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Supporting Information for

Subtropical gyre nutrient cycling in the upper ocean: Insights from a nutrient-ratio budget method

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Contents of this file

Introduction

The supporting information for this paper includes text describing the sensitivity of vertical nutrient supply ratios to the depth interval over which they are computed, figures illustrating details of the lateral (in)organic supply ratio calculations, and tables summarizing results from the Monte Carlo simulation and associated sensitivity studies.

Text S1.

Sensitivity of the vertical nutrient supply ratio to the depth interval chosen

The vertical nutrient supply ratio at each study site was computed using observations collected between the mixed layer depth (MLD) and 300m. The depth cutoff of 300 m was selected because biological nutrient uptake and remineralization dominate the nutrient transformations in water masses within this depth range (Quay et al., 2015; Quay & Wu, 2015). Vertical $(\Delta NO_3/\Delta PO_4)_v$ supply ratios may be sensitive to the choice of depth interval, so we examine the sensitivity of vertical $(\Delta NO_3/\Delta PO_4)_v$ supply ratios in four scenarios: (1) the reference scenario where the multi-year annual mean vertical supply ratio is calculated from annual vertical supply ratios, computed using data collected between the mean MLD and 300 m in each year; (2) same but for data collected between the mean MLD and 400 m; (3) same but for data collected between the mean MLD and 200 m; (4) the vertical supply ratio determined using all nutrient data collected between mean MLD and 300 m over the past ~30 years of time-series stations. The $(\Delta NO_3/\Delta PO_4)_v$ supply ratios from all scenarios are quite similar to each other at each respective station, except for scenario 3 (MLD–200 m) at Station ALOHA (Table S4): its ratio (mean±s.d.: 13.4±1.5) is significantly lower than the reference scenario (14.7±0.6) (t test; $p \ll 0.05$), both of which are much smaller than N/P ratios of sinking flux (Figure 3 & Tables S1-S2). The corresponding fractional contributions to nutrient sources or sinks derived from the Monte Carlo simulation are similar to the reference scenario. Overall, vertical $(\Delta NO_3/\Delta PO_4)_v$ supply is not very sensitive to the choice of depth interval and slight differences in vertical supply ratios between the scenarios would not change the main conclusions of this study.

