Large global variations in the carbon dioxide removal potential of seaweed farming due to biophysical constraints

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Supplementary Table 1 | Biological Parameters

Parameter	Genus	Standard Values	Monte Carlo Bounds	Values in the literature
V_{max} - $NO_3^{\dagger}$ (μmol-N (g-DW h)$^{-1}$) Maximum uptake rate	*Eucheuma/Kappaphycus*	9.2	[4.1, 16.3]	5.4[1], 13.0[2]
	Sargassum	16	[1.9, 36.9]	16[3]
	Porphyra	52.5	[26.3, 90]	70[4], 35[5]
	Macrocystis	12.9	[2.3, 38.1]	8.4[6], 16.9[7], 5.8[8], 30.5[9], 3[10]
	Saccharina	11.8	[1.9, 30]	11.8[11]
K_m - NO_3 (μM) Half-saturation constant	*Eucheuma/Kappaphycus*	5.6	[0.2, 13.8]	11[1‡]
	Sargassum	3.0	[1.1, 5.5]	2.3[3]
	Porphyra	5.2	[1.5, 12.7]	
	Macrocystis	10.1	[3.2, 18.1]	9.4[6], 10.9[9]
	Saccharina	2	[1.1, 4.2]	1.4[12], 2.6[13]
μ_{max} § (day^{-1}) Maximum growth rate	*Eucheuma/Kappaphycus*	0.2	[0.1, 0.3]	0.24[14], 0.13[15], 0.16[16]
	Sargassum	0.2	[0.1, 0.3]	0.21[17], 0.13[18]
	Porphyra	0.2	[0.1, 0.3]	0.5[19], 0.3[20]
	Macrocystis	0.2	[0.1, 0.3]	0.2[21], 0.2[22]
	Saccharina	0.2	[0.1, 0.3]	0.2[23], 0.3[24], 0.2[25], 0.3[26]
PAR_s (μmol photon m^{-2} s^{-1}) Saturating irradiance	*Eucheuma/Kappaphycus*	125.9	[52.1, 550]	134[27], 140[28], 118[29], 168[30], 69[31]
	Sargassum	303.9	[112.5, 643.8]	217[18], 391[32]
	Porphyra	104	[34.5, 233.8]	187[33], 79[34]
	Macrocystis	212.4	[105.8, 350]	239[35], 186[36]
	Saccharina	76.3	[11.3, 212.5]	50[37], 70[38], 109[13]
PAR_c (μmol photon m^{-2} s^{-1}) Compensating irradiance	*Eucheuma/Kappaphycus*	13.5	[3.8, 32.5]	16[27], 26[28], 5[29], 13[30], 7[31]
	Sargassum	26	[3.8, 46.3]	30[18], 22[32]
	Porphyra	24.8	[6.8, 54]	43[33], 22[34]
	Macrocystis	20.5	[7.5, 43.1]	10[35], 40[36]
	Saccharina	15.5	[5.7, 29.3]	8[37], 23[13]
Q_{min} (mg-N g-DW^{-1}) Minimum nitrogen cell quota	*Eucheuma/Kappaphycus*	5.8	[4.3, 7.2]	5.8[39]
	Sargassum	5.8	[4.3, 7.2]	5.8[39]
	Porphyra	10.2	[7.6, 12.7]	10.2[39]
	Macrocystis	10.2	[7.6, 12.7]	10.2[39]
	Saccharina	10.2	[7.6, 12.7]	10.2[39]
Q_{max} (mg-N g-DW^{-1}) Maximum nitrogen cell quota	*Eucheuma/Kappaphycus*	44	[33, 55]	44[39]
	Sargassum	44	[33, 55]	44[39]
	Porphyra	54	[40.5, 67.5]	54[39]
	Macrocystis	54	[40.5, 67.5]	54[39]
	Saccharina	54	[40.5, 67.5]	54[39]
C_D (unitless) Drag coefficient	*Eucheuma/Kappaphycus*	0.5	[0.01, 1]	
	Sargassum	0.5	[0.01, 1]	
	Porphyra	0.5	[0.01, 1]	
	Macrocystis	0.5	[0.01, 1]	0.1[40]
	Saccharina	0.5	[0.01, 1]	0.07[41]

Supplementary Table 1 – continued from previous page

Parameter	Genus	Standard Values	Monte Carlo Bounds	Values in the literature
B:SA (g-DW m^{-2}) Ratio of biomass to surface area	*Eucheuma/Kappaphycus*	94.8	[71.1, 118.5]	94.8 (L. Roberson; personal comm.)
	Sargassum	333	[249.8, 416.3]	333[11]
	Porphyra	10	[7.5, 12.5]	
	Macrocystis	58	[43.5, 72.5]	25[6], 31[9], 58[8], 71[42]
	Saccharina	58	[43.5, 72.5]	
E¶ (day^{-1}) Exudation	*Eucheuma/Kappaphycus*	0.01****	[0.001 0.02]	0.002[43], 0.05[44],0.09[45]
	Sargassum	0.01****	[0.001 0.02]	0.002[43], 0.05[44],0.09[45]
	Porphyra	0.01****	[0.001 0.02]	0.002[43], 0.05[44],0.09[45]
	Macrocystis	0.01****	[0.001 0.02]	0.002[43], 0.05[44],0.09[45]
	Saccharina	0.01****	[0.001 0.02]	0.002[43], 0.05[44],0.09[45]
d (day^{-1}) Death rate	*Eucheuma/Kappaphycus*	0.01	[0.003 0.03]	0.003[46], 0.01[45], 0.001[11], 0.02[43]
	Sargassum	0.01	[0.003 0.03]	0.003[46], 0.01[45], 0.001[11], 0.02[43]
	Porphyra	0.01	[0.003 0.03]	0.003[46], 0.01[45], 0.001[11], 0.02[43]
	Macrocystis	0.01	[0.003 0.03]	0.003[46], 0.01[45], 0.001[11], 0.02[43]
	Saccharina	0.01	[0.003 0.03]	0.003[46], 0.01[45], 0.001[11], 0.02[43]
Π (unitless) Wave factor	*Eucheuma/Kappaphycus*	1	[0.03 1.7]	
	Sargassum	1	[0.03 1.7]	
	Porphyra	1	[0.03 1.7]	
	Macrocystis	1	[0.03 1.7]	
	Saccharina	1	[0.03 1.7]	

†If the literature values include a Michaelis-Menten fit, then we report the average V_{max}. In the absence of a Michaelis-Menten fit, we report the maximum NO_3 uptake rate observed in each publication.
‡ We believe this value is too large and have chosen a lower K_m for our standard run.
§ The value of the standard run was ultimately based on previous work.[47]. The values reported here are corrected to correspond to 24-hour light exposure.
¶ It is difficult to determine if dissolved organic nitrogen (DON) measured in other publications is being exuded due to wound/breakage, grazing, or other tissue loss processes which we consider in our death rate term. Uncertainty in these rates is compounded by measured dissolved oranic carbon (DOC) exudation rates that are lower than these values[48, 49]. It seems incongruous that N-limited organisms would be excreting more N than C. Hence, our standard run nitrogen exudation rate is lower than the average from the literature. The Monte Carlo bounds are symmetric around the value of the standard run.

