Supporting Information for

Effect of phytoplankton size diversity on primary productivity in the North Pacific: trait distributions under environmental variability

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S.1 Supporting Text

S.1.1 Description of the three-dimensional (3D) regional ocean model
A regional 3D ocean model built on the Regional Ocean Modelling System (ROMS) (Shchepetkin & McWilliams 2005) was developed for the North Pacific (95.63 °E to 285.43 °E, 10.43 °S to 66.57 °N).

ROMS is a terrain following, free surface ocean model that solves hydrostatic, primitive equations. The spatial resolution is 1° x 1° with 40 vertical layers having finer vertical resolution at the sea surface (surface and bottom stretching parameters being 2.0 and 0.6, respectively). The normal year datasets of coordinated ocean-ice reference experiments (CORE) version 2 containing heat and freshwater fluxes, and wind speeds were used as surface forcing (Large & Yeager 2009). Surface temperature and salinity data were relaxed to the climatology of the World Ocean Atlas (WOA) 2003 (version 2; Boyer et al. 2013).

The model was started assuming no water motion, with initial conditions (January 1st) of temperature and salinity interpolated from the WOA2013 climatology. It was integrated for ten years to achieve quasi steady state, and the results of final year were examined.

S.1.2 Description of the ecosystem model

The ecosystem model contains 8 tracers in total: dissolved inorganic nitrogen (DIN, abbreviated as N in all the equations; unit: µmol N L⁻¹), phytoplankton biomass (P, µmol N L⁻¹), zooplankton biomass (Z,
µmol N L⁻¹), detritus in terms of nitrogen (D; µmol N L⁻¹) and iron (DFe; nmol Fe L⁻¹), dissolved iron (fer; nmol Fe L⁻¹), the products of \( P \bar{I} \) (abbreviated as \( P_\theta \)) and \( P(\nu + \bar{I}^2) \) (abbreviated as \( P_\phi \)) where \( \bar{I} \) (ln \( \mu m^3 \)) is the phytoplankton mean log cell volume and \( \nu \) ((ln \( \mu m^3 \))^2) is the log volume variance (Fig. S1).

The equation for phytoplankton biomass is:

\[
\frac{dP}{dt} = \mu_{\text{com}} - f(E_z, T)G(P)Z + \text{Adv}(P) + \text{Diff}(P)
\]

(1)

where \( \mu_{\text{com}} \) is the phytoplankton specific growth rate (d⁻¹) of the whole community (i.e. integrated over the whole size spectra). The operators \( \text{Adv}(\cdot) \) and \( \text{Diff}(\cdot) \) describe three dimensional water advection and diffusion, respectively. The Arrhenius function \( f(E, T) = e^{\frac{E_z}{k}(\frac{1}{T_0} - \frac{1}{T})} \) describes the temperature effects on rates with the activation energy \( E \) (in electron volts [eV], 1 eV = 96.49 kJ mol⁻¹). \( E_z \) and \( E_\rho \) denote for zooplankton and phytoplankton, respectively. The grazing function \( G(P) = I_{max} \frac{P^2}{P^2 + K_p^2} \) describes a Holling type III functional response of zooplankton grazing. \( I_{max} \) is the maximal per capita ingestion rate (d⁻¹), and \( K_p \) the half-saturation constant of grazing.

Following Merico et al. (2014) and Smith et al. (2016), the equations for \( \mu_{\text{com}}, \nu, \) and \( \nu \) are:

\[
\mu_{\text{com}} = \left( \mu + v \left( \frac{d^2 \mu}{dt^2} + u \frac{d^4 \mu}{dt^4} \right) \right)_{l = \bar{I}} - 3u \frac{d^3 \mu}{dt^3}
\]

(2)

\[
\frac{df}{dt} = \left. \left[ \nu \left( \frac{d\mu}{dt} + u \frac{d^3 \mu}{dt^3} \right) - 3u \frac{d\mu}{dt} \right] \right|_{l = \bar{I}}
\]

(3)

\[
\frac{dv}{dt} = \left. \{ v \left( \frac{d^2 \mu}{dt^2} - \frac{d^2 g}{dt^2} + u \frac{d^4 \mu}{dt^4} \right) - 5u \frac{d^3 \mu}{dt^3} \} + 2u \mu \right|_{l = \bar{I}}
\]

(4)
where $\mu$ is the phytoplankton growth rate ($d^{-1}$) at mean size $\bar{l}$. $u$ is the trait diffusion parameter. $\frac{d^2g}{dl^2}$ is the second derivative of zooplankton clearance rate ($d^{-1}$) against phytoplankton size and can be derived from the log-normal prey size distribution underlying our moment approximation and a log-normal size grazing kernel consistent with empirical data and mechanistic considerations (Wirtz 2014). This grazing kernel $e^{-s(l-l_{opt})^2}$ introduces the selectivity $s$ as the inverse feeding breadth. The KTW mechanism implies that the optimal prey size ($l_{opt}$) of zooplankton grazing always coincides with the mean (log) size of the phytoplankton size distribution.

