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A methodological guide to observe local-scale geodiversity for biodiversity research and management

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Abstract

1. Current global environmental change calls for comprehensive and complementing approaches for biodiversity conservation. According to recent research, consideration of the diversity of Earth's abiotic features (i.e. geodiversity) could provide new insights and applications into the investigation and management of biodiversity. However, methods to map and quantify geodiversity at local scale have not been developed although this scale is important for conservation planning. Here, we introduce a field methodology for observing plot-scale geodiversity, pilot the method in an Arctic–alpine tundra environment, provide empirical evidence on the plot-scale biodiversity–geodiversity relationship and give guidance for practitioners on the implementation of the method.
2. The field method is based on observation of geofeatures, that is, elements of geology, geomorphology and hydrology, from a given area surrounding a location of species observations. As a result, the method provides novel information on the variation of abiotic nature for biodiversity research and management. The method was piloted in northern Norway and Finland by observing geofeatures from 76 sites at three scales (5, 10 and 25 m radii). To explore the relationship between measures of biodiversity and geodiversity, the occurrence of vascular plant species was recorded from 2 m × 2 m plots at the same sites.
3. According to the results, vascular plant species richness was positively correlated with the richness of geofeatures (R_s = 0.18–0.59). The connection was strongest in habitats characterized by deciduous shrubs. The method has a high potential for observing geofeatures without extensive geological or geomorphological training or field survey experience and could be applied by conservation practitioners.
4. *Synthesis and applications*. Consideration of geodiversity in understanding, analysing and conserving biodiversity could facilitate environmental management and ensure the long-term sustainability of ecosystem functions. With the developed method, it is possible to cost-efficiently observe the elements of geodiversity that are useful in ecology and biodiversity conservation. Our approach

can be adapted in different ecosystems and biodiversity investigations. The method can be adjusted depending on the abiotic conditions, expertise of the observer(s) and the equipment available.

KEYWORDS
abiotic diversity, biodiversity conservation, biodiversity management, environmental data, environmental heterogeneity, geodiversity, plot-scale, species richness

1 | INTRODUCTION

The global biodiversity crisis has created an urgent need for methods to improve understanding and predictions of biodiversity patterns, and consequently, to support the existing conservation strategies (Cardinale et al., 2012; Knudson et al., 2018). The incorporation of geodiversity information into biodiversity investigations has high potential to provide a novel practical and complementary approach to explore biological assemblages and protect nature (Antonelli et al., 2018; Halvorsen et al., 2020). Geodiversity (i.e. the diversity of abiotic features on the Earth surface and subsurface) consists of variation in soils, rocks, water elements, landforms and topography (Gray, 2013). Geodiversity establishes local environmental heterogeneity and provides the foundation to resources, microtopography and microclimate, which in turn, create a diversity of niches, microhabitats and refugia for different organisms to exist (Kerr & Packer, 1997). Higher abiotic diversity should also increase probability of speciation events through isolation or adaptation to various conditions (Rosenzweig, 1995). Thus, areas that have high geodiversity should support higher biodiversity compared to abiotically monotonous areas (Beier et al., 2015). Nevertheless, geodiversity per se has relatively rarely been considered in biological conservation and management plans (Schrodt et al., 2019), although the theoretical linkages between biodiversity and geodiversity are strong (Lawler et al., 2015; Stein et al., 2014).

Emerging empirical evidence demonstrates that geodiversity has a positive relationship with different measures of biodiversity at the landscape and regional scales. Geodiversity has been positively linked with species richness of plants (Bailey et al., 2017; Hjort et al., 2012) and tetrapods (Antonelli et al., 2018), distribution and richness of rare species (e.g. plants, Lepidoptera, fungi, and beetles; Tukiainen et al., 2017) and measures of tree and bird diversity (Read et al., 2020). Other studies also suggest that individual factors of geodiversity, such as geomorphological processes and landforms, can be important in explaining current biodiversity patterns (e.g. Albano, 2015) or compositional changes under climate change (Virtanen et al., 2010). Abiotic elements have also been incorporated with biodiversity in broad conservation frameworks, such as the International Union for Conservation of Nature (IUCN) Global Ecosystem Typology (Keith et al., 2020).

Abiotic diversity is considered to be more stable over time compared to biotic diversity. A conservation framework called Conserving Nature's Stage (CNS; Beier et al., 2015) is based on this idea, suggesting that diverse physical environments can maintain higher levels of biodiversity over time. According to the CNS approach, it would be essential to explicitly integrate geodiversity into conservation planning and practice as a coarse filter strategy for current and future biodiversity (Beier et al., 2015; Knudson et al., 2018). Even though current conservation strategies are highly important, they may not necessarily ensure long-term diversity alone as species responses to global changes vary, and thus, current species communities and habitats may be markedly different in the future. Measures of geodiversity could complement and add value to current conservation approaches that are mainly concentrated on certain species or habitats (Knudson et al., 2018). This could be especially important for remote areas, where frequent and extensive mapping of biodiversity is often not possible.

To complement biodiversity assessments and conservation approaches, several methodologies to measure geodiversity have been proposed during the last two decades (Crisp et al., 2021). These include both qualitative geosite assessments (Zwoliński et al., 2018) and quantitative assessments of geodiversity, which are commonly based on geospatial data (e.g. digital elevation models, DEMs; Crisp et al., 2021). A major asset of geodiversity compared with simple DEM-based topographical variables is that it can provide high-quality information on habitat and edaphic conditions such as soil texture, geomorphological processes and hydrological conditions that are ecologically relevant in biodiversity analyses. Thus, elements of geodiversity characterize not only topography, but also provide detailed information on ground material (physical, chemical and moisture conditions), microclimate and ecological disturbances (Jonasson, 1986; le Roux & Luoto, 2014; Walker, 1995). However, biodiversity–geodiversity investigations have been carried out chiefly at the landscape scale, which is due to the lack of geodiversity data at finer spatial scales (for an exception, see Kärnä et al., 2018). Consequently, there is a need for estimating and applying geodiversity data at the scale that matches with the scale of the field-based biodiversity inventories. These local-scale investigations should be the key focus to meet essential conservation and management targets (Wyborn & Evans, 2021).

