Quantifying alpha, beta and gamma geodiversity

ABSTRACT

Geodiversity is an emerging, multi-faceted concept in Earth and environmental sciences. Knowledge on geodiversity is crucial for understanding functions of natural systems and in guiding sustainable development. Despite the critical nature of geodiversity information, data acquisition and analytical methods have lagged behind the conceptual developments in biosciences. Thus, we propose that geodiversity research could adopt the framework of alpha, beta, and gamma concepts widely used in biodiversity research. Especially, geodiversity research would benefit from widening its scope from the evaluation of individual sites towards more holistic geodiversity assessments, where between-site geodiversity is also considered. In this article, we explore the alpha, beta and gamma concepts and how they can be applied in a geodiversity framework. In addition, we scrutinize the statistical methodology related to alpha, beta and gamma geodiversity evaluations, with a special focus on distance metrics for measuring beta geodiversity. As an overview of the process, and to give practical guidelines for the application of the proposed methodology, we present a case study from a UNESCO Global Geopark area. Thus, this study not only develops the geodiversity concept, but also paves the way for simultaneous understanding of both geodiversity and biodiversity within a unified conceptual approach.

Keywords: biodiversity, beta diversity, distance metrics, geodiversity, geofeature, nature conservation

I. INTRODUCTION

Geodiversity is a recent concept in Earth and environmental sciences and refers to the variety of abiotic features and processes of the land surface and subsurface (Gray, 2013; Beier et al., 2015; Brilha et al., 2018; Alahuhta et al., 2020; Crofts et al., 2020; Schrodt et al., 2020). Although the concept is gaining increasing attention, general frameworks for quantifying geodiversity remain largely unestablished. Instead, a variety of approaches based on field measurements, numerical calculations, statistical methods and GIS-analyses have been applied to measure geodiversity (Zwoliński et al., 2018; Boothroyd and McHenry, 2019; Crisp et al., 2021). The resulting estimates vary substantially from sum-based variables (Hjort et al., 2012; Tukiainen et al., 2017; Antonelli et al., 2018) to different geodiversity indices (Serrano and Ruiz-Flaño, 2007; Ruban, 2010; de Paula Silva et al., 2021) and topographical variables derived from satellite remote sensing data (Zarnetske et al., 2019; Lausch et al., 2019; Read et al., 2020). These estimates are often difficult to compare across or between locations and scales. Moreover, most studies that assess geodiversity are focused mainly on exploring the degree of geodiversity at individual sites (Zwoliński et al., 2018) and, so far, no framework exists for quantifying geodiversity between sites (but see Ibañez et al., 1995 on pedodiversity). Thus, increased efforts towards attaining standardized methodology to quantify geodiversity are urgently needed (Crisp et al., 2021).

A recently introduced conservation strategy called ‘Conserving Nature´s Stage’ proposes that geodiversity forms the stage on which the actors, or organisms, live. The basic premise is that the more diverse this abiotic stage is, the more different kinds of organisms it harbours (Gillespie and Roderick, 2014; Beier et al., 2015; Knudson et al., 2018). Along with climate, historical and evolutionary effects, geodiversity is assumed to be one of the main determinants of species diversity variation at different scales (Nichols et al., 1998; Parks and Mulligan, 2010; Heino et al., 2013; Ibañez and Feoli, 2013; Antonelli et al., 2018; Bailey et al., 2018; Tukiainen et al., 2019; Zarnetske et al., 2019; Halvorsen et al., 2020; Read et al., 2020; De Falco et al., 2021). Thus, using the same analytical approaches in measuring both geodiversity and biodiversity would have strong implications in guiding nature conservation and for unifying research in environmental sciences.

Here, we propose a versatile framework that can be used to measure geodiversity systematically across different scales and areas, and which is applicable for various purposes. We suggest that an advantageous way to assess geodiversity is to apply the alpha, beta and gamma components and related analytical approaches that are widely acknowledged in biodiversity research (Whittaker, 1960, 1972; Anderson et al., 2011). First, we shortly introduce the alpha, beta and gamma components of species diversity and describe how they can be accommodated in the geodiversity framework. Second, we concentrate on the possibilities that distance metrics offer for beta geodiversity assessments and provide examples of the statistical methods that can be used in analyzing beta geodiversity. Third, we provide a detailed example of how alpha and beta geodiversity can be calculated from spatial data on geofeatures.