The second order derivative of the specific rate then fulfils the condition (Smith et al. 2016):

$$\left.\frac{d^2g}{dl^2}\right|_{l=\bar{l}} = -\frac{\alpha_g}{\nu} g(l)$$

in which

$$g(l)\big|_{l=\bar{l}} = \frac{g(P)}{\nu} \sqrt{1 + \alpha_g}$$

$\alpha_g > 0$ means zooplankton is engaged in selective grazing and has a feeding preference on abundant prey.

The equations of $P_l$ and $P_v$ follow:

$$\frac{dP_l}{dt} = P \left(\frac{dv}{dt} + \bar{l} \frac{dP_l}{dt}\right) + Adv(P_l) + Diff(P_l)$$

$$\frac{dP_v}{dt} = P \left(\frac{dv}{dt} + 2\bar{l} \frac{dP_v}{dt}\right) + (v + \bar{l}^2) \frac{dP_v}{dt} + Adv(P_v) + Diff(P_v)$$
The total ingested food by zooplankton is divided into net growth, excretion into the inorganic nitrogen pool, and defecation of unassimilated food into the detritus pool (Buitenhuis et al. 2010).

Zooplankton mortality is set to be proportional to the squares of its biomass and is also converted into detritus pool. As such, the dynamics of zooplankton follow:

\[
\frac{dz}{dt} = f(E_z, T)(ZG(P)NGE - m_z Z^2) + Av(Z) + Diff(Z) \tag{9}
\]

where NGE is the net growth efficiency of zooplankton. \(m_z\) is the mesozooplankton mortality coefficient \((d^{-1} \text{ (} \mu \text{mol N L}^{-1} \text{)})^{-1}\).

Detritus is converted to DIN at a rate \((R_{dn}, d^{-1})\) that has the same temperature sensitivity with zooplankton grazing. Detritus is also assumed to have a sinking rate \((W_d, d^{-1})\) that linearly relates to surface temperature \((SST)\) (Gregg 2008).

\[
W_d = W_0 (k + bSST) \tag{10}
\]

\[
\frac{dD}{dt} = f(E_z, T)(ZG(P)unass + m_z Z^2 - DR_{dn}) - W_d \frac{dD}{dz} + Adv(D) + Diff(D) \tag{11}
\]

where \textit{unass} represents the fraction of unassimilated food by zooplankton.

DIN is taken up by phytoplankton and is replenished by zooplankton excretion and detritus regeneration.

\[
\frac{dN}{dt} = -P \mu_{com} + f(E_z, T)(ZG(P)(1 - NGE - unass) + DR_{dn}) + Adv(N) + Diff(N) \tag{12}
\]
The sources and sinks of fer largely follow DIN with an additional source (atmospheric deposition; \( \text{Fe}_{\text{depo}} \)) and sink (scavenging; \( \text{fer}_{\text{scav}} \)) (Nickelsen et al. 2015):

\[
\frac{d\text{fer}}{dt} = \left[ -P\mu_{\text{com}} + f(E_z, T)(ZG(P)(1 - NGE - \text{unass})) + DR_{\text{dn}} \right] \text{R}_{\text{fer},N} + \text{Fe}_{\text{depo}} - \text{fer}_{\text{scav}} + \text{Adv(fer)} + \text{Diff(fer)}
\]