The development and utilization of local-scale geodiversity methods could be particularly useful in investigating biodiversity in the tundra and mountain ecosystems that are among the most vulnerable environments to the ongoing climate change (IPCC, 2021). Climate warming impacts have already pronouncedly changed tundra plant communities and their taxonomical and functional diversity (Aronsson et al., 2021). This has led to vegetation shifts, such as the shrub expansion and the greening of the Arctic, which can further activate or magnify various large-scale feedbacks related to the tundra carbon balance and the global carbon cycle (Pearson et al., 2013). While on-site surveys on plant communities and other biodiversity measurements frequently explore the effects of abiotic drivers (mainly temperature and moisture), they rarely include information on the whole range of the abiotic environment (see for instance Mod et al., 2016).

Here, we (i) introduce a field-based methodology for observing plot-scale geodiversity, (ii) pilot the method in Arctic–alpine tundra environment, (iii) provide preliminary empirical evidence on the plot-scale biodiversity–geodiversity relationship and (iv) give recommendations on the implementation of the method. This field method is based on observing elements of geodiversity from a given area surrounding an ecological survey site (for instance, a vegetation plot). The method provides a guide to observe the presence of different elements of geodiversity in high-latitude and high-altitude environments. However, geodiversity is present everywhere on Earth, and therefore the method is developed to be easily extended to other environments and applied to different nature conservation and management actions. In addition, it can be complemented by other investigations, such as sediment sampling and modern geospatial data technologies (e.g. laser scanning and drone imaging).

2 | MATERIALS AND METHODS

2.1 | Field-based observation of geodiversity

At first, it is important to determine the scale at which geodiversity is the most relevant for biodiversity investigations (Hjort et al., 2015). The finest scale of geodiversity is the level of 'particles' (atoms, molecules and energy processes; see Serrano & Ruiz-Flaño, 2007). However, this level is not applicable to most biodiversity studies, because it lacks a clear spatial dimension and features are difficult to map in practice. Consequently, we considered the next level, the 'elements' of geodiversity (i.e. *geofeatures*, specific features of geology, geomorphology and hydrology; Serrano & Ruiz-Flaño, 2007) in this field method. An exposed bedrock, silty sediment, river deposits and a spring are examples of geofeatures (Hjort et al., 2015; see Appendix S1 in Supporting Information). Geofeatures can be measured at a presence–absence (0/1) scale or quantitatively by determining the cover, proportion or number of a specific geofeature (Zwoliński et al., 2018). Here, the presence–absence scale is applied to keep the method simple and accessible, and further to maintain comparability with species richness (the presence–absence of species) approach, which is often used is biodiversity studies (e.g. Antonelli et al., 2018; Bailey et al., 2017).

One of the cornerstones of the geodiversity data collection is the classification system of geofeatures (Figure 1). The system should be detailed enough to separate different properties of geofeatures (Hjort et al., 2015) and, simultaneously, simple enough to be adopted also by a non-geomorphologist with a reasonable amount of training.

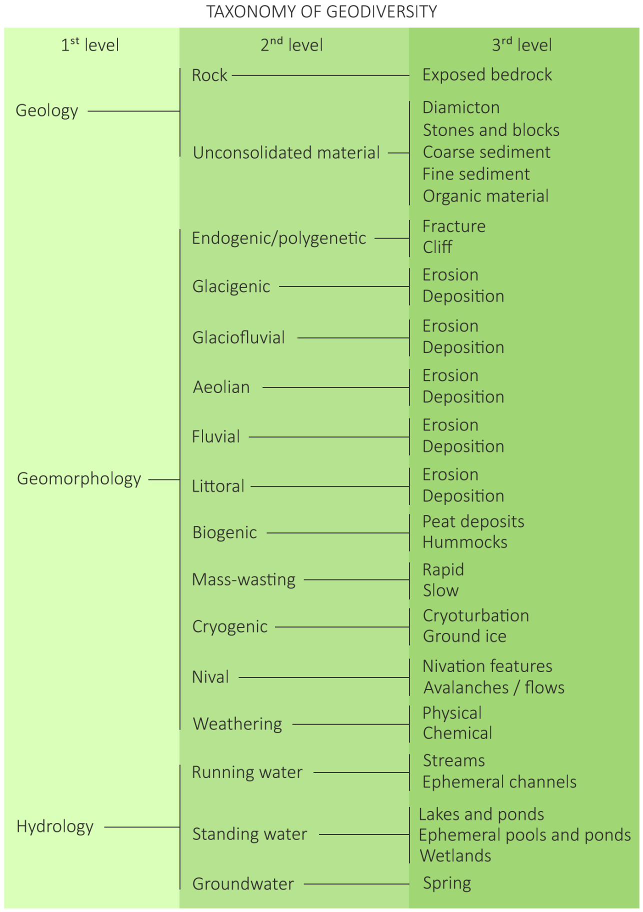

FIGURE 1 Classification of elements of geodiversity (i.e. geofeatures) at different hierarchical levels. The third level demonstrates the specific geofeatures considered in this study, which piloted the method in the Arctic–alpine tundra

This could be a few training days under the supervision of a more experienced geomorphologist, preferably in the field. Moreover, to enhance the accessibility and applicability of the method, data on geofeatures should be acquirable without expensive and sophisticated devices from several observation sites (>10) per one field day. Consequently, we present a classification system that includes 34 different geofeatures, which are relatively easy to observe in the field at a plot-scale. Most of the geofeatures belong to the group of geomorphology ($n = 22$), whereas geology ($n = 6$) and hydrology ($n = 6$) have less elements (Figure 1; Hjort & Luoto, 2010; Hjort et al., 2012, 2015).

