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Land to Sea Biogeochemical Fluxes in a Changing Arctic: Insights from Svalbard

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Our understanding of cryosphere-biosphere coupling in the polar regions is arguably weakest in the context of glaciers and their influence upon marine ecosystems. Major reasons include the lack of cross-disciplinary interaction and the sometime extreme difficulty faced by those trying to conduct field work where glaciers or glacial runoff meet the sea. This presentation therefore addresses this science gap with new insights into nutrient transport by glacial meltwaters into Svalbard coastal ecosystems. A particular emphasis is placed upon nitrogen, because it is a key, productivity-limiting nutrient and because the nitrogen cycle includes atmospheric, organic and even geogenic inputs to the glacial system that were defined for the first time by fieldwork conducted in Svalbard a quarter of a Century ago (e.g. Hodson et al. 2005; Wynn et al. 2007).

In spite of clear knowledge gaps in our understanding of the origins, magnitude and fate of nutrients transported by glacial runoff into Arctic coastal ecosystems, there have still been some major conceptual advances, such as:

1) It's the productivity-limiting nutrient(s) that matter most, and in Svalbard this means nitrogen and (less so?) silica. Both have received significant attention in recent years (e.g. Duarte et al. 2025; Halbach et al. 2019), although mostly in one location (Kongsfjord) whose representativeness deserves scrutiny.
2) Increasing glacial runoff volumes can dilute the concentrations of nitrogen in the photic zone, and even make photosynthesis more difficult due to high turbidity (e.g. Hopwood et al. 2020). Therefore the "big nutrient flux must count" theory for glacial runoff often seems naïve.
3) Particles responsible for the high turbidity constitute a very large proportion of the labile nutrient flux, especially for adsorbed NH_4 and amorphous Si particles (e.g. Wadham et al. 2016; Hendry et al. 2025).

4) Subglacial runoff from marine terminating glaciers with grounding lines deep beneath the fjord surface exerts a major influence upon nitrogen supply to the photic zone because its buoyant rise also entrains nitrogen-rich bottom waters and sends them towards the photic zone (e.g. Meire et al. 2017; Hoshiba et al. 2024).

Of the above, 4) has been particularly important because it redefined our understanding of how glacial runoff influences nitrogen availability in the photic zone. The intensity and the longevity of the buoyancy-driven circulation process is also intricately linked to climate, and so a lot of research attention is currently directed towards what happens after tidewater glaciers have retreated onto land (e.g. Meire et al. 2023; Santos-Garcia et al. 2022). Such a retreat is expected to result in an estuarine-type circulation process, wherein riverine inputs fail to induce the vertical mixing and therefore struggle to deliver sufficient nutrient supplies to sustain high primary production in the upper water column. However, whilst the retreat of marine-terminating glaciers onto land is an important aspect of projected future change, it is arguably less important in Svalbard than it is in Greenland. This is because several of Svalbard's fjords already underwent this transition during the Holocene in response to isostatic uplift: a process that outpaces rising sea level in West Spitsbergen even today. Others are very close to this transition, and have shallow grounding lines that are unlikely to see the development of strong buoyancy-driven upwellings. There is also the fact that not all Svalbard glaciers enter the sea via fjords, as is indeed the case near other Arctic archipelagos.

Multi-year, multi-site analysis of nitrogen concentrations, fluxes and stable isotope composition in Svalbard runoff reveal two critically important processes require consideration before the role of glacial runoff in the provision of productivity-limiting nitrate is to be fully understood: i) atmospheric nitrate release by snowmelt in early summer, and ii) microbial nitrate production by nitrification from mid-summer onwards. As a consequence of the latter, the nitrate content of glacial runoff is dominated by microbial production almost everywhere once the winter snow resource has been released by snowmelt (Wynn et al. 2007; Ansari et al. 2013). However, the impact of nitrification is far from spatially uniform, and there exist very significant "hotspots" in the vicinity of large bird colonies and in catchments underlain by shale-rich bedrock. The former is more localized, well-known, and effectively involves the recycling of marine nitrogen via guano (e.g. Finne et al. 2024; Zmudczyńska-Skarbek and Balazy 2017). However, the latter has received almost no attention to date (Dixon 2019; Polukhin et al. 2021), yet it occurs in landscapes that cover more than one third of the archipelago's land area. In extreme cases, new data show that the nitrate yields of shale-influenced glacier basins are enhanced by > 20 times those that would be expected from atmospheric nitrate alone. The erosion of shale by glacial and periglacial processes across much of Central and Eastern Svalbard therefore produces flowpaths highly conducive to the transformation of geological ammonium to nitrate during the melt season. This transformation is highly likely to respond to climate-driven changes in the thaw depth, rainfall infiltration and meltwater percolation in future.

Going forwards, we need to be able to predict atmospheric and microbial nitrate delivery to runoff if we want to forecast the future state of Svalbard fjord ecosystems. Atmospheric nitrate release via snowmelt demonstrates clear sensitivity to climate change, with earlier, smaller fluxes likely across much of the archipelago due to a shorter accumulation season and the earlier onset of melt (Osuch et al. 2022). However, it is also notable that snow cover is undergoing a recent increase in Heer Land and parts of Torell land, most likely due to enhanced moisture supply from local sources as a consequence of sea ice failure along the East coast. The atmospheric nitrate resource is therefore likely to be growing here as a consequence, although more needs to be done to understand the regional variations in the nitrate chemistry of snowcover before this can be predicted with any certainty. With respect to nitrate supply from nitrification, there exist greater challenges due to its requirement for ground thaw to proceed and for shallow groundwater and subglacial flow paths to open before it becomes influential (e.g. Wynn et al. 2007; Ansari et al. 2013). However, nitrification is important because it has the capacity to extend the duration of primary production after the winter nitrate and early summer snowmelt resources have been depleted. As a consequence, nitrification can compensate for the loss of supply via nitrate-rich bottom waters that occurs after the retreat of tidewater glaciers onto land. An understanding of the supply of reduced nitrogen that is required to sustain the process is also required, which will depend upon both extrinsic factors linked to climate and intrinsic factors linked to hydrological evolution of subglacial and proglacial drainage systems, permafrost change and soil development. Of particular importance is the redox evolution of high throughput shallow groundwaters in glacial and periglacial sediments. Will they shift toward more reducing conditions and thus favour nitrate removal via denitrification, or will they be conducive to nitrification by remaining oxic? At the time of writing, the overwhelming evidence is that the major rivers entering fjords largely show the latter and are thus predominantly sustained by flowpaths conducive to nitrification. By contrast denitrification in Svalbard seems most important in the active layer wetlands of lowland permafrost environments with low water yields and thus minimal influence upon fjord biogeochemistry. As a consequence, it is not surprising that a positive correlation between runoff and indices of primary production (Chlorophyll a) in Svalbard fjords and coastal waters has been found, even in places where deep subglacial inflows from marine-terminating glaciers are absent (Dunse et al. 2022).

In conclusion, while we can easily predict meltwater production in response to seasonal snowpack and glacier ablation, we still have a long way to go before we can predict the nutrient composition of this meltwater as it enters the sea. This is not so much due to a lack of empirical data resources but instead a lack of appropriate models that account for non-conservative nutrient behaviour following the onset of summer meltwater production. Recent focus upon marine nutrient resources (via the buoyancy-driven entrainment of bottom waters) has been important, but means that the importance of riverine inputs has been overlooked, which is not helpful in the case of nitrogen.

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