Global Biogeochemical Cycles

Supporting Information for

Manganese Limitation of Phytoplankton Physiology and Productivity in the Southern Ocean

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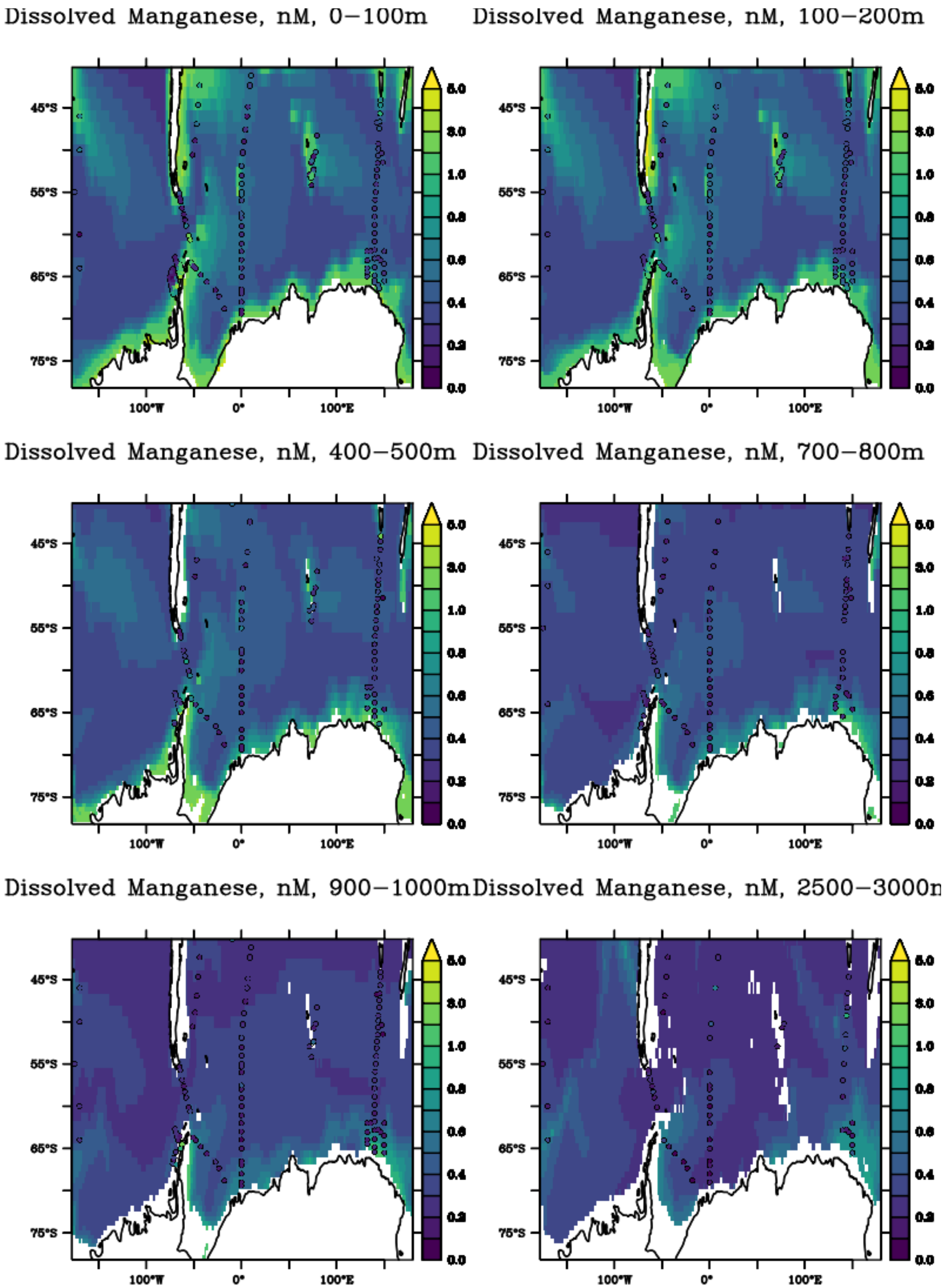

Fig. S1. Modelled dissolved manganese (dMn, annual average) and compiled observations from the Southern Ocean over various depth regions.

