

Review

Old Processes, New Movements: The Inclusion of Geodiversity in Biological and Ecological Discourse

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Abstract: There exists substantial variation in the qualitative and quantitative interpretations of the concept of geodiversity and its embedded elements and values. The resulting divergence and ambiguity in applications of the term constrain its present use as an operationalized concept in nature conservation research and discourse, unlike its seemingly analogous biotic term, ‘biodiversity’. This paper presents findings from a critical literature review of 299 academic journal articles and texts that define geodiversity values, or otherwise incorporate geodiversity or its derived elements and values as components of conservation. Contrary to previous suggestions, we have found that most geoscientists have united behind a single definition of geodiversity and applied it frequently in their primary and applied, geotouristic, research. Qualitative elements of geodiversity, including system support values and aesthetic appeals within nature conservation, have been largely confined to geoconservation and geoscientific literature and are nearly absent from biological discourse. Encouragingly, however, we have observed a more recent increase in research pertaining to quantitative interpretations of abiotic geodiversity elements and their relationship with the spatial distribution and abundance of species. Although the inclusion of geodiversity elements (quantitative and qualitative) in conservation assessment and biodiversity research has been and remains far less universal than for biodiversity elements, there is strong potential for further unification of these two concepts, especially through collaborative quantitative research. The more that geodiversity is discussed outside of geographic and geoscientific disciplines, broader recognition and validated use of the concept of geodiversity will be used in the understanding, interpretation, and protection of patterns and processes at the landscape scale.

Keywords: geoheritage; geoconservation; GIS; geoparks; soils; rocks; minerals; landforms

1. Introduction

The concept of natural diversity as one that can be divided into biotic and abiotic elements, and be measured quantitatively and qualitatively, is now widely recognized in the fields of biological conservation and geoconservation [1–5]. Variability (and rarity) of the *biotic* environment remains the dominant focus of conservation literature, however, and has sometimes been misinterpreted as an umbrella for *all* natural diversity. Concurrently, and throughout time, the concept of geodiversity has been subject to a variety of applied and theoretical interpretations in the literature and in practice. The varied use of the concept of geodiversity has been observed to have both constructive and problematic implications for geoheritage conservation and related disciplines [6], but also in the manner in which it can be meaningfully compared to the currently more tangible concept of biodiversity and accepted in protected areas research, planning, and professional discourse.

Geoscience disciplines recognized the intrinsic value of geodiversity [7] as an inseparable component of natural diversity in 1993 [5]. Early *thematic* definitions of geodiversity incorporated

aspects of bedrock, landform, and soil features alongside associated assemblages, systems, and processes [8–11] or the terrain and regional aspects of natural diversity [12]. Further refinements included scale- and or *area-based* bounds for the recognition of geodiversity [13]. These early definitions were synthesized by [14] into a concept that has been most frequently used by geoscientists and subsequently refined by [1] as “the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landform, topography, physical processes), soil and hydrological features. It includes their assemblages, structures, systems and contributions to landscapes.”.

Geodiversity is itself a value—a measure of abiotic variance—within a broader suite of values that comprise geoconservation (and nature conservation). The assessment of geodiversity is influenced by the value sets and perceptions of conservationists and/or researchers, and subsequently the geodiversity elements selected for assessment are also subject to values-based criteria. Typically, assessment recognizes spatial variability metrics and other values-based metrics, and, as such, geodiversity inventories comprise elements selected according to various degrees of quantitative and qualitative measurement [5,15]. Geodiversity inventories provide a tangible example of what the term represents in practice, and this informs new versions of the concept which contribute to an increasingly expansive and varied perspective of what the term geodiversity represents (Figure 1).

