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PERSPECTIVE

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Too much diversity—Multiple definitions of geodiversity hinder its potential in biodiversity research

Abstract

Geodiversity—the diversity of abiotic features and processes of the Earth's surface and subsurface—is an increasingly used concept in ecological research. A growing body of scientific literature has provided evidence of positive links between geodiversity and biodiversity. These studies highlight the potential of geodiversity to improve our understanding of biodiversity patterns and to complement current biodiversity conservation practices and strategies. However, definitions of geodiversity in ecological research vary widely. This can hinder the progress of geodiversity–biodiversity research and make it difficult to synthesize findings across studies. We therefore call for greater awareness of how geodiversity is currently defined and for more consistent use of the term 'geodiversity' in biodiversity research.

1 | INTRODUCTION

Geodiversity is the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landforms, topography, physical processes), soil and hydrological features, including their assemblages, structures, systems and contributions to landscapes (Gray, 2013). Together, these components form different geophysical environments that different organisms can inhabit (Beier et al., 2015; Gray, 2013). Geodiversity and the resulting variation in, for example, microclimates and resources (e.g. water, nutrients) can promote biodiversity by creating a greater variety of habitats and environmental conditions that harbour diverse ecological strategies and broaden environmental filtering, allowing more species to co-occur (Figure 1; Parks & Mulligan, 2010). Several recent studies have demonstrated that geodiversity has a positive relationship with species richness across taxonomic groups, spatial scales and different ecosystems (Bailey et al., 2017; Boothroyd & McHenry, 2019; Kärnä et al., 2018; Salminen et al., 2023; Toivanen et al., 2019; Tukiainen, Maliniemi, et al., 2023; Figure 2). Emerging evidence also indicates a positive influence on biodiversity beyond species richness, such as trait biodiversity (Read et al., 2020; Vernham et al., 2023) or different biodiversity indices (Ren et al., 2021), as well as on ecosystem functioning and services (Fox et al., 2020; Gordon & Barron, 2013; Stavi et al., 2019) and human health (Alahuhta et al., 2022). Recognizing the role of geodiversity provides important insights into understanding biodiversity patterns. In turn, this information can be used to enhance biodiversity conservation across scales, including through coarse-filter strategies like 'conserving nature's stage' (Knudson et al., 2018). This strategy aims to conserve areas of high geodiversity to conserve areas capable of harbouring high biodiversity (Beier et al., 2015; Lawler et al., 2015). Such integrated conservation strategies are becoming increasingly important as species shift their distributions due to rapid environmental change (e.g. climate change; Anderson & Ferree, 2010; Gordon et al., 2022).

Although the terms 'biodiversity' and 'geodiversity' originated in the 1980s and early 1990s, respectively (Gray, 2013), geodiversity research has lagged behind biodiversity research in becoming an established field capable of effectively supporting nature conservation and sustainable development strategies (Brilha et al., 2018; Chakraborty & Gray, 2020). In recent years, however, there has been an upsurge in ecological research papers using geodiversity, and in 2021, UNESCO approved the International Geodiversity Day, further cementing geodiversity's global recognition (Zwolinski et al., 2023). The inclusion of the concept of geodiversity, which emerges from geosciences, into ecological and biogeographical research is a good example of the multi- and interdisciplinary efforts that are increasingly appreciated and demanded in science. Nevertheless, the concept of geodiversity is systematically absent from the aims and strategies in the international biodiversity agenda, such as the United Nations Decade on Ecosystem Restoration (2021–2030) or the Assessment on the Diverse Values and Valuation of Nature made by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2022). Despite the potential of geodiversity for ecology, biogeography and conservation biology, scientific progress has been hampered by the wide range of views on

