

Sea ice loss drives a regime shift in Arctic Ocean nitrogen biogeochemistry

Corresponding Author: Ms Marta Santos-García

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Version 0:

Decision Letter:

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Dear Ms Santos-Garcia,

Please accept our apologies for the delay in sending a decision on your manuscript. Your manuscript titled "Sea ice loss drives a regime shift in Arctic Ocean nitrogen biogeochemistry" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment, provided remaining reviewer concerns are met.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers, which pertain to acknowledging other possible pathways for nitrogen fixation and other approaches for calculating benthic denitrification. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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Best regards,

Alice Drinkwater, PhD
Associate Editor
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REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

This is my third review of this paper and the authors have adequately addressed my earlier concerns. It is suitable for publication.

Reviewer #3 (Remarks to the Author):

Overview

Santos-Garcia et al. suggest a regime shift in the Polar Surface Water in the past decade with nitrogen as the main limiting factor. The authors suggest this signal might be due to benthic denitrification (BD). While this study explores an interesting perspective by examining pan-Arctic connections between localized BD and nitrogen "limitation" in the Fram Strait, I find that the work misses important pieces in several key aspects, which I will outline below.

General comments

Authors used the term "Nitrogen fixation". However, this term refers to the reduction of atmospheric N₂ to ammonia (Friesen et al., 2025) and this is not what is meant in the study.

According to the Lagrangian approach, the advection of the BD signal to the Fram Strait is presented as plausible. However, to achieve a comprehensive and integrated understanding of the processes governing nutrient ratio responses, the study likely overlooks other critical mechanisms. As a result, the quantitative significance of BD cannot be effectively disentangled from these additional processes. Turbulence (Randelhoff et al., 2020), lateral advection (Woodgate et al., 2025, which suggests a decadal increase in nitrate flux through the Bering Strait), and broader ocean physics (Waite et al., 2026) all play pivotal roles in nitrate supply and uptake within the photic zone. For instance, Waite et al. (2026) further argue that, at submesoscale levels, the physical supply of nitrate surpasses biological supply rates in the Fram Strait. Given the pan-Arctic scale of the approach, constructing a comprehensive budget approach would have been essential to rigorously evaluate the stated hypothesis.

While the relationship between net primary production (NPP) and BD is often simplified in the literature, it is widely adopted. Middleburg et al. (1996) offer a more sophisticated BD calculation method, which could be applied and compared to assess whether it corroborates the observed increase. If it does, the proposed hypothesis may be validated. Although a Monte Carlo analysis has been conducted for NPP estimates, a similar approach should be extended to BD calculations.

The authors briefly acknowledge that through BD sediments can also act as a nitrogen source, releasing ammonium back into the water column (see also Middleburg et al., 1996, p. 668). A steep nitrate gradient between bottom waters and sediments implies reduced nitrate availability for BD, potentially increasing the supply back to the water. Without direct measurements of benthic nitrogen fluxes (nitrate and ammonium), however, verifying the authors' claims remains challenging. There can be nitrate uptake by the sediments, but balanced by ammonium outflux. In other words, while enhanced BD aligns with nitrogen loss in the water, it does not necessarily confirm reduced nitrogen availability or limitation for NPP in the water column. In addition, there can be less nitrogen, but it does not necessarily mean per se it is limiting for phytoplankton cells. This represents a notable weakness in the study, particularly given the central role of BD in the analysis.

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MANUSCRIPT REVISIONS

Editor comment:

Address the remaining concerns of our reviewers, which pertain to acknowledging other possible pathways for nitrogen fixation and other approaches for calculating benthic denitrification.

Response:

We thank the Editor for the opportunity to address the remaining comments.

In the revised manuscript, we have included a brief discussion of additional nitrogen sources, namely nitrogen fixation and atmospheric deposition (lines 345-347). While these processes are not central to the nitrogen loss mechanism described here, their inclusion provides a more complete view of the Arctic nitrate budget and highlights their potential increasing relevance under the newly identified shift to a low-nitrate regime. We have also clarified the difference between fixed-N and N-fixation and made it clear in the introduction (lines 35-36).

