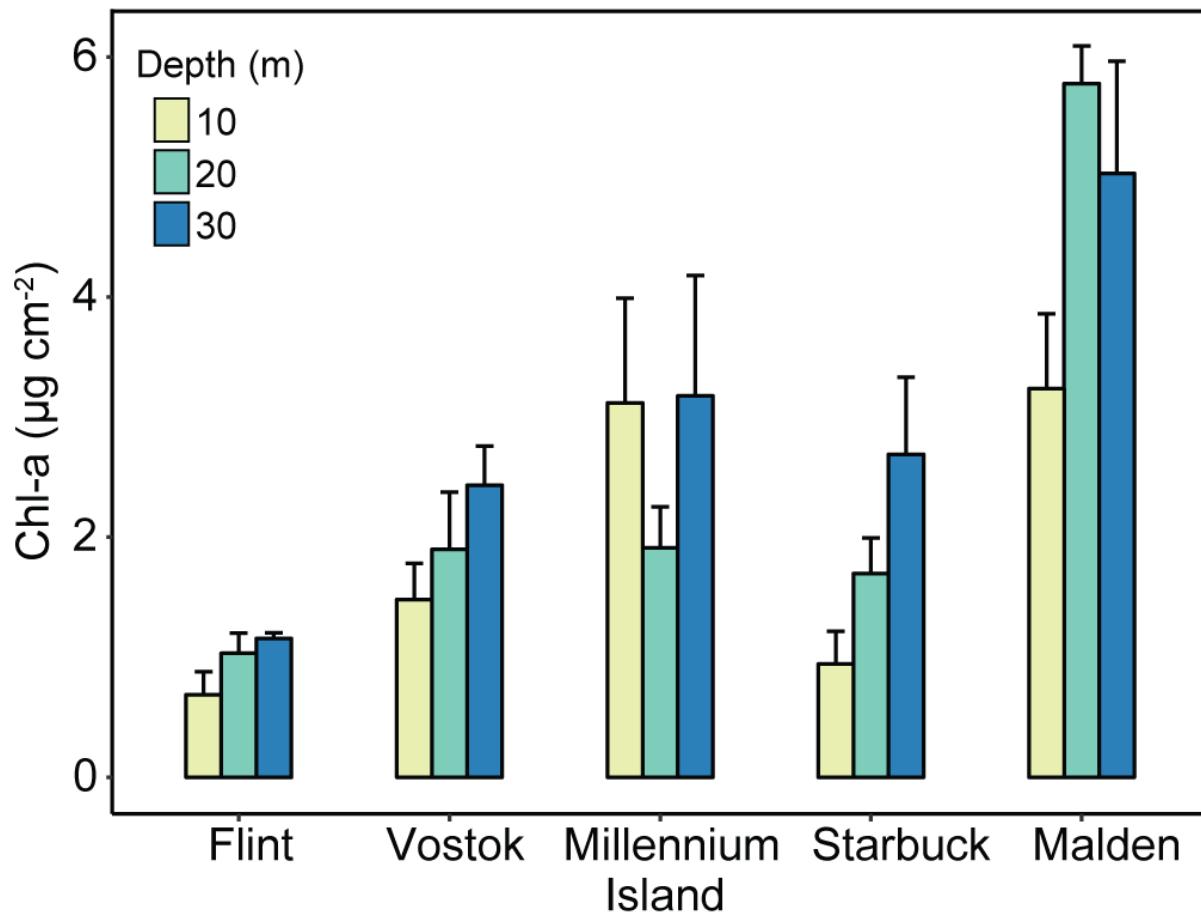


Figure S1. Surface area normalized chl-a concentrations ($\mu\text{g chl-a cm}^{-2}$) of *Pocillopora meandrina* across islands and depth. Related to Figures 1 and 2.

On all islands n = 5 except for Flint 30 m n=3. The islands are arranged from south to north from left to right, in order of increasing surface chl-a Error bars ± 1 SE.