To translate between nitrogen and iron in phytoplankton and zooplankton, a constant \( \frac{\text{fer}}{N} \) ratio \( (R_{\text{fer},N}) \) of 0.0265 is assumed. The data of monthly atmospheric deposition of total soluble iron are extracted from the Scenario III in Luo et al. (2008). Iron scavenging rate \( (\text{fer}_{\text{scav}}) \) is composed of both linear scavenging rate \( (k_{\text{scm}}, \text{d}^{-1}) \) and particle absorption rate \( (k_{\text{sc}}, \text{d}^{-1} (\text{M M N})^{-1}) \) (Nikelsen et al. 2015):

\[
\text{fer}_{\text{scav}} = (k_{\text{scm}} + k_{\text{sc}}Df(E_z, T))\text{Fe}_{\text{prime}}
\]

in which \( \text{Fe}_{\text{prime}} \) is the concentration (nmol L\(^{-1}\)) of free iron:

\[
\text{Fe}_{\text{prime}} = \frac{(-A + \sqrt{4\text{fer}k_{\text{eq}} + A^2})}{2k_{\text{eq}}}
\]

\[
A = 1 + (f_{\text{fe}} - \text{fer})k_{\text{eq}}
\]

where \( k_{\text{eq}} \) (unit: (mol lig L\(^{-1}\))\(^{-1}\)) is the equilibrium constant between free iron and ligands and is assumed to depend only on temperature:

\[
k_{\text{eq}} = 10^{(17.27 + \frac{1555.7}{T})}
\]
Note that $T$ is in absolute temperature (K). $l_j$ is the total iron ligand concentration that is assumed constant (0.6 nmol lig L$^{-1}$).

The equation for $D_{Fe}$ is:

$$\frac{dD_{Fe}}{dt} = f(E_2, T)(ZG(P)una + m_zZ^2 - R_{dn}D)R_{fe,n} - W_d \frac{dD_{Fe}}{dz} + fer_{scav} + Adv(D_{Fe}) + Diff(D_{Fe})$$  \hspace{1cm} (18)

Phytoplankton growth rate ($\mu$) depends on temperature ($T$, K), light ($I$, W m$^{-2}$), DIN and fer:

$$\mu = f(E_p,T)\mu_m \min \left( \frac{N}{N+K_N}, \frac{fer}{fer+K_{fer}} \right)(1 - e^{-\frac{a_{el}}{\mu (E_p,T)}})$$  \hspace{1cm} (19)

The trait parameters $\mu_m$, $K_N$, $K_{fer}$, and $a$ are all dependent on cell size $l$:

$$\mu_m = \mu_0 e^{\alpha_\mu l + \beta_\mu l^2}$$  \hspace{1cm} (21)

$$K_N = K_{0,N} e^{\alpha_K l}$$  \hspace{1cm} (22)

$$K_{fer} = K_{0,fer} e^{\alpha_{fer} l}$$  \hspace{1cm} (23)

$$a_c = a_{0,c} e^{\alpha_c l}$$  \hspace{1cm} (24)

Phytoplankton chlorophyll-to-carbon ($\theta$, g Chl (mol C)$^{-1}$) and nitrogen-to-carbon ($Q_N$, mol N (mol C)$^{-1}$) ratios are calculated from ambient light and nutrient levels:

$$\theta = \theta_{min} + \frac{\mu}{l_{ac}} (\theta_{max} - \theta_{min})$$  \hspace{1cm} (25)

$$Q_N = \frac{Q_{min}}{1 - \left(1 - \frac{Q_{min}}{Q_{max}} \right) \min \left( \frac{N}{N+K_N}, \frac{fer}{fer+K_{fer}} \right)}$$  \hspace{1cm} (26)
where $\theta_{\text{min}}$ and $\theta_{\text{max}}$ are minimal and maximal Chl:C ratios, respectively. $Q_{\text{min}}$ and $Q_{\text{max}}$ are minimal and maximal N:C ratios, respectively. Total Chl $a$ concentrations ($\text{Chl}, \mu g \text{ L}^{-1}$) and net primary production ($\text{NPP}, \mu g \text{ C L}^{-1} \text{ d}^{-1}$) integrated over the whole size range can be calculated as:

\[
\text{Chl} = P \left( \frac{\theta}{Q_N} + \frac{\mu}{2} \frac{d^2\theta}{dt^2} \right) \bigg|_{t=\overline{t}} \\
\text{NPP} = P \left( \frac{\mu}{Q_N} + \frac{\mu}{2} \frac{d^2\mu}{dt^2} \right) \bigg|_{t=\overline{t}}
\]

(27) (28)

Light levels ($I_z$) at depth $z$ were calculated based on PAR$_{0}$ and Chl $a$ concentrations following the Beer-Lambert law:

\[
I_z = PAR_0 e^{-(2K_w+K_{chl} \int_0^z \text{Chl}(x) dx)}
\]

(29)
in which $K_w$ and $K_{chl}$ are the attenuation coefficients for seawater and Chl $a$, respectively. To realistically estimate the average light field that a phytoplankton cell should experience in the surface mixed layer (Franks 2015), the ambient light level for phytoplankton is calculated as the average light throughout this layer. All the parameter descriptions and values are shown in Table S1.

