



*Supplement of*

## **A diatom extension to the cGENIE Earth system model – EcoGENIE 1.1**

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## Supplemental Material: A diatom extension of the cGENIE Earth system model – EcoGENIE 1.1

EcoGENIE 1.1 is a trait-based functional type ecosystem model developed from EcoGENIE 1.0 (Ward et al., 2018) to include diatom dynamics and silicon cycle in the Earth System model, cGENIE. EcoGENIE 1.0 captured the dynamic of size classes of phytoplankton and zooplankton based on allometric relationships for, e.g., uptake rate, grazing rate and nutrient affinity. EcoGENIE 1.1 depicts three new functional phytoplankton groups: picoplankton, eukaryote and diatom, each with two to three size classes relevant to their type (Table S1). To distinguish the different groups of phytoplankton, we used the allometric relationships as defined by Dutkiewicz et al. (2020) for the maximum photosynthetic rate for picoplankton and diatoms (Table S1).

	<b>EcoGENIE 1.0</b> <i>(Ward et al., 2018)</i>	<b>EcoGENIE 1.1</b> <i>This study</i>
<u>ECOSYSTEM</u>		
Ecosystem structure	8 size classes of phytoplankton and zooplankton (0.6, 1.9, 6.0, 19.0, 60.0, 190.0, 600.0, 1900.0)	3 size classes of diatoms (2.0, 20.0, 200.0) 2 size classes of picoplankton (0.6, 2.0) 2 size classes of eukaryote (20.0, 200.0) 4 size classes of zooplankton (6.0, 20.0, 200.0, 2000.0)
Maximum photosynthetic rate (Pmax)	Unimodal relationship for all plankton	Diatoms : $3.9V^{0.08} \text{ d}^{-1}$ (Dutkiewicz et al., 2020) Picoplankton : $0.9V^{0.08} \text{ d}^{-1}$ (Dutkiewicz et al., 2020) Eukaryotes: $2.2V^{0.08} \text{ d}^{-1}$ (assuming 20% lower than diatoms)
Diatom trade-offs	N/A	Benefits: Higher Pmax than other phytoplankton groups and better grazing protection Cost: Si requirement
Light limitation		Modified EcoGENIE 1.0 with diagnosed mixed-layer light penetration and no light under sea-ice
<u>BIOGEOCHEMISTRY</u>		
Iron cycle	Dust source: (Mahowald et al., 1999) TDFe and TL DOM $\tau$ = 1 Fesol = 1 Kscav = 1.338	Dust source: Albani et al. (2016) TDFe and TL DOM $\tau$ = 0.5 Fesol = 0.00244 Kscav = 0.225
Silicon cycle	N/A	bg_par_bio_red_POC_opal=0.65 bg_ctrl_bio_remin_opal_fixed=.false. bg_par_bio_remin_sinkingrate=125.0

Extend the temperature range for solubility and geochemical constants	N/A	gm_par_geochem_Tmin = -2.0 gm_par_geochem_Tmax = 45.0 gm_par_carbchem_Tmin = -2.0 gm_par_carbchem_Tmax = 45.0
Instantaneous remineralisation	N/A	bg_par_bio_remin_sinkingrate_physical=9.9E9; bg_par_bio_remin_sinkingrate_reaction=125.0
Geochemical reaction timescale	N/A	bg_par_bio_geochem_tau=90.0
Relative partitioning of C into DOM	N/A	eg_par_beta_POCToDOC=0.75
<b>PHYSICS</b>		
Configuration	Worlg4 (Worjh2 with modified wind)	Worjh2 (Cao et al., 2009)
Mixed-layer scheme	On	Off

Table S1: EcoGENIE 1.1 model setup in comparison to EcoGENIE 1.0

## Plankton physiology

State variables and their rates of change are defined by a variety of ecological processes. Further state variables are fully described in Ward et al. (2018).

### Temperature limitation

Metabolic processes within cells are temperature limited. We account for temperature limitation applying the following exponential function of temperature to all plankton.

$$\gamma^T = e^{A(T-T_{ref})} \quad (1)$$

Temperature sensitivity is described by the constant  $A = 0.05 \text{ } ^\circ\text{C}^{-1}$  and  $T = 20 \text{ } ^\circ\text{C}$  (ambient water temperature) and  $T_{ref}$  is a reference temperature where  $\gamma^T = 1$ . Temperature limitation of metabolic processes is consistent with every functional group (with same values of  $A$ ).

