Supplementary Methods

Model and data. The transport matrix used to compute physical fluxes is derived from the ECCO (‘Estimating the Currents and Climate of the Ocean’) configuration of the MIT ocean circulation model\textsuperscript{36}. Nutrient export is diagnosed in all model levels above the specified compensation depth ($z_{\text{comp}}$) set at 75m, the global mean value\textsuperscript{37}, in the initial simulations. The remineralization of particulate organic matter is simulated in the model by assuming the sinking flux ($J_{\text{POM}}$) of nutrient $C$ decreases with depth below $z_{\text{comp}}$ following:

$$J_{\text{POM}}(z) = J_{\text{ex}} \left(\frac{z}{z_{\text{comp}}}\right)^b$$ \hspace{1cm} (1)

where $J_{\text{ex}}$ is the sinking flux of $C$ at $z_{\text{comp}}$, and the parameter $b$ controls the shape of the remineralization profile\textsuperscript{19}. The production of dissolved organic matter ($J_{\text{org}}$) is simulated by assuming that equal fractions of total production are partitioned into DOM and sinking particles ($J_{\text{org}} = J_{\text{ex}}$), although our results are insensitive to this formulation. Parameters used in the initial set of simulations are given in Supplementary Table 1 below, and some are subject to sensitivity testing later (Supplementary Information – Sensitivity Testing).

All NO$_3^-$, PO$_4^{3-}$, and Si(OH)$_4$ data used as boundary conditions and to diagnose export rates in the simulations were taken from the World Ocean Atlas 2005 (WOA05) annually averaged dataset\textsuperscript{17}, interpolated to the model grid and smoothed using a 10° longitude x 5° latitude boxcar smoother. Boundary conditions for dissolved organic nutrient concentrations were taken from previous global-scale simulations\textsuperscript{38}.

Supplementary Table 1 | Parameters used in initial simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value, units</th>
<th>ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_{\text{org}}$</td>
<td>1 yr$^{-1}$</td>
<td>39</td>
</tr>
<tr>
<td>$\tau_{\text{damp}}$</td>
<td>2 months</td>
<td>23</td>
</tr>
<tr>
<td>$z_{\text{comp}}$</td>
<td>75 m</td>
<td>37</td>
</tr>
<tr>
<td>$b$</td>
<td>1.04, dimensionless</td>
<td>19</td>
</tr>
</tbody>
</table>

Simulations. The important features of each Southern Ocean simulation are summarized in Supplementary Table 2, below. The purpose of Model 1 was to predict the Southern Ocean N$^*$ distribution under the Redfield assumption, which could then be compared with observations. We therefore solved for nutrient concentrations throughout the Southern Ocean water column, using boundary conditions north of 35°S, and used a fixed N:P$_{\text{exp}}$ of 16:1. The purpose of Model 2 was to diagnose the spatial pattern of N:P$_{\text{exp}}$ most consistent with all available tracer observations. The model’s formulation of nutrient remineralization introduces a possible source of error into the subsurface predictions, so the Southern Ocean subsurface was incorporated into the boundary region, where concentrations are held at their observed values, to eliminate these errors and keep...
nutrient upwelling fluxes as realistic as possible. Model 3 was designed to test the mixing of remineralized nutrients by ocean circulation. The Southern Ocean subsurface was therefore reincorporated into the solution region and export fluxes of each nutrient diagnosed independently, allowing us to simulate the remineralization of organic particles with regionally variable N:P ratios. We then computed the physical nutrient fluxes from the boundary region and Southern Ocean surface waters into the Southern Ocean subsurface at steady state in this simulation. This transported component was then subtracted from the total subsurface nutrient concentrations to yield the distribution of remineralized nutrients ([NO$_3^-$]$_{rem}$ and [PO$_4^{3-}$]$_{rem}$).

**Supplementary Table 2** | Boundary conditions and export fluxes in model simulations.

<table>
<thead>
<tr>
<th>N:P of export flux</th>
<th>Fixed (16:1)</th>
<th>Variable (diagnosed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subsurface nutrient concentrations$^a$</td>
<td>Specified (WOA05)</td>
<td>None</td>
</tr>
<tr>
<td>Predicted</td>
<td>Model 1</td>
<td>Model 3</td>
</tr>
</tbody>
</table>

$^a$ In all simulations nutrient concentrations were specified at the 35°S boundary.

