

Supplementary Materials for Zooplankton grazing is the largest source of uncertainty for marine carbon cycling in CMIP6 models

Tyler Rohr,^{1,2*} Anthony J. Richardson,^{3,4} Andrew Lenton,⁵
Matthew A. Chamberlain,⁵ Elizabeth H. Shadwick^{1,5}

*To whom correspondence should be addressed; E-mail: tyler.rohr@utas.edu.au.

This PDF Includes

Supplementary Discussion 1

Supplementary Figures S1-S13

Supplementary Tables S1-S4

Supplemental Discussion 1

Sensitivity of Marine Carbon Cycling to the Functional Response Curve

Sensitivity in CMIP6 Simulations

While the functional response curve for models with a single pPFT and zPFT (i.e. iHAMOCC, CMOC, WOMBAT) is defined in two dimensions with just two parameters (Figure S1), it becomes a heavily parameterized, multivariate function of up to 7 state variables and 17 parameters in models with more PFTs and multiple prey options (Figure 1, 2). Instead of trying to analyse the functional response across so many dimensions, we define the Apparent Functional Response (AFR) as the emergent relationship between community-averaged zooplankton specific grazing rates and total phytoplankton biomass. Defining the AFR using the emergent model solution (rather than just the innate equations specified in the grazing formulation) allows us to integrate out the dynamical influence of trophic cascades (60) and prey selectivity (23–25) which can feedback to shape community composition and thus zooplankton specific grazing rates. This is important because the emergent food-web in BGC model has been shown to readily diverge from the one that was intended (18).

The AFR is thus determined semi-empirically by plotting total phytoplankton biomass against the median community-averaged zooplankton specific grazing rate simulated in all grid cells within the top 200 m of the water column with the specified total phytoplankton concentration (Figure S10). Note, total phytoplankton biomass is the sum of all pPFTs and the community averaged zooplankton specific grazing rate is the biomass-weighted mean specific grazing rate of all zPFTs. Importantly, the AFR is not a one-to-one function of total biomass in models with more than one zPFT and one pPFT. This is because community-averaged specific grazing rates can further vary with community composition and non-phytoplankton prey options. To quantify

this uncertainty, in Figure S10 we overlay the frequency distribution of qualifying grid cells and include uncertainty bounds defined by the 25th and 75th percentile specific grazing rates for each total phytoplankton concentration. At first glance, comparing the AFR of CMIP6 models illustrates just how dramatically community averaged grazing dynamics diverge across models, not just at the observed median phytoplankton concentration (as per the PGI) but across a large range of phytoplankton concentrations (Figure S10a, g).

Additionally, it becomes clear that models can achieve prey refuge (upward concavity) via different techniques, either explicitly via active-switching (BFM5.2, COBALTv2) or implicitly via a large prey thresholds (PISCESv2) or a type III response curve (WOMBAT, OECO-v2, CMOC, MEDUSA). Notably, most models with multi-trophic food webs (BFM5.2, COBALTv2, PISCESv2) experience a very fast escalation in grazing rates beyond their apparent threshold for prey refuge compared the more gradual (but still quadratic) escalation of models with a simple single-prey type III response. This highlights how the single-prey response does an imperfect job of implicitly averaging across the dynamics of a diverse community, even if it can still offer some degree of prey refuge. MEDUSA2.1, however, exhibits a nearly linear AFR with extremely tight uncertainty bounds after an initial period of refuge. In other words, it is dynamically very similar to a single-prey Mayzaud–Poulet response (74). It is not immediately obvious why this is, but worth noting it is the only multi-trophic model in which large phytoplankton have only a single predator. On the other hand, all models without active switching and a type II response curves retain high grazing rates on low phytoplankton concentrations (MARBL, iHAMOCC, CanOE).

Further, some models also appear to exhibit non-maximal feeding, or an apparent reduction in specific grazing rates with increasing prey. True non-maximal feeding (25) is only possible in models with active switching (COBALTv2 and BFM5.2). However a local maxima in community averaged grazing rates also appears to occur in PISCESv2, MARBL, and to a lesser degree

CanOE, none of which include active switching. This can be explained by the fact that the AFR does not represent the simple additional of prey, but is an empirical and emergent property the integrates over the influence of both community compositing and temperature. So, for example, the appearance of non-maximal feeding could actually be related to the emergence of higher biomass water in colder, nutrient rich high latitude waters, where grazing is strongly limited by temperature. This appears to be the case in PISCESv2 and MARBL which have temperature limited grazing, but must be explained by shift in community composition in CanOE.

Finally, we examine the association between the AFR and marine carbon cycling and community composition. In Figure S11 we replace the frequency distributions overlaid on the AFR in Figure S10 with the mean NPP, export ratio, grazing efficiency, fraction of small phytoplankton, fraction of small zooplankton, and zooplankton to phytoplankton ratio simulated all qualifying grid-cells. There is a great deal to unpack here, and we recommend others extends this analysis; however, we wish to highlight a few key points.

First, models without prey refuge are more susceptible to competitive exclusion. This is well known (22–25, 97, 108) and seen clearly in MARBL, where the phytoplankton community is almost always entirely dominated by the small or large pPFT (Figure S11d). Interestingly though, there is much more biodiversity in CanOE, which uses an Ivlev function response without prey refuge. The key difference is a second explicit zooplankton group in CanOE. This highlights how the emergent food-web derived from single zPFT but multi pPFT structure can readily collapse to something more like single pPFT food-web with regionally specialized pPFTs (18).

Second, there are clear ecological niches in which community composition and associated trophic controls appear to modify export and grazing efficiency. However, it is not clear that there is a consistent pattern explaining their emergence across models. In CanOE (Figure S11h, i, j, k), COBALT (Figure S11ll, mm, nn, oo), and to a lesser degree MEDUSA2.1 (Figure S11n, o, p, q) high export efficiency is associated with the dominance of large phytoplankton and small

zooplankton, lower than average grazing rates, and weak grazing efficiency. Importantly, small zooplankton can not consume large phytoplankton in any of these models. This explains how larger pools of more efficiently exporting large biomass are able to emerge. However, it is not obvious how predators with very little prey are able to persist. It is possible that these niches, which occurs with relatively low frequency (Figure S10h, i, m) are capturing a brief period of species succession. On the other hand, BFM5.2 PISCESv2 also exhibit a high export niche, but here it is associated with a much larger proportion of large zooplankton biomass.

Lastly, while most models exhibit the largest NPP during low frequency periods (Figure S10) of high phytoplankton biomass and rapid grazing (Figure S11; Column 1), consistent with canonical bloom dynamics, MEDUSA2.1 appears able to sustain near-peak NPP with less phytoplankton biomass and slower grazing (Figure S11m). Interestingly, this niche is associated with a ‘valley’ in which the larger zooplankton group dominates (Figure S11q) amidst a more balanced phytoplankton community (Figure S11p). On either side of this valley the smaller zooplankton dominate either because of abundant prey (small phytoplankton) or a predator pool diverted by more preferred prey (large phytoplankton). The larger zooplankton group in MEDUSA2.1 has a substantially a slower saturation grazing rate than the smaller zooplankton group which may help drive elevated NPP during short, high biomass events that get averaged out in the monthly mean fields.

Moving forward, much more detailed analysis is needed to identify biogeochemically important niches that can emerge in these models and discern if they are biases associated with unforeseen artifacts in the food web and grazing structure or plausible natural phenomena. If the former, they should be avoided. If the later, we should work to understand how climate drivers may or may not favour their emergence in a warming ocean.

Sensitivity in a Controlled Sensitivity Study

Unlike some of the more complex CMIP6 formulations addressed above, In WOMBAT, the ‘shape’ of the multivariate grazing formulation can only be modified three ways: the value of two parameters ($K_{1/2}$ and $g_{\max}$) and the selection of a functional response curve (typically Type II or III). Here we use the WOMBAT sensitivity study to control for other inter-model differences and explicitly examine the sensitivity of carbon cycling to isolated variations in each of three most fundamental components of the grazing formulation.

