

Supplementary Information for:

Turf algae drives coral bioerosion under high CO₂

Joshua Heitzman¹, Layla Iijima¹, Guinther Mitushasi¹, Davide Spatafora^{1,2}, Shigeki Wada¹,
Ben P. Harvey¹, Haruko Kurihara³, Sylvain Agostini¹

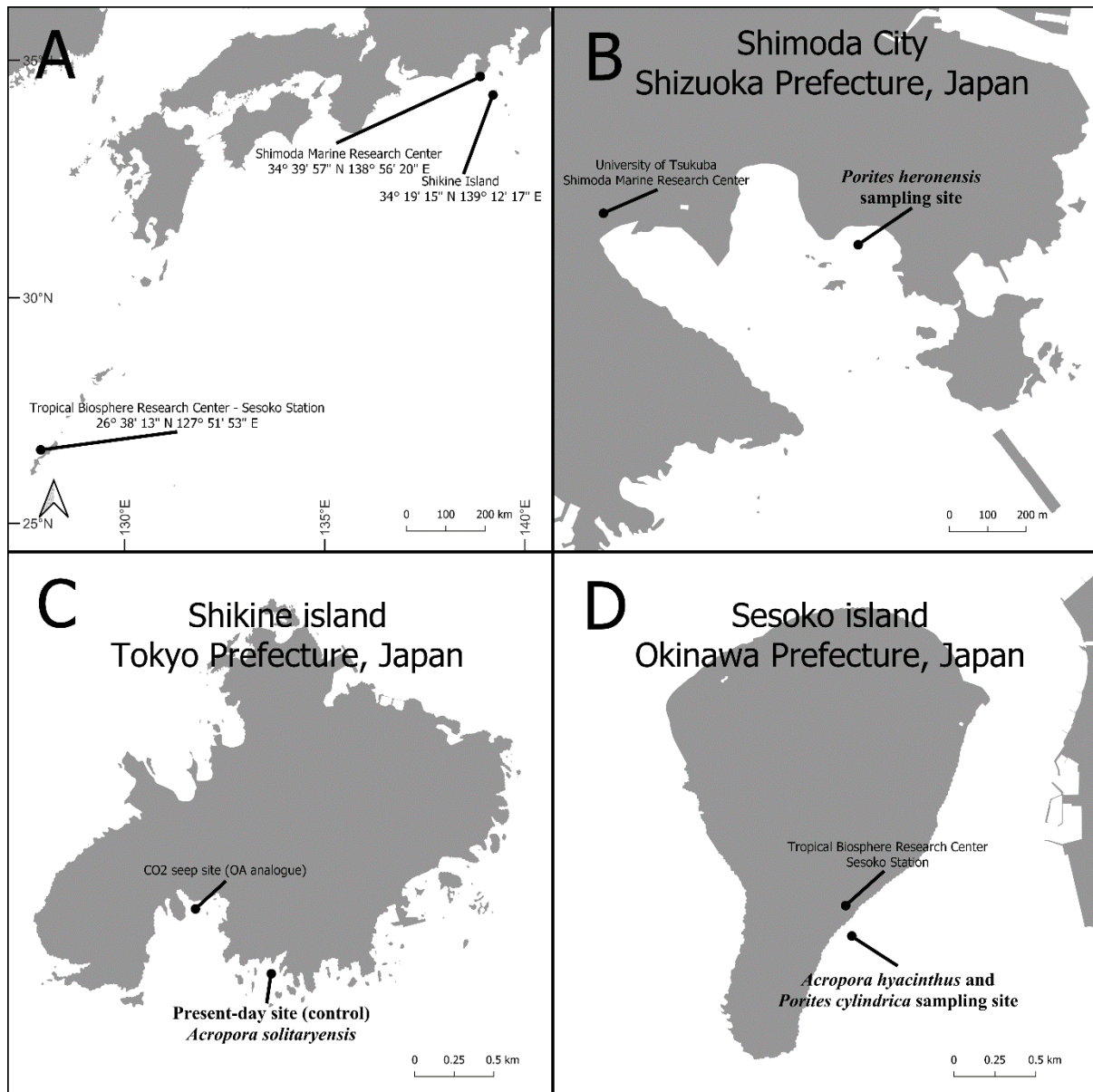
1. Shimoda Marine Research Center, University of Tsukuba, 5-10-1 Shimoda, Shizuoka, Japan

2. Stazione Zoologica Anton Dohrn Department of Integrative Marine Ecology, Sicily Marine Center,
Lungomare Cristoforo Colombo (complesso Roosevelt), 90149, Palermo, Italy

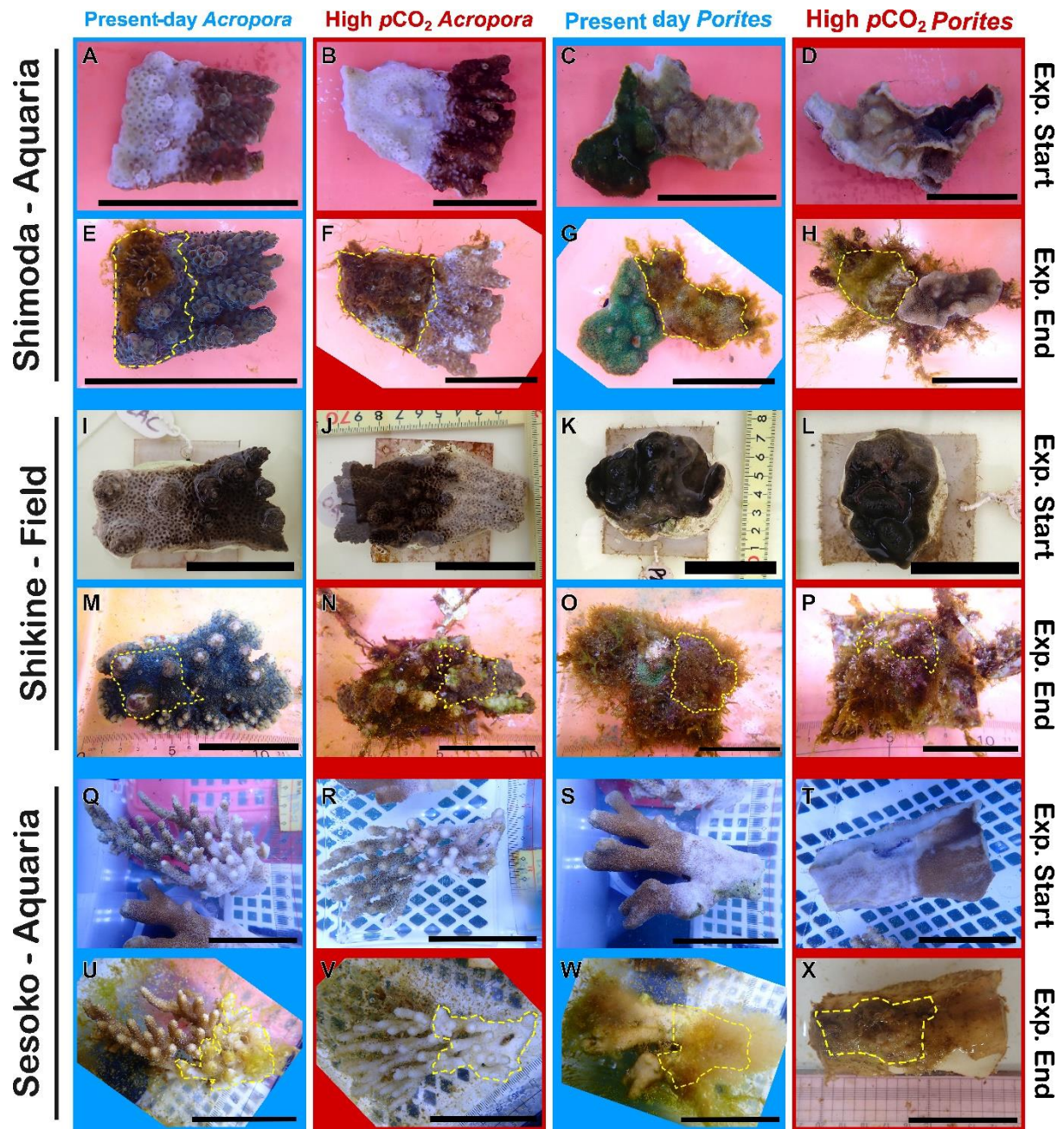
3. Department of Chemistry, Biology, and Marine Science, Faculty of Science,
University of the Ryukyus, 1 Senbaru, Nishihara, Okinawa, 903-0213, Japan

