



Supplement of

Ensemble simulation of the Last Glacial Maximum marine biogeochemistry and atmospheric $p\text{CO}_2$ drawdown due to the soft-tissue biological carbon pump

Chia-Te Chien et al.

Correspondence to: Chia-Te Chien (cchien308@ntu.edu.tw)

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Table S1. Atmospheric pCO₂, concentrations of globally-averaged dissolved inorganic carbon (DIC), O₂, NO₃⁻, dissolved Fe (dFe), and surface (0–50 m) NO₃⁻, dFe, and PO₄⁻. Values represent means and standard deviations of 20 simulations for each configuration.

Configuration	pCO ₂ (ppm)	DIC	O ₂	NO ₃ ⁻ (mmol m ⁻³)	surface NO ₃ ⁻	surface PO ₄ ⁻	dFe (nmol m ⁻³)	surface dFe
Pictl_PIallbgc	284.4±0.1	2308±8	179±9	31.1±1.0	5.7±0.5	0.62±0.07	596±14	398±14
Pictl_LGMFedep	261.7±4.4	2310±9	160±10	30.2±1.5	4.7±0.8	0.53±0.07	670±12	574±10
Pictl_LGMFesed	337.1±8.9	2301±7	234±4	21.6±0.6	4.8±0.4	0.97±0.06	387±9	110±11
Pictl_LGMPO ₄	285.3±1.0	2307±8	179±9	32.5±1.0	6.3±0.6	0.80±0.08	599±14	391±15
Pictl_LGMbdeni	283.7±0.6	2308±9	177±8	33.1±1.1	6.7±0.7	0.61±0.07	607±14	402±15
Pictl_LGMallbgc	283.6±4.7	2308±9	179±9	34.7±1.2	8.7±1.3	0.88±0.09	574±10	330±14
LGMatmctl_PIallbgc	250.2±3.2	2323±9	174±10	31.9±1.5	5.6±0.6	0.48±0.05	546±14	367±15
LGMatmctl_LGMFedep	221.2±5.4	2327±9	150±9	28.3±3.4	3.9±0.8	0.4±0.05	636±13	581±11
LGMatmctl_LGMFesed	313.9±7.2	2315±8	241±5	22.8±0.7	4.7±0.3	0.82±0.06	354±9	110±10
LGMatmctl_LGMPO ₄	250.5±3.3	2323±9	172±10	33.7±1.4	6.3±0.6	0.64±0.07	550±14	354±14
LGMatmctl_LGMbdeni	249.1±3.6	2323±9	172±10	32.9±1.8	6.2±0.7	0.48±0.05	555±14	371±16
LGMatmctl_LGMallbgc	240.9±4.8	2324±9	169±9	32.9±2.0	6.1±1.1	0.67±0.08	549±8	369±13
LGMatmws_PIallbgc	264.3±2.3	2322±9	174±10	31.3±1.3	6.0±0.6	0.56±0.06	556±14	349±15
LGMatmws_LGMFedep	234.5±5.2	2326±9	149±9	27.5±3.8	4.2±0.9	0.45±0.06	646±13	559±12
LGMatmws_LGMFesed	327.6±7.9	2314±8	239±5	21.8±0.6	4.7±0.3	0.91±0.06	359±9	101±10
LGMatmws_LGMPO ₄	265.0±2.4	2322±9	173±9	33.0±1.2	6.6±0.6	0.73±0.08	559±14	340±14
LGMatmws_LGMbdeni	263.1±2.8	2322±9	171±9	32.4±1.6	6.6±0.7	0.55±0.06	566±14	353±16
LGMatmws_LGMallbgc	257.5±4.1	2323±9	171±9	32.6±1.8	6.8±1.1	0.78±0.09	551±9	344±13
LGMatmpi_PIallbgc	265.3±1.6	2322±9	174±9	31.3±1.1	6.1±0.6	0.57±0.06	554±14	344±13
LGMatmpi_LGMFedep	241.7±4.4	2325±9	154±10	31.5±2.1	5.0±0.9	0.47±0.06	637±12	535±11
LGMatmpi_LGMFesed	325.7±8.2	2314±8	236±5	22.2±0.6	5.1±0.3	0.91±0.06	360±9	102±10
LGMatmpi_LGMPO ₄	265.6±1.3	2322±9	173±9	33.0±1.0	6.7±0.6	0.74±0.08	557±14	335±13
LGMatmpi_LGMbdeni	264.3±1.7	2322±9	172±9	32.7±1.3	6.8±0.7	0.57±0.06	563±14	345±14
LGMatmpi_LGMallbgc	258.5±4.0	2323±9	170±9	33.6±1.5	7.6±1.1	0.80±0.09	552±9	336±13

Table S2. Net primary production (NPP), particulate organic matter (POC) export at 130 m, nitrogen fixation, water-column and benthic denitrification (WC and benthic N-loss), and particulate organic matter nitrogen:carbon (pN:C), phosphorous:carbon (pP:C), and nitrogen:phosphorous (pN:P) ratios. Values represent means and standard deviations of the 20 simulations in each configuration. For pN:C, pP:C, and pN:P, values are medians and standard deviations for the surface ocean (0–50 m), with ice-covered areas excluded.