The implementation of the method includes several steps, which start with adjusting it to the local environmental conditions (e.g. adapting the geofeature classification) and ends with processing, analysing and utilizing the obtained data (Figure 2). It is important to adjust the method to the biological data before the actual field work. In the field, the presence of a geofeature is determined from a circular mapping area around a vegetation plot or site of any other biological data (Figure 2c). If the plots are not marked in the field with permanent markers, the GPS accuracy of the geolocated plots should be high enough (<few m location error) when compared to

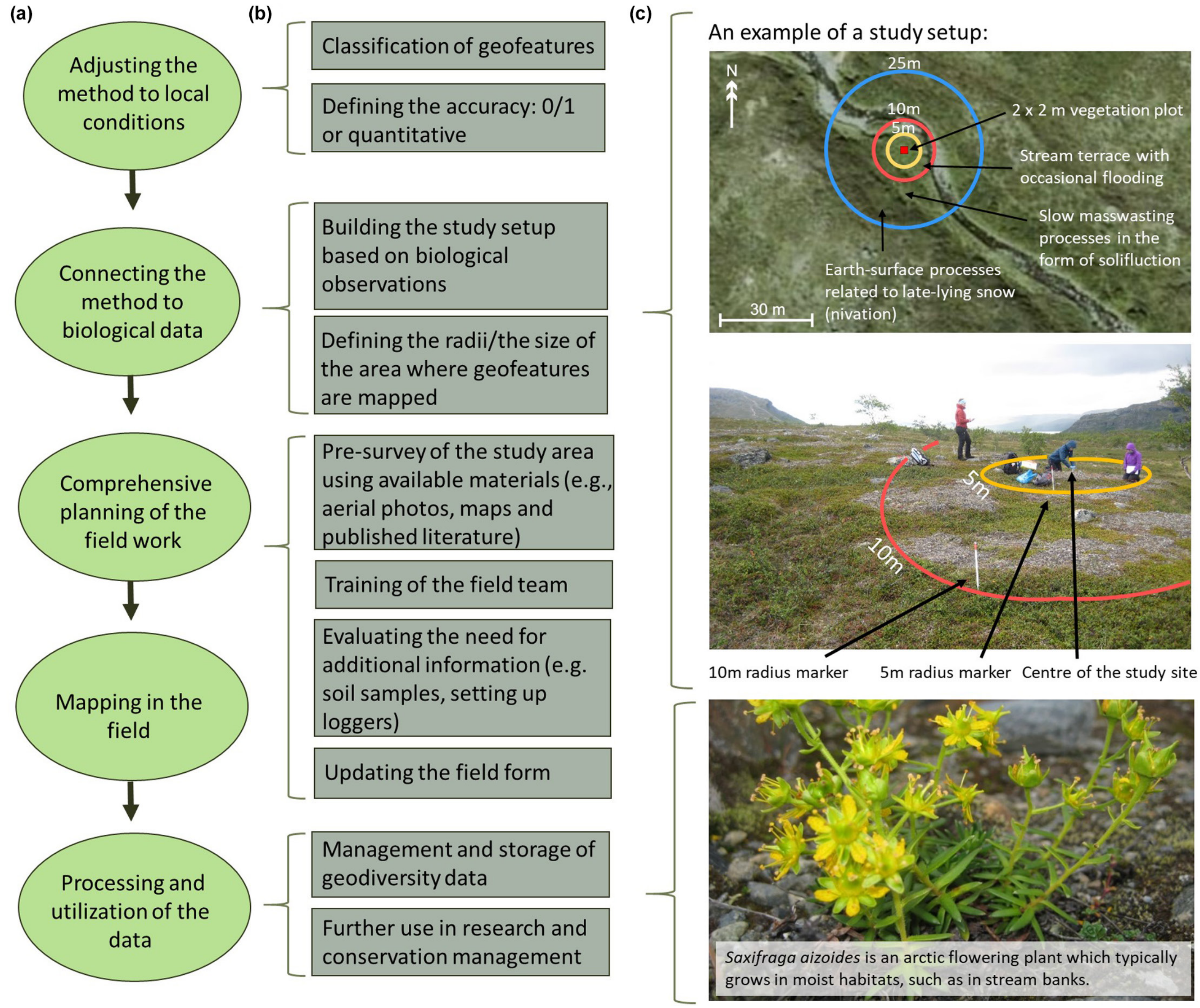

FIGURE 2 A schematic summary of the implementation of the method divided into main steps (a) and examples of practical tasks included into the steps (b). Photographs (c) illustrate the study set up with different radii

the size of the mapping areas. The exact radius of the area depends on the purpose of the study, the size of the biodiversity observation plot and resources (i.e. time and labour) available for mapping. The mapping area can also be a square (a grid cell, e.g. 10 m × 10 m), if it fits better to the study design, biological observations or management objectives.

The midpoint of the circular mapping area is determined based on biodiversity observation plot and the mapping area can be delineated with a suitable string and marks (Figure 2c). If information on geofeatures is gathered only at one scale, a radius of 5–10 m larger than the size of the plot is recommended. In optimal case, information is acquired at different scales (e.g. radius = 5, 10 and 25 m; Figure 2c). It is important that the mapping area extends beyond the plot because geofeatures (especially geomorphological processes and landforms) commonly affect the conditions nearby, and thus, biodiversity in the plot. For example, a stream nearby to an observation plot likely affects the surveyed community by flooding or individuals of species inhabiting stream banks may exist further away in the riparian zone (Figure 2c).

2.2 | Geological geofeatures

Geological geofeatures are determined based on the material per se and not based on the genesis of the material (e.g. Hjort & Luoto, 2010). The classification of sediments is based on the granulometry of parent material to keep the classification system approachable (Table 1; Appendix S1). In addition, exposed bedrock and organic material (peat or mud) are considered to be distinct geofeatures at the Earth's surface. Minerogenic sediments are classified to diamicton (i.e. non-sorted material), blocky material (stones and blocks), coarse sediments (sand and gravel) and fine sediments (e.g. silty materials). Determination of sediment type and granulometry often requires examination of parent

TABLE 1 Geological geofeatures, their identification and examples of ecological relevance. In the identification, geological features can be covered by vegetation but not by other sediments (e.g. photographs, see Appendix S1)