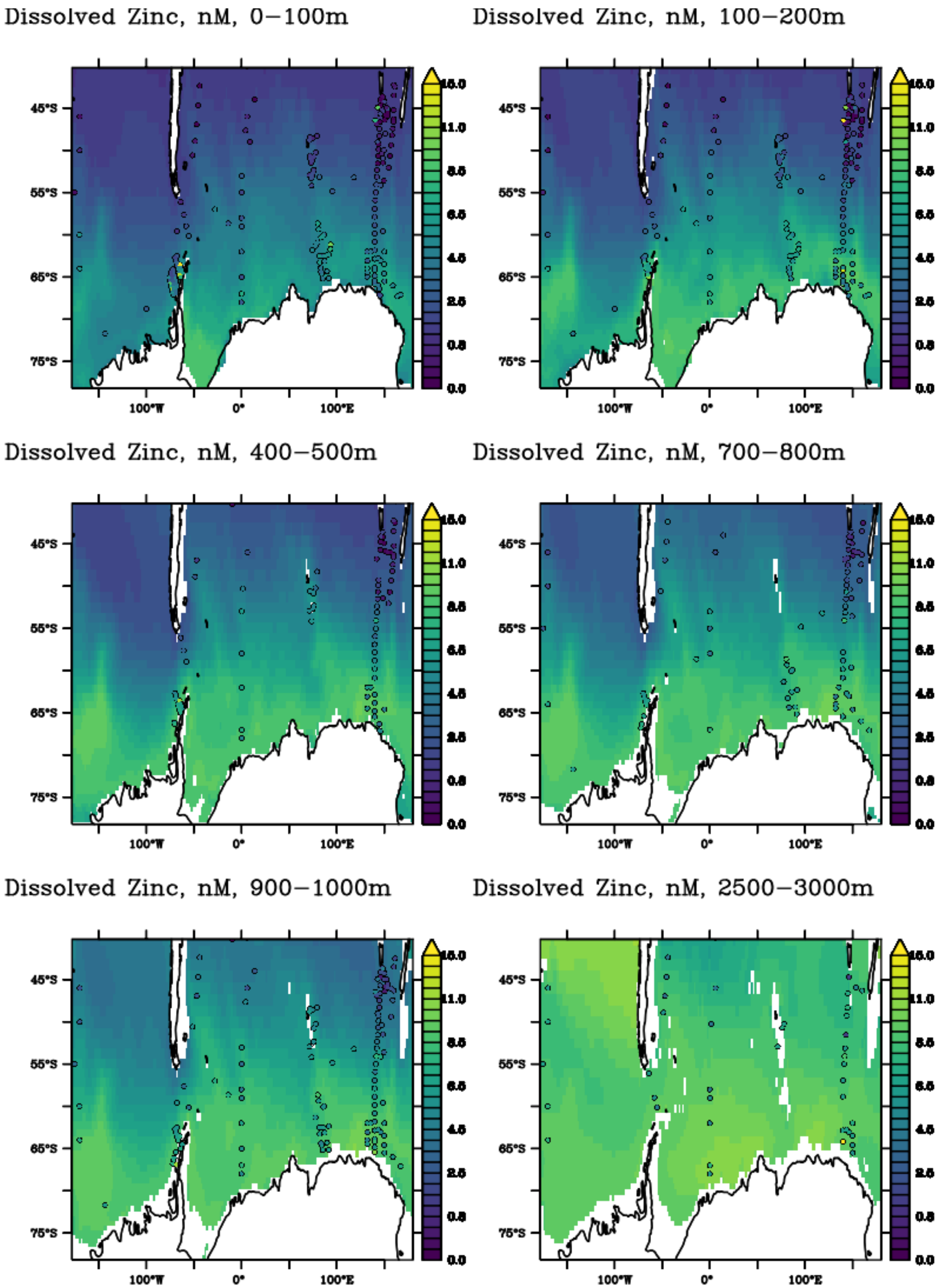

Fig. S2. Modelled dissolved zinc (dZn, annual average) and compiled observations from the Southern Ocean over various depth regions.