Separating the sensitivity of $\overline{NPP}$, $\overline{EP}$, and $\overline{GSP}$ into isolated changes to $K_{1/2}$ and $g_{\max}$, we find that carbon cycling is substantially more sensitive to proportional changes in $K_{1/2}$ than $g_{\max}$ (Figure S12). Decreasing $K_{1/2}$ and increasing $g_{\max}$ both increase the PGI (Figure S1), leading to a monotonic decrease in $\overline{NPP}$ (Figure S12a) and $\overline{EP}$ (Figure S12c) and a dome-shaped response in $\overline{GSP}$ (Figure S12b). Increasing $g_{\max}$ shifts the inflection point in $\overline{GSP}$ towards higher $K_{1/2}$ values. However, in all cases, productivity is nearly twice as sensitive to $K_{1/2}$ than $g_{\max}$. On average, doubling or halving $K_{1/2}$ yields a 7.4 PgC yr^{-1} change in $\overline{NPP}$, a 1.8 PgC yr^{-1} change in $\overline{EP}$, and a 3.7 PgC yr^{-1} change in $\overline{GSP}$, compared to 3.9, 0.9, and 2.1 PgC yr^{-1} for proportional changes to $g_{\max}$. This occurs because $K_{1/2}$ more directly modifies the shape of the response curve at low phytoplankton concentrations, where phytoplankton population dynamics are most sensitive to changes in grazing (39).

We repeated the sensitivity experiments with a type II response (see “Methods”) and found the sensitivity of all variables to the PGI increases dramatically when a type II response is employed (Figure S8; dashed lines). For example, the collapse in $\overline{NPP}$ from 40 to 10 PgC yr^{-1} requires increasing the PGI by roughly 40-fold (from $\sim .02$ to $.76 \text{ d}^{-1}$) when using a type III response, but only a 5-fold (from $\sim .05$ to $.29 \text{ d}^{-1}$) when using a type II response. This is because, compared to a type III response, a type II response prescribes faster grazing rates below $K_{1/2}$ (thus eliminating prey refuge) even though takes longer to reach saturation above

$K_{1/2}$. Thus, it is the change in grazing rates at low prey concentrations that win out, again highlighting how marine carbon cycling is more sensitive to the rate of grazing prescribed at low-moderate prey concentrations than when nearing saturation during a bloom. Assuming that the global ocean is neither entirely nutrient replete or deplete, this means there is a much narrower range of viable grazing parameterizations when employing a type II response.

1 Supplemental Figures

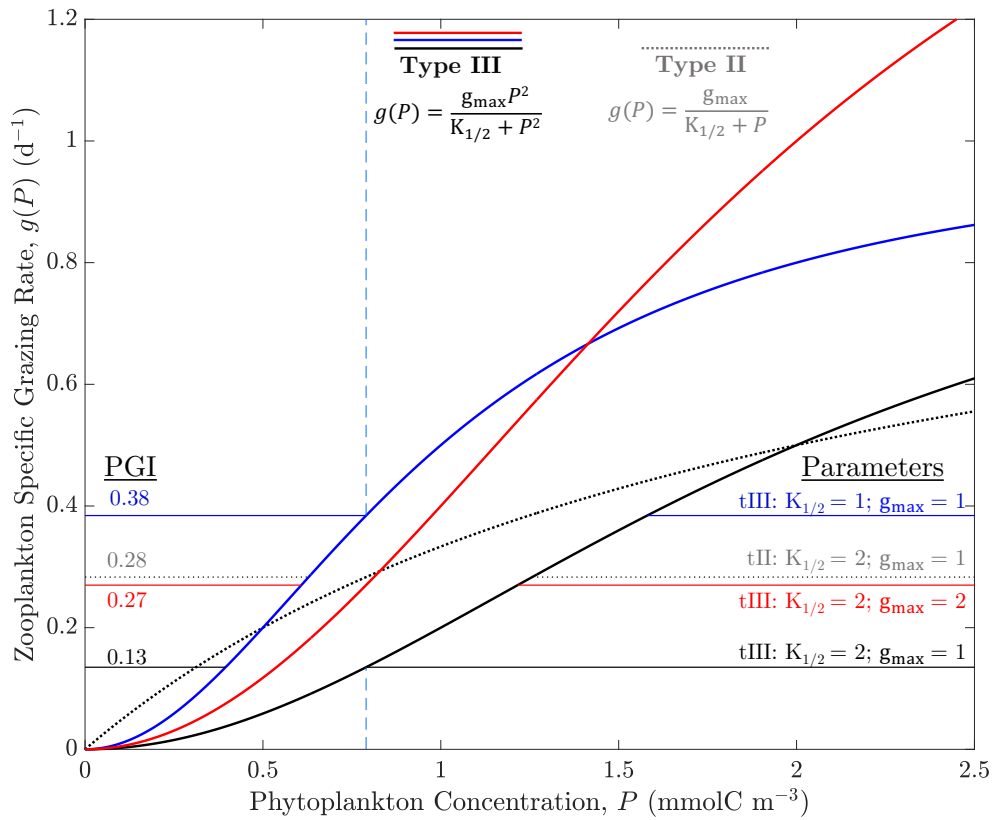


Figure S1: Schematic of the functional response curve and the Prescribed Grazing Index (PGI). A type III single-prey response curve, parameterized with $K_{1/2}=2$ and $g_{\max}=1$ is shown in black along with it's associated PGI. The PGI is computed by evaluating the curve the global, median phytoplankton concentration ($0.79 \text{ mmolC m}^{-3}$; dashed light blue line). It is then shown how the response curve, and its associated PGI, is modified by halving $K_{1/2}$ (blue), doubling $g_{\max}$ (red), or switching to a type II response (grey).

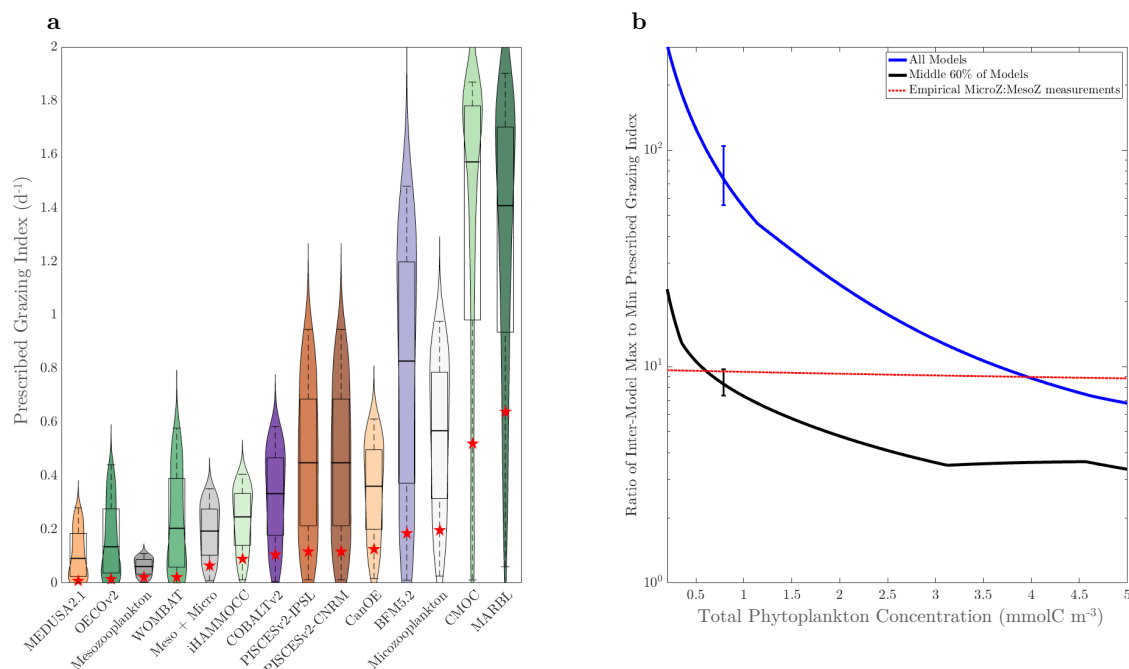


Figure S2: Sensitivity of the Prescribed Grazing Index (PGI) to the standardized prey field. Instead of using the global observed median phytoplankton concentration (Table S1), the PGI was evaluated at a range of total phytoplankton concentrations from 0.01-5 mmolC m^{-3} . **a.** A box and whisker plot (median and IQR with whiskers outlier threshold) over a violin plot of the distribution of PGI values computed when evaluated at each concentration, for each model. Red stars refer to the PGI when evaluated at the global median. **b.** The ratio of the maximum to minimum PGI across all models and the middle 60% of models is plotted against the phytoplankton concentration at which the PGI was evaluated. Uncertainty bars show the range when of the max to min ration when the PGI is computed at the observed global median $\pm 25\%$.