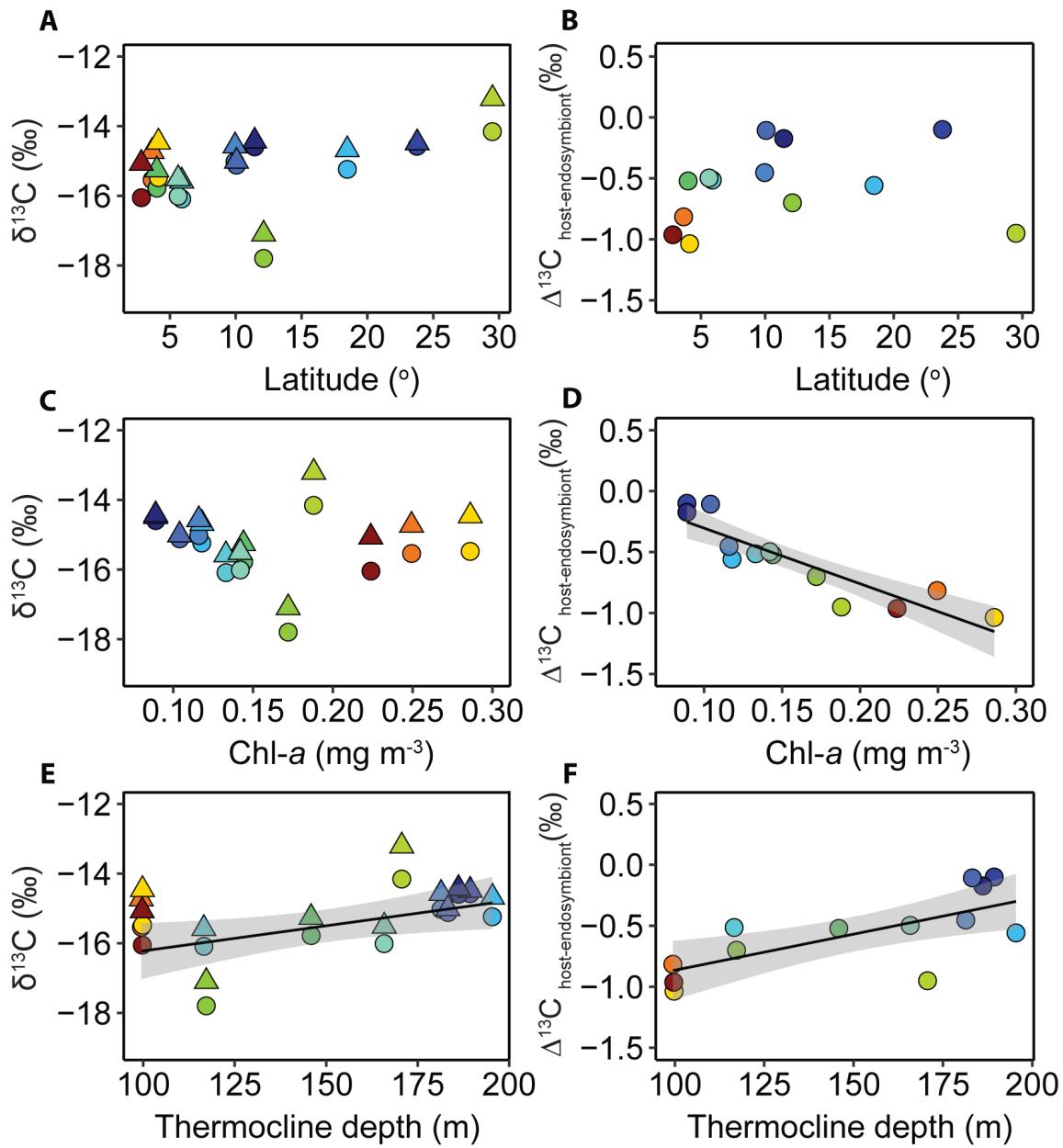


Figure S2. Linear relationships between mean coral and symbionts $\delta^{13}\text{C}$ and $\Delta^{13}\text{C}$ with latitude, mean chl-a, and estimated depth of the thermocline. Related to Figure 3 and Table S4.

