COVER SHEET

What constitutes fine-scale geodiversity? Taxonomic geodiversity mapping across environmental gradients in a sub-Arctic mountain environment

Karjalainen, O.*[1], Maliniemi, T. [1], Riikonen, A.-M. [1], Salminen, H. [1] & Hjort, J. [1]

1 Geography Research Unit, University of Oulu, Pentti Kaiteran katu 1, FI-90100, Oulu, Finland

* Corresponding author: Olli Karjalainen (olli.karjalainen@oulu.fi)

ORCID: https://orcid.org/0000-0003-2429-4595

What constitutes fine-scale geodiversity? Taxonomic geodiversity mapping across environmental gradients in a sub-Arctic mountain environment

Karjalainen, O.[1], Maliniemi, T.[1], Riikonen, A.-M.[1], Salminen, H.[1] & Hjort, J.[1]

1 Geography Research Unit, University of Oulu, Pentti Kaiteran katu 1, FI-90100, Oulu, Finland

Abstract

The integration of geodiversity information, i.e., the diversity of abiotic features in the Earth surface and subsurface, into assessments of the sustainability and resilience of natural environments and ecosystems is increasingly considered important. However, geodiversity data is highly scale-dependent and there is an urgent need to find optimal ways on how geodiversity should be quantified and utilized. We use a recently proposed taxonomy of geodiversity framework to map geodiversity in a sub-Arctic environment in northern Finland characterized by a complex glacial footprint and diverse abiotic conditions. Field work was conducted at 193 study sites using 5- and 20-meter survey radii to map geofeatures, e.g., rock types, landforms, soils, hydrological, and topographical (geomorphons) elements at a very high thematic and spatial resolution. We additionally explored the spatial variability of geodiversity across cryogenic process activity, vegetation productivity, and climate gradients. Overall, 161 different geofeatures were recorded. Surveyed sites contained 15 geofeatures within 20 m radius, on average, while the most diverse sites hosted up to 28 different geofeatures. Individual components of geodiversity demonstrated distinct spatial patterns and relationship with environmental conditions underlining the multiple dimensions of geodiversity. Geofeature richness (georichness) increased most strongly along cryogenic activity gradient. Vegetation productivity had an overall negative association with georichness. Thematically detailed information on fine-scale geodiversity can improve our understanding of high-latitude geodiversity and further provide insights into the less studied aspects, such as functional geodiversity. The results also pave way for holistic geo- and biodiversity assessments, inform geoconservation efforts, and serve as a tool for identifying and monitoring environmental change and resilience.

Keywords: geodiversity, georichness, cryogenic processes, field mapping, statistical modelling

1 Introduction

Global climate change and environmental degradation have created an urgent need for novel approaches to support existing conservation strategies (Schrodt et al., 2019; Crisp et al., 2020). The development and utilization of new approaches, such as information on geodiversity, i.e., diversity of abiotic features in the Earth surface and subsurface (Gray, 2013), could be particularly useful in high-latitude ecosystems, which are among the most vulnerable environments to ongoing climate change. Geodiversity research, both as a field in its own, and as a framework for studying ecosystem services, environmental resilience, biogeochemical cycles and biodiversity, for example, has been gaining traction and recognition recently (Brilha et al., 2018; Tukiainen et al., 2025; Scammacca and Bétard 2026; Toivanen et al., 2026). However, an emerging paradigm requires more field-verified data (Alahuhta et al., 2020; Schrodt et al., 2024).

The fundamental challenge in diversity mapping is the need to categorize objects into classes that can be judged to be distinctive enough (Huston, 1994; Beierkuhnlein et al., 2025; Zwoliński et al., 2025). Varying definitions of geodiversity complicate mapping and analysis efforts, and holistic measures and monitoring schemes of local-scale geodiversity are yet to be developed (Serrano et al., 2007; Crisp et al., 2020; Record et al., 2020; Maliniemi et al., 2024; but see Hjort et al., 2022). The increased availability of spatially and temporally high-resolution remote sensing data has improved assessments of geodiversity locally (Schrodt et al., 2024), but important and more detailed aspects of geodiversity (e.g., geology, soils, and processes) fall beyond the abilities of remote sensing (Gray, 2021) and require field-based approaches. Holistic approach to field-based geodiversity mapping requires a lightweight and cost-effective methodology that is applicable over extensive areas with minimal instrumentation. Such design would enable producing data that can be used for improving the understanding of distribution and key constituents of geodiversity.

Recently, Scammacca and Bétard (2026) argued that geodiversity requires a hierarchical classification system that would enable specifically identifying which typologies are different and on what criteria. Hjort et al. (2024) proposed a hierarchical taxonomy of geodiversity in which geological (rocks, tectonics) geomorphological (landforms, Earth surface processes), pedological (soil pedons and materials) and hydrological (surface and subsurface water features) components of geodiversity are classified according to their genesis, physicochemical properties, and morphology. The approach was developed to address often-occurring categorical inconsistency in geodiversity data (Hjort et al., 2024; Scammacca and Betard, 2026), and to achieve a holistic geodiversity monitoring system. The system is also scalable, meaning that more detailed lower-level observations can be upscaled to higher levels of taxonomy.

In this study, we apply the geodiversity taxonomy (Hjort et al., 2024) in the field to produce thematically and spatially detailed data on surface and subsurface geofeatures in a sub-Arctic environment. Moreover, we examine the distributions of geodiversity components (geological, geomorphological, pedological, and hydrological) as well as topographical diversity spatially and along key environmental gradients. The considered gradients are cryogenic activity (cryoturbation and solifluction), remotely sensed vegetation productivity, and near-surface air temperature conditions. Analyzing the structuring of geodiversity along natural gradients enables assessing its site-scale association with environmental conditions (Fukami and Wardle, 2005; Tukiainen et al., 2017).

Cryogenic activity is considered to create and maintain fine-scale geodiversity through its effects on landforms and subsurface features. Increased environmental heterogeneity due to cryogenic landforms and processes at centimeter to landscape scales have been previously documented in permafrost environments without explicit geodiversity approach (e.g., Siewert et al., 2021; Kokelj et al., 2026). Vegetation productivity has been shown to reflect the environmental heterogeneity in high latitude regions at a landscape scale (Lara et al., 2018). We examine whether this relationship can be found at a local scale with fine-scale geodiversity data. In general, geodiversity should be lower with dense vegetation owing to the lack of surface manifestations of processes and materials, yet vegetation cover does not necessarily preclude high topographical or hydrological diversity, for example. Finally, both cryogenic activity and vegetation productivity are often strongly controlled by air temperature, which undergoes substantial variation along the elevation gradient. Here, we explore if air temperature poses additional explanatory power for geodiversity in the study area.

Our specific goals are to:

1) conduct and evaluate the applicability of holistic geodiversity mapping at fine taxonomic and spatial detail across an extensive and diverse sub-Arctic environment,

2) explore the spatial distribution of geodiversity and its components, and

3) relate spatial patterns of geodiversity and its components to environmental gradients.

Achieving these goals could promote the usage of hierarchical geodiversity data in monitoring and conserving natural diversity. The focus in this study is on exploring novel geodiversity data, but outcomes can be highly useful also for assessments of environmental resilience (Toivanen et al., 2026), ecosystem services (Brilha et al., 2018), and biodiversity-geodiversity connection (e.g., Bailey et al., 2017; Gakou et al., 2026).

2 Data and methods

2.1 Study area

The study area is located in northwestern Finland at around 69th latitude. Climate is sub-Arctic with an annual average air temperature of -1.4 °C at Kilpisjärvi meteorological station (1991–2010; 482 m a.s.l., Jokinen et al., 2021). The studied mountains were formed when the Caledonian cover pushed over the older Archaean bedrock around 400–500 Ma ago (Fig. 1; Lehtovaara, 1995). The overthrust fault consists of sedimentary and metamorphic rocks, such as shale, schist, dolomite, and arkose quartzite, which is the topmost, hard layer at the ground surface on the fells. The Archaean base is 2.7–2.8 Ga old and mostly gneissose granodiorites (Lehtovaara, 1995). The study area was glaciated during the last Pleistocene glaciations. During the last glaciation, the area located in interlobate region north of the Central Lapland ice divide area. The movement of advancing glaciation was around S-N and SE-NW (Johansson, 2007; Ahokangas et al., 2021). Large-scale erosion is visible on the mountain sides of glacially scoured U-valleys. Soil in the sub-Arctic parts of Europe is young and shows low (e.g., Regosols) to moderate (e.g., Podzols) evidence of soil profile development (Marion et al., 1997).

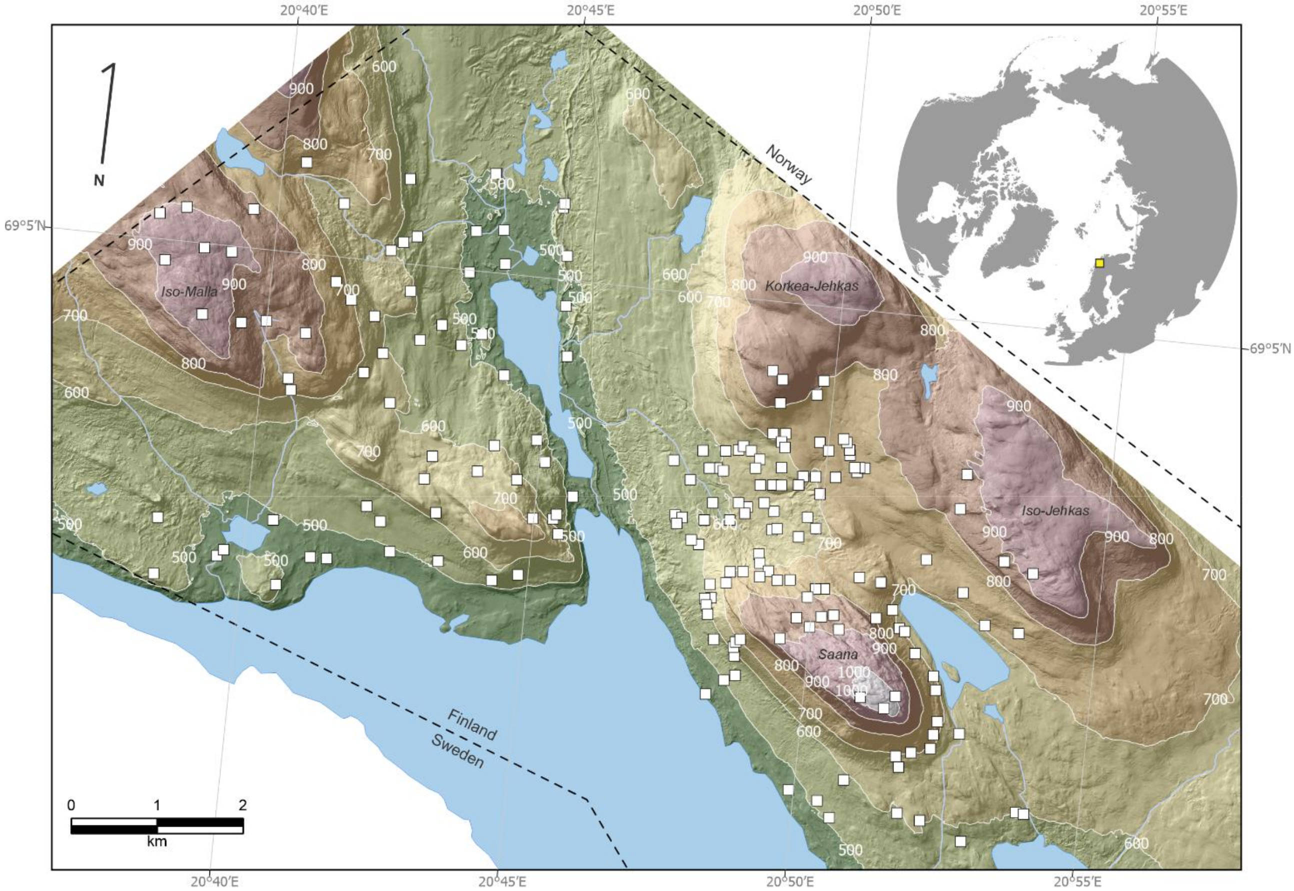

Figure 1. Study area and the sites visited denoted with white squares. The inset index map shows the position of the study area within the Arctic. Background map shows hillshade with elevation contours (National Land Survey of Finland, 2025).

2.2 Geodiversity mapping

Geodiversity mapping was conducted in July–August 2025. The number of different elements of geodiversity, or *geofeatures*, was summarized within 5 and 20 meters from the site center (Hjort et al., 2022; Salminen et al., 2023). We conducted geodiversity mapping at established study locations with abundant pre-existing ecological and geomorphological data. The sites were originally selected to cover a wide range of geomorphological, topographical, vegetation, snow, microclimate and hydrological conditions (see Kemppinen et al., 2021; Peña-Aguilera et al., 2023; Niittynen et al., 2024).

The taxonomy (Hjort et al., 2024) encompasses six levels, of which level 1 is the broadest and equals geodiversity *components*, i.e., geological, geomorphological, pedological and hydrological components (Gray, 2013; Vernham et al., 2023). The field mapping was conducted at level 5 of taxonomy (*geofeatures*; Table 1). Geofeatures at this level, e.g., rock fall, drumlin, or turbulent running water, are indicators of processes, not the processes themselves (Bradbury, 2014; Hjort et al., 2024). Topographic diversity was mapped as an additional component of geodiversity by utilizing geomorphological phonotypes, or geomorphons (Jasiewicz and Stepinski, 2013; Tukiainen et al., 2024).

Table 1. Examples of the taxonomy system for the four main components of geodiversity.

Level 1	**Level 2**	**Level 3**	**Level 4**	**Level 5**	**Level 6**
Component	Geofeature class	Geofeature group	Geofeature subgroup	Geofeature	Geofeature subtypes
Geological	Rocks	Igneous	Intrusive	Granite	Subtypes based on chemical properties OR Identification of mineral species
Geomorphological	Exogenic features	Deposition	Glacigenic	Hummocky moraine	Subtypes of landforms and processes
Pedological	Mineral	Characteristic Fe/Al chemistry	Podzols	Entic Podzol	Based on supplementary qualifiers
Hydrological	Surface water	Running water	Ephemeral	Braided	Subdivision based on physical properties

The total sum of geofeatures per site, *georichness*, in the results section omits rock types that were mapped at level 4 of taxonomy. Their inclusion would inflate geofeature count at sites with visible rocks on ground surface at the expense of sites with continuous vegetation or peat cover. Georichness is computed in two ways; 1) including the mapped geomorphons (Georichness) and 2) using only the four components (Georichness2; Table 1). Field mapping was supplemented with 1-m digital elevation model (DEM) based on laser altimetry data (National Land Survey of Finland, 2025). Fine-resolution DEMs can help in identifying certain low relief (macro)forms, such as glacial flutings or proglacial deposits, that are indiscernible in the field. In the following subsections, the methods to identify geofeatures in the field are presented.