Geological geofeatures		Identification	Examples of ecological relevance
ROCK	Exposed bedrock	• Solid/intact rock (substantially broken and jointed rock surface, e.g. by weathering, is not considered to be intact)	• Open (e.g. high insolation), stable and barren habitat for lichens and specialized organisms • Extreme temperature and moisture conditions
UNCONSOLIDATED MATERIAL	Diamicton	• Non-sorted mineral material (e.g. till) that is, a mixture of material from clay-size particles to boulders • >10 cm thick layer	• Moderate moisture-holding capacity • Often variability in minerals • Can have high microscale topographic heterogeneity owing to the mixed-sized particles
	Stones and blocks	• Particle size over 6 cm in diameter • A continuous field (e.g. >1 m^2) and not just scattered stones and/or blocks	• Open (e.g. high insolation) and barren habitat for lichens and specialized organisms • Relatively stable temperature and moisture conditions between stones and blocks
	Coarse sediment	• Particle size 0.06–6 cm (sand or gravel) • >10 cm thick layer	• Dry (and barren) substrate owing to high permeability of water • Often unstable substrate (e.g. screes) • Often nutrient-poor substrate
	Fine sediment	• Particle size <0.06 mm • >10 cm thick layer	• Good moisture-holding capacity • Capillary action provides moisture during dry seasons • Often nutrient-rich substrate
	Organic material	• Dead (autochthonous or allochthonous) organic material (e.g. peat) • >10 cm thick layer	• From dry to waterlogged substrate • Nutrition to organisms • Can be acid substrate

material that can be conducted with a shovel or a simple soil probe. Different unconsolidated deposits may have highly variable spatial extents, and thus, there is no minimum cover (m^2), but the material layer should be thick enough (>10 cm) to develop environmental conditions characteristic to the ground material type (Table 1; Appendix S1).

2.3 | Geomorphological geofeatures

Geomorphological geofeatures (Appendix S1) are classified into 11 main process groups, each containing two separate feature types (Table 2). The aim is not to identify and name specific landforms, such as cut banks or sorted circles, because this could be challenging for an unexperienced mapper, who is not trained to identify different geomorphological features. Instead, the aim is to observe landforms and signs of sediment characteristics that can be classified to the geomorphological process groups (Figure 1). Moreover, mapping of all the possible landforms could bias the classification system towards those geomorphological process classes and landforms, which have traditionally been subdivided into numerous subtypes (French, 2017).

Several of the geomorphological processes and landforms can be subdivided into erosional and depositional features (e.g. aeolian erosion and aeolian accumulation). However, there are many features, such as endogenic/polygenetic, biogenic and cryogenic, that cannot be classified into erosion or accumulation claases or into any other distinct classes within their process group. Geofeatures in these remaining process groups were classified into two groups considering the basic characteristics of the landforms or processes. For example, mass movements were divided into rapid and slow, cryogenic to cryoturbation and ground ice related and weathering to physical and chemical. Because of the varying effect and size of geomorphological features (from <1 m^2 to >1 km^2), a landform does not need to be completely inside the mapping area to be 'present' (the stream terrace as an example of fluvial erosion in Figure 2).

2.4 | Hydrological geofeatures

The classification of hydrological geofeatures is based on the type of the water element (Table 3; Appendix S1). The basic types are running water, standing water and groundwater. In addition, seasonality of running and standing water elements is considered because some environments, like tundra and semi-arid areas, may have highly variable hydrological conditions affected by seasonality or winter conditions (Kemppinen et al., 2019). Thus, a dry channel with ephemeral stream flow conditions and seasonally drying pools/ponds are listed as specific geofeatures (Table 3).

TABLE 2 Geomorphological geofeatures, their identification and examples of ecological relevance (e.g. see Appendix S1)

Geomorphological geofeatures		Identification and examples of landforms	Examples of ecological relevance
ENDOGENIC/ POLYGENETIC	Cliff	• Vertical, or nearly vertical, >50 cm high rock exposure	• Exposed/sheltered conditions on and nearby the feature
	Fracture	• >5 cm wide crack in bedrock (can be filled with stones or sediments)	• Barren microhabitat with extreme growth conditions
GLACIGENIC	Erosion	• Glacially rounded bedrock, roche moutonnée like features	• Stable habitat for lichens and specialized organisms
	Deposition	• A distinct landform (moraine hummocks and ridges; not just an undulating till cover) • An erratic block (diameter >1.5 m, clearly transported by a glacier i.e. rounded corners)	• Local topographic heterogeneity • Exposed/shady conditions for lichens and mosses
GLACIO-FLUVIAL	Erosion	• Melt water channels (extramarginal, gorge, lateral and subglacial channels)	• Moist/humid (bottom) and dry/exposed habitats (slopes) • Local topographic heterogeneity
	Deposition	• A distinct landform (e.g. a kame-landform; not just an undulating sand or gravel cover)	• Local topographic heterogeneity • Well-drained habitat
AEOLIAN	Erosion	• Marks of wind erosion; a deflation surface or a blowout	• Competitive advantage for pioneer species
	Deposition	• Wind deposited silt (loess material) or fine sand; a sand dune	• Variability in moisture-holding capacity and nutrients
FLUVIAL	Erosion	• Signs of stream erosion; a stony stream bottom; >20 cm deep channel; cut bank (>10 cm high); a gully; a rill; an outside bend of a meandering stream	• Microscale topographic heterogeneity • Competitive advantage for pioneer species
	Deposition	• Sediment deposits including small sand/silt bars above or below water surface; inside bend of a meandering stream (a point bar); flood deposits	• Moist/humid habitats with variable sediment characteristics • Disturbance (sedimentation)
LITTORAL	Erosion	• Stony zone in the shoreline or waterside (>50 cm wide); cut bank (>10 cm high)	• Microtopographic heterogeneity • Ecoton with disturbance
	Deposition	• Sand/gravel deposits including small beach ridges and sandbars above or below water surface	• Moist/humid habitats with barren substrate
BIOGENIC	Peat deposits	• Deposits levelling off the fine-scale topographical variation caused by mineral sediments	• Moist substrate (often acid) • Stable microclimatology
	Hummocks	• Peat hummocks (>10 cm high) like turf hummocks	• Variable growth and moisture conditions
MASS MOVEMENT	Rapid (occasional)	• Scars or sediment deposits of landslides and earth flows (e.g. debris flows)	• Novel ecospaces • Topographic heterogeneity
	Slow (mm-level per year)	• Signs of slow movement of water-saturated sediments (e.g. a solifluction lobe, terrace or step)	• Intermediate disturbance • Microtopographic heterogeneity
CRYOGENIC	Cryoturbation	• Signs or landforms of ground frost ('frost boils', patterned ground, earth hummocks)	• Mixing and circulation of nutrients and organic material
	Ground ice	• Signs or landforms indicating permanent ice in the ground (e.g. palsa, pingo, ice-wedge)	• Permafrost disturbance • Topographic heterogeneity
NIVAL	Nivation features	• Signs or depressions indicating late-lying snow (nivation patch or hollow)	• Snow protection, variability in moisture conditions • Multiple geomorphic processes present
	Snow avalanche and slush flow	• Deposits or sediments of snow avalanche or slush flow	• Novel ecospaces • Physical disturbance
WEATHERING	Physical	• Deposits or landforms of weathered material (e.g. frost shattered block fields [>1 m^2] or talus)	• Barren habitat with exposed rock material
	Chemical	• Signs of chemical weathering on stones or bedrock	• Nutrient supply • Microtopographic heterogeneity