II. ALPHA, BETA AND GAMMA COMPONENTS

1. The alpha, beta and gamma components of species diversity

Biodiversity is a broad concept that builds on biological variation, covering the variety of genes, organisms, species, communities and ecosystems (Gaston, 2000). Therefore, biodiversity can be viewed from many different perspectives, including the original concepts of alpha (α), beta (β) and gamma (γ) diversity (Whittaker, 1972, 1960). In this context, alpha diversity refers to species diversity (such as species richness) at local sites. It can be measured for a single community or as a mean of several local communities (Whittaker, 1972, 1960). Incorporating abundance data allows the use of diversity and evenness indices, such as the Shannon and the Simpson indices, which include shares of different species at a site (Whittaker, 1972). Gamma diversity refers to overall species diversity in a region and can be measured using the same techniques and indices as alpha diversity (Whittaker, 1960).

Beta diversity is of particular interest in biodiversity research since it provides a direct link between alpha and gamma diversity (Anderson et al., 2011). Basically, there are two types of beta diversity patterns: (1) non-directional variation measures the differences in community composition among sample units within a given area, whereas (2) directional turnover measures the changes in community composition along a specific spatial, temporal or environmental gradient (Anderson et al., 2011).

2. Defining alpha, beta and gamma geodiversity

Before defining the alpha, beta and gamma components of geodiversity, it is important to consider at which scale geodiversity is the most suitable to apply in this framework (Wiens, 1989).

Following Serrano and Ruiz-Flaño (2007), we consider the 'elements' of geodiversity (geofeatures, or specific features of geology, geomorphology, and hydrology) as the basic unit in the framework (Fig. 1). Geofeatures are easy to map and use in applications when compared to the more precise levels of abiotic diversity, and have been in the focus of land management and conservation policies (Serrano and Ruiz-Flaño, 2007). A sand dune, a pond and weathered bedrock are examples of individual geofeatures (Fig. 1). It should be noted that the typical applications of geofeatures, such as geoheritage and geoconservation (Gray, 2013; Brilha, 2016) are not considered in this article.

[insert Figure 1.]

Based on the information on geofeatures, it is possible to measure geodiversity at alpha, beta and gamma levels (Fig. 1). **Alpha geodiversity** can be defined as *the variability of rock types, soils, landforms, and hydrological features at a site.* The size of the site can vary from less than one square meter to thousands of square kilometres (e.g. from a small stream to a watershed). At the finest spatial scales, only one or a few components of geodiversity can be observed. For example, the granulometric and mineralogical variability of a soil sample could be the alpha geodiversity of that sample. At broader spatial scales, alpha diversity could be a simple sum of different rock types, soil types, landforms, and hydrological features of the study site. Additionally, commonly used diversity indices (e.g. Shannon and Simpson) can be applied to measure alpha geodiversity of a site. **Beta geodiversity** can be defined as *the difference of geofeatures between two sites*. Thus, beta geodiversity measures dissimilarities in the composition of geofeatures between different sites. Here, it is important to note that two sites may both have a high alpha geodiversity and share the same geofeatures, resulting in low beta geodiversity. On the contrary, two sites with low alpha diversity may contain completely different sets of geofeatures, thereby showing a high level of beta geodiversity. Finally, **gamma geodiversity** can be defined as *the variability of rock types, soils, landforms and hydrological features across sites in a region*.

III. EXPLORING ALPHA, BETA AND GAMMA GEODIVERSITY

1. Measuring alpha and gamma geodiversity

The most common measure of geodiversity is the number of different geofeatures within a study area (Ibañez and Feoli, 2013; Alahuhta et al., 2020), which can be regarded as alpha or gamma geodiversity, depending on the resolution of the measures. A few previous studies have extended geodiversity assessments beyond simple richness measures by incorporating diversity and evenness indices to geodiversity research (Ibañez et al., 1995; Benito-Calvo et al., 2009; Amatulli et al., 2018; Read et al., 2020). New technological advances, such as fine-scale remote sensing or global-scale GIS data, enable the observation of alpha and gamma diversity across broad spatial scales (Amatulli et al., 2018; Antonelli et al., 2018).