2.2.1 Geological component

Geological diversity refers to the multitude of consolidated (rocks) and unconsolidated (sediments) materials (Gray, 2013). At the most detailed level, this refers to the rocks and their component minerals (Hjort et al., 2024). We made observations at level 4 to record *geofeature subgroups* (e.g., intrusive igneous rocks, or clastic sedimentary rocks). We also recorded earth materials based on their granulometry and sortedness; adequately thick (>1–2 cm) layers of sorted silt or sand were observed as separate geofeatures from unsorted glacial till (Fig. 2). Gravel, stones and boulders were also considered as geofeatures whenever they formed a conspicuous, continuous cover larger than 1–2 m^2 (Hjort et al., 2024). Peat was classified based on its field-estimated stage of decomposition (fibric, hemic, or sapric) and nutrient level (oligotrophic, mesotrophic, or eutrophic) whenever thicker than 10–20 cm (Fig. 2d). Decomposition stage was determined manually based on a peat sample from hand-held probe; fibric peat was considered to contain intact fibre, hemic to be partially decomposed, and in sapric no to miniscule amount of plant structure can be identified. Nutrient levels were evaluated based on surrounding vegetation and environmental setting, which in the study area give good indications of soil fertility.

Figure 2. Examples of geological (a–f) and geomorphological (g–l) components of geodiversity. Earth surface materials are represented by layers of stones (a), till (b), boulders (c), and peat (d). Panels e and f show examples of rock types. Glacigenic erosion forms include roches moutonnées (g), and glaciofluvial meltwater channel (h), and depositional landforms are represented by lateral moraine deposit on the slope of a fell (i). Cryogenic landforms include nivation hollow with late-lying snow and vegetation-covered solifluction lobe in non-sorted material (j) and earth hummocks in cryoturbated soil (k). Physical weathering is visible as frost cracking in shale (l). Photographs by Olli Karjalainen

2.2.2 Geomorphological component

Geomorphological component encompasses a large variety of erosional and depositional landforms formed through either glacial, fluvial, littoral, weathering, organic, or cryogenic processes. Glacial till covers most of the area, although on mountain tops the soil is thin or absent. The signs of glacial and glaciofluvial erosion are visible as polished and oriented bedrock surface and meltwater channels, respectively, in the region (Fig. 2g–h). The surficial sediments and glacial deposits are inherited from the latest deglaciation period ca. 11,000 years BP. Glacigenic hummocky, ribbed and lateral moraines are prevalent at lower altitudes (Fig. 2i). A single larger esker system runs from S to N on the valley bottom between Malla and Jehkas mountains (Fig. 1). In addition, coarse sandurs, small deltas, floodplain deposits and slushflow accumulations, e.g., in Skirhasjohka valley (Clark and Seppälä, 1988), characterize the geomorphological landscape.

Surface soil in the study area is strongly affected by seasonal frost (le Roux et al., 2013). Cryogenic conditions promote periglacial process activity; cryoturbation, solifluction, and nivation. Cryoturbation refers to mixing of soil material due to cyclic freezing and thawing of soils, and manifests in a multitude of cryogenic geofeatures, such as patterned ground, frost boils, or earth hummocks (Bockheim and Tarnocai, 1998; Hjort, 2006; Fig. 2k). The term solifluction refers to a suite of slow mass wasting processes, which in periglacial conditions are markedly affected by soil freezing and thawing and subsequent changes in pore pressure and viscosity in soil material (Matsuoka, 2001). Frost activity has a pronounced effect on geo- and biodiversity through its influence on soils, topography, and the accumulation and decomposition of organic matter (e.g., Becher et al., 2018; Siewert et al., 2021; Svetlin et al., 2026). Characteristic geofeatures related to slow mass wasting include rock- or turf-banked solifluction lobes, stone stripes, and ploughing boulders (Fig. 2j). Snow is an integral part of sub-Arctic ecology (Rixen et al., 2022) and landscape development (Christiansen 1998; Mitchell et al., 2023). In this study, we observed the erosional geofeatures associated with late-lying snow and involved nivation processes, which promote erosional and transportational activity (Fig. 2j).

Physical and chemical weathering can create geofeatures from the microscale (cracks or solution on rock surfaces) to the macroscale (boulder fields). We mapped physical weathering caused by frost and exfoliation, and chemical weathering caused by hydrolysis, carbonation and oxidation, and microbial weathering caused by lichens and bryophytes (Fig. 2l). In field conditions, it is often difficult to determine the degree to which rock is weathered by physical processes relative to chemical weathering, and, for example in tundra environments, physical weathering due to frost or high winds can remove the signs of chemical weathering on coarse-grained rocks (Birkeland, 1999). Three types of mapped chemical weathering were combined into a single level-4 chemical weathering class.

2.2.3 Pedological component

Pedological diversity refers to the number or variability of different soil types, properties and horizon development in an area (Ibánez and Brevik, 2022; Schillaci et al., 2026). Soil mapping and classification in Fennoscandia has predominantly focused on agricultural and forest lands and very scarce surveying has been conducted in sub-Arctic areas. Hence, standardized approaches to classifying sub-Arctic soils are not well developed. In this study, soil classification was based on the most recent version of the World Reference Base (WRB) soil classification system (IUSS Working Group WRB, 2022). To localize the WRB classification, we applied Finnish Soil Database methodology (Lilja et al., 2017) and research from similar locations in sub-Arctic Finland (Holtmeier et al., 2003; Płaczkowska et al., 2023) and Norway (Stutter et al., 2025). According to Finnish Soil Database, Podzols, Leptosols, and Histosols are the most common soils in the area (Lilja et al., 2017). In addition, the few local field studies have observed Gleysols at partly water-logged valley bottoms (Holtmeier et al., 2003) and at nivation sites (Płaczkowska et al., 2022). Our aim was to use a classification scheme that complies with prior methodologies and is applicable across the range of soil conditions in the study region.

There are slight differences between the WRB and Finnish systems. For example, a less pronounced B-horizon in podzolized soils is required for the soil to be classified as a Podzol because the layer is commonly lighter in color in northern environments (Lilja et al., 2017). Moreover, we further localized the classification by extending Regosol (with varying principal qualifiers) to encompass glacial till terrain with dominantly silty texture, whenever no podzolization or cambic horizons, or other dominant soil-forming structures (e.g., fluvial depositions or peat accumulation) were developed. Holtmeier et al. (2003) also observed Regosols on sparsely vegetated convex slopes in the study area. Arenosol class was limited to locations with pronounced deposition of fine to coarse sand sediments (e.g., glaciofluvial deposits).

Large parts of the study area in the Kilpisjärvi region are legally protected from extractive activities or off-trail access. Soil classification was therefore done using a hand-held soil probe to minimize disturbance. Undisruptive soil probing was limited to 1 m depth, and no soil pits were excavated (but see Fig. 3*a*–b for pre-existing cut profiles). In the absence of soil pits or laboratory analyses, we applied a conservative classification scheme, in which only one principal qualifier was assigned to each soil group. These qualifiers described the thickness (e.g., *leptic, lithic*), grain size (e.g., *siltic*, *arenic*), stoniness (e.g, *skeletic*, *hyperskeletic*), and visible horizontal development (e.g, *entic*, *cambic*) of the soils. In most conditions, these properties could be determined with reasonably confidence in field conditions based on probing of the soil and the material captured in the sampling groove.

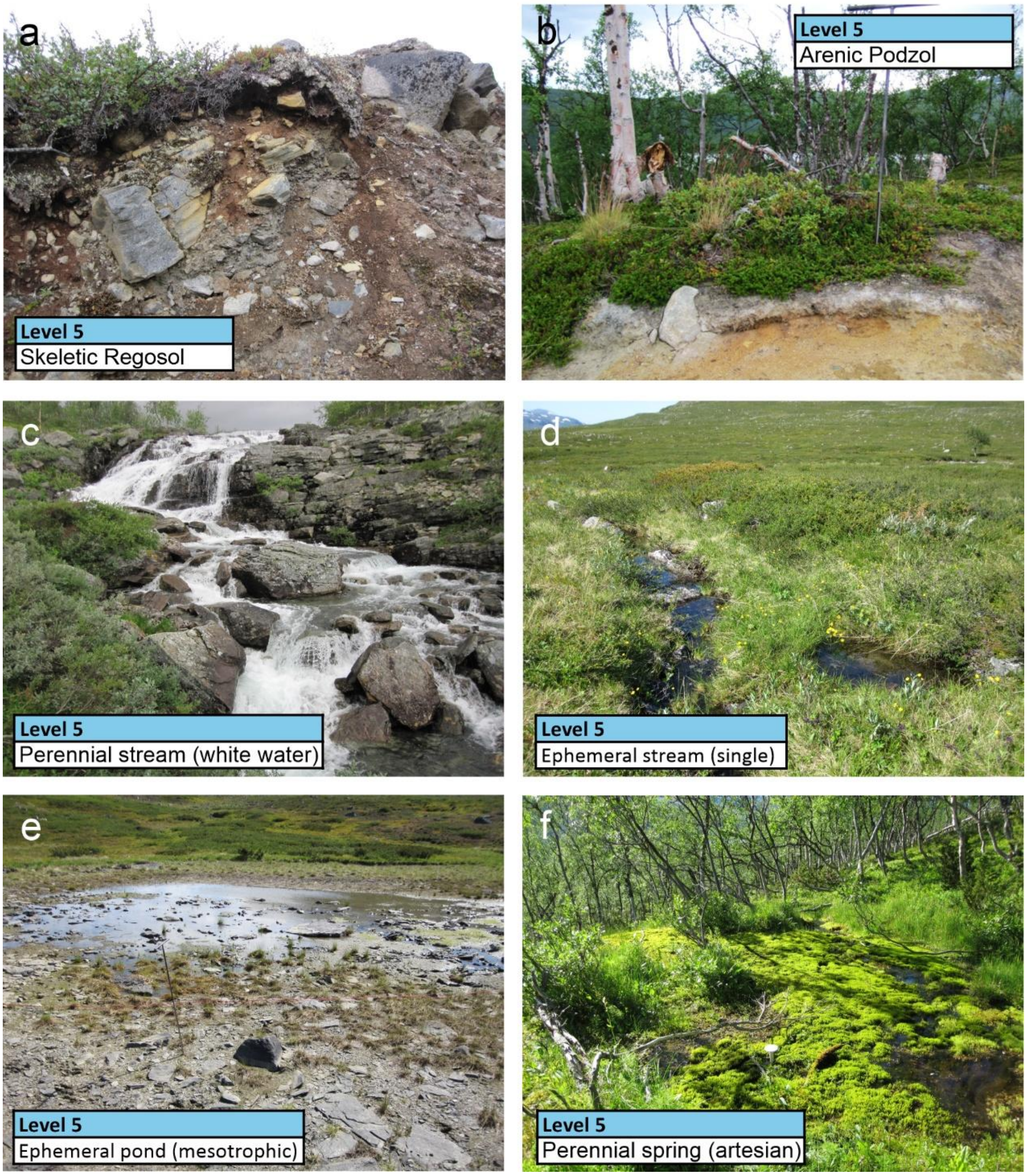

Figure 3. Examples of pedological (a–b) and hydrological (c–f) components of geodiversity. Excavations show typical profiles in a hummocky moraine with silty skeletic Regosol (a) and kame deposits with arenic Podzol (b). Examples of perennial and ephemeral surface water features are perennial running water of white-water flow type (c), ephemeral single-channel running water (d) and mesotrophic standing water (e). Panel f depicts a perennial spring with artesian type of groundwater recharge. Photographs by Olli Karjalainen

2.2.4 Hydrological component

The occurrence and properties of standing and running water features and springs were assessed to classify hydrological geofeatures. Running water features could be large (Fig. 3c) or small (Fig. 3d) in size, but different in their stream types or seasonality. The perennial or ephemeral state of water features was assessed visually at the field based on vegetation or lichen coverage, or signs of fluvial erosion and deposition. We also assessed flow types of running water (Fig. 3), which affect the erosion and deposition potential (Makaske, 2001) and have been used as a geodiversity proxy (Kärnä et al., 2018). Standing water features were classified based on their estimated trophic state to either oligotrophic, mesotrophic or eutrophic based on the color of water and the amount of aquatic vegetation. No water samples were collected, so the classification is indicative and relevant only when comparing the relative trophic state within the study region. Springs were classified based on the recharge mechanism of groundwater to either seepage, stream, pool, artesian, and underground (Hjort et al., 2024, Fig. 3f). Groundwater aquifers were categorized to level 4 of taxonomy owing to unavailability of technical data on area's aquifers or soil properties. Eskers in Finland are usually unconfined aquifers (Rossi et al., 2012).

2.2.5 Topographical component

Topographical diversity was assessed based on the number of geomorphons (e.g., slope or hollow; Jasiewicz and Stepinski, 2013) mapped in the field within 5 and 20 m radii of site center. To achieve comparable level of detail with the level 5 geofeatures in other components, we assigned each geomorphon an additional qualifier describing direction, shape, or relative position of the feature (e.g., north slope, U-shape hollow, spur on slope; Fig. 4). Geomorphons allow for recording fine-scale topographical variations that would not fall within any distinct geomorphological landform. However, to be qualified as a geomorphon in the field, the length and area of a shoulder or footslope, for example, had to exceed 2–3 meters (see Tukiainen et al., 2024). Otherwise, the site would be assigned with the geomorphon flat (with the qualifier; in valley, on slope, or on summit; Fig. 4). The same site can simultaneously contain flat and more rugged geomorphons.