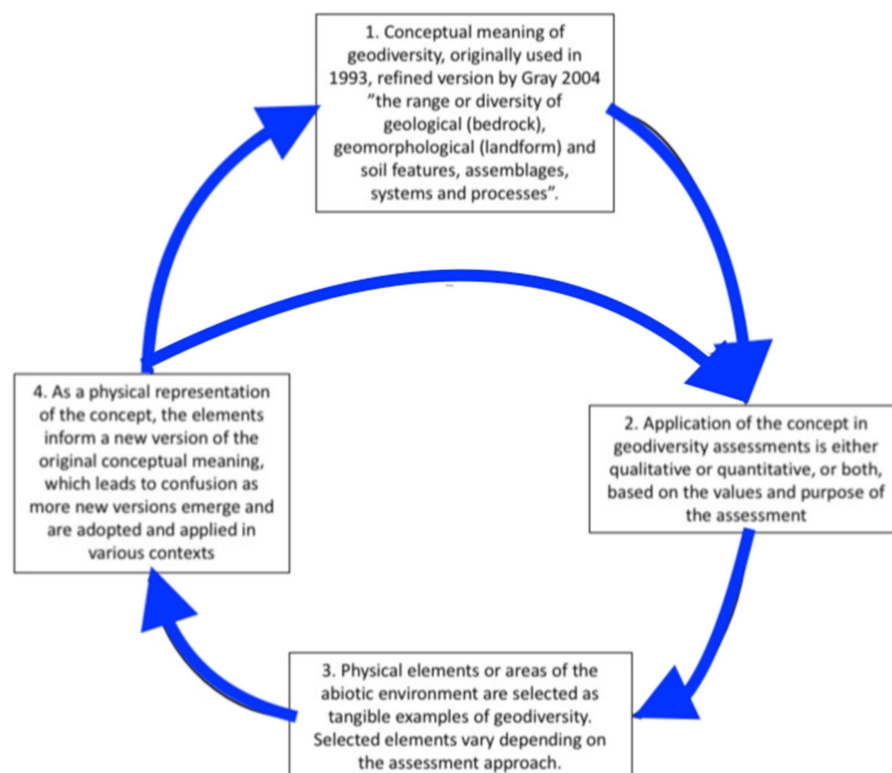


Figure 1. Geodiversity appears to be understood in geoscientific literature to have a definition (1) relating to the diversity of abiotic components. Challenges arise in the application and/or interpretation of this concept, which translates into vastly different values expressions and representations of geodiversity in published discourse.

Due to the myriad possibilities of how geodiversity could be interpreted from a values-based perspective, and on a qualitative-quantitative axis, it is no surprise that challenges in operationalizing the concept have arisen due to (a) the ambiguity and application of the term geodiversity in the literature and research and (b) the scale at which geodiversity could or should be considered according to the focus of the investigation or practice. For the latter, the potentially expansive implications of geodiversity that challenge the possibility of a practical, easy-to-use definition include temporal components of geodiversity (landscape evolution, creation, and destruction of soils and landforms),

and how to interpret, include, or exclude interactions with the atmosphere or even bioturbations in the landscape (quantitative challenges). With respect to the former, a lack of a defined conceptualization of geodiversity will inhibit potential inclusion in protected areas and ecosystem conservation frameworks (qualitative and values-based challenges).

Global research pertaining to the value of geodiversity as part of nature conservation or management is recent, even though the UNESCO World Heritage Criteria has recognized geological diversity to be of outstanding universal value (criteria VIII) in and of its own right since 1972 [16]. Elements of geodiversity are primarily selected for conservation on the basis of geoscientific value, as a subject for scientific research and inquiry, or for their intrinsic importance as a rare or representative component of natural diversity. However, the values that humans attribute to geodiversity often extend beyond geoscientific values and intrinsic value. These values have been classified as additional values, and include aesthetic, economic, cultural heritage, educational, and historic values [17]. Additional values arise from the recognition of the contribution of geodiversity to ecosystem services and as a supporting environment for biodiversity [1,18], and through a broader recognition of the role of the abiotic environment in past and present socio-cultural contexts [19].

Geodiversity additionally contributes to ecosystem functioning, through ecosystem service provisions of rocks, minerals, soils, and surface waters, the regulating services between land–surface–atmosphere feedbacks and geographically-regulated flows and distributions of biological media [18,20]. Therefore, it might be expected that geodiversity elements would be incorporated or otherwise recognised as essential components of ecological and biodiversity research.

This paper explores the various interpretations of the term geodiversity and the range of values that appear to motivate the recognition or inclusion of geodiversity as a concept across a range of sub-disciplines. Via a systematic literature review (primarily of journal articles and key books) and applications of semantic discourse approaches (where geodiversity concepts have been implied but not specifically defined), we explore:

1. The range of geodiversity definitions and concepts used in academic literature;
2. The fields of research in which geodiversity is being considered as an area of research and application; and,
3. The perceived value of geodiversity as a component of research and practice in domains such as nature conservation, restoration ecology, geosciences, and heritage studies.

