Ecosystem community composition and biogeochemical cycles: Community Earth System Model Simulations with multiple plankton functional types

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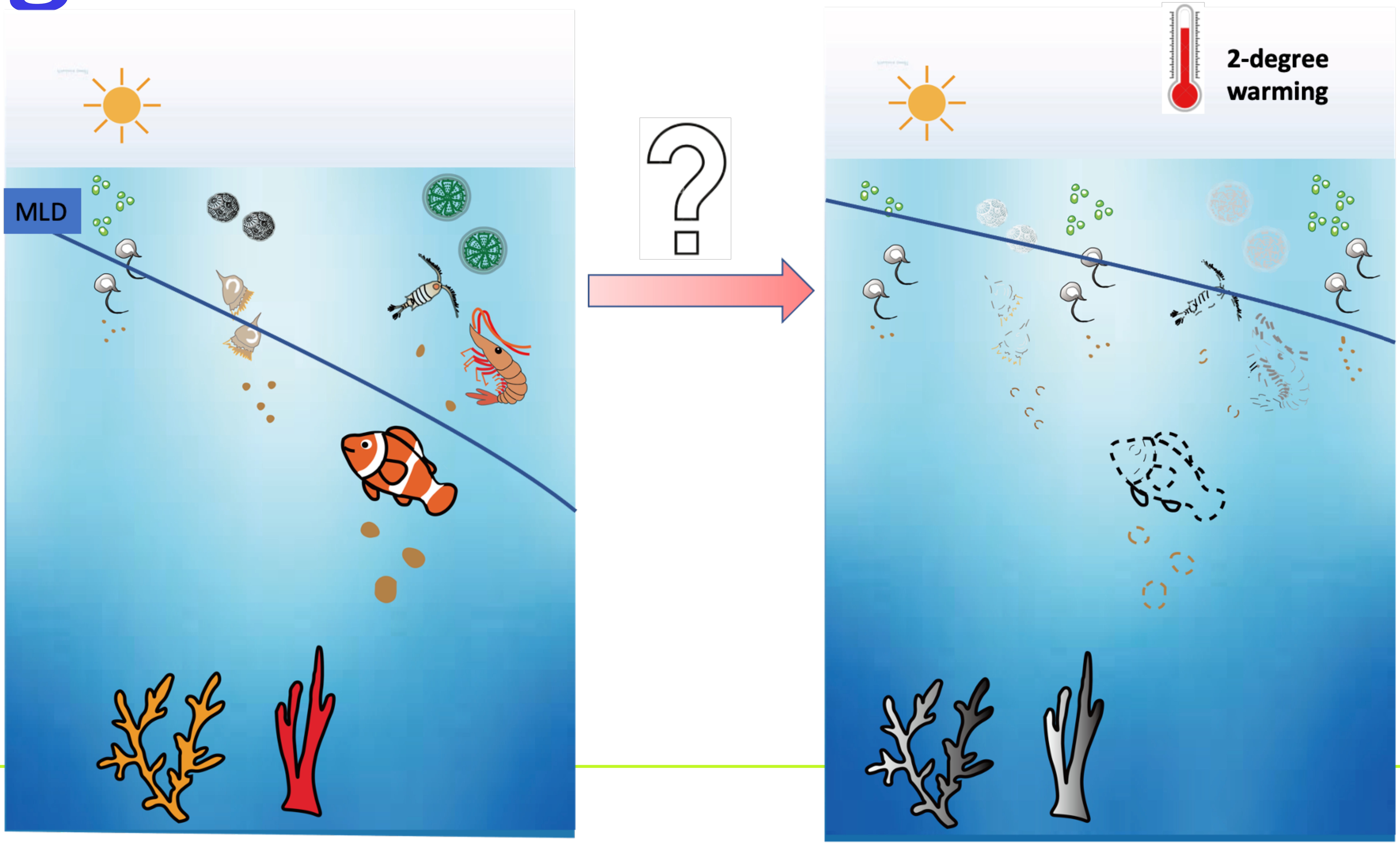
Background



PERSPECTIVE
https://doi.org/10.1038/s41561-022-00927-0
nature geoscience

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Uncertain response of ocean biological carbon export in a changing world

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The transfer of organic carbon from the upper to the deep ocean by particulate export flux is the starting point for the long-term storage of photosynthetically fixed carbon. This 'biological carbon pump' is a critical component of the global carbon cycle, reducing atmospheric CO_2 levels by ~200 ppm relative to a world without export flux. This carbon flux also fuels the productivity of the mesopelagic zone, including important fisheries. Here we show that, despite its importance for understanding future ocean carbon cycling, Earth system models disagree on the projected response of the global export flux to climate change, with estimates ranging from −41% to +1.8%. Fundamental constraints to understanding export flux arise because a myriad of interconnected processes make the biological carbon pump challenging to both observe and model. Our synthesis prioritizes the processes likely to be most important to include in modern-day estimates (particle fragmentation and zooplankton vertical migration) and future projections (phytoplankton and particle size spectra and temperature-dependent remineralization) of export. We also identify the observations required to achieve more robust characterization, and hence improved model parameterization, of export flux and thus reduce uncertainties in current and future estimates in the overall cycling of carbon in the ocean.

- Henson et al., (2022)