Corresponding author:

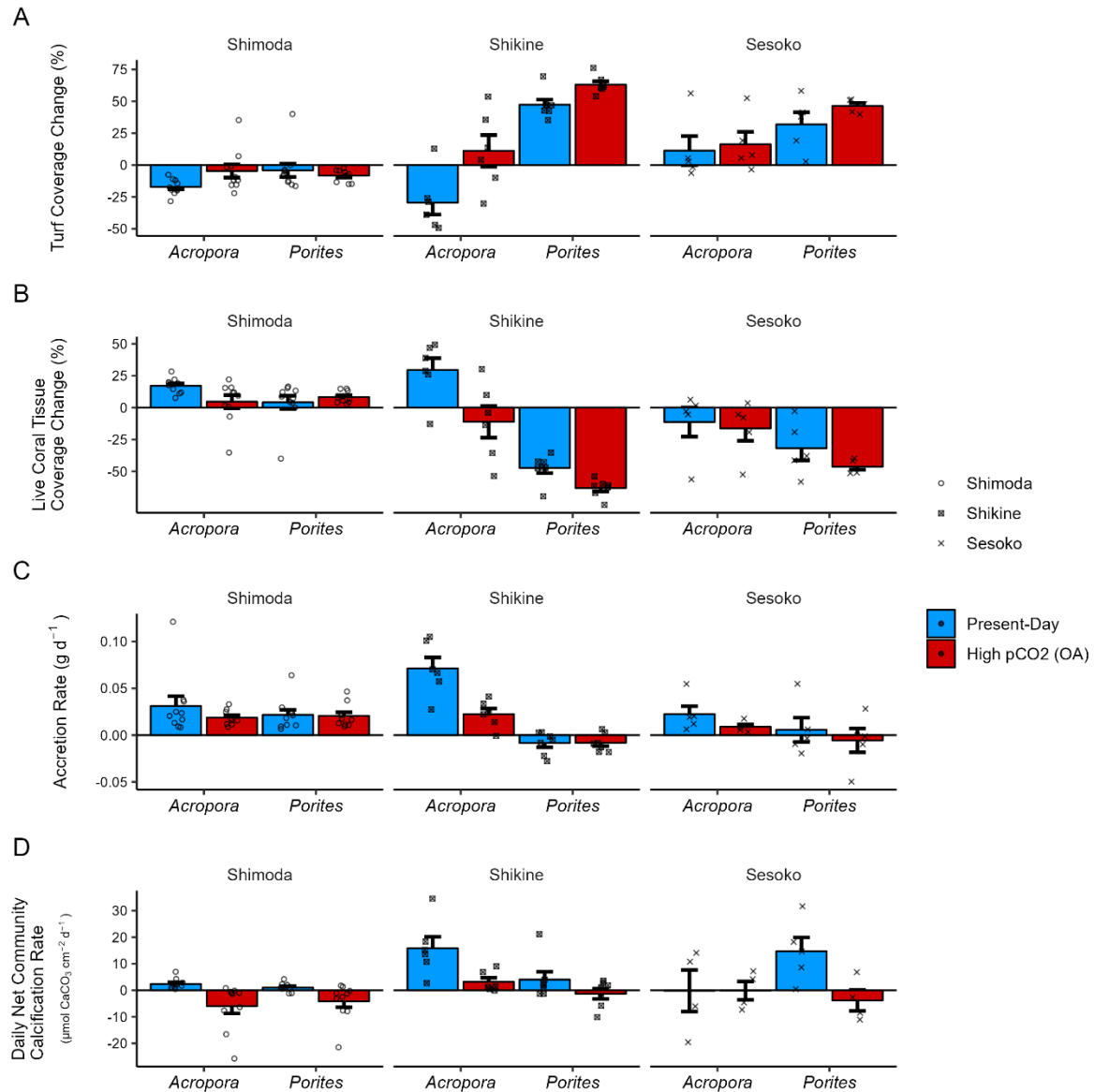
Sylvain Agostini: agostini.sylvain@shimoda.tsukuba.ac.jp