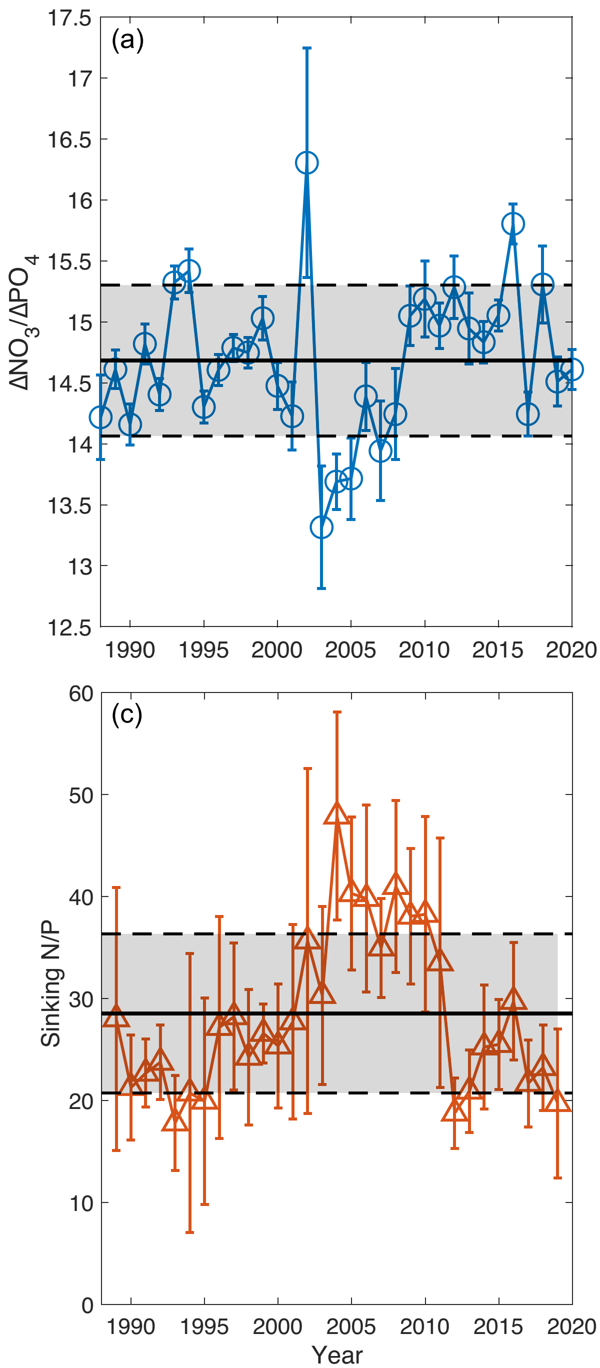

Figure S1. Annual vertical inorganic nutrient supply ratios (MLD–300 m) (a-b) and annual weighted mean N/P ratios of sinking particles at 150 m (c-d) at Station ALOHA and BATS between 1988 and 2020. (a) and (c) are data from Station ALOHA. (b) and (d) are from BATS. Robust regression is used to minimize the influence of outliers to estimate annual vertical inorganic nutrient supply ratio. The solid black lines in (a) and (b) are the mean vertical inorganic nutrient supply ratio for all years, $(\Delta NO_3/\Delta PO_4)_v$, and the dashed lines are ±1 standard deviation. The p values of all slopes are smaller than 0.05. The solid black lines in (c) and (d) are the multi-year weighted mean N/P ratios of sinking particles and the dashed lines are ±1 standard deviation. No significant changes with time are observed for both parameters at Station ALOHA and BATS ($p>0.05$).