TABLE 3 Hydrological geofeatures, their identification and examples of ecological relevance (e.g. photographs, see Appendix S1)

Hydrological geofeatures		Identification	Examples of ecological relevance
RUNNING WATER	A river, stream or rivulet	• Continuous water flow regardless of width/depth	• Permanent aquatic habitat/corridor for various taxonomic groups • Moisture for terrestrial habitats
	An ephemeral channel	• An ephemeral stream or a dry channel (e.g. seasonal flood channels)	• Variable growth conditions • Microtopographical heterogeneity
STANDING WATER	Lake, pond or pool	• Permanent but water level can fluctuate • >1 m^2	• Permanent aquatic habitat for various taxonomic groups • Ecotone (shores)
	An ephemeral pond/pool	• An ephemeral or a dry pond/pool (e.g., seasonal flood ponds)	• Accumulation of sediments • Groundwater level near the surface
	A wetland	• Water-saturated grounds with a thin (<5 cm) or missing organic layer • >1 m^2	• Abundant moisture supply • Buffers against freezing in growing season
GROUNDWATER	A spring	• All kinds of groundwater discharge, that is, movement of groundwater from the subsurface to the surface (pool and seepage)	• Stable microclimatological conditions (during cold/dry season) • Potentially nutrient-rich water

3 | PILOT STUDY

3.1 | Study area, materials and methods

The study area is located in northern Europe, in Norway and Finland (Figure 3). The area is characterized by (rounded) mountains, valleys and generally varying topography. The bedrock consists of Precambrian and Palaeozoic sedimentary rocks (Lehtovaara, 1995). Climate is subarctic with mean annual air temperatures below 0°C and precipitation of ca. 500 mm/year. (Pirinen et al., 2012). The study plots ($n = 76$) are located at dwarf shrub dominated oligotrophic Arctic–alpine tundra (Figure 3). The major habitat types in the studied tundra are distinctively dominated by either deciduous shrubs (*Vaccinium myrtillus*, *Betula nana*, $n = 36$) or evergreen shrubs (*Empetrum nigrum* ssp. *hermaphroditum*, $n = 40$), mainly based on differences in mesotopography. Former habitat types tend to be moister and situate on sites with thicker snow cover, while the latter tend to be drier and situate on more wind-exposed sites with thinner snow cover (Haapasaari, 1988; Maliniemi et al., 2018).

The geodiversity method was piloted by observing geofeatures around 76 rectangular 2 m × 2 m vegetation plots during the summer 2020. For species richness estimate, each vascular plant species was recorded from the vegetation plots (species list in Appendix S2). Plot locations were based on an old vegetation survey from 1960s (Haapasaari, 1988). Geofeatures were observed at 5, 10 and 25 m radii starting from the shortest (printable and digital field forms in Appendices S3 and S4). In the beginning of the field campaign, observation of geofeatures within the three radii took approximately an hour per plot for the pilot group (H. Salminen, H. Snåre and P. Kiilunen), who had basic theoretical and practical training in physical geography but were not experienced in geomorphological mapping. However, relatively soon the pilot group managed to assess one plot in ca. 30 min. It should be noted that the members of the pilot group did not participate in the development of the field method before the field surveys. No permission for fieldwork nor ethical approval was required for this study.

Based on the field survey data, the proportional frequencies of individual geofeatures were calculated to describe the abiotic variation and the prevalence of different geofeatures in the study area. The sum of different geofeatures in each category (geological, geomorphological and hydrological richness), as well as the total sum of geofeatures (georichness) were calculated at three different radii. Kruskal–Wallis test was used to analyse whether the average georichness differed between the different radii. Spearman's correlations (R_s) were calculated to explore correlations between geological, geomorphological and hydrological richness, total georichness and vascular plant species richness. Moreover, correlations between the total georichness and vascular plant species richness in habitats dominated by deciduous or evergreen shrubs were explored.

The replicability of the method was explored by re-observing geofeatures from 10% of the vegetation plots ($n = 7$, a total of 21 circular mapping areas at 5, 10 and 25 m radii). The re-observing was carried out by an independent group of MSc students in physical geography with no prior information on the data recorded by the pilot group and with no previous experience of field mapping of geofeatures. The student group had ca. 5 hr to familiarize the method,