The initial conditions (January 1st) of inorganic nitrogen were interpolated from the WOA2013. The initial conditions of phytoplankton biomass were estimated from the SeaWIFS chlorophyll monthly climatology with the chlorophyll-to-carbon and nitrogen-to-carbon ratios calculated from the ambient nitrate, light, and temperature following the model developed by Pahlow et al. (2013). The vertical
profiles of chlorophyll were calculated based on surface values following Morel and Berthon (1989). The initial conditions of zooplankton and detritus were assumed 0.78 and 0.2 times the phytoplankton biomass, respectively, following previous model results (Ward et al. 2012). Initial $I$ and $v$ were set globally set to $1 \log \mu m^3$ (approximating an equivalent spherical diameter of 1.7 $\mu m$) and 1 $(\log \mu m)^2$, respectively. The initial $Fer$ conditions were extracted from the output of the Pelagic Interaction Scheme for Carbon and Ecosystem Studies (PISCES) ocean biogeochemical model that has been validated against iron fertilization experiments (Aumont & Bopp 2006). $DETFe$ was initialized as $10^{-3}$ (mol Fe (mol N)$^{-1}$) of phytoplankton biomass.

We admit several limitations of our model. For example, $N_2$ fixation is not taken into account. We already know that in terrestrial BEF experiments, the complementarity between $N_2$ fixing legumes and other plants is an important factor leading to the positive BEF relationship. While $N_2$ fixation is certainly important in some parts of the North Pacific, the active process of denitrification due to the low oxygen environment essentially maintains the subtropical North Pacific limited by nitrogen. This suggests that we need to incorporate denitrification as well as oxygen cycle into the model if we plan to include $N_2$ fixation, which will add more complexity and uncertainty. Another limitation is that although we included two different nutrients, dissolved nitrogen and iron, phytoplankton species with different sizes
do not differ in their uptake ratios of N: Fe according to the common parameterizations of size dependency of nutrient uptake on nitrogen and iron (Ward et al. 2012). Thus, we are essentially simulating a phytoplankton community competing for a single set of nutrients, which however does not imply that different size classes cannot coexist.

**S.1.3 Comparisons between model outputs and observational data**

We compared model outputs of dissolved inorganic nitrogen (DIN, µM), Chl a concentrations (µg L⁻¹), net primary production (NPP, µg C L⁻¹ d⁻¹) and fractions of picophytoplankton (<2 µm) from the simulation using the largest “trait diffusion” (TD) coefficient with observational data (Fig. S2). The outputs from the simulation using the largest “kill-the-winner” (KTW) coefficient are largely similar with those using the largest TD coefficient. Reducing the coefficients of TD or KTW does not have a large impact on bulk properties such as nutrient, Chl a, or NPP, but has some effects on size structure (see Fig. 2 of the main text).

We used the nitrate data of World Ocean Atlas (WOA) 2013 (version 2; Garcia et al. 2014) as the observational data for DIN. Chl a of SeaWIFS satellite monthly climatology product (https://oceancolor.gsfc.nasa.gov/SeaWiFS/) was used to compare with model outputs. For NPP, two
versions (vgpm and cbpm) of NPP data were downloaded from

https://www.science.oregonstate.edu/ocean.productivity, which give different patterns of NPP. The vgpm and cbpm versions of NPP data were calculated based on the algorithms in Behrenfeld & Falkowski (1997) and Westberry et al. (2008), respectively. We used the algorithm (equation 2) in Ward (2015) to calculate the fractions of picophytoplankton from observed total Chl $a$ and temperature.