Coral host values are displayed as circles and the endosymbionts as triangles. Colors correspond to the islands illustrated in Figure 3. Shaded regions represent $\pm 1\text{SE}$ of linear fit and for panel E the solid line refers to the coral host fraction. Please see Table S5 and the STAR Methods section Quantification and Statistical Analysis - *Global relationships between coral isotopic ratios and oceanic primary productivity* for a complete explanation of all models.

Tissue	Variable	Factor	df	MS	F	P	Pairwise Contrasts
Coral Host	$\delta^{13}\text{C}$	Depth	1	22.01	109.15	<0.001	FLI MAL
		Island	4	0.72	3.57	0.025	
		Depth*Island	4	0.28	1.34	0.29	
		Error	19	0.20			
Endosymbiont		Depth	1	19.05	93.83	<0.001	
		Island	4	0.52	2.54	0.074	
		Depth*Island	4	0.14	0.70	0.60	
		Error	19	0.20			
Host-Endosymbiont	$\Delta^{13}\text{C}$	Depth	1	0.11	5.98	0.02	FLI VOS MIL STA MAL
		Island	4	0.10	5.55	<0.01	
		Depth*Island	4	0.06	3.472	0.03	
		Error	19	0.02	-	-	
Coral Host	$\delta^{15}\text{N}$	Depth	1	4.37	11.63	<0.01	FLI VOS MIL STA MAL
		Island	4	50.88	135.46	<0.001	
		Depth*Island	4	1.5	3.98	0.02	
		Error	19	0.38			
Endosymbiont	$\delta^{15}\text{N}$	Depth	1	5.60	10.89	<0.01	FLI VOS MIL STA MAL
		Island	4	40.70	79.22	<0.001	
		Depth*Island	4	0.37	0.73	0.58	
		Error	19	0.51			
Host-Endosymbiont	$\Delta^{15}\text{N}$	Depth	1	0.08	0.40	0.53	FLI VOS MIL STA ; FLI VOS MAL
		Island	4	0.79	4.20	0.01	
		Depth*Island	4	0.62	3.31	0.03	
		Error	19	0.19	-	-	
Coral Host	C:N	Depth	1	0.45	3.35	0.08	FLI VOS MIL STA MAL
		Island	4	1.34	9.99	<0.001	
		Depth*Island	4	0.24	1.79	0.17	
		Error	19	0.13			
Endosymbiont	C:N	Depth	1	0.21	2.11	0.16	
		Island	4	0.15	1.53	0.23	
		Depth*Island	4	0.04	0.41	0.80	
		Error	19				
Host-Endosymbiont	$\Delta\text{C:N}$	Depth	1	0.04	0.34	0.57	FLI VOS MIL STA MAL
		Island	4	4.46	8.65	<0.001	
		Depth*Island	4	0.76	1.48	0.25	
		Error	19	2.45			

Table S1. Analysis of Covariance (ANCOVA) results examining coral and endosymbiont isotope geochemistry and their difference (Δ) as a function of island and depth. Related to Figure 2.

Significant factors are indicated in bold and pairwise contrasts between islands at the p <0.05 level are indicated with |. Island abbreviations are the first three letters of each island.

Table S2. Global data set of coral $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ and nearshore chl- a concentrations. Related to Figures 2 and 3.

Mean isotopic estimates of coral host tissue and zooxanthellae data are compiled from literature and unpublished studies and are used to calculate $\Delta\delta^{13}\text{C}$ and $\Delta\delta^{15}\text{N}$. Climatological mean chl- a concentrations are reported for the time period 2004-2015. All reported data are from 10 m depth with the exception of Lesser et al. 2010, which had data from 9 m. Data from Maier et al. 2010 only include *M. auretenra* branch tips to be consistent with the samples collected in this study and reported elsewhere.