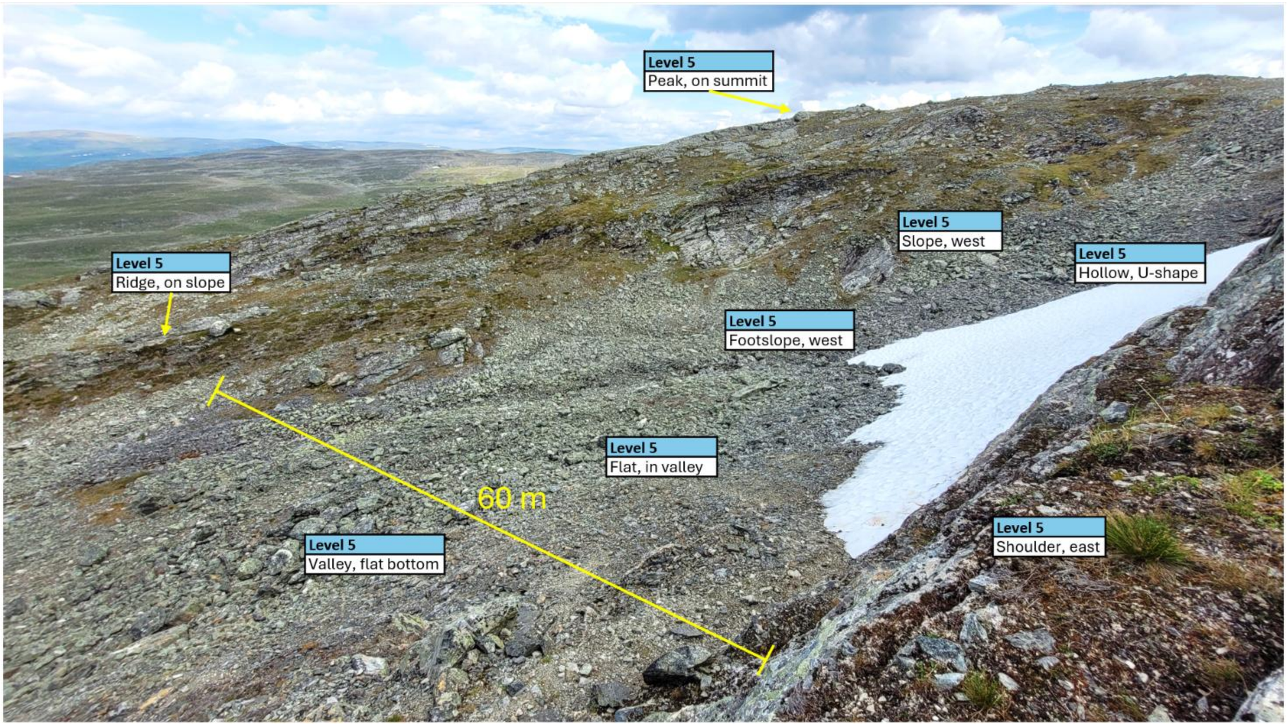

Figure 4. Several geomorphons indicated in a high-elevation landscape with one qualifier characterizing the direction, shape, or relative position of the feature. The photograph (Olli Karjalainen) was taken on the Saana massif, near Kilpisjärvi, July 25th, 2025.

2.3 Statistical analyses

We investigated geodiversity variation along environmental gradients to assess the contributing factors of geodiversity and determine optimal conditions for different components of geodiversity. The percentage cover of active solifluction and cryoturbation processes was estimated inside a 10 by 10-meter area in the field during the geodiversity mapping. The presence of active processes was determined based on microforms (such as, lobes, streams, patterned ground), frost-related vertical and horizontal surface movements indicated by exposed bare ground, sorting of surface soil materials, and occurrence of cryptogamic crust (Hjort and Luoto 2009; Klaus et al., 2013; Rouyet et al., 2021). For the final variable, the coverages of each process were summarized and log-transformed due to strong right skewness.

Normalized difference vegetation index (NDVI) is often used to represent vegetation productivity at multiple scales (e.g., Lara et al., 2018). We computed the median July 2025 NDVI from six cloud-free Sentinel-2 scenes. NDVI reflects the amount of green vegetation and ranges from -1 (no vegetation) to 1 (maximum vegetation greenness). Mean annual air surface temperature (MAAT) at 20 cm above ground surface was computed from a 3-m raster prediction layer produced for the study area using microclimate loggers (Niittynen et al., 2024). For the 20 m radius analyses, both NDVI and MAAT values were averaged over a buffer of 20 m to match geodiversity measurements. We additionally computed the independent contributions of the three gradients to georichness. Here, we used hierarchical partitioning (HP) using *rdacca.hp* package in R (Lai et al., 2022; version 1.1-1).

3 Results

3.1 Spatial distribution of georichness

Across the study sites, 149 different geofeatures were mapped at 5 m radius and 161 at 20 m radius (Table 2; Table S1). The number of unique geofeatures at each site, i.e., georichness, was highly site-specific and showed notable spatial variability (Fig. 5). The most frequent geofeatures per site were either geological or geomorphological but also topographical geofeatures were prevalent, especially at 20 m radius (Fig. 5e; Table 2). Some of the geofeatures were almost ubiquitous (e.g., glacial till, overthrust fault; Table 2; Fig. S1–5), whereas some were only observed at a single site. The correlations among the five geodiversity components were all positive and 0.5 or lower (Fig. S6). The strongest correlations occurred between geological, geomorphological and pedological components. Hydrological geofeatures had the lowest albeit statistically significant (p-value <0.05) correlation with other components. Correlations with georichness were the same or slightly higher for each component at 20-m radius, which contained a higher number of geofeatures, but a more notable rise was found in case of topographical component from 0.64 to 0.73 (Fig. S6). However, when geomorphons were not included in the overall geodiversity count, the respective correlations dropped to 0.39 and 0.44 (Fig. S6).

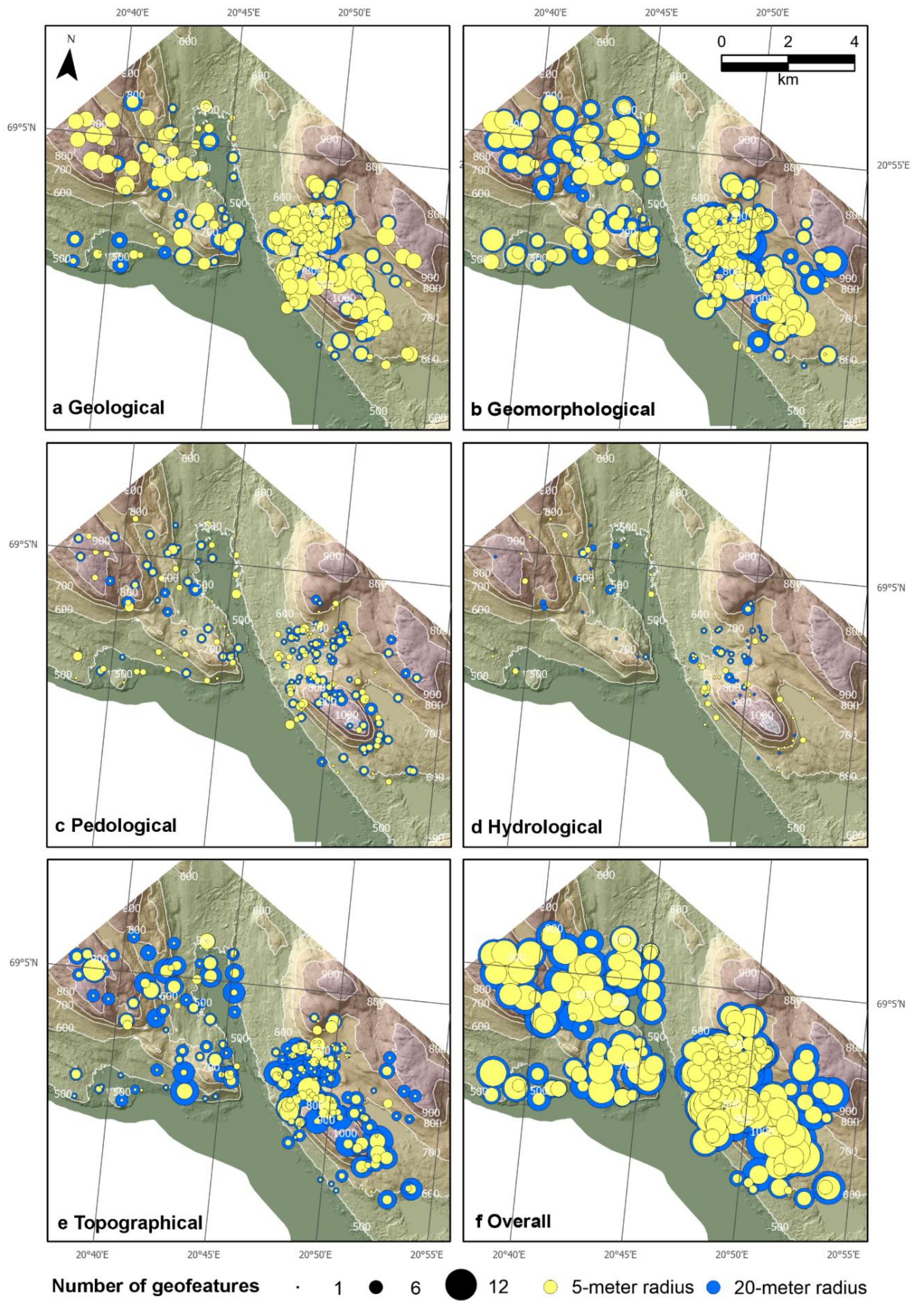

Figure 5. Mapped total georichness by components; geological (a), geomorphological (b), pedological (c), hydrological (d), topographical (e), and sum of the components, i.e., overall geodiversity (f). Blue symbols show the number of geofeatures within a 20-meter radius, yellow within 5 meters. No symbol is shown if no geofeature is present.

Table 2. Statistics for the mapped geofeatures and associated environmental conditions.

N. of sites 193	Geofeatures: mean (range)		Unique geofeatures across all sites		Most common geofeature, N.	
Radius (m)	**5**	**20**	**5**	**20**	**5**	**20**
Geological	2.2 (1-5)	2.7 (1-6)	15	15	Till, 170	Till, 176
Geomorphological	4.0 (0-8)	5.4 (0-10)	52	54	Overthrust fault, 180	Overthrust fault, 180
Pedological	1.6 (1-4)	2.3 (1-4)	37	39	Regosol (skeletic), 38	Podzol (haplic), 46
Hydrological	0.4 (0-3)	0.8 (0-4)	19	22	Stream (turbulent), 21	Stream (turbulent), 40
Topographical	2.2 (1-7)	4.1 (1-10)	26	31	Slope (west), 47	Slope (south), 68
Overall	10.5 (3-24)	15.2 (4-28)	149	161	Overthrust fault, 180	Overthrust fault, 180

On average, highest geodiversity occurred at sites above 900 m a.s.l. with 14 geofeatures at minimum, while the lowest elevations had the lowest median geodiversity (Fig. 5). However, some of the most diverse individual sites at lower elevations scored higher georichness than any sites at high elevations. The most diverse site was situated at an elevation of ~650 m a.s.l. Moreso, one site simultaneously had one of the lowest elevations (486 m a.s.l.) and one of the highest geodiversity (5-m radius = 18, 20-m radius = 27) owing to locally elevated topographical position on hummocky moraine with specific topography and soil materials, as well as active cryoturbation and deflation features.

High geological diversity was associated with disturbed locations, such as sites with streambeds and subsequently diverse soil materials, whereas few geofeatures were documented at sites where peat or till, for example, was the only geological feature (Fig. 6a). Most diverse sites by geomorphology were commonly characterized by the occurrence of geofeatures related to indicators of weathering and cryogenic processes, and least diverse sites by their absence (Fig. 6b). Pedological diversity peaked at sites where thin (Leptosols) and thicker soils (e.g., Regosols) co-occurred, whereas boulder fields or peatlands, for example, typically consisted of a single pedon (Fig. 6c). Complex spring sites including seepage, pooled water, and running water accounted for most hydrological diversity (Fig. 6d). Finally, sites containing prominent hillocks (e.g., lateral moraine, Fig. 6e) or hollows exhibited most topographical diversity owing to multidirectional slopes, shoulder, or footslopes among other geomorphons (Fig. 6e).

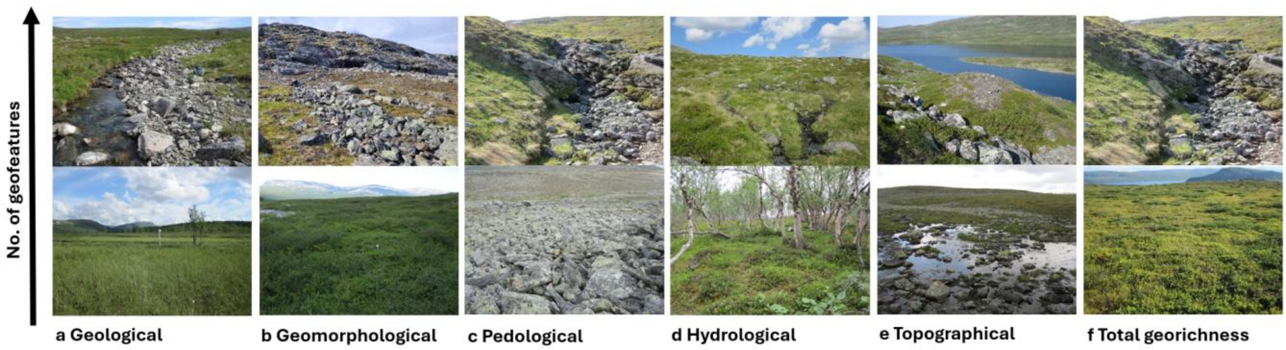

Figure 6. Example sites with maximal (upper photo) and minimal (lower) mapped geofeature number at 20 m radius. Photographs by Olli Karjalainen

The relatively slowly rising accumulation curves showed that new geofeatures were encountered across the range of sites indicating high between-site variation in geofeature composition (Fig. S7). While stabilization was visible toward the maximum number of sites, the curve was not fully saturated, indicating that additional, currently unmapped geofeatures would likely be detected with further sampling.

3.2 Geodiversity along environmental gradients

Quantification of geodiversity components along environmental gradients indicated a mostly positive association with cryogenic activity and a negative trend with NDVI (Fig. 7). Of the individual components, cryogenic activity (average over all sites 11.0 m^2, range 0 – 100 m^2) was most closely reflected in geomorphological and geological diversity at 5-m radius. NDVI (average 0.65, range -0.08–0.89) similarly showed the strongest association with the geomorphological component, indicating that diverse geomorphology was found with sparse vegetation, which in turn was partly due to disturbance by cryogenic activity (Fig. 7, Fig. S8–9). MAAT (average 1.07 °C, range -1.3–2.2°C) had a weaker association with georichness, although a clear negative trend with geomorphological and a positive trend with hydrological diversity were found (Fig. 7). The relationships between site-scale geodiversity and NDVI and MAAT were similar at both radii. However, pedological and geomorphological diversity had somewhat stronger associations at 20-m, whereas the geological component exhibited higher R^2 values at 5-m radius.