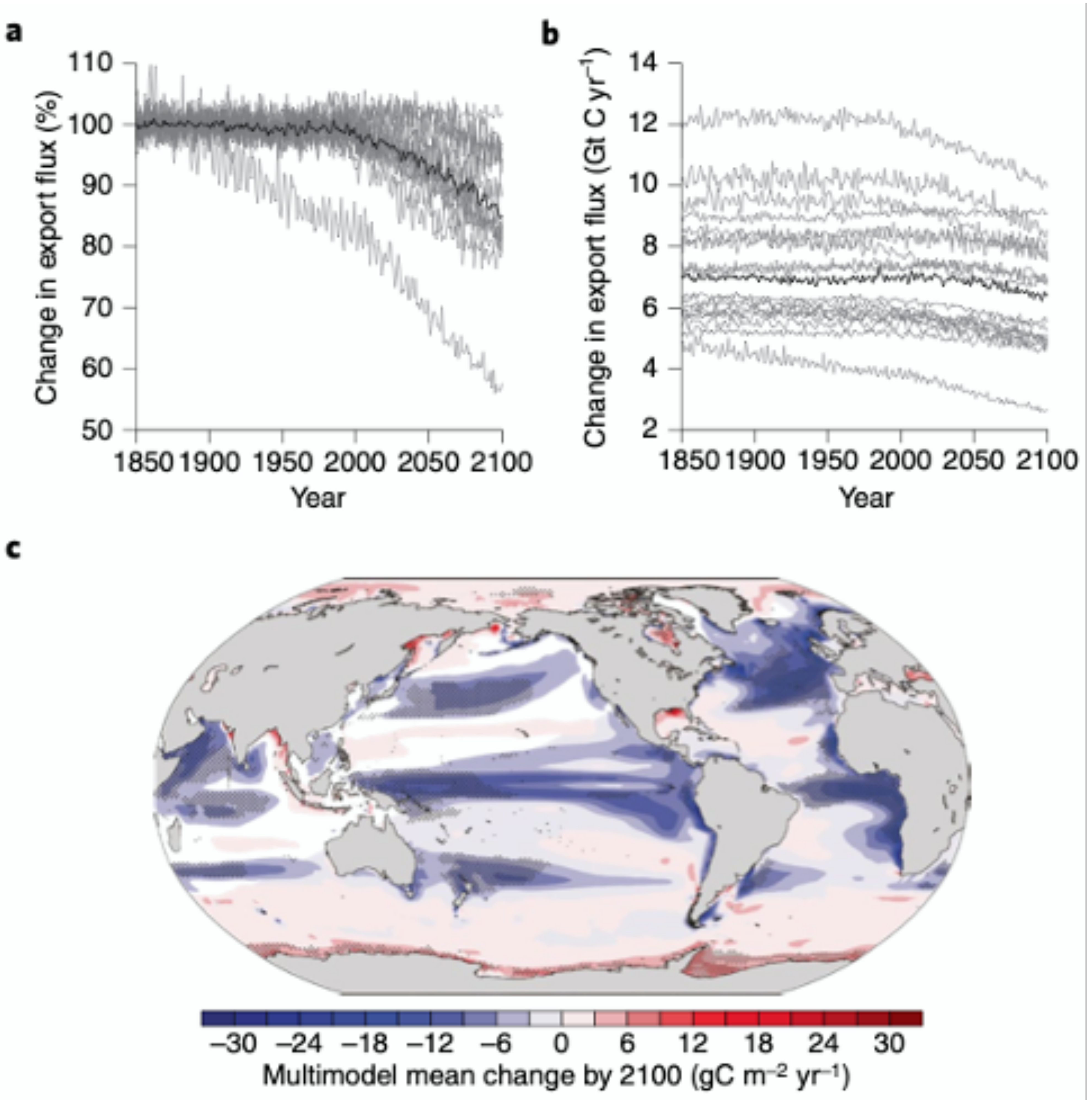


Fig. 1 | Uncertain response of export flux to climate change. **a**,**b**, Percentage change (**a**) and absolute change (**b**) in globally averaged export flux in 19 coupled climate models forced with the SSP5-8.5 scenario[72] taken from the Coupled Model Intercomparison Project phase 6 (CMIP6) archive[73]. Percentage change is calculated with respect to the mean of years 1850-1900 for each model. Multimodel mean is shown as a thick black line. **c**, Multimodel mean change in export flux between the averages of 2080-2100 and 1850-1900. Hatching indicates where 90% of models (at least 17 of 19) agree on the sign of the change in export flux.

Supplementary Table 1: Full model analysis of whether export flux processes are excluded/included. We surveyed the IPCC CMIP6 archive for global climate models which incorporate explicit marine biogeochemistry (total of 19; Supplementary Table 4). The model structure was examined to determine whether the processes we identify as important to export flux are included, and the particle sinking rate and model resolution were also assessed.

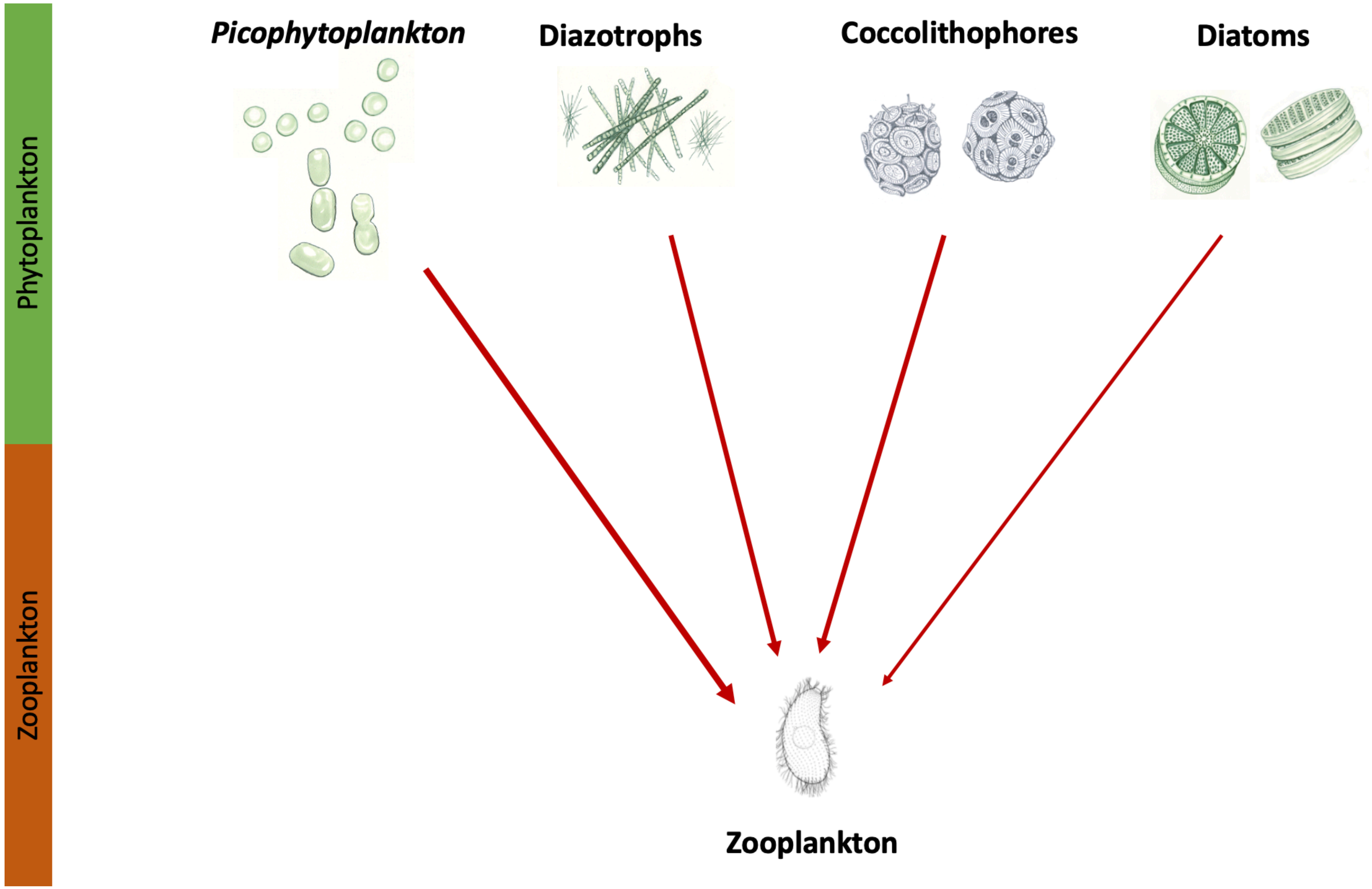
Model & *ecosystem module*	Fragmentation	Zooplankton vertical migration	Phytoplankton size effect on sinking (*1)	Temperature dependent remineralization	Oxygen dependent remineralization	Viscosity of seawater	Mineral ballasting	Mineral protection	Fish migration	TEP production /stickiness	Variable stoichiometry (*2)	Sinking rate (small & large POC) (*3)	Model resolution (*4)
Can ESM5	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	8 m d^{-1}	(*5)
CanESM5-CanOE	✗	✗	✓	✓	✗ (*6)	✗	✗	✗	✗	✗	✗	2 & 30 m d^{-1}	(*5)
CESM & CESM-WACCM *MARBL* (*7)	✗	✗	✗ (*12)	✗	✓	✗	✓	✓	✗	✗	✗	No explicit sinking	1°
CMCC-ESM2 *BFM5.2*	✗	✗	✗	✓	✓	✗	✗	✗	✗	✗	✓	1 m d^{-1}	1°
CNRM, EC-Earth-CC & IPSL *PISCES2* (*7)	✓ (*9)	✗	✓	✓	✓	✗	✗	✗	✗	✗	✗	2 & 30-200 m d^{-1}, depth dependent	1°
CSIRO *WOMBAT*	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	24 m d^{-1}	1°
GFDL-CM4 *BLING*	✗	✗	✗	✓	✓	✗	✓	✓	✗	✗	✗	50-180 m d^{-1}, depth dependent	¼°
GFDL-ESM4 *COBALT*	✗	✗	✗ (*12)	✓	✓	✗	✓	✓	✗	✗	✗	100 m d^{-1}	½°
MIROC	✗	✗	✗	✓	✓	✗	✗	✗	✗	✗	✗	5 m d^{-1} from 0-200 m	1°
MPI HR & MPI LR *Hamocc6* (*7,*8)	✗	✗	✗	✗	✗ (*6)	✗	✗	✗	✗	✗	✗	3.5-80 m d^{-1}, depth dependent	½°
MRI	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	2 m d^{-1}	(*10)
NASA-GISS	✗ (*11)	✗	✓	✓	✗	✓	✗	✗	✗	✗	✗	Varies with viscosity	1°
NorESM LM & NorESM MM *Hamocc5.1* (*7)	✗	✗	✗	✗	✗ (*6)	✗	✗	✗	✗	✗	✗	5 m d^{-1}	1°
UK-ESM *Medusa*	✗	✗	✓	✓	✗	✗	✗	✓	✗	✗	✗	2.5 m d^{-1}	1°
Summary (19 models total)	✗ 18 ✓ 1	✗ 19 ✓ 0	✗ 13 ✓ 6	✗ 8 ✓ 11	✗ 9 ✓ 10	✗ 18 ✓ 1	✗ 14 ✓ 5	✗ 14 ✓ 5	✗ 19 ✓ 0	✗ 19 ✓ 0	✗ 18 ✓ 1	1-200 m d^{-1}	¼ - 1°