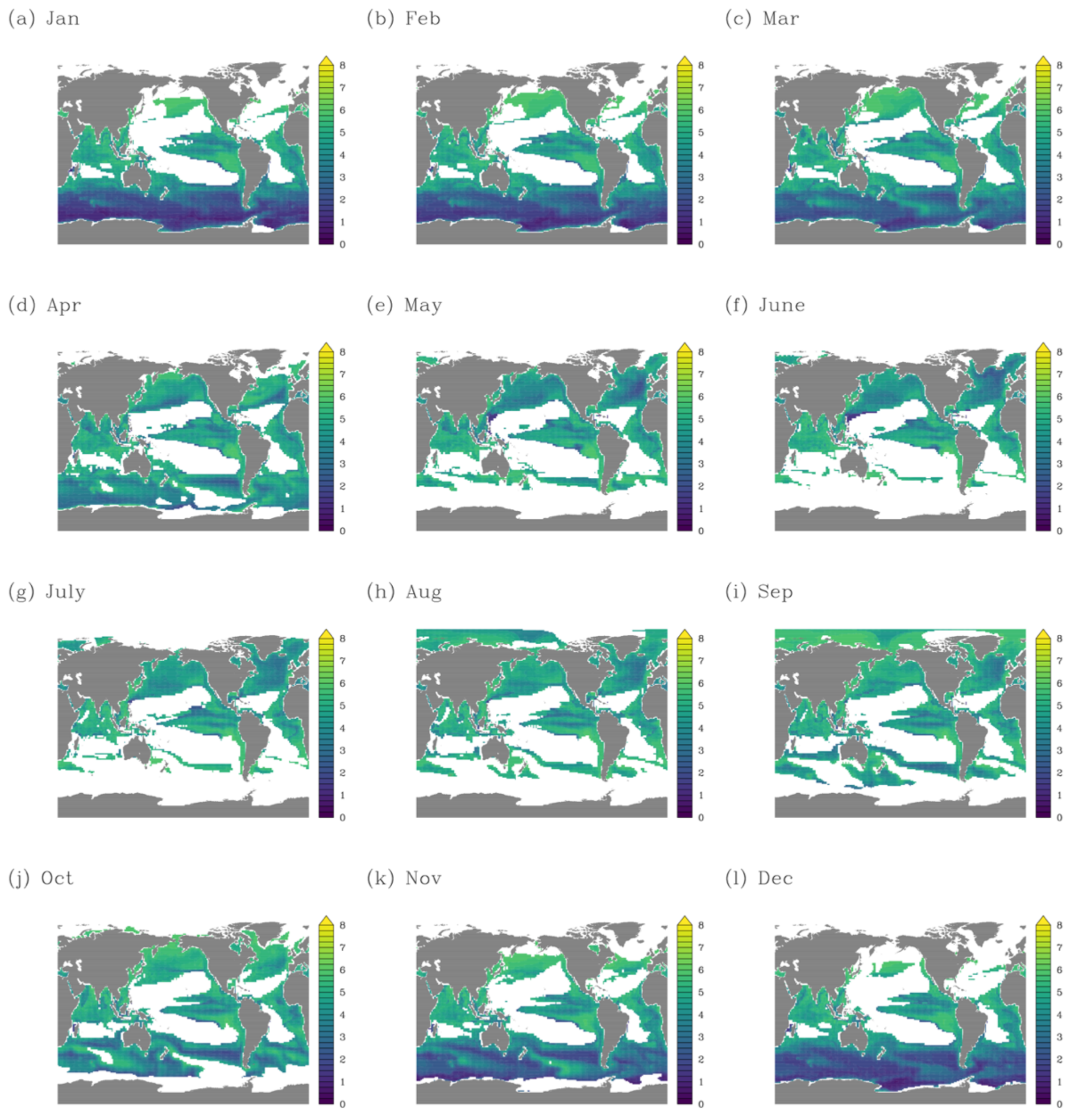

Fig. S3. Modelled Mn quotas across the global ocean in PISCES-BYONIC in in µmol Mn (mol C)$^{-1}$. Areas where phytoplankton carbon biomass falls below 1 x 10^{-6} mol C L^{-1} are masked in white.