Supplementary Table 2 | Details from Publications on Farmed Tropical Red Seaweed

Reference & Genus	Coordinates/Area*	Seed Density (g-DW m^{-2})	Max. NO_3 (μM)	Harvest Period (days)	Mean Harvest (g-DW m^{-2})**
Ref. 50 (*Kappaphycus*)	12.8ºE, 124.1ºN	20	N/A	45	38
Ref. 51 (*Kappaphycus*)	23ºS, 43.9ºW	150	N/A	47	488
Ref. 52 (*Eucheuma*)	China: Hainan (19.1ºN, 109.6ºE)	N/A	N/A	45	154
Ref. 53 (*Eucheuma/Kappaphycus*)	Tanzania: Mlingotini (6.5ºS, 39ºE)	N/A	N/A	42	350
Ref. 54 (*Eucheuma*)	0.1ºS, 120.04ºE	25	N/A	45	724
Ref. 55 (*Kappaphycus*)	India: Tamil Nadu (8.5ºN to 12.5ºN, 78ºE to 80.5ºE)	444	N/A	45	111
Ref. 56 (*Kappaphycus*)	Philippines: Tigtabon Island (6.89ºN, 122.16ºE) Baligtang (4.7ºN, 119.4ºE) Marcilla Coron (12ºN, 120.3ºE) Sipangkot Island (4.9ºN, 119.4ºE) Layag-Layag (6.9ºN, 122.1ºE) Arena Blanco (6.9ºN, 122.1ºE)	N/A	N/A	45	878

Supplementary Table 2 – continued from previous page

Reference & Genus	Coordinates/Area*	Seed Density (g-DW m^{-2})	Max. NO_3 (μM)	Harvest Period (days)	Mean Harvest (g-DW m^{-2})**
Ref. 57 (*Eucheuma*)	Indonesia: South Sulawesi Bali Nusa Tenggara Timur South Central Sulawesi (9ºS to 1.5ºN, 113.5ºE to 125.5ºE)	N/A	N/A	45	1090
Ref. 58 (*Kappaphycus*)	India: Vellar Estuary (10.1ºN, 79.3ºE)	400	N/A	45	465
Ref. 15 (*Eucheuma*)	Venezuela: Bahía de Charagato (10.8ºN, 64.2ºW)	60	N/A	42	254
Ref. 59 (*Kappaphycus*)	India: Chepala Timmapuram (17.8ºN, 83.4ºE)	100	2.2	45	350
Ref. 60 (*Kappaphycus*)	9.3ºN, 79.1ºE	666	3.5	45	313
Ref. 16 (*Eucheuma/Kappaphycus*)	4.6ºS, 39.6ºE	100	3.3	42	932

Supplementary Table 2 – continued from previous page

Reference & Genus	Coordinates/Area*	Seed Density (g-DW m^{-2})	Max. NO_3 (μM)	Harvest Period (days)	Mean Harvest (g-DW m^{-2})**
Ref. 61 (*Kappaphycus*)	India: Okha Mandal (21.7ºN, 72.3ºE) Arambhada (20.9ºN, 71.4ºE) Miyani Village (21.7ºN, 72.7ºE) Diu (22.5ºN, 69ºE) Simar Village (22.4ºN, 69ºE) Rajapara (21.8ºN, 69.4ºE) Jafrabad (20.7ºN, 71ºE) Ghogha (20.8ºN, 71.2ºE)	28	1.3	60	793
Ref. 62 (*Kappaphycus*)	22.5ºN, 69.1ºE	410	30	45	2208
Ref. 63 (*Eucheuma*)	Indonesia: Northwest Kemojan (5.8ºS, 110.5ºE)	200	6	42	478
Ref. 64 (*Eucheuma*)	5.8ºS, 110.5ºE	400	N/A	21	132
Ref. 65 (*Eucheuma*)	5.6ºS, 120ºE	N/A	N/A	45	93

*Some papers reported a general area, rather than specific coordinates. In that case, representative coordinates are provided in parenthesis.

**Mean harvested biomass density without including seed density.

Supplementary Table 3 | Details from Publications on Wild Tropical Brown Seaweed*

Reference & Genus	Coordinates/Area**	Standing Stock g-DW m^{-2}
Ref. 66 (*Sargassum*)	Philippines: Bolinao, Pangasinan (16.4ºN, 119.9ºE)	175
Ref. 67 (*Sargassum*)	India: Valinokkam (8.5ºN, 78.1ºE) Hare Island (8.1ºN, 78.2ºE)	100
Ref. 68 (*Sargassum*)	18ºN, 120.5ºE	176
Ref. 69 (*Sargassum*)	Curaçao Michiel (12.1ºN, 69ºW) Westpunt (12.4ºN, 69ºW)	156
Ref. 70 (*Sargassum*)	11.3ºN, 74.2ºW	154
Ref. 71 (*Sargassum*)	Funafuti Atoll (8.5ºS, 178.5ºE)	186
Ref. 72 (*Sargassum*)	New Caledonia (23ºS to 18ºS, 162ºE to 168ºE)	357
Ref. 73 (*Sargassum*)	9.6ºN, 123.2ºE 9.4ºN, 123.3ºE 9.1ºN, 122.9ºE	247
Ref. 74 (*Sargassum*)	21.9ºS, 114ºE 23.2ºS, 113.8ºE	220
Ref. 75 (*Sargassum*)	18.7ºS, 146.6ºE 18.7ºS, 146.5ºE 18.2ºS, 146.3ºE	88.6

*No nutrient information was available for this seaweed category.

**Some papers reported a general area, rather than specific coordinates. In that case, representative coordinates are provided in parenthesis.

Supplementary Table 4 | Details from Publications on Farmed Temperate Red Seaweed

Reference & Genus	Coordinates/Area*	NO_3 (μM)	Harvest Period	Mean Biomass/Harvest Yield** (g-DW m^{-2})
Ref. 76 (*Pyropia*)	31.5Nº to 33.7Nº, 120.5ºE to 121.7ºE	N/A	Nov. to Apr.	55.3 (B)
Ref. 77 (*Pyropia*)	Korea (34.2ºN to 38.3ºN, 126ºE to 130ºE)	N/A	Nov. to Apr.	30.9 (H)
Ref. 78 (*Porphyra*)	32.1ºN,121.6ºE	39	Sep. to Apr.	16 (H)
Ref. 52 (*Pyropia*)	China: Fujian (25.9ºN, 119.7ºE)	N/A	Nov. to Apr.	35.2 (H)

*Some papers reported a general area, rather than specific coordinates. In that case, representative coordinates are provided in parenthesis.

**Some papers reported harvested biomass (denoted by an "H"), while others reported measured biomass during the farming process (denoted by a "B").

Supplementary Table 5 | Details from Publications on Farmed and Wild Temperate Brown Seaweed

Reference & Genus	Farmed/Wild	Coordinates/Area*	NO_3 (μM)	Harvest Period	Mean Biomass/Harvest Yield**
Ref. 79 (*Laminaria*)	Wild	58ºN to 71ºN, 5ºE to 30ºE	N/A	N/A	976 g-DW m^{-2} (B)
Ref. 80 (*Laminaria* & *Saccharina*)	Wild	44.5ºN, 63.6ºW 44.5ºN, 63.5ºW 44.6ºN, 64.0ºW 44.5ºN, 63.9ºW	N/A	N/A	567.9 g-DW m^{-2} (B)
Ref. 81 (*Laminaria*)	Wild	West Norway (62.8ºN, 6ºE)	N/A	N/A	1694 g-DW m^{-2} (B)
Ref. 82 (*Laminaria*)	Wild	United Kingdom (59.0ºN, 3.3ºW) (58.9ºN, 3.3ºW) (56.5ºN, 5.5ºW) (56.4ºN, 5.6ºW) (50.3ºN, 4.1ºW) (50.3ºN, 4.1ºW) (50.3ºN, 4.0ºW) (51.8ºN, 5.2ºW)	N/A	N/A	1682 g-DW m^{-2} (B)
Ref. 43 (*Macrocystis*)	Wild	California: Mohawk Reef (34.47ºN, 120.1ºW) Arroyo Seco (34.4ºN, 119.7ºW) Arroyo Burro (34.4ºN, 119.7ºW)	N/A	N/A	547 g-DW m^{-2} (B)
Ref. 83 (*Laminaria*)	Wild	62.8ºN, 6.5ºE	N/A	N/A	1354 g-DW m^{-2} (B)
Ref. 84 (*Laminaria*)	Wild	50.4ºN, 4.1ºW	N/A	N/A	2042 g-DW m^{-2} (B)
Ref. 85 (*Macrocystis*)	Farmed	26.6ºS, 70.7ºW	3	May to May	639 g-DW m^{-1} (H)
Ref. 86 (*Macrocystis*)	Farmed	Chile: Flamenco Bay (26.6ºS, 70.7ºW)	N/A	May to Sep.	1960 g-DW m^{-1} (H)

