

WP3, D3.1, D15 Efficacy of glacial flour as a fertilizer of oligotrophic ecosystems

Project number:	10107276
Project name:	Center for Glacial Biome Doctoral Network
Project acronym:	ICEBIO
Call:	HORIZON-MSCA-2021-DN-01
Topic:	HORIZON-MSCA-2021-DN-01-01
Type of action:	HORIZON-TMA-MSCA-DN
Service:	REA/A/01
Project start date:	1 October 2022
Project duration:	48 months
Deliverable title:	Efficacy of glacial flour as a fertilizer of oligotrophic ecosystems
Deliverable number:	D3.1, D15
Type:	Document, report
Due date (month)	August 2025 (month 35)
Lead beneficiary:	UGrA
Dissemination level:	PU – Public
Work package number:	WP3
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the European Union



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This research is funded by the European Union under the HORIZON-MSCA-2021-DN-01 programme, project number 101072761: ICEBIO. Views and opinions expressed are, however, those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

Preface

This report aims to evaluate the potential for glacial rock flours to act as a fertilizer to various oligotrophic ecosystems which, by definition, offer low availability of nutrients to support life. To achieve this, the characteristics of glacial rock flour are discussed, the export of glacial rock flour is described in quantitative terms where available, and the scientific literature on its fertilizing potential to relevant oligotrophic environments is briefly summarized. This report overlaps with Deliverable 2.2: *An evaluation of the potential of glacial flour to fertilize downstream food webs* and aims to complement it with additional glacial flour transport mechanisms and evidence for whether glacial rock flour is a fertilizer of oligotrophic ecosystems specifically.

1. Getting to know glacial rock flour

Glacial rock flour is a fine rock sediment produced subglacially by the movement of a glacier over a bedrock surface.¹ There is not a strict definition for the particle size or texture classification of glacial rock flour; however, most studies report large fractions to be clay and silt sized (< 63 μm).²⁻⁴ The small particle sizes enable suspension in the water column which allows glacial meltwater to transport the material to downstream ecosystems such as oceans, fjords, rivers, lakes, and glacial forefields. From glacial forefield and exposed riverbeds, glacial rock flour might also be transported by wind onto a glacier's surface or to the marine environment. However, only a portion of glacial rock flour produced in the subglacial environment will be exported with meltwater. Therefore, this material is also weathered in the subglacial environment on varying timescales.⁵

Modeling efforts have resulted in an estimate that 23 Gt of bedrock is eroded by glaciers globally each year.⁶ The total annual export of glacial rock flour from these glaciers is unknown. However, the quantity is likely massive, as the total annual sediment flux from all of Greenland's marine-terminating glaciers was reported to be 1.324 ± 0.79 Gt yr⁻¹ over the period 2010-2020.⁷ Land-terminating glaciers in Greenland are reported to exhibit smaller catchment sizes and slower velocity on average, indicating lesser overall capacity for erosion and sediment export.⁷ Though also likely considerably smaller, it is extremely difficult to estimate sediment export from alpine land-terminating glaciers due to the complex factors that govern the hydrology, sediment export, and deposition.⁸

2. The fertilizing potential of glacial rock flour

In biological terms, a fertilizer is a material that provides essential nutrients for growth. It is a term most frequently used in relation to plants, but other ecosystem members such as microorganisms can benefit from the same nutrient inputs. In this report, fertilization of oligotrophic ecosystems will be discussed with both types of organisms in mind.

The small particle size, high specific surface area, and large quantities of glacial flour produced suggest that it may be a fertilizing agent to oligotrophic environments.^{9,10} Glacial rock flour is a material that has undergone significant mechanical weathering.¹¹ The large surface area of glacial rock flour provides abundant opportunity for biotic weathering through interaction with microorganisms and plant roots, while simultaneously offering a large surface for abiotic weathering through geochemical reactions which might release or alter nutrients. The ability for microorganisms to release nutrients from mineral matrices through biotic weathering processes can bridge the gap between a nutrient-containing material existing in the ecosystem and plant-access to a nutrient.¹² Microbial organic matter can also serve as source of nutrients in oligotrophic ecosystems.¹³ Therefore, indirect fertilization must be considered. The

mineral content of glacial flours differ based on bedrock geology, but many studied to date contain mineral sources of plant-essential nutrients such as iron, phosphorous, potassium, magnesium, manganese, sodium, copper, and calcium.^{9,10,14-16} The primary limiting nutrients for plants include nitrogen and phosphorous.¹⁷ These nutrients can also be considered growth-rate limiting for many microorganisms.¹⁸ Other nutrients such as Iron are also required by microorganisms in smaller quantities as coenzymes for key physiologic reactions.¹⁹