Regarding our benthic denitrification (BD) estimates, we have provided a detailed justification in the response clarifying why Middelberg et al methodology is not appropriate for pan-Arctic application and reaffirm the rationale behind our chosen approach.

Finally, we identify the key process in play using time series data. We identify a regime shift using N levels in Polar Surface Waters and, in combination with other stoichiometric changes, identify benthic denitrification on the shelves as the key process, investigate the source of the signal in a spatial scale, estimate N loss and discuss the implications. As such we have disentangled the key process using data in contrast to Referee 3 comments. This is not to say that other processes mentioned by the referee are not occurring in the Arctic ocean, but to say that these cannot adequately explain the regime shift identified in the time series data which is the focus of the study.

Santos-Garcia et al. suggest a regime shift in the Polar Surface Water in the past decade with nitrogen as the main limiting factor. The authors suggest this signal might be due to benthic denitrification (BD). While this study explores an interesting perspective by examining pan-Arctic connections between localized BD and nitrogen “limitation” in the Fram Strait, I find that the work misses important pieces in several key aspects, which I will outline below.

Reviewer comment:

Authors used the term “Nitrogen fixation”. However, this term refers to the reduction of atmospheric N₂ to ammonia (Friesen et al., 2025) and this is not what is meant in the study.

Response:

We would like to clarify that we have not used the term “nitrogen fixation” in this

manuscript. Fixed-N is the term that we use which means mainly nitrate in the ocean with minor contributions from ammonia and nitrite. This we now explain in line 35-36.

Reviewer comment:

According to the Lagrangian approach, the advection of the BD signal to the Fram Strait is presented as plausible. However, to achieve a comprehensive and integrated understanding of the processes governing nutrient ratio responses, the study likely overlooks other critical mechanisms. As a result, the quantitative significance of BD cannot be effectively disentangled from these additional processes. Turbulence (Randelhoff et al., 2020), lateral advection (Woodgate et al., 2025, which suggests a decadal increase in nitrate flux through the Bering Strait), and broader ocean physics (Waite et al., 2026) all play pivotal roles in nitrate supply and uptake within the photic zone. For instance, Waite et al. (2026) further argue that, at submesoscale levels, the physical supply of nitrate surpasses biological supply rates in the Fram Strait. Given the pan-Arctic scale of the approach, constructing a comprehensive budget approach would have been essential to rigorously evaluate the stated hypothesis.

Response:

The purpose of this study is to present the evidence for the regime shift in time series nitrate data and identify the key process responsible for low nitrate concentrations, investigate its source and provide an estimation of N losses. Using nitrate concentration and stoichiometric data, we identify that the BD is the key process that leads to low nitrate levels in the Arctic halocline and provide an estimate of N loss and discuss the implications. None of the processes listed here in the Referee comments can explain the step-like decline in nitrate levels, the step-like increase in Si/N and decrease in N/P associated with the regime shift around 2009. Only BD changes can. The train of thinking is presented in lines 61-78 and shown in Figure 2.

Additionally, the processes described by Waite et al. (2026) pertain to Atlantic-derived waters in the West Spitsbergen Current, located in the eastern Fram Strait, which are comparatively weakly stratified and therefore more susceptible to vertical mixing and physical nitrate supply. As we discuss in lines 43-45, the Polar Surface Waters examined in this study occupy the western Fram Strait and originate from Arctic shelves; these waters are strongly stratified and exhibit increasing stratification over time (Tremblay et al., 2015; see also Fig. 2d). This strong stratification effectively inhibits vertical exchange with underlying Atlantic waters, limiting any upward supply of nitrate. If such mixing were significant, it would introduce nitrate-rich Atlantic waters, leading to higher N:P ratios and lower Si:N ratios. However, the observed trends show the opposite behaviour, with declining N:P and increasing Si:N, indicating that vertical mixing is not the dominant control in these waters. Instead, the biogeochemical signature is consistent with increasing nitrate depletion originating on the shelves and transported within Polar Surface Waters, supporting benthic denitrification as the primary driver of the observed changes.