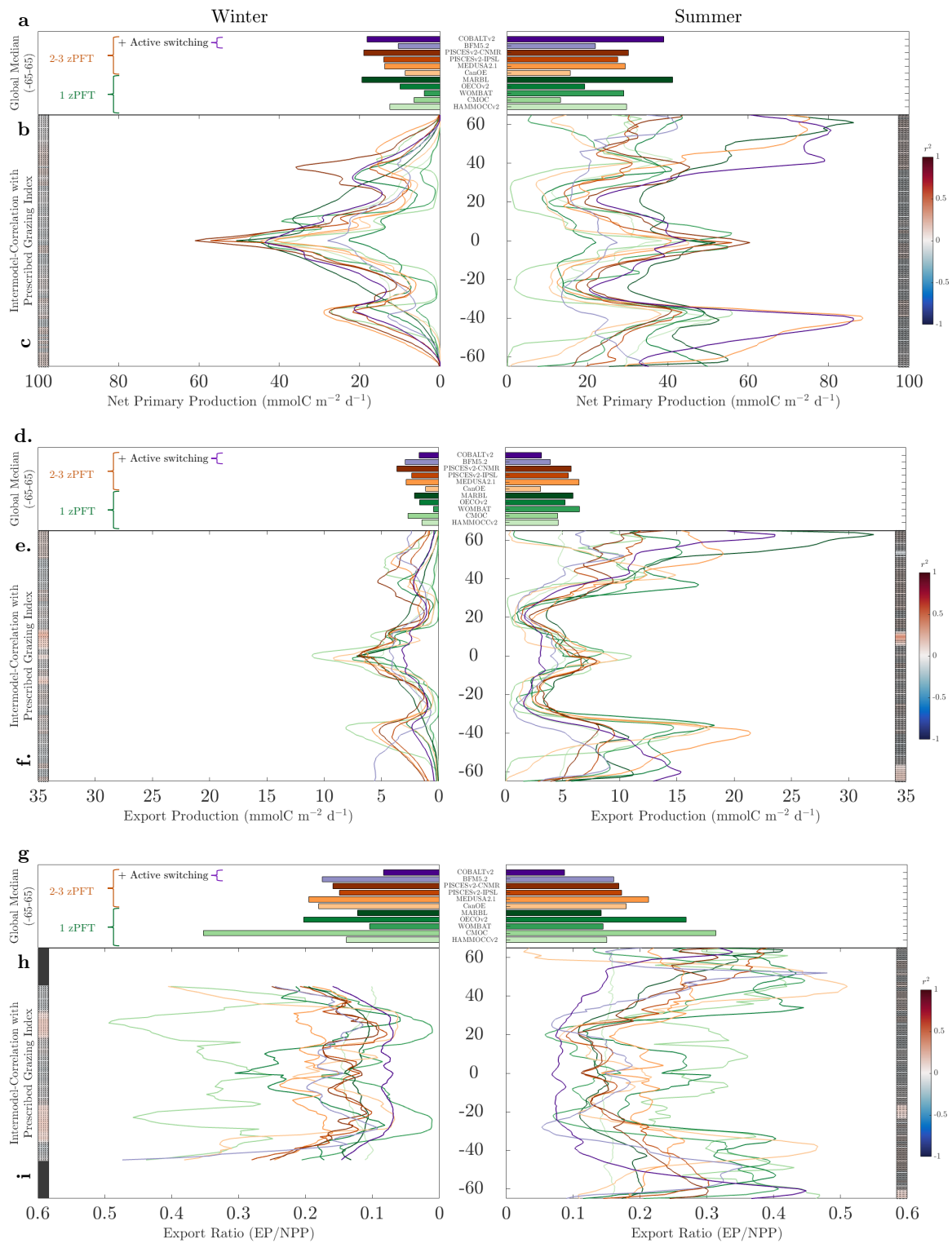


Figure S3: Inter-model variability in productivity. Distribution of median **a-c**) NPP, **d-f**) EP, and **g-i**) export ratio. Otherwise, as per Figure 5.

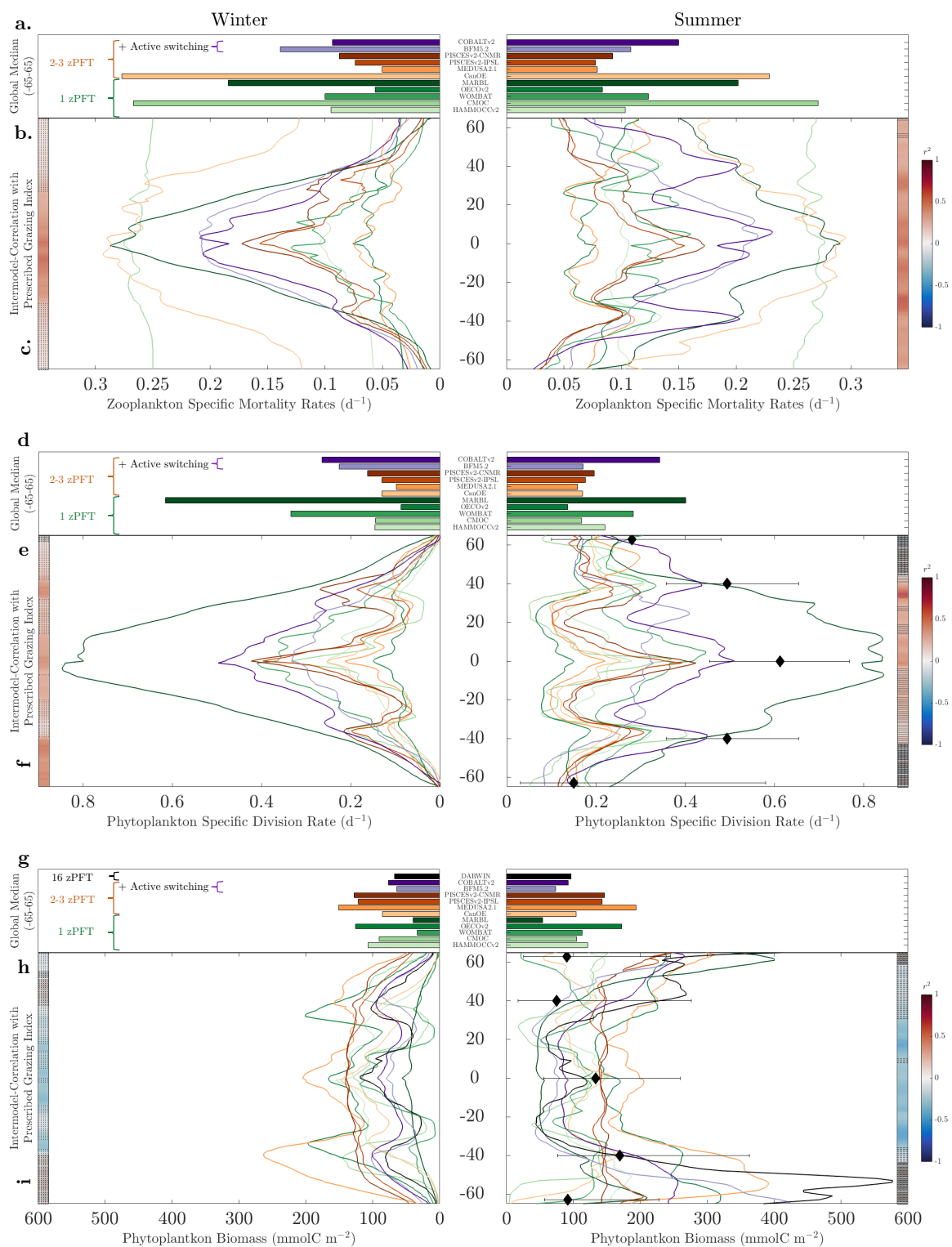


Figure S4: Inter-model Vvariability in population dynamics. Distribution of median **a-c**) zooplankton specific mortality rates, **d-f**) phytoplankton specific division rates, and **g-i**) phytoplankton biomass. Otherwise, as per Figure 5.