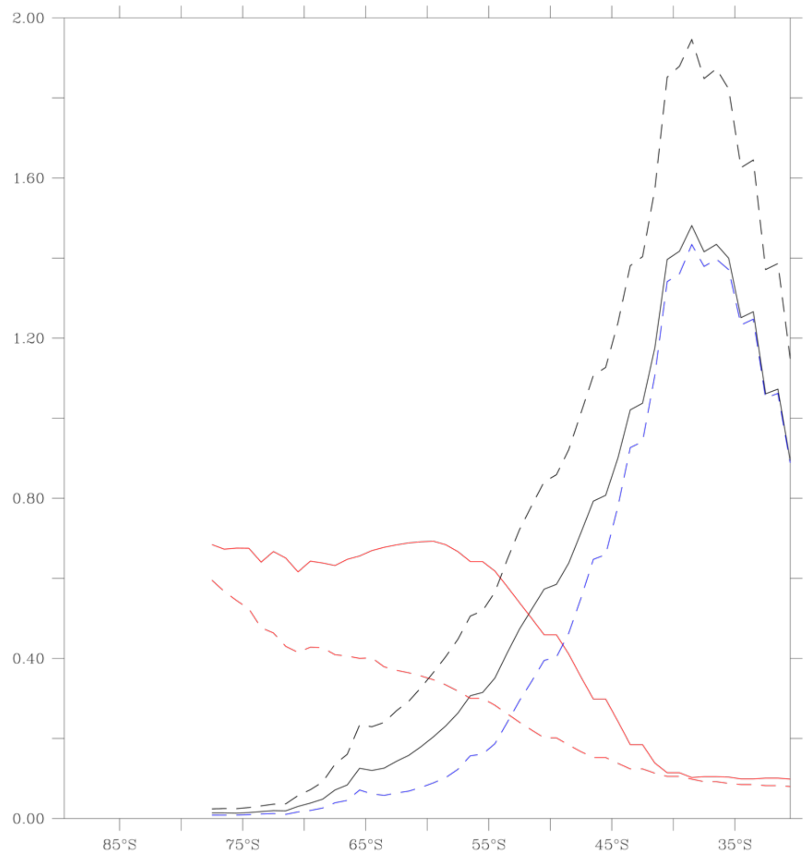

Fig. S4. Zonally integrated rates of Mn uptake (μmol m^{-1} $year^{-1}$) for the standard PISCES-BYONIC model (black line), and sensitivity experiments with 1) no Zn-Mn transporter competition (black dash), and 2) a feedback forcing downregulation of Mn transporters at elevated Q_{Zn} (blue dash). Also shown are zonal averages of dissolved Zn (in nM, divided by 10 for scale, red dash) and phytoplankton Zn quota normalized to the maximum Zn quota (range 0 – 1, red line). Compare with Figure 5 in the Main Text.