The model largely captured the high levels of nitrate and Chl $a$ in the subarctic and equatorial Pacific, which contrasted with the low nitrate and Chl $a$ in the subtropics. Although Chl $a$ may be overestimated in the subarctic and equatorial regions, satellite observations may underestimate Chl $a$ in winter (data not shown). As such, the modeled fractions of picophytoplankton were lower than those predicted based on the algorithm in Ward (2015) since lower fractions of picophytoplankton were associated with higher Chl concentrations. The two algorithms, vgpm and cbpm, gave different patterns of NPP. The algorithm of vgpm predicted higher NPP in the subarctic, while cbpm predicted higher NPP in the equatorial region. The model patterns were between the two empirical algorithms, predicting the highest NPP in the equatorial region and moderately high NPP in the subarctic. The Taylor diagram shown in Fig. S2 suggests general correspondence between observations and model outputs, particularly for nitrate, Chl, and fractions of picophytoplankton.
We also compared model outputs with the data of nitrate and Chl \(a\) concentrations collected within the surface mixed layer at five times-series stations (ALOHA (158 °W, 22.75 °N), S1 (145 °E, 30 °N), K2 (160 °E, 47 °N), P (145 °W, 50 °N), Equatorial Pacific (140 °W, 0 °N); Fig. S3). The data of station ALOHA were downloaded from http://hahana.soest.hawaii.edu/hot/. The data at stations K2 and S1 were obtained from the K2S1 project (https://ebcrpa.jamstec.go.jp/k2s1/en/index.html). The data of three other stations were obtained from the JGOFS dataset (https://rda.ucar.edu/datasets/ds259.0/). While the model underestimated (e.g. ALOHA) or overestimated nitrate and Chl \(a\) concentrations (e.g. S1), it roughly captures the main seasonal cycles and spatial differences across a large environmental gradient in the North Pacific.

**S.1.4 Spatial patterns of phytoplankton properties**

Simulated patterns of important ecosystem variables are displayed in Fig. S4. Dissolved iron concentrations were highest at middle latitudes (20~40 °N), consistent with the high rate of atmospheric dust deposition there. Similar to Chl \(a\) concentration, phytoplankton biomass was also higher in the subarctic and equatorial regions, but lower in the subtropics. Based on the patterns of phytoplankton growth rates, mean size, the extents of light, nitrogen and iron limitation, N:C and Chl:C ratios, the
North Pacific can be classified into three main provinces: subarctic, subtropical and eastern equatorial Pacific.

The subarctic North Pacific is characterized by low temperature, relatively low light, high nitrate, large phytoplankton size and high biomass. Although the atmospheric dust deposition is not low in the subarctic Pacific, abundance in nitrate increases iron limitation of phytoplankton growth. But in general, light makes the main limitation factor in the subarctic and Chl:C and N:C ratios are generally high.

The subtropical Pacific the most oligotrophic area in the whole North Pacific, characterized by low nitrogen concentration due to strong water column stratification. The phytoplankton community is dominated by picophytoplankton. Light levels usually allow for sufficient productivity, also due to a shallow mixed layer. Due to the dual effects of strong light and low nitrogen, Chl:C and N:C ratios are low.

The eastern equatorial Pacific is characterized by strong upwelling, which leads to deep mixing and transport of nitrate into surface waters. This also leads to the paradoxical pattern that although surface light is strong in the equatorial regions, phytoplankton can be light-limited due to deep mixing. Also due to the scarce dust deposition, iron instead of nitrogen generally limits phytoplankton growth and particularly phytoplankton size. Therefore, the eastern equatorial Pacific is similar to the subarctic in
many aspects except for temperature. Consequently, the highest primary production is found in this area, consistent with the output of the cbpm algorithm.

S.1.5 Temporal changes of phytoplankton size and productivity in two selected hotspots

To more thoroughly understand the effects of size diversity on productivity, we select two hotspots where the effects of size diversity on productivity were the most positive (hotspot A) and negative (hotspot B), respectively (Fig. S5). The hotspot A was located within the North Pacific subtropical gyre, while the hotspot B was in the eastern equatorial Pacific.

At hotspot A, the $\mu_{i=l}$ (i.e. the growth rate of the dominant species) in the high diversity treatment was usually higher than those in the low diversity treatment, suggesting that the size of the dominant species was closer to the optimal size in the highest than in the lowest diversity treatment (Fig. S6). This behavior is inherent to our model equations and is consistent with the insurance hypothesis that the high diversity confers the phytoplankton community to more rapidly adapt to the changing environment by maintaining more species (Yachi & Loreau 1999; Norberg et al. 2001; Merico et al. 2014; Smith et al. 2016; Vallina et al. 2017). One side effect of this was that the higher $\mu$ was often associated with a more negative $\frac{d^2 \mu}{dt^2}$ (i.e. the difference of growth rates between productive and unproductive
species is greater when growth rates are higher), because higher growth tends to induce stronger interspecific competition (Hutson 1979). In addition, the community becomes more diverse, containing more unproductive species (i.e. larger $v$), and thereby reducing the productivity at the community level.