### Nutrient uptake

Environmental availability ( $[R_{i_r}]$ ) of a nutrient ( $i_r = i_b$ ) governs phytoplankton uptake rate, along with maximum uptake rate ( $V^{max}$ ), quota saturation term, temperature limitation and nutrient affinity ( $\alpha_{j,i_r}$ ).

$$V_{j,i_r} = \frac{V_{j,i_r}^{max} \alpha_{j,i_r} [R_{i_r}]}{V_{j,i_r}^{max} + \alpha_{j,i_r} [R_{i_r}]} Q_{j,i_b}^{stat} \cdot \gamma^T \quad (2)$$

This equation modifies the Michaelis-Menten-type response by including nutrient affinity rather than the half saturation constant.

### Plankton “quota” saturation

Saturation of nutrient biomass relative to carbon is prevented by setting the uptake capacity to zero when the cellular nutrient quota,  $Q$ , is satisfied (Ward et al., 2012). This quota is determined by the ratio of nutrients assimilated to carbon biomass.

$$Q_{j,i_b}^{stat} = \left( \frac{Q_{j,i_b}^{max} - Q_{j,i_b}}{Q_{j,i_b}^{max} - Q_{j,i_b}^{min}} \right) h \quad (3)$$

The general uptake regulation term,  $i_b$ , for a given element  $j$  is a linear function of the nutrient status, which is altered by the shape parameter  $h = 0.1$  (Geider et al., 1998).

### Photosynthesis

We use a photosynthesis model for phytoplankton adapted from Geider et al. (1998) and Moore et al. (2001) where light limitation ( $\gamma_{j,l}$ ) relates to the Poisson function. This function depends on local irradiance ( $I$ ) depends on the chlorophyll  $a$ : carbon ratio ( $Q_{j,chl}$ ) and iron-dependent initial slope of the  $P$ - $I$  curve ( $\alpha \cdot \gamma_{j,Fe}$ ).

$$\gamma_{j,l} = 1 - \exp\left( \frac{-\alpha \cdot \gamma_{j,Fe} \cdot Q_{j,chl} \cdot I}{P_{j,C}^{sat}} \right) \quad (4)$$

$P^{sat}$  refers to the maximum light-saturated growth rate, which depends on a maximum rate of  $P^{max}$  with respect to the temperature and nutrient limitations.

$$P_{j,C}^{sat} = P_{j,C}^{max} \cdot \gamma^T \cdot \min [\gamma_{j,P}, \gamma_{j,Fe}] \quad (5)$$

The resulting gross photosynthetic growth rate ( $P_{j,C}$ ) is thus calculated as:

$$P_{j,C} = \gamma_{j,l} P_{j,C}^{sat} \quad (6)$$

### Grazing

We determine a predator's ( $j_{pred}$ ) predator-biomass specific grazing rate on its prey ( $j_{prey}$ ) by the overall grazing rate, the prey switching term ( $\phi$ ) and prey refuge ( $1 - e^{-A \cdot F_{j_{pred},C}}$ ) where grazing will reduce if availability is low.

$$G_{j_{pred},j_{prey},C} = \gamma^T \cdot G_{j_{pred},C}^{max} \cdot \frac{F_{j_{pred},C}}{k_{j_{prey},C} + F_{j_{pred},C}} \cdot \phi_{j_{pred},j_{prey}} \cdot (1 - e^{-A \cdot F_{j_{pred},C}}) \quad (7)$$

$G^{max}$  represents the maximum grazing rate, with a half-saturation concentration for all prey denoted  $k_{j_{prey},C}$  and total available food as  $F_{j_{pred},C}$ . The “prey-switching” term is optional with the details outlined in Ward et al. (2018) with EcoGENIE 1.1 also allowing for active switching by setting pre-switching term(s) to 2. We assume that predators do not feed on detrital organic matter.