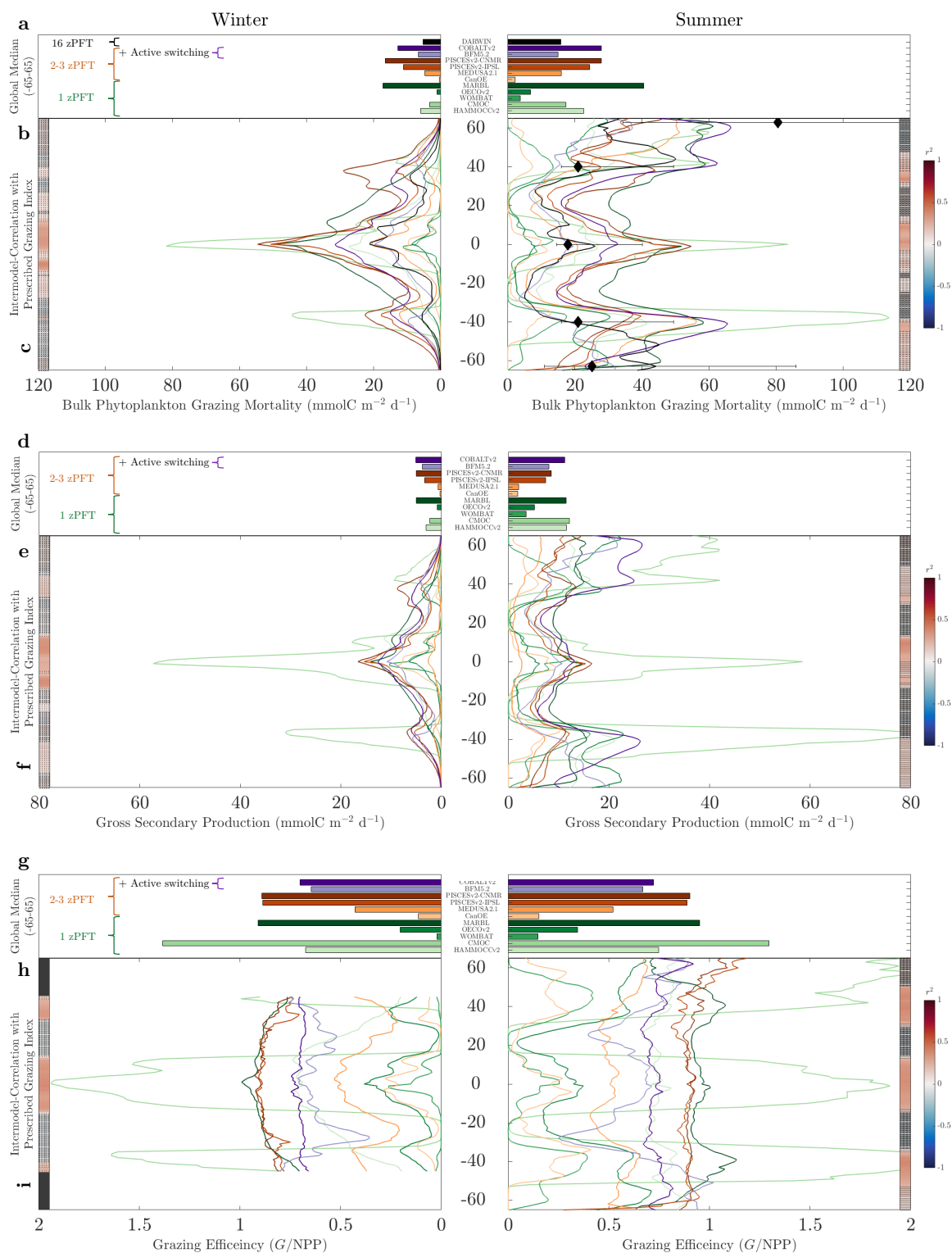


Figure S5: Inter-model variability in zooplankton population dynamics. Distribution of median **a-c**) bulk phytoplankton grazing mortality, **d-f**) gross secondary production, and **g-i**) grazing efficiency. Otherwise, as per Figure 5.

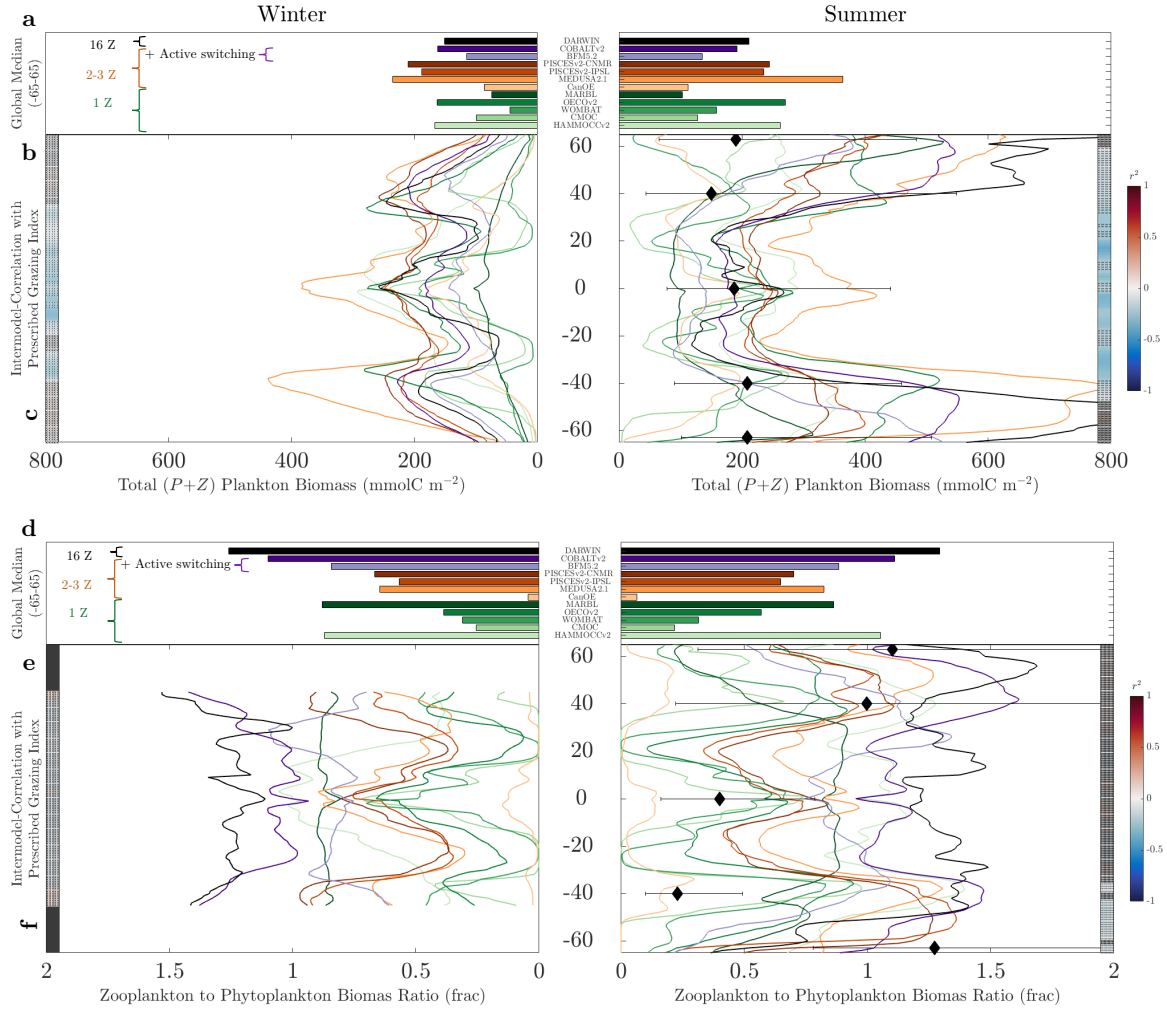


Figure S6: Inter-model variability in plankton biomass. Distribution of median **a-c**) total phytoplankton plus zooplankton biomass and **d-f**) the ratio of zooplankton to phytoplankton biomass. Otherwise, as per Figure 5.