Configuration	NPP (Pg C yr ⁻¹)	POC export (Pg C yr ⁻¹)	N ₂ fixation (Tg N yr ⁻¹)	WC N-loss (Tg N yr ⁻¹)	Benthic N-loss (Tg N yr ⁻¹)	pC:N (mol mol ⁻¹)	pC:P (mol mol ⁻¹)	pN:P (mol mol ⁻¹)
PIctl_PIallbgc	63.9±8.3	9.2±0.6	186±44	40±33	144±14	8.0±0.5	134±8	16.5±0.7
PIctl_LGMFedep	67.0±9.0	10±0.6	253±61	100±49	151±14	9.1±0.6	146±8	17.1±0.6
PIctl_LGMFesed	36.3±5.4	5.6±0.4	86±6	0±0	85±6	6.8±0.5	87±10	12.1±0.7
PIctl_LGMPO ₄	65.2±8.2	9.3±0.6	192±48	43±36	148±16	7.7±0.5	121±8	15.5±0.7
PIctl_LGMbdeni	66.5±8.5	9.4±0.6	150±42	57±37	91±12	7.7±0.6	135±9	17.0±0.6
PIctl_LGMallbgc	57.0±6.5	8.7±0.5	109±25	21±16	87±12	6.6±0.3	110±7	16.0±0.7
LGMatmctl_PIallbgc	52.3±7.5	8.7±0.6	175±41	28±30	145±15	8.7±0.6	151±9	17.5±0.6
LGMatmctl_LGMFedep	54.4±8	9.5±0.6	246±61	90±50	154±13	10.1±0.6	172±12	18.3±0.6
LGMatmctl_LGMFesed	29.4±4.8	5.3±0.4	83±6	0±0	84±7	7.1±0.6	89±11	11.7±0.7
LGMatmctl_LGMPO ₄	54.2±7.4	8.8±0.6	186±45	33±34	151±16	8.2±0.6	135±8	16.3±0.6
LGMatmctl_LGMbdeni	53.7±7.5	8.8±0.6	148±40	42±34	104±13	8.5±0.7	153±10	17.9±0.6
LGMatmctl_LGMallbgc	46.5±5.7	8.3±0.5	129±30	26±20	104±13	7.4±0.7	120±6	16.0±0.6
LGMatmws_PIallbgc	53.5±7.4	8.8±0.6	177±42	29±30	146±15	8.2±0.6	139±9	16.8±0.6
LGMatmws_LGMFedep	56.6±8.0	9.7±0.6	263±69	106±58	155±14	9.7±0.6	158±10	17.5±0.5
LGMatmws_LGMFesed	29.1±4.7	5.2±0.4	81±6	0±0	82±6	7.0±0.6	85±11	11.2±0.7
LGMatmws_LGMPO ₄	55±7.2	8.9±0.6	185±44	33±33	151±16	7.8±0.6	125±8	15.6±0.6
LGMatmws_LGMbdeni	55.1±7.4	8.9±0.6	149±41	45±35	102±13	8.0±0.7	140±10	17.2±0.5
LGMatmws_LGMallbgc	47±5.6	8.3±0.5	126±29	26±20	100±13	7.0±0.5	113±7	15.4±0.7
LGMatmpi_PIallbgc	51.6±7.0	8.6±0.6	162±33	16±21	144±15	7.9±0.5	134±8	16.5±0.6
LGMatmpi_LGMFedep	54.5±7.6	9.5±0.6	199±49	41±35	152±14	9.0±0.6	152±8	17.6±0.6
LGMatmpi_LGMFesed	29.1±4.6	5.2±0.4	81±5	0±0	82±6	6.7±0.5	82±10	11.5±0.7
LGMatmpi_LGMPO ₄	53.1±6.9	8.7±0.6	171±36	19±23	150±16	7.5±0.5	121±7	15.5±0.6
LGMatmpi_LGMbdeni	53.4±7.2	8.7±0.6	130±31	28±24	100±13	7.6±0.6	135±9	17.0±0.5
LGMatmpi_LGMallbgc	46.8±5.6	8.3±0.5	115±23	16±13	99±13	6.8±0.4	112±6	15.7±0.7

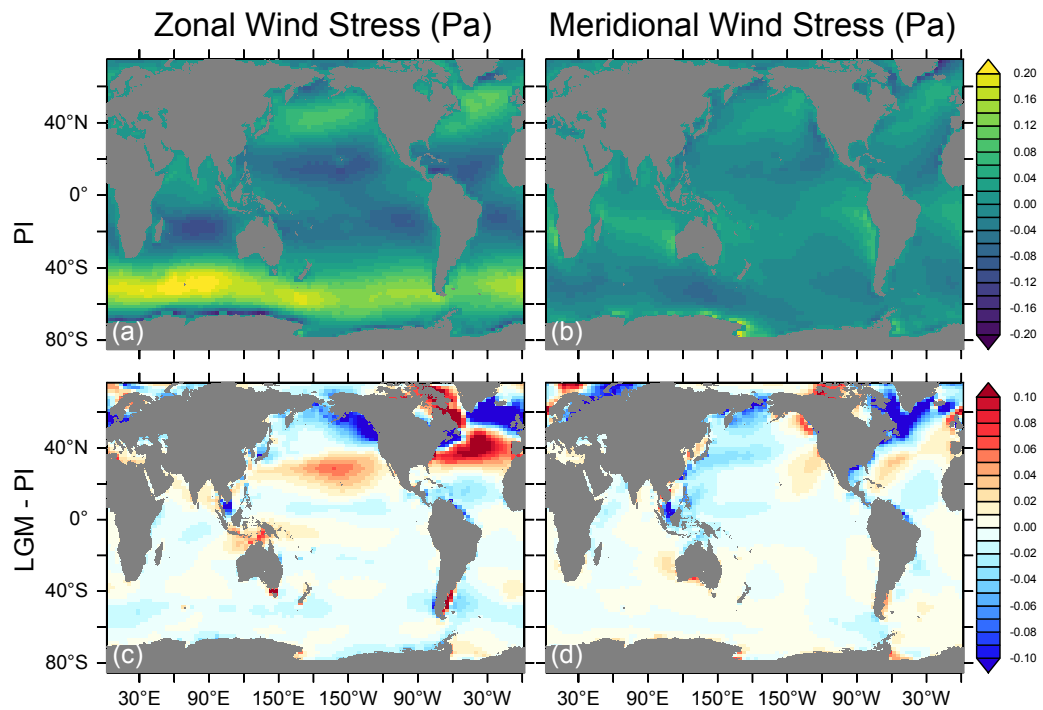


Figure S1. Zonal and meridional wind stress in the PI physical conditions (a, b) and the differences between LGM and PI (c, d).