Motivation

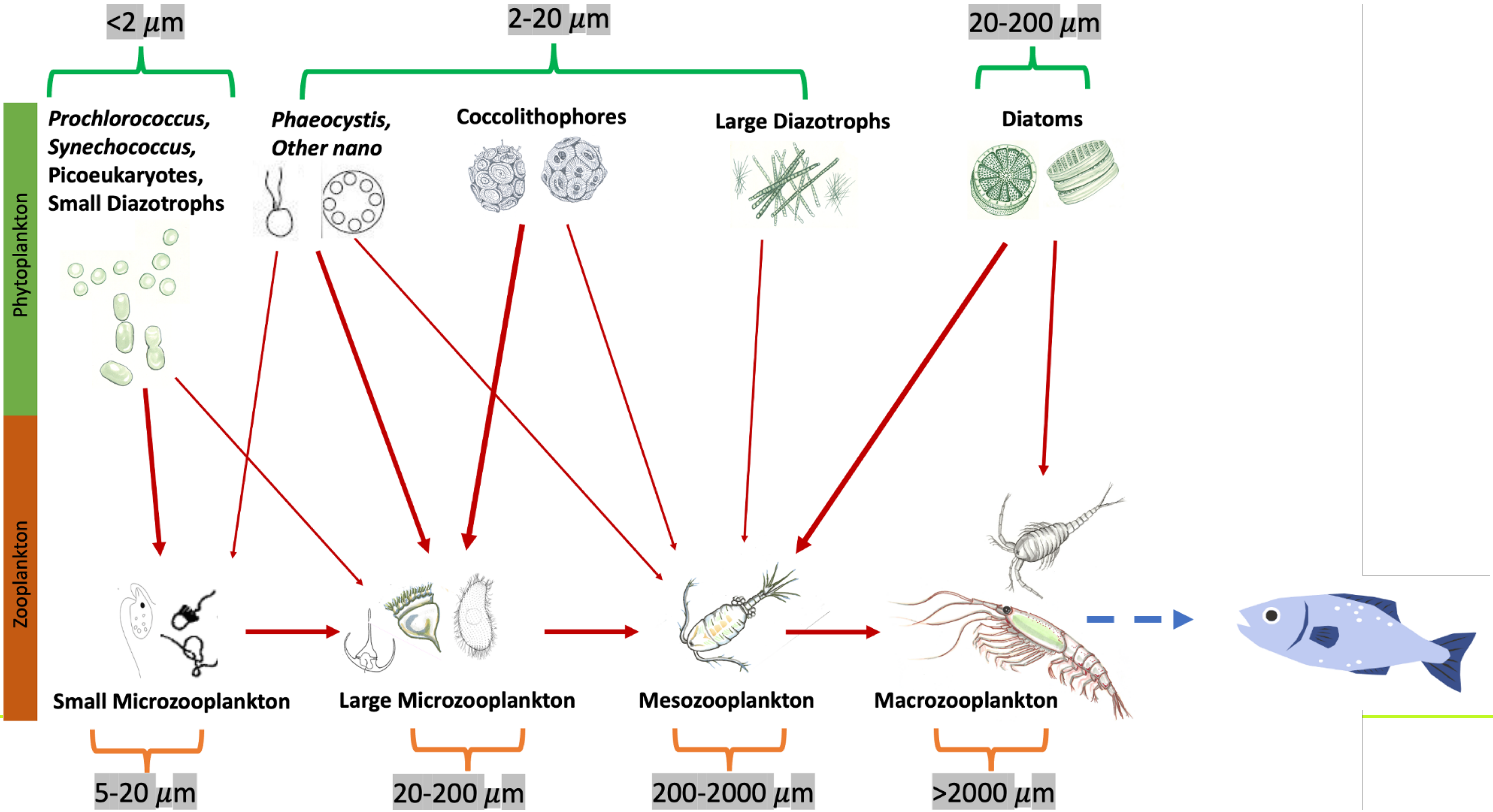
- There are large uncertainties in export flux estimation in current CMIP6 models;
- Current marine ecosystem representation is too simplified in the most CMIP6 models (typically 2-3 types of phytoplankton, 1-2 types of zooplankton)
- The "inclusion of dynamic plankton and sinking particle sizes is likely to have the most notable effect on modeled future export flux" (Henson et al., 2022).

→ An **Intermediate complexity marine ecosystem** model is needed to better capture the future changes in export carbon flux.