## Mortality

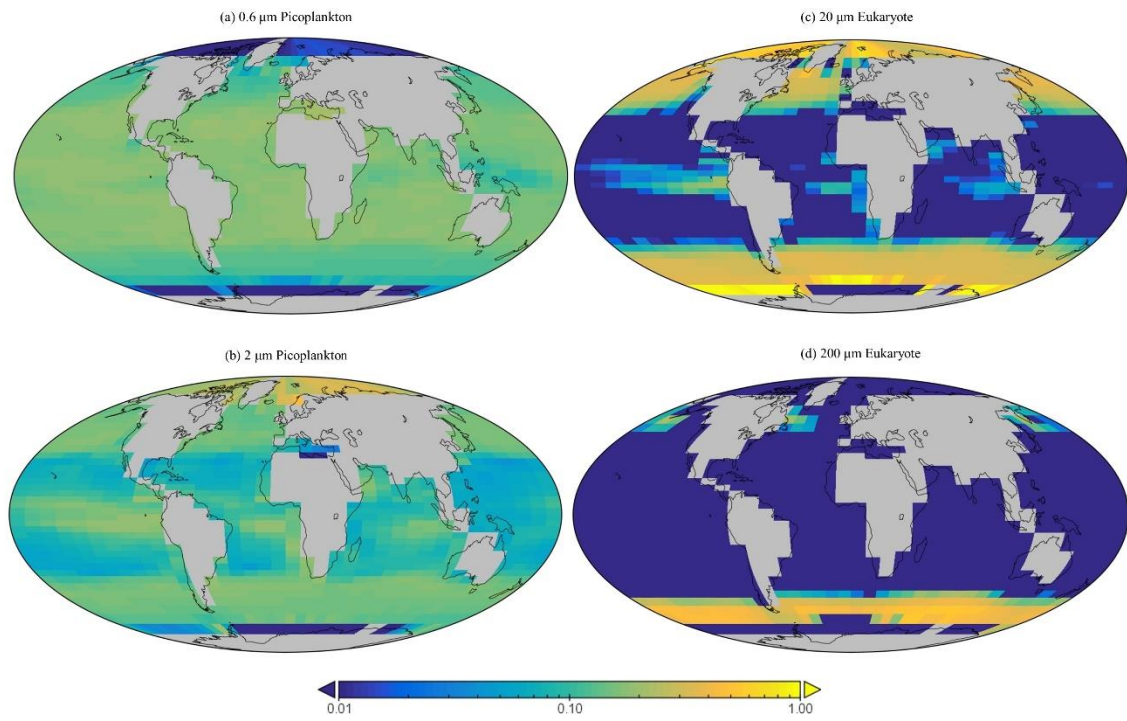
Biomass loss also occurs via mortality via a linear biomass mortality rate ( $m_j$ ).

$$m_j = m_p (1 - e^{-10^{10} \cdot B_{j,C}}) \quad (8)$$

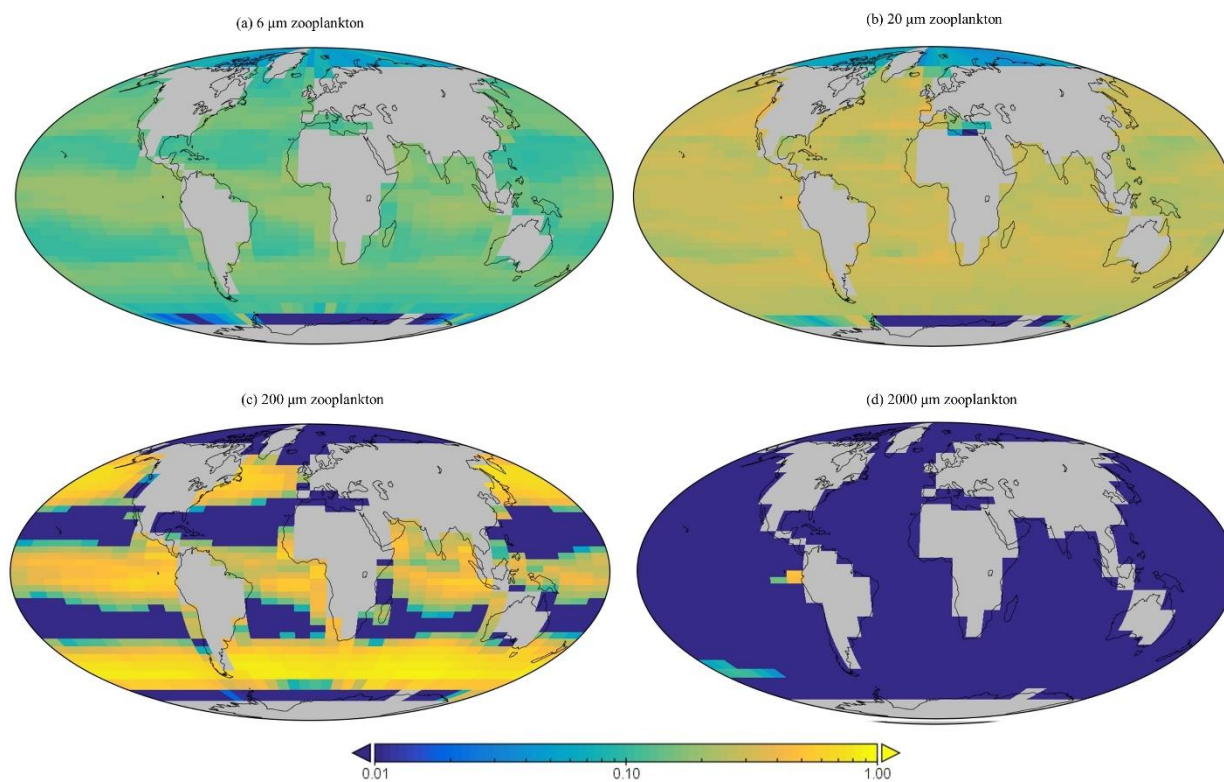
$m_j$  reduces when population carbon biomass (represented by the vector  $B_C$ ) is smaller than  $10^{-10}$  mmol C m<sup>-3</sup>, to help support low biomass population to ensure that every surface grid cell houses a viable population.