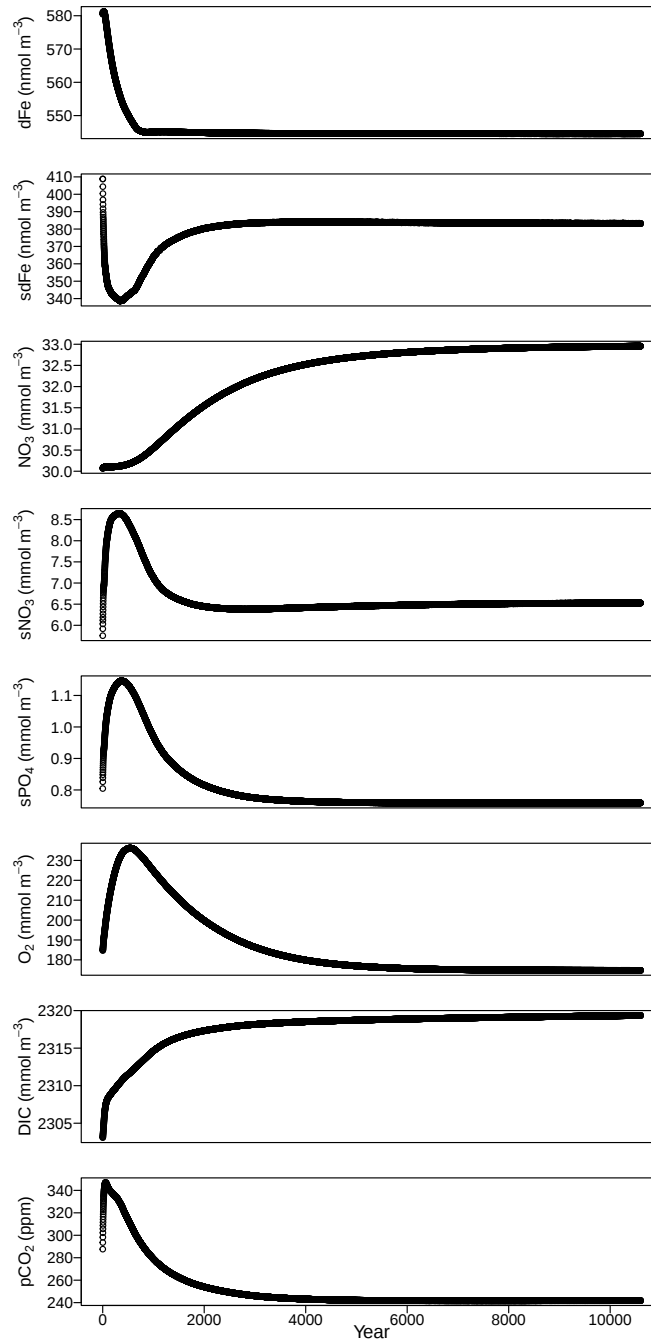


Figure S2. Globally averaged (a) dissolved iron (dFe), (b) surface dissolved iron (sdFe; 0–50 m), (c) NO_3^- , (d) surface NO_3^- (s NO_3^-), (e) surface PO_4^{3-} (s PO_4^{3-}), (f) O_2 , (g) dissolved inorganic carbon (DIC), and (h) atmospheric pCO_2 during the spin-up of one of the 20 LGMatmctl_LGMallbgc simulations. Most variables approach quasi-steady conditions after the initial adjustment, with only small residual drifts and negligible interannual variability.