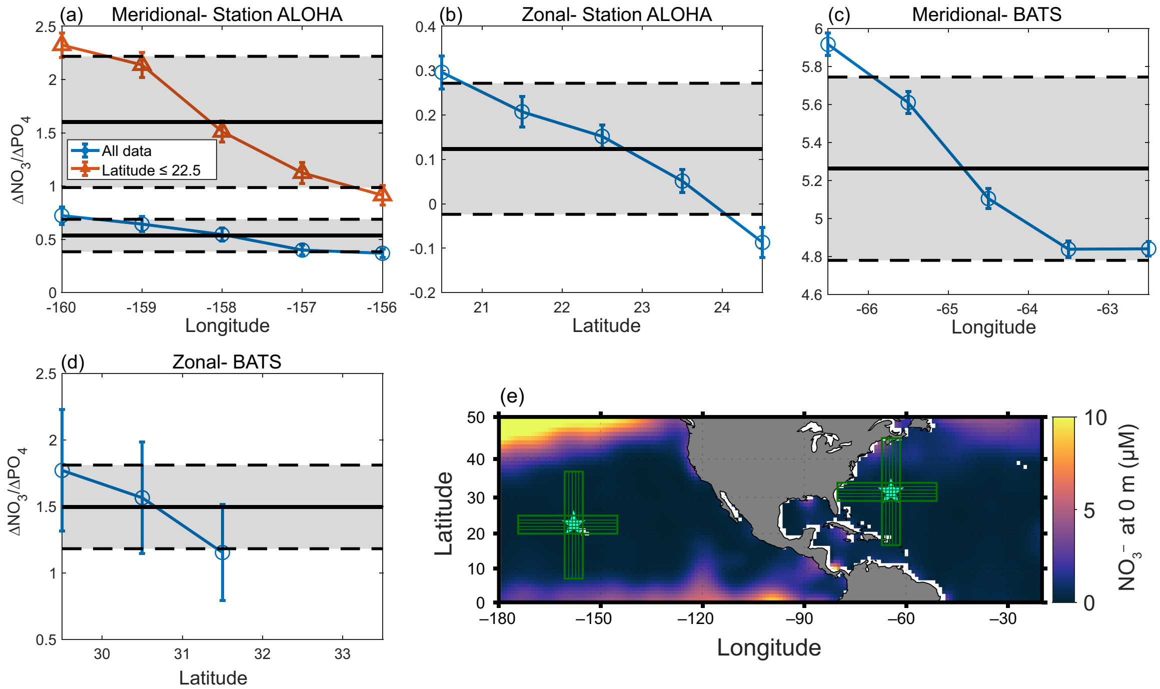

Figure S2. N/P ratios of lateral supply in the surface ocean at Station ALOHA (a-b) and BATS (c-d) in the meridional (a, c) and zonal (b, d) directions using WOA18 monthly climatology (Garcia et al., 2018). Regions of data used in the calculation are highlighted with four green boxes that are 30˚×5˚ in (e). Each box is divided into five 1-degree latitude or longitude bands to calculate the mean zonal or meridional supply ratios, $(\Delta NO_3/\Delta PO_4)_l$, as the solid black lines. Robust regression is used in all fits and only slopes with p values smaller than 0.05 are shown. We further constrain the latitude range used in the meridional transect at Station ALOHA (7–37˚ N & 155.5–160.5˚ W box) in (a) to latitude ≤ 22.5 ˚N to best represent the surface flux ratio from the Equatorial region.