2. Distance metrics for measuring beta geodiversity

A key aspect in the measurement of beta geodiversity is to consider the original geofeatures as if they were single biological species, which is the typical approach in biodiversity research (Anderson et al., 2011). For instance, let us consider a situation where we have three sites, and from each site we have recordings of six hypothetical biological species and a set of six geofeatures (Fig. 2). From such data, we could measure dissimilarities (or distances) between two sites using ecological resemblance coefficients (Legendre and Legendre, 2012). These dissimilarities can be based either on a set of species in biodiversity research or on a set of geofeatures in geodiversity research (Fig. 2).

[insert Figure 2.]

Basically, beta geodiversity can be assessed with the same set of resemblance coefficients as beta biodiversity. Here, we provide three examples of general situations where these resemblance coefficients can be applied in beta geodiversity research. *First*, if the original geofeature variables are recorded as simple presences and absences at a site, classic qualitative coefficients (Legendre and Legendre, 2012), such as Jaccard or Sørensen, can be used to measure abiotic dissimilarities between sites. *Second*, if all original geofeature variables are quantitative (i.e. the area covered by each geofeature is known), one can use Euclidean distance or standardized Euclidean distance, depending on whether the original variables were measured using the same units or not, respectively. *Third*, if there is a mixed set of both continuous and categorical variables among the set of original geofeature variables, one can apply Gower distance (Gower, 1971).

3. Analytical methods to examine beta geodiversity

All distance-based ecological methods can be used to examine and test patterns in beta geodiversity. Starting from a dissimilarity (or distance) matrix describing abiotic differences between sites, one could apply ordination analysis, cluster analysis and various methods testing statistically significant differences between two or more sets of sites (Anderson et al., 2011; Fig. 3). In the following, we introduce five analytical approaches as examples.

[insert Figure 3.]

First, distance-based unconstrained ordination, including Principal Coordinates Analysis (PCoA; Gower, 1966) or non-metric multidimensional scaling (NMDS; Kruskal, 1964), can be used for descriptive analysis of patterns in beta geodiversity across a set of sites in a reduced ordination space of two or more ordination axes. *Second*, clustering methods, such as Unweighted Pair Group Method with Arithmetic Mean (UPGMA; Sokal and Michener, 1958), can be used to classify sites to groups where sites share similar abiotic conditions. Third, methods testing differences in average abiotic conditions (Permutational Multivariate Analysis of Variance, PERMANOVA; Anderson, 2001) and heterogeneity in abiotic conditions (Permutational Analysis of Multivariate Dispersions, PERMDISP; Anderson et al., 2006) are useful for examining differences in beta geodiversity among sets of sites. *Fourth*, for examining variation in beta geodiversity along spatial gradients, for example, Mantel test (Mantel, 1967) or Multiple Regression of Distance matrices (Lichstein, 2007) can be used. In addition, to get further insight into beta geodiversity, one can use Mantel correlograms (Oden and Sokal, 1986) to examine spatial autocorrelation based on different spatial distance classes. *Finally*, for associating beta biodiversity and beta geodiversity, Mantel test and Regression of Distance Matrices can be further used to test the match between biotic and abiotic distance matrices.

IV. A PRACTICAL EXAMPLE OF QUANTIFYING ALPHA AND BETA GEODIVERSITY

As an example of applying the proposed framework in geodiversity assessments, we demonstrate how alpha and beta geodiversity can be calculated using spatial data on soils, rocks, geomorphology and hydrology within the Rokua UNESCO Global Geopark in Finland (Fig. 4). The Rokua Geopark is a member of the UNESCO Global Geoparks network which consists of sites and landscapes of international geological significance (Henriques and Brilha 2017). The geology of Rokua is characterized by various landforms shaped by the last Ice Age, such as extensive dunes, glacial ridges, aapa mires and kettle-hole lakes.

[insert Figure 4.]

1. Material and methods

The calculation of alpha and beta geodiversity requires spatial data on different geofeatures. In this study (Fig. 4), we considered data on landforms (Aartolahti 1973; National Land Survey of Finland 2019), rock types (Geological Survey of Finland 2010a), soil types (Geological Survey of Finland 2010b), and hydrological features (Finnish Environment Institute 2013, 2015a, 2015b). We created a 1x1 km grid, consisting of 265 cells, to cover the core are of the Rokua

UNESCO Global Geopark, the Rokuanvaara area (Fig. 5). We recorded the absence or presence of each geofeature and calculated their coverage (m^2) in each 1x1 km grid cell with ArcGIS Pro.

[insert Figure 5.]