Region	Island	Ocean Basin	Family	Species	Mean Host $\delta^{13}\text{C}$	Mean Symbiont $\delta^{13}\text{C}$	Mean $\Delta^{13}\text{C}$	Mean Host $\delta^{15}\text{N}$	Mean Symbiont $\delta^{15}\text{N}$	Mean $\Delta^{15}\text{N}$	12 yr Chl- a	Reference
Bahamans	Lee Stocking	Atlantic	Faviidae	<i>Montastrea cavernosa</i>	-14.58	-14.48	-0.10	1.72	2.15	0.435	0.095	Lesser et al. 2010 [1]
Caribbean	Curacao	Caribbean Sea	Astrocoeniidae	<i>Madracis auretenra</i>	-17.80	-17.10	-0.70	-	-	-	0.172	Maier et al. 2010 [2]
Caribbean	Jamaica	Caribbean Sea	Acroporidae	<i>Acropora cervicornis</i>	-15.34	-14.05	-1.29	1.86	1.68	0.180	0.118	Muscatine et al. 1989 [3]
			Acroporidae	<i>Acropora palmata</i>	-15.19	-14.72	-0.47	1.48	2.13	-0.650	-	-
			Agariciidae	<i>Agaricia agaricites</i>	-15.63	-13.91	-1.72	-	-	-	-	-
			Meandrinidae	<i>Dendrogyra cylindrus</i>	-15.50	-14.94	-0.56	2.23	2.43	-0.200	-	-
			Meandrinidae	<i>Eusimilia fastigiata</i>	-15.39	-15.12	-0.27	2.52	2.18	0.340	-	-
			Astrocoeniidae	<i>Madracis mirabilis</i>	-17.74	-16.79	-0.95	3.05	3.26	-0.210	-	-
			Faviidae	<i>Montastraea annularis</i>	-13.63	-13.87	0.24	2.41	1.83	0.580	-	-
			Faviidae	<i>Montastraea cavernosa</i>	-13.49	-14.04	0.55	1.11	0.35	0.760	-	-
Northern Line Islands	Palmyra Atoll		Pocilloporidae	<i>Pocillopora meandrina</i>	-16.09	-15.58	-0.51	11.35	10.54	0.810	0.133	Williams et al. 2018 [4]
Southern Line Islands	Flint	Pacific	Pocilloporidae	<i>Pocillopora meandrina</i>	-14.60	-14.43	-0.17	15.04	14.96	0.080	0.089	This study
	Malden		Pocilloporidae	-	-15.78	-15.26	-0.52	10.19	10.17	0.020	0.144	This study
	Millennium Atoll		Pocilloporidae	-	-15.03	-14.57	-0.45	15.03	14.17	0.860	0.116	This study
	Starbuck		Pocilloporidae	-	-16.01	-15.51	-0.50	8.57	8.65	-0.080	0.142	This study
	Vostok		Pocilloporidae	-	-15.12	-15.01	-0.11	14.61	14.35	0.260	0.104	This study
Maldives	Vaavu Atoll	Indian	Pocilloporidae	<i>Pocillopora verrucosa</i>	-17.68	-16.82	-0.87	5.94	5.17	0.770	0.260	Radice Unpublished Data
			Oculinidae	<i>Galaxea fascicularis</i>	-15.31	-14.43	-0.89	5.92	4.43	1.490	-	-
			Agariciidae	<i>Pachyseris speciosa</i>	-15.15	-14.25	-0.91	5.30	5.41	0.070	-	-
	Maafushi Atoll		Agariciidae	<i>Pachyseris speciosa</i>	-15.03	-14.29	-0.74	5.26	5.52	-0.260	0.239	Radice Unpublished Data
	Meemu Atoll		Pocilloporidae	<i>Pocillopora verrucosa</i>	-18.23	-17.35	-0.88	5.57	5.35	0.220	0.230	Radice Unpublished Data
			Oculinidae	<i>Galaxea fascicularis</i>	-15.48	-15.20	-0.27	5.36	4.08	1.280	-	-
			Agariciidae	<i>Pachyseris speciosa</i>	-15.09	-13.60	-1.49	4.99	5.18	-0.190	-	-
	Male Atoll		Agariciidae	<i>Pachyseris speciosa</i>	-14.71	-12.76	-1.95	5.22	4.94	0.280	0.281	Radice Unpublished Data
			Oculinidae	<i>Galaxea fascicularis</i>	-14.84	-14.25	-0.59	4.89	4.32	0.570	-	-
	Dhaalu Atoll		Pocilloporidae	<i>Pocillopora verrucosa</i>	-16.20	-15.11	-1.09	5.97	5.89	0.080	0.217	Radice Unpublished Data
			Oculinidae	<i>Galaxea fascicularis</i>	-15.03	-15.20	0.17	6.07	4.44	1.630	-	-
			Agariciidae	<i>Pachyseris speciosa</i>	-16.28	-13.98	-2.31	4.54	5.41	-0.870	-	-
	Ari Atoll		Pocilloporidae	<i>Pocillopora verrucosa</i>	-17.25	-16.14	-1.12	5.66	5.21	0.450	0.291	Radice Unpublished Data
			Oculinidae	<i>Galaxea fascicularis</i>	-16.60	-15.66	-0.94	5.44	4.52	0.920	-	-
			Agariciidae	<i>Pachyseris speciosa</i>	-14.73	-14.43	-0.30	5.68	5.80	-0.120	-	-
Gulf of Eilat	-	Red Sea	Pocilloporidae	<i>Stylophora pistillata</i>	-16.43	-14.82	-1.61	1.42	0.20	1.221	0.188	Einbinder et al. 2009 [5]
			Pocilloporidae	<i>Stylophora pistillata</i>	-14.21	-13.14	-1.06	-	-	-	-	Alamaru et al. 2009 [6]
			Faviidae	<i>Favia favus</i>	-11.84	-11.67	-0.17	2.56	1.33	1.230	-	Alamaru et al. 2009 [6]