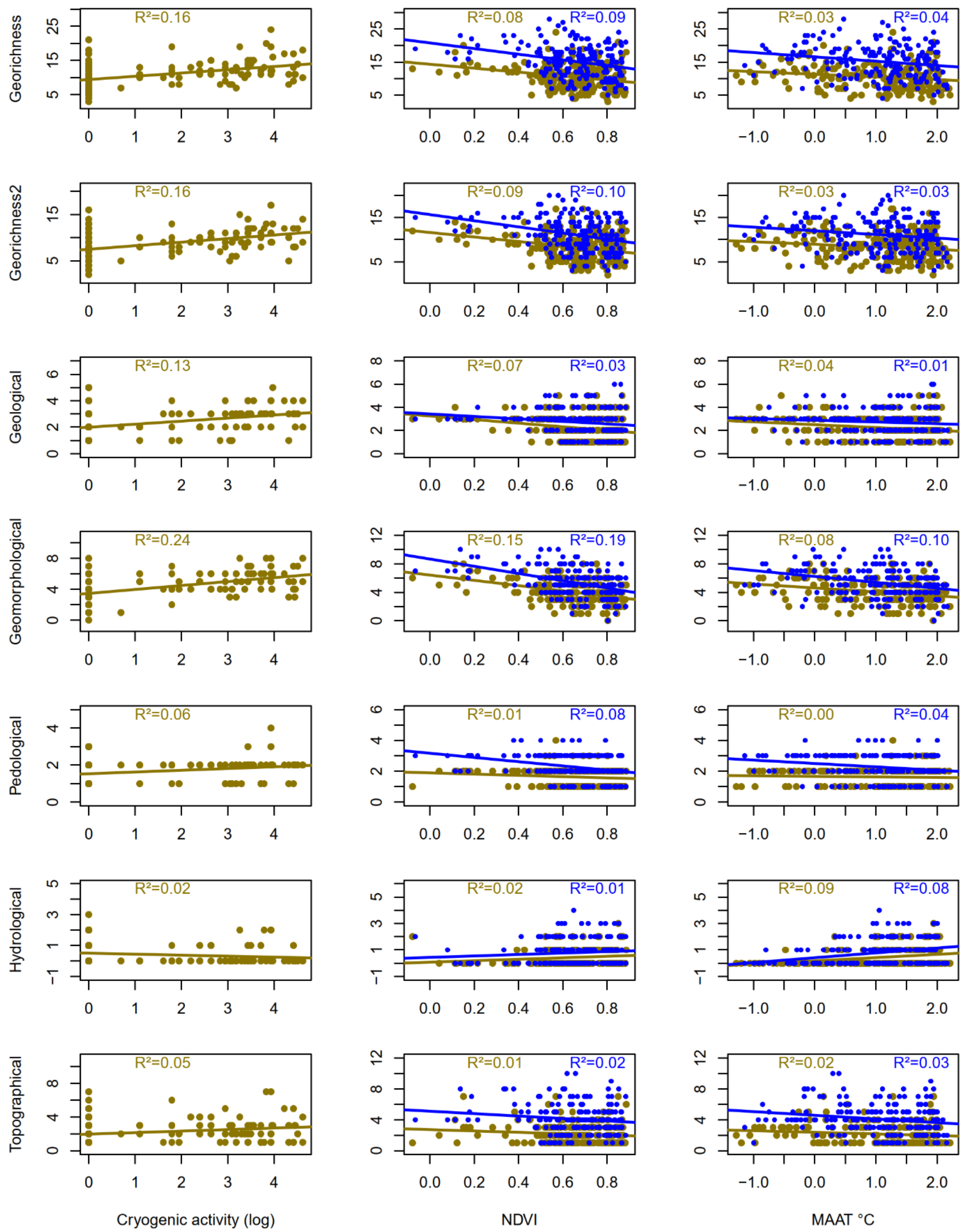

Figure 7. Relationship of georichness at 5 m (gold) and 20 m radius (blue) by geodiversity components and environmental gradients. The connection between cryogenic activity and geodiversity was not assessed at 20-m radius, as activity measurements at 10x10 m plots were not representative of the larger area. Trend lines show linear fits and coefficients of determination R^2. NDVI stands for normalized difference vegetation index and MAAT for mean annual air temperature. Georichness is the geofeature sum including geomorphons and Georichness2 without geomorphons.

Hierarchical partitioning indicated that cryogenic activity exerted the highest individual importance for all geodiversity components except hydrological diversity (Fig. S10). NDVI exerted a moderate and similar importance with MAAT for each component apart from hydrological with which MAAT's contribution stood out. Under these warmer and more hydrologically diverse conditions cryogenic activity played a minimal role. Apart from the small contribution of cryogenic activity, explored gradients exerted limited importance for topographical diversity.

4 Discussion

4.1 Applicability of geodiversity taxonomy in the field

We used the taxonomy of geodiversity (Hjort et al., 2024) for the first time in field conditions to evaluate its applicability in geodiversity data production. Moreover, we investigated how such novel data can be used to quantify the spatial distribution and environmental context of local geodiversity. The high number of mapped unique geofeatures was expected against the established level of detail in the geodiversity taxonomy but also attributed to the region's complex, polygenetic relief. The substantial variation in geofeature composition between study sites also translated into high spatial variability. Based solely on maps of georichness distribution, clear spatial patterns or regional trends were not evident. However, by quantifying georichness along key environmental gradients, we were able to find theoretically robust trends and provide new insights into what constitutes fine-scale geodiversity.

Results suggest that a hierarchical mapping system offers a number of new opportunities for geodiversity research. First, the systematic taxonomy classification scheme can help in reducing subjectivity and ambiguity related to assigning abiotic conditions to components of geodiversity. Second, mapping at lower levels of taxonomy enables identifying potentially hundreds of geofeatures, which serves the purpose of distinguishing subtle spatial differences in georichness and recognizing geoenvironments. Involved Earth surface and subsurface processes affect the functionality of geosystems and hence ecological conditions, such as biodiversity (Becher et al., 2018; Kemppinen et al., 2022). Thus, thirdly, spatially and environmentally comprehensive datasets could benefit, e.g., biodiversity, environmental resilience, and ecosystem service assessments across broad gradients by facilitating more informed conservation and land-use management.

4.2 Geodiversity in sub-Arctic context

Among the studied environmental gradients, the strongest association with georichness was found along the cryogenic activity gradient. This underlines the local importance of cryogenic processes for geodiversification in the sub-Arctic context, i.e., development or diversification of geodiversity through time due to active processes (Stojilkovic and Gray, 2024). We argue that quantifying the contribution of cryogenic activity via geodiversity offers a way to assess its current and potential future roles as a part of creating and maintaining natural diversity. Indeed, cryogenic activity gradient is not independent from MAAT and NDVI gradients, which also affect cryogenic activity and are mutually strongly correlated (Fig. S8–9). Vegetation has a two-way effect on cryogenic activity by both restricting active processes and being subject to disturbance by them (Kemppinen et al., 2022; Eichel et al., 2023). The contribution of MAAT should be understood through its interconnectedness with the former two and other unaddressed gradients (e.g., snow persistence), and not as direct, even though a positive connection with hydrological and negative with geomorphological diversity was found (Fig. 7).

Hierarchical partitioning further stressed the individual and central role of cryogenic activity (Fig. S10). Part of the connection derives from the autocorrelation with the assessed overall geodiversity scores. That is, cryogenic activity creates features that are counted as geomorphological geofeatures. However, cryogenic gradient also was the most important for several geodiversity components not including cryogenic features. All this suggests that cryogenic processes play a role in creating and maintaining diverse abiotic conditions in periglacial areas. Process-level association comes from cryogenic activity creating differentiation in soil surface material and landforms as well as in near-surface layers, as previously shown in permafrost conditions (Bockheim and Tarnocai, 1998; Siewert et al., 2021). In the field, elevated pedological diversity is also evident in patchy soil profiles owing to frost activity and cryogenic landforms, such as turbid soils or boulder fields (e.g. Ping et al., 2008).

The negative relationship of NDVI with georichness was expected and reflects more prominent surface manifestations of Earth surface processes and soil materials when vegetation cover is sparse or absent. To reduce the potential bias owing to this, rock types were excluded from georichness sums, as they could be determined only when rocks were visible. In completely vegetation-covered conditions, georichness was lower, on average (Fig. 7, Fig. S8–9), but underwent a substantial range. For example, sites with an NDVI of up to 0.8 hosted more than 20 geofeatures even within 5-meter radius (Fig. 7). In such cases, georichness was attributed to abundant hydrological geofeatures and associated fluvial erosion and deposition, as well as topographical heterogeneity. Moreover, most sparsely vegetated sites, or those cryogenically active, did not consistently score top georichness, which instead occurred at sites with intermediate disturbance albeit with substantial variation. This finding is compatible with the known ecological hypothesis of intermediate disturbance (Connell, 1978; Salminen et al., 2025), stating that intermediate disturbance creates highest biodiversity.

The variable contributions of geodiversity components to total georichness and the role of previously often overlooked subsurface diversity (pedodiversity) suggest that holistic approaches pose potential to further the understanding and applications of site-scale geodiversity and biodiversity data (Gakou et al., 2026). Results show that while relatively few soil pedons were found at individual sites (Table 2), they underwent complex spatial variability. Indeed, pedological associations along the environmental gradients were weak, which suggested that site-scale soil profile differentiation is due to other factors. Globally, the interaction of climate-controlled vegetation productivity and weathering are largely controlling soil diversity (Ibáñez et al., 1998; Amundson et al., 2015). In cold conditions, both those processes are relatively slow, and thus geological and geomorphological conditions, including cryogenic activity (e.g., soil mixing and organic carbon sequestration due to cryoturbation), are argued to be of considerable importance (Siewert et al., 2021; Fig. 7).

In this study, geomorphons were mapped in the field to assess their contribution to overall geodiversity. Being able to reasonably derive geodiversity data solely from topographic features, also derivable using high-resolution remote sensing data, would allow a highly cost-efficient method for geodiversity and ecological research (Record et al., 2020). Topography should be considered a proxy because topographical variability is not naturally separable from the classical components of geodiversity as defined by Gray (2013), for example. Rather, topographical variability is integrated in landform assemblages and soil development, and as such a relevant and widely used proxy for geodiversity (Vernham et al., 2023).

As topographical diversity is primarily generated by macroscale processes such as plate tectonics and glacial cycles (Stojilkovic and Gray, 2024), it was expected to show weaker association with the environmental gradients examined in this study (Fig. 7; Fig. S10). However, cryogenic activity exerted a small contribution, likely because some periglacial landforms (e.g., large solifluction lobes) can create site-scale topographical variation. Previously, Hjort and Luoto (2010) used a grid-based approach to show that at landscape scale geodiversity is associated with complex topographies. At the mesoscale, no significant correlation was found by Salminen et al. (2023). The moderate correlations of the topographical component with the four geodiversity components separately and combined (Fig. S6), suggested that field-verified, fine-scale topographical data can serve as a limited, but not negligible, indirect indicator of holistic site-scale geodiversity (see Bailey et al., 2017). Field-quantified data can be useful in biodiversity studies via topographic influence on soil moisture and microclimate (Kemppinen et al., 2021; Tukiainen et al., 2025).

4.3 Limitations

Key limitations to the mapping system and interpretability of the results relate to the field identification of certain geofeatures at matching levels of taxonomy and avoiding double counting of geofeatures under one or more components of geodiversity. For example, soil pedons are ideally determined using excavated soil profiles to examine soil horizons and color properties, and often soil samples are collected for laboratory tests (Birkeland, 1999). Auger-based sampling is used as a more applicable method over diverse areas (Schillaci et al., 2026). In this study, material sampled in the soil probe groove did not usually enable the identification of crossbedding in fluvial sediments or signs of mottling in reducing conditions. This is why *stagnic* properties involving the determination of *reductimorphic* and *oximorphic* features due to fluctuating reducing conditions (IUSS Working Group WRB, 2022) were not assigned to the soils in this study.

Sites affected by (semi-)permanent groundwater saturation (i.e., springs, and sites with visible greyish blue layers) were interpreted to be Gleysols or assigned with the *gleyic* qualifier owing to interpreted reducing conditions due to groundwater saturation. Groundwater aquifer properties themselves are a complex interplay of geological and geomorphological history that form impermeable soil layers and water conduction conditions (Rossi et al., 2012). Due to the lack of groundwater level or soil stratigraphy data, we did not attempt to classify groundwater types apart from identifying the sites on the Siilasjärvi groundwater recharge area (the esker system between Iso-Malla and Korkea-Jehkas, Fig. 1; Finnish Environmental Institute, 2021). In future, it should be studied how the applied soil classification could be used as a proxy for, or in union, with continuous characteristics of soils, such as thickness of the entire soil profile or separate layers, and associated diversity (see Vernham et al., 2023) to support, e.g., biogeochemical, environmental resilience or biodiversity research (see Brilha et al., 2018; Tukiainen et al., 2024; Toivanen et al., 2026).

Importantly, geodiversity mapping requires a field methodology that is applicable over large areas without extensive instrumentation or measurement equipment (e.g., Hjort et al., 2022). Relatively high levels of expertise will be required, however, if the purpose is to operate at the lowest levels of taxonomy, e.g., to identify rocks and minerals or chemical water properties at levels 5 or 6 of taxonomy. In addition, the use of lower taxonomic levels requires a relatively high number of study sites to characterize the entire variation in geofeatures across the study area (see Salminen et al., 2025). In this study, the multitude of mapped geofeatures delayed the saturation of accumulation curve (Fig. S7), indicating that additional sampling could be needed to approach a clear asymptote. Both factors increase the time and financial resources required for field work, which can hinder cost-efficiency. However, the current dataset was collected entirely by a singly investigator during approximately 20 field days, which is a moderate amount of work compared to typical geographical or ecological field campaigns. Moreover, the hierarchical nature of the taxonomy enables scaling and comparisons between datasets at higher levels of taxonomy (Scammacca and Betard, 2026), even if the finer scale is lost in the process. The optimal resolution or taxonomy level of geodiversity data remains to be established and determined by the purpose of data use.

Finally, any geodiversity mapping should carefully consider what is considered as double counting of geofeatures to avoid inflating geodiversity scores. For example, hydrological elements are potentially assigned with several geofeatures; stream type (e.g., turbulent), fluvial erosion (e.g., cut bank, rocky pediments), and deposition (e.g., sand bar). However, each of these indicates different processes that affect landscape development and create microtopographical and ecological conditions. As such, assigned geofeatures represent the diversity of the location. To refine and further evaluate here applied taxonomy, it will next need to be tested in different morphoclimatic conditions.