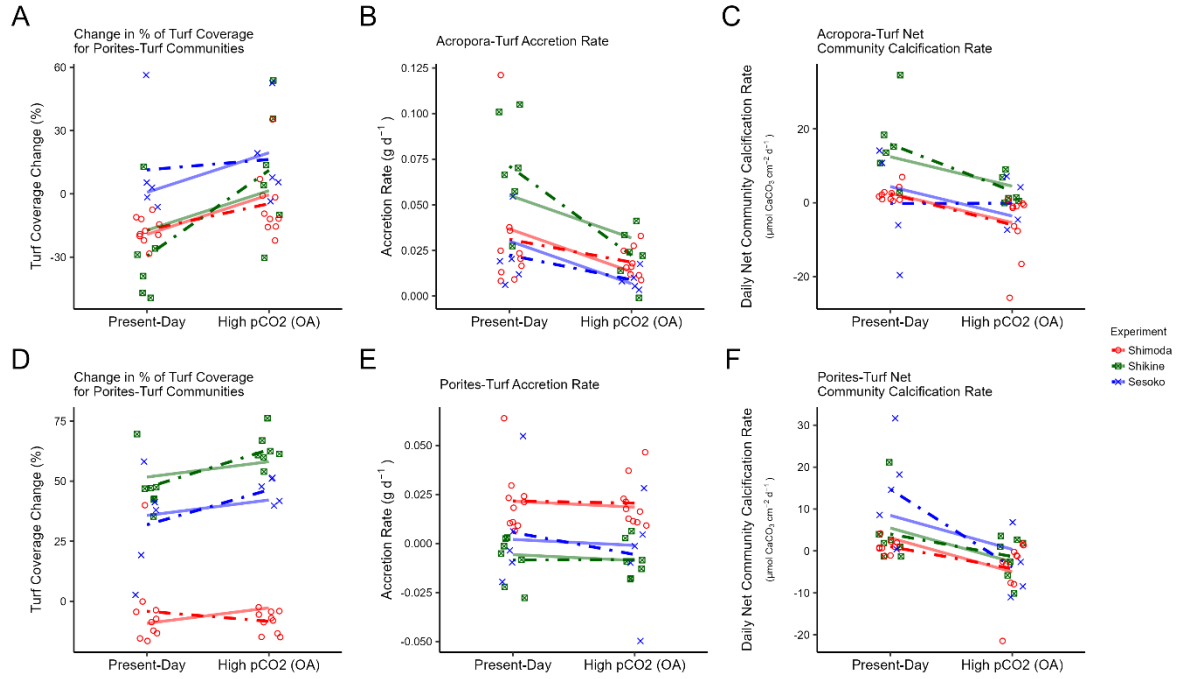
Supplementary Figure 1 – A four panel map figure showing all sampling and study sites. (A) A map of Japan with three dots demarking the locations of Shimoda city, Shikine island, and Sesoko island. (B) A close-up map of Shimoda city, showing where the aquaria experiment was conducted (Shimoda Marine Research Center) and the *Porites heronensis* sampling site (Shidagaura bay, Shimoda city). (C) A close-up map of Shikine island, with the transplantation sites labelled (Present day, control; CO₂ seep site, OA analogue). All *Acropora solitaryensis* individuals were sampled at the ‘present-day’ site. (D) A close-up of Sesoko island, with the dots showing the location of the Sesoko station and the sampling site for *Acropora hyacinthus* and *Porites cylindrica*. Exact coordinates for each sampling/transplantation site are also listed on SI Table 1, alongside environmental data.



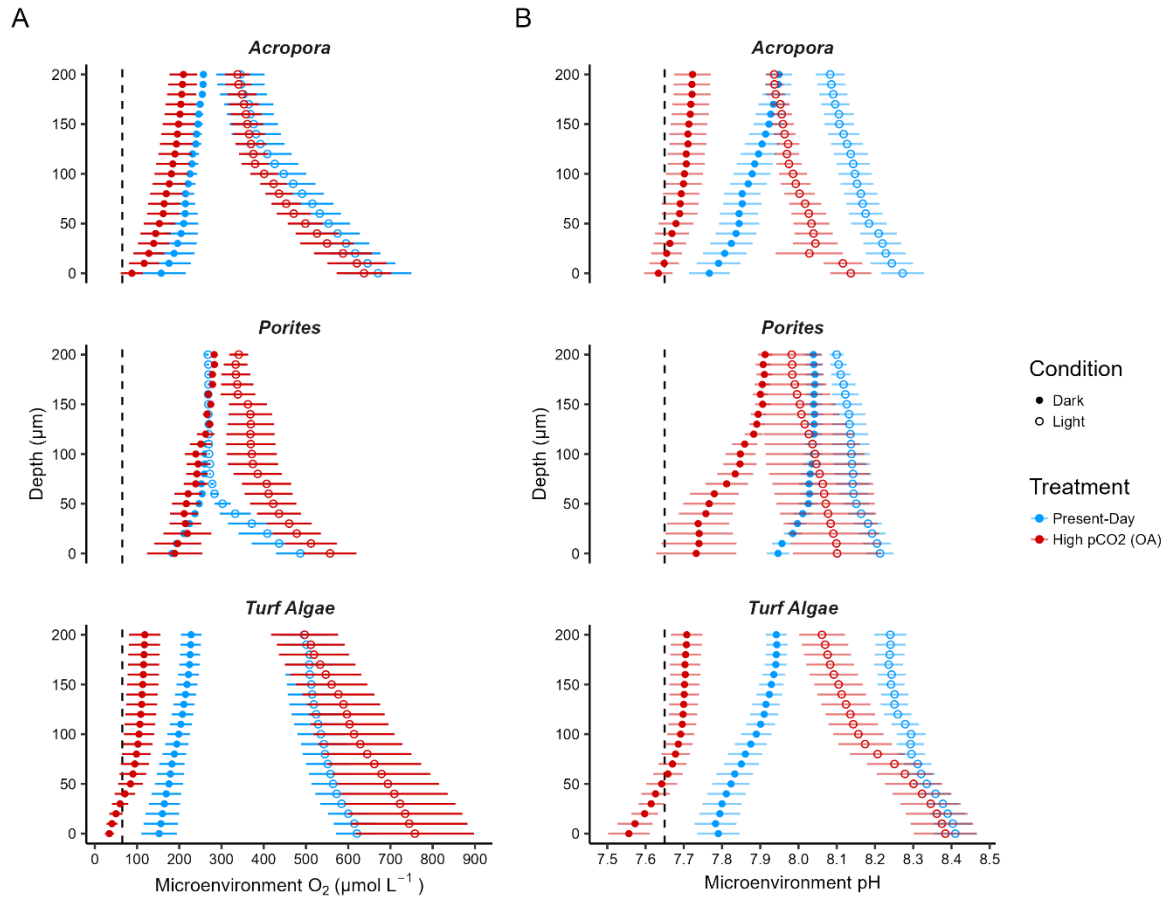
Supplementary Figure 2 – Coral-algae communities from all experiments (Shimoda aquaria, Shikine transplantation and Sesoko aquaria experiments) under present-day and high $p\text{CO}_2$ conditions at the start (Exp. Start) and end (Exp. End) of each respective experiment. (A, E, I, M, Q, U) Present-day *Acropora*, (B, F, J, N, R, V), High $p\text{CO}_2$ *Acropora*, (C, G, K, O, S, W), and Present-day *Porites*, (D, H, L, P, T, X) High $p\text{CO}_2$ *Porites*. Dashed lines represent to scale the portion of exposed coral skeleton colonized by turf algae (yellow) at the start of the experiment. All scale bars represent 5 cm.