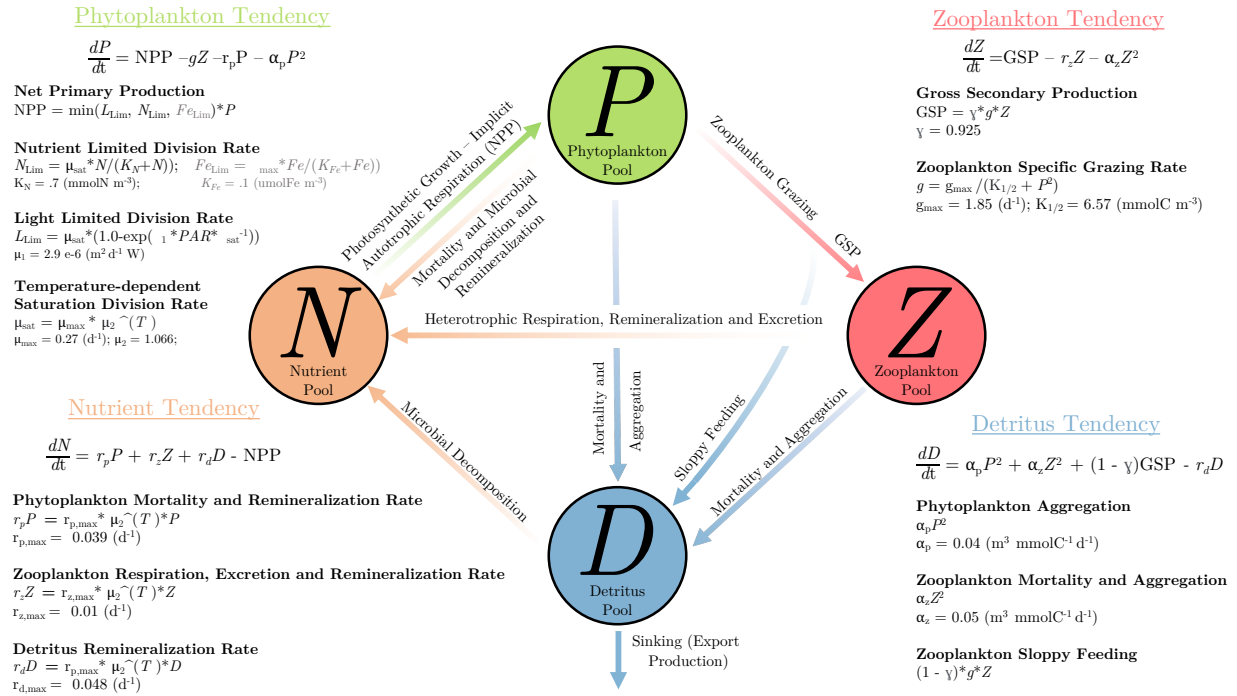


Figure S7: Partial schematic of the control WOMBAT BGC model configuration. Only includes Nutrient (N), Phytoplankton (P), Zooplankton (Z), Detritus (D) state variables. The tendency for each variable is reported beside it, with positive contribution to the tendency detailed below. Note, iron is included in the CMIP6 simulation of WOMBAT analysed here, but not the sensitivity experiments.

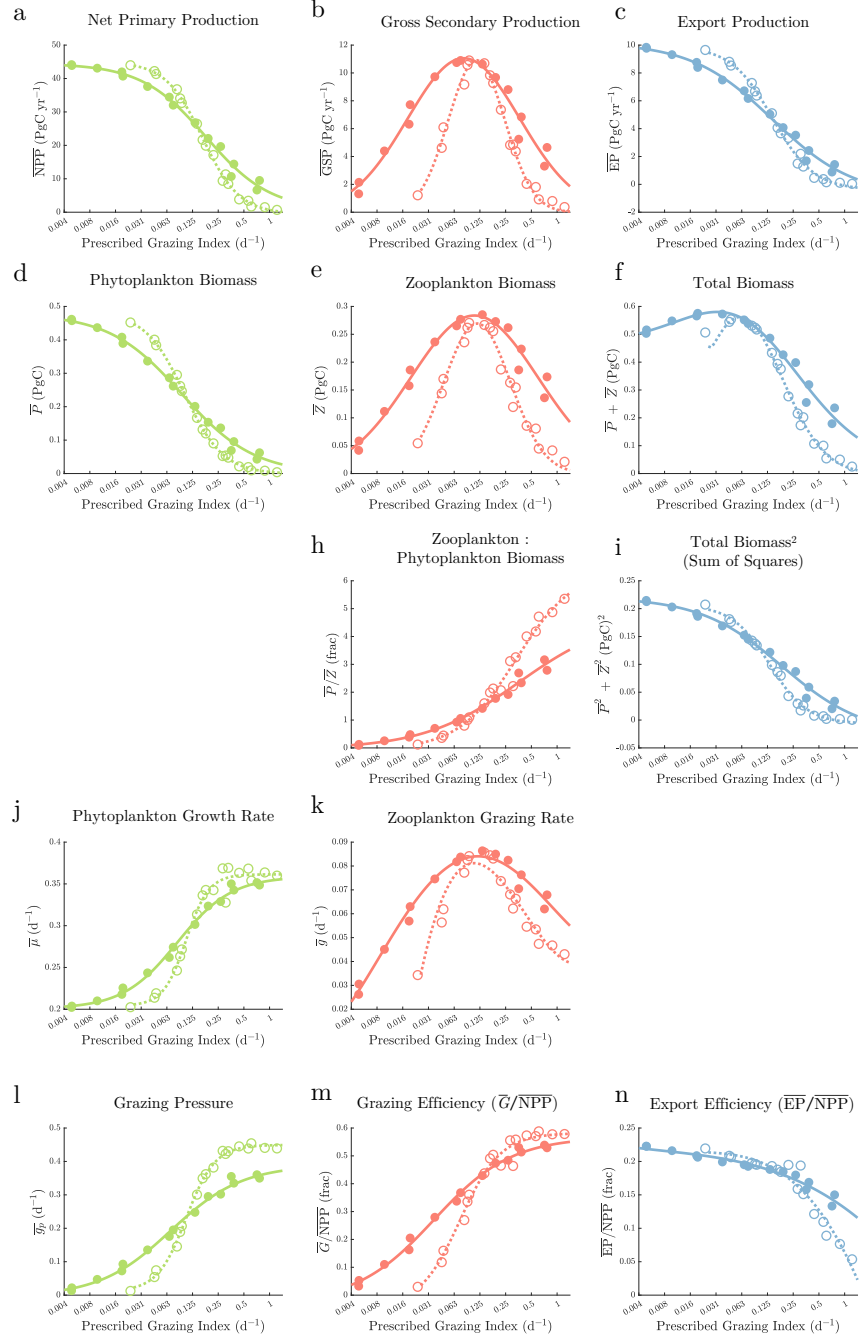


Figure S8: Sensitivity of marine carbon cycling to the Prescribed Grazing Index. Global, annually averaged model output for simulations from the ‘Slow Turnover’ experiment suite, which uses a type III response (solid line) and from the ‘type II’ experiment suite (dashed line) are plotted against their PGI. Note, **A-C** NPP, GSP and EP from the ‘Slow Turnover’ experiment suite are identical to that of Figure 7 **a-c**.