## Other plankton distribution

The carbon biomass distributions of the base functional types of our plankton community and their grazers (zooplankton) are shown in Figure S1 and S2. Global distributions of 0.6 μm picoplankton are generally consistent across high and low latitudes, with subtropical gyres housing far less of the 2 μm class. Eukaryotes, being of the micro size, exhibit distinct regions of habitancy relative to picoplankton, their larger 200 μm class is restricted to high latitudes whilst the 20 μm class also emanates in equatorial zones. Respective zooplankton size classes are intuitively determined by the presence of their prey (i.e. groups at least 10 times smaller than them), thus we observe larger zooplankton occupying increasingly smaller ecological niches.



**Figure S1.** Surface concentrations of carbon biomass for picoplankton ((a) and (b)), and eukaryotes ((c) and (d)) size classes ( $\text{mmol C m}^{-3}$ ).

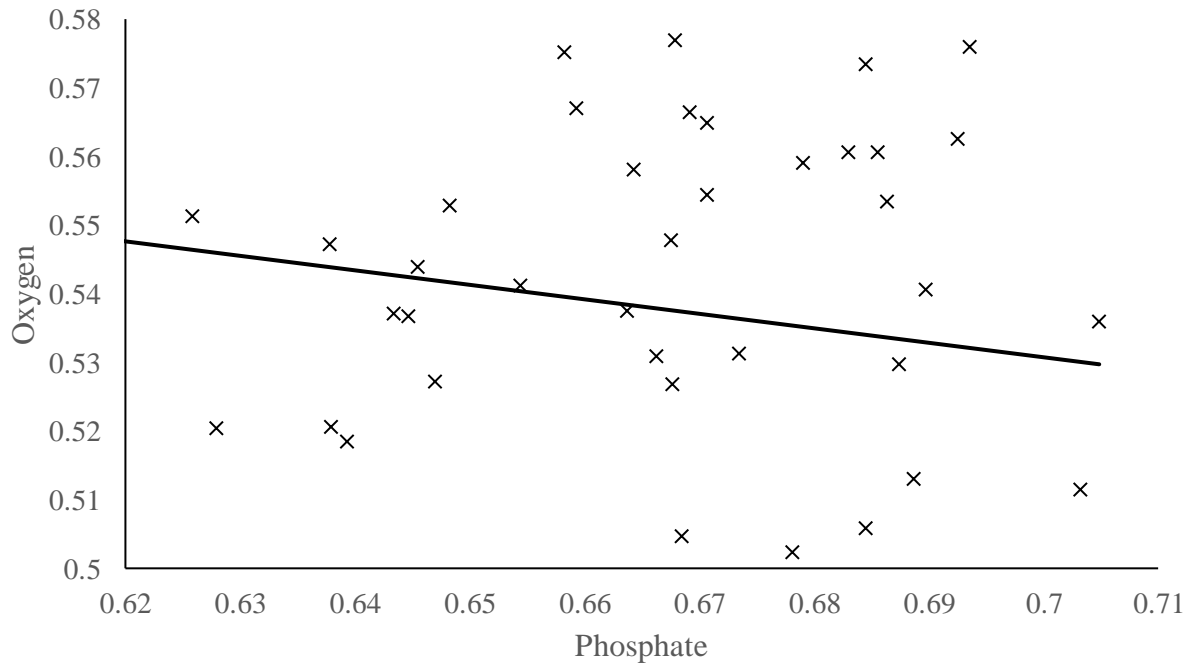


**Figure S2.** Surface concentrations of carbon biomass for each zooplankton size class ( $\text{mmol C m}^{-3}$ ).

### M-score trade-off

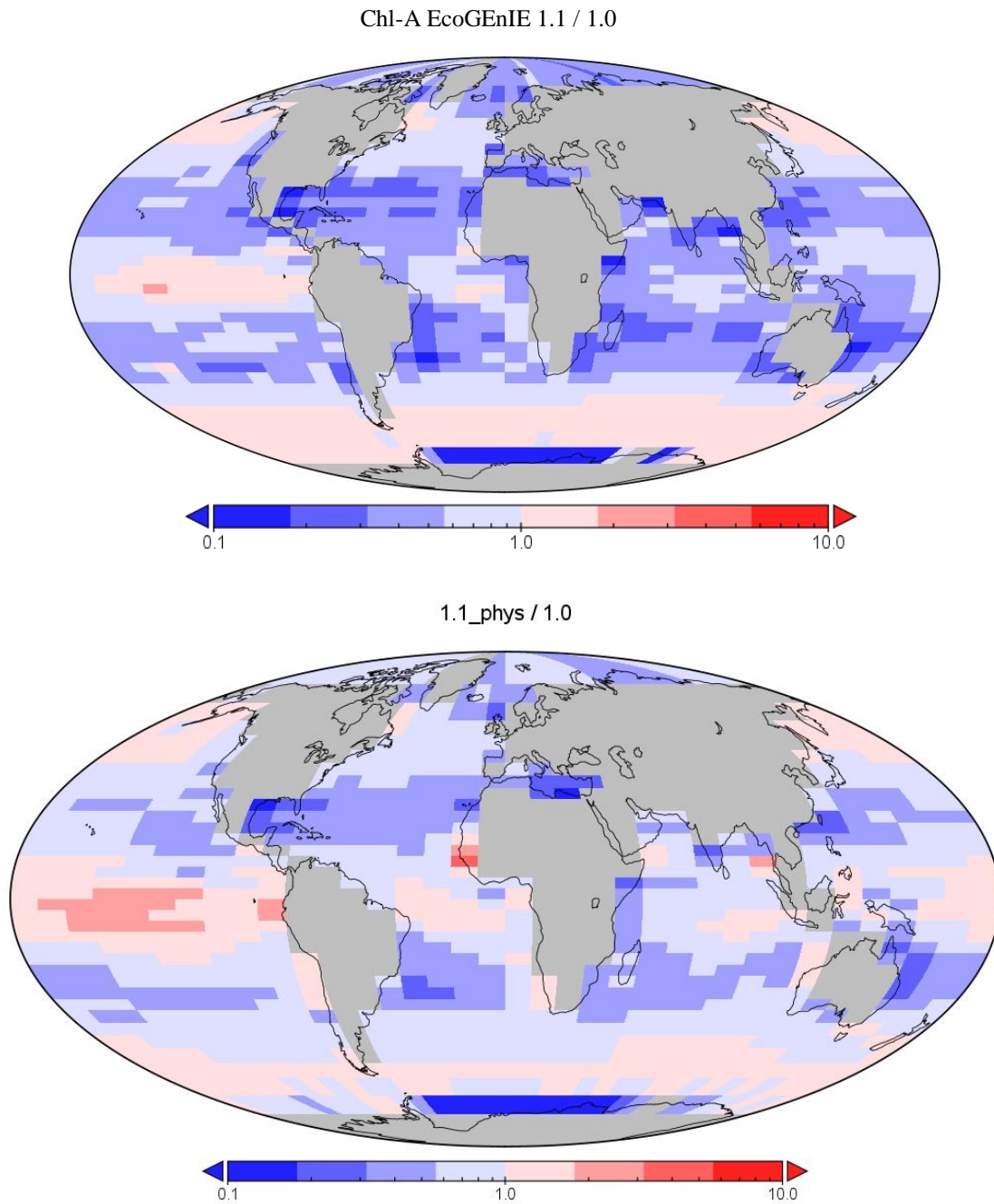
Phosphate is regulated by decomposition of sinking material (traded off with  $O_2$ ), whereas silica is regulated by the dissolution of sinking opal. As decomposition requires respiration ( $O_2$  consumption), improving model performance of phosphate (e.g. within the intermediate Pacific) would likely push oxygen to less realistic concentrations. Silica is not influenced by this trade-off thus higher M-scores are achievable. It is worth noting that achieving accurate oxygen performance is a common issue amongst GCMs and PFTs (Ciavatta et al., 2018).