Tissue type		df	F	Slope (m)	Intercept (b)	p	r2
Model 1: All raw data							
$\delta^{13}\text{Chost}$	32	1.32	-3.83 (3.34)	-14.79 (0.66)	0.26	0.04	
$\delta^{13}\text{Csymbiont}$	32	0.02	-0.47 (3.12)	-14.69 (0.61)	0.88	0	
$\Delta^{13}\text{C}$	32	4.97	-3.37 (1.52)	-0.10 (0.30)	0.03	0.13	
Model 2: Global model of means							
$\delta^{13}\text{Chost}$	14	0.87	-3.17 (3.40)	-14.98 (0.64)	0.37	0.06	
$\delta^{13}\text{Csymbiont}$	14	0.09	1.04 (3.5)	-15.08 (0.66)	0.77	0.01	
$\Delta^{13}\text{C}$	14	46.24	-4.34 (0.64)	0.13 (0.12)	<0.001	0.77	
Model 3: No Jamaica							
$\delta^{13}\text{Chost}$	13	0.72	-3.06 (3.62)	-15.00 (0.70)	0.413	0.05	
$\delta^{13}\text{Csymbiont}$	13	0.12	1.30 (3.72)	-15.15 (0.71)	0.73	0.01	
$\Delta^{13}\text{C}$	13	47.58	-4.54 (0.66)	0.17 (0.13)	<0.001	0.79	
Model 4: No Eilat							
$\delta^{13}\text{Chost}$	13	1.15	-3.41 (3.18)	-15.03 (0.60)	0.30	0.08	
$\delta^{13}\text{Csymbiont}$	13	0.06	0.75 (3.15)	-15.14 (0.60)	0.82	0.00	
$\Delta^{13}\text{C}$	13	50.51	-4.33 (0.61)	0.14 (0.12)	<0.001	0.80	
Model 5: No Curacao							
$\delta^{13}\text{Chost}$	13	1.7	-3.30 (2.53)	-14.8 (0.48)	0.22	0.12	
$\delta^{13}\text{Csymbiont}$	13	0.11	0.92 (2.75)	-14.91 (0.52)	0.74	0.01	
$\Delta^{13}\text{C}$	13	43.61	-4.38 (0.66)	0.13 (0.13)	<0.001	0.77	
Model 6: No Jam, Eil, Cur							
$\delta^{13}\text{Chost}$	11	2.16	-3.49 (2.38)	-14.86 (0.46)	0.17	0.16	
$\delta^{13}\text{Csymbiont}$	11	0.12	0.86 (2.43)	-15.03 (0.47)	0.73	0.01	
$\Delta^{13}\text{C}$	11	51.75	-4.52 (0.63)	0.19 (0.12)	<0.001	0.81	
Model 7: Single species only per location							
$\delta^{13}\text{Chost}$	11	5.75	-10.6 (4.42)	-14.16 (0.79)	0.04	0.34	
$\delta^{13}\text{Csymbiont}$	11	1.42	-5.44 (4.57)	-14.37 (0.82)	0.26	0.11	
$\Delta^{13}\text{C}$	11	25.99	-5.12 (1.00)	0.22 (0.18)	<0.001	0.70	
Model 8: <i>Pocillopora</i> spp. only							
$\delta^{13}\text{Chost}$	8	5.33	-9.88 (4.28)	-14.24 (0.79)	0.05	0.4	
$\delta^{13}\text{Csymbiont}$	8	1.55	-5.21 (4.18)	-14.42 (0.78)	0.25	0.16	
$\Delta^{13}\text{C}$	8	50.84	-4.63 (0.65)	0.18 (0.12)	<0.001	0.86	
Coefficients of Variation							
$\delta^{13}\text{Chost}$				65.60	2.50		
$\delta^{13}\text{Csymbiont}$				372.90	2.26		
$\Delta^{13}\text{C}$				6.04	20.57		