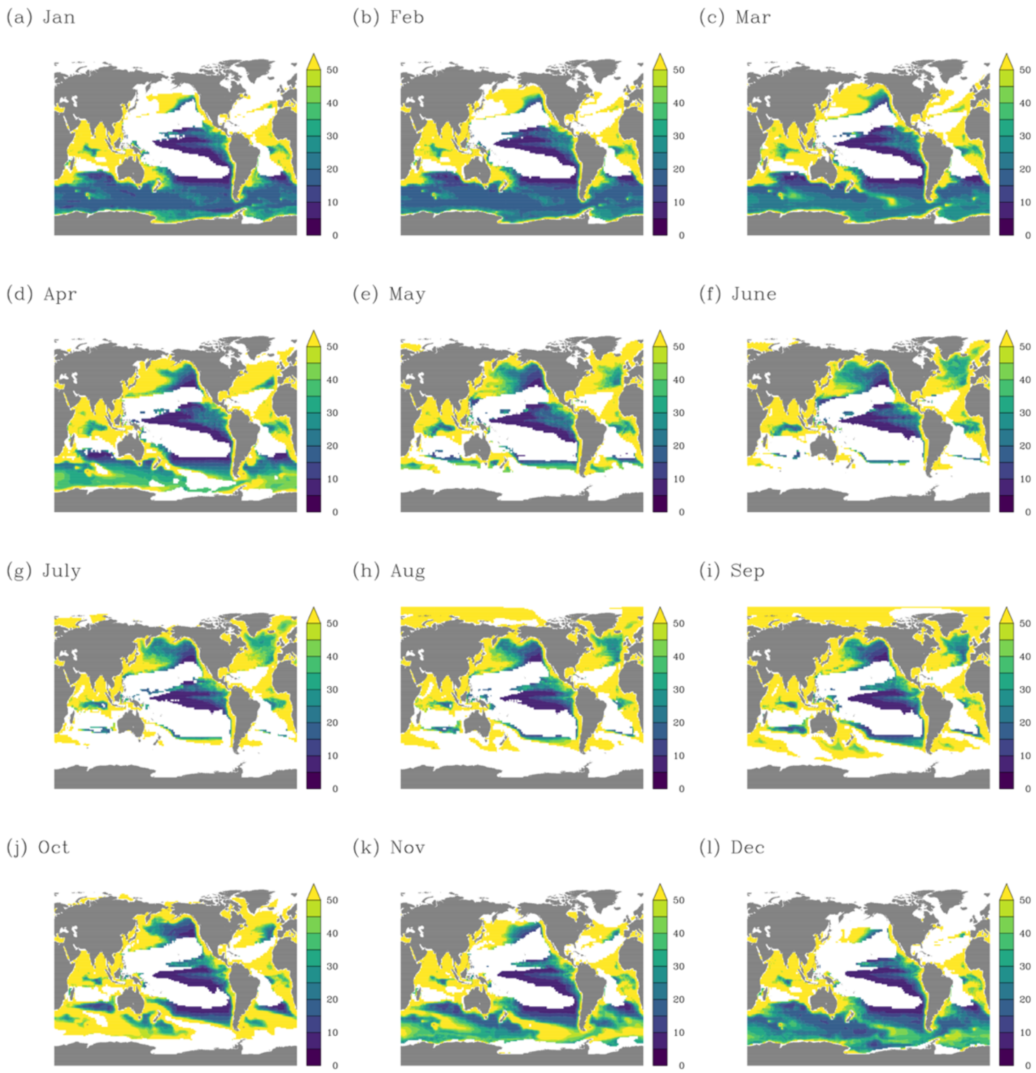

Fig. S5. Modelled Fe quotas across the global ocean in PISCES-BYONIC in µmol Fe (mol C)$^{-1}$. Areas where phytoplankton carbon biomass falls below 1 x 10^{-6} mol C L^{-1} are masked in white.