We used previously introduced statistical methods to assess geodiversity at alpha and beta levels in the study area. All the analyses were made in R (R Core Team, 2021). The data and the code for the study are available at Zenodo (Anonymous, 2021). We quantified alpha geodiversity by calculating the total number of different geofeatures in each grid cell and visualized this variation as a map (Fig. 5). For assessing beta geodiversity, we calculated pairwise dissimilarity matrices based on Jaccard (presence-absence data) and Euclidean (coverage data) dissimilarity coefficients using the function vegdist from R package vegan (Oksanen et al., 2020; R Core Team, 2021).

We visualized beta geodiversity patterns on the map based on three-dimensional NMDS ordinations that were run for the Jaccard and Euclidean distance matrices (Fig. 5) using the function metaMDS from R package vegan (Oksanen et al., 2020). Stresses of the final NMDS solutions were acceptable (0.095 and 0.119, respectively). We did the visualization with the functions recluster.col and recluster.plot.sites.col from R package recluster (Dapporto et al., 2020). The former projects the NMDS result into an RGB space, thus allowing the axes to be displayed simultaneously, and the latter produces an RGB colour map for the study area. To measure beta diversity, we also implemented hierarchical cluster analysis for both dissimilarity matrices using UPGMA and set the number of clusters to ten (Fig. 5). We performed the cluster analysis with the functions hclust and cutree from R package stats (R Core Team, 2021).

We used correlograms to examine the variation in spatial distribution of alpha and beta geodiversity (Fig. 6). For alpha geodiversity, we calculated Moran's coefficients using correlog function from the R package pgirmess (Giraudoux et al., 2018), whereas for beta geodiversity, we calculated Mantel correlations for both dissimilarity matrices using the function mantel.correlog from R package vegan (Oksanen et al., 2020).

[insert Figure 6.]

2. Results and discussion

The results show that geodiversity varies considerably on both alpha and beta levels across the study area (Fig. 5). The grid cells with high alpha geodiversity are scattered across the study area, while especially the south-western part of the region has a low number of geofeatures. Pairwise dissimilarities in compositions of geofeatures among grid cells, as well as clustering of the grid cells, are somewhat distinct between the centre of the study area (characterized by varying topography and kettle-hole lakes), and the surrounding grid cells. In addition, the cluster analysis results highlight the unique beta diversity of the Oulujoki river valley in the northern/north-eastern part of the study area. There is some spatial autocorrelation, indicating that grid cells close to each other are more similar in geofeature composition than grid cells further apart (Fig. 6). Interestingly, the analyses based on quantitative data on geofeature coverage reveal more nuanced variation in beta diversity than the analyses based on presences and absences of geofeatures (Fig. 5).

In this case study, we demonstrated the utility of practical assessment of alpha and beta geodiversity with digital spatial data. We used data on landforms, rock types, soil types and hydrological features in this example study (Fig. 4), but the introduced approach is applicable to any kinds of spatial data on geofeatures. Ordination and clustering methods are easy to apply to geofeature datasets, and the analyses at beta diversity level provide additional information on the geodiversity of the area when compared to mere alpha geodiversity. Information on the hotspots of local geodiversity (alpha geodiversity) as well as areas that are clearly distinguishable in terms of their geofeature composition (beta geodiversity) in the study area can be further utilized, for instance, in planning the conservation or recreation in the Rokua UNESCO Global Geopark. Furthermore, by using this framework, any area can be explored if digital spatial data on geofeatures is available.

V. CONCLUSION

We argue that developing the geodiversity framework and methods to measure geodiversity is essential for better understanding of the natural diversity on the earth. One step towards achieving this goal could be the implementation of the alpha, beta and gamma concepts, and related analytical methods, that are widely used in biodiversity research. Using this conceptual approach would not only contribute to the unification of different disciplines, but it would also set new standards for geodiversity research (see also Ibáñez and Brevik, 2019; Schrodt et al., 2019; Crisp et al., 2021). Specifically, applications of beta geodiversity will provide novel insights into environmental sciences and nature conservation practices.

DECLARATION OF CONFLICTING INTERESTS

The authors declared no potential conflicts of interestwith respect to the research, authorship, and/or publicationof this article

REFERENCES

Aartolahti T (1973) Morphology, vegetation and development of Rokuanvaara, an esker and dune complex in Finland. *Fennia* 127. Societas geographica Fenniae, Helsinki.