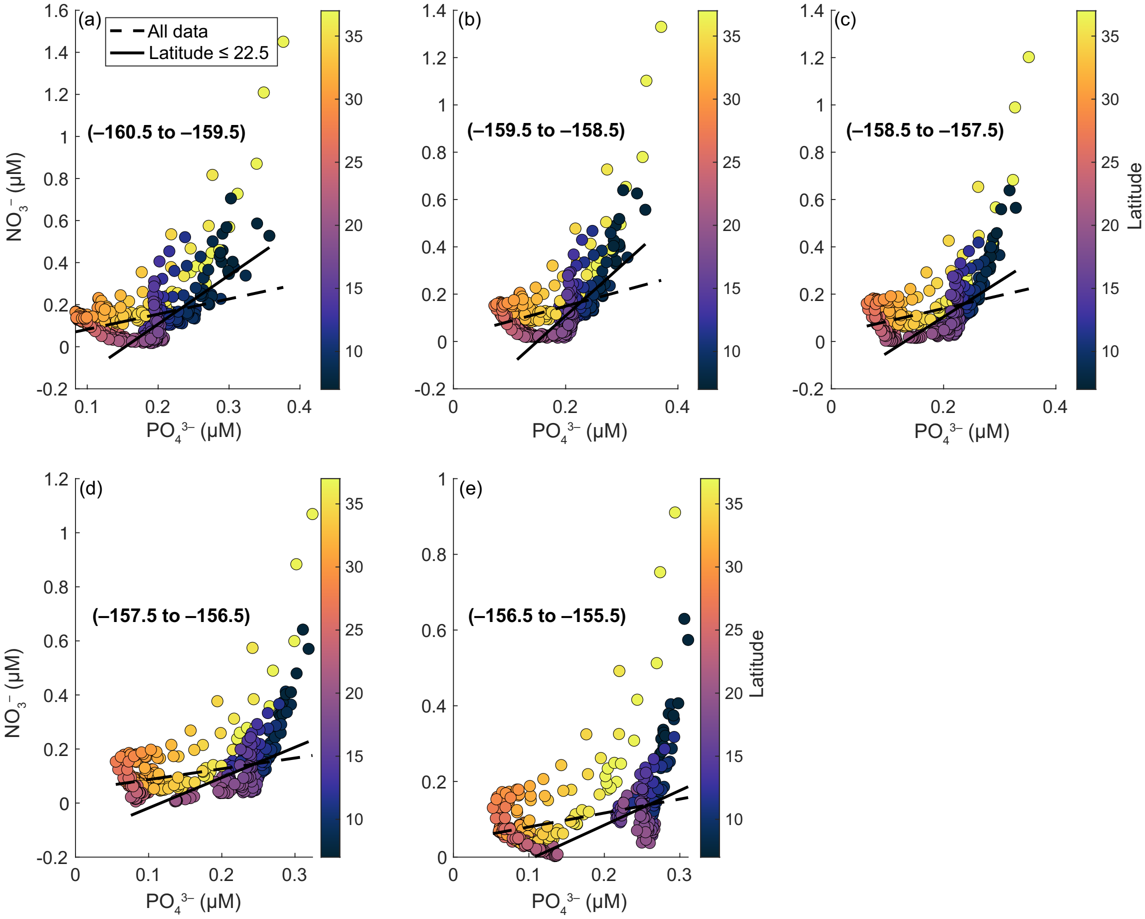

Figure S3. Relationships between NO_3^- and PO_4^{3-} in five 1-degree longitude bands (30˚ latitude×1˚ longitude) near Station ALOHA. (a) 159.5–160.5˚ W; (b) 158.5–159.5˚ W; (c) 157.5–158.5˚ W; (d) 156.5–157.5˚ W; (e) 155.5–156.5˚ W. Robust regression is used in all fits. All solid lines are fit only with data from latitude ≤ 22.5 ˚N. The color bar is latitude.

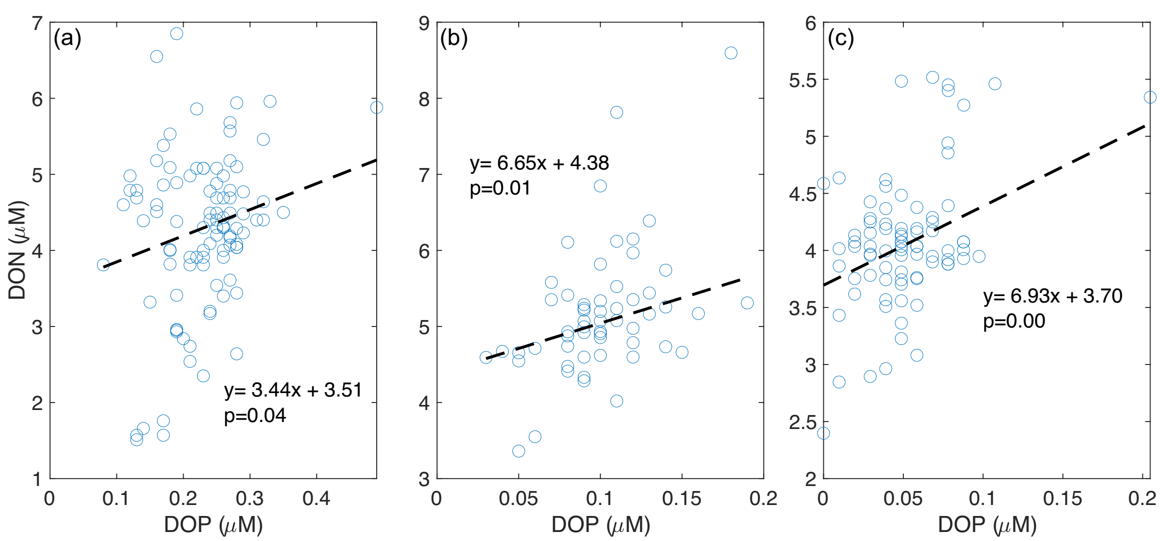

Figure S4. Lateral supply ratios of $(\Delta DON/\Delta DOP)_l$ within the mixed layer depth in the NPSTG (a) and NASTG (b-c). (a) Meridional supply ratios at Station ALOHA (Church et al., 2008); (b) meridional supply ratios at BATS (Cavender-Bares et al., 2001); (c) zonal supply ratios at BATS (Torres-Valdés et al., 2009). Robust regression is used in all fits. Negative DOP concentrations in the BODC 36˚N cruise, which are likely values below the detection limit, are not included in the regression fit.