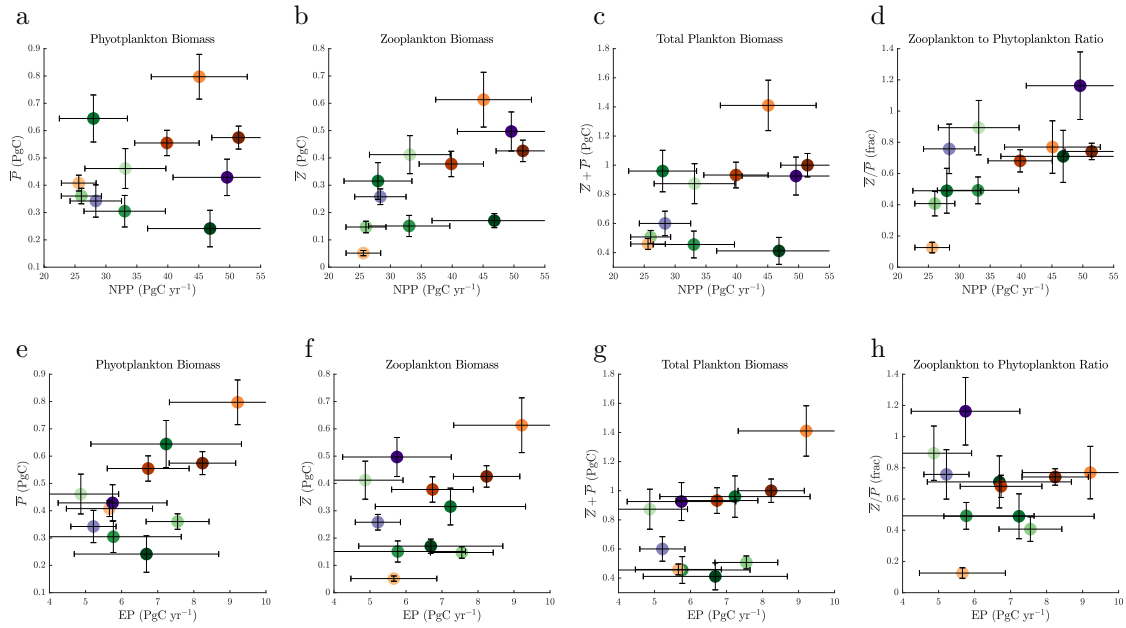


Figure S9: Models exhibit large differences in plankton biomass despite being tuned to similar productivity. Global, annually integrated **a, d**) Phytoplankton Biomass, **b, e**) Zooplankton Biomass, **c, f**) Total Biomass and **d, g**) Zooplankton to Phytoplankton biomass are plotted against **a-d**) $\overline{\text{NPP}}$ and **a-d**) $\overline{\text{EP}}$. Vertical and Horizontal error bars refer to the amplitude of the seasonal cycle, computed separately in the northern and southern hemisphere, then averaged.

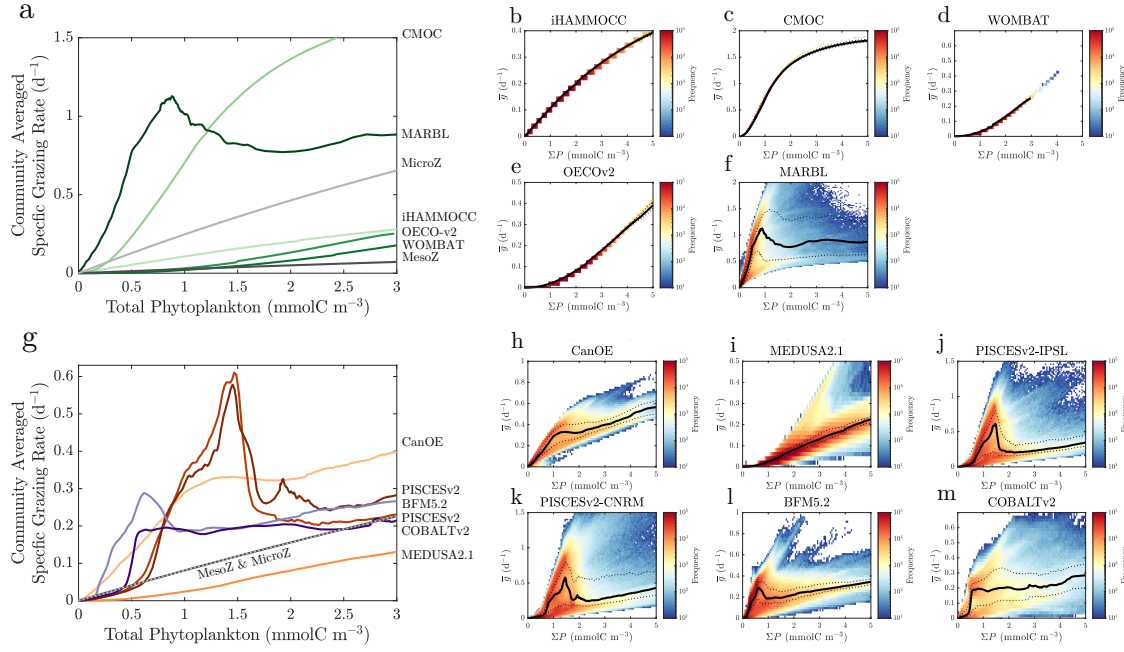


Figure S10: Variability in the Apparent Functional Response. The Apparent Functional Response as described in ‘Supplemental Discussion 1’ is plotted for models with *a-f* one or multiple *g-m* zooplankton groups. Sub-panels for each model on the right show the frequency distribution of zooplankton specific grazing rates plotted against total biomass, from which the apparent functional response was computed empirically. All grid cells from 0-200 m are included. The Apparent Functional Response is shown as the median ($\pm 25\%$; dashed lines) specific grazing rate occurring in all grid-cells containing each phytoplankton concentration.

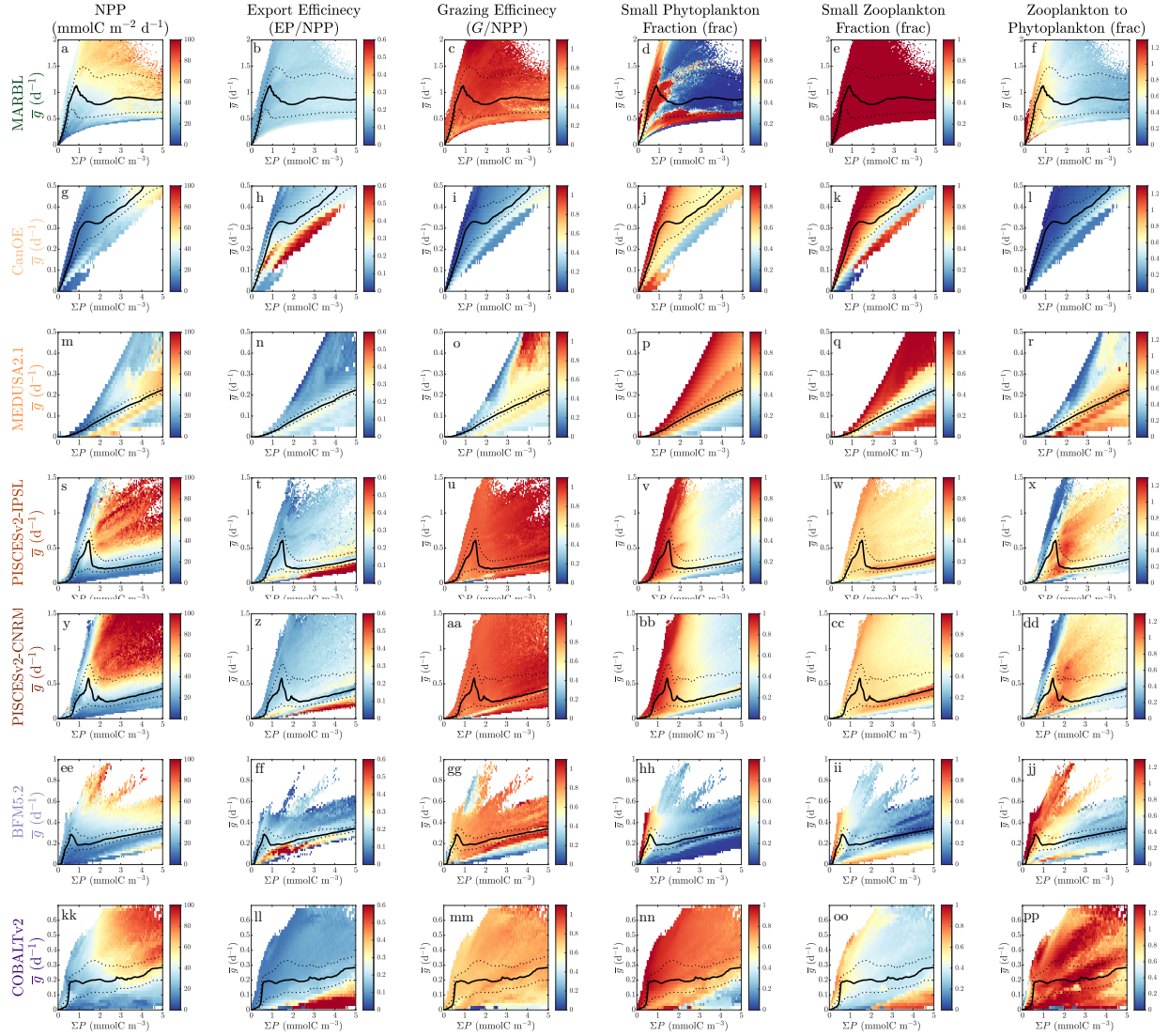


Figure S11: Sensitivity of marine carbon cycling and community composition to the Apparent Functional Response. **a-pp.** The Apparent Functional Response is plotted as per Figure S10. However, now instead of the grid-cell frequency on the color axis, the mean NPP, export ratio, export efficiency, fraction of small phytoplankton, fraction of small zooplankton, and total zooplankton to phytoplankton ratio of all qualifying grid-cells is plotted. Note, in COBALTv2, medium sized PFTs are included as small.