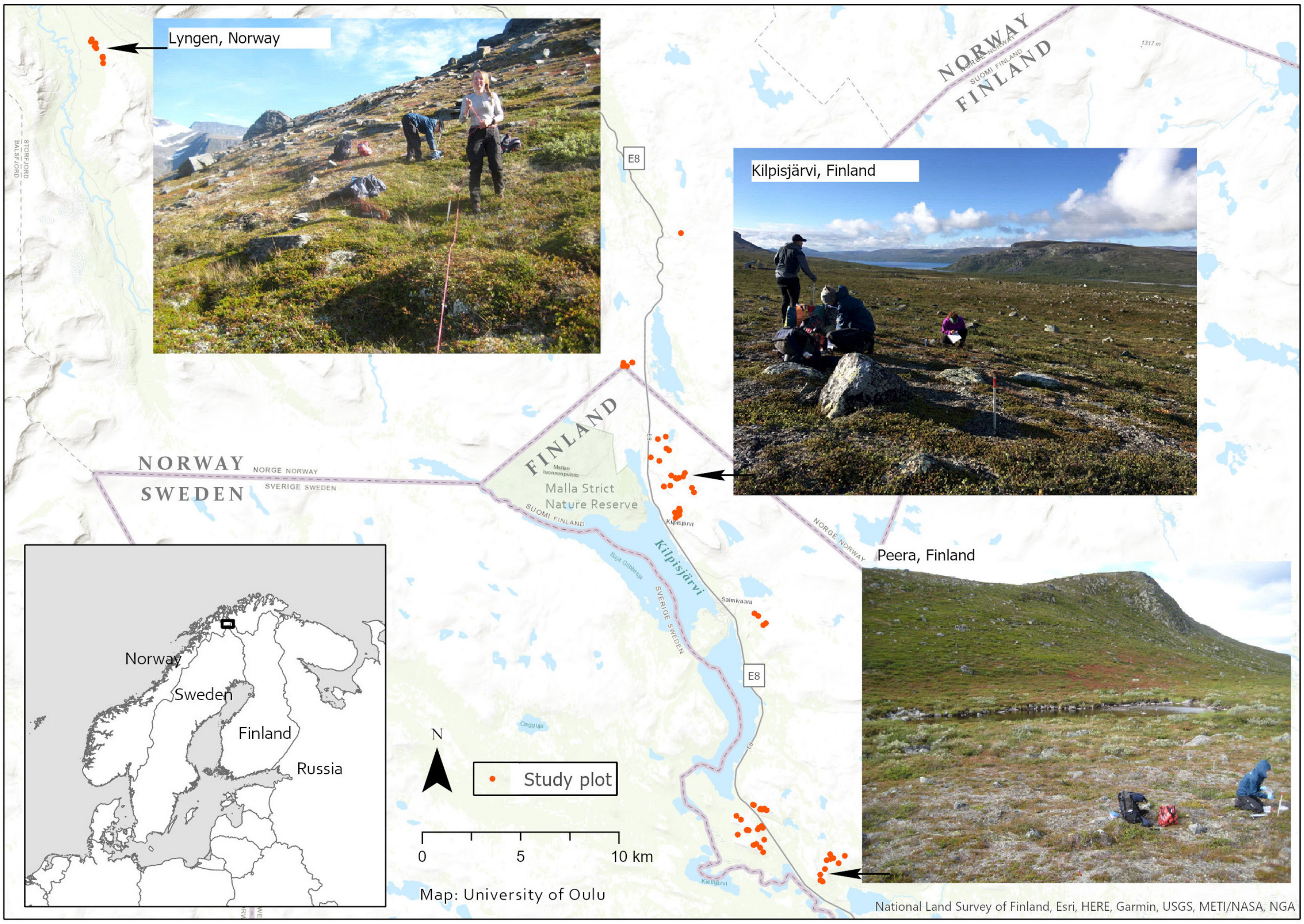

FIGURE 3 The field methodology for observing plot-scale geodiversity was piloted in an Arctic–alpine tundra environment. The studied plots ($n = 76$) are located in northern Norway and Finland. The photographs represent the typical landscapes and dominant vegetation (dwarf shrub tundra) of the studied plots

after which they carried out the field work under the supervision of J. Hjort.

3.2 | Results

A majority of the listed geofeatures (25 of 34) were recorded from the study plots (Figure 4a). The most common geological geofeature was diamicton that was found in all plots at all radii. The most common geomorphological and hydrological geofeatures were physical weathering and dry channel respectively. Radius had a positive effect on the number of geofeatures as the average georichness tended to get higher as the radius of the observed increased (Figure 4b). This was the case for each category (geology, $\chi^2 = 22.3$, $p < 0.001$; geomorphology, $\chi^2 = 67.1$, $p < 0.001$; hydrology, $\chi^2 = 16.4$, $p < 0.001$) as well as for the total georichness ($\chi^2 = 68.9$, $p < 0.001$). The mean, minimum and maximum difference was 1.0, 0 (in eight circles) and 3 (in two circles), respectively, between the total georichness values recorded by the pilot group and the student group. The correlation between species richness and total georichness was positive across scales (Figure 5a). Especially, relatively strong correlation was observed between species richness and total georichness in habitats dominated by deciduous shrubs (Figure 5b). Total georichness correlated strongly with geomorphological richness across observation radii, yet geomorphological richness alone was not significantly related to species richness at any radii (Figure 5c).

4 | DISCUSSION

As biodiversity conservation and management needs re-orientation from global evaluations to local-scale diversity investigations (Wyborn & Evans, 2021), more attention should be paid to local patterns of the abiotic environment underlying biodiversity (e.g. Zellweger et al., 2020). In this study, we developed an accessible field method to observe geodiversity at a plot-scale and applied it in an Arctic–alpine tundra environment. Our results indicated high potential of the method, as the pilot group successfully observed geofeatures with relatively little experience in geomorphology and field mapping. The geofeatures that the pilot group found from each site were typical for the local conditions (French, 2017; Hjort & Luoto, 2010; le Roux & Luoto, 2014). The observed geofeatures