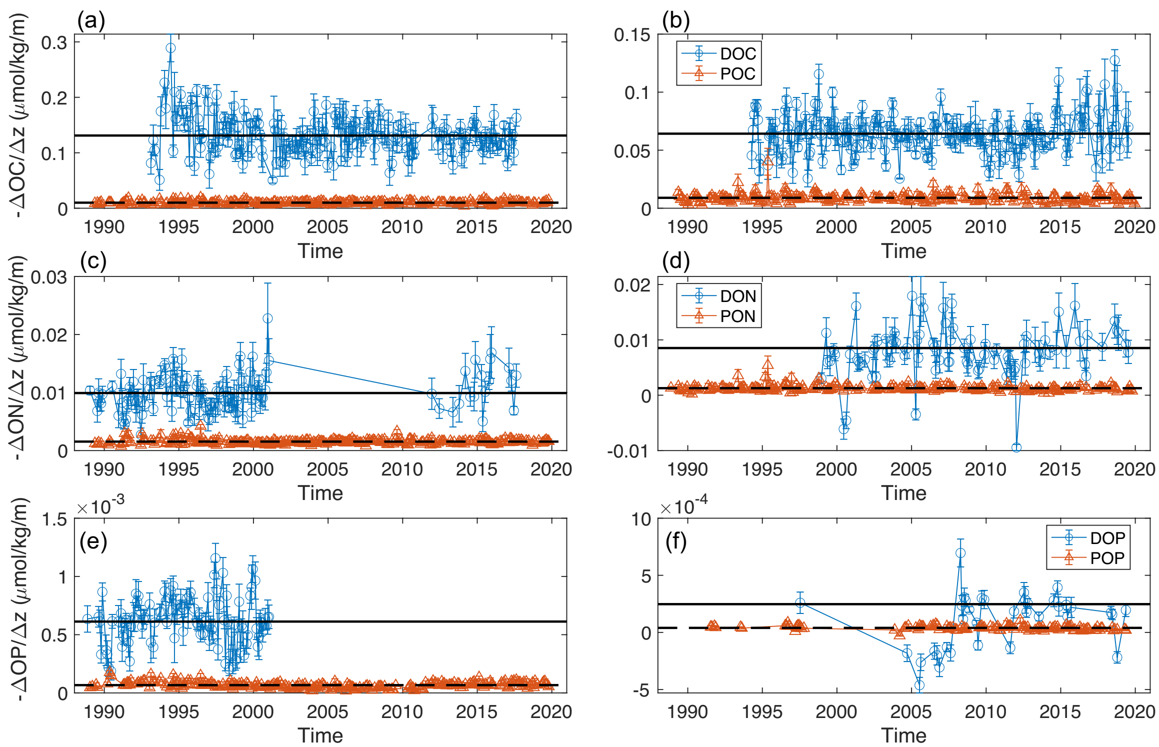

Figure S5. Depth gradients of dissolved organic matter (blue circles) and particulate organic matter (orange triangles) at Station ALOHA (a, c, e) and BATS (b, d, f) estimated using monthly data (monthly mean mixed layer depth to 300 m) between 1988 and 2020. (a-b): depth gradients of organic carbon (OC); (c-d): depth gradients of organic nitrogen (ON); (e-f): depth gradients of organic phosphorus (OP). The solid line is the mean depth gradient of dissolved organic matter, and the dashed line is the mean depth gradient of particulate organic matter. The p values of all gradients are smaller than 0.05.