It is important to consider that glacial rock flour may contain essential nutrients but may simultaneously contain potentially bio-toxic elements depending on bedrock lithology.³ For example, Alaskan glacial rock flours were reported to contain Pb, Cd, and Cu,^{20,21} Himalayan glacial rock flours were reported to contain As,³ and weathering of bedrock is hypothesized to contribute Hg to marine ecosystems.²²

3. Subglacial fertilization

Though inhospitable by human standards, the subglacial environment hosts a variety of microorganisms adapted to the cryospheric environment.¹³ The harsh conditions are characterized by a lack of light, cold temperatures, and limited sources of nutrients.²³ Inorganic nutrient inputs from weathering of bedrock, rock debris, and sediment can be considered a major input to the ecosystem.²⁴ Glacial rock flour may be the primary source of inorganic nutrients.¹³ The nutrients available will depend on the bedrock lithology. For example, apatite can be a source of phosphorus,²⁵ feldspars and micas like muscovite can be sources of ammonium,²⁶ and pyrite can serve as a source of iron.²⁷ In addition, the mechanical weathering that produces glacial rock flour can result in large quantities of amorphous silica.²⁸⁻³⁰ Crushing experiments have indicated that certain bedrock types could yield bioavailable methane, ammonium, fatty acids, and dihydrogen which are key substrates for some microorganisms.¹¹ Though these may not be the typical nutrients that come to mind as fertilizers, they are molecules that support the essential physiological processes of life for some microorganisms, and thus support the subglacial ecosystem.

The availability of inorganic nutrients from glacial rock flour may select for microorganisms able to utilize these nutrient inputs. For example, subglacial chemolithoautotrophs that perform iron and sulfide oxidation on pyrite may drive primary production and mineral dissolution in the subglacial environment.²⁷ This activity results in protons that contribute to further dissolution of nutrients from sediment and rock.²⁷ Iron sourced from pyrite can act as a terminal electron acceptor in microbial processes such as dissimilatory nitrate reduction to ammonium (DNRA).³¹ Ammonium is a key nitrogen source for many microorganisms and plants. Trace metals that may be supplied by glacial rock flour minerals like Fe, Ni, Co, Mo, and Zn are also important cofactors during methanogenesis.³² There is evidence for subglacial methanogenic communities which may persist when there is a lack of more energetically

favorable electron acceptors at times in the subglacial environment.^{33,34} Though snow melt and ice melt which reaches the subglacial environment through glacial features such as moulins and can also be a source nitrogen, carbon, and phosphorous, glacial sediments appear to be an important nutrient source that shapes the subglacial microbiome.¹³

4. Pro-glacial forefields

As glaciers retreat, exposing more land, glacial forefields expand. Pro-glacial forefields are considered some of the fastest changing environments in the world.³⁵ This newly exposed land is characterized by rocky, slow-developing, oligotrophic soils which face harsh environmental conditions.³⁶ Pioneering microorganisms are the first to colonize these soils in large numbers, followed by plants.^{37,38} For this to occur, adequate sources of essential nutrients must be present to support microbial life. As noted previously, glacial rock flour can provide a source of essential nutrients depending on bedrock lithology. Some of these nutrients could support the function of key microbial biogeochemical cycling. Glacial rock flour may improve glacial forefield fertility over time directly through abiotic and biotic weathering of the material, or indirectly through accumulation of organic nutrients deriving from microbial biomass.²³ Glacial rock flour may be deposited where it meets topographical or hydrological features that allow it to settle out of a meltwater stream, or it may be exposed as a glacier recedes. Though inorganic nutrients may be available from bedrock and larger glacial debris, the physical characteristics of glacial flour support microbial access to the material.

Sediment grain size is a major determinant of plant colonization in glacial forefields, with smaller sizes favored.³⁹ However, as with microbial colonization, no current reports discuss the plant colonization of glacial rock flour sediment specifically in the natural environment. Outside of glacial forefields, loess soils which are comprised of silt size particles and were produced by earth-surface processes like glacial grinding, are responsible for the fertility of many of the most productive agricultural regions across the globe.⁴⁰ This may indicate that glacial rock flour may generally yield a terrestrial fertilization effect. However, many questions remain regarding which nutrients can be released from glacial rock flour matrices and on what timescales. Whether microorganisms play an essential role in releasing nutrients that then become available to plant has yet to be investigated for forefield glacial rock flour samples. Potential mechanisms for indirect plant fertilization through biotic weathering include mechanical forces and acid production which can release nutrients from minerals.¹² One lab-based experiment reported that while incubating glacial forefield granite crushed to a grain size of < 0.6 mm with microbial isolates from the same forefield, observed weathering activity resulted from microbially produced oxalic acid and freed Fe, Ca, K, Mg, and Mn.⁴¹ These elements can support microbial physiology, but it is unknown whether microbial-mediated release of them would occur in the field and whether the nutrient availability would transfer to plants. The research on glacial rock