Supplementary Table 5 – continued from previous page

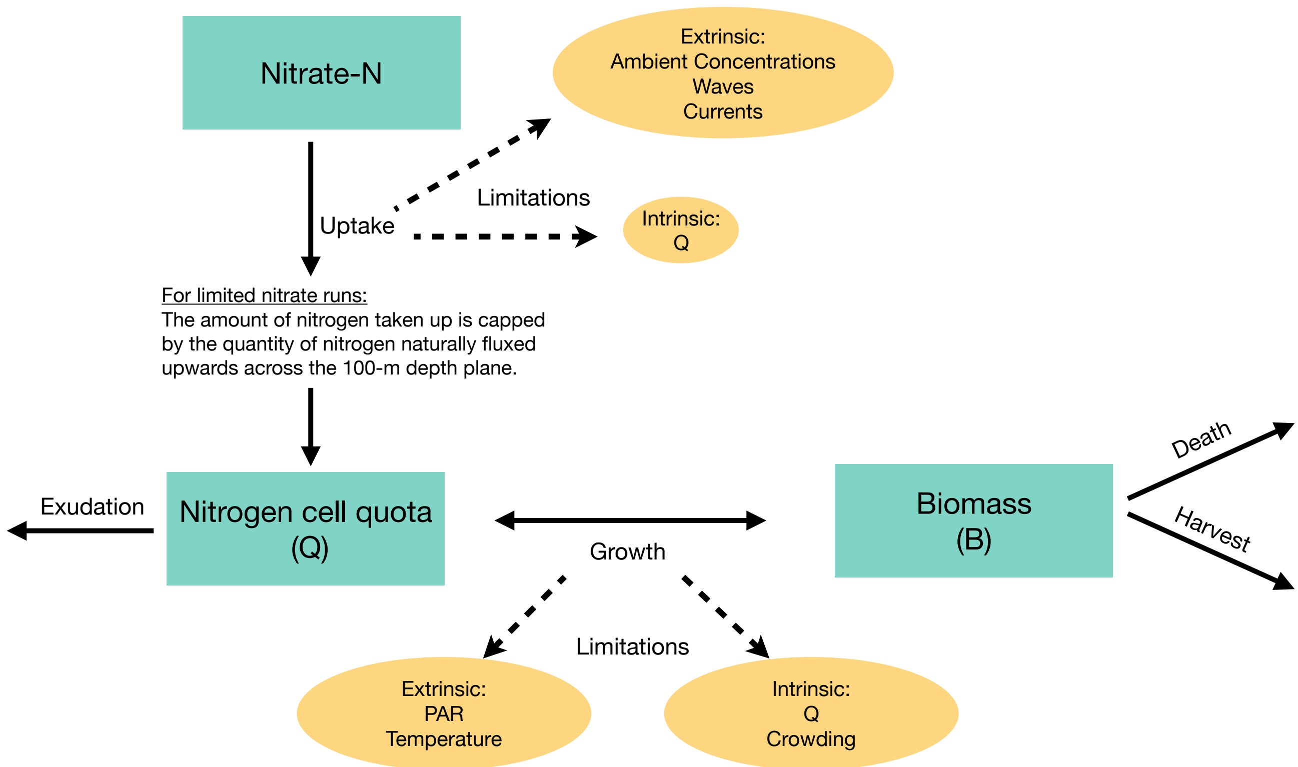
Reference & Genus	Farmed/Wild	Coordinates/Area*	NO_3 (μM)	Harvest Period	Mean Biomass/Harvest Yield**
Ref. 87 (*Saccharina*)	Farmed	60.2ºN, 5.2ºE 58.1ºN, 7.9ºE 63.7ºN, 8.9ºE 61ºN, 4.7ºE 69.8ºN, 19.0ºE	N/A	Feb. to Sep.	216 g-DW m^{-1} (H)
Ref. 25 (*Saccharina*)	Farmed	43.4ºN, 8.3ºW	N/A	Nov. to Apr.	2067 g-DW m^{-1} (H)
Ref. 88 (*Saccharina*)	Farmed	44.3ºN, 68.1ºW 43.8ºN, 69.6ºW	N/A	Nov. to May	1811 g-DW m^{-1} (H)
Ref. 89 (*Saccharina*)	Farmed	56.5ºN, 11.0ºE 56.8ºN, 9.1ºE 55.8ºN, 10.1ºE	8	Sep. to Jun.	95 g-DW m^{-1} (H)
Ref. 90 (*Saccharina*)	Farmed	34.2ºN, 126.7ºE	N/A	Dec. to Jul.	2250 g-DW m^{-1} (H)
Ref. 91 (*Saccharina*)	Farmed	6.3ºN, 6.9ºW	N/A	Nov. to Aug.	1442.5 g-DW m^{-1} (H)
Ref. 92 (*Saccharina*)	Farmed	43.5ºN, 3.8ºW	5	Mar. to Jun.	912 g-DW m^{-1} (H)
Ref. 93 (*Saccharina*)	Farmed	43.4ºN, 8.3ºW	7	Dec. to Apr.	1640 g-DW m^{-1} (H)
Ref. 94 (*Macrocystis*)	Farmed	42.4ºS, 73.6ºW	N/A	May to Nov.	2065 g-DW m^{-1} (H)
Ref. 95 (*Macrocystis*)	Farmed	41.8ºS, 73.1ºW	N/A	Apr. to Nov.	1440 g-DW m^{-1} (H)
Ref. 96 (*Macrocystis*)	Farmed	Tasmania: Okehampton Bay (42.5ºS, 148.0ºE) Great Taylor Bay (43.4ºS, 147.1ºE)	2.8	Apr. to Nov.	1200 g-DW m^{-1} (H)
Ref. 97 (*Saccharina*)	Farmed	58.1ºN, 11.5ºE	N/A	Nov. to May	207 g-DW m^{-1} (H)

*Some papers reported a general area, rather than specific coordinates. In that case, representative coordinates are provided in parenthesis.