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

Amatulli G, Domisch S, Tuanmu M-N, Parmentier B, Ranipeta A, Malczyk J and Jetz W (2018) A suite of global, cross-scale topographic variables for environmental and biodiversity modelling. *Scientific data* 5: 180040. https://doi.org/10.1038/sdata.2018.40

Anderson MJ (2001) A new method for non-parametric multivariate analysis of variance. *Austral Ecology* 26: 32– 46. https://doi.org/10.1111/j.1442-9993.2001.01070.pp.x

Anderson MJ, Crist TO, Chase JM, Vellend M, Inouye BD, Freestone AL, Sanders NJ, Cornell HV, Comita LS, Davies KF, Harrison SP, Kraft NJB, Stegen JC and Swenson NG (2011) Navigating the multiple meanings of β diversity: a roadmap for the practicing ecologist:

Ecol. Lett. 14: 19–28. https://doi.org/10.1111/j.1461-0248.2010.01552.x

Anderson MJ, Ellingsen KE and McArdle BH (2006) Multivariate dispersion as a measure of beta diversity. *Ecology Letters* 9: 683–693. https://doi.org/10.1111/j.1461-0248.2006.00926.x

Anonymous (2021) Data and code for the paper "Quantifying alpha, beta and gamma geodiversity" *Zenodo*: http://doi.org/10.5281/zenodo.4610019

Antonelli A, Kissling WD, Flantua SGA, et al (2018) Geological and climatic influences on mountain biodiversity. *Nature Geoscience* 11: 718–725. https://doi.org/10.1038/s41561-018-0236-z

Bailey JJ, Boyd DS and Field, R (2018) Models of upland species' distributions are improved by accounting for geodiversity. *Landscape Ecology* 33: 2071–2087. https://doi.org/10.1007/s10980-018-0723-z

Beier P, Hunter ML and Anderson M (2015) Introduction. Special Section: Conserving Nature's Stage. *Conservation Biology* 29: 613–617. https://doi.org/10.1111/cobi.12511

Benito-Calvo A, Pérez-González A, Magri O and Meza P (2009) Assessing regional geodiversity: the Iberian Peninsula. *Earth Surface Processes and Landforms* 34: 1433-1445. https://doi.org/10.1002/esp.1840

Boothroyd A and McHenry M (2019) Old Processes, New Movements: The Inclusion of Geodiversity in Biological and Ecological Discourse. *Diversity* 11: 216. https://doi.org/10.3390/d11110216

Brilha J (2016) Inventory and Quantitative Assessment of Geosites and Geodiversity Sites: a Review. *Geoheritage* 8: 119–134. https://doi.org/10.1007/s12371-014-0139-3

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

Crisp JR, Ellison JC and Fischer A (2021) Current trends and future directions in quantitative geodiversity assessment. *Progress in Physical Geography: Earth and Environment* 45: 515–540. https://doi.org/10.1177/0309133320967219

Crofts R, et al (2020). Guidelines for geoconservation in protected and conserved areas. *IUCN Best Practice Protected Area Guidelines Series* 31.

Dapporto L, Ramazzotti M, Fattorini S, Vila R, Talavera G and Dennis RHL (2020) Package "recluster: Ordination Methods for the Analysis of Beta-Diversity Indices (R package version 2.9). https://cran.r-project.org/web/packages/recluster

de Paula Silva J, Alves GB, Ross JLS, et al (2021) The Geodiversity of Brazil: Quantification, Distribution, and Implications for Conservation Areas. *Geoheritage* 13: 75. https://doi.org/10.1007/s12371-021-00598-0

De Falco N, Tal-Berger R, Hjazin A, Yizhaq H, Stavi I and Rachmilevitch S (2021) Geodiversity impacts plant community structure in a semi-arid region. Sci Rep 11: 15259. https://doi.org/10.1038/s41598-021-94698-0

Finnish Environment Institute (2015a) River areas. Available at: https://paikkatieto.ymparisto.fi/lapio/latauspalvelu.html.

Finnish Environment Institute (2015b) Lakes. Available at: https://paikkatieto.ymparisto.fi/lapio/latauspalvelu.html

Finnish Environment Institute (2013) Ground water areas. Available at: https://paikkatieto.ymparisto.fi/lapio/latauspalvelu.html

Gaston K (2000) Global patterns in biodiversity. *Nature* 405: 220–227.

https://doi.org/10.1038/35012228

Geological Survey of Finland (2010a) Bedrock of Finland 1:200 000. Available at: http://hakku.gtk.fi/en/locations/search

Geological Survey of Finland (2010b) Superficial Deposits of Finland 1:200 000. Available at: http://hakku.gtk.fi/en/locations/search (2010b).