flour fertilization to plants currently focuses on the material being added into soil in an agricultural context rather than focusing on deposits in glacial forefield ecosystems themselves. Therefore, fertilization results do not translate directly to a forefield setting where the composition of soils will be far more inorganic and distinct weathering conditions will be present. In the agricultural studies which have investigated the effects to common crops like maize, potatoes, and soybean, Glacial rock flour has been reported to deliver essential nutrients such as Mg, K, Ca, Si, and P.^{3,9,16} However, the results and methods vary and fertilization cannot be generalized to all proglacial forefields due the difference in parent bedrock lithology, grain size, and baseline soil fertility in these agricultural experiments.

In situ experiments involving native plants and further field sampling of glacial rock flour deposits in forefields would provide information about whether glacial rock flour plays a key fertilizing role in pro-glacial forefields.

5. Glacial flour impacts on aquatic environments

5.1 Glacier-fed streams

The first aquatic ecosystem that glacial rock flour enters from land-terminating glaciers is a glacier-fed stream. The turbidity and volume of these streams follow diurnal and seasonal patterns related to temperature and glacial melt rates.^{42,43} The ecology of glacier-fed streams are dominated by biofilms and rock-attached algae or “epithilon” which are key primary producers.^{44,45} Glacier-fed streams apply intense selective pressures to microbial communities including low temperatures, transitory high turbidity due to sediment transport, and variable water levels.^{13,46} These characteristics generally lead to peak biomass during periods of the year with lower glacial-melt inputs and lower turbidity.⁴³ Brandani et al. reported that benthic biofilms were more biodiverse in tributaries compared to glacier-fed streams studied at three proglacial floodplains in the Swiss Alps.⁴⁷ Similar findings indicating that greater glacial influence is negatively associated with biomass parameters for biofilms in glacier-fed streams were reported in a New Zealand-based study.⁴⁸ Though lower turbidity provides favourable conditions for primary producers, suspended sediment is at least partially responsible for delivery of essential nutrients such as phosphate and nitrogen to these ecosystems.¹³ Microorganisms that utilize these nutrients but remain adapted to greater turbidity may be unique members of glacier-fed stream ecosystems.

Based on available information, glacial rock flour plays both a fertilizing and inhibitory role in glacier-fed stream ecosystems. Current findings indicate that high sediment load may inhibit biomass accumulation by preventing the establishment of algae, the primary source of organic matter in glacier-fed streams.⁴⁷ Suspended glacial rock flour transport blocks light, reducing primary production, while the fine sediment may also deliver a material which contributes

essential nitrogen, phosphorous, silica, or iron depending on the bedrock of origin. These findings suggest that whether glacial rock flour is acting as a fertilizer to pro-glacial streams may depend on the turbidity and flow rate. Multiple predictions have been made that overall ecosystem biodiversity may increase with reduced glacial influence but species uniquely adapted to harsh glacial conditions will suffer.^{46,49} This may indicate that without suspended glacial flour, streams become more fertile; however, weathering of streambed glacial rock flour and potential fertilization to benthic ecosystems has not yet been explored.

5.2 Pro-glacial lakes

Many of the same glacial flour fertilization dynamics applied to glacier-fed streams apply to pro-glacial lakes. For example, the turbidity, depth, and temperature of proglacial lakes may vary seasonally, and smaller diurnal variations may also be observed.⁵⁰ Peter and Sommaruga (2016) reported that proglacial lakes with high turbidity due to suspended sediment housed unique microbial community members that were not detected in proglacial lakes that no longer received turbid meltwater inputs due to glacial retreat.⁵¹ It is possible that the glacial meltwater and suspended glacial flour sediment provide a selective fertilization effect in addition to blocking light required by autotrophs.⁵¹ While similarly-sized organic-rich particles are known to be colonized by bacteria in freshwater lakes,⁵² Sommaruga and Kandolf (2014) did not observe any glacial rock flour particles, which are not organic-rich, with attached bacteria during their study of a turbid pro-glacial lake.⁵³ Since particle-attached microbes could biotically weather the suspended particles to gain a fertilization effect, it follows that without microbial attachment, a any fertilization effect would be dominated by abiotic chemical dissolution of the glacial rock flour suspended in water.