In spite of the negative impacts of larger $v$ and more negative $\frac{d^2\mu}{dt^2}$, the community productivity calculated as $\left(\mu + \frac{v d^2\mu}{2 dt^2}\right)_{t=1}$ was still larger in the high diversity treatment, although the differences were small (Fig. S6g).

At hotspot B, despite of the differences in the temporal trajectories of mean sizes due to the different size diversity, growth rates were almost identical between the two treatments (Fig. S6i-l). Due to the higher size diversity and negative $\frac{d^2\mu}{dt^2}$ values, the high diversity treatment had the slightly lower community productivity than the low diversity treatment, but the differences were negligible (Fig. S6n).

The key difference between the oligotrophic hotspot A and mesotrophic hotspot B is that in A, the sensitivity of $\mu$ to mean size $\bar{t}$ was greater than in B so that faster adjusting $\bar{t}$ gave greater increases in growth rate $\mu$. These adjustments reflect a model community that has to optimize the tradeoff between achieving the highest productivity by retaining less unproductive species and the capacity to adapt to environmental fluctuation by increasing diversity. In general, the adaptive capacity is preferred when environmental fluctuation amplitudes are large (Smith et al. 2016).
S.1.6 Spatial patterns of covariances and second partial derivatives in surface waters

In Fig. S7, we compare the spatial distributions of temporal variances of $\tilde{I}$ ($\sigma^2_{\tilde{I}}$), covariances between $\tilde{I}$ and light ($\sigma_{\tilde{I}L}$), nitrate ($\sigma_{\tilde{I}N}$), and iron ($\sigma_{\tilde{I}Fe}$) in surface waters in both low- and high-diversity treatments. Compared to the low diversity treatment, $\sigma^2_{\tilde{I}}$ increased substantially along the fronts between the central gyre and the two adjoining subarctic and equatorial Pacific. Note that because $\frac{\partial^2 \mu}{\partial \tilde{I}^2} |_{\tilde{I}=\bar{I}_0}$ was usually negative, increases of temporal variances of mean size in the high diversity treatment actually reduced phytoplankton growth rate. The enhancement of $\sigma_{\tilde{I}Fe}$ in the high diversity treatment was evident only in a few coastal areas. $\sigma_{\tilde{I}N}$ also increased substantially along the fronts in the high-diversity treatment and also decreased evidently in the subarctic Pacific where phytoplankton growth is mostly limited by light. Comparatively, the enhancement of $\sigma_{\tilde{I}N}$ was mostly pronounced in the light-limiting subarctic Pacific, while it mostly decreased in the western Pacific east of Japan.

S.1.7 Idealized numerical experiments

In the continuous case of the idealized numerical experiments, the model resolves only two compartments, nutrient ($N$) and phytoplankton ($P$).
\[
\frac{dN}{dt} = N_0(t) - DN - P\mu_{com}
\]  
(30)

\[
\frac{dP}{dt} = P(\mu_{com} - m)
\]  
(31)

where \( D \) is the nutrient turnover rate (d\(^{-1}\)). \( \mu_{com} \) is the phytoplankton community-based growth rate (d\(^{-1}\)).

As in the 3D simulations, we assume that phytoplankton size (log cell volume \( l \), ln \( \mu \), \( m \)) follow a normal distribution with the mean \( l \) and variance \( v \) (\( \ln \mu \)). The average growth rate of the community can then be calculated as:

\[
\mu_{com} = \left(\mu + \frac{v}{2} \frac{d^2\mu}{dl^2}\right)|_{l=L}
\]  
(31)

where \( \mu(l) \) is the growth rate at mean size, which depends on nutrient concentration \( N \).

\[
\mu(l) = \mu_m(l) \frac{N}{N + K_N(l)}
\]  
(32)

in which both \( \mu_m \) and \( K_N \) are functions of \( l \), similar to the 3D simulations:

\[
\mu_m(l) = \mu_{0,m} e^{a \mu l + \beta l^2}
\]  
(33)

\[
K_N(l) = K_{0,N} e^{\alpha \lambda l}
\]  
(34)

Nutrient inflow \( N_0(t) \) is a seasonally varying sinusoidal function:

\[
N_0(t) = S_0 \left(1 + A \sin \frac{2\pi t}{\lambda}\right)
\]  
(35)

where \( S_0 \) is the time-averaged nutrient supply. \( A \) and \( \lambda \) are the amplitude and period of the nutrient fluctuation, respectively.
In the simulations of investigating relationships between primary production and species richness (R), we randomly sample R species (1 ≤ R ≤ 10) with the sizes between 0.5 µm and 200 µm. The dynamics of nutrients and phytoplankton follow:

\[
\frac{dN}{dt} = N_0(t) - DN - \sum_{i=1}^{R} P_i \mu_i \tag{36}
\]

\[
\frac{dP_i}{dt} = P_i (\mu_i - m) \tag{37}
\]

where \( P_i \) and \( \mu_i \) are the biomass and growth rate of the \( i \)th species. \( \mu_i \) depends on the size of the species as in Eq. (32-34).