The old CESM2 model (4P1Z)

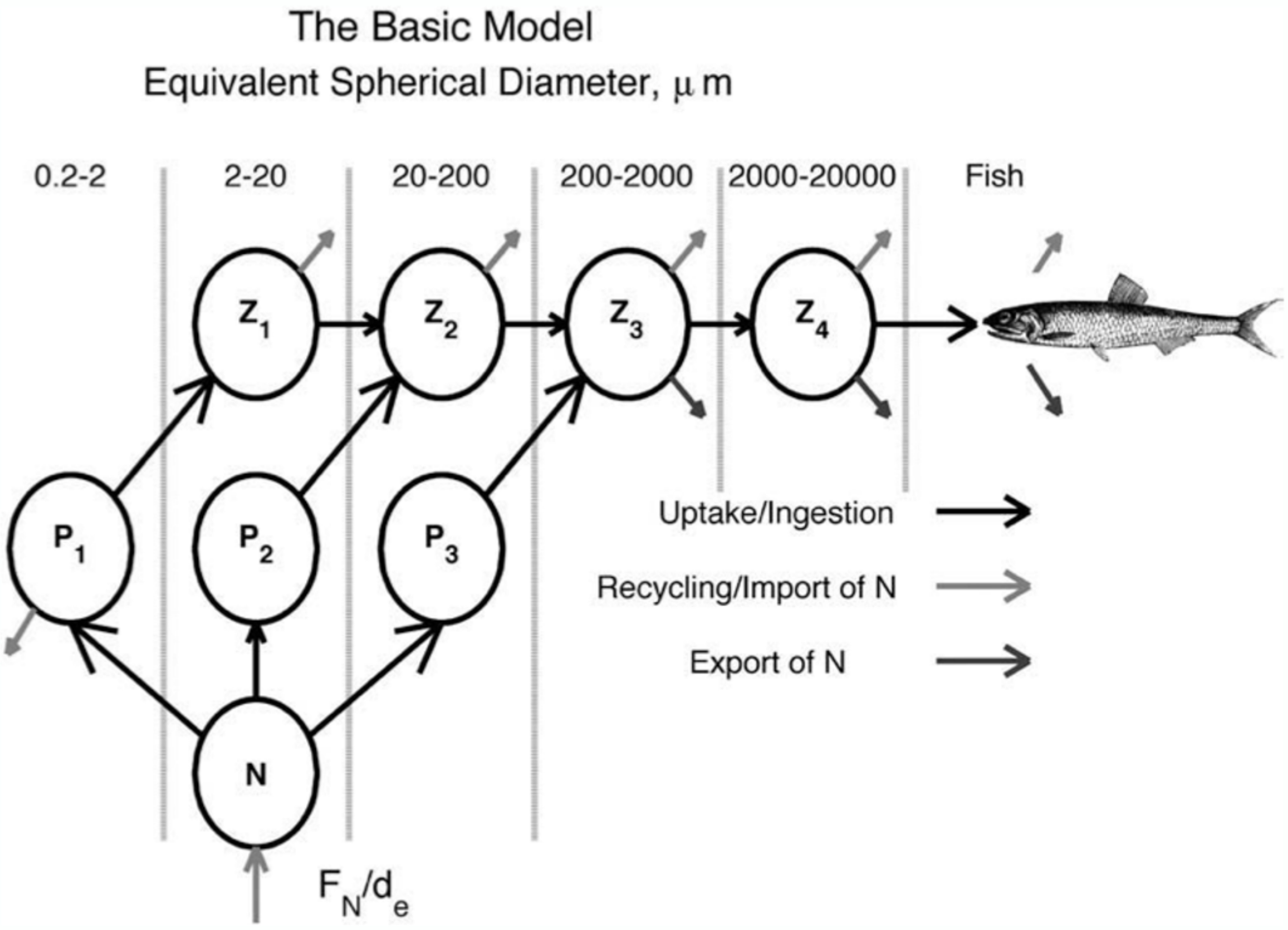


The 8P4Z model



Grazing relationship

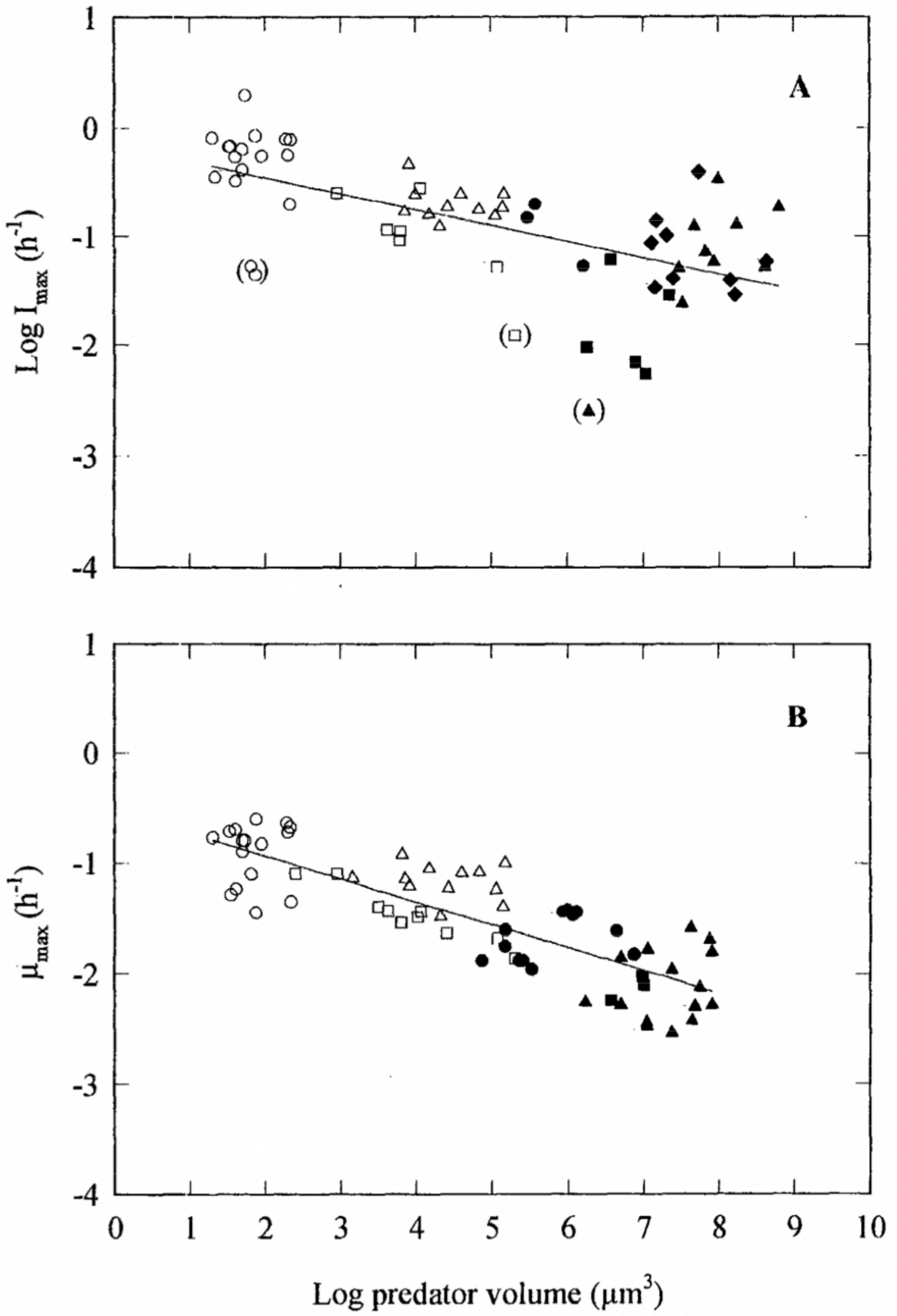
The food web grazing relationships initially follow the optimum predator-prey size ratio (Stock et al. 2014)