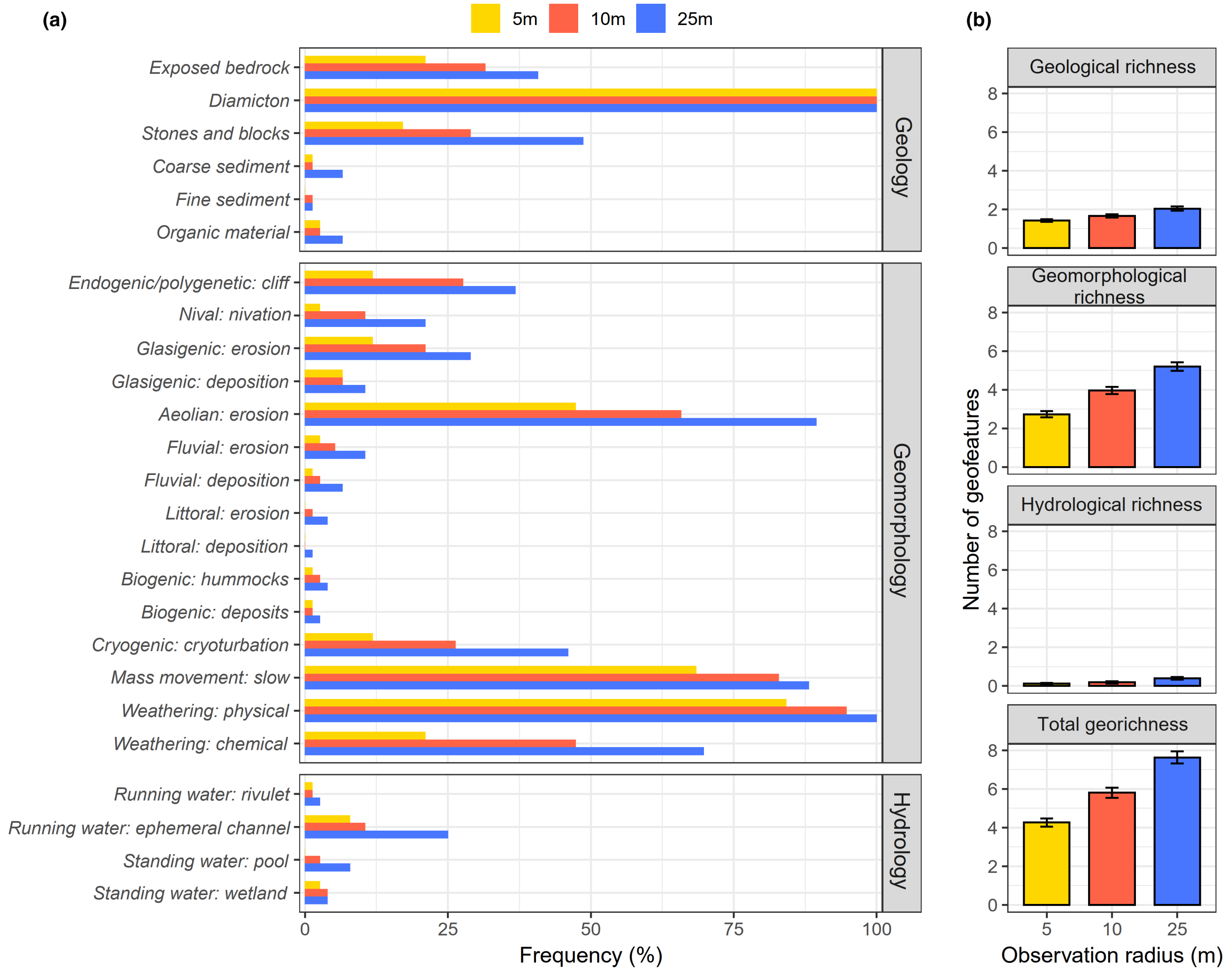

FIGURE 4 Observed geofeatures (elements of geodiversity) in the study area. (a) Frequencies of geofeatures within three different radii (5, 10 and 25 m). (b) Mean ± standard error of geological, geomorphological and hydrological richness and total georichness (sum of all geofeatures)

were further linked with vascular plant data. Our results suggested that vascular plant richness was positively correlated with georichness. This highlights the potential of incorporating field-based geodiversity information into biodiversity investigations in high-latitude tundra and mountain ecosystems, which is promising for the conservation and sustainable management of these sensitive terrestrial systems.

In our pilot study, we found a significant positive correlation between georichness and vascular plant richness. Observing geodiversity from the imminent surroundings (5 m radius) of the vegetation plot seemed the most suitable option in the studied environment, indicating that increasing the observation radius for geodiversity would also require a larger vegetation plot. We note that other radiuses can be more appropriate in other environments. Importantly, our results demonstrate that while geodiversity is composed to a great degree of geomorphological geofeatures in the study area, those alone were not enough for finding a significant link with biodiversity. Additional analyses (not shown here) indicated that georichness was not correlated with elevation or geographical location. Owing to the focus of the study (i.e. presentation of a field method) and lack of fine-scale environmental data from the studied plots (e.g. temperature and sediment chemistry) multivariate explorations were not conducted. Thus, further studies should include sets of ecologically meaningful explanatory variables to understand the importance of georichness among other variables (cf. Antonelli et al., 2018; le Roux & Luoto, 2014). Moreover, future studies should look for mechanisms that underlie the positive effect of geodiversity on species richness (Alahuhta et al., 2020; Lawler et al., 2015).

Interestingly, the correlation between georichness and species richness was clearly different between habitats dominated by deciduous and evergreen shrubs ($R_s = 0.59$, $p = 0.004$; $R_s = 0.23$, $p = 0.145$ respectively). *Empetrum nigrum* ssp. *hermaphroditum*, the dominant species in the latter habitat type, has been shown to have a negative impact on vascular plant richness in the tundra (Bråthen &