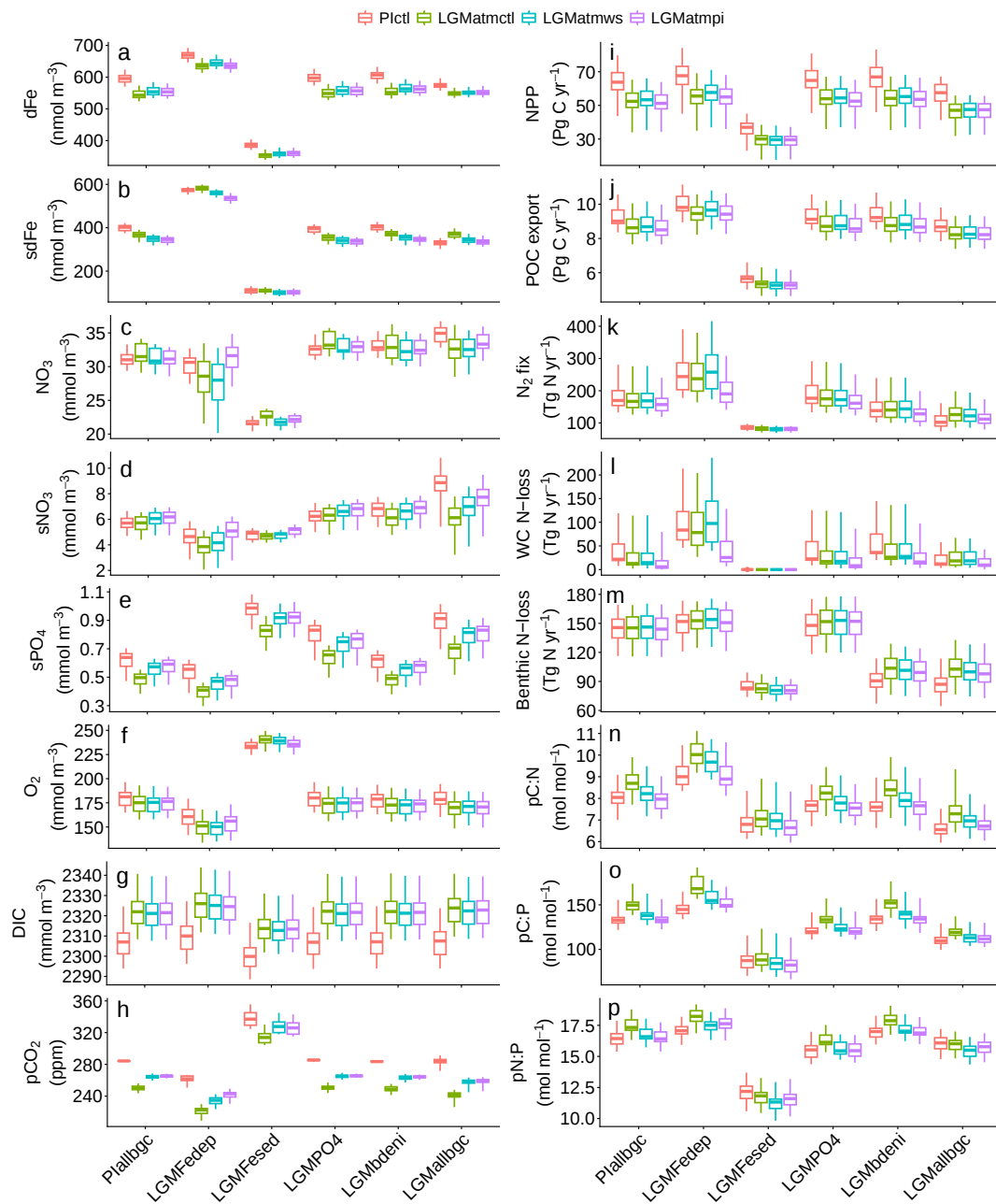


Figure S3. Globally-averaged (a) dissolved iron (dFe), (b) surface dFe (sdFe), (c) NO_3^- , (d) surface NO_3^- (sNO_3^-), (e) surface PO_4^{3-} (sPO_4^{3-}), (f) O_2 , (g) DIC, (h) pCO_2 , (i) globally-integrated net primary production (NPP), (j) particulate organic carbon (POC) export at 130 m depth, (k) N_2 fixation (N_2 fix), (l) water column denitrification (WC N-loss), (m) benthic denitrification (benthic N-loss), and global medians of surface (n) particulate carbon to nitrogen (pC:N), (o) carbon to phosphorus (pC:P), and (p) nitrogen to phosphorus (pN:P) ratios of the 20 simulations in each of the 24 model configurations. The lower, middle, and upper hinges indicate the first, second, and third quartiles, respectively, representing the spread of solutions of the 20 ensemble members. The whiskers here extend to the minimum and maximum values. Data from ice-covered area were excluded for the particulate elemental ratios, because there extremely low POC could cause unrealistically low pC:N and pC:P values.

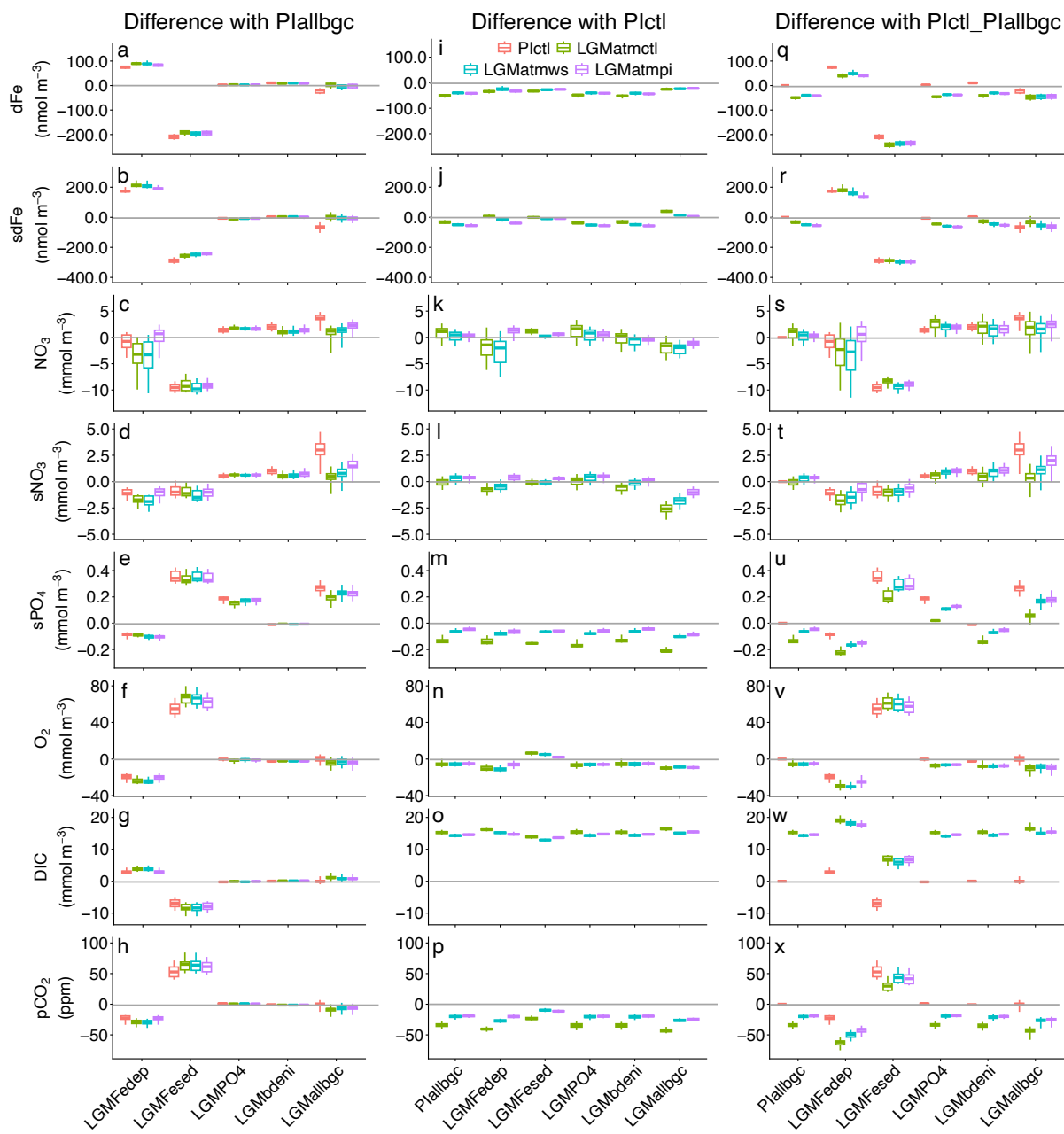


Figure S4. Differences in globally averaged tracer concentrations with respect to default biogeochemical conditions (PIallbgc, left panels), pre-industrial physical conditions (PIctl, mid panels), and the pre-industrial reference condition (PIctl_PIallbgc, right panels). The panels show (from top to bottom) globally-averaged dissolved Fe (dFe), surface dFe (sdFe), NO_3^- , surface NO_3^- (sNO_3^-), surface PO_4^{3-} (sPO_4^{3-}), O_2 , DIC, and atmospheric pCO_2 for the 20 simulations in each of the physical and biogeochemical configurations. The lower, middle, and upper hinges indicate the first, second, and third quartiles, respectively. The whiskers here extend to the minimum and maximum values. Horizontal gray lines indicate no difference from the tracer values under pre-industrial conditions.