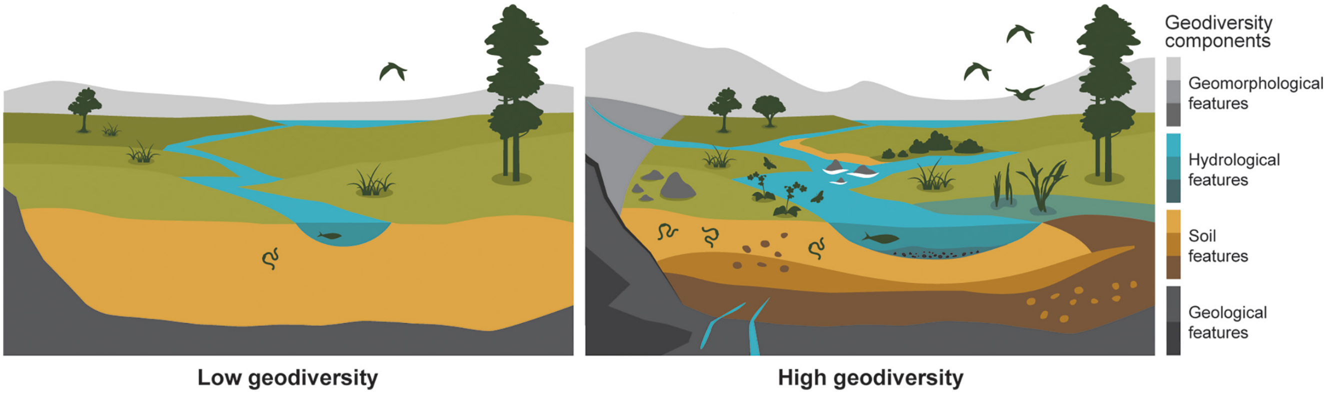

FIGURE 1 Geodiversity and biodiversity are positively linked. As geodiversity increases, it creates more habitats and environmental conditions for different species to co-occur.

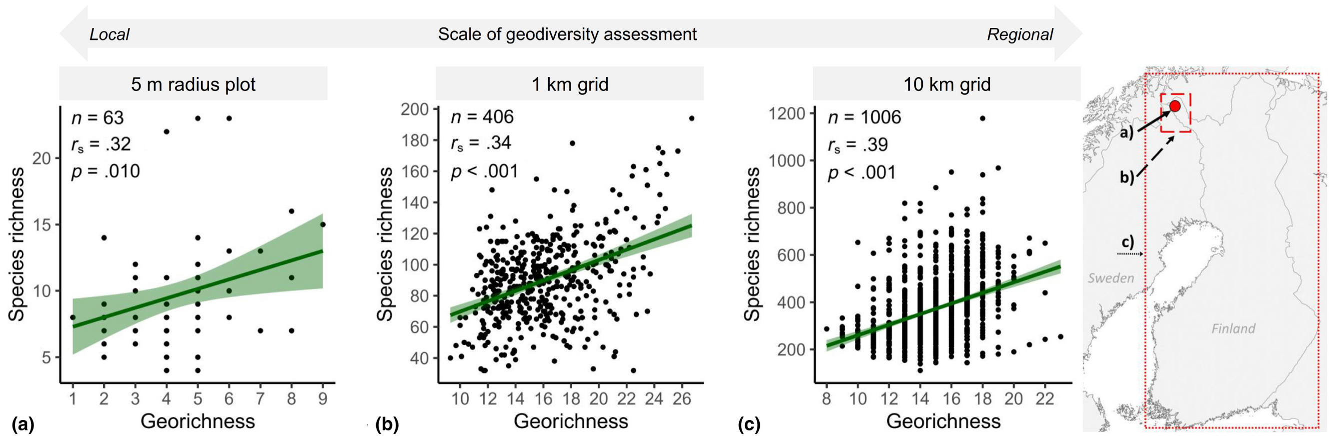

FIGURE 2 Examples of positive correlations (Spearman's rho) between geodiversity and biodiversity at different scales in Finland. In each panel, geodiversity is quantified as georichness, which is the sum of different geofeatures of the geodiversity component classes (see Figure 1), and species richness is the richness of vascular plant species. (a) Geofeatures were measured in the field (based on Hjort et al., 2022) in Kilpisjärvi, NE Finland, from a 5 m radius around 2 × 2 m vegetation plots from which species richness was derived (data from Salminen et al., 2023). (b) Georichness and species richness were derived from 1 × 1 km grid cells from the municipality of Enontekiö, NE Finland (data from Tukiainen et al., 2017). (c) Georichness and species richness were derived from 10 × 10 km grids across Finland (data from Alahuhta et al., 2018). In (b) and (c), geofeatures were obtained using GIS and modelling (based on Hjort & Luoto, 2012). The measured geofeatures vary to some extent between the scales and are described in detail in the source publications.

geodiversity's definition. We argue that a common definition is necessary to avoid difficulties in scientific synthesis and communication between researchers, environmental and park managers, land-use planners, policy makers and the general public.