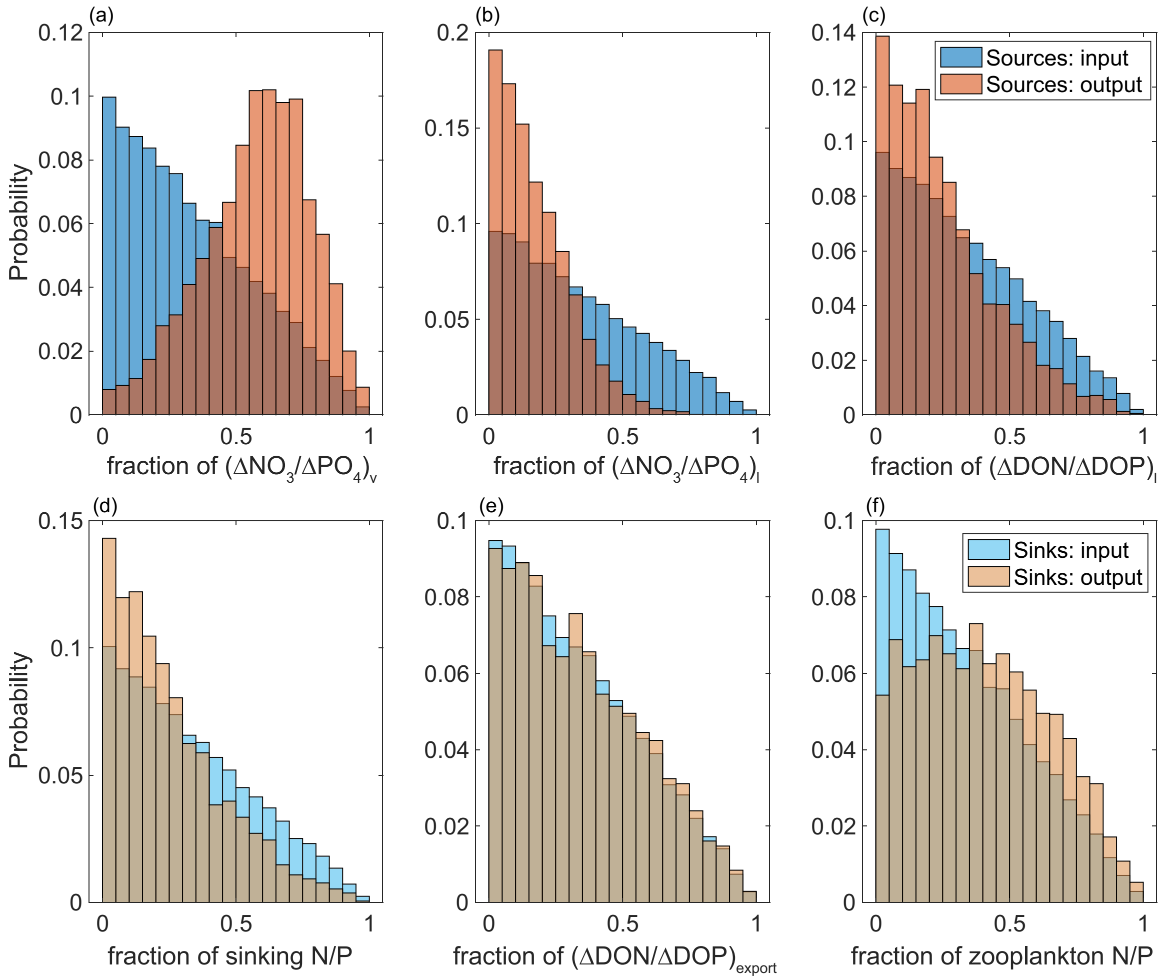

Figure S6. Comparison between initial inputs of fractions into the Monte Carlo method (all) and outputs of fractions constrained by N_{src}/N_{exp} (0.3–0.5) at Station ALOHA. Panels shown the fractions of (a) vertical inorganic nutrient supply, (b) lateral inorganic nutrient supply, (c) lateral organic nutrient supply, and nutrient export through (d) sinking particles, (e) semilabile DOM export, and (f) zooplankton excretion. Each randomly selected fraction input (blue bars) into the Monte Carlo method has a positively skewed distribution due to their sum of 1.