**Sources of N:P variability.** The sinking flux of biogenic Si was diagnosed by restoring surface Si(OH)$_4$ concentrations towards their observed values in Model 2. The export of N by diatoms was then estimated assuming Fe-dependent Si:N of diatoms:

\[
Si:N = \begin{cases} 
5, & \text{if } [Fe] < 0.2\text{nM} \\
1, & \text{if } [Fe] > 0.2\text{nM} 
\end{cases} 
\]  

(2)

This was then used to determine the fraction of total N export that can be attributed to diatoms. We also correlated the diagnosed pattern of N:P$_{exp}$ against a range of environmental properties known to influence algal stoichiometry at the phenotypic level. Solar Radiation Dose data was used to characterize the annual average light intensity experienced by the community, and was taken from the ISCCP climatology. We used temperature data from World Ocean Atlas 2005 and a simulated Fe distribution from the NCAR Community Climate System Model (CCSM). Summertime growth rates were estimated from December-February temperature, nutrients and SRD using standard multiplicative functions:

\[
\mu = \mu_{\max} \exp(k(T - T_{\max})) \cdot \frac{1}{\sqrt{I^2 + K_i}} \cdot \min \left \{ \frac{N}{N + K_i}, \frac{P}{P + K_p}, \frac{Fe}{Fe + K_{Fe}} \right \} 
\]

(3)

As the purpose was to test whether phenotypic acclimation within a constant community was consistent with the diagnosed pattern of N:P$_{exp}$, we made a single choice for each parameter based on the mean of reported diatom and small plankton values (Supplementary Table 3).
Supplementary Table 3 | Parameters used in growth rate estimates.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
<th>ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{\text{max}}$ (day$^{-1}$)</td>
<td>Maximum growth rate</td>
<td>1.5</td>
<td>42</td>
</tr>
<tr>
<td>$T_{\text{max}}$ (°C)</td>
<td>Optimal growth temperature</td>
<td>20</td>
<td>39</td>
</tr>
<tr>
<td>$K_l$ (W m$^{-2}$)</td>
<td>Half-saturation constant for light</td>
<td>40</td>
<td>39</td>
</tr>
<tr>
<td>$K_N$ (mmol m$^{-3}$)</td>
<td>Half-saturation constant for nitrate</td>
<td>1.5</td>
<td>42,43</td>
</tr>
<tr>
<td>$K_P$ (mmol m$^{-3}$)</td>
<td>Half-saturation constant for phosphate</td>
<td>0.005</td>
<td>42,43</td>
</tr>
<tr>
<td>$K_F$ (nmol m$^{-3}$)</td>
<td>Half-saturation constant for iron</td>
<td>100</td>
<td>42,43</td>
</tr>
</tbody>
</table>

Supplementary Notes – Sensitivity Testing

We tested our central result, the spatial distribution of export ratios in the Southern Ocean, against a number of methodological uncertainties. Model 2 was repeated numerous times, varying the factors that could influence the diagnosed pattern of $N:P_{\text{exp}}$. The range of zonal mean values of $N:P_{\text{exp}}$ was taken as a measure of uncertainty and included in figure 3b (grey shading) in the main text. Factors tested were:

- **Compensation depth.** Nutrient export is diagnosed by damping nutrient concentrations towards their observed values above the compensation depth ($z_{\text{comp}}$). In the original diagnosis, $z_{\text{comp}}$ was set at 75m, in agreement with the estimated global-mean value$^{37}$. In the sensitivity testing we used the largest range of reasonable depths afforded by the model resolution: 30, 50, 75 and 100m. Nutrient export fluxes differed in each simulation, and the best agreement with other published model and data-derived estimates$^{19}$ was obtained in the original simulation using $z_{\text{comp}}$ of 75m. The spatial pattern of $N:P_{\text{exp}}$ also varied in each simulation (Fig. S2a), particularly in the Antarctic Zone, where the high $N^*$ signal is relatively shallow. However, the meridional transition from low $N:P_{\text{exp}}$ in the Antarctic Zone to high $N:P_{\text{exp}}$ in the Subantarctic is not sensitive to the choice of compensation depth (Fig. S2b).

- **DOM cycling parameters.** Dissolved organic N and P are advected with the flow until they are bacterially degraded into inorganic forms$^{39}$. This represents another nutrient supply process that could influence the export of $NO_3^-$ and $PO_4^{3-}$ diagnosed by the model. To determine whether this contributed to the diagnosed pattern of $N:P_{\text{exp}}$, we repeated Model 2 without DOM cycling (all DOM fluxes set to zero in Eq. 1, Methods). We also tested the sensitivity of our results to the degradation timescales prescribed for DON and DOP by repeating the experiment with $\tau_{\text{DON}} = 2$ years and $\tau_{\text{DOP}} = 0.5$ years (ref 38). The simulation with no DOM cycling yielded almost identical results to the original experiment (Fig. S3a,b). Changing the degradation timescales resulted in slightly lower $N:P_{\text{exp}}$ throughout the Southern Ocean, particularly in the Antarctic region, as more N was advected out of the domain as DON (Fig S3c). However, the difference in the meridional trend was not large (Fig S3d).
• **Damping timescale.** The timescale over which surface nutrient concentrations are damped towards their observed values controls the relative strength of biological fluxes, which produce the $N^*$ signal in the surface, and physical fluxes that mix across nutrient gradients and destroy the $N^*$ signal. A shorter timescale increases the relative strength of biological fluxes, whereas longer timescales allow a higher degree of mixing. We tested the robustness of our results against a wide range of damping timescales, between 2 weeks and 1 year. Although the magnitude of export fluxes was highly sensitive to these changes, the meridional gradient in $N:P_{\text{exp}}$ was not (Figure S4). The original experiment, with a damping timescale of 2 months produced export fluxes most consistent with previous estimates.

