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WP2, D2.5, D14 Amount of nutrients released by glacial runoff

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DISCLAIMER

WP2, D2.5, D14 Amount of nutrients released by glacial runoff

1) Introduction

Glaciers are now recognized as active hotspots for biogeochemical cycles of nutrients. A range of supraglacial and subglacial processes (atmospheric deposition, biological activity, physical and chemical weathering) take part in these complex nutrient cycles (Figure 1). As glaciers and ice sheets melt, they mobilize nutrients in dissolved and particulate forms. Glacial meltwaters are a significant source of nutrients to downstream environments, which links the cryosphere with riverine, fjord, and marine ecosystems (Hawkings et al., 2015; Wadham et al., 2016).

Supraglacial nutrient sources include atmospheric deposition, aeolian dust, and *in situ* biological activity. Dust transported from the proglacial zone and deglaciated areas supplies phosphorus, iron, and trace metals (Stibal et al., 2008; McCutcheon et al., 2021). Marine aerosols can contribute to salts and micronutrients delivery to coastal glacier surfaces. Biology also plays a major role. Cyanobacteria in cryoconite holes are capable of fixing nitrogen, snow and glacier ice algae produce organic matter though photosynthesis, and heterotrophic bacteria and fungi remineralize organic carbon and nitrogen, all contributing to nutrient cycling in supraglacial environments. These nutrients generated and cycled in supraglacial environments can also be exported during surface melt events to subglacial environments or directly through rivers to oceans fuelling bio-productivity downstream.

Below the ice, the mechanical grinding of bedrock by glacier pressure produces fine mineral particles (glacial flour) with large surface areas and high reactivity (Raiswell et al., 2016). These particles often contain high amounts of nutrient-bearing minerals such as poorly ordered (and thus highly reactive) iron oxides, or calcium phosphates, or amorphous silica. A significant proportion of these particles are in the nano- to micrometer size range, are highly reactive and bioavailable and they might remain suspended in meltwaters and in rivers for long distances and, thus, they be delivered directly to estuaries or fjords, becoming available for the oceanic food web.

Chemical weathering beneath the ice—enhanced by pressure melting, high rock–water ratios, and microbially mediated oxidation of sulfides—releases dissolved nutrients including silica, iron, phosphorus, and nitrogen species (Tranter & Brown, 1993; Wadham et al. 2016, Hawkings et al. 2016, Hawkings et al., 2017). Combined with the supraglacial inputs, these dissolved (and particulate) nutrients are often highly bioavailable. Furthermore, in subglacial environments, microbial remineralization of organic matter and chemolithotrophic metabolism alter nutrient speciation and increase solute concentrations.