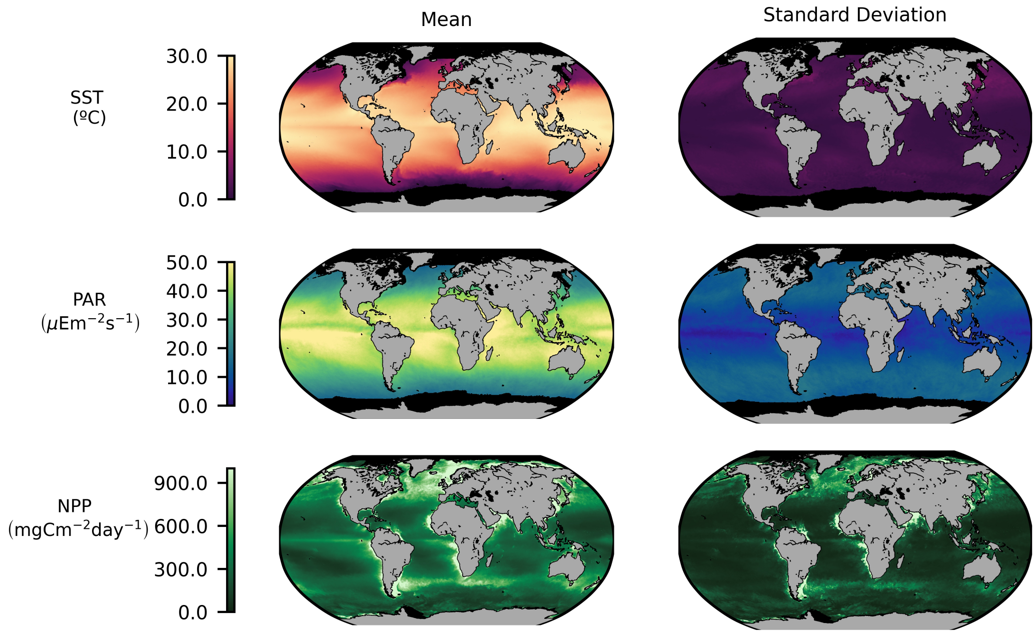
**Some papers reported harvested biomass (denoted by an “H”), while others reported standing stock (denoted by a “B”).

Supplementary Table 6 | Temperature Parameters Used in Equation 10 of the Main Manuscript

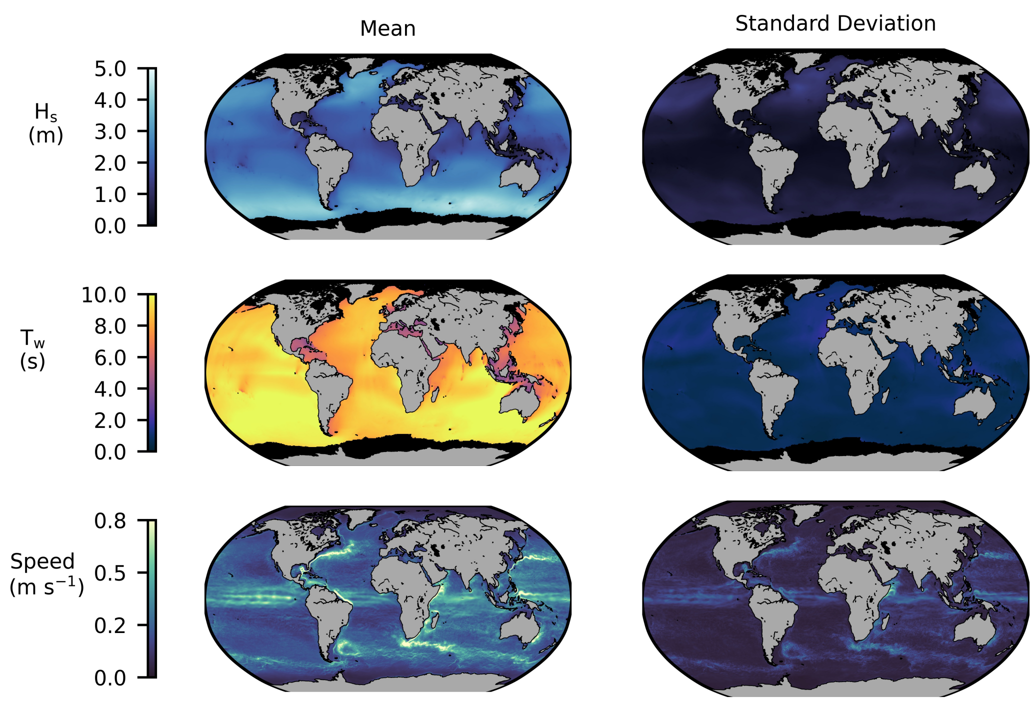
Genus	T_{opt} (°C)	β_1	β_2	References
Eucheuma	22.5-27.5	0.09	0.09	98–100
Sargassum	22.5-27.5	0.09	0.09	101, 102
Porphyra	12-17	0.03	0.09	34, 103
Macrocystis	13-18	0.04	0.05	104, 105
Saccharina	10-15	0.03	0.1	24, 26, 38



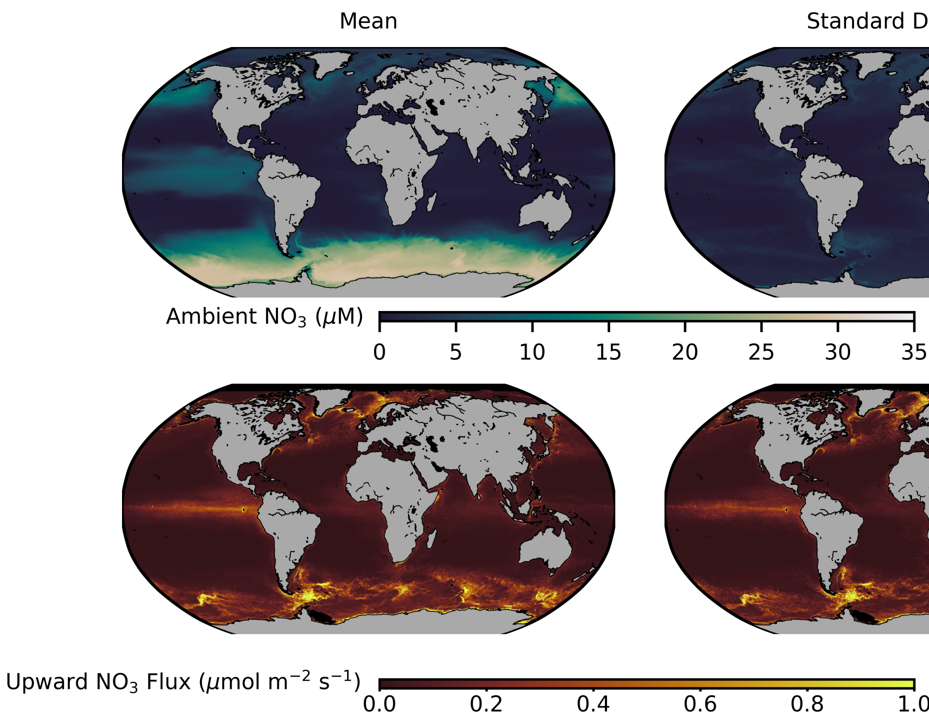
Supplementary Figure 1 | Schematic overview of G-MACMODS. For details, please refer to the Methods section of the manuscript.