According to a recent review by Boothroyd and McHenry (2019), the most widely used definition of geodiversity in ecological and biodiversity research is the aforementioned definition by Gray (2013). According to this definition, geodiversity is part of a broader concept of environmental heterogeneity, which typically also includes biotic and climatic components when studied in relation to species richness (Stein & Kreft, 2015). Distinguishing between the major components of abiotic environmental heterogeneity, that is, climate diversity and geodiversity (sensu Gray, 2013), is essential because they have individual contributions to biodiversity across scales (Bailey et al., 2017; Read et al., 2020; Salminen et al., 2023; Tukiainen et al., 2017). Disentangling the effects of climate and geodiversity is also important because climate may sometimes mask the effects of geodiversity on biodiversity. This is particularly important because the climate is changing rapidly, while the more enduring geophysical variables tend to change more slowly. Thus, compared to environmental heterogeneity, which is often a much coarser and variably defined concept that can include both biotic and abiotic variables (including climate), geodiversity can more specifically capture abiotic variation on the Earth's surface and subsurface. In biodiversity studies, however, geodiversity is often considered as one, some or all of the components listed by Gray (2013), but a number of other elements, such as climatic or biotic variables, have also been included in the concept of geodiversity in recent decades (Tukiainen, Maliniemi, et al., 2023).

Conceptual development of new terms can often lead to differing definitions tailored to specific research agendas and aims. It is therefore expected that a range of definitions for an umbrella term like geodiversity would emerge. Moreover, translating concepts between disciplines can be challenging because new concepts can be perceived from subjective perspectives and disciplinary traditions. However, now that interest in geodiversity–biodiversity studies is growing considerably, we call for greater awareness of how geodiversity is understood, defined and used in ecological research, as well as greater consistency in its use. This is important because different definitions of geodiversity create challenges in identifying what geodiversity is, what variables it refers to, and what its novelty is compared to other features and measures of environmental heterogeneity. Key issues and misconceptions about geodiversity in biodiversity studies need to be addressed in order to promote coherent and high-quality geodiversity–biodiversity research in the future.

2 | CURRENT ISSUES AND MISCONCEPTIONS

Based on our experience, discussions and peer-review feedback, one of the most common misconceptions is that geodiversity is perceived either too broadly or too narrowly (Figure 3). For instance, geodiversity is sometimes equated with the full range of environmental heterogeneity, or it includes biotic components (Wallis et al., 2022) or climate variation (Parks & Mulligan, 2010; Zarnetske et al., 2019). On the other hand, geodiversity is sometimes considered as a synonym for a single abiotic variable or its heterogeneity (such as a single geological feature or topographical heterogeneity; Crisp et al., 2023) or is thought to cover only the subsurface (van Ree & van Beukering, 2016). Currently, different definitions of geodiversity make it difficult to compare the growing number of studies on geodiversity and biodiversity. This complicates our ability to synthesize research and therefore identify patterns linking geodiversity and biodiversity. Furthermore, the development of measures, methods and guidelines for quantifying and qualifying geodiversity may be slowed down by the ambiguous definition of the term.