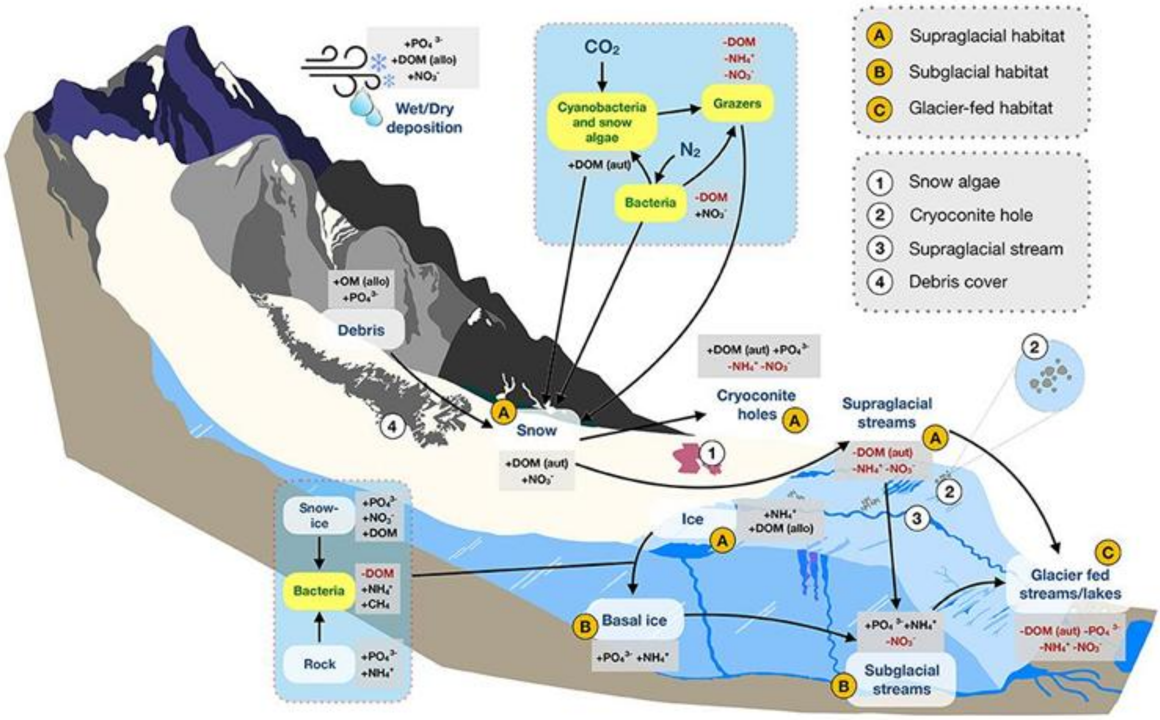

Figure 1: Schematic representation of nutrient dynamics and microbial habitats in glacier environments, showing nutrient cycles, the role of microbial communities (e.g., cyanobacteria, algae, grazers, bacteria) and the physical compartments including supraglacial, subglacial and proglacial. The diagram highlights key processes of atmospheric deposition, biological uptake and transformation and nutrient fluxes through snow, ice and meltwater pathways. (Ren et al. 2019)

Nutrients from glaciers and ice sheets also changes through various inorganic and biological processes along glacier fed rivers which in turn also gain further inputs along their paths from groundwaters springs or other sources (e.g., geothermal waters, permafrostagricultural inputs). Along such river paths, the dissolved and particulate loads further interact and as a result, glacially-derived meltwaters, can contain and carry downstream a complex mixture of dissolved inorganic nutrients, dissolved organic compounds, and particulate forms of nutrients, making glaciers and ice sheets worldwide an important source of macro and micronutrients to downstream ecosystems.

2) Influence of bedrock and glacier size on nutrient concentrations and speciation

Bedrock lithology influences both the concentration and chemical form of nutrients in meltwaters. Mafic and ultramafic rocks release high dissolved silica and iron concentrations, while carbonate-rich bedrocks produce meltwaters with elevated calcium, magnesium, and high alkalinity but generally lower silica (Hatton et al., 2019). Glaciers overlaying phosphate-bearing lithologies, such as apatite-rich igneous or metamorphic rocks, often contain higher particulate and dissolved phosphorus loads, yet these are poorly quantified. Finally, sulfide-rich (e.g., pyrite containing) rocks will, upon weathering, release Fe^{2+}, which in turn will often bind to inorganic or organic anionic ligands in the waters, prolonging iron residence time in rivers and ultimately seawater (Raiswell et al., 2016). The activity of microbial communities beneath glaciers is also influenced by bedrock geochemistry, and this in turn affects nutrient transformations (Dunham et al. 2023).

Glacier / ice sheet size influences both the scale and temporal patterns of nutrient export (Wadham et al. 2010). Ice sheets such as Greenland and Antarctica have large catchments with complex subglacial drainage systems that store and process significant nutrient loads. Annual nutrient fluxes from the Greenland Ice Sheet were estimated to be ~0.20 Tmol of silica, 408 Gg of phosphorous, 0.4–2.54 Tg bioavailable iron, and 40 Ggof nitrogen (Hawkings et al., 2015; Hawkings et al. 2016, Hawkings et al., 2017). Antarctic marine-terminating glaciers can deliver even higher iron concentrations due to longer subglacial water–rock contact times (Hawkings et al., 2020). On the other hand, alpine glaciers, while smaller, can have high nutrient concentrations due to short, reactive flowpaths and strong seasonal hydrological variability. Total fluxes are lower, but their impact on small mountain watersheds can be significant, particularly where meltwater constitutes a major proportion of annual river discharge (Hood et al., 2015). Large glaciers dominate global-scale nutrient budgets, while small glaciers have localized ecological impacts.

3) Seasonal trends of nutrient transport

Nutrient export from glaciers is obviously regulated by the seasonal melt cycle. The onset of the melt season often corresponds to a flushing event of solute-rich waters that have been stored in subglacial environments over winter. The long residence times beneath the ice, allowing prolonged water–rock interaction and microbial processing, result in higher concentrations of dissolved silica, iron, phosphorus, and dissolved inorganic nitrogen (Wadham et al., 2016; Hawkings et al. 2016, Hawkings et al., 2017).

In mid-summer, once a supraglacial drainage network (made of supraglacial streams, crevasses and moulins) fully develop, water inputs from the glacier surface increase. This can dilute certain dissolved nutrient but simultaneously enhance particulate fluxes due to higher meltwater discharge and sediment mobilization (Hawkings et al., 2015). Nitrogen often peaks during mid-summer in some catchments, hinting towards a supraglacial input (Wadham et al. 2016).

Late-season meltwaters can show elevated dissolved nutrient concentrations as supraglacial water input decreases and water residence times beneath the ice increase, leading to higher chemical weathering rates. In some years, late-season pulses may also contain nutrients built up in subglacial systems during the summer (Bhatia et al., 2013).