Gillespie R, Roderick G (2014) Geology and climate drive diversification. *Nature* 509: 297–298. https://doi.org/10.1038/509297a

Giraudoux P, Antonietti J-P, Beale C, Pleydell D and Treglia M (2018) Package "pgirmess": Spatial Analysis and Data Mining for Field Ecologists (R package version 1.6.9). https://cran.r-project.org/web/packages/pgirmess

Gower JC (1966) Some Distance Properties of Latent Root and Vector Methods Used in Multivariate Analysis. *Biometrika* 53: 325–338. https://doi.org/10.1093/biomet/53.3-4.325

Gower JC (1971) A general coefficient of similarity and some of its properties. *Biometrics* 27: 857–874. https://doi.org/10.2307/2528823

Gray M (2013) *Geodiversity: valuing and conserving abiotic nature*. Chichester: Wiley-Blackwell, 512 p.

Halvorsen R, et al (2020) Towards a systematics of ecodiversity: The EcoSyst framework. *Global Ecol Biogeogr* 29: 1887–1906. https://doi.org/10.1111/geb.13164

Heino J, Grönroos M, Ilmonen J, Karhu T, Niva M and Paasivirta L (2013) Environmental heterogeneity and β diversity of stream macroinvertebrate communities at intermediate spatial scales. *Freshwater Science* 32: 142–154. https://doi.org/10.1899/12-083.1

Henriques MH and Brilha J (2017) UNESCO Global Geoparks: a strategy towards global understanding and sustainability. *Episodes* 40: 349–355. https://doi.org/10.18814/EPIIUGS/2017/V40I4/017036

Hjort J, Heikkinen R, Luoto M (2012) Inclusion of explicit measures of geodiversity improve biodiversity models in a boreal landscape. *Biodiversity and Conservation* 21: 3487–3506. https://doi.org/10.1007/s10531-012-0376-1

Ibáñez JJ and Brevik EC (2019) Divergence in natural diversity studies: The need to standardize methods and goals. *Catena* 182: 104110. https://doi.org/10.1016/j.catena.2019.104110

Ibañez JJ and Feoli E (2013) Global Relationships of Pedodiversity and Biodiversity. *Vadose Zone Journal* 12: 1–5. https://doi.org/10.2136/vzj2012.0186

Ibañez JJ, De-Alba S, Bermfidez FF and Garcla-Alvarez A (1995) Pedodiversity: concepts and measures. *Catena* 24: 215–232. https://doi.org/10.1016/0341-8162(95)00028-Q

Knudson C, Kay K, Fisher S (2018) Appraising geodiversity and cultural diversity approaches to building resilience through conservation. *Nature Climate Change* 8: 678–685. https://doi.org/10.1038/s41558-018-0188-8

Kruskal JB (1964) Multidimensional scaling by optimizing goodness of fit to a nonmetric hypothesis. *Psychometrika* 29: 1–27. https://doi.org/10.1007/BF02289565

Lausch A, et al (2019) Linking Remote Sensing and Geodiversity and Their Traits Relevant to Biodiversity—Part I: Soil Characteristics. *Remote sensing* 11: 2356. https://doi.org/10.3390/rs11202356

Legendre P and Legendre L (2012) *Numerical Ecology*. Amsterdam: Elsevier, 1006 p.

Lichstein JW (2007) Multiple regression on distance matrices: a multivariate spatial analysis tool. *Plant Ecology* 188: 117–131. https://doi.org/10.1007/s11258-006-9126-3

Mantel N (1967) The detection of disease clustering and a generalized regression approach: *Cancer Research* 27: 209–220. PMID: 6018555.