The following parameters were used in the simulation:

- \( S_0 = 0.3 \ \mu M \ \text{N d}^{-1}; A = 0.4 \ \text{and} \ 0.8 \ \text{d}^{-1}; \lambda = 360 \ \text{d}; D = 0.3 \ \text{d}^{-1}; m = 0.5 \ \text{d}^{-1}; \mu_{0,m} = 0.8 \ \text{d}^{-1}; a_\mu = 0.2 \ (\ln \ \mu \ \text{m}^{-1}); \beta_\mu = -0.01 \ (\ln \ \mu \ \text{m}^{-1})^{-2}; K_{0,N} = 0.2 \ \mu M \ \text{N}; a_K = 0.27 \ (\ln \ \mu \ \text{m}^{-1})^{-1}.

The initial N and total P are 1 and 0.001 µM N, respectively.
S.2 Supporting Table S1. Parameters of the ecosystem model with a continuous size distribution for phytoplankton.

| Symbol | Description | Value | Unit |
|--------|-------------|-------|------|
| \(K_w\) | Light attenuation coefficient of seawater | 0.04 | m\(^{-1}\) |
| \(K_{chl}\) | Light attenuation coefficient of chlorophyll | 0.025 | (mg Chl a m\(^{-2}\))\(^{-1}\) |
| \(E_p\) | Activation energy of phytoplankton rates | 0.41 | eV |
| \(E_z\) | Activation energy of heterotrophic rates | 0.65 | eV |
| \(\theta_{min}\) | Minimal chlorophyll-to-carbon ratio | 0.02 | gChl molC\(^{-1}\) |
| \(\theta_{max}\) | Maximal chlorophyll-to-carbon ratio | 0.62 | gChl molC\(^{-1}\) |
| \(\mu_{unass}\) | Fraction of unassimilated food by zooplankton | 0.24 | dimensionless |
| \(NGE\) | Net growth efficiency of zooplankton | 0.3 | dimensionless |
| \(R_{dn}\) | Conversion rate of detritus to inorganic nitrogen | 0.1 | d\(^{-1}\) |
| \(l_f\) | Total iron ligand concentration | 0.6 | nM |
| \(K_{scm}\) | Minimal iron scavenging rate | 5 x 10\(^{-3}\) | d\(^{-1}\) |
| \(K_{sc}\) | Particle dependent scavenging rate | 0.03 | (\(\mu\)M N)\(^{-1}\) d\(^{-1}\) |
| \(R_{Fe_N}\) | Plankton iron-to-nitrogen ratio | 0.0265 | nM: \(\mu\)M |
| \(\mu_{0,m}\) | Phytoplankton maximal growth rate at 1 \(\mu\)m\(^3\) at 15 \(^\circ\)C | 0.8 | d\(^{-1}\) |
| \(a_0\) | First-order size scaling component for \(\mu_m\) | 0.2 | (ln \(\mu\)m\(^3\))\(^{-1}\) |
| \(\beta_0\) | Second-order size scaling component for \(\mu_m\) | -0.01 | (ln \(\mu\)m\(^3\))\(^{-2}\) |
| \(a_K\) | Size scaling exponent for \(K_N\) | 0.27 | (ln \(\mu\)m\(^3\))\(^{-1}\) |
| \(a_{fer}\) | Size scaling exponent for \(K_{fer}\) | 0.27 | (ln \(\mu\)m\(^3\))\(^{-1}\) |
| \(Q_{min}\) | Phytoplankton minimal N:C ratio | 0.06 | mol N: mol C |
| \(Q_{max}\) | Phytoplankton maximal N:C ratio | 0.18 | mol N: mol C |
| \(a_{gr}\) | Initial slope of photosynthesis versus light at 1 \(\mu\)m\(^3\) | 0.03 | (W m\(^{-2}\))\(^{-1}\) d\(^{-1}\) |
| \(a_l\) | Size scaling exponent for \(\alpha\) | -0.13 | (ln \(\mu\)m\(^3\))\(^{-1}\) |
| \(W_0\) | Normalized sinking rate of detritus | 20 | m d\(^{-1}\) |
| \(k\) | Intercept of detrital sinking rate vs. SST | 0.3 | dimensionless |
| Symbol | Description                                                                 | Value  |
|-------|------------------------------------------------------------------------------|--------|
| $b$   | Slope of detrital sinking rate vs. SST                                        | 0.03$^\circ$C^{-1} |
| $g_m$ | Maximal microzooplankton ingestion rate at 15 $^\circ$C                      | 1.0$^k$ d^{-1} |
| $m_c$ | Coefficient of zooplankton mortality at 15 $^\circ$C                         | 0.1$^a$ (µM N)$^{-1}$ d^{-1} |
| $K_p$ | Grazing half-saturation constant of zooplankton                             | 0.5$^k$ µM N |
| $K_{0,N}$ | Growth half-saturation constant for nitrogen for a phytoplankton cell of 1 µm$^3$ | 0.2$^e$ µM N |
| $K_{0,Fe}$ | Growth half-saturation constant for iron of phytoplankton with 1 µm$^3$ | 0.02$^e$ nM Fe |