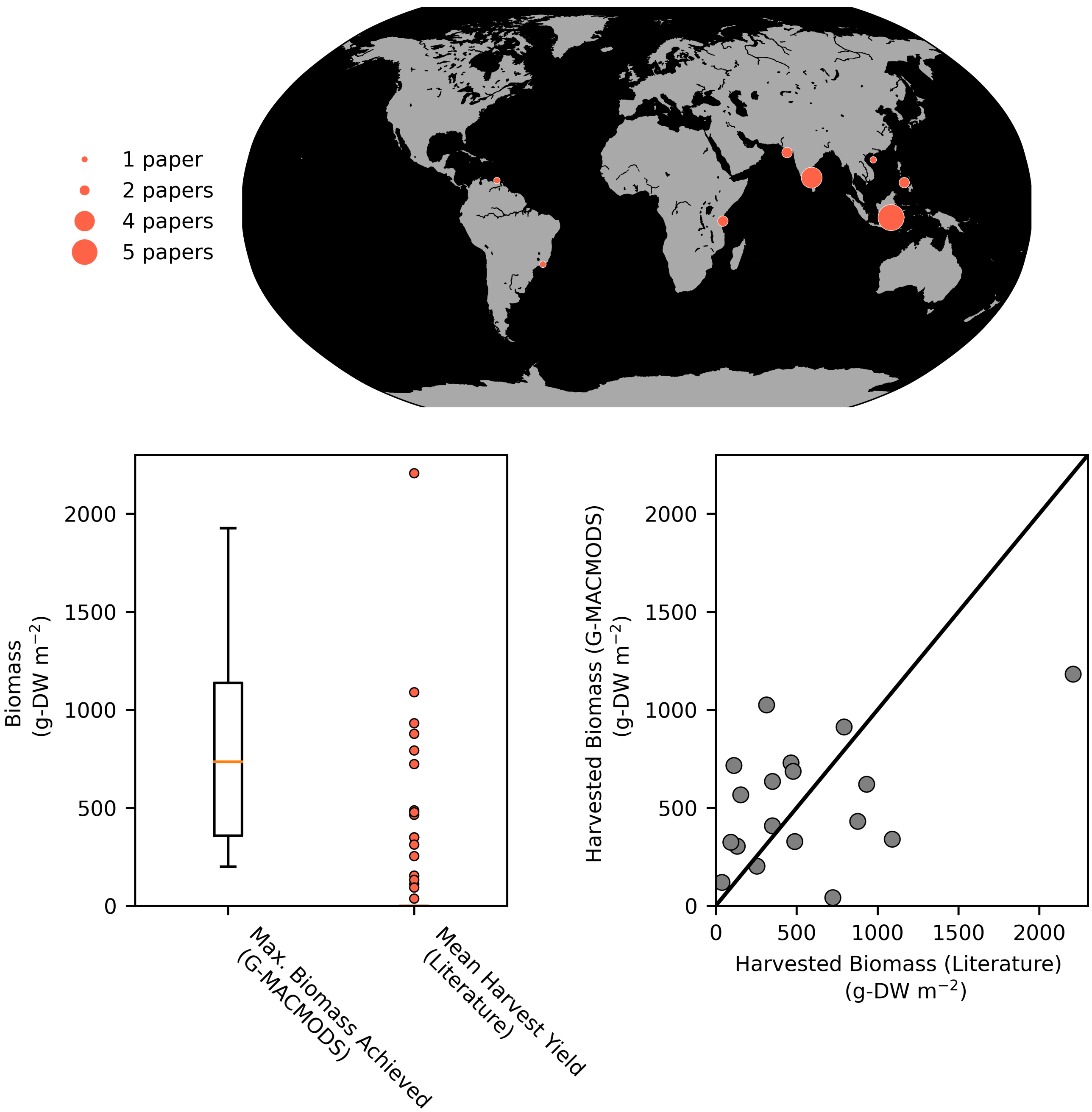
Supplementary Figure 2 | Satellite-derived variables. Temporal mean and standard deviation of the 2017 MODIS sea surface temperature (SST; top row), surface irradiance (PAR; middle row), and phytoplankton net primary productivity (NPP; bottom row).



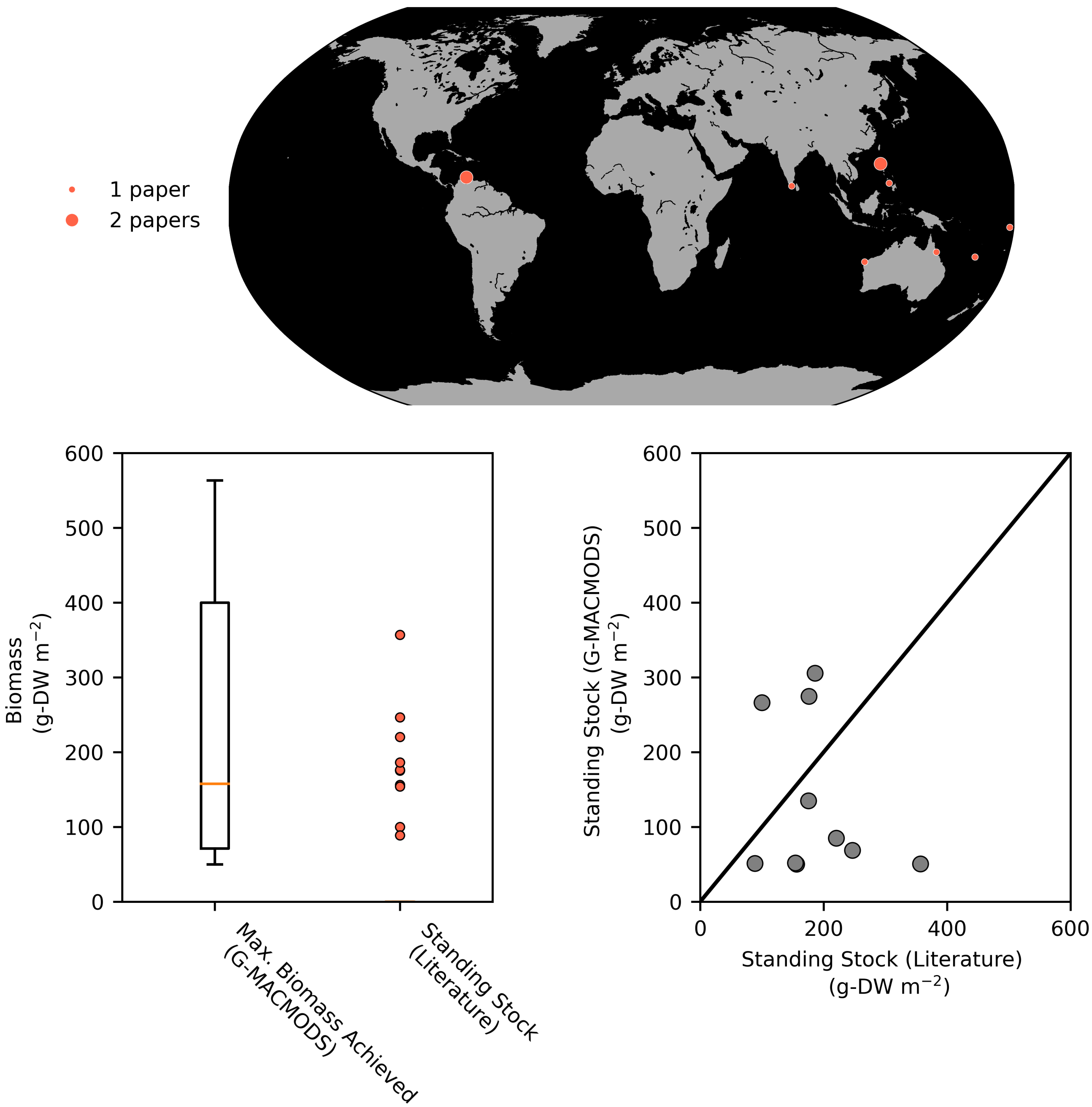
Supplementary Figure 3 | Hydrodynamic variables. Temporal mean and standard deviation of the 2017 significant wave height and mean wave period from ECMWF (top and middle row, respectively), as well as the 2017 surface current speed from HYCOM (bottom row).