Supplementary Figure 3 – (A) Turf algae and (B) live coral tissue coverage change (%) together with the (C) accretion rates (g d^{-1}) of colonies from the start to the end of the aquaria experiments in Shimoda (circle) and Sesoko (cross), and at the end of the transplantation at the natural analogue of OA at Shikine (square) for Acropora and Porites coral-algae communities. (C) the daily net community calcification rate ($\mu\text{mol CaCO}_3 \text{ cm}^{-2} \text{ d}^{-1}$) of coral-turf algae communities at the end of each respective experiment. Present-day (blue) and future high pCO_2 (OA, red) conditions, with raw values shown as points.

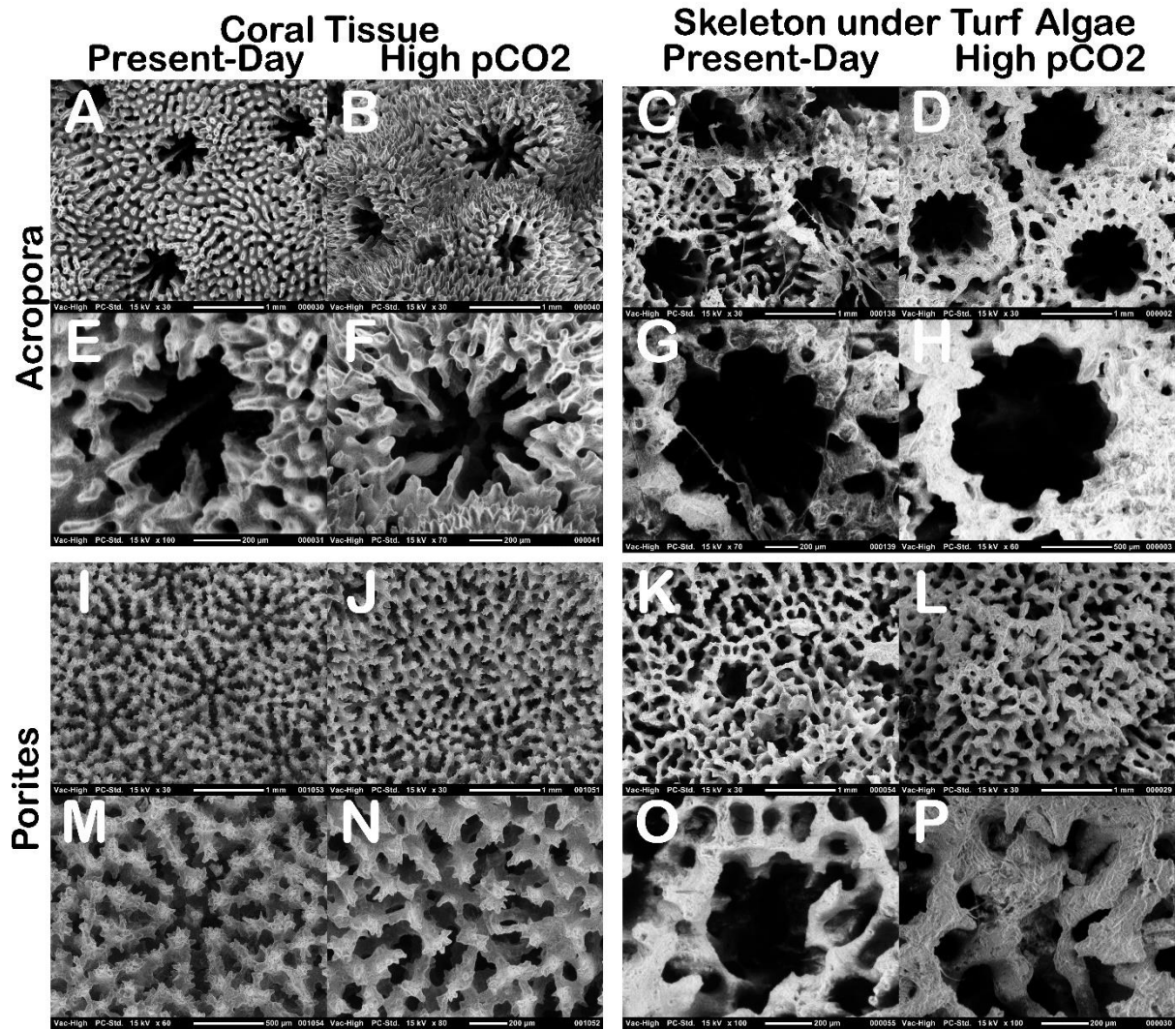


Supplementary Figure 4 – (A, D) Turf coverage change (%) and (B, E) accretion rates (g d^{-1}) of colonies from the start to the end of the aquaria experiments in Shimoda (red circle) and Sesoko (blue cross), and at the end of the transplantation at the natural analogue of OA at Shikine (green square) for *Acropora* and *Porites* coral-algae communities. (C, F) the daily net community calcification rate ($\mu\text{mol CaCO}_3 \text{ cm}^{-2} \text{ d}^{-1}$). Present-day (blue) and future high pCO_2 (OA, red) conditions, with raw values shown as points. Comparisons between mean values (dashed lines) from each pCO_2 conditions and experiment (Shimoda, Shikine, Sesoko) plotted together with the predicted mean values (solid lines) from our linear mixed model for each coral-algae community genera (*Acropora*, *Porites*) for (A, D) competition outcome, (B, E) accretion rates and (C, F) net community calcification rates.