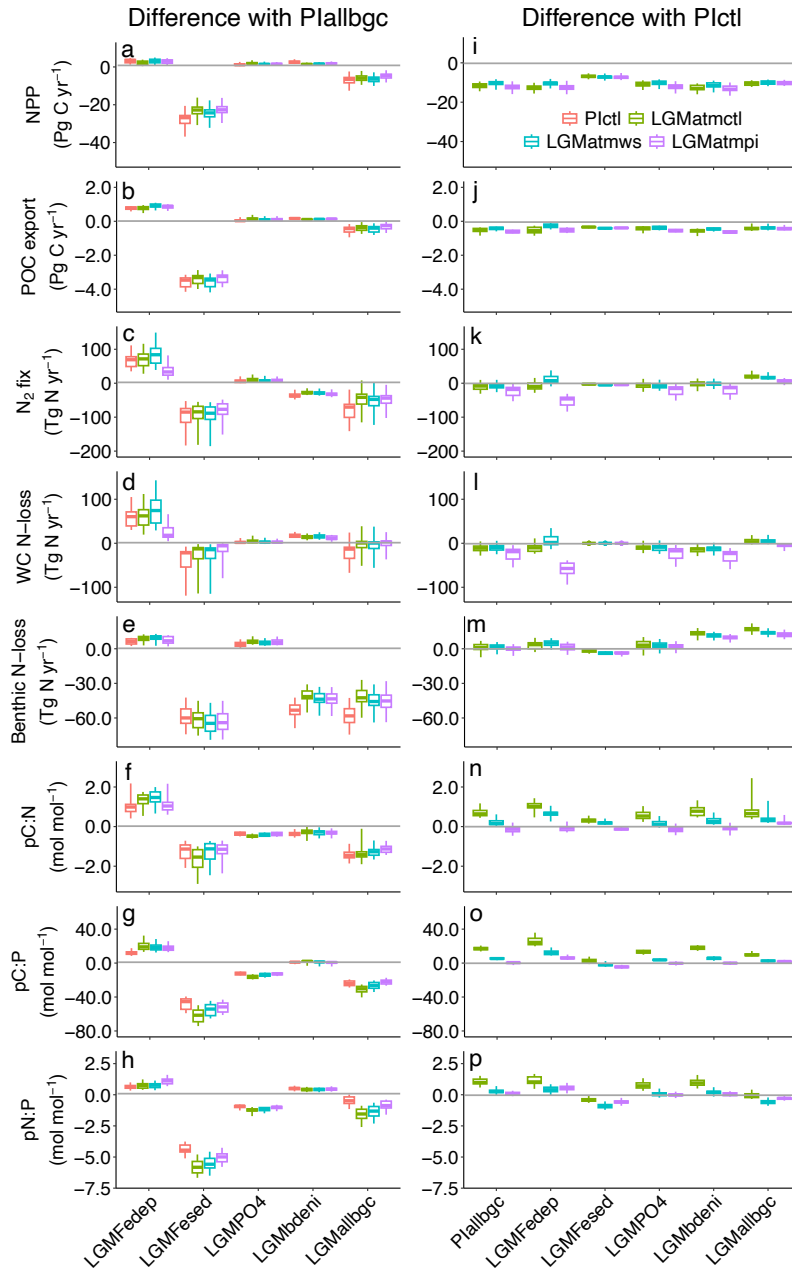


Figure S5. Differences in fluxes and elemental ratios with respect to default biogeochemical conditions (PIallbgc, left panels) and pre-industrial physical conditions (PIctl, right panels). The panels show (from top to bottom) net primary production (NPP), particulate organic carbon (POC) export, N_2 fixation (N_2 fix), water-column denitrification (WC N-loss), benthic N-loss, and particulate organic nitrogen to carbon (pN:C), phosphorus to carbon (pC:P), and nitrogen to phosphorus (pN:P) ratios for the 20 simulations in each of the physical and biogeochemical configurations. The lower, middle, and upper hinges indicate the first, second, and third quartiles, respectively. The whiskers here extend to the minimum and maximum values. The gray lines indicate zero change for each flux or ratio.