Together with seasonal variations, diurnal cycles also affect the nutrient concentrations in meltwaters. This has both been observed in in alpine glaciers and ice sheets (Tranter & Brown, 1993, Beaton et al. 2017). An inverse relationship between dissolved nutrient concentrations and discharge has been observed.

Because of climate warming, the season of meltwater nutrient delivery is lengthening. Extreme melt years have been associated with anomalously high nutrient export (Hawkings et al., 2015). Understanding seasonal and interannual shifts is essential for predicting downstream impacts.

4) Dissolved nutrient concentration in meltwaters: examples for Greenland andIceland

Climate change is increasing glacial melt, potentially enhancing the export of solutes and particles to downstream environments (Aciego et al. 2015 and Eiriksdottir et al. 2015). Glacial meltwater rivers contain different dissolved and particulate nutrients forms. Dissolved species include nitrate (NO_3^-), phosphate (PO_4^{3-}), dissolved silica (DSi), dissolved organic carbon (DOC), dissolved iron (Fe) and trace elements. Each nutrient has characteristic sources and dynamics that are influenced by seasonal melt, catchment geology and microbial activity (Anderson, 2007; Tranter et al., 2005). In general, subglacial environments are sources for weathering derived nutrient, such as silica, iron, phosphate and various trace elements due to prolonged rock–water interaction (Wadham et al., 2010; Hawkings et al., 2016). Supraglacial contributions can also be relevant, depending on the nutrient and hydrological conditions. For instance, in Greenland supraglacial meltwaters were found to provide the majority of nitrate to runoff waters at certain points of the melt season (Wadham et al., 2016). Identifying the supraglacial and subglacial origin of nutrient is important for understanding fluxes to downstream environments.

The table below compares concentrations of macro and micro nutrients in two glacial rivers located in two different areas: the Watson River in Greenland and the Hvita River in Iceland.

Table 1: dissolved concentrations of macro and micro nutrients in glacial meltwaters in Greenland and Iceland. Values are expressed both in µM or in µg/L.

Nutrient	Greenland (Watson River)	Hvita River (Iceland)	Source
Nitrate (NO3-)	0.96–5.79 µM	0.4 – 1.8 µM	Beaton et al. 2017; Wadham et al. 2016; Vives et al. 2025
Phosphate (PO4^3-)	Up to ~0.35 µM	0.1 – 0.6 µM	Hawkings et al. 2016
Dissolved silica (DSi)	0.8–41.4 µM	0.5 - 200 µM	Hawkings et al. 2017
Dissolved organic carbon (DOC)	0.05–0.80 mg/L	0.15 - 0.85 mg/L	Bhatia et al. 2013; Hood et al. 2015; Lawson et al. 2014
Fe	12.50 – 128.94 µg/L	5 -85 µg/L	Vives et al. 2025; Hawkings et al. 2020; Bhatia et al. 2013
Mn	2.92 – 10.26 µg/L	0.14 - 21.3 µg/L	Vives et al. 2025; Hawkings et al. 2020
Co	<0.10 – 0.18 µg/L	0.11 - 54,5 µg/L	Vives et al. 2025; Hawkings et al. 2020
Cu	0.58 – 3.10 µg/L	0.55 - 2.42 µg/L	Vives et al. 2025
Zn	3.96 – 48.15 µg/L	0.16 - 5.72 µg/L	Vives et al. 2025; Hawkings et al. 2020
Ni	0.40 – 1.54 µg/L	0.26 - 0. 34 µg/L	Vives et al. 2025
Mo	<0.10 – 0.20 µg/L	0.25 - 1.34 µg/L	Vives et al. 2025

The values for Greenland were taken from the literature, while the ones for Iceland were measured within an ICEBIO project looking at seasonal variability of nutrients in glacial meltwaters. The differences in concentrations reflects the different bedrock of the two areas: predominantly

metamorphic rocks (gneiss in this case) in Greenland, while basalt is the primary constituent of Icelandic bedrock. This explains the higher concentrations of dissolved silica in Iceland compared to Greenland, with maximum values up to 200 µM for the first and 40 µM in the second.
Other differences can be instead linked to different abundance of supra and subglacial microbial processes. As an example, nitrate in Greenland has higher concentrations, reflecting thriving microbial communities which are instead less relevant in Iceland.

5) Consequences of meltwater discharge in downstream ecosystems

Terrestrial input of macro and micronutrients is key for sustaining primary production in the ocean. Several studies have shown the effect of riverine nutrients fluxes at high latitudes. Because of how significantly these areas are impacted by climate change, there is a concrete scientific interest in understanding and quantifying terrestrial nutrient fluxes in the Arctic and Antarctic regions. Glacially derived meltwaters are among the most dynamic sources of nutrients to the ocean. Their influence on coastal systems is highly variable and not yet fully characterized and understood.