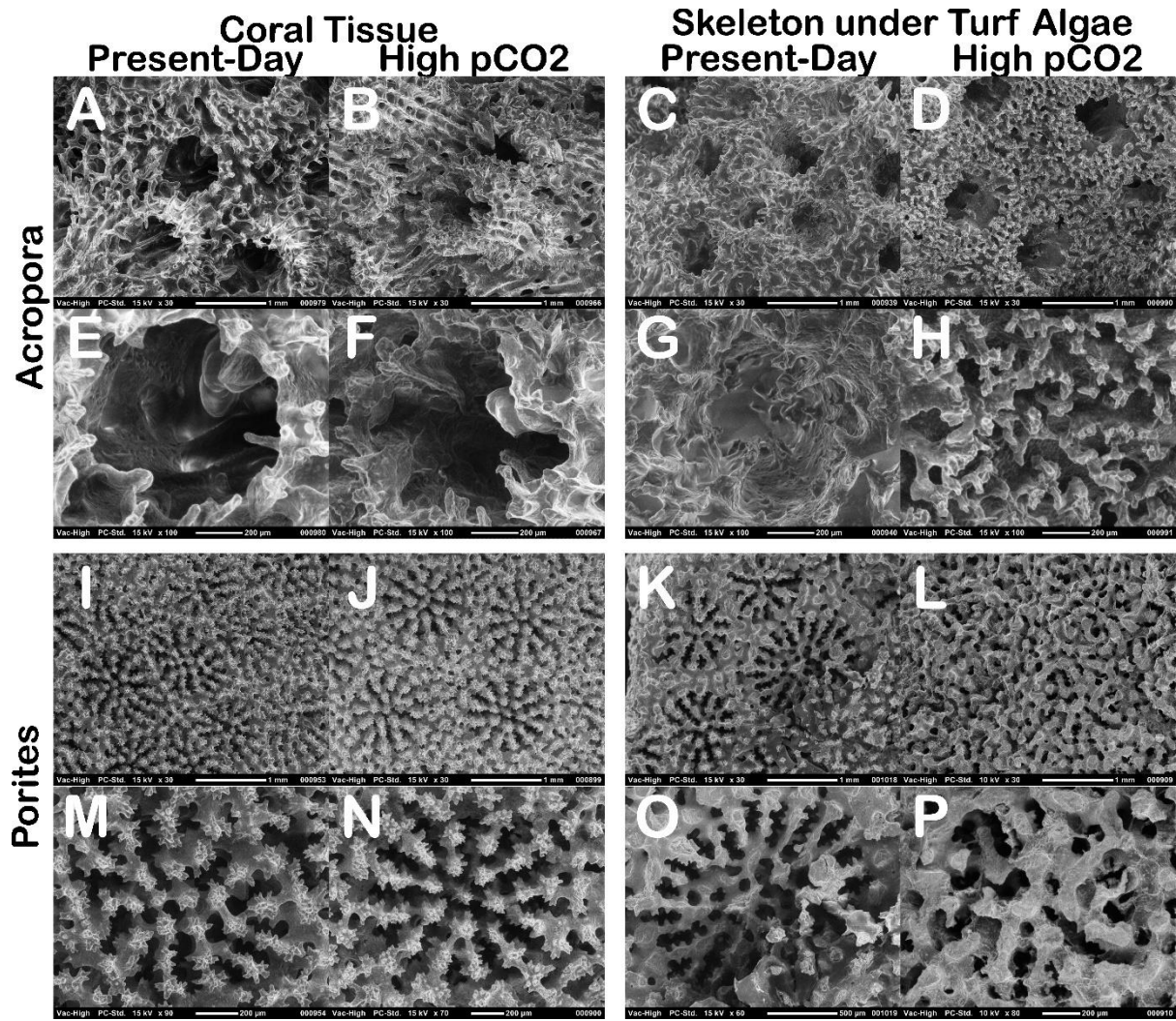
Supplementary Figure 5 – (A) O₂ and (B) pH microsensor profiles of the coral-turf algae community (Top: *Acropora* live coral tissue, Middle: *Porites* live coral tissue, Bottom: Turf-covered exposed coral skeleton) in light (open circle) and dark (filled circle) settings under present-day (Present-Day, blue) and future high pCO₂ (OA, red) conditions. Values are shown as mean ± se for each measurement depth (μm).

Shimoda (Aquaria)

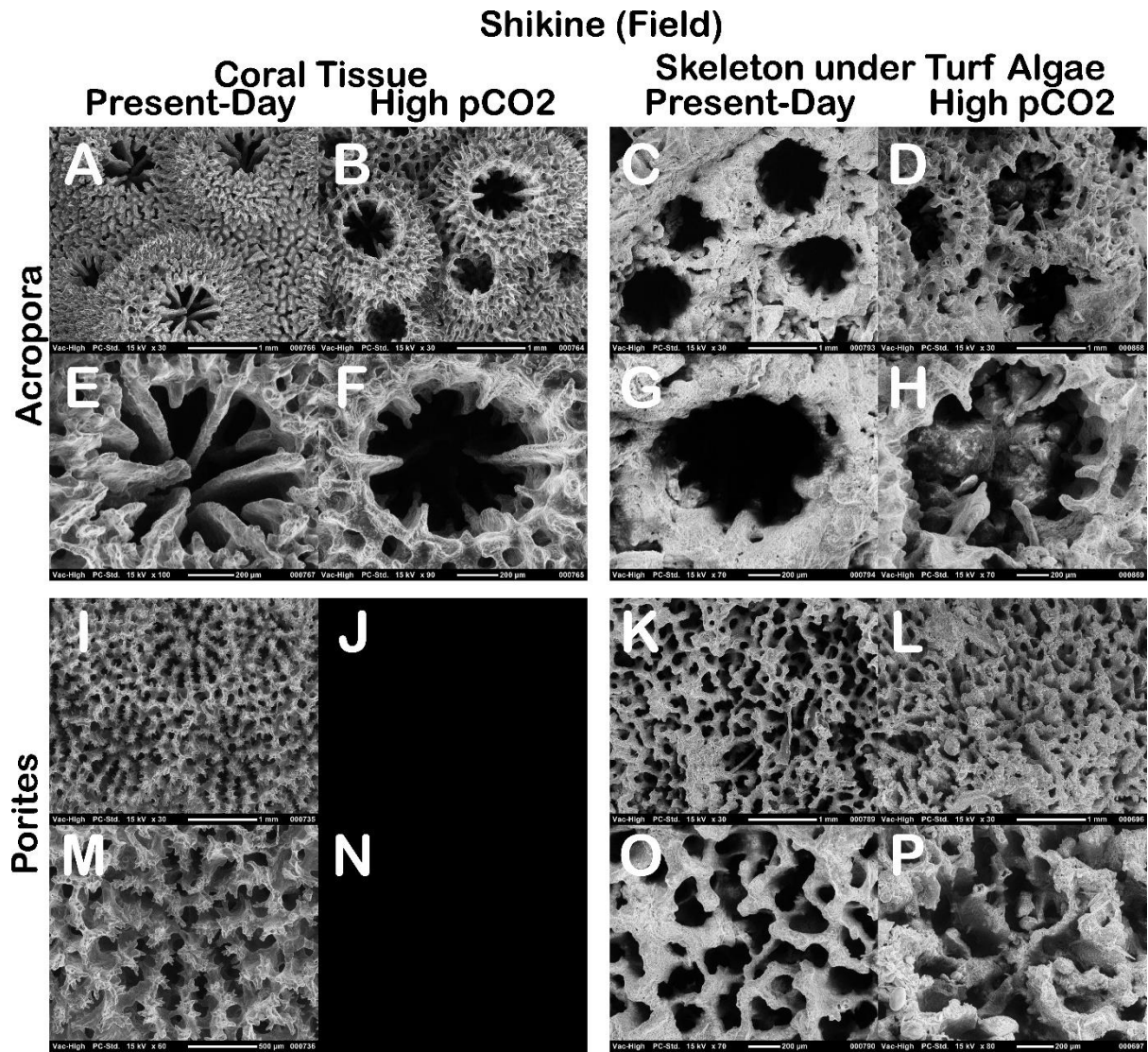


Supplementary Figure 6 – SEM micrography of the coral skeleton that was under live *Acropora solitaryensis* (A, B, E, F) and *Porites heronensis* (I, J, M, N) tissue and exposed coral skeleton underneath turf algae (Acropora: C, D, G, H; Porites: K, L, O, P) that were under present-day and high pCO₂ conditions from the Shimoda aquaria experiment.