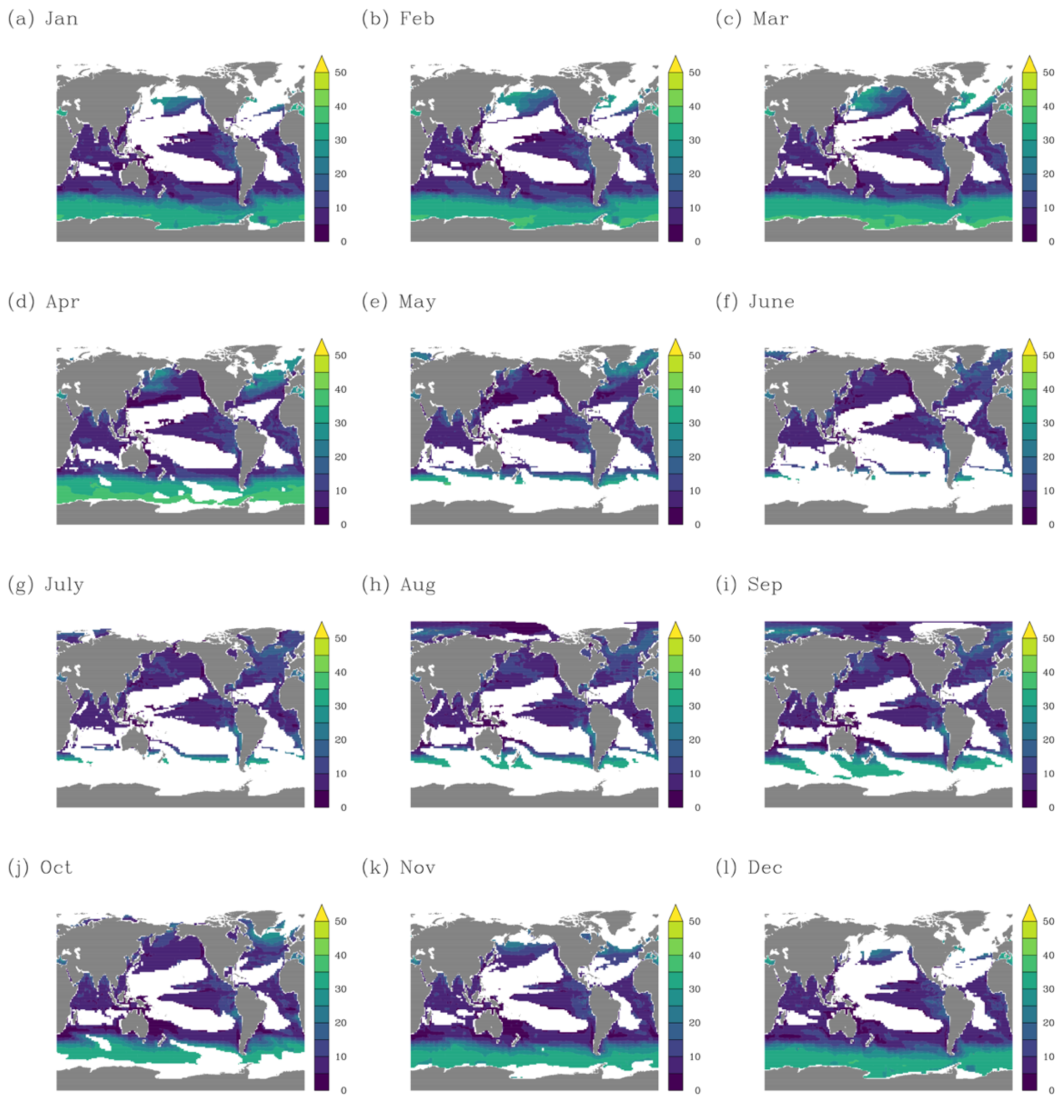

Fig. S6. Modelled Zn quotas across the global ocean in PISCES-BYONIC in µmol Zn (mol C)$^{-1}$. Areas where phytoplankton carbon biomass falls below 1 x 10^{-6} mol C L^{-1} are masked in white.