As described in previous paragraphs, glacial meltwaters transport a wide range of nutrients, from macronutrients trace elements. Glacial meltwaters can be either enriched or depleted in N, Si, P, Fe, DOC and micronutrients (either in the dissolved or particulate form) compared to surface coastal waters. Glacially derived nutrient inputs can significantly influence downstream primary productivity.

Nitrogen supports phytoplankton growth, phosphorus is critical for ATP and nucleic acids and silica is essential for diatom. Iron is a key limiting nutrient, as it is essential for photosynthesis. Trace elements such as Mn, Co, and Zn act as enzymatic cofactors. DOC serves as a carbon and energy source for heterotrophic microbial communities in downstream ecosystems.

However, the net impact of meltwater discharge on marine productivity can be either positive or negative, depending on glacier type (marine- vs. land-terminating), fjord geometry, freshwater flux, and the limiting resource—light, macronutrients, or micronutrients—in a given place and time (Hopwood et al., 2020) (Figure 2). For example, high-discharge, sediment-rich plumes may reduce euphotic depth and hindering primary production despite abundant nutrients delivery. Low-turbidity meltwater inputs in nutrient-limited systems may trigger intense blooms. Regional circulation, mixing intensity, and the timing of nutrient delivery relative to light availability further modulate these effects, resulting in an often heterogenic ecosystem response to glacially derived inputs.

In marine-terminating glacier systems, subglacial meltwater creates buoyant plumes that entrain nutrient-rich deep waters into the photic zone, stimulating phytoplankton blooms even under stratified summer conditions (Hopwood et al., 2020; Wood et al., 2025). In land-terminating systems, nutrients delivered via proglacial rivers may be attenuated or transformed before reaching the ocean, resulting in less direct or delayed ecosystem responses (Hopwood et al., 2020).

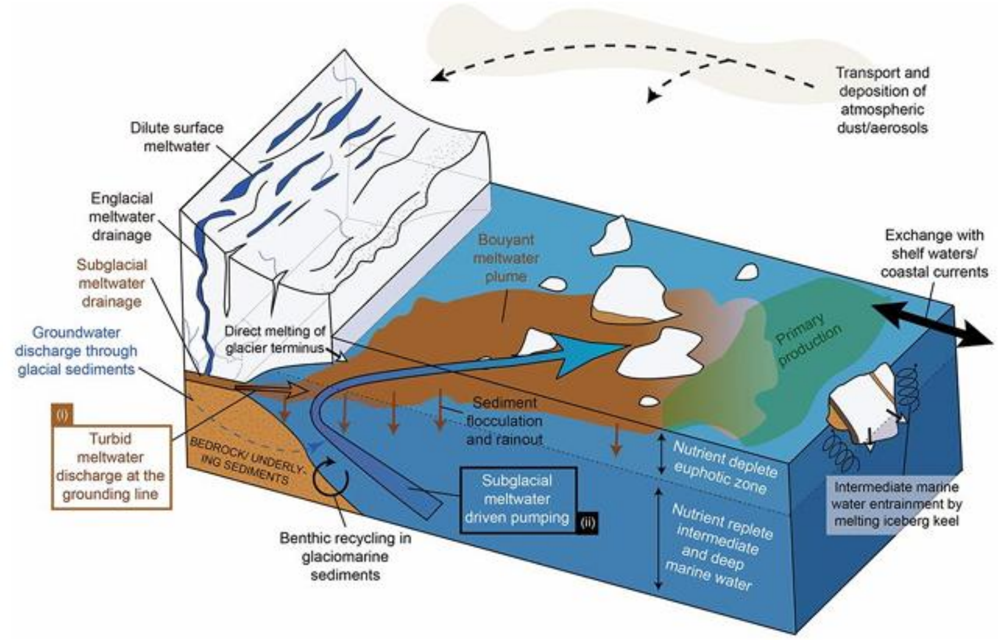

Figure 2: Schematic diagram of nutrients dynamics discharged by meltwaters into coastal environments from marine terminating glaciers (adapted from Hawkings et al. 2021)

Fluxes and nutrients forms are not well constrained. It's not only unclear what the effects of glacial fed rivers discharge are on coastal/fjords waters, but there's also a severe lack of data on the fluxes and forms of nutrients delivered from glacial discharge. As mentioned in the introduction, because climate change is reshaping the water discharge coming from glaciers, it's important to better constrain the nutrient fluxes and in channel processes. In summary, in order to get a clearer picture of nutrients cycles in coastal sea waters adjacent to glacial systems, we must first of all better characterize nutrient fluxes coming from glaciers.

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