Another common criticism of research focusing on geodiversity and its relationship to biodiversity is whether defining geodiversity as an umbrella term encompassing geological, geomorphological, hydrological and soil components is useful for biodiversity research (Figure 3; Gray, 2021). In ecological research, abiotic drivers have traditionally been explored independently when explaining biodiversity patterns. It has also been a common approach to study only certain components of geodiversity (e.g. soil diversity; Crisp et al., 2023). Although these are fundamental contributions, they differ from 'geodiversity'. We argue that defining geodiversity according to Gray (2013) captures the holistic and dynamic links between these components allowing researchers to better understand their collective contributions to biodiversity. Furthermore, we argue that a collective definition incentivizes research that captures the complex and dynamic nature of the Earth's abiotic surface and subsurface. For instance, techniques such as structural models, that have become increasingly popular in ecology (Fan et al., 2016), can be used to analyse direct and indirect effects of each geodiversity component on dimensions of biodiversity. Finally, a common thought that we have encountered is that geodiversity has no value for biodiversity conservation (Figure 3). This stems not only from confusion about geodiversity as a concept but also from an incomplete awareness of the purposes of geodiversity–biodiversity studies—specifically, how they support conservation strategies, such as 'conserving nature's stage' (Lawler et al., 2015).

3 | SOLUTIONS AND THE WAY FORWARD

A key approach to overcoming misconceptions about geodiversity is to raise awareness of the current range of definitions and to establish a common understanding of the concept of geodiversity (Figure 3). With an established definition, it will also be easier to

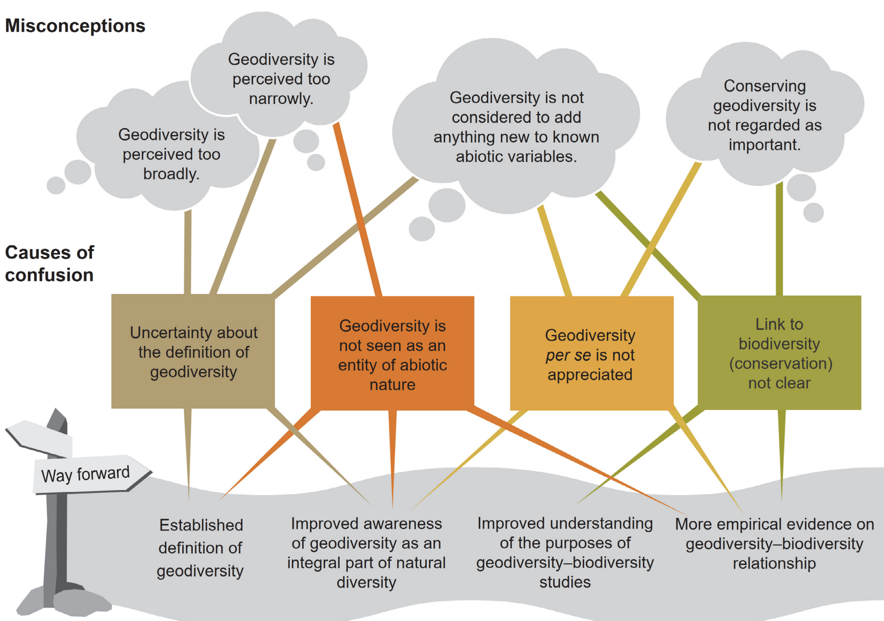

FIGURE 3 Common misconceptions of geodiversity in biodiversity studies based on published literature, interdisciplinary discussions and peer-review comments that we have received in relation to geodiversity–biodiversity studies. We propose likely causes of these misconceptions and suggest a way forward to advance future geodiversity–biodiversity research.

perceive geodiversity as an integral part of nature. It is also important to recognize that there are different purposes of geodiversity–biodiversity studies; for instance, the aim might be to find abiotic features that are relevant to biodiversity or to explore whether conserving geodiverse areas would improve biodiversity conservation. As many of the components included in the proposed geodiversity definition have been explored independently in ecology (e.g. hydrological diversity, Lawson et al., 2015; soil diversity, Stark et al., 2017; geological diversity, Antonelli et al., 2018), there is an opportunity to integrate and synthesize this research with existing research linking biodiversity and geodiversity (Crisp et al., 2023). Finally, while reaching a common agreement on the definition of geodiversity, it is essential to continue gathering empirical, and ideally experimental, evidence on geodiversity–biodiversity relationships from different ecosystems and at different spatial and temporal scales (Alahuhta et al., 2020). In particular, temporal evidence to empirically support the 'conserving nature's stage' -perspective (Beier et al., 2015; Lawler et al., 2015) would be of great importance (Gordon et al., 2022).