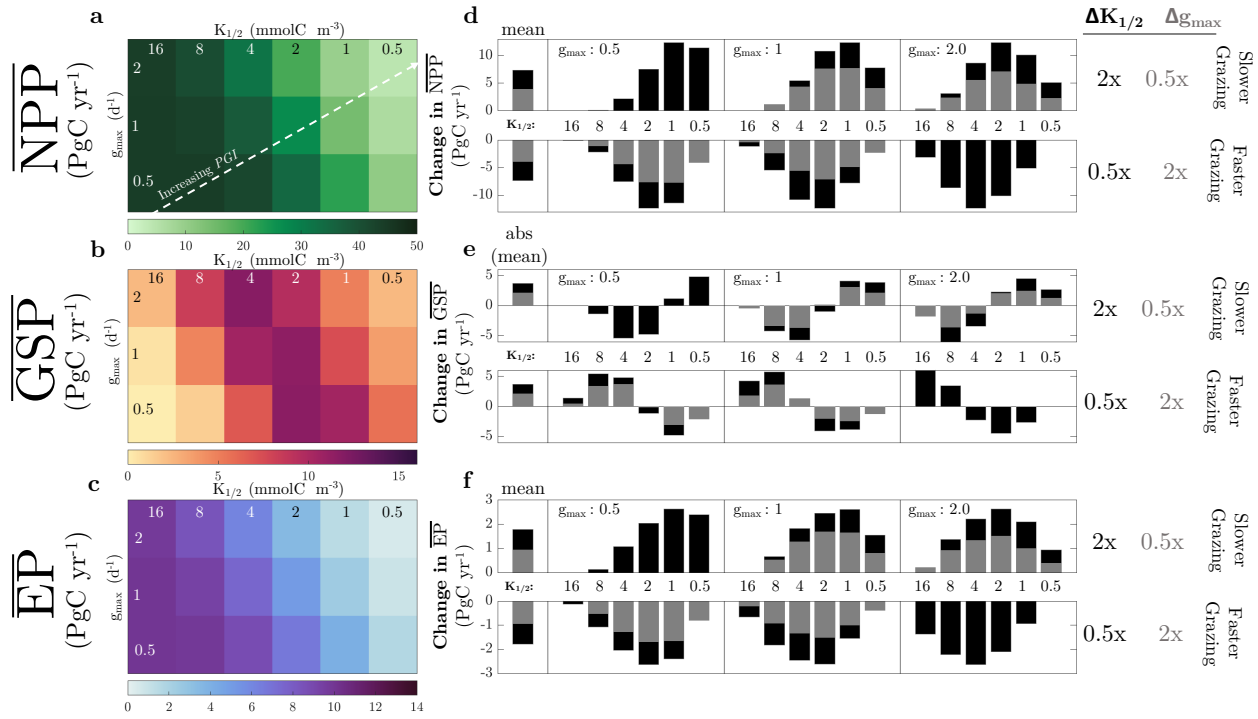


Figure S12: The sensitivity of global productivity to $K_{1/2}$ and $g_{\max}$ parameters. **a** $\overline{\text{NPP}}$, **b** $\overline{\text{GSP}}$, and **c** $\overline{\text{EP}}$ are plotted against the prescribed $K_{1/2}$ and $g_{\max}$ parameter values from each run in the ‘Slow Turnover’ suite of WOMBAT simulations (see Table S3; “Methods”). $K_{1/2}$ is plotted in reverse such that PGI increases from the bottom left to the top right, by either reducing $K_{1/2}$ or increasing $g_{\max}$. **d**, **e**, **f** To the right, the percent change associated with a doubling or halving of $K_{1/2}$ (black) or $g_{\max}$ (grey) is shown for each run.

BGC Model; Earth System Model	Zooplankton Group	Mortality Rate	Parameters
iHAMOCC NorESM2-LM	Zoo. (Z)	$r_1 Z' + \alpha Z'^2$ $Z' = \min(0, Z - Z_{\min})$	$r_1 = 0.06$ $\alpha = 0.025$ $Z_{\min} = 0.012$
CMOC; CanESM5	Zoo. (Z)	$r_1 Z + \alpha Z^2$	$r_1 = 0.25$ $\alpha = 0.015$
WOMBAT; ACCESS ESM1.5	Zoo. (Z)	$r_1 T_{Lim} Z + \alpha Z^2$ $T_{Lim} = 1.066^T$	$r_1 = 0.01$ $\alpha = 0.05$
OEEO-v2; MIROC-ES2L	Zoo. (Z)	$r_1 Z + \alpha Z^2$	$r_1 = 0.03$ $\alpha = 0.03$
MARBL; CESM2	Zoo. (Z)	$r_1 T_{Lim} Z' + \alpha T_{Lim} Z'^2$ $T_{Lim} = 1.7^{(T-30)/10}$ $Z' = \min(0, Z - Z_{\min})$	$r_1 = 0.1$ $\alpha = 0.4$ $Z_{\min} = f(\text{depth})$ $= 0.0 - 0.075$
CanOE ^A ; CanESM5-CanOE	Microzoo. (Z _{sm})	$(r_1 T_{Lim} + r_2) Z_{sm} + \alpha Z_{sm}^2$ $T_{Lim} = e^{-4.5e3(\frac{1}{T+273.15} - \frac{1}{298.15})}$	$r_1 = f(P_{C:N:Fe})$ $= 0.0 - 0.1$ $r_2 = 0.05$ $\alpha = 0.06$
	Mesozoo. (Z _{md})	$(r_1 T_{Lim} + r_2) Z_{md} + \alpha Z_{md}^2$ $T_{Lim} = e^{-4.5e3(\frac{1}{T+273.15} - \frac{1}{298.15})}$	$r_1 = f(P_{C:N:Fe})$ $= 0.0 - 0.3$ $r_2 = 0.1$ $\alpha = 0.06$
	Assimilation Inefficiency	$(1 - \gamma) g_{Z_{sm}}^{Z_{md}} Z_{md}$	$\gamma = 0.8$
MEDUSA2.1; UKESM1-0-LL	Microzoo. (Z _{sm})	$r_1 Z_{sm} + r_2 (\frac{Z_{sm}}{2.8 + Z_{sm}}) Z_{sm}$	$r_1 = 0.02$ $r_2 = 0.1$
	Mesozoo (Z _{md})	$r_1 Z_{md} + r_2 (\frac{Z_{md}}{4.2 + Z_{md}}) Z_{md}$	$r_1 = 0.02$ $r_2 = 0.2$
	Assimilation Inefficiency	$(1 - \gamma) g_{Z_{sm}}^{Z_{md}} Z_{md}$	$\gamma = 0.41$
PISCESv2 ^B ; IPSL-CM6a-LR & CNRM-ESM2.1	Microzoo. (Z _{sm})	$(r_1 + \Delta O_2) T_{Lim} Z_{sm} + \alpha T_{Lim} Z_{sm}^2$ $T_{Lim} = 1.079^T$	$r_1 = 0.03$ $\alpha = 0.004$
	Mesozoo. (Z _{md})	$(r_1 + \Delta O_2) T_{Lim} Z_{md} + \alpha T_{Lim} Z_{md}^2$ $T_{Lim} = 1.079^T$	$r_1 = 0.005$ $\alpha = 0.03$
	Assimilation Inefficiency	$(1 - \gamma) g_{Z_{sm}}^{Z_{md}} Z_{md}$	$\gamma = 0.35$
BFM5.2 ^B ; CMCC-ESM2	Microzoo. (Z _{sm})	$(r_1 + r_2 + r_3 \Delta O_2) T_{Lim} Z_{sm}$ $T_{Lim} = 2^{(T-10)/10}$	$r_1 = 0.01$ $r_2 = 0.01$ $r_3 = .25$
	Mesozoo. (Z _{md})	$(r_2 + r_3 \Delta O_2) T_{Lim} Z_{md} + \alpha T_{Lim} Z_{md}^2$ $T_{Lim} = 2^{(T-10)/10}$	$r_2 = 0.02$ $r_3 = 0.01$ $\alpha = 0.01$
	Assimilation Inefficiency	$(1 - \gamma_{sm}) g_{Z_{sm}}^{Z_{sm}} Z_{sm} + (1 - \gamma_{md}) (g_{Z_{sm}}^{Z_{md}} + g_{Z_{md}}^{Z_{md}}) Z_{md}$	$\gamma_{sm} = 0.5$ $\gamma_{md} = 0.6$
COBALTv2 ^C ; GFDL-ESM4.1	Small Zoo. (Z _{sm})	$r_1 T_{Lim} Z_{sm}$ $T_{Lim} = 2^{(T)/10}$	$r_1 = 0.08$
	Med. Zoo. (Z _{md})	$r_1 T_{Lim} Z_{md} + g_{Z_{md}}^{HP} (Z_{md} + Z_{lg})$ $T_{Lim} = 2^{(T)/10}$	$r_1 = .008$ $K_{HP} = 8.28$ $g_{HP} = 0.09$
	Large Zoo. (Z _{lg})	$r_1 T_{Lim} Z_{lg} + g_{Z_{lg}}^{HP} (Z_{md} + Z_{lg})$ $T_{Lim} = 2^{(T)/10}$	$r_1 = .0032$ $K_{HP} = 8.28$ $g_{HP} = 0.09$
	Assimilation Inefficiency	$(1 - \gamma) g_{Z_{sm}}^{Z_{md}} Z_{md} + (1 - \gamma) g_{Z_{md}}^{Z_{lg}} Z_{lg}$	$\gamma = 0.4$