Overall, the effect of glacial rock flour appears to be inhibitory to biomass accumulation in pro-glacial lakes. However, like glacier-fed streams, the ecology and biogeochemistry of these frequently impermanent lakes are understudied. As glaciers retreat completely, pro-glacial lakes that persist will clear as sediment settles out of the water column. In this long-term outlook, it is possible that wind-driven mixing could carry nutrients released from benthic glacial sediments throughout the water column with a fertilization effect; however, this has not been studied.

5.3 Fjords and marine ecosystems

Glacial rock flour can reach the marine environment and fjords through glacier-fed streams/rivers in the case of land-terminating glaciers or through direct deposition in the case of marine-terminating glaciers. Marine environments are distinguished from freshwater aquatic ecosystems by distinct physiochemical characteristics such as increased salinity which might alter the impact of glacial rock flour to the ecosystem. Silica and other nutrient sources like

ammonium and phosphorus associated to glacial rock flour may be more bioavailable in saline water compared to freshwater.⁵⁴

Opportunities for both wind-driven and buoyancy-driven upwellings exist at sites of glacial meltwater input to marine ecosystems from marine-terminating glaciers. As explained by Hawkings et al. (2021), the sediment-rich freshwater is more buoyant than surrounding saltwater which causes an upwelling of nutrient-rich marine water which mixes with the meltwater and makes its way to the euphotic zone.⁵⁵ High levels of nitrogen, phosphorous, and silica have been measured at such sites, supporting overall primary productivity in these areas through nutrient-delivery from marine-glacial sediment deposits.^{29,55-58} This increase in nutrients and support for primary productivity occurs despite localized areas where suspended glacial rock flour reduces light penetration and the activity of photoautotrophs in the marine water.

In contrast, input of glacial flour-rich meltwater from land-terminating glaciers into fjords and marine systems does not result in the same upwelling dynamic.^{59,60} These marine systems show lower primary productivity due to compromised light penetration and reduced opportunity for the upwelling of nutrient-rich deep waters.^{59,61} Greater stratification and reduced mixing have been observed at these sites.^{60,61} This difference further highlights the need to study the complex effects of glacial meltwater inputs on marine ecosystems on a case by case basis.⁶¹

Purely considering the fertilizing potential of glacial rock flour based on nutrient availabilities from the material without considering the natural dynamics that introduce it into a marine system provides some insight but will not capture the whole story. For example, Koffman et al. (2021) reported that glacial rock flour from Alaska was much higher in bioavailable iron than either volcanic ash or desert dust investigated in the study.⁶² The sediment could also provide higher quantities of metals essential for phytoplankton growth such as Co, Ni, Zn, Mo, and Cd, but also potentially toxic elements like Cu and Pb.⁶² Through a purely nutritive perspective, the glacial rock flour could be a fertilizing agent, but presence of this sediment in the marine ecosystem would also contribute potential biotoxins. Depending on the mechanism of entrance to the marine ecosystem (e.g. land or marine-terminating glacier), there could also be inhibitory effects on the phytoplankton community through alterations to light penetration in the euphotic zone which should be considered.

6. Wind transfer of glacial rock flour: supraglacial and marine impacts

Glacial rock flour can be light enough to be carried and deposited by wind. It is then considered glaciogenic loess. The material can enter oligotrophic ecosystems such as glacial surfaces or the ocean via this transport mechanism. In the case of the supraglacial ecosystem,

glacial rock flour deposition could contribute phosphorous or nitrogen to the habitat in the same way that general rock debris is known to.¹³ Meltwater from rock-covered glaciers are known to contain far more nitrogen than surface glaciers.⁶³ It is possible that the rock flour could similarly deliver inorganic nitrogen to the glacial surface. Deposition of glacial rock flour to the supraglacial environment could also encourage the formation of cryoconites which are known to form at sites with low-albedo due to dark debris presence and consist partly of mineral material.⁶⁴ Cryoconites are hotspots of supraglacial microbial activity, so biotic weathering forces would be applied to the glacial rock flour, potentially releasing nutrients. The contribution of this sediment size fraction to cryoconite fertilization has not yet been explored.

Wind transport of glacial rock flour to the open ocean is thought to contribute significant quantities of iron to certain oligotrophic marine ecosystems.^{21,65} For example, glacial dust transfer events deposit iron-containing glacial rock flour offshore in the Gulf of Alaska.^{20,21} The glacial flour fertilizes phytoplankton blooms which are Fe-limited in the subarctic marine ecosystem.^{20,21} This phenomenon has not been studied extensively, and deserves further attention, especially regarding fertilization with nutrients other than iron.