5 Conclusions

This study presented a novel approach to map and quantify fine-scale geodiversity in a sub-Arctic landscape using a taxonomy system for geodiversity. The field work demonstrated that detailed taxonomic data on geodiversity can be produced relatively cost-effectively across extensive areas. However, we also recognized that a few geofeature groups will require relatively high expertise or additional instrumentation to be identified at the lowest levels of taxonomy. The field data revealed highly variable spatial distribution of geofeature richness across the diverse sub-Arctic region. Moreover, geodiversity components demonstrated distinct spatial patterns and relationships with environmental conditions highlighting the many dimensions of geodiversity. The observed variation in site-scale georichness was strongly positively associated with cryogenic activity gradient and negative association with increasing vegetation productivity. Geofeatures associated with running water, cryogenic processes, organic accumulation, and weathering were found to be key contributors of elevated site-scale geodiversity. Such processes also have important socio-ecological implications through carbon emissions as well as sediment and nutrient output to rivers.

Going further, identification of geoenvironments formed by geofeature assemblages could be utilized to address the need to describe functional geodiversity and thereby narrow the gap between scientific knowledge and socio-ecological functioning of geodiversity. Moreover, quantitative and qualitative assessments of individual geofeatures and processes should be pursued to understand and evaluate functional contributions of geodiversity to biodiversity, ecosystem services, and environmental resilience. The current approach is argued to provide crucial information to improve the understanding of distribution and key constituents of geodiversity and as such to help to highlight environments that pose scientific, conservational, or educational potential.

Acknowledgments

We thank Kilpisjärvi Biological Station for excellent facilities during the field work.

Declaration of conflicting interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding statement

OK, A-MR and JH acknowledge funding from the Kvantum Institute, University of Oulu. TM and HS acknowledge funding from the Research Council of Finland (grant number: 370154).

Ethical approval and informed consent statements

All necessary research permits to move and work in study areas with protected status were acquired from Metsähallitus (Finnish Forest Administration).

Data availability statement

Data will be made openly available in Zenodo upon publication.

References

Ahokangas E, Ojala AEK, Tuunainen A, et al. (2021) The distribution of glacial meltwater routes and associated murtoo fields in Finland. *Geomorphology* 389: 107854. https://doi.org/10.1016/j.geomorph.2021.107854

Alahuhta J, Toivanen M and Hjort J (2020) Geodiversity-biodiversity relationship needs more empirical evidence. *Nature Ecology & Evolution* 4: 2-3. https://doi.org/10.1038/s41559-019-1051-7

Amundson R, Berhe AA, Hopmans JW, et al. (2015) Soil and human security in the 21st century. Science 348: 1261071. https://doi.org/10.1126/science.1261071

Bailey JJ, Boyd DS, Hjort J, et al. (2017) Modelling native and alien vascular plant species richness: At which scales is geodiversity most relevant? *Global Ecology and Biogeography* 26: 763-776. https://doi.org/10.1111/geb.12574

Becher M, Olofsson J, Berglund L, et al. (2018) Decreased cryogenic disturbance: One of the potential mechanisms behind the vegetation change in the Arctic. *Polar Biology* 41: 101-110. https://doi.org/10.1007/s00300-017-2173-5

Beierkuhnlein C, Pugh B, Justice S, et al. (2025) Towards a comprehensive geodiversity-biodiversity nexus in terrestrial ecosystems. *Earth-Science Reviews* 264: 105075. https://doi.org/10.1016/j.earscirev.2025.105075

Birkeland PW (1999) *Soils and Geomorphology*. 3rd ed. New York: Oxford University Press.

Bockheim JG and Tarnocai C (1998) Recognition of cryoturbation for classifying permafrost-affected soils. *Geoderma* 81: 281-293. https://doi.org/10.1016/S0016-7061(97)00115-8

Bradbury J (2014) A keyed classification of natural geodiversity for land management and nature conservation purposes. *Proceedings of the Geologists' Association* 125: 329-349. https://doi.org/10.1016/j.pgeola.2014.03.006

Brilha J, Gray M, Pereira DI, et al. (2018) Geodiversity: An integrative review as a contribution to the sustainable management of the whole of nature. *Environmental Science & Policy* 86: 19-28. https://doi.org/10.1016/j.envsci.2018.05.001

Christiansen HH (1998) Nivation forms and processes in unconsolidated sediments, NE Greenland. *Earth Surface Processes and Landforms* 23: 751-760.

Clark MJ and Seppälä M (1988) Slushflows in a subarctic environment, Kilpisjärvi, Finnish Lapland. *Arctic and Alpine Research* 20(1): 97-105. https://doi.org/10.2307/1551702

Crisp JRA, Ellison JC and Fischer A (2020) Current trends and future directions in quantitative geodiversity assessment. *Progress in Physical Geography: Earth and Environment* 45(4): 514-540. https://doi.org/10.1177/0309133320967219

Eichel J, Stoffel, M, and Wipf S (2023) Go or grow? Feedbacks between moving slopes and shifting plants in high mountain environments. *Progress in Physical Geography: Earth and Environment* 47(6): 967-985. https://doi.org/10.1177/03091333231193844

Finnish Environmental Institute (2021). Groundwater Bodies [geospatial dataset]. Finnish Environment Institute. https://ckan.ymparisto.fi/dataset/pohjavesialueet

Fukami T and Wardle DA (2005) Long-term ecological dynamics: Reciprocal insights from natural and anthropogenic gradients. *Proceedings of the Royal Society B* 272: 2105-2115. https://doi.org/10.1098/rspb.2005.3277

Gakou M, Souhil T, Barragan-Jason G, et al. (2026). Unveiling the spatial link between geodiversity and biodiversity: a multi-taxon study in the South of France. *Landscape Ecology* 41, 81. https://doi.org/10.1007/s10980-026-02330-1

Gray M (2013) *Geodiversity: Valuing and Conserving Abiotic Nature*. Chichester: Wiley-Blackwell.

Gray M (2021) Geodiversity: A significant, multi-faceted and evolving geoscientific paradigm rather than a redundant term. *Proceedings of the Geologists' Association* 132: 605-619. https://doi.org/10.1016/j.pgeola.2021.09.001

Hjort, J. (2006). *Environmental factors affecting the occurrence of periglacial landforms in Finnish Lapland: a numerical approach*. 149 p. Shaker Verlag GmbH, Aachen

Hjort J and Luoto M (2009) Interaction of geomorphic and ecologic features across altitudinal zones in a subarctic landscape. *Geomorphology* 112: 324-333. https://doi.org/10.1016/j.geomorph.2009.06.019

Hjort J and Luoto M (2010) Geodiversity of high-latitude landscapes in northern Finland. *Geomorphology* 115: 109-116. https://doi.org/10.1016/j.geomorph.2009.09.039

Hjort J, Tukiainen H, Salminen H, et al. (2022). A methodological guide to observe local-scale geodiversity for biodiversity research and management. *Journal of Applied Ecology*, 59, 1756–1768. https://doi.org/10.1111/1365-2664.14183

Hjort J, Seijmonsbergen AC, Kemppinen J, et al. (2024) Towards a taxonomy of geodiversity. *Philosophical Transactions of the Royal Society A* 382: 20230060. https://doi.org/10.1098/rsta.2023.0060

Holtmeier F-K, Broll G, Müterthies A, et al. (2003) Regeneration of trees in the treeline ecotone: Northern Finnish Lapland. *Fennia* 181: 103-128.

Huston MA (1994) *Biological Diversity: The Coexistence of Species on Changing Landscapes.* Cambridge: Cambridge University Press.

Ibáñez JJ, De-Alba S, Lobo A, et al. (1998) Pedodiversity and global soil patterns at coarse scales (with discussion). *Geoderma* 83: 171-192.

IUSS Working Group WRB (2022) *World Reference Base for Soil Resources: International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*. 4th ed. Vienna: International Union of Soil Sciences (IUSS).

Jasiewicz J and Stepinski TF (2013) Geomorphons: A pattern recognition approach to classification and mapping of landforms. *Geomorphology* 182: 147-156. https://doi.org/10.1016/j.geomorph.2012.11.005

Johansson P (2007) Late Weichselian deglaciation in Finnish Lapland. *Geological Survey of Finland, Special Paper* 46: 47-54.

Jokinen P, Pirinen P, Kaukoranta J-P, et al. (2021) Climatological and oceanographic statistics of Finland 1991-2020. Finnish Meteorological Institute Reports 2021:8. https://doi.org/10.35614/isbn.9789523361485

Kemppinen J, Niittynen P, Riihimäki H, et al. (2021) Modelling soil moisture in a high-latitude landscape using LiDAR and soil data. *Earth Surface Processes and Landforms* 43: 1019–1031. https://doi.org/10.1002/esp.4301

Kemppinen J, Niittynen P, Happonen K, et al. (2022) Geomorphological processes shape plant community traits in the Arctic. *Global Ecology and Biogeography* 31: 1381-1398. https://doi.org/10.1111/geb.13512

Klaus M, Becher M and Klaminder J (2013) Cryogenic soil activity along bioclimatic gradients in northern Sweden: Insights from eight different proxies. *Permafrost and Periglacial Processes* 24: 210-223. https://doi.org/10.1002/ppp.1778

Kokelj SV, Wolfe SA, Weiss N, et al. (2026) Permafrost landsystems define regional variability in climate change effects on northern environments. *Nature Communications* 17: 4799. https://doi.org/10.1038/s41467-026-71216-2

Kärnä O-M, Heino J, Grönroos M, et al. (2018) The added value of geodiversity indices in explaining variation of stream macroinvertebrate diversity. *Ecological Indicators* 94: 420-429. https://doi.org/10.1016/j.ecolind.2018.06.034

Lai J, Zou Y, Zhang J, et al. (2022) Generalizing hierarchical and variation partitioning in multiple regression and canonical analyses using the rdacca.hp R package. *Methods in Ecology and Evolution* 13: 782-788. https://doi.org/10.1111/2041-210X.13800

Lara MJ, Nitze I, Grosse G, et al. (2018) Reduced arctic tundra productivity linked with landform and climate change interactions. *Scientific Reports* 8: 2345. https://doi.org/10.1038/s41598-018-20692-8

le Roux PC, Virtanen R and Luoto M (2013) Geomorphological disturbance is necessary for predicting fine-scale species distributions. *Ecography* 36: 800-808. https://doi.org/10.1111/j.1600-0587.2012.07922.x

Lehtovaara JJ (1995) Kilpisjärven ja Haltin kartta-alueiden kallioperä. Suomen geologinen kartta 1:100 000, kallioperäkarttojen selitykset, lehdet 1832 ja 1842. Espoo: Geologian tutkimuskeskus.

Lilja H, Uusitalo R, Yli-Halla M, et al. (2017) Suomen maannostietokanta: Käyttöopas. Luonnonvara- ja biotalouden tutkimus 6/2017.

Makaske B (2001) Anastomosing rivers: A review of their classification, origin and sedimentary products. *Earth-Science Reviews* 53: 149-196. https://doi.org/10.1016/S0012-8252(00)00038-6

Maliniemi T, Tukiainen H, Hjort J, et al. (2024) Too much diversity—Multiple definitions of geodiversity hinder its potential in biodiversity research. *Diversity and Distributions* 30: e13843. https://doi.org/10.1111/ddi.13843

Marion GM, Bockheim JG and Brown J (1997) Arctic soils and the ITEX experiment. *Global Change Biology* 3: 33-43.

Matsuoka N (2001) Solifluction rates, processes and landforms: A global review. *Earth-Science Reviews* 55: 107-134. https://doi.org/10.1016/S0012-8252(01)00057-5

Mitchell RJ, Nelson FE and Nyland KE (2023) Little tools, big job: The periglacial conveyor system in cryoplanated uplands. *Permafrost and Periglacial Processes* 34: 384-398. https://doi.org/10.1002/ppp.2193

National Land Survey of Finland (2025) Laser scanning data 0.5 p. Acquired: August 28th 2025. https://www.maanmittauslaitos.fi/en/maps-and-spatial-data/datasets-and-interfaces/product-descriptions/laser-scanning-data-05-p

Niittynen P, Salminen H, Peña-Aguilera P, et al. (2024) A gridded microclimate dataset from a sub-Arctic biodiversity hotspot in Finland. bioRxiv 2024.03.30.587419. https://doi.org/10.1101/2024.03.30.587419

Peña-Aguilera P, Schmidt NM, Stewart L, et al. (2023) Consistent imprints of elevation, soil temperature and moisture on plant and arthropod communities across two subarctic landscapes. *Insect Conservation and Diversity* 16(5), 684-700 https://doi.org/10.1111/icad.12667

Ping CL, Michaelson GJ, Kimble JM, et al. (2008) Cryogenesis and soil formation along a bioclimate gradient in Arctic North America. Journal of Geophysical Research: *Biogeosciences* 113: G03S12. https://doi.org/10.1029/2008JG000744

Płaczkowska E, Wasak-Sęk K, Żelazny M, et al. (2023) Headwater chemistry in subarctic areas with different plant communities (Finnish Lapland). *Episodes* 46: 239-257. https://doi.org/10.18814/epiiugs/2022/022026

Record S, Dahlin KM, Zarnetske, PL, et al. (2020) Remote sensing of geodiversity as a link to biodiversity. In: Cavender-Bares J, Gamon JA and Townsend PA (eds) *Remote Sensing of Plant Biodiversity*. Cham: Springer, pp. 163-188. https://doi.org/10.1007/978-3-030-33157-3_10

Rixen C, Høye TT, Macek P, et al. (2022) Winters are changing: Snow effects on Arctic and alpine tundra ecosystems. *Arctic Science* 8(3): 572-608. https://doi.org/10.1139/as-2020-0058

Rossi PM, Ala-aho P, Ronkanen A-K, et al. (2012) Groundwater-surface water interaction between an esker aquifer and a drained fen. *Journal of Hydrology* 432-433: 52-60. https://doi.org/10.1016/j.jhydrol.2012.02.026

Rouyet L, Karjalainen O, Niittynen P, et al. (2021) Environmental controls of InSAR-based periglacial ground dynamics in a sub-Arctic landscape. *Journal of Geophysical Research: Earth Surface* 128: e2021JF006175. https://doi.org/10.1029/2021JF006175