Figure S13: Bulk zooplankton mortality rates in CMIP6 models. Note, all loss terms which vary with zooplankton biomass, including basal metabolic rates, are included and considered mortality. Loss terms that vary with ingestion are considered assimilation inefficiencies and not included except for in models with carnivorous zooplankton to account for biomass lost to sloppy feeding, egestion, and in some cases respiration during trophic transfer. Biomass that is assimilated via carnivorous grazing is not considered part of the bulk mortality term as it remains in the total zooplankton pool. The g_i^j term is the specific grazing rates between zooplankton groups as described in Figure 2. Linear loss rate parameters, r , are reported in units of d^{-1} and quadratic loss rates parameters, α , are reported in units of $m^3 \text{ mmolC}^{-1} d^{-1}$. ^A The temperature limited respiration (r_1) in CanOE drops out when excess carbon is available in prey relative the fixed stoichiometry of the zooplankton. ^B The ΔO_2 terms in PISCESv2 and BFM5.2 increases mortality rates in anoxic conditions and were accounted for but are relatively small. Equations can be found in their respective BGC documentation (see Table S2). ^C In COBALTv2, medium and large zooplankton are lost to an implicit higher predator (HP) with a specific grazing rates ($g_{Z_j}^{HP}$), computed analogously to zooplankton (see Figure 2) using equal preference and parameters K_{HP} and g_{HP} .

2 Supplemental Tables

Field	MAREDAT Group	Observed Global Median Prey Field	Mean Modelled Global Median Prey Field	Observational Reference
Phytoplankton (mmolC m ⁻³)				
Small	Picophytoplankton	0.46	0.37	(28,154)
Large	Diatoms + Phaeocystis	0.33	0.24	(28,155,158)
Diazotrophs	Diazotrophs	2.5e-3	0.02	(28,157)
Total	Pico+Diat +Phae+Diat	0.79	0.61	(28,154-158)
Zooplankton (mmolC m ⁻³)				
Small	Microzooplankton	0.26	0.17	(28,93)
Medium	Mesozooplankton	0.23	0.16	(28,94)
Large	Macrozooplankton	0.02	0.04	(28,154)
Total	Micro+Meso+Macro	0.51	0.34	(28,93,94,154)
Other Carbon Reservoirs (mmolC m ⁻³)				
Bacteria	Picoheterotrophs	0.55	0.57	(28,151)
Detritus	-	2.65	1.12	(28,150)
Temperature (°C)				
SST	-	15.30	15.61	(149)

Table S1: Standardized prey field for the Prescribed Grazing Index. All observed values are described in detail the “Methods” Section “Description of observations”). Modelled carbon stocks are the global (-60S-60N) median concentration over the upper water column (1-200 m), averaged across models that include the specified carbon pool. Model temperature is weighted by zooplankton biomass in the top 200 m such that it reflects the temperature the median zooplankton experiences, then averaged across models with temperature limited grazing. Note, mean model values are not used anywhere in the computation of the Prescribed Grazing Index or offline computation of emergent grazing rates, but confirm that the standardized observed values are reasonably representative of the median prognostic model fields.

	Zooplankton Group	Studies	Volume (μm^3)	g_{max} (d^{-1})	$K_{1/2}$ (mmolC m^{-3})	PGI (d^{-1})
	Nanoflagellates	18	5.9e1	8.36	23.5	0.270
	Dinoflagellates	7	6.3e3	1.63	25	0.050
	Ciliates	14	2e4	2.76	6.30	0.307
	Rotifers	6	2.9e5	2.24	25.2	0.068
	Microzooplankton	45	7.1e3	3.71	14	0.117
	Meroplankton Larvae	16	5.4e6	0.12	7.1	0.012
	Cladocerans	32	3.1e7	0.65	35.4	0.014
	Copepods	14	1.4e8	1.44	24.7	0.045
	Mesozooplankton	62	2.8e7	0.58	21	0.009

Table S2: Empirical estimates of the PGI for 9 zPFTs derived from the functional response curves measured in 107 empirical experiments. See the “Methods” Section “Description of observations” for description of empirical experiments and derived products.

	BGC Model	Earth System Model	Simulation	Model ID	Institution (Location)	Personal Communication
	iHAMOCC (64)	NorESM2-LM (64)	Historical (82)	r2ilp1fl	NCC (NOR)	Jerry Tjiputra Jörg Schwinger
	CMOC (65)	CanESM5 (69)	Historical (83)	r1ilp2fl	CCCma (CAN)	Jim Christian
	WOMBAT (66)	ACCESS ESM1.5 (66)	Historical (84)	r1ilp1fl	CSIRO (CAN)	Matthew Chamberlain
	OECO-v2 (67)	MIROC-ES2L (67)	Historical (85)	r1ilp1f2	JAMSTEC (JAP)	-
	MARBL (68)	CESM2 (78)	Historical (86)	r1ilp1fl	NCAR (USA)	Matt C. Long
	CanOE (69)	CanESM5-CanOE (69)	Historical (87)	r2ilp2fl	ECCC (CAN)	Jim Christian
	MEDUSA2.1 (70)	UKESM1-0-LL (70)	Historical (88)	r1ilp1f2	Met Office, NERC (UK)	-
	PISCESv2 (71)	IPSL-CM6A-LR (79)	Historical (89)	r10ilp1fl	IPSL (FR)	-
	PISCESv2 (71)	CNRM-ESM2.1 (80)	Historical (90)	r1ilp1f2	CNMR (FR)	-
	BFM5.2 (72)	CMCC-ESM2 (72)	Historical (91)	r1ilp1fl	CMCC (ITA)	Tomas Lovato
	COBALTv2 (73)	GFDL4.1 (81)	Historical (92)	r1ilp1fl	GFDL (USA)	Charlie Stock

Table S3: CMIP6 Simulations. References in columns 1-3 refer to the description of the BGC component, coupled Earth system model, and the publicly hosted model output, respectively. Personal communications are noted where required to fill in unpublished parameter values or field questions about the model formulation.

Experiment Suite	Control	Slow Turnover	High Turnover	Type II
Zooplankton functional response	Type III	Type III	Type III	Type II
Phytoplankton saturation growth rate at 16°C μ_{sat} (d ⁻¹)	0.75	0.75	2.38 (MARBL)	0.75
Zooplankton specific Saturation grazing rates g_{max} (d ⁻¹)	1.575	[0.5,1,2]	[0.5,1,2]	[0.5,1,2]
Half saturation Concentration $K_{1/2}$ (mmolC m ⁻³)	6.57	[0.5,1,2,4,8,16]	[0.5,1,2,4,8,16]	[0.5,1,2,4,8,16]
Ensemble mean PGI (d ⁻¹)		0.10	0.35	

Table S4: Description of parameterization of WOMBAT sensitivity studies.