Sesoko (Aquaria)

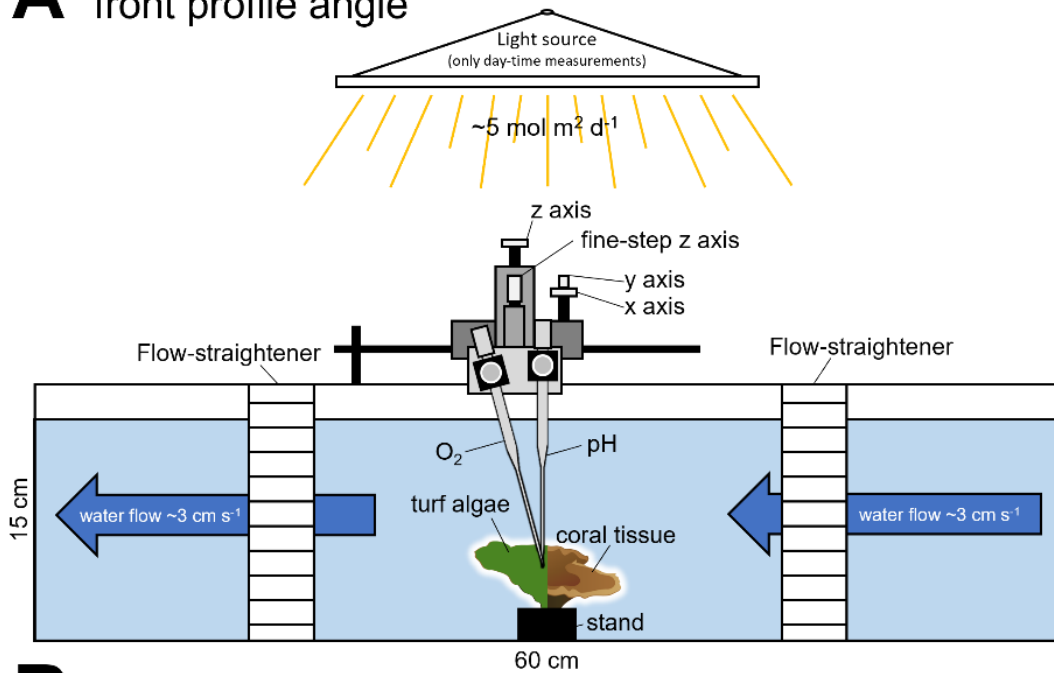


Supplementary Figure 7 – SEM micrography of the coral skeleton that was under live *Acropora hyacinthus* (A, B, E, F) and *Porites cylindrica* (I, J, M, N) tissue and exposed coral skeleton underneath turf algae (Acropora: C, D, G, H; Porites: K, L, O, P) that were under present-day and high pCO₂ conditions from the Sesoko aquaria experiment.

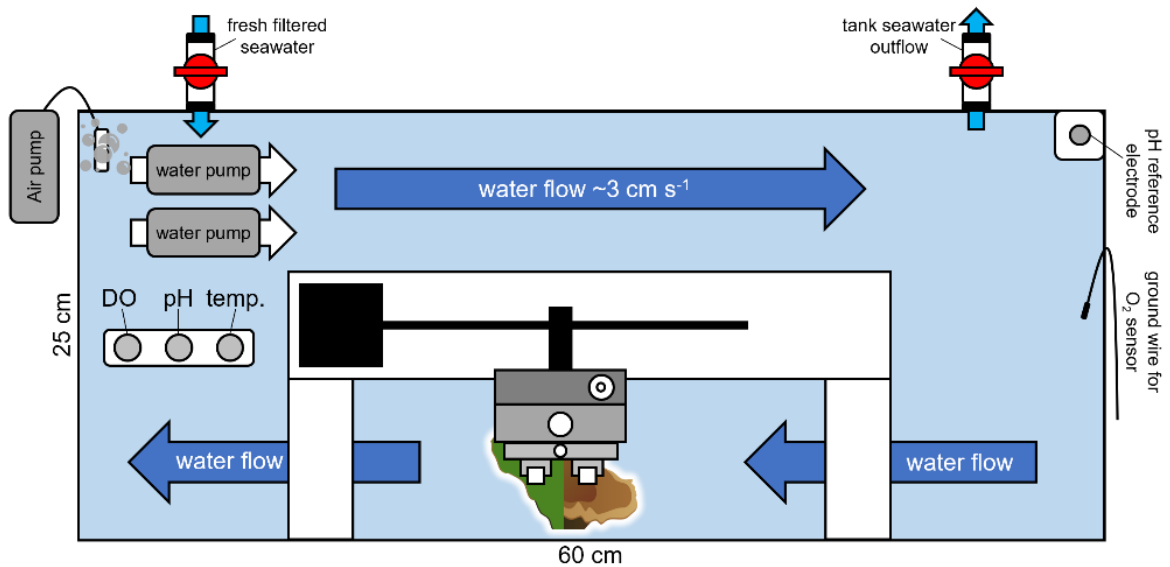


Supplementary Figure 8 – SEM micrography of the coral skeleton that was under live *Acropora solitaryensis* (A, B, E, F) and *Porites heronensis* (I, J, M, N) tissue and exposed coral skeleton underneath turf algae (Acropora: C, D, G, H; Porites: K, L, O, P) that were under present-day and high pCO₂ conditions from the Shikine island transplantation experiment. No live high pCO₂ *Porites heronensis* tissue were present at the end of the experiment, hence the black boxes (J, N).