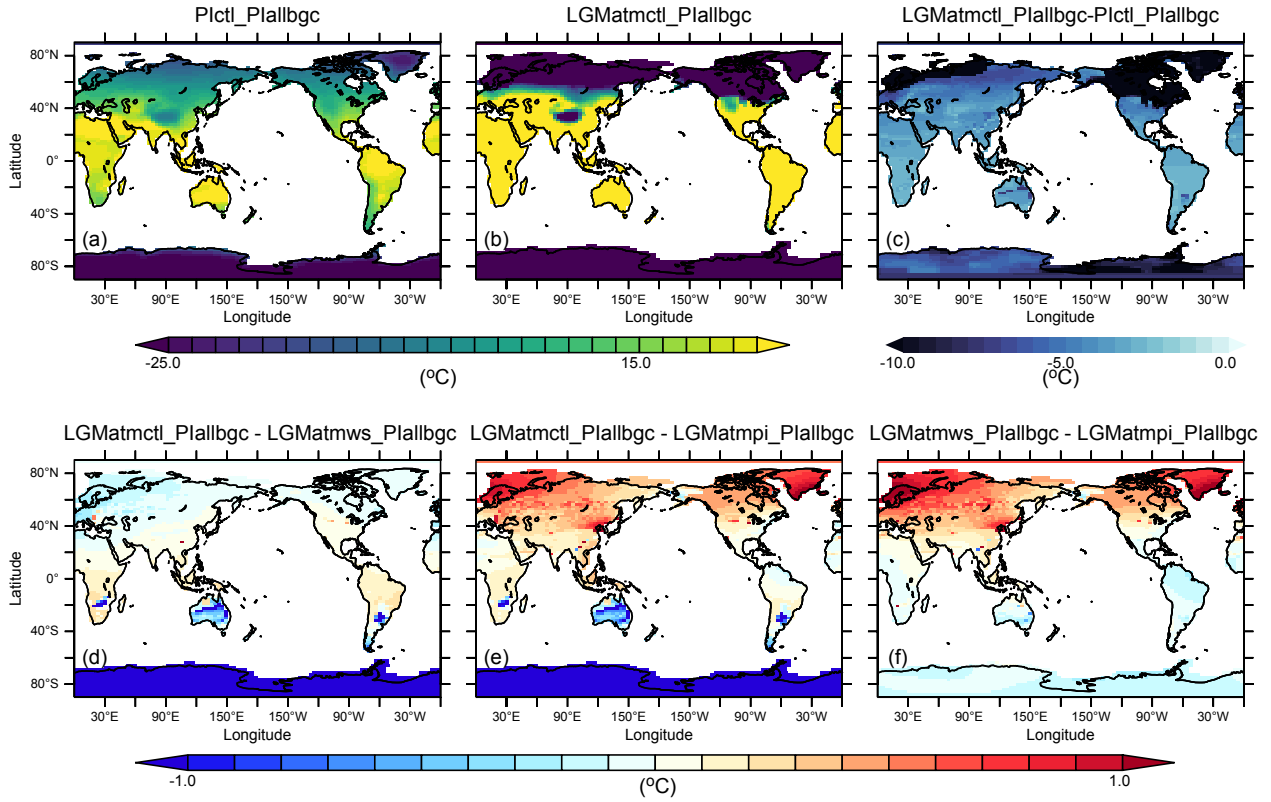


Figure S6. Land temperature in Pictl_PIallbgc (a), LGMatmctl_PIallbgc (b), and the difference between LGMatmctl_PIallbgc and Pictl_PIallbgc (c), between LGMatmctl_PIallbgc and LGMatmws_PIallbgc (d), between LGMatmctl_PIallbgc and LGMatmpi_PIallbgc (e), and between LGMatmws_PIallbgc and LGMatmpi_PIallbgc (f).

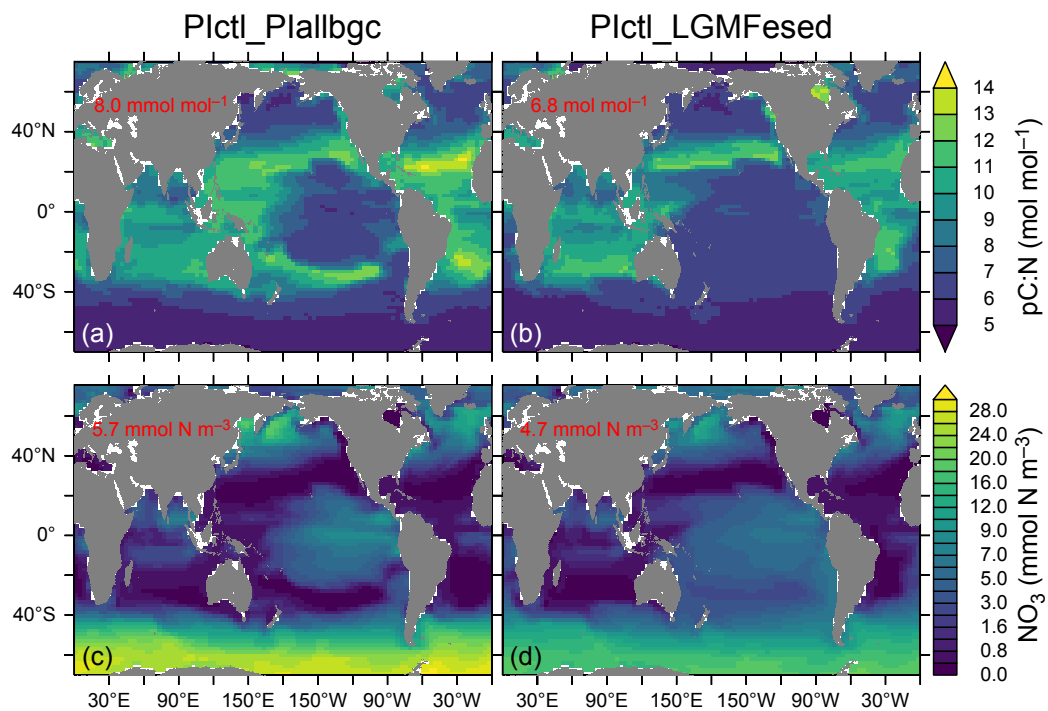


Figure S7. Surface pC:N (a, b) and NO_3^- (c, d) in Pictl_Plallbgc (a, c) and Pictl_LGMFesed (b, d) simulations. The panels show averages of 20 simulations for each configuration. Global medians of pC:N and means of NO_3^- are shown in red.

