Supplementary Information – Sensitivity Analysis

A systematic examination of methodological uncertainties is facilitated by returning to the relationship between N₂ fixation and nutrient transport: \( J_{\text{fix}}(N) = \frac{\text{d}N}{\text{d}t} = -\lambda \nabla \Phi(P_t^*) \). Because variations in the non-dimensional parameter \( \lambda \) are small, nutrient transport constitutes the primary source of potential error in diagnosed N₂ fixation. Transport errors can be considered a product of errors in the physical flow (velocity and diffusivity), and errors in the observed gradients of \( P_t^* \). We address each of these below, showing that within reasonable bounds, neither factor is able to reverse our conclusions regarding the basin scale patterns of N₂ fixation.

First, we investigate the potential for changes in the wind-driven circulation to affect the patterns of inferred N₂ fixation. To do this, we calculate nutrient transports using a circulation that is forced by the wind stress climatology of Hellerman and Rosenstein [1983] (HR) in place of the European Centre (ECMWF) winds used in our original results [Figure S9]. Compared to ECMWF, the HR windstress is generally weaker in the southern ocean due to underestimated wind speeds, but stronger in low latitudes due to an unrealistically high drag coefficient. This change in wind forcing has a corresponding impact on the strength of major circulation systems such as the North Pacific Subtropical Gyre. This results, for example, in a slight shift of inferred N₂ fixation between different regions of the North Pacific gyre, but it does not shift N₂ fixation out of the subtropical North Pacific as a whole [figure S6]. In addition, the globally integrated N₂ fixation rate is within 10% of the original model using ECMWF winds. Thus, we find that even a large (arguably unrealistic) change in the wind-driven circulation has only a very modest effect on patterns of diagnosed N₂ fixation that is regional in nature.

An additional uncertainty in the calculation of physical nutrient fluxes arises from the poorly known strength of vertical mixing across the stably stratified thermocline. Elementary scaling of the tracer conservation equations suggests that errors in the vertical diffusivity are likely to be negligible when compared to the importance of upwelling or downwelling at the vertical scale of interest (H~100 m). (The time it takes to propagate a tracer anomaly across 100 m depth of water with a typical vertical velocity (w) of 10⁻⁴ cm/s is on the order of 1 year (H/w~10⁸ s), whereas diffusive propagation of the same anomaly would take 10 times longer (H²/kᵥ~10⁹ s) according to empirical tracer diffusivity of kᵥ, 0.1 cm²/s). However, ocean mixing can also affect nutrient transport by altering the advective mass fluxes. We therefore perform another model integration in which vertical diffusivity is increased four-fold. When combined with a doubling of isopycnal diffusion, the model is able to maintain the structure of the low-latitude pycnocline, in accordance with theory. This more diffusive model ocean supports roughly twice as much new production as its less diffusive (and more realistic) configuration. Despite large changes in the overall nutrient supply, the inferred pattern of N₂ fixation is again seen to be robust, and the integrated rate is within 10% of the standard model.
Another potential source of error in our calculation stems from the observed nutrient fields, whose gradients are used to compute physical nutrient transports. We have investigated the influence of uncertainty in nutrient distributions, both inorganic and organic, by diagnosing N\textsubscript{2} fixation rates using 3 different nutrient data sets [Figure S3]:

1) The annual mean P* field from World Ocean Atlas \textsuperscript{5} used in our original result.
2) The annual mean P* according to the Levitus climatology \textsuperscript{6}.
3) The global WOCE-era P* field objectively mapped onto the model grid (see refs \textsuperscript{7} and \textsuperscript{8} for data sources).

The World Ocean Atlas 2001 combines the relatively sparse but high-quality WOCE nutrient data with the older climatology of Levitus [1994], which contains more data than WOCE with less quality control. Each of these datasets reveals a similar large-scale pattern of excess PO\textsubscript{4} (i.e. P*), in addition to small scale differences. There are clear inconsistencies between the datasets in the Southern Ocean, where observations are sparse, leading us to disregard the results south of 40° S. Despite the influence of regional P* differences on inferred patterns of N\textsubscript{2} fixation [figure S7], the overall impression from these experiments is that diagnosed N\textsubscript{2} fixation is robust at the basin scale.