A front profile angle



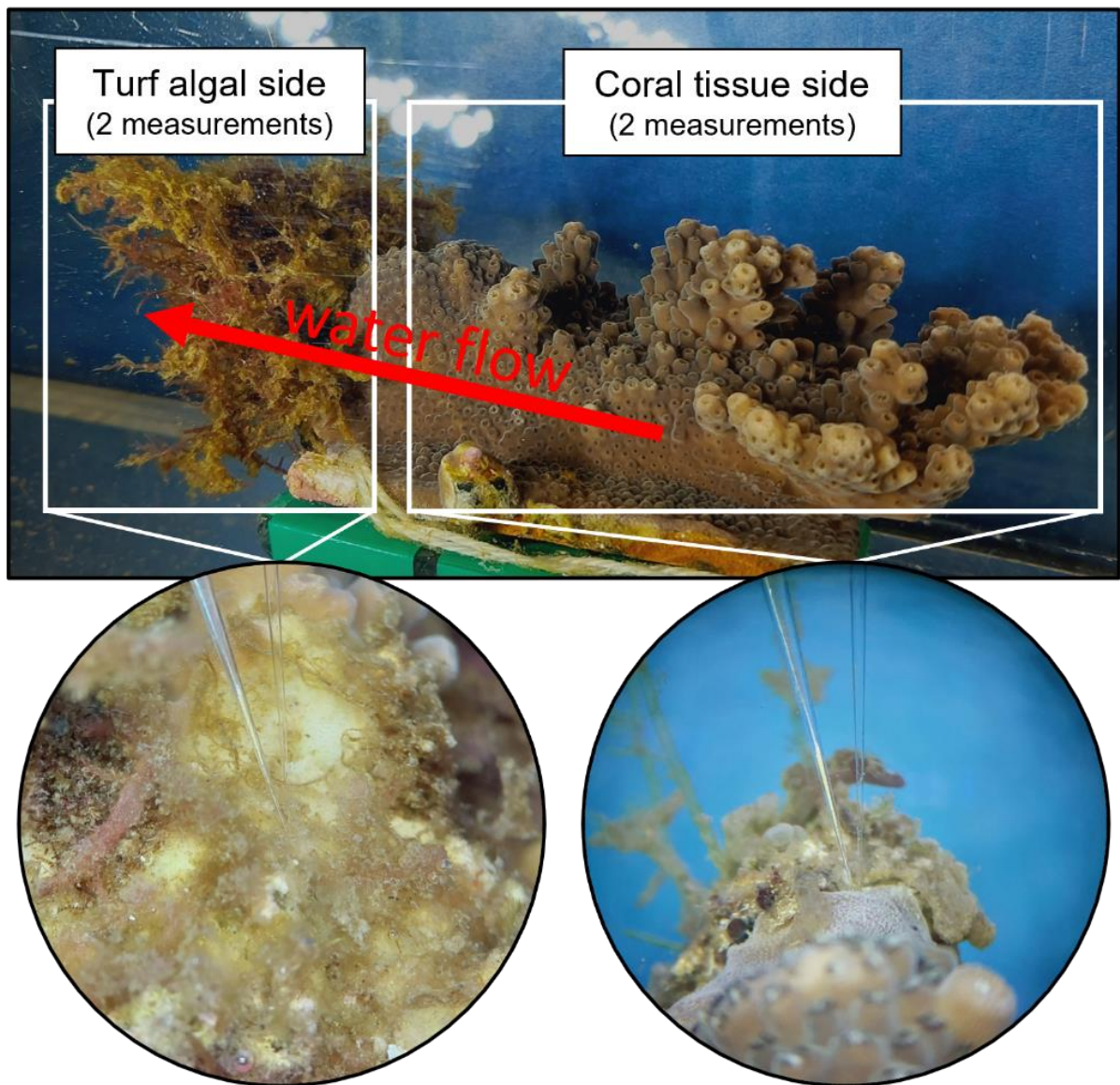
B top-down angle



Supplementary Figure 9 – A schematic diagram outlining the microsensor setup. (A) a front-profile angle of the system, showing the general locations of flow-straighteners, the micromanipulator and profiled sample. (B) a top-down angle of the system, showing the method used to maintain seawater, filling and draining of the system, locations of sensor-related apparatus, and other system qualities. The total dimensions of the system are $60 \times 25 \times 15 \text{ cm}$ (Length $\times$ Width $\times$ Height).

Coral-algae community

measurement locations



Supplementary Figure 10 – Close-up photographs of coral-turf algae individuals measured, with water flow direction highlighted in red. Two measurements were taken on both sites (coral tissue, turf algae) for a total of four measurements per colony per light condition (light, dark). On the bottom, circular photographs show where microsensor profiles were taken in the (left) turf algae and (right) on coral tissue.

Supplementary Table 1 – Table of the environmental conditions at the transplantation site (Field Experiment; Shikine island, Japan) and aquaria tanks (Aquaria Experiments; Shimoda city and Sesoko Island, Japan). All values are shown as mean $\pm$ sd.

Experiment	Site	Coordinates	Treatment	Light (mol photons m ² d ⁻¹)	pH (NBS scale)	Temperature (°C)	Total Alkalinity (μmol g ⁻¹)	pCO ₂ (μatm)	Ω Arag
Field - Shikine	Control	34° 19' 01" N 139° 12' 36" E	Present-day	3.63 $\pm$ 0.02	8.26 $\pm$ 0.05	23.38 $\pm$ 1.02	2275.19 $\pm$ 10.5	358.7 $\pm$ 24.8	3.50 $\pm$ 0.14
Field - Shikine	Mikawa - High CO ₂	34° 19' 15" N 139° 12' 17" E	High pCO ₂ (OA)	2.27 $\pm$ 0.01	7.83 $\pm$ 0.12	23.48 $\pm$ 1.02	2270.77 $\pm$ 2.08	885.6 $\pm$ 215.7	1.91 $\pm$ 0.30
Aquaria - Sesoko	Aquaria	26° 38' 13" N 127° 51' 53" E	Present-day	5.01 $\pm$ 1.43	8.15 $\pm$ 0.14	29.70 $\pm$ 0.84	2236.07 $\pm$ 12.62	327.6 $\pm$ 33.9	4.05 $\pm$ 0.26
Aquaria - Sesoko	Aquaria	26° 38' 13" N 127° 51' 53" E	High pCO ₂ (OA)	5.01 $\pm$ 1.43	7.93 $\pm$ 0.11	29.71 $\pm$ 0.83	2231.43 $\pm$ 20.16	953.9 $\pm$ 191.9	2.02 $\pm$ 0.27
Aquaria - Shimoda	Aquaria	34° 39' 57" N 138° 56' 20" E	Present-day	5.01 $\pm$ 1.43	8.18 $\pm$ 0.16	20.76 $\pm$ 2.83	2251.87 $\pm$ 79.47	444.9 $\pm$ 60.9	3.43 $\pm$ 0.41
Aquaria - Shimoda	Aquaria	34° 39' 57" N 138° 56' 20" E	High pCO ₂ (OA)	5.01 $\pm$ 1.43	7.85 $\pm$ 0.33	20.71 $\pm$ 2.88	2239 $\pm$ 44.14	926.7 $\pm$ 425.8	1.88 $\pm$ 0.57