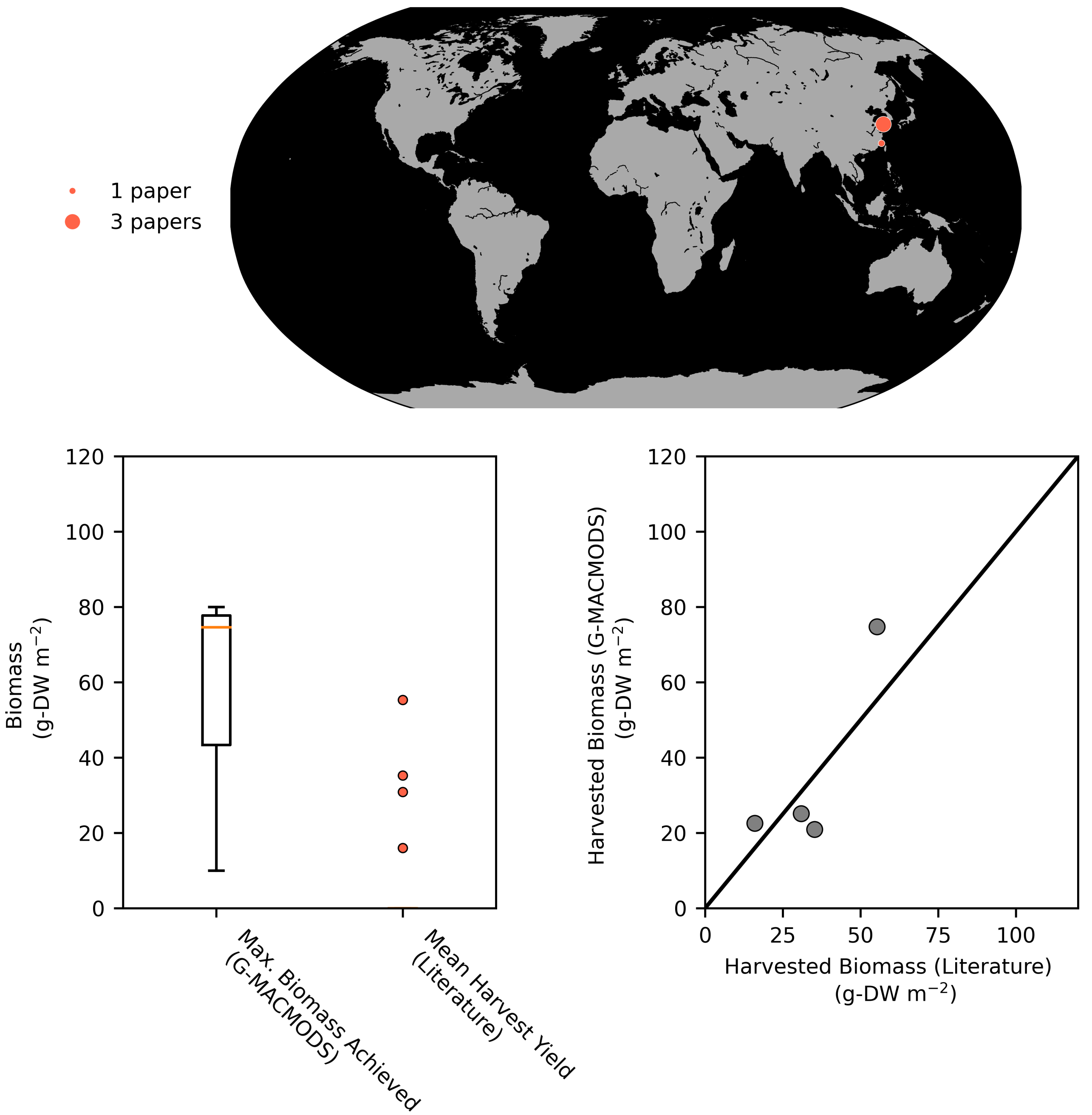
Supplementary Figure 4 | CESM NO_3. Temporal mean and standard deviation of the CESM depth-average ambient NO_3 concentrations (top row) and upward NO_3 flux across the 100-m depth plane (bottom row).



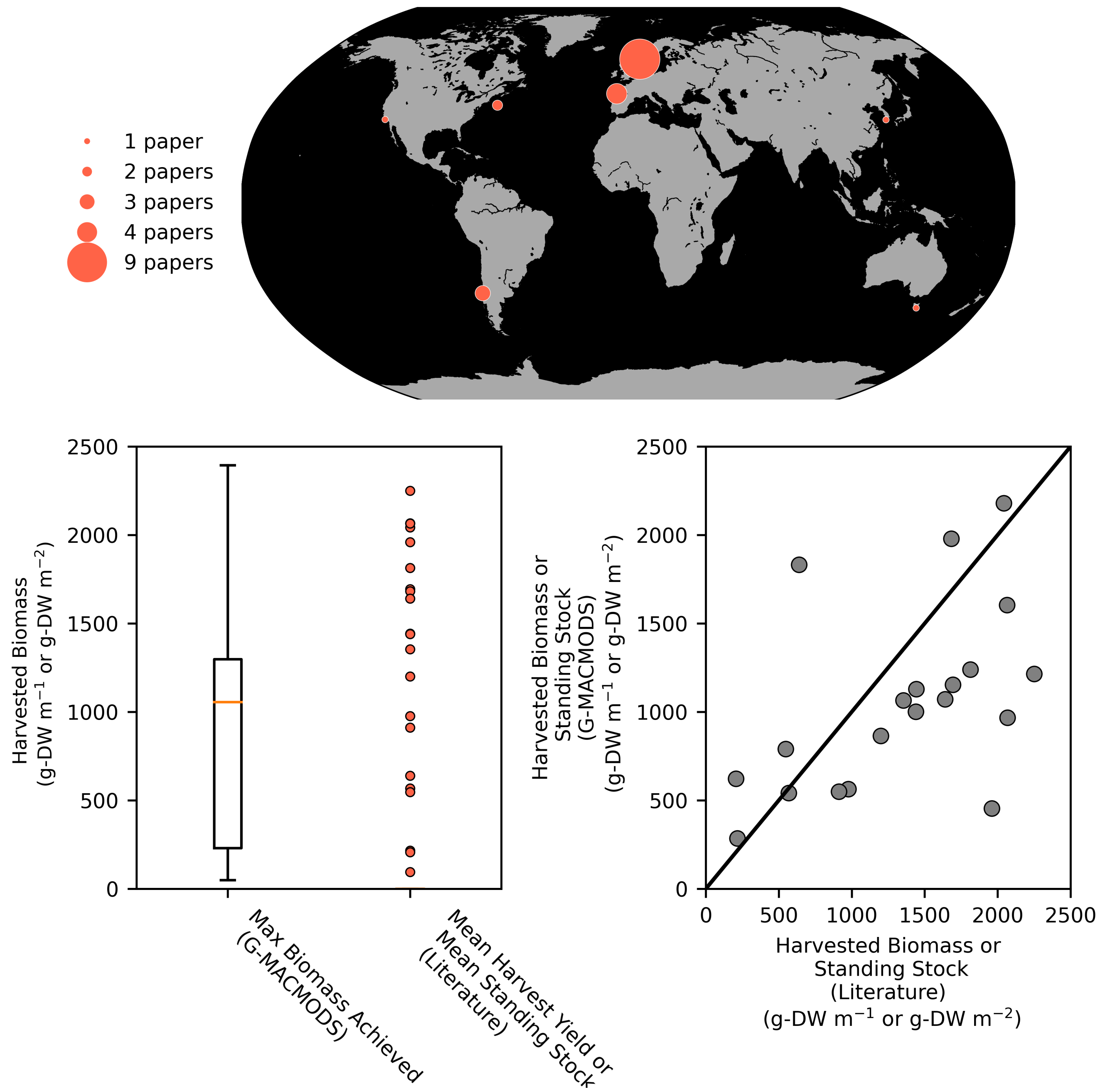
Supplementary Figure 5 | Model-field comparisons (tropical red seaweed). (a) Locations of farmed *Eucheuma* and *Kappaphycus* observations listed in Supplementary Table 2. (b) Boxplot of maximum biomass achieved by G-MACMODS over the course of a year as compared to the mean harvested biomass from the available literature (details in Supplementary Table 2). Boxplots represent values across all G-MACMODS grid cells. Only values above a biomass of 200 g-DW m^{-2} (the seed density for tropical red seaweed in G-MACMODS) are portrayed. (c) Comparison of the mean harvested biomass in the available literature to the maximum harvestable biomass in corresponding G-MACMODS locations. For details, please refer to the Methods section in the manuscript.