Table S3. The results of linear regression analyses designed to examine the influence of taxonomic resolution and location on the global relationship between $\Delta^{13}\text{C}$ and chl-a. Related to Figure 3.

Significant models are indicated in bold and the SE of estimates of slope (m) and intercept (b) are reported in (). The coefficient of variation (CV) for all models (excluding the raw data) is calculated for the slope and intercept estimates. Please see the STAR methods section, Quantification and Statistical Analysis - *Global relationships between coral isotopic ratios and oceanic primary productivity* for a complete explanation of all models.

Variable	Tissue type	df	F	Slope (m)	Intercept (b)	p	r2	
$\delta^{13}\text{C}$	Latitude	$\delta^{13}\text{Chost}$	11	4.01	0.06 (0.03)	-16.12 (0.38)	0.07	0.27
		$\delta^{13}\text{Csymbiont}$	11	3.2	0.05 (0.03)	-15.48 (0.38)	0.10	0.22
		$\Delta^{13}\text{C}$	11	0.37	0.01 (0.01)	-0.64 (0.15)	0.56	0.03
	Chl- α	$\delta^{13}\text{Chost}$	11	0.79	-3.80 (4.28)	-14.90 (0.72)	0.39	0.07
		$\delta^{13}\text{Csymbiont}$	11	0.03	0.73 (4.27)	-15.05 (0.72)	0.87	0.003
		$\Delta^{13}\text{C}$	11	46.41	-4.56 (0.67)	0.15 (0.11)	<0.001	0.81
	22° isotherm	$\delta^{13}\text{Chost}$	11	6.14	0.01 (0.01)	-17.66 (0.90)	0.03	0.36
		$\delta^{13}\text{Csymbiont}$	11	1.72	0.01 (0.01)	-16.21 (1.0)	0.22	0.14
		$\Delta^{13}\text{C}$	11	11.24	0.01 (0.001)	-1.46 (0.27)	<0.01	0.51
$\delta^{15}\text{N}$	Latitude	$\delta^{15}\text{NChost}$	10	2.65	-0.21 (0.17)	10.98 (2.23)	0.14	0.21
		$\delta^{15}\text{Nsymbiont}$	10	2.82	-0.28 (0.16)	10.70 (2.23)	0.12	0.22
		$\Delta^{15}\text{N}$	10	2.15	0.02 (0.01)	0.22 (0.17)	0.17	0.18
	Chl- α	$\delta^{15}\text{NChost}$	10	1.98	-31.94 (22.68)	13.09 (3.83)	0.19	0.17
		$\delta^{15}\text{Nsymbiont}$	10	2.39	-34.44 (22.23)	13.13 (3.75)	0.15	0.19
		$\Delta^{15}\text{N}$	10	0.45	1.23 (1.84)	0.23 (0.31)	0.52	0.04
	22° isotherm	$\delta^{15}\text{NChost}$	10	0.23	0.02 (0.04)	5.06 (6.53)	0.64	0.02
		$\delta^{15}\text{Nsymbiont}$	10	0.31	0.02 (0.04)	4.24 (6.48)	0.59	0.03
		$\Delta^{15}\text{N}$	10	0.18	-0.001 (0.003)	0.62 (0.50)	0.68	0.02
Pacific and Indian Ocean Pocillopora								
Latitude		$\delta^{15}\text{NChost}$	7	44.25	1.15 (0.17)	2.86 (1.23)	<0.001	0.86
		$\delta^{15}\text{Nsymbiont}$	7	42.48	1.15 (0.18)	2.52 (1.25)	<0.001	0.86
		$\Delta^{15}\text{N}$	7	0.01	0.004 (0.04)	0.34 (0.30)	0.93	0.01
Chl- α		$\delta^{15}\text{NChost}$	7	33.98	-52.21 (8.96)	18.87 (1.59)	<0.001	0.83
		$\delta^{15}\text{Nsymbiont}$	7	43.84	-53.201 (8.04)	18.66 (1.43)	<0.001	0.86
		$\Delta^{15}\text{N}$	7	0.26	0.99 (1.94)	0.21 (0.35)	0.63	0.04
22° isotherm		$\delta^{15}\text{NChost}$	7	22.79	0.09 (0.02)	-2.72 (2.80)	0.002	0.77
		$\delta^{15}\text{Nsymbiont}$	7	30.41	0.09 (0.02)	-3.48 (2.50)	<0.001	0.81
		$\Delta^{15}\text{N}$	7	0.63	-0.003 (0.003)	0.76 (0.50)	0.45	0.08