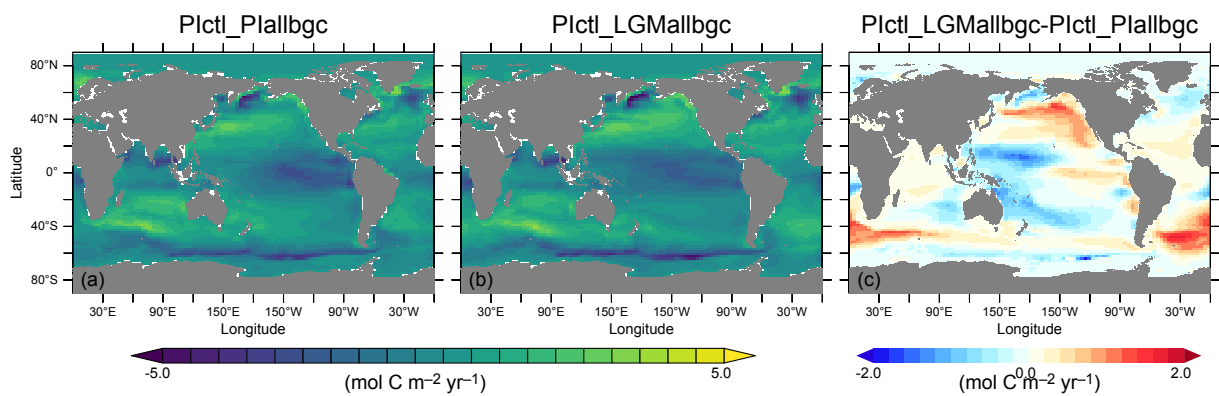


Figure S8. Air-sea CO₂ flux (positive downwards) in Pictl_Plallbgc (a), Pictl_LGMallbgc (b), and the difference (c).

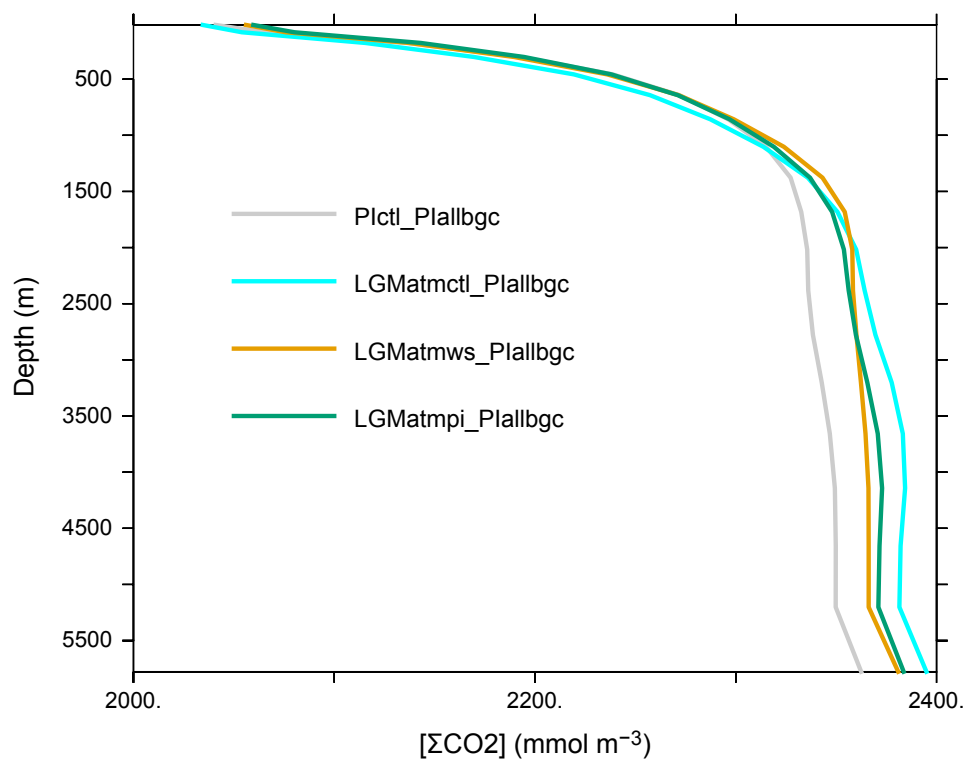


Figure S9. Globally-averaged vertical profiles of DIC (ΣCO_2) in Pictl_PIallbgc, LGMatmctl_PIallbgc, LGMatmws_PIallbgc, and LGMatmpi_PIallbgc simulations.