Biological nutrient fluxes implied by the transports of NO\textsubscript{3} and PO\textsubscript{4} provide a framework on which to construct cycles of DON and DOP that are internally consistent with respect to both circulation and NO\textsubscript{3} and PO\textsubscript{4} fields. If DON and DOP are produced in proportion to the respective rates of N and P uptake (10\% for both), and also degrade at the same rate (a half-life of 1 year for both), concentrations of both DON and DOP are similar to observed, but the variations in their ratio, or DOP*, is not [figure S4a]. Specifically, there is no appreciable latitudinal gradient in simulated DOP*, whereas an excess of DOP has been measured in the Ekman layer of the tropical Pacific (~10° N), that disappears as waters drift northward into the subtropical gyre \textsuperscript{9}. The observed tropical excess of DOP requires that the fractional production of DOP is greater than for DON. When this is accounted for in the model DOM cycles (along with a more rapid degradation of DOP), we are able to better reproduce both the concentrations and covariations of DON and DOP [figure S4b].

When the production and degradation parameters for DON and DOP are equal, the cycling of DOM has little effect on the N:P stoichiometry of inferred nutrient uptake and yields an N\textsubscript{2} fixation pattern [Figure S5a] indistinguishable from that derived from inorganic nutrients alone [Figure 2b]. In contrast, a relatively rapid generation of DOP versus DON reduces any excess uptake of P in productive areas, but only until the DOM is degraded downstream, at which point the excess P supply is enhanced, affecting a shift of inferred N\textsubscript{2} fixation from upwelling zones toward oligotrophic regions [Figure S5b]. The paucity of DON and DOP observations, particularly in productive regions, prevents a more thorough evaluation of the degree of differential DON and DOP cycling. However, these sensitivity experiments have shown it to be of secondary importance to the large-scale pattern and global magnitude of N\textsubscript{2} fixation.
Supplementary Information – Figure Captions

**Figure S1.** Dependence of $\lambda$, the number of moles of N fixed per mole of excess P supply, on the fractional export of organic matter production ($\gamma_e$) and the N:P ratio of N$_2$ fixers, $r_f$. Over most of the ocean, nutrient recycling is very efficient ($\gamma_e << 1$), and the excess physical supply of PO$_4^{3-}$ can be balanced by N$_2$ fixation with a ratio of $r_m$, regardless of the N:P ratio of N$_2$ fixing organisms. Observed and estimated values of $r_f$ and $\gamma_e$ under a range of oceanic conditions are indicated by black arrows (refs 10 11 12). The spatial distribution of $\lambda$ is shown in figure S2.

**Figure S2.** The spatial distribution of $\lambda$ based on a model $^{12}$ of particle export ratio ($\gamma_e$) and an N:P ratio of N$_2$ fixers, $r_f$, of 50:1 [see ref $^{11}$].

**Figure S3.** The global distribution of surface (0-100 m) P* values (P* = [PO$_4$] – [NO$_3$])/15, in µmol/kg) from: a) the annual mean nutrient climatology of World Ocean Atlas $^7$, b) annual mean nutrient climatology of Levitus [1994], and c) nutrient data from cruises affiliated with the World Ocean Circulation Experiment (WOCE) that are quality-controlled, pooled, and objectively mapped (see refs $^7$ and $^8$).

**Figure S4.** Comparison of DOP* along $\sim$135°W from observations $^9$ and two models: one with DON and DOP treated equally ($\tau_{DON}=\tau_{DOP}=1$ year; $\gamma_{DON}=\gamma_{DOP}=0.1$, panel a) and another with a more rapid production and degradation of DOP, relative to DON ($\tau_{DON}=2$ years, $\tau_{DOP}=0.5$ years; $\gamma_{DON}=0.06$, $\gamma_{DOP}=0.25$, panel b).