We conduct this review with a view to deconstructing some of the challenges for the inclusion of geodiversity as a robust concept in other conservation sciences, in addition to highlighting areas of promising research in other fields that could be used to unite discourse in the future.

2. Materials and Methods

We conducted a systematic literature review based on literature searches in the databases Google Scholar and Scopus in May 2019 (Figure 2) using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [21]. We wanted to find articles for which a definition of geodiversity was supplied, or could be inferred, from primarily ecological, geoscientific, or conservation literature, with an emphasis on journal articles and scholarly books that focused directly on geodiversity or geoconservation.

Initial search terms were ‘geodiversity’ or the phrase ‘geological diversity’ plus the additional delimiting terms ‘anthropogenic’, ‘assessment’, ‘biodiversity’, ‘education’, ‘features’, ‘geo/tourism’, ‘values’, and ‘scientific’. After removing duplicates, completely irrelevant articles and books (i.e., articles that cite papers containing the search terms but are not related to these search terms with respect to content or articles and/or papers that did not rely on a working definition or inherent consideration of geodiversity as a concept) and 15 papers that we could not access the full-text for from the initial sample of 956 database records, we included 299 papers in our subsequent analyses.

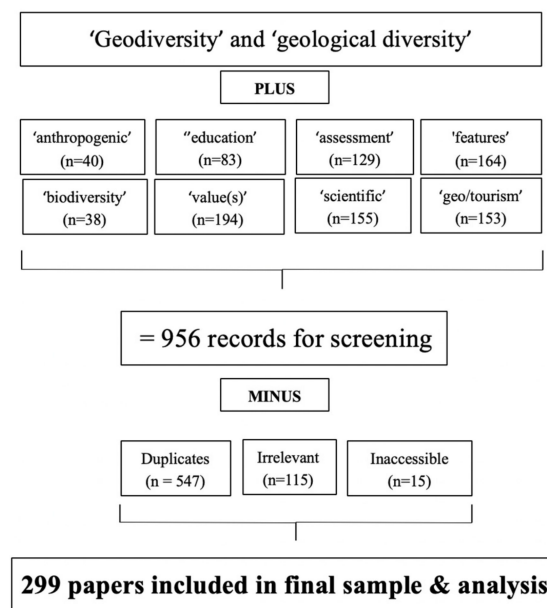


Figure 2. Results of a literature search for scholarly literature, books, and published manuals containing the terms ‘geodiversity’ and/or ‘geological diversity’ from searches of Google Scholar and Scopus Databases.

2.1. Classification of Data

The final sample was classified using the text analysis software program NVivo 12.1 2018 [22]. Initial themes were identified from key literature and new themes were added as they emerged throughout the review process. Theme keywords were used to extract relevant selections of text, which were then coded to categories called ‘nodes’. Nodes included item topic or focus, definitions of terminology, types of geodiversity elements, and recognised geoconservation values. Additional dimensions such as publication date and geographic location were extracted from the data so as to draw additional relationships between key themes.

2.2. Data Analysis

Approximately one third of documents in the sample explicitly defined the term geodiversity. These were classified into groups based on adherence to the definition provided at [1] as ‘Yes’ (where authors explicitly used this geodiversity definition); ‘Yes with additions’ (where the definition provided in [1] was expanded upon, with additional abiotic or geoscientific inclusions); ‘Similar’ (where geodiversity was explicitly defined by authors and sounded very similar to the definition provided in [1], but for which [1] was not cited); and ‘No’ (where geodiversity was explicitly defined but in a manner completely different to that in [1]).

In the other two-thirds of the sample, definitions of geodiversity were inferred from the text. Here, classifications were grouped as ‘Seems like’ (where the terms of reference seemed exactly like in [1]); ‘Seemingly, with additions’ (where authors’ terms of reference were similar to those in [1] but with some additional details); and ‘Seemingly not’ (where the description had a conceptual meaning that varied distinctly from that of [1]).