Table S4. Results of linear regression analysis examining the relationship between coral $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ with absolute latitude, chl- α , and estimated thermocline depth. Related to Figures 3 and S2.

Significant models are indicated in bold and the SE of estimates of slope (m) and intercept (b) are reported in (). Please see the STAR methods section Quantification and Statistical Analysis - *Global relationships between coral isotopic ratios and oceanic primary productivity* for a complete explanation of all models.

Supplemental References

- S1. Lesser, M.P., Slattery, M., Stat, M., Ojimi, M., Gates, R.D., and Grottoli, A. (2010). Photoacclimatization by the coral *Montastraea cavernosa* in the mesophotic zone: light, food, and genetics. *Ecology* 91, 990-1003.
- S2. Maier, C., Weinbauer, M.G., and Pätzold, J. (2010). Stable isotopes reveal limitations in C and N assimilation in the Caribbean reef corals Madracis auretenra, M. carmabi and M. formosa. *Mar. Ecol. Prog. Ser.* 412, 103-112.
- S3. Muscatine, L., Porter, J.W., and Kaplan, I.R. (1989). Resource partitioning by reef corals as determined from stable isotope composition. I $\delta^{13}\text{C}$ of zooxanthellae and animal tissue vs depth. *Mar. Biol.* 100, 185-193.
- S4. Williams, G.J., Sandin, S.A., Zgliczynski, B., Fox, M.D., Furby, K., Gove, J.M., Rogers, J.S., Hartmann, A.C., Caldwell, Z.R., Price, N.N., et al. (2018). Biophysical drivers of coral trophic depth zonation. *Mar. Biol.* 165, 60.
- S5. Einbinder, S., Mass, T., Brokovich, E., Dubinsky, Z., Erez, J., and Tchernov, D. (2009). Changes in morphology and diet of the coral *Stylophora pistillata* along a depth gradient. *Mar. Ecol. Prog. Ser.* 381, 167-174.
- S6. Alamaru, A., Loya, Y., Brokovich, E., Yam, R., and Shemesh, A. (2009). Carbon and nitrogen utilization in two species of Red Sea corals along a depth gradient: Insights from stable isotope analysis of total organic material and lipids. *Geochem. Cosmochim. Ac.* 73, 5333-5342.