Supplementary Table 2 – Details on each linear mixed model (lmm) used in the study, with output values from the subsequent anova including Chi squared (Chisq), degrees of freedom (Df) and p-value (p). The final model (M_1 , fixed factor CO₂ condition & random factor experiment location) and a model including just the random factor (M_2 , random factor experiment location) were compared using an anova, with output Akaike information criteria (AIC) for each model shown in the table. Model fit indices for the final model (M_1) are also shown: AIC, AICc, BIC (Bayesian information criterion), R² conditional, R² marginal, ICC (Intraclass correlation), RMSE (Root-mean square deviation), and Sigma.

linear mixed model (three experiments)			Final model (car::Anova)			Model Comparison (stats::anova)		Intercepts (nlme::ranef(conditional variance for random factor))			Final model fit indices performance::performance							
Measurement Type	Coral-Algae Community	replicates (n) per CO ₂ condition	Chisq	Df	p	AIC (M_1)	AIC (M_2)	Shimoda	Sesoko	Shikine	AIC	AICc	BIC	R ² (cond.)	R ² (marg.)	ICC	RMSE	Sigma
Competition Outcome	Acropora-Turf	21	8.441	1	0.004	385.42	391.23	-7.29	-5.334	12.624	374.854	375.935	381.805	0.353	0.133	0.253	19.973	20.9
	Porites-Turf	22	2.756	1	0.097							n.s.						
Accretion Rate	Acropora-Turf	Present-day = 21 high pCO ₂ = 20	10.337	1	0.001	-180.93	-173.6	-0.004	-0.0105	0.014	-164.41	-163.3	-157.56	0.388	0.158	0.273	0.022	0.023
	Porites-Turf	22	0.33	1	0.566							n.s.						
Net Community (Coral-algae comm.) Calcification Rate	Acropora-Turf	20	9.418	1	0.002	293.54	300.15	-3.877	-2.102	5.979	286.337	287.48	293.092	0.42	0.14	0.325	7.818	8.207
	Porites-Turf	Present-day = 22 high pCO ₂ = 21	13.642	1	0.0002	301.27	311.41	-2.575	2.792	-0.2166737	295.43	296.482	302.474	0.342	0.214	0.163	6.89	7.183
pH Microsensor Profile (Depth = 0) Two experiments: Shimoda & Shikine	Light: <i>Acropora</i> Coral Tissue	12	3.052	1	0.081							n.s.						
	Dark: <i>Acropora</i> Coral Tissue	12	6.304	1	0.012	-19.21	-15.435	-0.0849		0.085	-11.152	-9.047	-6.44	0.546	0.124	0.482	0.122	0.13
	Light: <i>Porites</i> Coral Tissue	Present-day = 10 high pCO ₂ = 6	1.276	1	0.259							n.s.						
	Dark: <i>Porites</i> Coral Tissue	Present-day = 10 high pCO ₂ = 7	5.883	1	0.015	-5.2988	-1.6858	0		0	3.021	6.657	6.111		0.282		0.16	0.171
	Light: Turf algae	24	0.068	1	0.794							n.s.						
	Dark: Turf algae	24	9.141	1	0.002	15.809	22.509	3.49E-21		-3.49E-21	24.49	25.42	31.975		0.163		0.262	0.268

Supplementary Table 3 – Microenvironment data from O₂ and pH microsensor profiles on the coral tissue surface and underneath the turf algal mat (depth = 0). Values shown (mean ± sd) include O₂ (μmol L⁻¹), pH (NBS scale), pCO₂ (μatm) and aragonite saturation state (Ω Arag).

Treatment	Condition	Location	O₂ (μmol L⁻¹)	pH (NBS)	pCO₂ (μatm)	Ω Arag
High pCO ₂ (OA)	Light	Coral Tissue	597.27 ± 154.18	8.12 ± 0.21	210.54 ± 102.53	2.48 ± 1.11
High pCO ₂ (OA)	Light	Turf Algae	757.85 ± 484.04	8.38 ± 0.4	154.74 ± 192.55	4.17 ± 2.44
High pCO ₂ (OA)	Dark	Coral Tissue	138.46 ± 128.17	7.67 ± 0.18	714.29 ± 345.25	0.93 ± 0.4
High pCO ₂ (OA)	Dark	Turf Algae	34.43 ± 36.81	7.56 ± 0.26	1269.03 ± 2149.21	0.75 ± 0.28
Present-Day	Light	Coral Tissue	578.65 ± 188.33	8.25 ± 0.16	142.72 ± 54.94	3.04 ± 0.94
Present-Day	Light	Turf Algae	620.68 ± 170.51	8.41 ± 0.27	102.39 ± 66.85	4.13 ± 1.79
Present-Day	Dark	Coral Tissue	170.07 ± 97.12	7.85 ± 0.17	442.34 ± 234.68	1.39 ± 0.45
Present-Day	Dark	Turf Algae	152.24 ± 145.12	7.79 ± 0.27	568.15 ± 369.27	1.35 ± 1.01

Supplementary Table 4 – Table of the calculated diffusive oxygen flux ($\mu\text{mol O}_2 \text{ cm}^{-2} \text{ sec}^{-1}$, mean $\pm$ sd) at surface of the turf algae covered exposed coral skeleton (0-50 μm) for both $p\text{CO}_2$ conditions (present-day, high $p\text{CO}_2$ (OA)), both genera of coral-turf algae communities (*Acropora*, *Porites*) and both light conditions (Light, Dark; $n = 6$ per $p\text{CO}_2$, genera, and light condition). Kruskal-Wallis (KW) tests and output scores (Chisq, degrees of freedom (Df, p-value) comparing flux differences between $p\text{CO}_2$ conditions are also shown for each genera of coral-turf algal community and light condition.

$p\text{CO}_2$ conditions	Turf algae origin genera	Condition	O ₂ Diffusive Flux: $\mu\text{mol O}_2 \text{ cm}^{-2} \text{ sec}^{-1}$ (mean $\pm$ sd)	KW comparison (fixed factor: $p\text{CO}_2$ conditions)		
				Chisq	Df	p-value
Present-day	<i>Acropora</i>	Dark	-0.08 ± 0.63	0.92308	1	0.3367
High $p\text{CO}_2$ (OA)	<i>Acropora</i>	Dark	0.39 ± 0.62			
Present-day	<i>Acropora</i>	Light	-0.53 ± 1.29	0.41026	1	0.5218
High $p\text{CO}_2$ (OA)	<i>Acropora</i>	Light	-0.69 ± 1.11			
Present-day	<i>Porites</i>	Dark	0.63 ± 0.55	0.64103	1	0.4233
High $p\text{CO}_2$ (OA)	<i>Porites</i>	Dark	0.79 ± 1.16			
Present-day	<i>Porites</i>	Light	-0.8 ± 1.16	0	1	1
High $p\text{CO}_2$ (OA)	<i>Porites</i>	Light	-0.81 ± 1.13			