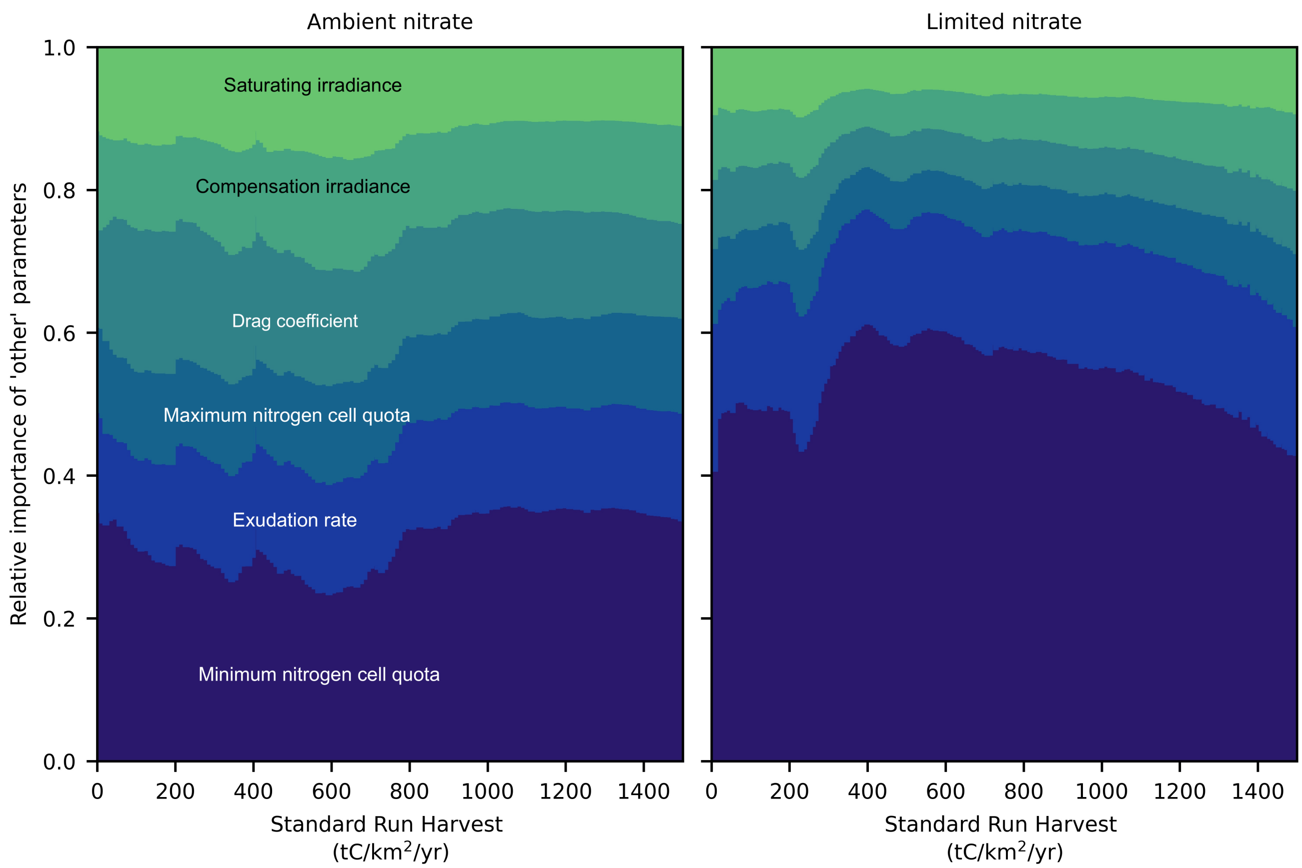
Supplementary Figure 6 | Model-field comparisons (tropical brown seaweed). (a) Locations of wild *Sargassum* observations listed in Supplementary Table 3. (b) Boxplot of maximum biomass achieved by G-MACMODS over the course of a year as compared to the mean standing stock from the available literature (details in Supplementary Table 3). Boxplots represent values across all G-MACMODS grid cells. Only values above a biomass of 50 g-DW m^{-2} (the seed density for tropical brown seaweed in G-MACMODS) are portrayed. (c) Comparison of the standing stock biomass in the available literature to the maximum biomass achieved across a year in corresponding G-MACMODS locations. For details, please refer to the Methods section in the manuscript.