Grazing term

$$G = \frac{g^{max} \cdot T_f \cdot \sum_{i=1}^{n} \boldsymbol{d_i}\, p_i}{K + \sum_{i=1}^{n} \boldsymbol{d_i}\, p_i}$$

$$\boldsymbol{d_i} = \frac{p_i}{\sqrt{p_1^2 + p_2^2 + \cdots + p_n^2}}$$

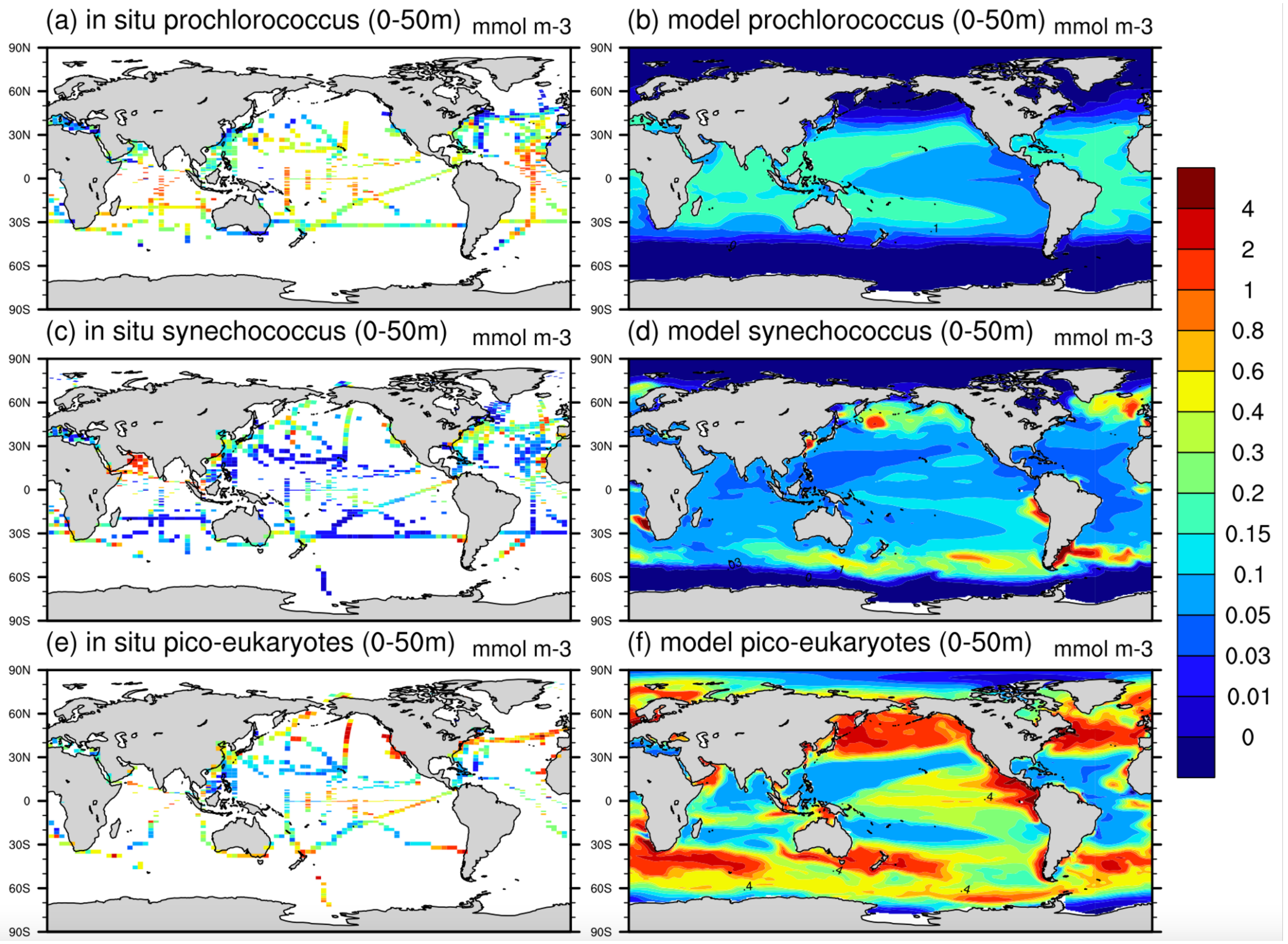


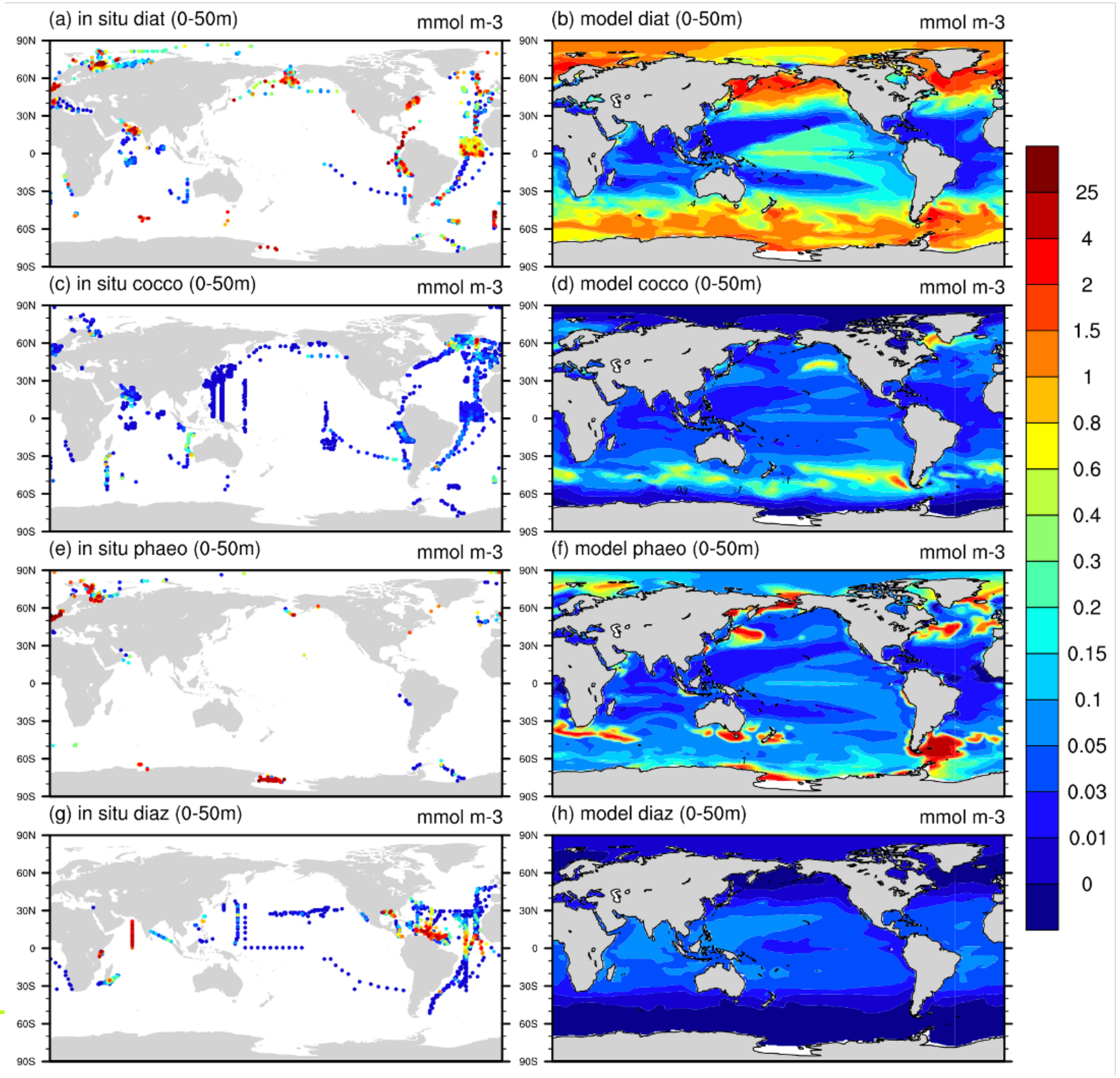
- Maximum specific grazing rates (g^{max}) will be decreased with predator size (Hansen et al., 1997);