Salminen H, Tukiainen H, Alahuhta J et al. (2023) Assessing the relation between geodiversity and species richness in mountain heaths and tundra landscapes. *Landscape Ecology* 38: 2227-2240. https://doi.org/10.1007/s10980-023-01702-1

Salminen H, Huusko K, Tukiainen H, et al. (2025) The effects of land use on fine-scale geodiversity: Ski resorts as an example. *Science of the Total Environment* 988: 179830. https://doi.org/10.1016/j.scitotenv.2025.179830

Scammacca O and Bétard F (2026) The multiple dimensions of geodiversity. *Communications Sustainability* 1: 15. https://doi.org/10.1038/s44458-025-00017-3

Schillaci C, Alves GB, Bayad M et al. (2026) Soil profiles: A window into soil genesis and degradation. *European Journal of Soil Science* 77: e70322. https://doi.org/10.1111/ejss.70322

Schrodt F, Bailey JJ, Kissling WD, et al. (2019) To advance sustainable stewardship, we must document not only biodiversity but geodiversity. *Proceedings of the National Academy of Sciences of the United States of America* 116(33): 16155-16158. https://doi.org/10.1073/pnas.1911799116

Schrodt F, Vernham G, Bailey J, et al. (2024) The status and future of essential geodiversity variables. *Philosophical Transactions of the Royal Society A* 382: 20230052. https://doi.org/10.1098/rsta.2023.0052

Serrano E and Ruiz-Flaño P (2007) Geodiversity: A theoretical and applied concept. *Geographica Helvetica* 62: 140-147. https://doi.org/10.5194/gh-62-140-2007

Siewert MB, Lantuit H, Richter A, et al. (2021) Permafrost causes unique fine-scale spatial variability across tundra soils. *Global Biogeochemical Cycles* 35: e2020GB006659. https://doi.org/10.1029/2020GB006659

Stojilković B and Gray M (2024) Geodiversification: The evolution of geodiversity through time. *Geoheritage* 16: 91. https://doi.org/10.1007/s12371-024-00987-1

Stutter M, Jackson-Blake L, McGovern, M et al. (2025) Riparian soils inform dissolved organic matter delivery in a Norwegian subarctic river. *European Journal of Soil Science* 76(5): e70185. https://doi.org/10.1111/ejss.70185

Svetlin D, Ogrin M and Kermavnar J (2026) Frost hollows as interesting areas of geo- and biodiversity in the Alps. In: Zorn M, Pelcer-Vujačić O and Mikša P (eds) *Discourses on Mountains of Montenegro and Slovenia*. *Historical Geography and Geosciences*. Cham: Springer. https://doi.org/10.1007/978-3-031-99017-5_28

Toivanen M, Santos D and Räsänen A (2026) Geodiversity and resilience: A scoping review. *Ambio*. https://doi.org/10.1007/s13280-026-02409-8

Tukiainen H, Alahuhta J, Field R, et al. (2017) Spatial relationship between biodiversity and geodiversity across a gradient of land-use intensity in high-latitude landscapes. *Landscape Ecology* 32: 1049-1063. https://doi.org/10.1007/s10980-017-0508-9

Tukiainen H, Maliniemi T, Brilha J, et al. (2024) A framework for quantifying geodiversity at the local scale: A case study from the Rokua UNESCO Global Geopark. *Philosophical Transactions of the Royal Society A* 382: 20230059. https://doi.org/10.1098/rsta.2023.0059

Tukiainen H, Bailey JJ and Hjort J (2025) Geodiversity and biodiversity linkages in theory and practice for nature conservation. In: Reynard E and Brilha J (eds) *Geoheritage*. 2nd ed. Amsterdam: Elsevier, pp. 73-94. https://doi.org/10.1016/B978-0-443-28997-2.00013-3

Vernham G, Bailey JJ, Chase J, et al. (2023) Understanding trait diversity: The role of geodiversity. *Trends in Ecology & Evolution* 38: 736-748. https://doi.org/10.1016/j.tree.2023.02.010

Zwoliński Z, Najwer A and Giardino M (2025) Methods for assessing geodiversity. In: Reynard E and Brilha J (eds) *Geoheritage*. 2nd ed. Amsterdam: Elsevier, pp. 31-57. https://doi.org/10.1016/B978-0-443-28997-2.00024-8

Supplementary material

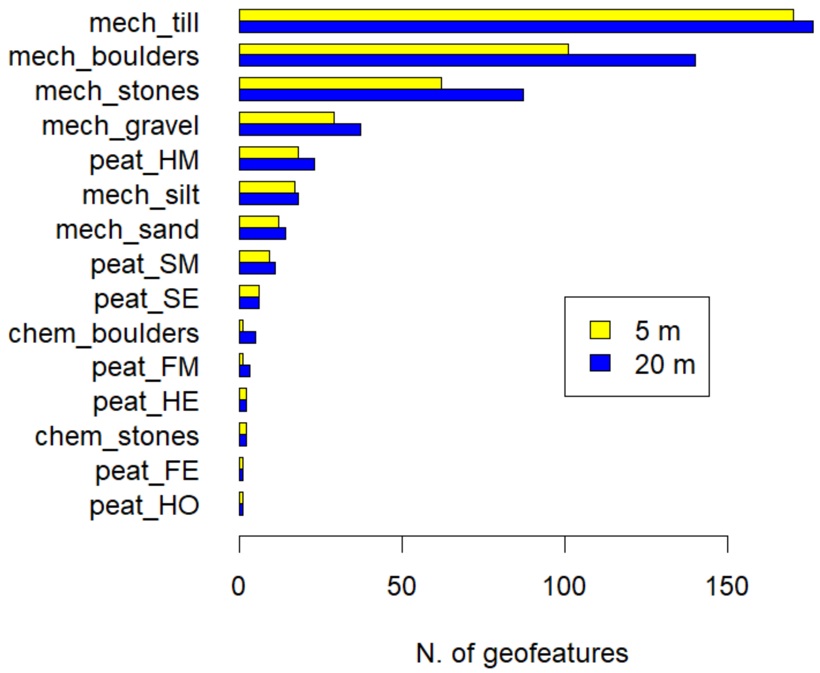

Figure S1. Geological geofeatures mapped at 193 sites.

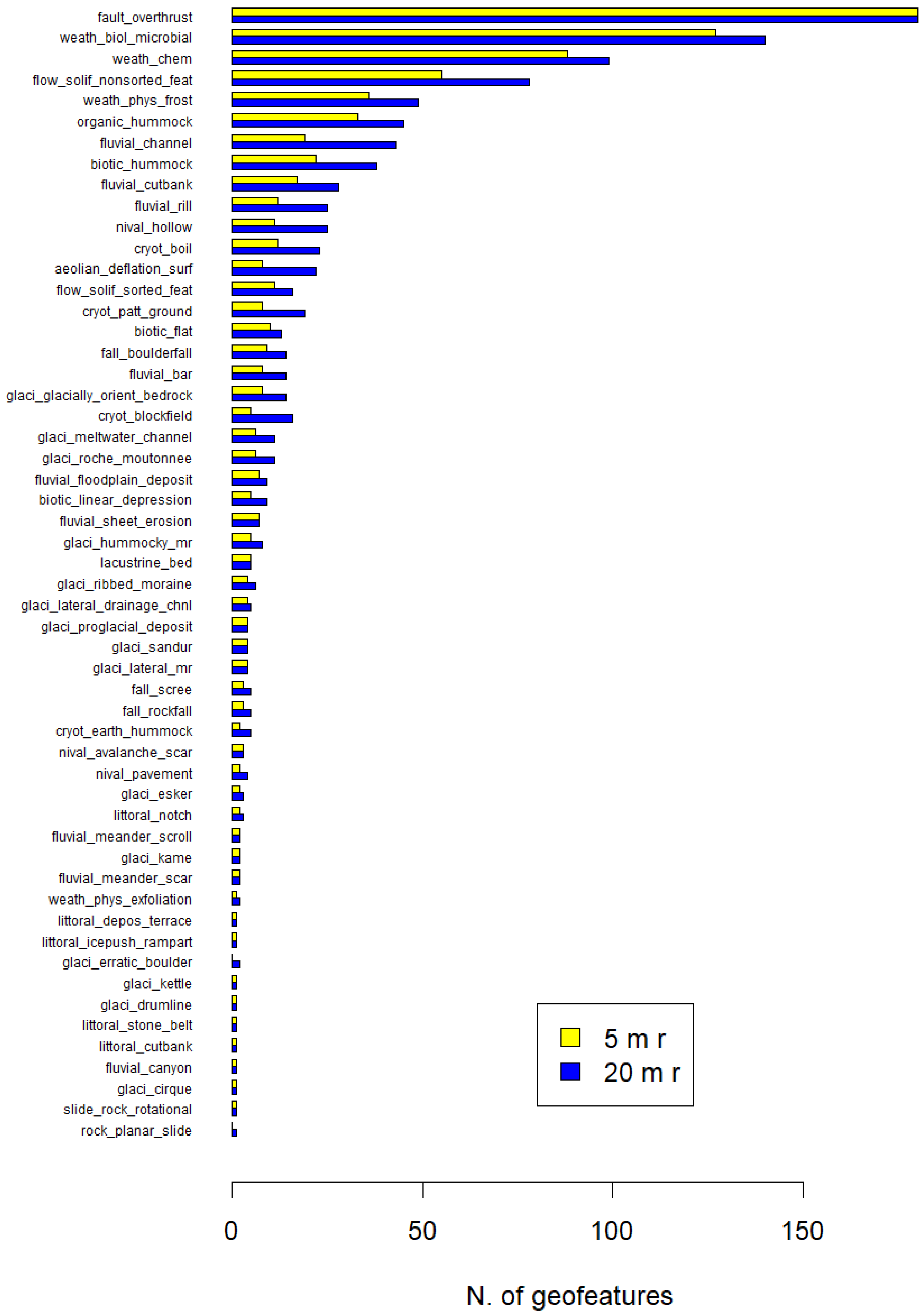

Figure S2. Geomorphological geofeatures mapped at 193 sites.

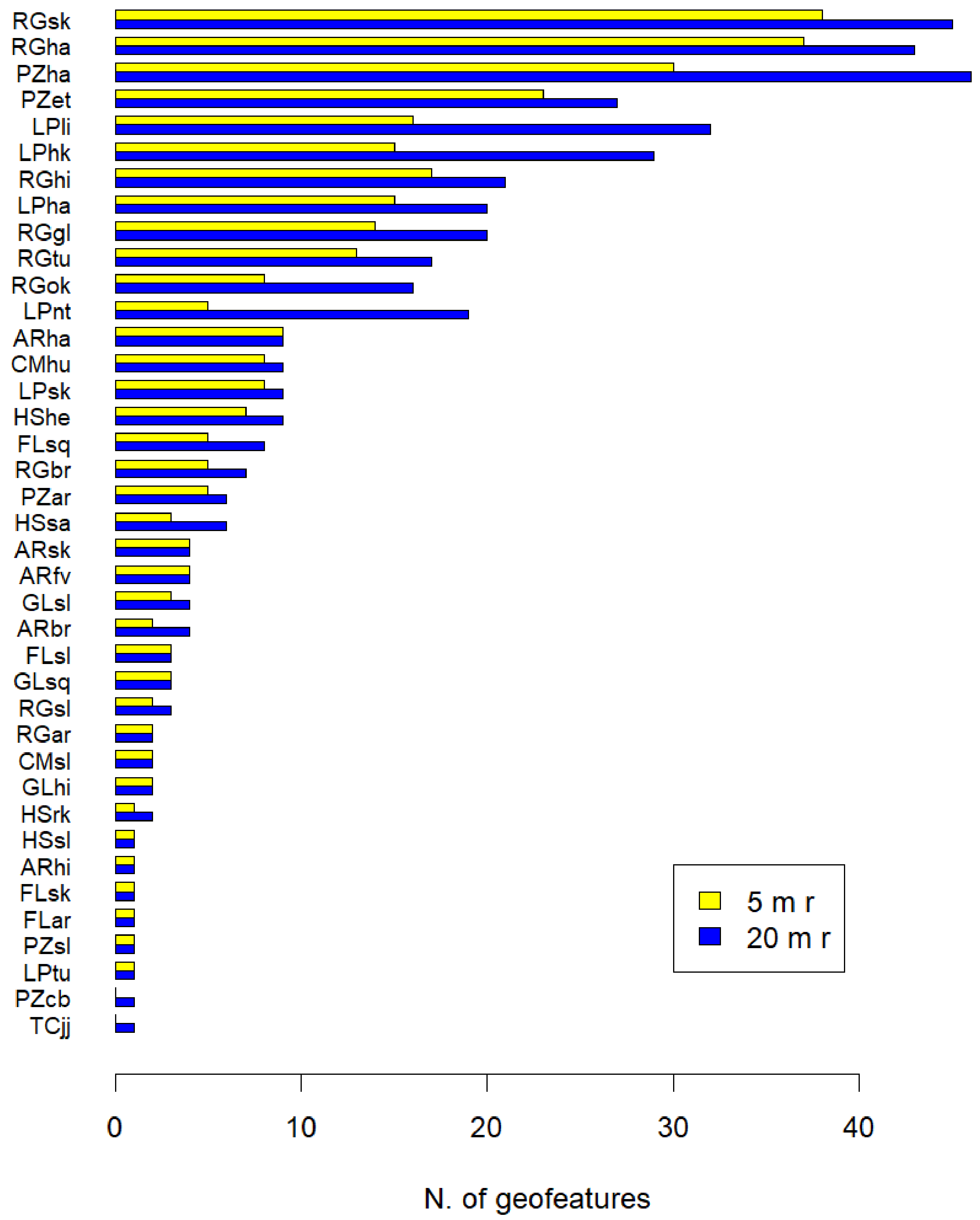

Figure S3. Pedological geofeatures mapped at 193 sites.