Research topics, and the way in which geodiversity was used as a value were then classified from the reading of papers and clustering into nodes (Figure 3). Because multiple classifications were possible in some instances (e.g., a paper about GIS techniques could also present a case study of a protected area as part of the primary research content), data presented were not always mutually exclusive. Descriptive statistics and narrative discourse were used to review and explore the results.

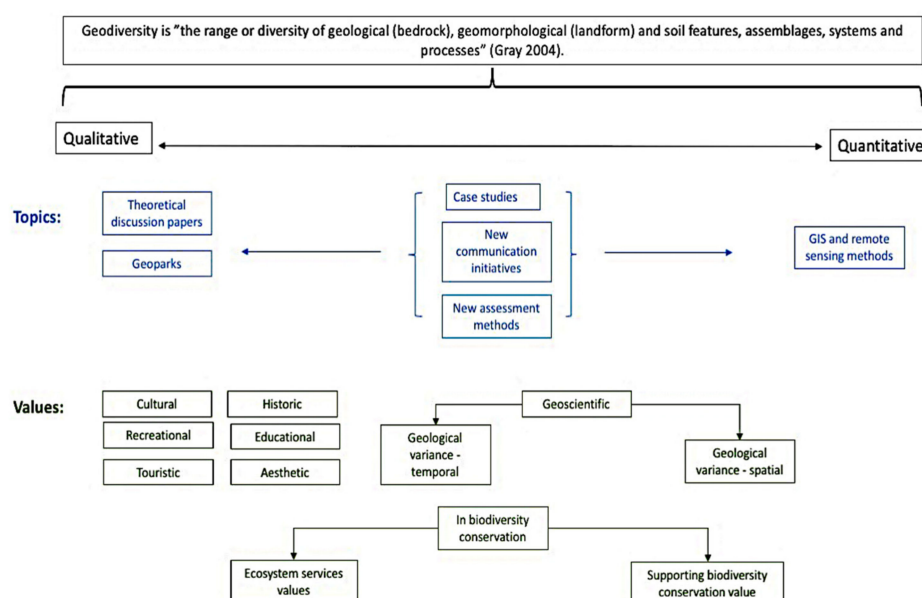


Figure 3. Node classification map of topics and derived values contained within 299 journal articles and books containing the terms ‘geodiversity’ and/or ‘geological diversity’ from searches of Google Scholar and Scopus Databases. These are expressed along a qualitative–quantitative axis.

3. Results

3.1. Variations on the Definition of Geodiversity in Published Works

In this research, we identified 144 documents that contained an explicit definition of geodiversity and a further 155 documents that provided sufficient information so as to infer the definition (of geodiversity) from the methods section from the period of October 1993 to 1 May 2019. Geodiversity mentions that used the verbatim definition first suggested by [1] or added to or were similar to this concept comprised ~88% ($n = 127$) of the explicitly-defined sample, while definitions that seemed like, or seemingly built upon [1] comprised 78% of the sample from which the definition of geodiversity was inferred from the text (Table 1).

Table 1. Percentage of papers and books that contained either an explicit definition of geodiversity ($n = 144$) or from which a definition of geodiversity could be reasonably inferred ($n = 155$) that was the same, similar to, or not like the popular concept (in geoscientific literature) described by [1].

The Explicit Definition (of Geodiversity) Provided In-Text Was That of [1] (or [14]):	The Definition (of Geodiversity) Inferred from Text:
Yes: 41%	
Yes, with some additions: 27%	Seemed like that of [1] (or [14]): 36%
Similar: 20%	was seemingly like [1] (or [14]), but with additions: 42%
No: 12%	Was seemingly not like [1] (or [14]): 22%

There were significant differences, however, in the use of geodiversity definitions according to publication topic (Pearson = 58.85, d.f. = 30) (Table 2). The most frequent document categories referring to geodiversity were ‘case studies’ and ‘explorations of theory and concepts’ (n case studies = 93 explicit/111 implied; n ‘explorations’ = 59 explicit/32 implied).

Table 2. Explicit and implied definitions of geodiversity found in 299 published articles containing the word ‘geodiversity’ as part of this research, and the broad focus of these works.