**Figure S3** shows a trade-off in oxygen and phosphate M-scores, a factor we took into consideration when selecting our best run.



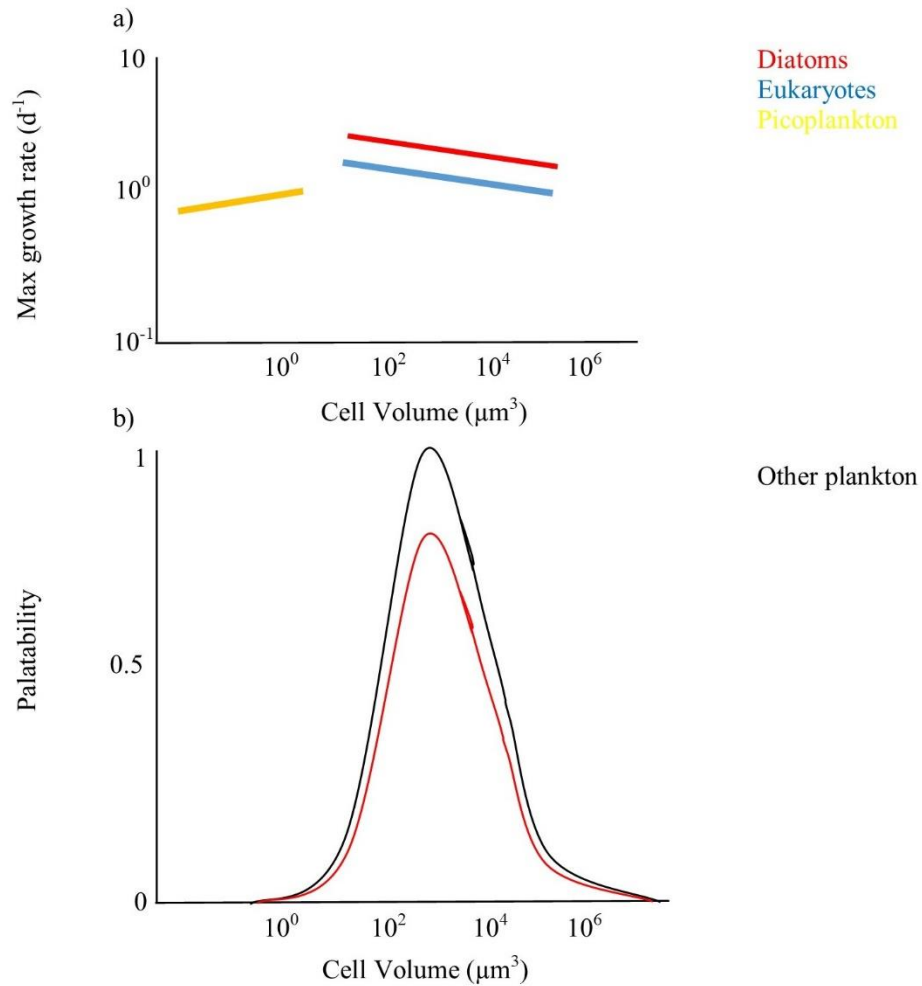


**Figure S4.** Difference plot between EcoGenIE 1.1 and 1.0 for surface chlorophyll a concentration ( $\text{mg Chl m}^{-3}$ ).



**Figure S5.** Difference plot between EcoGenIE 1.1\_phys and 1.0 for global POC export

The distribution change when switching to our new ecosystem is minimal vs the switch of physics. Figure S5 is a POC export difference plot of EcoGenIE 1.1\_phys and EcoGenIE 1.0. It bears similarity to Figure 14a, suggesting that the physics switch together with the addition of the diatom functional group is primarily responsible for the differences between EcoGenIE 1.0 and 1.1 (notably the equatorial Pacific).



**Figure S6.** Graphs of key differences ((a) maximum growth rate, (b) palatability) between diatoms and other plankton within EcoGENIE 1.1.

To account for the presence of frustules within diatoms, there is a slightly different grazing kernel applied from the model tuning. Diatoms are not preferentially grazed relative to the rest of the prey (0.93 vs 1). Growth rates as a function of cell size are taken from (Dutkiewicz et al., 2020) instead of the previous unimodal approach, the smaller group (picoplankton) have an increase in growth rate with size whereas larger phytoplankton experience the opposite due to a trade-off between synthesising biomass and topping up cell quotas.

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