- increasing K values with predator size to represent the less chance for larger zooplankton to encounter their preferred prey;

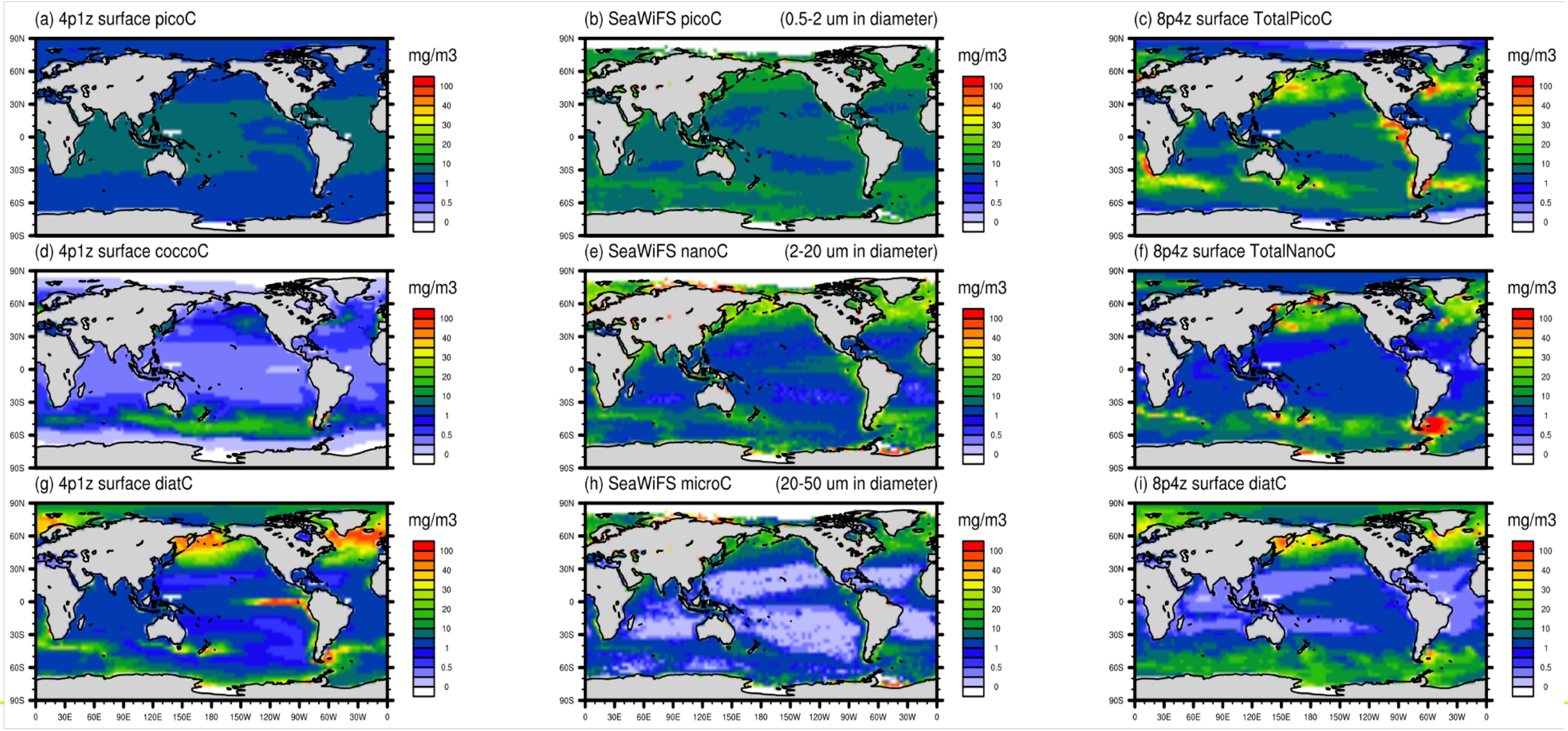
- Density-dependent grazing to stabilize model dynamics by creating a refuge for the less abundant prey species