Focus of Paper	Description of Classification	Explicit (n) ¹	Inferred (n) ¹
<i>Case Studies</i>	Research on specific abiotic, geological, or landform elements and physical environments, typically so as to highlight their geoscientific, geoheritage, or ecological significance.	93	111
<i>GIS and Remote Sensing</i>	Research documenting or employing GIS or remote sensing techniques to ‘quantify’ or ‘assess’ geodiversity.	25	16
<i>Geopark Studies</i>	Primary or secondary research relating to national or UNESCO geoparks.	23	28
<i>New Assessment Frameworks</i>	New methods of assessing or determining geoheritage, landform significance, or geodiversity.	24	22
<i>New Communication Initiatives</i>	Authors and practitioners devised new inventory or instrument solutions to communicate and explore landforms, geographic elements, and/or geodiversity.	10	13
<i>Theory and Discussion</i>	The concept of geodiversity was explored or re-conceptualized as part of a major work (primarily qualitative).	59	32

¹ Categories are not mutually exclusive, and hence some papers were classified under two or more headings.

Being more qualitative in nature, these categories also comprised the broadest definitions of geodiversity (Figure 4), meaning that the narrative ranged from the direct or apparent adoption of the definition found in [1] through to those who specifically supplied or appeared to propose alternative definitions of geodiversity. Conversely, documents that were about ‘GIS and remote sensing of geodiversity’ were more quantitative in nature, and along with those that explored ‘new communication initiatives’ these were almost exclusively written by authors who used, or appeared to use, the definition found in [1].

Across the entire sample, the most popular contexts in which geodiversity was discussed related to its inclusion in geoscientific research (26% of explicit samples/24% of inferred samples), such as in the context of the quantitative measurement and detection of geodiversity or the inclusion of geodiversity as part of a geoheritage assessment criteria. Geodiversity has also been used in literature concerning geotourism, including primarily qualitative assessments of geoparks, aesthetic tourism values, and the touristic-economic value of geodiversity in geoparks (22% of explicit samples/26% of inferred samples).

Irrespective of the topic or context in which geodiversity was considered in our literature sample, there was consistency in the adoption of [1] or [1]-like definitions over definitions that were completely different in their intent. Where explicit definitions of geodiversity were supplied, significantly more authors used the definition found in [1] than a definition completely different to that in [1] (d.f. = 3, $F = 5.80$, $p = 0.003$). Where definitions were inferred, significantly more authors used [1]-like or [1]-like plus other related concepts than concepts that were completely different to that found in [1] (d.f. = 2, $F = 10.01$, $p = 0.001$).