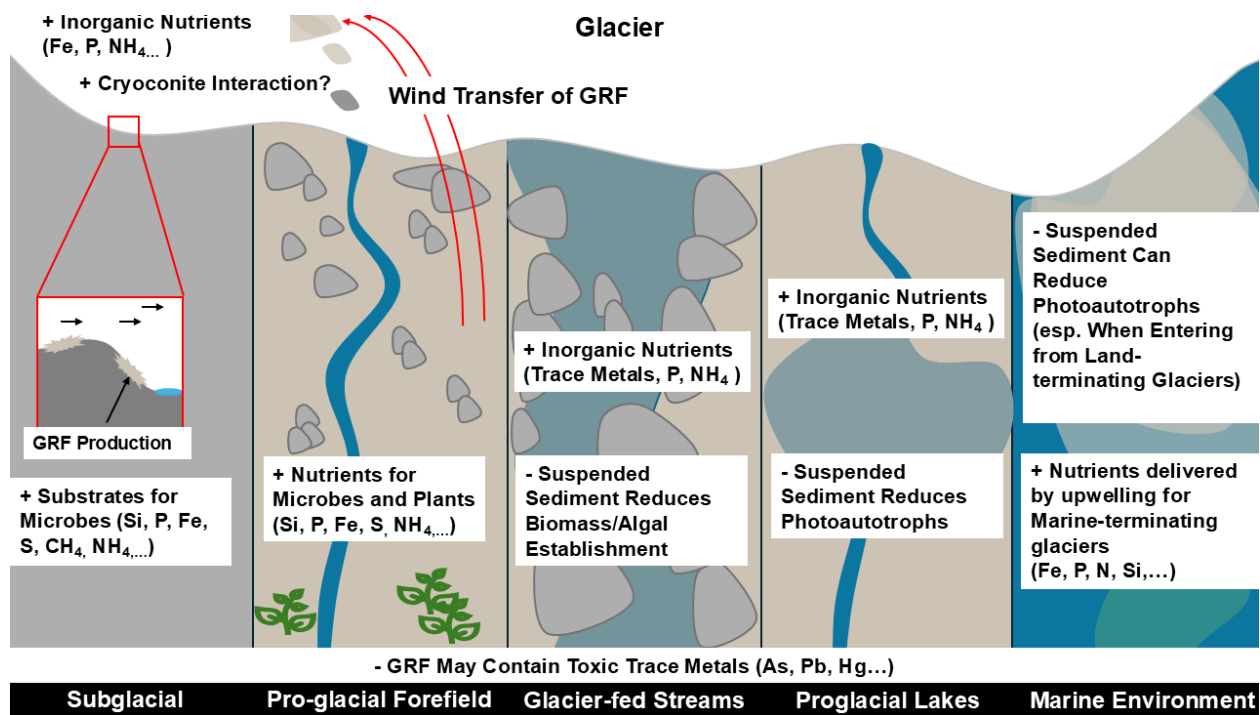


Figure 1. A summary of the potential positive (+) and negative (-) fertilizing actions of glacial rock flour (GRF) in different oligotrophic ecosystems.

7. Conclusions

Though glacial rock flour has been reported to contain several nutrients considered to be essential to plants and microorganisms, it cannot be considered as a fertilizer to all oligotrophic ecosystems in every case. In each oligotrophic ecosystem discussed, the potential that glacial rock flour contains biotoxic elements that could inhibit plant and microbial growth must be considered. While for terrestrial, subglacial, and supraglacial ecosystems, it is more likely that glacial rock flour can be considered a fertilizer, the effect in freshwater and marine aquatic ecosystems appears to be more nuanced. A multitude of variables shape glacial rock flour's effect on light-penetration through the water column in the case of these distinct aquatic ecosystems. However, the potential for glacial flour to inhibit primary production by photoautotrophs is the shared inhibitory effect that can prevent short-term fertilization of these ecosystems. The fertilization potential should also be considered on multiple temporal scales. While glacial rock flour may initially inhibit photoautotrophic activity, it may settle out of the water column with time and eventually contribute to benthic fertilization or nutrient-rich upwelling characteristics that support fertility.

Additional research on the oligotrophic ecosystems discussed and the effect of glacial rock flour on them over temporal and spatial scales will be necessary to make stronger conclusions about the fertilization potential of glacial rock flour.

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Palaeogeography, Palaeoclimatology, Palaeoecology. 1999/01/01/ 1999;145(1):61-77.
doi:[https://doi.org/10.1016/S0031-0182\(98\)00093-5](https://doi.org/10.1016/S0031-0182(98)00093-5)