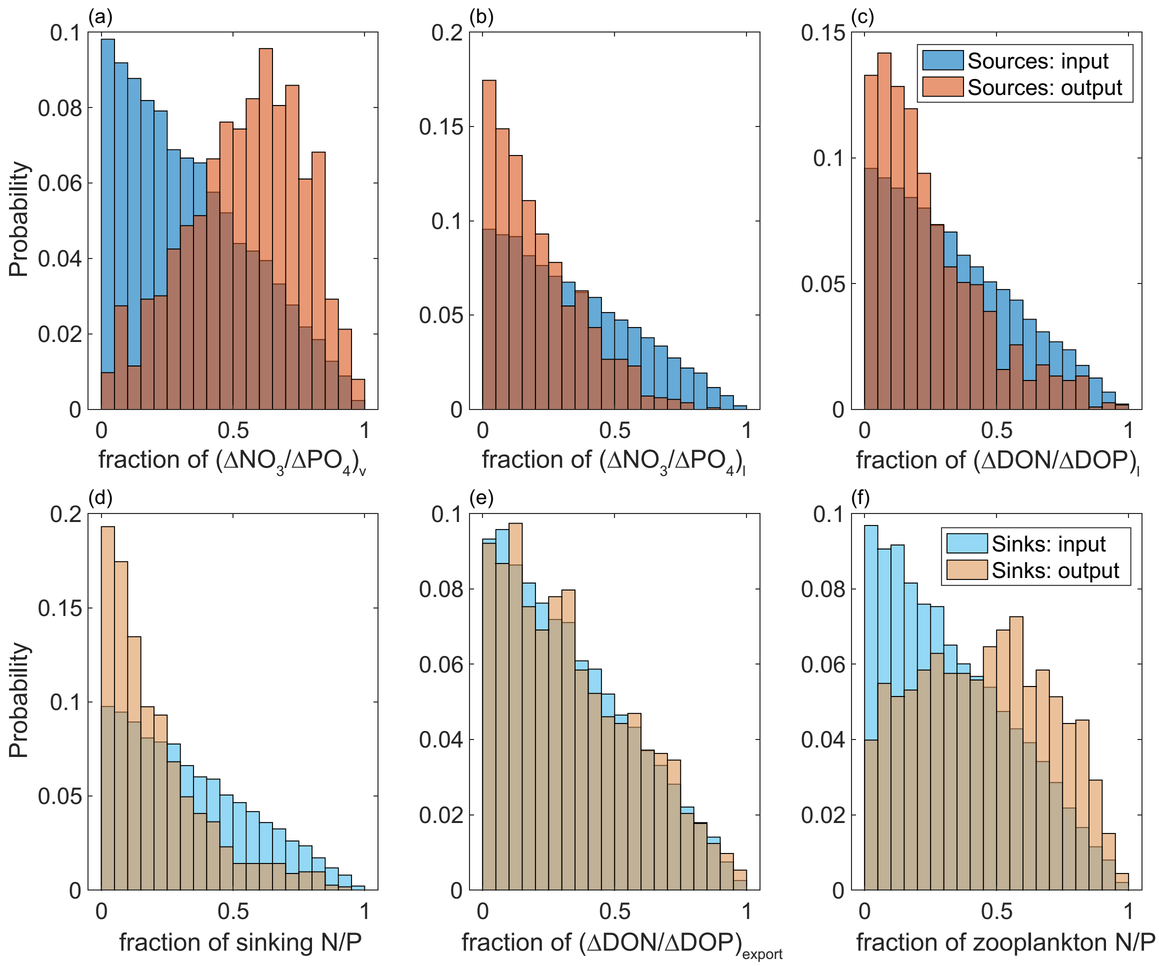

Figure S7. Comparison between initial inputs of fractions into the Monte Carlo method (all) and outputs of fractions constrained by N_{src}/N_{exp} (0–0.15) at BATS. Panel arrangements and notations as for Figure S6.

		N/P ratios	Mean fraction	Median fraction	25th–75th percentile fraction	Skewness
Nutrient source terms	$(\Delta NO_3/\Delta PO_4)_v$	14.7±0.6	0.58	0.60	0.45–0.72	–0.45
	$(\Delta NO_3/\Delta PO_4)_l$	1.6±0.6	0.17	0.14	0.07–0.25	1.03
	$(\Delta DON/\Delta DOP)_l$	4.0±2.9	0.25	0.20	0.10–0.36	0.98
Nutrient sink terms	Sinking N/P	28.5±7.8	0.25	0.21	0.09–0.37	0.98
	$(\Delta DON/\Delta DOP)_{exp}$	20±3[1]	0.34	0.31	0.14–0.51	0.52
	Zooplankton N/P	12.0±4.9[2]	0.40	0.39	0.20–0.59	0.25

Table S1. Summary of end member N/P ratios and fractional contributions at Station ALOHA. The $(\Delta DON/\Delta DOP)_{exp}$ and Zooplankton N/P ratios are not calculated in this study. Data sources are 1: Hopkinson and Vallino (2005); 2: Steinberg et al. (2002).