Model validation

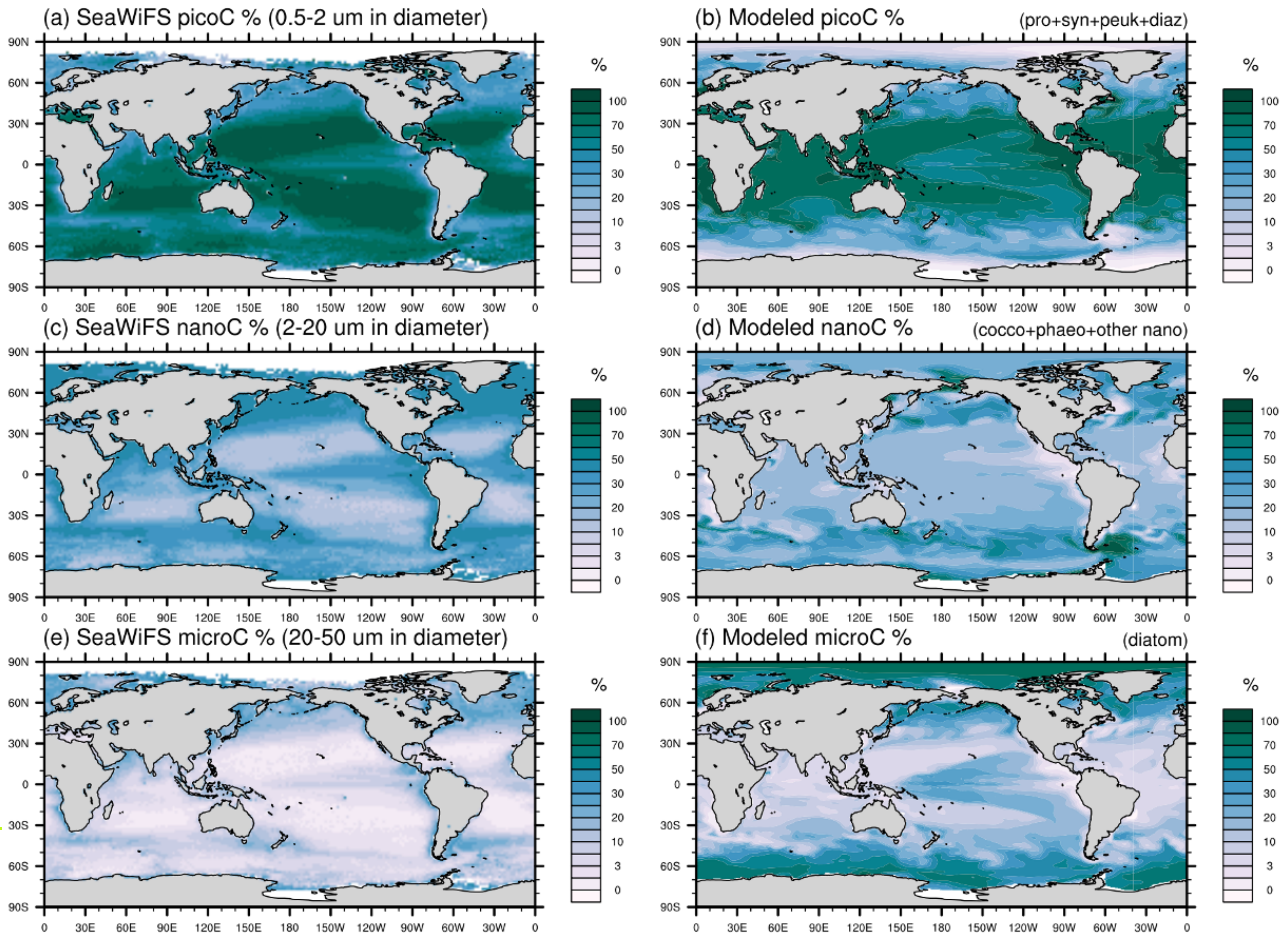


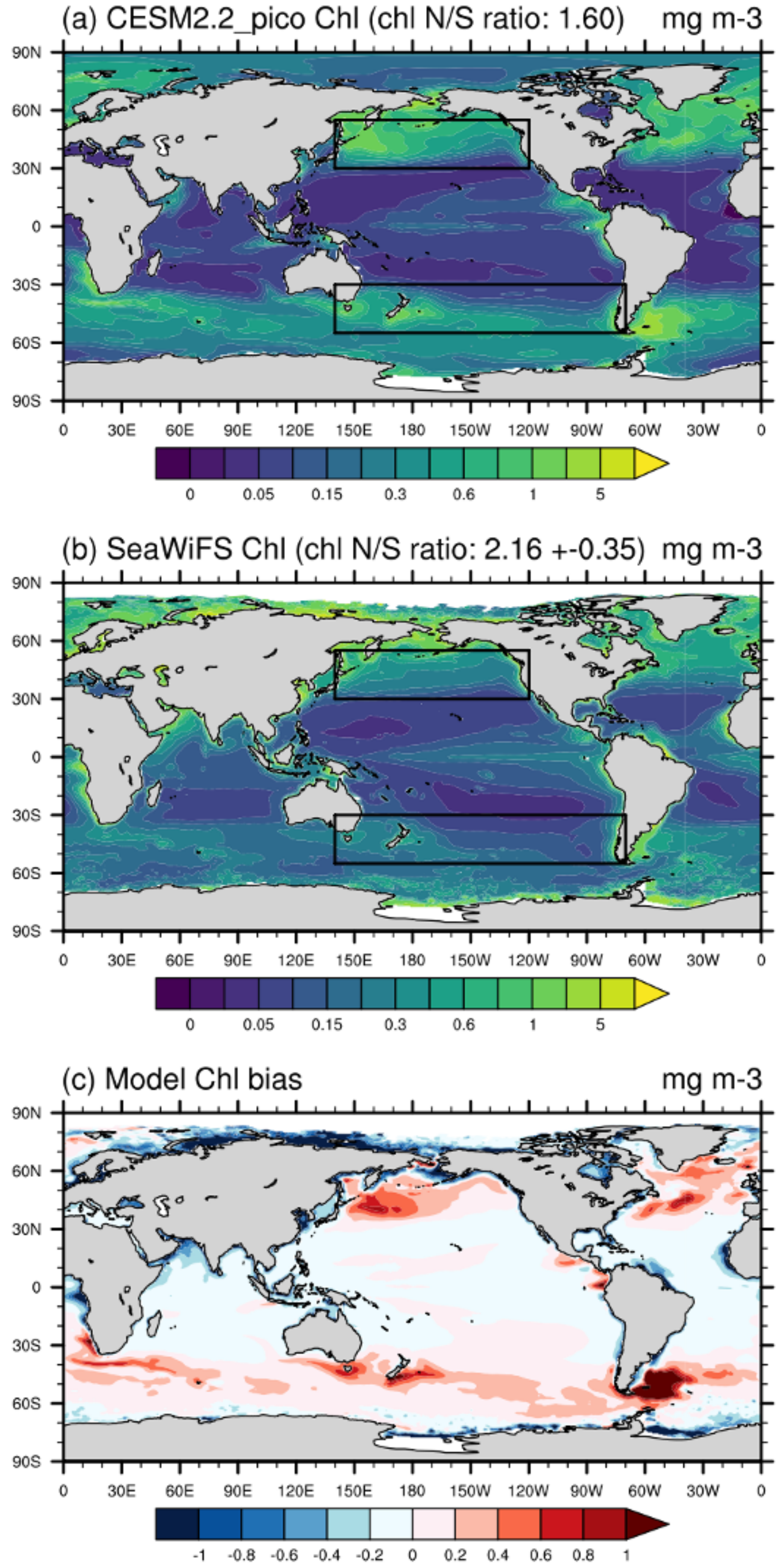


Ecosystem composition

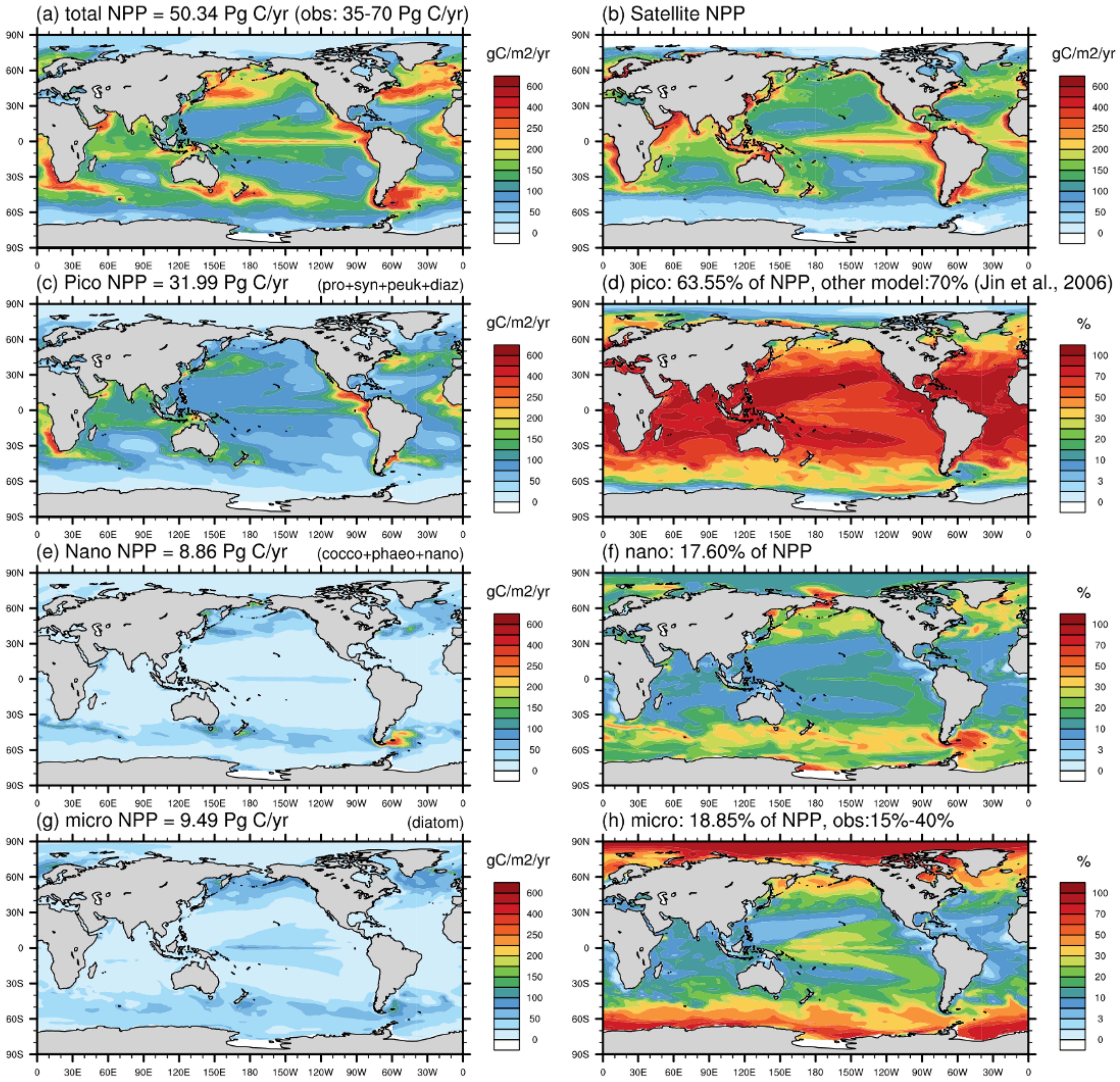


Ecosystem composition



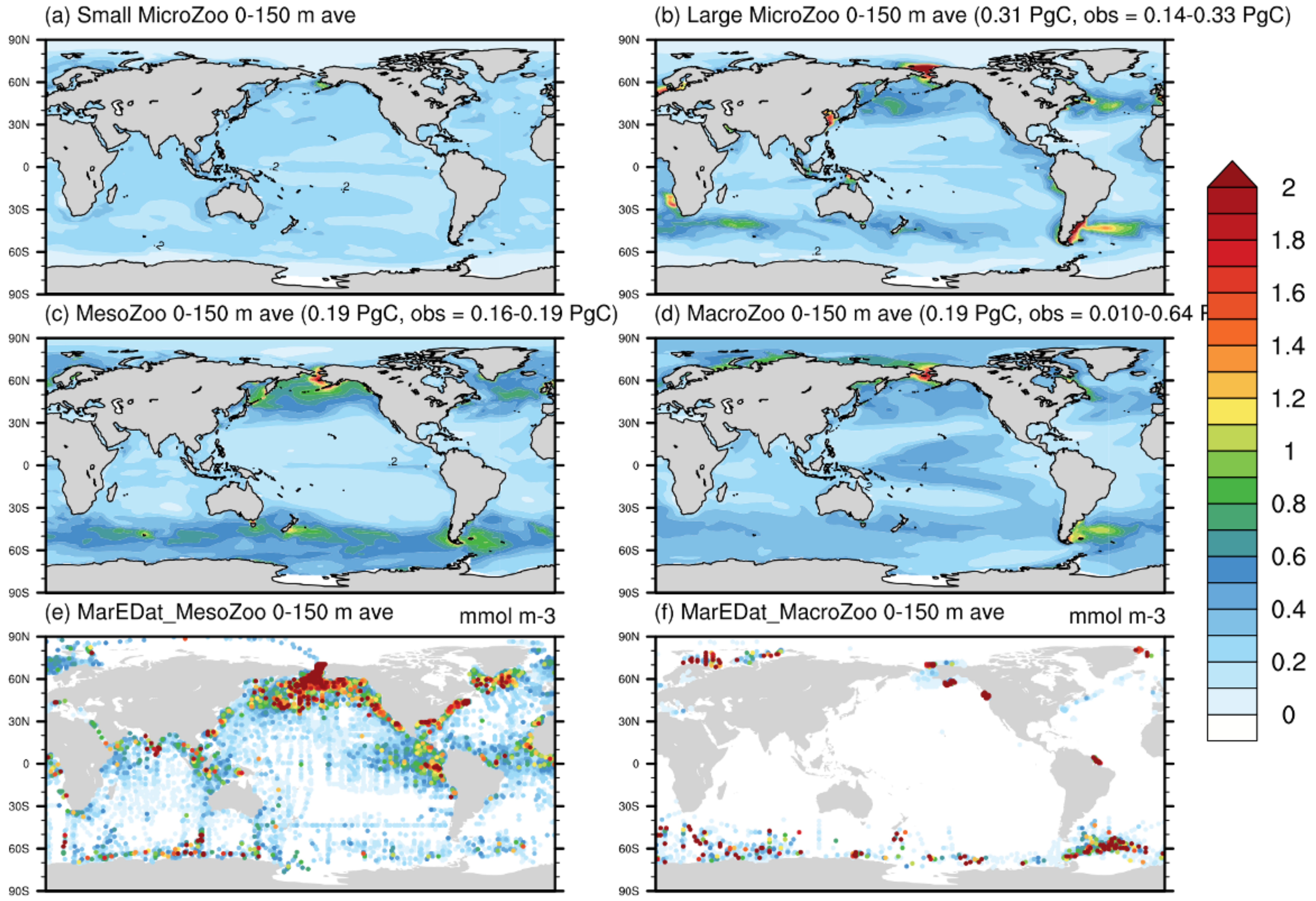


(a) CESM2.2_pico Chl (chl N/S ratio: 1.60)
mg m-3
(b) SeaWiFS Chl (chl N/S ratio: 2.16 +-0.35)
mg m-3
(c) Model Chl bias
mg m-3



(a) total NPP = 50.34 Pg C/yr (obs: 35-70 Pg C/yr)
gC/m2/yr
(b) Satellite NPP
gC/m2/yr
(c) Pico NPP = 31.99 Pg C/yr
(pro+syn+peuk+diaz)
gC/m2/yr
(d) pico: 63.55% of NPP, other model:70% (Jin et al., 2006)
%
(e) Nano NPP = 8.86 Pg C/yr
(cocco+phaeo+nano)
gC/m2/yr
(f) nano: 17.60% of NPP
%
(g) micro NPP = 9.49 Pg C/yr
(diatom)
gC/m2/yr
(h) micro: 18.85% of NPP, obs:15%-40%
%

Zooplankton distribution



Implication

- Build one next-generation marine ecosystem model with intermediate complexity that can be used to do coupled climate simulations.
- Provide a big picture of how plankton size affects the biological pump, enabling better predictions of future marine carbon export.
- Provide the opportunity to incorporate more key missing ecosystem processes (e.g., zooplankton vertical migration) that regulate the efficiency of the biological pump.
- Allow for ecosystem extension for Earth System Model to include higher trophic levels (including fisheries, penguins, etc.).

Thank you !