National Land Survey of Finland (2019) Topographic database. MTK-suo. Available at: https://paituli.csc.fi/download.html

Nichols WF, Killingbeck KT and August PV (1998) The influence of geomorphological heterogeneity on biodiversity: II. A landscape perspective. *Conservation Biology* 12: 371–379. http://www.jstor.org/stable/2387507

Oden NL and Sokal RR (1986) Directional autocorrelation: an extension of spatial correlograms to two dimensions. *Systematic Zoology* 35: 608–617. https://doi.org/10.2307/2413120

Oksanen J, Blanchet FG, Friendly M, et al (2020). Package "vegan": Community Ecology Package (R package version 2.5-7). https://cran.r-project.org/web/packages/vegan

Parks KE and Mulligan M (2010) On the relationship between a resource based measure of geodiversity and broad scale biodiversity patterns. *Biodiversity and Conservation* 19: 2751–2766. https://doi.org/10.1007/s10531-010-9876-z

R Core Team (2021) R: A language and environment for statistical computing (Version 4.0.3): R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Read QD, Zarnetske PL, Record S, et al (2020) Beyond counts and averages: Relating geodiversity to dimensions of biodiversity. *Global Ecology and Biogeography* 29: 696–710. https://doi.org/10.1111/geb.13061

Ruban D (2010) Quantification of geodiversity and its loss. *Proceedings of the Geologists' Association* 121: 326–333. https://doi.org/10.1016/j.pgeola.2010.07.002

Schrodt F, Bailey JJ, Kissling D, et al (2019). Opinion: To advance sustainable stewardship, we must document not only biodiversity but geodiversity. *PNAS* 116: 16155–16158.

https://doi.org/10.1073/pnas.1911799116

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

Sokal RR and Michener CD (1958) A statistical method for evaluating systematic relationships. *University of Kansas Science Bulletin* 38: 1409–1438.

Tukiainen H, Bailey JJ, Field R, Kangas K and Hjort J (2017) Combining geodiversity with climate and topography to account for threatened species richness. *Conservation Biology* 31: 364–375. https://doi.org/10.1111/cobi.12799

Tukiainen H, Kiuttu M, Kalliola R, Alahuhta J and Hjort J (2019) Landforms contribute to plant biodiversity at alpha, beta and gamma levels. *Journal of Biogeography* 46: 1699–1710. https://doi.org/10.1111/jbi.13569

Whittaker RH (1972) Evolution and Measurement of Species Diversity. *Taxon* 21: 213–251. https://doi.org/10.2307/1218190

Whittaker RH (1960) Vegetation of the Siskiyou Mountains, Oregon and California. *Ecological Monographs* 30: 279–338. https://doi.org/10.2307/1943563

Wiens JA (1989) Spatial Scaling in Ecology. *Functional Ecology* 3: 385–397. https://www.jstor.org/stable/2389612

Zarnetske PL et al (2019) Towards connecting biodiversity and geodiversity across scales with satellite remote sensing. *Global Ecology and Biogeography* 28: 548–556. https://doi.org/10.1111/geb.12887

Zwoliński Z, Najwer A and Giardino M (2018) *Methods for Assessing Geodiversity*. In: Reynard, E., and Brilha, J. (eds.) Geoheritage: Assessment, Protection, and Management. Elsevier.

FIGURE CAPTIONS

Figure 1. A demonstration of geodiversity data (A) and how it can be described as alpha (α), beta (β) and gamma (γ) geodiversity with examples of their potential applications (B). Example site is from Rokua UNESCO Global Geopark in Finland. Hillshade background: National Land Survey of Finland.

Figure 2. Schematic examples starting from sites-by-variables matrices that result in measures of beta (β) biodiversity (a) and beta (β) geodiversity (b).

Figure 3. Selected approaches and methods that can be used for measuring beta geodiversity. Figure is modified from the ideas presented by Anderson et al (2011) for biodiversity research.

Figure 4. Geofeature datasets which were used in calculating the alpha and beta geodiversity of the study area. Reference map hillshade background: National Land Survey of Finland.

Figure 5. Panel A displays the spatial variation in alpha geodiversity (i.e. number of geofeatures per each grid cell) in the study area. In panel B, beta geodiversity patterns are visualized with RGB colors based on reclustering of non-metric multidimensional scaling ordination axes (B1-B2), and with hierarchical cluster analysis, where each grid cell is grouped in one of ten clusters (B3-B4).

Figure 6. Correlograms of spatial autocorrelation for alpha and beta geodiversity. Moran's coefficients for alpha geodiversity (A) and Mantel correlations for beta geodiversity with

Euclidean (B) and Jaccard (C) dissimilarity matrices. Euclidean dissimilarity is calculated with continuous data (area of geofeatures), and Jaccard dissimilarity with binary data (count of geofeatures). Red circles in the correlograms indicate statistically significant ($p < 0.05$) spatial autocorrelation.