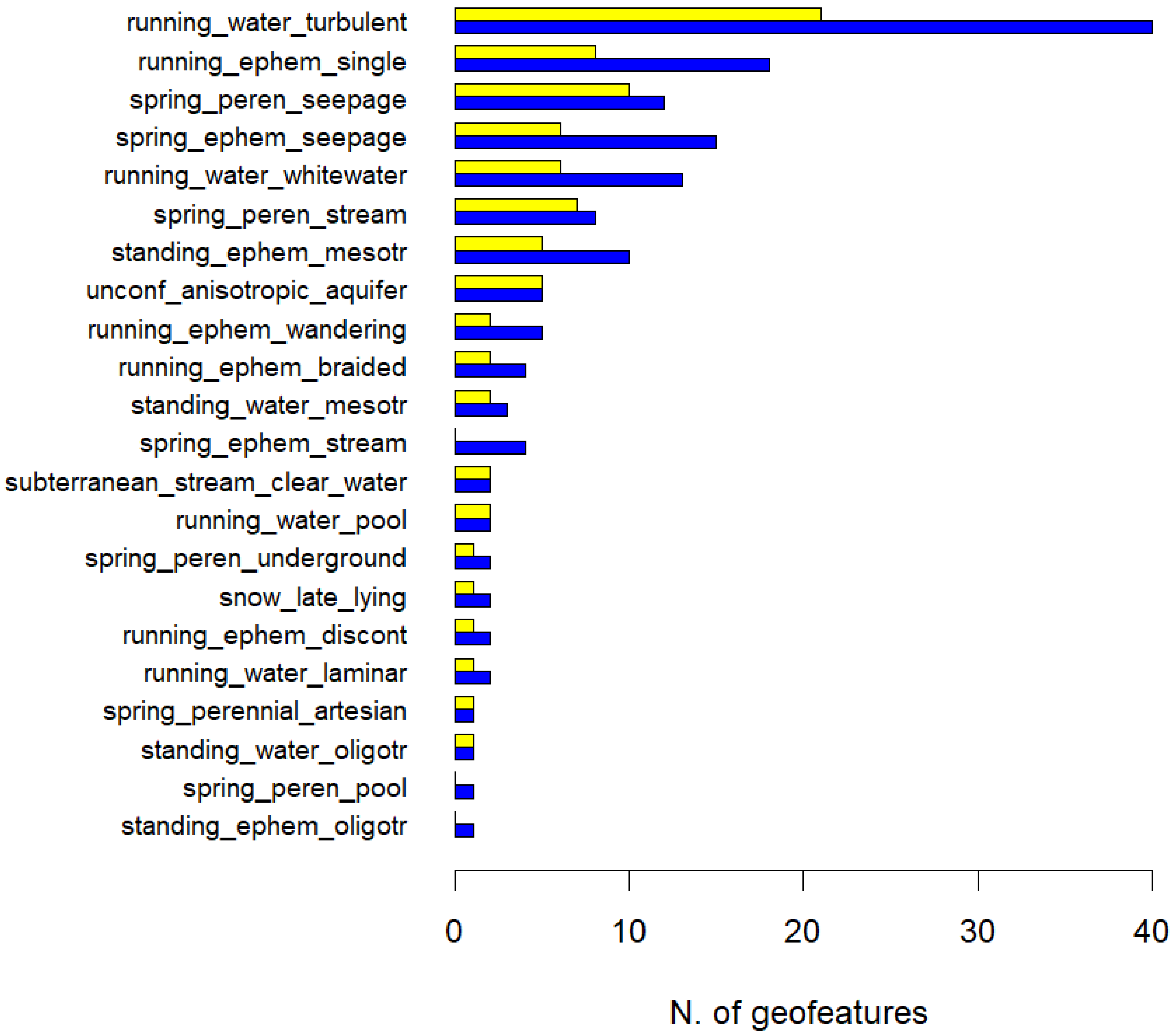

Figure S4. Hydrological geofeatures mapped at 193 sites.

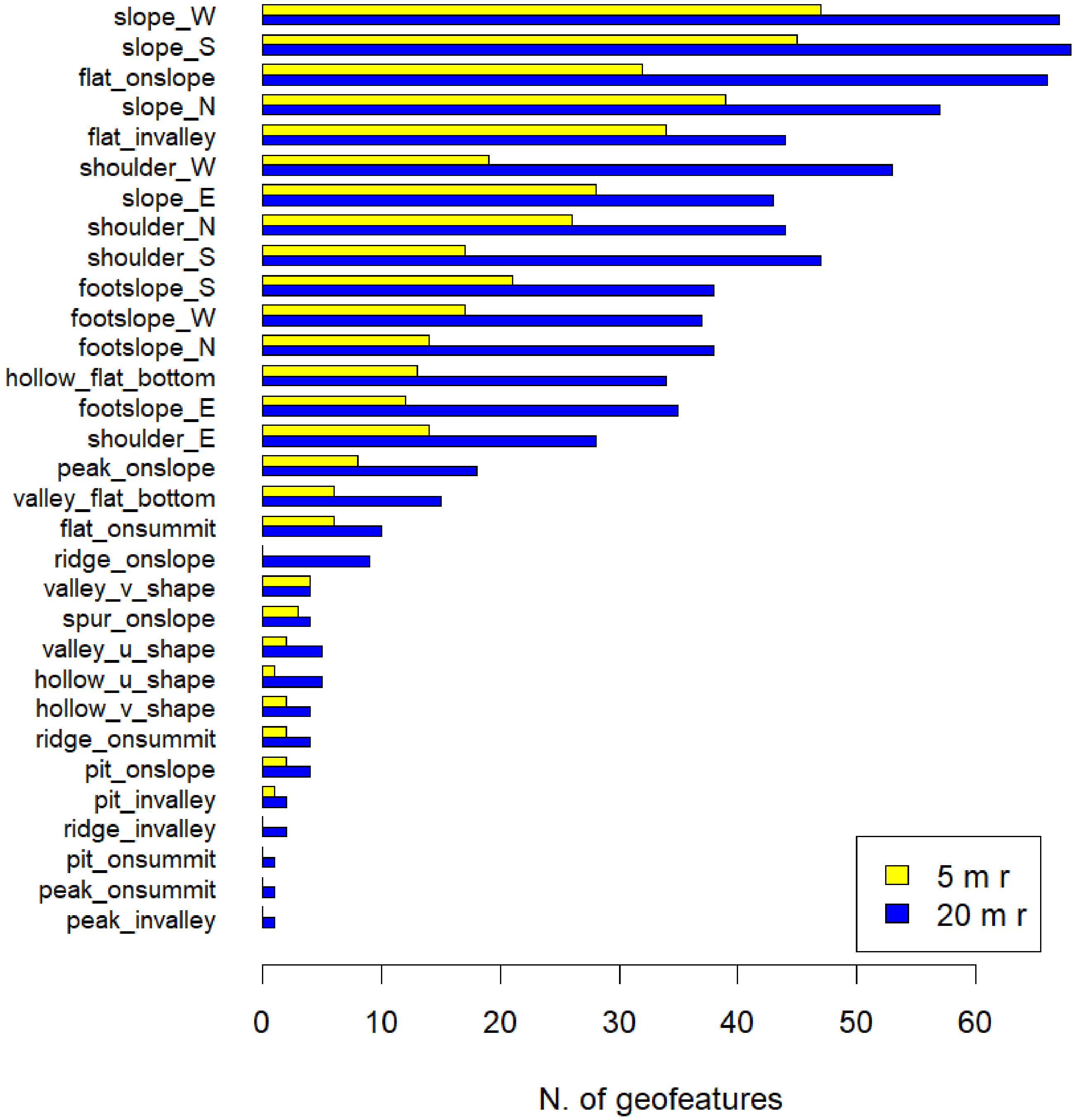

Figure S5. Topographical geofeatures mapped at 193 sites.

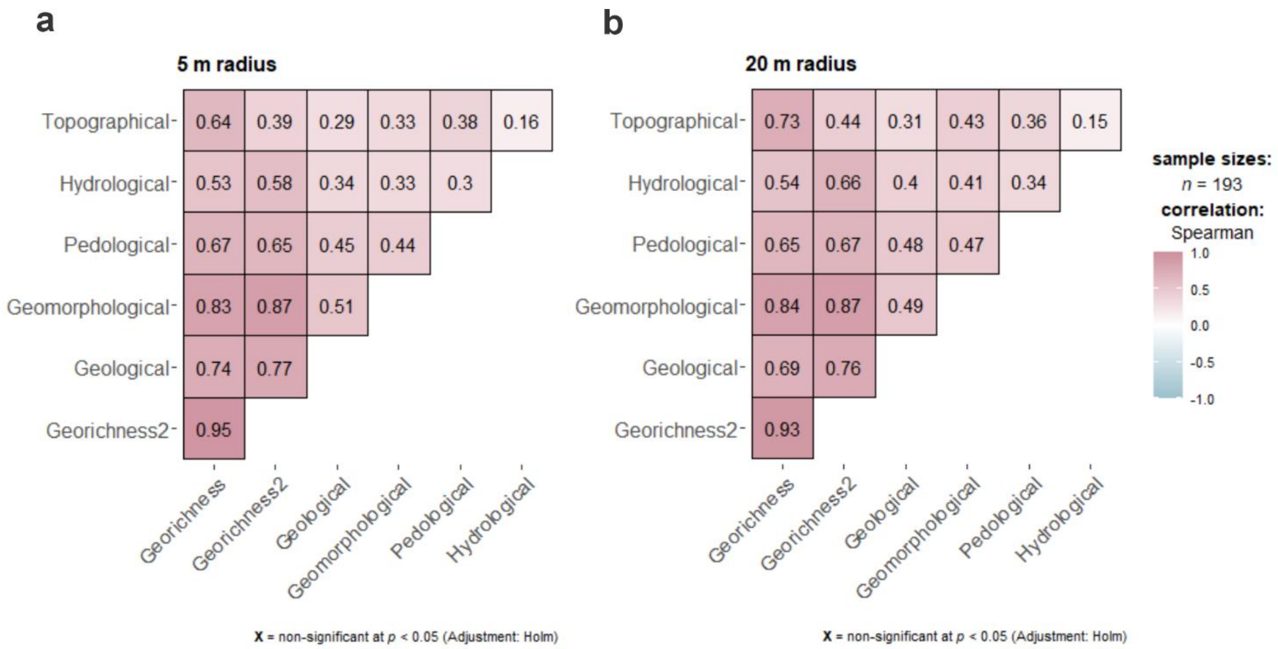

Figure S6. Spearman rank-order correlations between geodiversity components mapped within a 5-meter (a) and 20-meter radius (b) from site center. Georichness is the geofeature sum including geomorphons and Georichness2 without geomorphons.

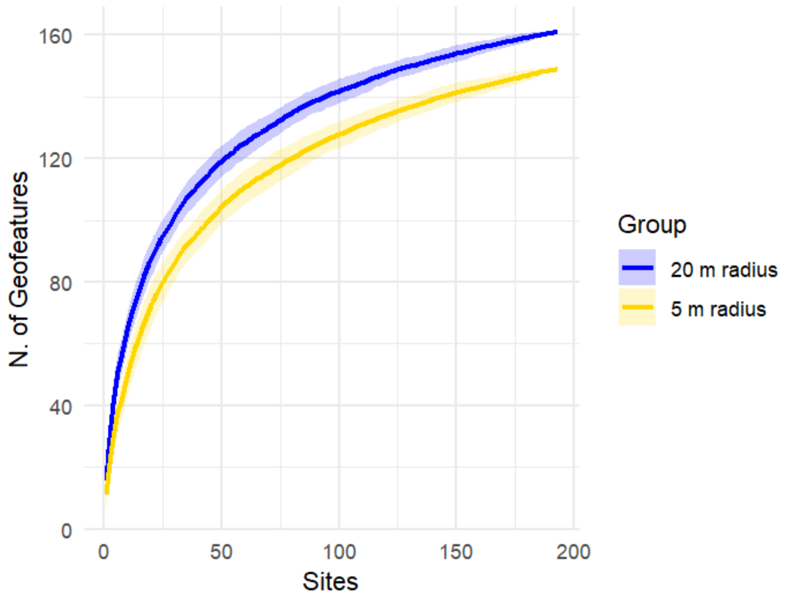

Figure S7. The cumulative number of geofeatures per site for the 5 and 20-m radii.

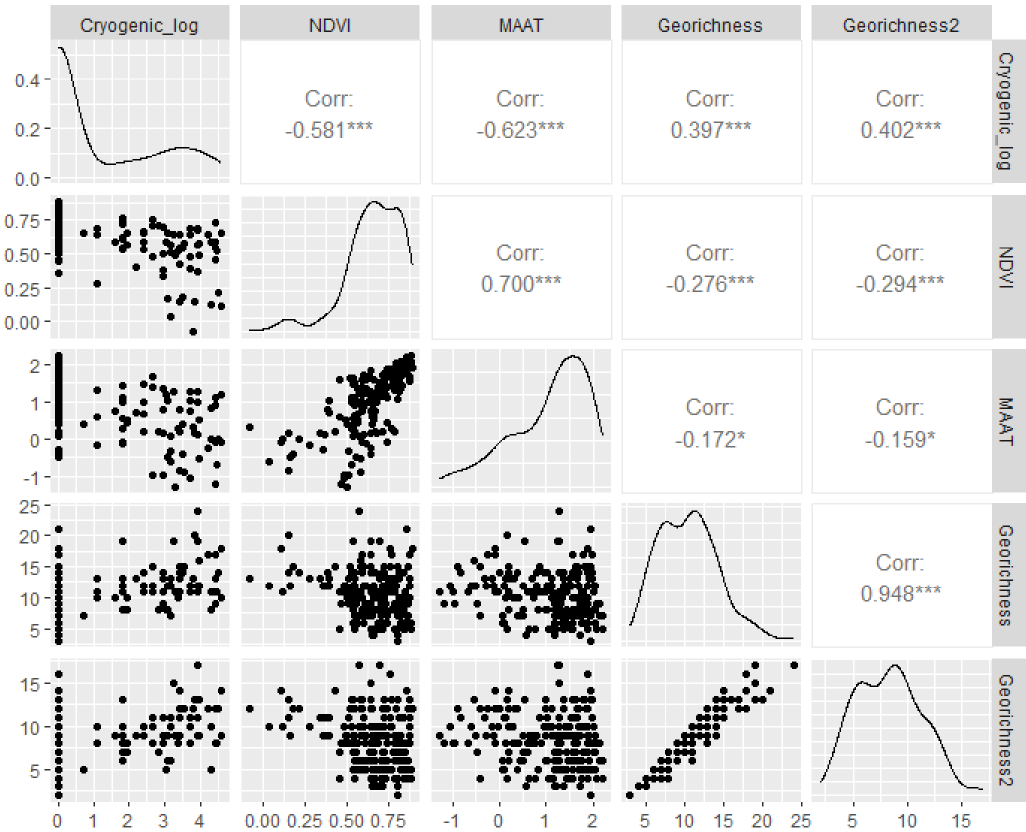

Figure S8. Correlations between the total number of geofeatures mapped within a 5-meter radius from site center and environmental gradients; logarithmic transformation of cryogenic activity (Cryogenic_log), normalized difference vegetation index (NDVI), and mean annual air temperature (MAAT). Georichness is the geofeature sum including geomorphons and Georichness2 without geomorphons.