		N/P ratios	Mean fraction	Median fraction	25th–75th percentile fraction	Skewness
Nutrient source terms	$(\Delta NO_3/\Delta PO_4)_v$	19.6±5.2	0.55	0.57	0.40–0.72	–0.37
	$(\Delta NO_3/\Delta PO_4)_l$	5.3±0.5	0.21	0.17	0.07–0.31	0.98
	$(\Delta DON/\Delta DOP)_l$	6.7±4.4	0.25	0.19	0.09–0.35	1.14
Nutrient sink terms	Sinking N/P	40.5±15.7	0.21	0.15	0.07–0.29	1.38
	$(\Delta DON/\Delta DOP)_{exp}$	20±3[1]	0.34	0.30	0.13–0.52	0.56
	Zooplankton N/P	12.0±4.9[2]	0.45	0.46	0.24–0.65	0.04

Table S2. Summary of end member N/P ratios and fractional contributions at BATS. The $(\Delta DON/\Delta DOP)_{exp}$ and Zooplankton N/P ratios are not calculated in this study. Data sources are 1: Hopkinson and Vallino (2005); 2: Steinberg et al. (2002).

Fractional contribution (Mean±s.d.)		Nutrient sources			Nutrient sinks		
		1- Vertical inorganic	2- Lateral inorganic	3- Lateral organic	4- Sinking particles	5- DOM export	6- Zoo. excretion
Station ALOHA	Original	0.58±0.20	0.17±0.13	0.25±0.20	0.25±0.20	0.34±0.24	0.40±0.24
	w/o s.d.-1	0.58±0.19	0.18±0.14	0.24±0.19	0.26±0.20	0.35±0.24	0.40±0.24
	w/o s.d.-2	0.57±0.20	0.18±0.14	0.25±0.19	0.26±0.21	0.33±0.23	0.40±0.24
	w/o s.d.-3	**0.61±0.17**	0.18±0.14	**0.21±0.16**	0.26±0.21	0.34±0.24	0.40±0.24
	w/o s.d.-4	0.60±0.20	0.17±0.14	**0.23±0.18**	**0.24±0.18**	0.34±0.24	0.42±0.24
	w/o s.d.-5	0.57±0.20	0.18±0.14	0.25±0.19	0.25±0.20	0.34±0.24	0.41±0.24
	w/o s.d.-6	**0.58±0.18**	0.17±0.13	0.24±0.19	0.26±0.20	0.34±0.24	0.41±0.24
BATS	Original	0.55±0.22	0.21±0.17	0.25±0.20	0.21±0.19	0.34±0.24	0.45±0.25
	w/o s.d.-1	0.56±0.23	0.19±0.17	0.25±0.21	0.21±0.19	0.32±0.24	0.47±0.25
	w/o s.d.-2	0.57±0.22	0.20±0.16	0.23±0.20	0.20±0.19	0.32±0.24	0.48±0.25
	w/o s.d.-3	**0.60±0.20**	0.20±0.16	**0.21±0.17**	0.20±0.18	0.32±0.23	0.48±0.25
	w/o s.d.-4	0.59±0.22	**0.18±0.15**	0.23±0.19	**0.11±0.08**	0.33±0.24	**0.56±0.23**
	w/o s.d.-5	0.58±0.23	0.18±0.16	0.23±0.20	0.19±0.19	0.33±0.23	0.48±0.24
	w/o s.d.-6	**0.60±0.20**	**0.17±0.13**	0.24±0.20	**0.18±0.17**	0.32±0.23	0.51±0.25

Table S3. Sensitivity study results showing how the uncertainty (standard deviation) on each source and sink term N/P value individually contributes to the spread in plausible source and sink fractional contributions. The Monte Carlo method is run by excluding the standard deviation of one nutrient source or sink term N/P value at a time to identify how the spread in plausible source and sink fractional contributions changes at Station ALOHA and BATS. A reduction in the fractional contribution spread reflects tighter constraint on that term. Bold numbers indicate a reduction in the fractional contribution standard deviation by ≥ 0.02 relative to the original run.

Vertical $(\Delta NO_3/\Delta PO_4)_v$	Scenario 1 (MLD–300 m)	Scenario 2 (MLD–400 m)	Scenario 3 (MLD–200 m)	Scenario 4 (all data; MLD–300 m)
Station ALOHA	14.7±0.6	14.8±0.3	13.4±1.5	14.5±0.04
BATS	19.6±5.2	19.4±3.3	19.3±7.9	19.5±0.2

Table S4. Sensitivity studies of vertical $(\Delta NO_3/\Delta PO_4)_v$ supply ratios