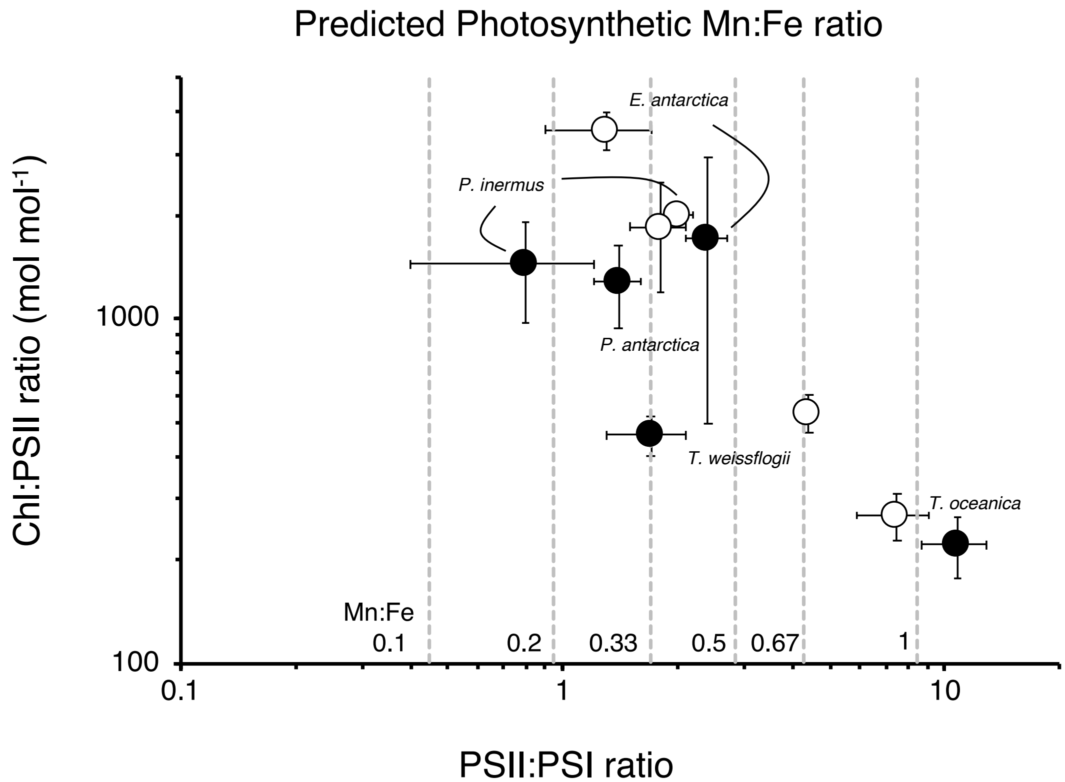

Fig. S7. Comparison of PSII : PSI ratios and Chl : PSII ratios among Southern Ocean phytoplankton and the temperate diatoms *T. oceanica* and *T. weissflogii* using low iron (open circles) and high iron (filled circles) culture experiments from Strzepek et al. (2019). Dotted lines show predicted relative Mn : Fe requirements for photosynthesis (i.e. a ratio of 0.1 indicated 10-times more Fe is required than Mn). Required Mn:Fe ratios were calculated assuming 1) PSII contains 2 Fe atoms and 4 Mn atoms, 2) PSI contains 12 Fe and cytochrome b6 contains 5 Fe, and 3) that PSI and cytochrome b6 are in a 1:1 ratio. We note that *T. oceanica* is predicted to require as much Mn as Fe due to high PSII : PSI ratios, which is consistent with experimental data presented by Sunda (1989).

Table S1. Estimated Chlorophyll *a*:PSII ratios from culture and field studies.

Organism / Region	Chl *a* : PSII (mol mol^{-1})	Reference
Temperate Phytoplankton		
Thalassiosira weissflogii	130 – 260	Dubinsky et al., 1986
	560 – 590	Suggett et al., 2004
	320 – 480	Strzepek & Harrison, 2004
	461 – 534	Strzepek et al., 2019
	1,000	Silsbe et al., 2015
Thalasiosira pseudonana	420 – 930	Sunda & Huntsman, 1998
	1,650	Silsbe et al., 2015
Thalassiosira oceanica	260 – 270	Strzepek & Harrison, 2004
	220 – 270	Strzepek et al., 2019
Skeletonema costatum	590 – 610	Falkowski et al., 1981
	1,151	Silsbe et al., 2015
Ditylum brightwellii	1,110	Silsbe et al., 2015
Phaeodactylum tricornutum	420 – 570	Friedman & Alberte, 1986
Chaetocerus muelleri	520 – 590	Suggett et al., 2004
	1,042	Silsbe et al., 2015
Dunaliella tertiolecta	590 – 620	Falkowski et al., 1981
	540 – 740	Suggett et al., 2004
Emiliana huxleyi	540 – 650	Suggett et al., 2004
	480 – 720	Suggett et al., 2007
	775	Silsbe et al., 2015
Isochrysis galbana	51 – 219	Dubinsky et al., 1986
Phaeocystis globosa	961	Silsbe et al., 2015
Aureococcus anophageffrens	720 – 950	Suggett et al., 2004
Prorocentrum minimum	260 – 365	Dubinsky et al., 1986
	430 – 530	Suggett et al., 2004
	725	Silsbe et al., 2015
Tetraselmis striata	790	Silsbe et al., 2015
Pycnococcus provasolii	621 – 930	Suggett et al., 2004
Rhodomonas salina	470 – 510	Suggett et al., 2004
Storeatula major	440 – 520	Suggett et al., 2004
Prochlorococcus strain SS120	270	Bibby et al., 2001, 2003
Synechococcus WH7803	240 – 290	Suggett et al., 2004
Antarctic Phytoplankton		
Phaeocystis antarctica	1280 – 1850	Strzepek et al., 2019
	630 – 1960	Trimborn et al., 2019
Proboscia inermis	1440 – 2070	Strzepek et al., 2019
Eucampia antarctica	1710 – 3540	Strzepek et al., 2019
Chaetoceros debilis	120 – 2540	Trimborn et al., 2019
Field studies		
Subtropical and Tropical Atlantic	330 – 420	Suggett et al., 2006
Celtic Sea	530 – 720	Moore et al., 2006
Subpolar North Atlantic*)*	380 – 1700	Macey et al., 2014
	400 – 833	Moore et al., 2005
Subarctic Pacific	280 – 450 (coastal)	Schuback & Tortell, 2019
	520 – 580 (open ocean)	
Southern Ocean	450 ± 350 (winter)	Ryan-Keogh et al., 2018
	1580 ± 1400 (summer)	
Biogeochemical Model		
Global	1000 (500 – 2000)	This study

Table S2. Summary of phytoplankton metal quota samples included in Figure 2.