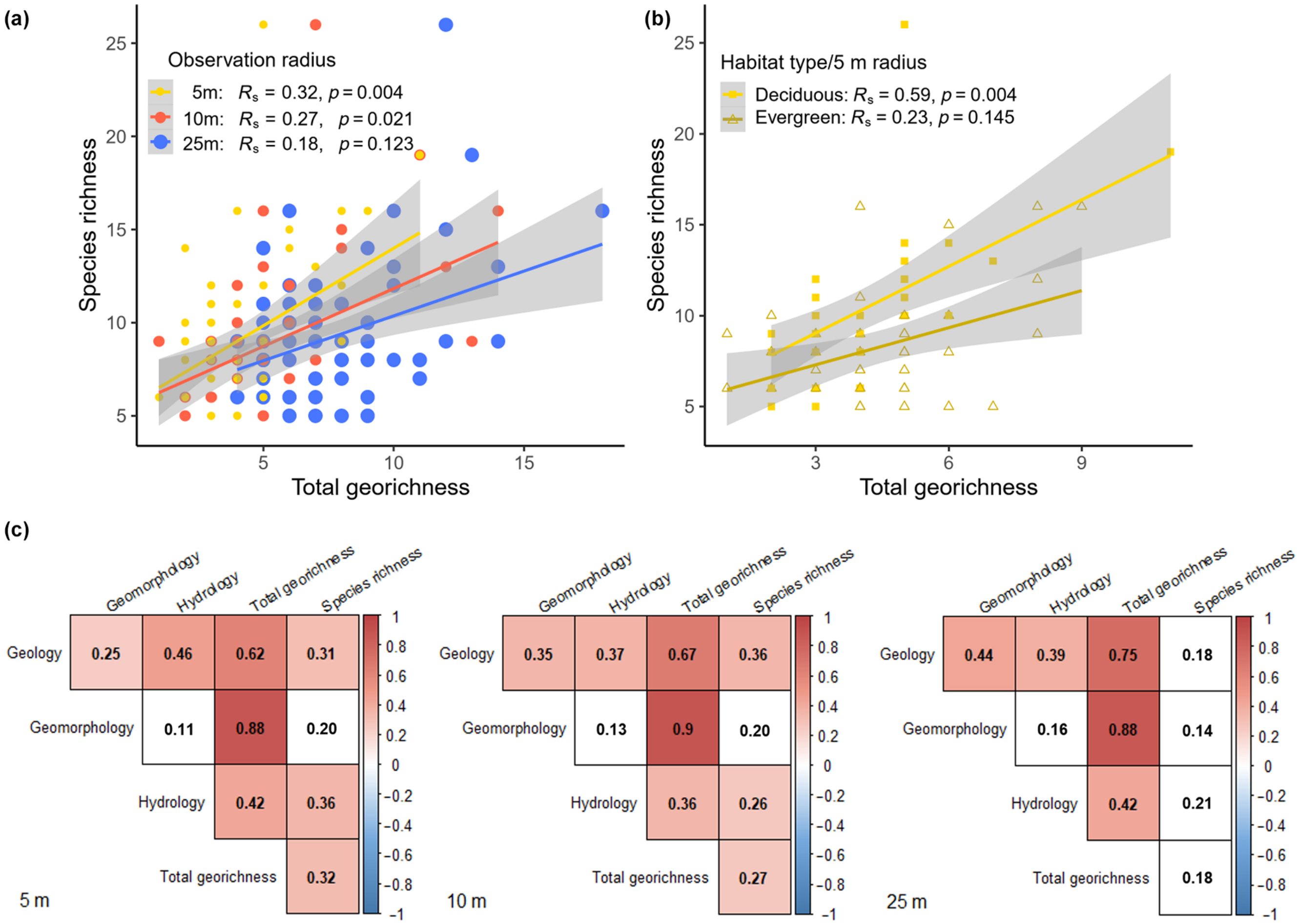

FIGURE 5 (a) The relationship between vascular plant species richness and total georichness (sum of all geofeatures) at 5, 10 and 25 m radii. (b) The relationship between species richness and total georichness in different habitat types within 5 m observation radius. Correlations in (a) and (b) are Spearman's coefficients (R_s) with statistical significance (p). (c) R_s between geological richness, geomorphological richness, hydrological richness, total georichness and species richness at different radii. Significant correlations ($p < 0.05$) are indicated with coloured background

Ravolainen, 2015). Importantly, its abundance has strongly increased in northern European tundra over the recent decades (Maliniemi et al., 2018), and this may have a strong control over current species compositions. Another strong biotic control in the study area is relatively heavy reindeer grazing that can have strong influence on species richness (Kaarlejärvi et al., 2017). Consequently, strong biotic controls likely influence the magnitude of the observed positive correlation between georichness and species richness and may partly obscure it. Therefore, it is possible that this linkage is stronger in areas where biotic controls are less abundant. Nevertheless, our results suggest that local geodiversity may improve understanding, interpretation and predictions on drivers affecting biodiversity patterns.

The presented observation system focuses on the presence/absence observations of geofeatures (the first level of expertise). If the acquired data are too simple or limited to facilitate plot-scale biodiversity analyses and conservation, the method can be developed further for the compilation of a more comprehensive set of field data on geofeatures and geodiversity. Additional information can be acquired using sampling (sediment or rock sampling), measuring (e.g. terrestrial laser scanning) and drone imaging (e.g. thermal and hyperspectral imaging). Consequently, the method can be utilized at higher proficiency levels with more geological and geomorphological training and surveying devices. The next (second) level of expertise could include quantitative mapping of geofeatures, that is, the determination of their cover (le Roux & Luoto, 2014). In the third proficiency level, information on geology (rock types and sediment properties) and activity of landforms could be acquired (see Kemppinen et al., 2019; le Roux & Luoto, 2014; Virtanen et al., 2010). Moreover, the method can be adjusted, if it is applied in closed forests or other densely vegetated ecosystems. Dense undergrowth may compromise the detection of geofeatures or there may be relatively few geofeatures to observe owing to the dominance of one or few abiotic processes or abundant vegetation. In these cases, the observation systems must be adjusted considering the local abiotic conditions, for example, by developing the systems to include topography-based landform elements (Bailey et al., 2017) (e.g. in boreal forests) or geofeatures at lower hierarchical levels (e.g. in arid and semi-arid environments dominated by one or few processes), or by enlarging the mapping area (e.g. in temperate and tropical forests). In the end, similar to vegetation surveys, the observation of geofeatures should be comparable within a dataset. This can be reached when the same person(s) map geofeatures across all the study sites. Then, despite the challenges that might arise, within-study data are comparable.

The introduced field survey method for observing plot-scale geodiversity efficiently captures the abiotic variation and can be used to complement other environmental data in biodiversity conservation and management. The method is cost-efficient, applicable and accessible even to non-experts of geodiversity, such as conservation ecologists and environmental managers. With the field method, terrestrial conservation and management can be directed to actions that better sustain and protect wide range of biological diversity (cf. Bailey et al., 2017; Lawler et al., 2015). This is because areas of high local geodiversity typically include higher levels of biodiversity (Beier et al., 2015), as seen in our preliminary empirical evidence on the positive influence of plot-scale geodiversity on plant species richness in Arctic–alpine tundra environment. For example, geodiverse areas identified using the developed field approach could act as a proxy for higher biodiversity to broaden and enhance current conservation areas at local, regional and national levels. Moreover, the developed field protocol to observe plot-scale geodiversity can potentially be used to improve identification of habitats important for a particular species or species having similar traits. This is highly promising for biodiversity conservation and management because species trait-based diversity measures explain variation in ecosystem functioning better than simple species observations (Cadotte et al., 2011). Practical potentiality of the developed field method is thus versatile, as it can be extended to investigate various environments (also human-disturbed) and organismal groups as geodiversity is present everywhere.

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CONFLICT OF INTEREST

The authors have no conflict of interest.

AUTHORS' CONTRIBUTIONS

J.H., T.M. and H.T. conceived the ideas, designed the methodology and led the writing of the manuscript; H.Sa., P.K. and H.Sn. collected the data; T.M., H.T. and H.Sa. analysed the data. All authors contributed critically to the drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

Data available via the Dryad Digital Repository https://doi.org/10.5061/dryad.n02v6wx0h (Hjort et al., 2022).

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