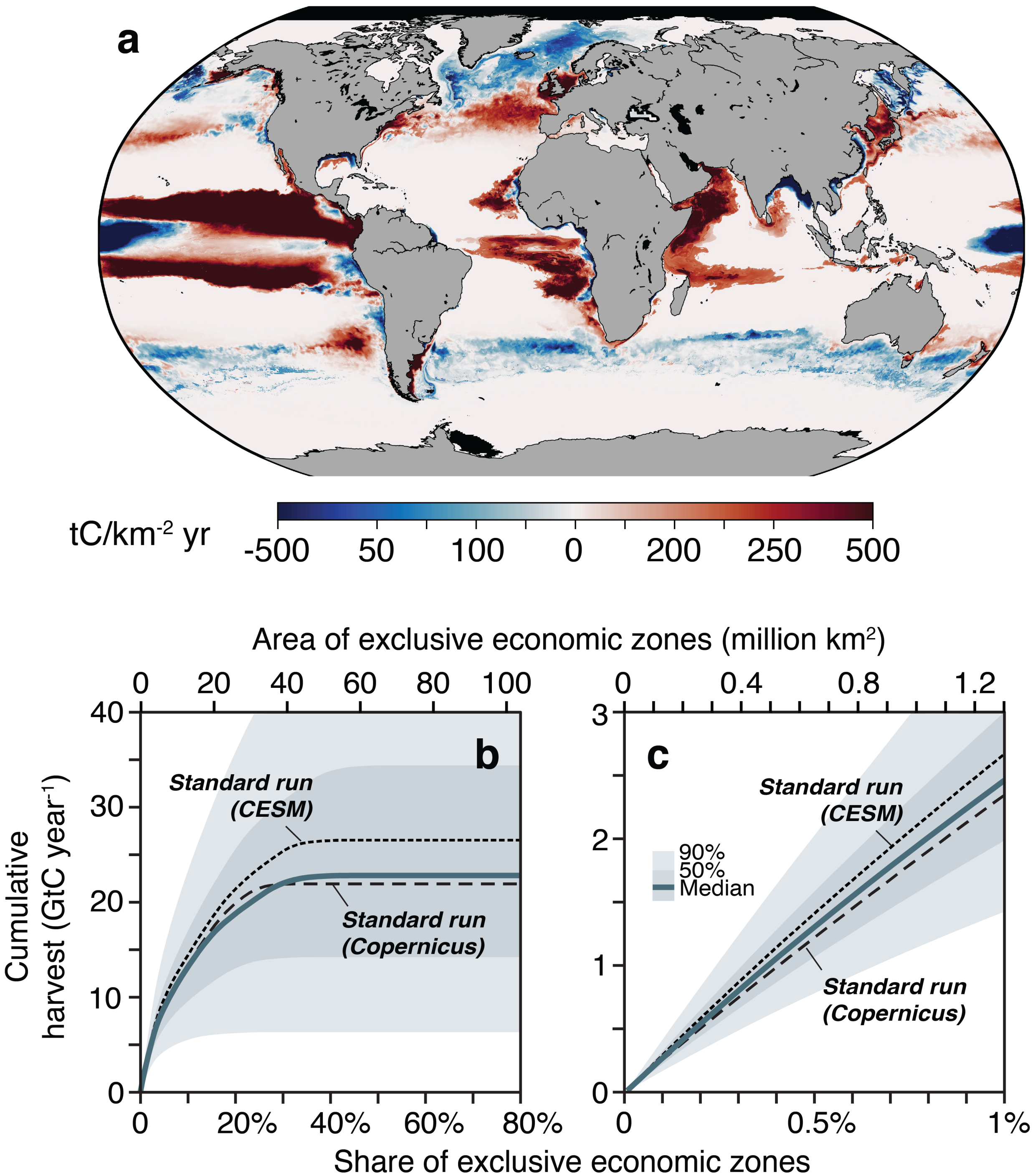
Supplementary Figure 7 | Model-field comparisons (temperate red seaweed). (a) Locations of farmed *Porphyra* and *Pyropia* observations listed in Supplementary Table 4. (b) Boxplot of maximum biomass achieved by G-MACMODS over the course of a year as compared to the mean harvested biomass from the available literature (details in Supplementary Table 4). Boxplots represent values across all G-MACMODS grid cells. Only values above a biomass of 10 g-DW m^{-2} (the seed density for temperate red seaweed in G-MACMODS) are portrayed. (c) Comparison of the mean harvested biomass in the available literature to the mean harvested biomass in corresponding G-MACMODS locations. For details, please refer to the Methods section in the manuscript.



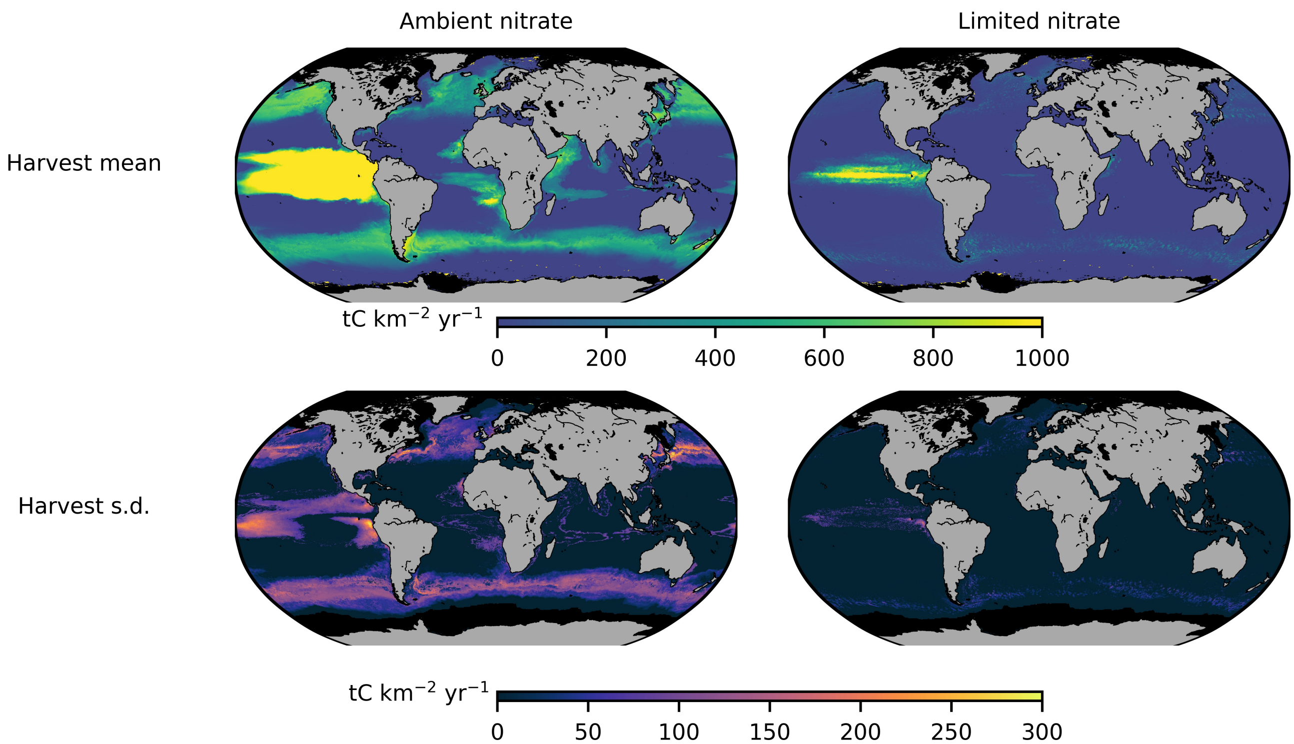
Supplementary Figure 8 | Model-field comparisons (temperate brown seaweed). (a) Locations of *Macrocystis* and *Saccharina* (farmed and wild) observations listed in Supplementary Table 5. (b) Boxplot of maximum biomass achieved by G-MACMODS over the course of a year as compared to the mean harvested biomass from the available literature (details in Supplementary Table 5). Boxplots represent values across all G-MACMODS grid cells. Only values above a biomass of 50 g-DW m^{-2} (the seed density for temperate brown seaweed in G-MACMODS) are portrayed. (c) Comparison of macroalgae biomass in the available literature (harvested yield or wild standing stock) to the biomass in corresponding G-MACMODS locations (harvested yield or maximum standing stock). For details, please refer to the Methods section in the manuscript.



Supplementary Figure 9 | Random forest results. Focused view of the ”other” category in Figure 3 of the main manuscript. The results have been normalized to reflect the relative importance of each parameter. For parameter information, please refer to Supplementary Table 1.



Supplementary Figure 10 | Alternate nutrient inputs. (a) Difference in annual harvested yield (in tC/km^2 year^{-1}) between standard runs executed with CESM nutrients and those carried out with nutrients distributed by the E.U. Copernicus Marine Service Information (DOI:10.48670/moi-00019; referred to as "Copernicus" in the figure above). Positive (negative) values denote locations where the G-MACMODS standard runs with CESM nutrient inputs resulted in larger (smaller) annual harvested yields than those carried out with Copernicus nutrients. (b–c) Cumulative distribution functions of annual seaweed carbon harvested relative to the share of global EEZs farmed. Results from the ambient standard runs using CESM and Copernicus nutrients are depicted as dashed lines. The solid line and surrounding shading denote the range of cumulative harvested yields resulting from the Monte Carlo simulations with CESM ambient nutrients (see the Methods section in manuscript). The harvested yields from the standard run carried out with Copernicus nutrients fall within the range of results from the Monte Carlo simulations.



Supplementary Figure 11 | Inter-annual harvest variability. Harvest yield temporal mean (top row) and standard deviation (bottom row) across 2002–2019.

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