• **Circulation model.** The largest source of possible error in our experiments is in the ability of the ocean circulation model to simulate real transport processes. These errors are also the most difficult to quantify, but a good test of our results robustness is to see whether a similar pattern of $N:P_{\text{exp}}$ emerges using a different circulation model. For this purpose we use a coarse resolution configuration of the MITgcm, with horizontal resolution of 2.8° and 15 vertical layers and no data assimilation\textsuperscript{44}. When we compare simulations with similar compensation depths (those closest to 50m and 100m) we find good agreement between the two models (Fig. S5). From the observed distribution of $N^*$ (Fig. 1a), it is apparent that any circulation scheme that captures the broad pattern of Southern Ocean overturning will diagnose low $N:P_{\text{exp}}$ in the Antarctic ocean and high $N:P_{\text{exp}}$ in the Subantarctic.
Figure S1 | Schematic of model configuration and primary result. The lower panel depicts the configuration of Model 2, simplified into three boxes: an Antarctic surface box (1), a Subantarctic surface box (2), and boundary box (B). The boundary box comprises the ocean below 75m and north of 35°S, where nutrient concentrations (C = NO$_3^-$ or PO$_4^{3-}$) are held at their observed values (C$_{B,obs}$). Biological nutrient export (green arrows) is diagnosed by simulating the physical transport of nutrients into (red arrows) and out of (blue arrows) the two surface boxes, and damping the concentrations (C$_1$, C$_2$) towards their observed values. The two upper panels depict the qualitative results of the diagnosis shown on vector plots of NO$_3^-$ vs PO$_4^{3-}$. The nutrient inflow (red arrows) acts to increase the concentrations of both nutrients above their observed values. Biological export (green arrows) removes a fraction of the excess nutrients, and the remainder is advected out (blue arrows), bringing the concentrations back to their observed values. Processes occurring at the Redfield ratio would move nutrient concentrations along lines of constant $N^*$ (dashed lines). The diagnosis reveals that nutrient export occurs below the Redfield N:P in the Antarctic box (1) and above the Redfield ratio in the Subantarctic box (2). This pattern of N:P$_\text{exp}$ is governed largely by differences in the plankton community structure between the two major biomes of the Southern Ocean.
**Figure S2** | Sensitivity to compensation depth. Spatial pattern (a) and zonal mean trend (b) of N:P<sub>exp</sub> diagnosed by repeating Model 2 with compensation depths of 30, 50 and 100m.
**Figure S3| Sensitivity to DOM cycling.** Differences between N:P$_{exp}$ in Model 2 and repeats that included (a,b) no DOM cycling and (c,d) different degradation timescales for DON and DOP ($\tau_{\text{DON}} = 2$ years, $\tau_{\text{DOP}} = 0.5$ years).

**Figure S4| Sensitivity to damping timescale.** Difference between N:P$_{exp}$ in Model 2 and repeats using a range of damping timescales between 2 weeks and 1 year.
**Figure S5** | **Sensitivity to OGCM.** Spatial pattern of N:P$_{exp}$ diagnosed by repeating Model 2 with a coarse resolution OGCM, compared to similar compensation depth simulations using the standard model.
**Figure S6** | Redfield and non-Redfield thermocline N* predictions. Distributions of subsurface N* predicted in Models 1 & 3, which simulated the sinking and degradation of particulate organic matter in the Southern Ocean water column. 

**a,** Prediction of Model 1, where N:P<sub>exp</sub> was held constant at 16:1. As uptake and remineralization at the Redfield ratio do not modify N*, this signal is transported from the boundary at 35°S, and not modified biologically. 

**b,** Prediction of Model 3, where N:P<sub>exp</sub> was diagnosed from observations, and remineralization occurs at the export ratio. Although this simulation was forced to reproduce surface nutrient distributions, there was no forcing in the subsurface. The improvement in this prediction over the Redfield case (when compared to observations, Fig. 1a) provides independent support for the diagnosed pattern of N:P<sub>exp</sub>. Small differences remaining between observations and the prediction may result from the preferential of remineralization of one nutrient over another by bacteria in different regions, but there appears to be no systematic pattern to this.
References 1-35 refer to those listed in the main manuscript.