$^a$Fennel et al. (2006); $^b$Chen & Laws (2017); $^c$Flynn (2003); $^d$Pahlow et al. (2013); $^e$Buitenhuis et al. (2010); $^f$Nickelsen et al. (2015); $^g$Ward et al. (2012); $^h$Marañón et al. (2013); $^i$Edwards et al. (2015); $^j$Gregg (2008); $^k$Chai et al. (2002).
S.3 Supporting Figures

Fig. S1 Schematic description of the ecosystem model with the continuous size distribution for phytoplankton. Thick arrows indicate nitrogen flows and dashed lines indicate the iron cycle. The inset denotes a phytoplankton community with a lognormal size distribution.
Fig. S2 Comparison of annual spatial patterns of nitrate, Chl a concentration, net primary production (NPP, µg C L⁻¹ d⁻¹), and fraction of picophytoplankton (<2 µm) between the simulation using the largest “trait diffusion” (TD) coefficient and observational data. The right panel at bottom is a Taylor diagram that summarizes the comparisons between model and data. The correlation coefficients between the model and data are indicated by the values (0.1~0.99) along the arc. The distances between the origin and the color points indicate the normalized standard deviation. The distances between the reference point [1, 0] and the color points indicate the root mean squared error.
Fig. S3 Comparisons of seasonal cycles of nitrate (left column) and Chl $\alpha$ concentrations (right column) within the surface mixed layer at five time-series observational stations in the North Pacific. Solid lines represent model outputs and dots represent observational data.
Fig. S4 Annual spatial patterns of dissolved iron, phytoplankton biomass, nitrogen-to-carbon ratios, chlorophyll-to-carbon ratios, phytoplankton mean ESD, the variance of log cell volume, growth rate at mean size, whether iron is limiting (1 indicating iron limitation and 0 indicating nitrogen limitation), and the extent of light and nutrient limitations (1 means no-limiting and 0 means 100% limiting and no growth). Note that we set that phytoplankton growth can be limited only by iron or nitrogen, whichever is more limiting. But the phytoplankton growth rate is a multiplicative function of light and nutrient terms, indicating both light and nutrient can be limiting.
Fig. S5 Logarithmic ratios of NPP between the high- and low-diversity treatment (the same as Fig. 4d) overlaid with two hotspots.
Fig. S6 Seasonal changes of dissolved inorganic nitrogen (DIN), dissolved iron, mean size, size diversity, growth rate at mean size, second derivative of growth rate at mean size, and community productivity at two selected hotspots where negative and positive effects of diversity are most evident (see Fig. S5).
Fig. S7 Spatial comparison of temporal (a, b) variances of mean size and covariances (c, d) between mean size and light, (e, f) between mean size and nitrate, and (g, h) between mean size and iron within the surface mixed layer in the high- and low-diversity treatments.
Fig. S8 Spatial comparisons of (a, b) $\frac{\partial^2 \mu}{\partial t^2}$, (c, d) $\frac{\partial^2 \mu}{\partial \theta \partial f}$, (e, f) $\frac{\partial^2 \mu}{\partial \partial N}$, (g, h) $\frac{\partial^2 \mu}{\partial \partial l}$ within the surface mixed layer in the high- and low-diversity treatments. $X_0$ represents the annual mean value of variable $X$. 
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