Pacific inputs are important but this increase is controversial, and even if present, the increase is small relative to the increase in BD. Importantly it did not happen in stepwise fashion or correspond in time with regime shift. This is now presented in lines 210-213.

Reviewer comment:

While the relationship between net primary production (NPP) and BD is often simplified in the literature, it is widely adopted. Middleburg et al. (1996) offer a more sophisticated BD calculation method, which could be applied and compared to assess whether it corroborates the observed increase. If it does, the proposed hypothesis may be validated. Although a Monte Carlo analysis has been conducted for NPP estimates, a similar approach should be extended to BD calculations.

Response:

We are well aware of Middelburg et al. (1996); however, its application at the pan-Arctic scale is not feasible given it requires detailed, spatially resolved inputs such as sedimentation rates, bioturbation intensity, porosity profiles of O_2 , NO_3^- , NH_4^+ , and bottom-water biogeochemical conditions. In addition, given the spatial heterogeneity of the Arctic shelves, scaling up such model at a basin scale is also problematic and would require a large number of assumptions, which would introduce significant and difficult-to-quantify uncertainties in the resulting estimates.

In contrast, the approach adopted, although simpler, is suitable for basin scale studies and has been specifically developed and previously applied for Arctic-scale studies (e.g., Chang and Devol, 2009) and could be applied to time series observations in the Arctic. In the manuscript we do validate our BD estimates independently using isotope-based and stoichiometric constraints (see ‘Supplementary Discussion’). For these reasons, we consider that the chosen approach provides the most appropriate balance between process representation and observational constraint for a pan-Arctic analysis and verifiable using available data.

Reviewer comment:

The authors briefly acknowledge that through BD sediments can also act as a nitrogen source, releasing ammonium back into the water column (see also Middleburg et al., 1996, p. 668). A steep nitrate gradient between bottom waters and sediments implies reduced nitrate availability for BD, potentially increasing the supply back to the water. Without direct measurements of benthic nitrogen fluxes (nitrate and ammonium), however, verifying the authors’ claims remains challenging. There can be nitrate uptake by the sediments, but balanced by ammonium outflux. In other words, while enhanced BD aligns with nitrogen loss in the water, it does not necessarily confirm reduced nitrogen availability or limitation for NPP in the water column. In addition, there can be less nitrogen, but it does not necessarily mean per se it is limiting for phytoplankton cells. This represents a notable weakness in the study, particularly given the central role of BD in the analysis.

Response:

The comments focus on processes and mechanistic pathways of benthic nitrogen cycling and denitrification (eg Brown et al., 2015). For simplicity, we use the term “benthic denitrification” (BD) throughout the manuscript; however, we expand (see Supplementary Discussion) and explain that this predominantly occurs via coupled nitrification–denitrification, which includes these processes outlined by the referee comments.

Simply stated, sediments can release ammonium back to the overlying water column, this flux does not fully offset for diffusive flux of nitrate into the sediments and losses associated with denitrification. This released ammonium flux from sediments is derived ultimately from organic nitrogen that was originally supplied from the water column, and its partial return represents recycling rather than a new nitrogen source. In contrast, denitrification removes fixed nitrogen irreversibly from the system as N_2 and N_2O , leading to net nitrate loss.

We agree that lower nitrogen concentrations do not inherently imply N limitation; however, many studies have shown that those under or close to the threshold concentration of $\sim 2 \mu M$ nitrate can limit phytoplankton growth. In the manuscript we provide references of this threshold response in the Arctic Ocean (lines 319-323).

References

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- Tremblay, J. É., Anderson, L. G., Matrai, P., Coupel, P., Bélanger, S., Michel, C., & Reigstad, M. (2015). Global and regional drivers of nutrient supply, primary production and CO_2 drawdown in the changing Arctic Ocean. *Progress in Oceanography*, 139, 171-196.
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