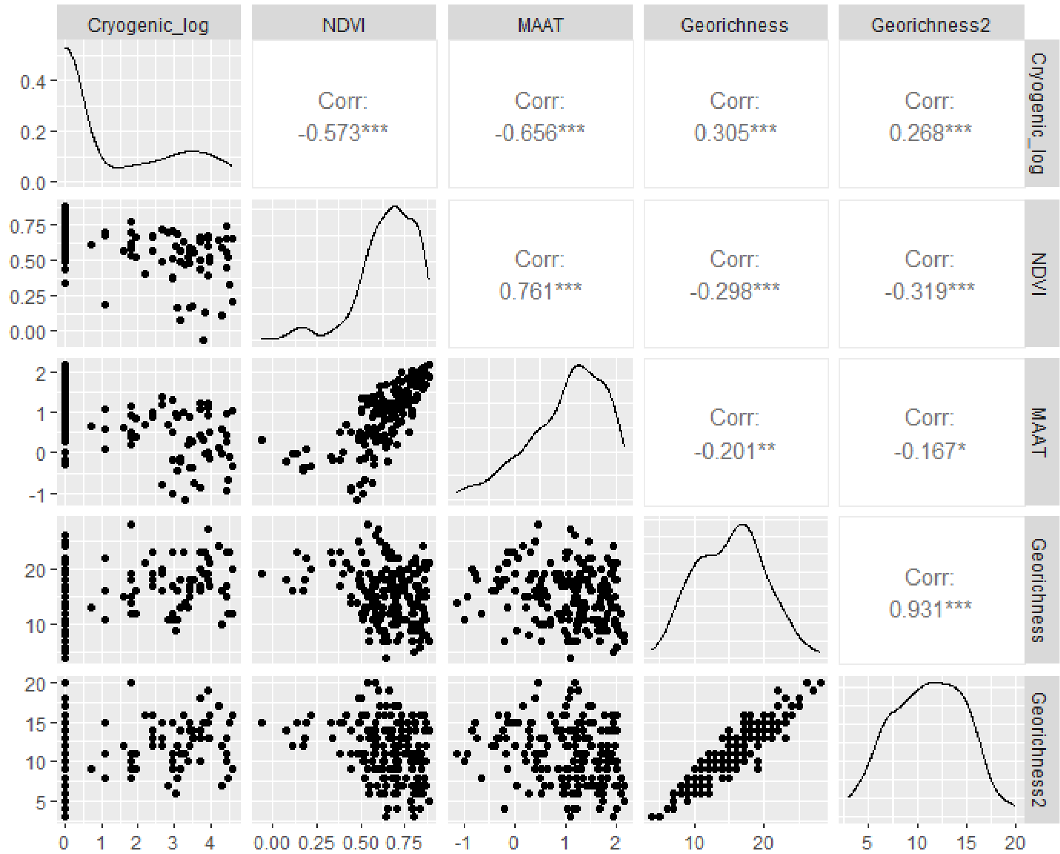

Figure S9. Correlations between the total number of geofeatures mapped within a 20-meter radius from site center and environmental gradients; logarithmic transformation of cryogenic activity (Cryogenic_log), normalized difference vegetation index (NDVI), and mean annual air temperature (MAAT). Georichness is the geofeature sum including geomorphons and Georichness2 without geomorphons.

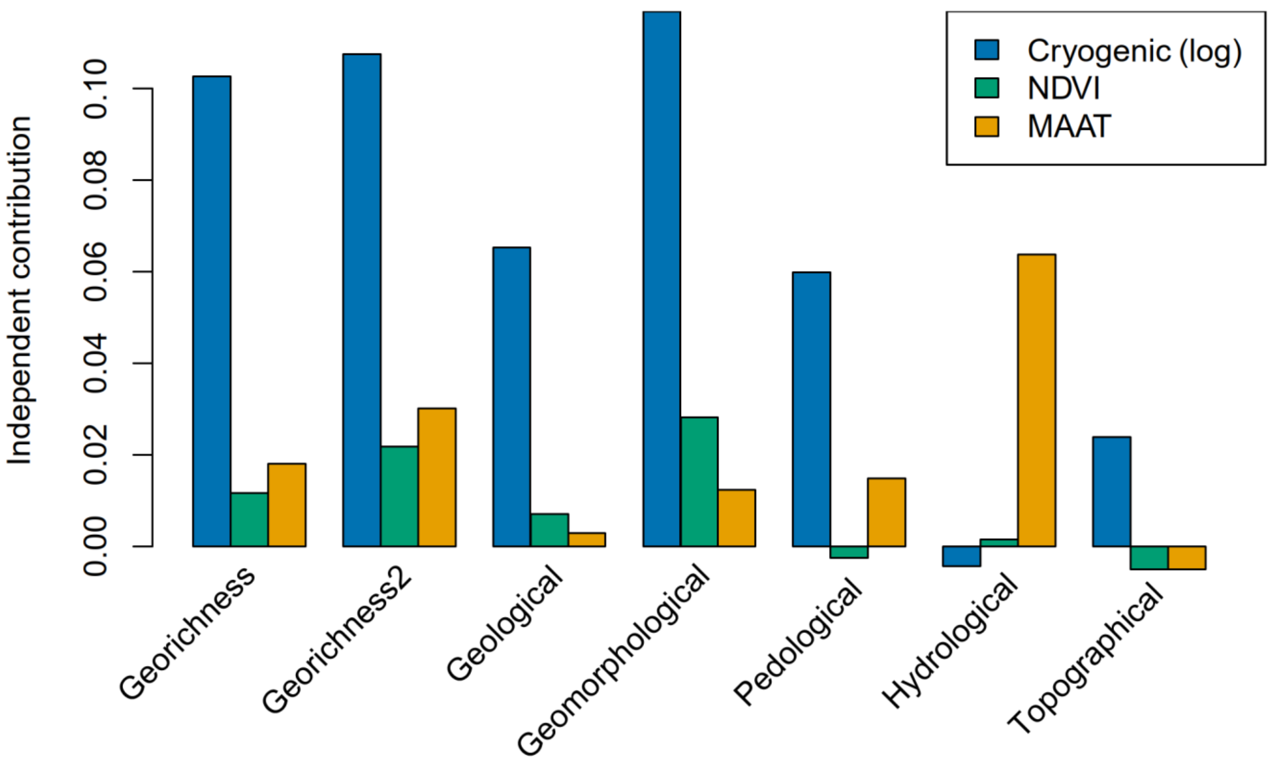

Figure S10. Hierarchical partitioning by georichness in each geodiversity component at 5 m radius grouped by studied environmental gradients. NDVI stands for normalized difference vegetation index and MAAT for mean annual air temperature. Georichness is the geofeature sum including geomorphons and Georichness2 without geomorphons.

Table S1. Interpretation key to the abbreviated geofeatures in taxonomy of geodiversity that were used. Geofeatures are listed alphabetically within each component of geodiversity.

Abbreviation	Definition	Abbreviation	Definition
Geological		**Geomorphological**	
chem_boulders	Boulders (chemical)	*aeolian_deflation_surf*	Deflation surface
chem_stones	Stones (chemical)	*biotic_flat*	Flat deposition of biotic material (mire)
mech_boulders	Boulders (mechanical)	*biotic_hummock*	Hummock of biotic origin/maintenance
mech_gravel	Gravel (mechanical)	*biotic_linear_depression*	Linear depression, reindeer path
mech_sand	Sand (mechanical)	*cryot_blockfield*	Cryoturbation blockfield
mech_silt	Silt (mechanical)	*cryot_boil*	Cryoturbation boil
mech_stones	Stones (mechanical)	*cryot_earth_hummock*	Cryoturbation earth hummock
mech_till	Glacial till	*cryot_patt_ground*	Cryoturbation patterned ground
peat_FE	Fibric-eutrophic peat	*fall_boulderfall*	Boulder fall
peat_FM	Fibric-mesotrophic peat	*fall_rockfall*	Rock fall
peat_HE	Hemic-eutrophic peat	*fall_scree*	Scree
peat_HM	Hemic-mesotrophic peat	*fault_overthrust*	Overthrust fault
peat_HO	Hemic-oligotrophic peat	*flow_solif_nonsorted_feat*	Non-sorted solifluction feature
peat_SE	Sapric-eutrophic peat	*flow_solif_sorted_feat*	Sorted solifluction feature
peat_SM	Sapric-mesotrophic peat	*fluvial_bar*	Sand/gravel bar in fluvial environment
		fluvial_canyon	Canyon
Pedological		*fluvial_channel*	Fluvial channel
ARbr	Brunic Arenosol	*fluvial_cutbank*	Fluvial cutbank
ARfv	Fluvial Arenosol	*fluvial_floodplain_deposit*	Floodplain deposit
ARha	Haplic Arenosol	*fluvial_meander_scar*	Fluvial meander scar
ARhi	Histic Arenosol	*fluvial_meander_scroll*	Meander scroll
ARsk	Skeletic Arenosol	*fluvial_rill*	Rill erosion
CMhu	Humic Cambisol	*fluvial_sheet_erosion*	Fluvial sheet erosion
CMsl	Siltic Cambisol	*glaci_cirque*	Glacigenic cirque
Flar	Arenic Fluvisol	*glaci_drumline*	Glacigenic drumlin
FLsk	Skeletic Fluvisol	*glaci_erratic_boulder*	Glacigenic erratic boulder
FLsl	Siltic Fluvisol	*glaci_esker*	Glacifluvial esker
FLsq	Subaquatic Fluvisol	*glaci_glacially_orient_bedrock*	Glacigenic oriented bedrock
GLhi	Histic Gleysol	*glaci_hummocky_mr*	Glacigenic hummocky moraine
GLsl	Siltic Gleysol	*glaci_kame*	Glacifluvial kame
GLsq	Subaquatic Gleysol	*glaci_kettle*	Glacifluvial kettle hole
HShe	Hemic Histosol	*glaci_lateral_drainage_chnl*	Glacifluvial lateral drainage channel
HSrk	Rockic Histosol	*glaci_lateral_mr*	Glacigenic lateral moraine
HSsa	Sapric Histosol	*glaci_meltwater_channel*	Glacifluvial meltwater channel
HSsl	Siltic Histosol	*glaci_proglacial_deposit*	Proglacial deposit
LPha	Haplic Leptosol	*glaci_ribbed_moraine*	Glacigenic ribbed moraine
LPhk	Hyperskeletic Leptosol	*glaci_roche_moutonnee*	Roche moutonnee
LPli	Lithic Leptosol	*glaci_sandur*	Glacifluvial sandur
LPnt	Nudilithic Leptosol	*lacustrine_bed*	Lacustrine bed
LPsk	Skeletic Leptosol	*littoral_cutbank*	Littoral cutbank
LPtu	Turbic Leptosol	*littoral_depos_terrace*	Littoral depositional terrace
PZar	Arenic Podzol	*littoral_icepush_rampart*	Ice push rampart
PZcb	Cambic Podzol	*littoral_notch*	Littoral erosion notch
PZet	Entic Podzol	*littoral_stone_belt*	Littoral stone belt
PZha	Haplic Podzol	*nival_avalanche_scar*	Avalanche scar
PZsl	Siltic Podzol	*nival_hollow*	Nivation hollow
RGar	Arenic Regosol	*nival_pavement*	Nivation pavement
RGbr	Brunic Regosol	*organic_hummock*	Hummock of organic material
RGgl	Gleyic Regosol	*rock_planar_slide*	Planar rock slide
RGha	Haplic Regosol	*slide_rock_rotational*	Rotational rockslide
RGhi	Histic Regosol	*weath_biol_microbial*	Biological weathering (microbial)
RGok	Orthoskeletic Regosol	*weath_chem*	Chemical weathering
RGsk	Skeletic Regosol	*weath_phys_exfoliation*	Physical weathering (exfoliation)
RGsl	Siltic Regosol	*weath_phys_frost*	Physical weathering (frost-induced)
RGtu	Turbic Regosol		
TCjj	Hyperspolic Technosol		

Table S1. Continued.

Abbreviation	Definition
Hydrological	
running_ephem_braided	Ephemeral running water, braided
running_ephem_discont	Ephemeral running water, discontinuous
running_ephem_single	Ephemeral running water, single-channel
running_ephem_wandering	Ephemeral running water, wandering
running_water_laminar	Running water, laminar
running_water_pool	Running water, pooled
running_water_turbulent	Running water, turbulent
running_water_whitewater	Running water, white water
snow_late_lying	Late-lying snow
spring_ephem_seepage	Ephemeral spring, seepage
spring_ephem_stream	Ephemeral spring, stream
spring_peren_pool	Perennial spring, pool
spring_peren_seepage	Perennial spring, seepage
spring_peren_stream	Perennial spring, stream
spring_peren_underground	Perennial spring, underground
spring_perennial_artesian	Perennial spring, artesian
standing_ephem_mesotr	Ephemeral standing water, mesotrophic
standing_ephem_oligotr	Ephemeral standing water, oligotrophic
standing_water_mesotr	Perennial standing water, mesotrophic
standing_water_oligotr	Perennial standing water, oligotrophic
subterranean_stream_clear_water	Subterranean stream
unconf_anisotropic_aquifer	Unconfined anisotropic aquifer
Topographical	
flat_invalley	Flat, in valley
flat_onslope	Flat, on slope
flat_onsummit	Flat, on summit
footslope_E	Footslope, east-facing
footslope_N	Footslope, north-facing
footslope_S	Footslope, south-facing
footslope_W	Footslope, west-facing
hollow_flat_bottom	Hollow, flat bottom
hollow_u_shape	Hollow, U-shape
hollow_v_shape	Hollow, V-shape
peak_invalley	Peak, in valley
peak_onslope	Peak, on slope
peak_onsummit	Peak, on summit
pit_invalley	Pit, in valley
pit_onslope	Pit, on slope
pit_onsummit	Pit, on summit
ridge_invalley	Ridge, in valley
ridge_onslope	Ridge, on slope
ridge_onsummit	Ridge, on summit
shoulder_E	Shoulder, east-facing
shoulder_N	Shoulder, north-facing
shoulder_S	Shoulder, south-facing
shoulder_W	Shoulder, west-facing
slope_E	Slope, east-facing
slope_N	Slope, north-facing
slope_S	Slope, south-facing
slope_W	Slope, west-facing
spur_onslope	Spur, on slope
valley_flat_bottom	Valley, flat bottom
valley_u_shape	Valley, U-shape
valley_v_shape	Valley, V-shape