**Figure S5.** Rates of N$_2$ fixation integrated from 0-120 m depth for a model where DON and DOP parameters are equal (as in Figure S4a), and the difference between N$_2$ fixation in that model and the original model.

**Figure S6.** Rates of N$_2$ fixation integrated from 0-120 m depth for the three data-based distributions of P* shown in Figure S3.

**Figure S7.** Rates of N$_2$ fixation integrated from 0-120 m depth for a range of model circulations, including a) a model forced by reanalysis winds from ECMWF, as presented in the manuscript, b) a model forced by an alternate wind stress $^{13}$, and c) a model with higher (4x) diapycnal and isopycnal (2x) mixing.

**Figure S8.** Map of diagnosed transport convergence of P$_t$*, multiplied by $r_n=15$ to convert to approximate N units. Areas of low-latitude P$_t$* convergence (positive values) indicating excess P uptake are interpreted as N$_2$ fixation (c.f. Figure 2c), whereas regions of P$_t$* divergence (negative values), suggesting a high N:P nutrient drawdown, are found where thermocline waters provide a rapid nutrient supply to the surface that is relatively N-rich, primarily in mid- and high-latitude regions of convective winter mixing and to a lesser degree in areas of tropical upwelling away from active denitrification zones.
**Figure S9.** Annual mean wind stress from (a) Hellerman and Rosenstein [1983] and (b) ECMWF reanalysis, and (c,d) the resulting model surface currents (0-100 m). Shading indicates magnitude of windstress (a,b) and surface currents (c,d).

**Table S1.** Surface DON and DOP concentrations [µmol/kg] from time series stations in the subtropical gyres of the North Pacific (HOT) and North Atlantic (BATS). Observed values are as reported in ref 14. Model values are annual averages from 0-50 m and assume an additional refractory DON concentration of 2.4 µmol/kg, based on deep ocean (> 2500 m) values at HOT. Model DOM cycles were tuned to reproduce independent DON and DOP observations from a single Pacific transect 9, but also quite closely match observed values at time series locations.


Figure S1. Dependence of $\lambda$, the number of moles of N fixed per mole of excess P supply, on the fractional export of organic matter production ($\gamma_e$) and the N:P ratio of N$_2$ fixers, $r_f$. Over most of the ocean, nutrient recycling is very efficient ($\gamma_e<<1$), and the excess physical supply of PO$_4^{3-}$ can be balanced by N$_2$ fixation with a ratio of $r_n$, regardless of the N:P ratio of N$_2$ fixing organisms. Observed and estimated values of $r_f$ and $\gamma_e$ under a range of oceanic conditions are indicated by black arrows (see text for references). The spatial distribution of $\lambda$ is shown in figure S2.
**Figure S2.** The spatial distribution of $\lambda$ based on a model of particle export ratio ($\gamma_c$) [Dunne et al., 2005] and an N:P ratio of N$_2$ fixers, $r_p$, of 50:1 [Letelier and Karl, 1996].
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**Figure S4: Comparison of DOP* along ~155°W from observations (Abell et al [2000]) and two models: one with DON and DOP treated equally ($\tau_{DON}=\tau_{DOP}=1$ year; $\gamma_{DON}=\gamma_{DOP}=0.1$, panel a) and another with a more rapid production and degradation of DOP, relative to DON (panel b).**
Figure S5. (panel a) Rates of $\text{N}_2$ fixation integrated from 0-120 m depth for a model where DON and DOP parameters are equal, and b) the difference between $\text{N}_2$ fixation in that model and the original model (Figure 2c).
Figure S6. Rates of $N_2$ fixation integrated from 0-120 m depth for a range of model circulations: a) forced by reanalysis wind stress from ECMWF, as presented in the manuscript, b) forced by surface winds according to Hellerman and Rosenstein [1983], and c) similar to (b) but with higher diapycnal (4x) and isopycnal (2x) mixing.
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