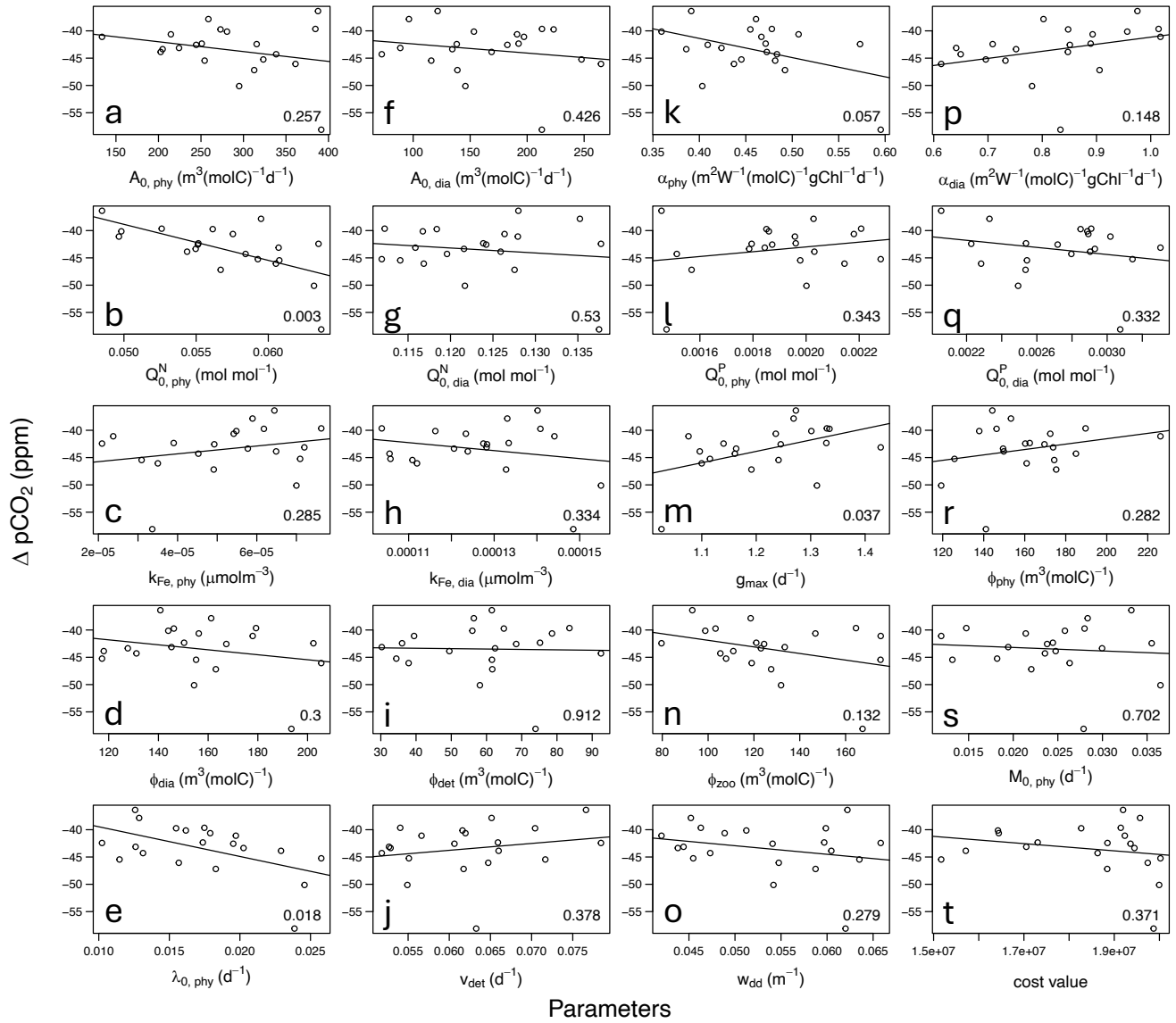


Figure S10. Changes in atmospheric $p\text{CO}_2$ from Pictl_Piallbgc to LGMatmctl_LGMallbgc in the 20 simulations with different parameter settings. P values are listed inside each panel.

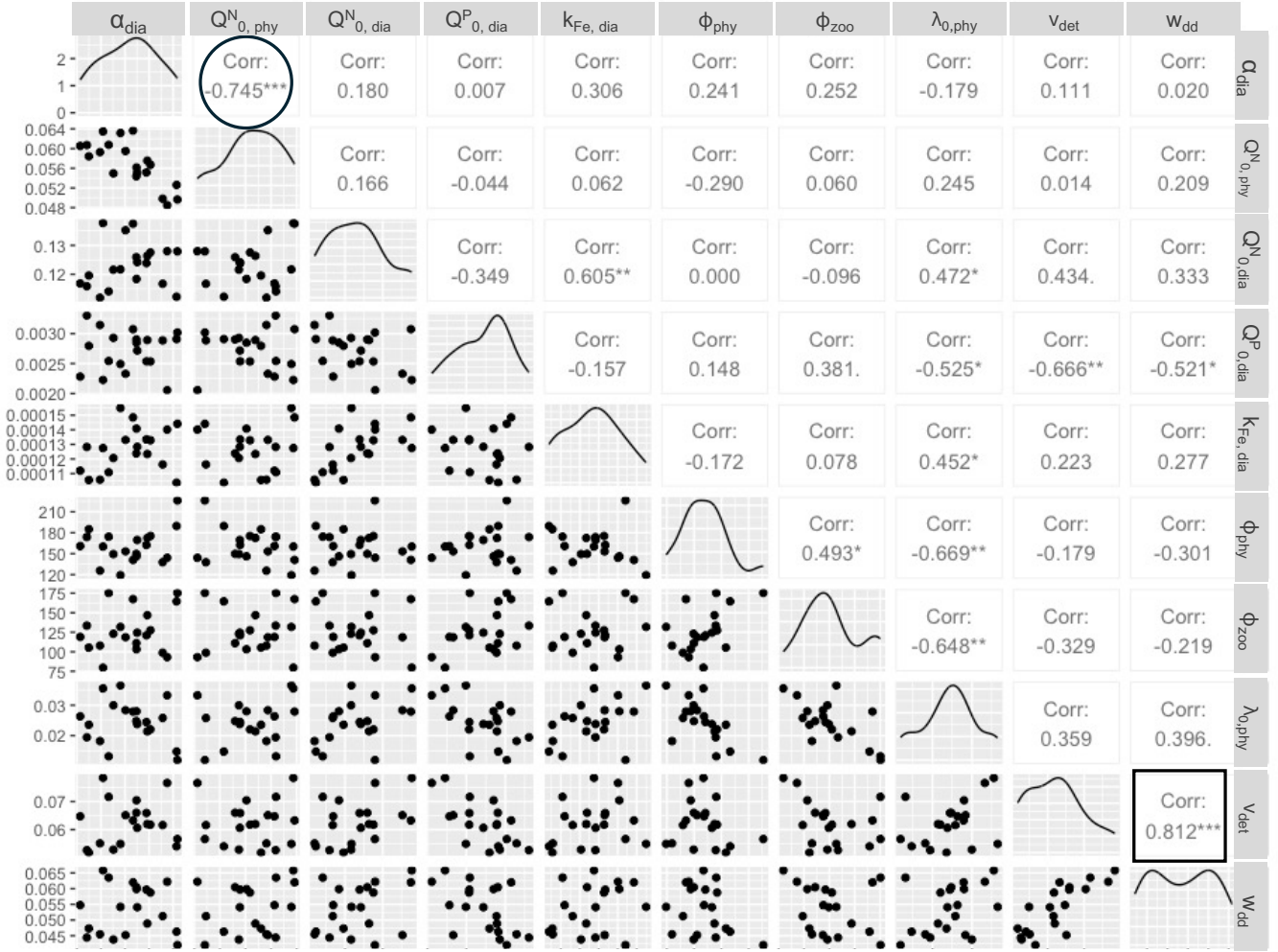


Figure S11. Relationships between the parameters applied in the model experiments. Numbers in the top right panels indicate the correlation coefficient between the parameters, and the asterisks show the statistical significance, where *: $p < 0.05$, **: $p < 0.01$, and ***: $p < 0.001$. Bottom left and the diagonal panels are scatter and density plots for each of the parameter pairs, respectively. The square and circle indicate the most positively and negatively correlated parameter pairs, respectively. Parameters are excluded if none of their pairwise correlation coefficients exceed an absolute value of 0.6.