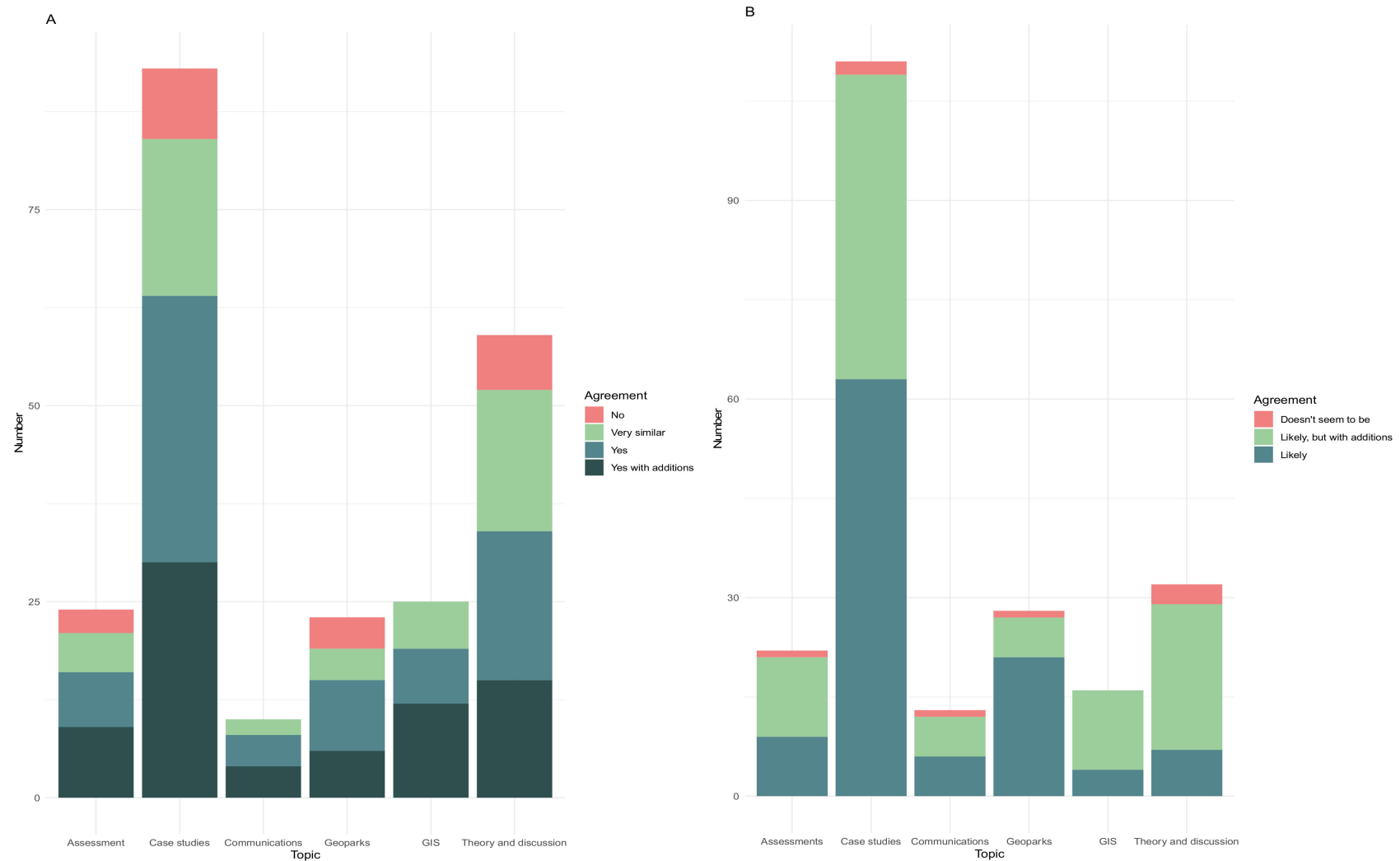


Figure 4. Explicit (A) and implied (B) definitions of geodiversity compared with the dominant definition given in [1] across the six most common topics of publications mentioning the concept from 1993–May 2019. * Numbers provided should not be considered mutually exclusive.

Except for papers that considered geodiversity in the context of either geoscientific value or measurement, or tourism value and economics, almost all other contexts used a definition of geodiversity so similar or like that in [1] that it was more informative to simply divide paper contexts into those who fit the status quo (like or similar to that in [1]) and those that did not (Figure 5).