Region	Cruise	Station	Lat (°N)	Lon (°E)	Depth (m)	Date	# cells	Reference
Antarctic	SOFeX	19	-66	-172	20	24 Jan 2002	17	Twining, Baines, & Fisher, 2004; Twining, Baines, Fisher, et al., 2004
		27	-66	-172	20	2 Feb 2002	17	Twining, Baines, & Fisher, 2004; Twining, Baines, Fisher, et al., 2004
Subantarctic	SOFeX	7	-56	-172	20	12 Jan 2002	6	Twining, Baines, & Fisher, 2004; Twining, Baines, Fisher, et al., 2004
		11	-56	-172	20	20 Jan 2002	9	Twining, Baines, & Fisher, 2004; Twining, Baines, Fisher, et al., 2004
	SOTS	TM02	-47	142	15-30	7 Mar 2018	25	*
		TM04	-47	142	15-40	9 Mar 2018	18	*
		TM05	-47	142	15-30	18 Mar 2018	16	*
N. Atlantic	GA02	2011-10	32	-64	25	19 Nov 2011	30	Twining et al., 2015
		2011-12	30	-57	25	23 Nov 2011	13	Twining et al., 2015
		2011-16	26	-45	25	30 Nov 2011	24	Twining et al., 2015
		2011-20	22	-36	25	3 Dec 2011	9	Twining et al., 2015
	ZIPLoC	2	22	-54	40	11 July 2017	22	*
		7	22	-31	40	5 Aug 2017	15	*

* Sofen et al. Metal contents of autotrophic flagellates from contrasting open-ocean ecosystems. *Limnology and Oceanography Letters.* In Review.

Table S3. Summary of published Southern Ocean Mn addition bio-assays.

Study / Reference	Region	Lat (°N)	Lon (°E)	Month	Limiting Nutrient
Browning et al., 2021	Drake passage (Northern)	-54.7	-58.0	Nov	Fe
		-55.4	-57.7	Nov	Fe
		-55.6	-58.0	Nov	Fe
		-55.8	-57.8	Nov	Fe
	Drake Passage (Central)	-56.6	-57.4	Nov	Mn
		-56.8	-57.2	Nov	Mn/Fe
		-58.1	-56.4	Nov	Mn
	Drake Passage (Southern)	-58.7	-56.1	Nov	Fe
		-59.6	-55.5	Nov	Fe
		-61.0	-54.6	Nov	Replete
Wu et al., 2019	Ross Sea (McMurdo Sound)	-77.62	165.4	Dec	Replete
		-77.62	165.4	Jan	Mn/Fe
Sedwick et al., 2000	Ross Sea	-76.3	-179.6	Nov	Replete
		-76.3	-177.5	Dec	Replete
		-75	-172	Dec	Fe
		-76.3	-117.4	Jan	Fe
Sedwick & DiTullio, 1997	Ross Sea	-76.3	-170.4	Dec	Fe
		-76.3	-170.4	Jan	Fe
Scharek et al., 1997	Atlantic Sector, Polar Front	-47	-6	Oct/Nov	Fe
		-50	-6	Oct/Nov	Fe
	Atlantic Sector, ACC	-53	-6	Oct/Nov	Fe
	Weddell Sea	-59	-6.2	Oct/Nov	Fe
Buma et al., 1991	Weddell/ACC confluence	-59	-49	Dec	Mn/Fe
	Weddell Sea	-62	-47	Dec	Fe
	Scotia Sea	-57	-49	Dec	Fe
Martin et al., 1990	Ross Sea	-75	-173	Jan/Feb	Fe
		-72	167	Jan/Feb	Fe

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