Similar to biodiversity, geodiversity is a multivariate concept that often requires practical tools to be applied in science and in practice. Gray's (2013) definition allows identifying and capturing specific variables to measure and parameterize geodiversity (Zwolinski et al., 2018). Each of these variables belongs to a certain geodiversity component class (Figure 1) and can be, for example, different state and process variables such as Essential Geodiversity Variables (Schrodt et al., 2019), or comparable 'geofeatures' that can be mapped in the field (Hjort et al., 2022) or derived from GIS (geographical information system; Toivanen et al., 2024) and remote sensing data (Hjort & Luoto, 2012; Ren et al., 2021; Zarnetske et al., 2019). Importantly, the spatial scale and associated data of the study will determine the specific geodiversity variables, that is, plot-scale studies may benefit from including, for example, small-scale variation in soil types and textures and in-situ measurements, whereas landscape-scale studies may only need to include coarser soil classes that can be derived using GIS and remote sensing. A recently developed taxonomy of geodiversity can help to determine which variables should be measured at different scales (Hjort et al., 2024). The clear definition of geodiversity also allows its explicit quantification, which can be done in the same way as for biodiversity. For instance, different geodiversity variables can be summed up to form 'georichness' (Figure 2) analogous to different species forming species richness. To date, using such sum variables has been one of the most common practices to relate geodiversity and biodiversity in quantitative studies (Tukiainen, Toivanen, & Maliniemi, 2023). Using abundance data, in turn, allows calculating also other metrics, for instance, different geoindices or abundance-based betageodiversity (analogous to beta biodiversity, Tukiainen, Maliniemi, et al., 2023).

Confusion about geodiversity is not unique to the geodiversity–biodiversity context (Boothroyd & McHenry, 2019; Fox et al., 2020; Gray, 2021), and similar discrepancies in concept development and definitions have been discussed in relation to environmental heterogeneity (Stein & Kreft, 2015) and biodiversity (Agapow et al., 2004). As geodiversity research is a relatively young discipline without well-established terminology, a wrong turn in the development of a concept could affect how useful it is perceived to be by the scientific community and policymakers. Current misconceptions about the use of geodiversity in biodiversity studies undermine our ability to conduct holistic environmental research and create effective management plans. Apart from hampering scientific progress, the presented misconceptions can have serious consequences at the policy-making level, as geodiversity information is increasingly used to delineate conservation actions (Anderson et al., 2015), achieve the Sustainable Development Goals and work towards disaster risk reduction (Schrodt et al., 2019).

4 | CONCLUSIONS AND RECOMMENDATIONS

Along with many researchers studying geodiversity and biodiversity (Boothroyd & McHenry, 2019; Crisp et al., 2023), we suggest that Gray's (2013) definition and terminology should be used consistently when bringing geodiversity into biodiversity research. We also recommend clearly communicating which components of geodiversity—all or some—from Gray's (2013) definition are included in biodiversity studies, as has been suggested in relation to ecosystem services (Fox et al., 2020). Once commonly agreed upon, the definition will allow the development of a more consistent framework, such as common assessment protocols and analytical tools, which are still needed to improve the coherence of geodiversity–biodiversity studies. In addition, we encourage researchers to clearly communicate how they use geodiversity information in an ecological context. We expect that consideration of these recommendations will help to reduce confusion over the use of geodiversity in biodiversity studies.

KEYWORDS
abiotic diversity, biodiversity patterns, conservation strategies, conserving nature's stage, definition of geodiversity, environmental heterogeneity, geodiversity terminology

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data are available in the article Data S1.

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BIOSKETCHES

The authors include geographers, ecologists, geologists and environmental scientists with an interest in the relationship between geodiversity and biodiversity. They represent different research groups and career stages from doctoral students to postdoctoral fellows, senior researchers and professors. They actively conduct and follow geodiversity–biodiversity research and participate in discussions on the topic in various academic venues.

Author contributions: TM initiated the original idea and led the writing with support by HT and JA. MT designed and finalized the figures. All authors contributed discussions, commented and edited the manuscript and gave their final acceptance.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.