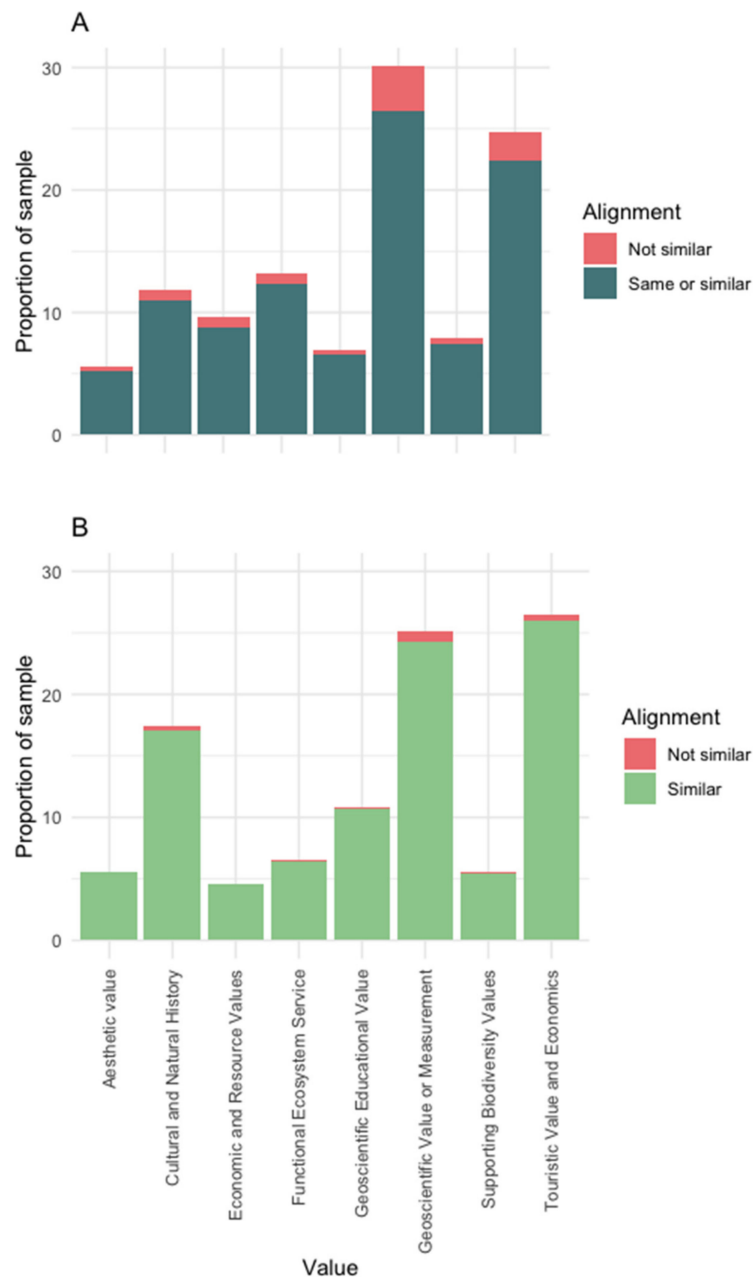


Figure 5. The proportion of geodiversity definitions across the entire sample that associated the definition with different value sets. The sample is stratified by the alignment with [1]’s concept where (A) geodiversity was explicitly defined, or (B) could be inferred from the text.

3.2. Geodiversity, Biodiversity, and Ecosystem Services

A number of published works using the term geodiversity were concerned with its pivotal value in the provision of *ecosystem services* and/or the distribution and abundance of undefined taxa ($n = 45/299$) or an otherwise important component of the ecosystem ($n = 35/299$).

Geodiversity is “the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landform processes, physical processes), soil features, their assemblages, relationships, properties, interpretations and systems.”

Geodiversity concepts were discussed or considered as part of literature exploring *biodiversity* in 7.5% of explicitly-defined papers and 5.5% of papers from which definitions of geodiversity were inferred. These works specifically suggested that geodiversity was, or could be a possible, defining criteria in the distribution and/or abundance of marshland taxa [23], invertebrates [24,25], plants [26–31], and marine taxa [32], primarily in a qualitative sense. Newer research was more quantitative in nature, and considered geodiversity parameters such as soil textural variation and landform rugosity as a component of species and habitat distribution modelling [33–38].

Where geodiversity was discussed or considered in literature exploring *functional ecosystem services*, papers that included explicitly-defined concepts comprised 12.5% of the relevant sample, while papers from which the definition of geodiversity was inferred comprised 6.5% of the relevant sample (Figure 5).

All of the aforementioned papers that were concerned with the relationship between or value of geodiversity in the provision of functional ecosystem services were written from the perspective of geoscientists and/or published in serials and books concerned primarily with geoconservation, geosciences, or (geo)tourism and protected areas. Most of these papers simply considered ecosystem services to be another possible way in which the conservation of or inclusion of geodiversity indices and values in conservation strategies could be useful.

4. Discussion

Despite the relatively simultaneous recognition of the concepts of biological and geological diversity as components of natural diversity [3], recognition of geodiversity in nature conservation and protected areas research appears constrained and even geocentric. The reasons for the seemingly limited incorporation or recognition of geodiversity in biological research are numerous. The discordant measurement and application of geodiversity elements and variable recognition, understanding, or acceptance of its possible qualitative and quantitative dimensions limit ease and utility of the concept. Contrary to earlier reports [20], however, it does appear that a firm ‘definition’ of ‘geodiversity’ is evident, at least to those in the geoscientific, geoconservation, and geoscientific fields.

In our research we did not detect statistically significant quantitative or qualitative biases in geodiversity elements selected by authors across the various ‘topic’ areas. However, we did note a general tendency for conservation-focused papers to value (and assess) geodiversity elements in a quantitative sense when considering biodiversity but to consider geodiversity as a qualitative value of ecosystem services (for instance, [39]). Thus, an apparent tendency towards a consensus on the definition of geodiversity is only a small part of a much larger set of challenges and opportunities for the conservation and research recognition of abiotic elements and values. We discuss below the current usage and future potential of geodiversity in nature conservation and protected areas research.

4.1. Geodiversity is a Term Used in Geoheritage, Geoscientific, and Geotourism Research, Where (Most) People Use A Specific Definition ...

Our research has confirmed that the most widely accepted definition of geodiversity is that proposed by [1] (and later [14]), i.e., “... the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landform, topography, physical processes), soil and hydrological features, including their assemblage, structures, systems and contributions to landscapes.” Increasingly, geodiversity has become associated with terms recognized almost exclusively by those interested in geoconservation such as ‘geoheritage’, ‘geotourism’, ‘geosites’, ‘geomorphosites’, ‘geopark’, ‘secondary geodiversity’, ‘geosingularities’, and even ‘geomythology’, as defined within the geoscientific and geotouristic literature.

We did indeed note that the number of papers published containing quite different definitions of geodiversity than the concept found in [1] are in fact increasing; however, this was from a very low

base (e.g., 30 papers contained a [1] or [1]-like definition of geodiversity in our 2019 sample versus five papers that were quite different).

In our research it became evident that much of the discussion and application of the term geodiversity in the academic literature was from the perspective of geoscientific and geoconservation (and sometimes, geotouristic) professionals. This is unsurprising, given the more recent recognition of geodiversity as a concept (albeit given that ‘geological conservation’ has been discussed for at least the past two centuries). Both the qualitative and quantitative interpretations of geodiversity have been applied in theory and practice in geoscientific and geoheritage discourse as these disciplines continued to evolve [40] into more technical and values-oriented fields, respectively. The vast majority of geodiversity discourse was found to pertain to geoconservation case studies nominating geodiversity as a component or unique element of conservation of abiotic physical geography, of conservation of geodiversity within ‘Geoparks’ (UNESCO-listed protected areas [41] and/or non-protected national tourist parks), in the discussion of new conservation frameworks specifically for abiotic physical geography, and as part of techniques for communicating or describing (e.g., via GIS and remote sensing) geodiversity and abiotic physical geography. Thus, while abiotic conservation and geodiversity is being recognized, explored, and appreciated by geoscientists, it is largely absent from broader discourse.

4.2. ... (But) Not Everyone Applies the Same Elements of Geodiversity

The usage and conceptualization of geodiversity did not always align with the definition found in [1] in the works we analysed. These variable applications manifested in refinements or sharpening of [1]’s ‘established’ concept (such as in [7], in which the distinction was made between geosites and geodiversity sites) or involved expansion upon the definition to encompass ex situ elements such as building stones [42], surface waters [43], and non-renewable energy sources and paleontological elements [44]. Some alternative perspectives included those which recognized the broad qualitative values of geodiversity as including all elements of the geosphere, such as climate [45,46] surface waters, and atmosphere and physiotores [47], in a geodiversity assessment. Others [48] also included elements important in the interactions of the asthenosphere, lithosphere, biosphere, and atmosphere, and components of extra-terrestrial influence. Still more included landscapes and elements of biodiversity that were influenced by underlying geology, as well as anthropogenic elements such as geologically inspired culture and art, [49] a definition more closely related to the current concept of secondary geodiversity [50]

Wholly alternative definitions and/or interpretations of the concept of geodiversity were, however, relatively uncommon in our sample. Some geoconservation researchers proposed that geodiversity should be delineated from ‘geosites’. The latter was to refer only to places containing abiotic features with scientific value, while geodiversity was a term for the additional values, such as cultural and aesthetic values, identified in the abiotic environment [51]. Comparatively, [52] suggested that geodiversity is both a term for the range of geosite types as well as representative of the qualitative values of the abiotic environment. Additional terminology that has emerged as researchers have sought to further refine and define the concept of geodiversity supports an alignment of the concept with geological and geomorphological foci [9,53,54] and natural history or geotouristic/aesthetic and geoscientific components [7].

Some alternative quantitative interpretations have emerged to address the issue of spatial scale which is inherent in any assessment of diversity [3]. [13] used the term to refer to region-specific diversity of abiotic elements and [55] used the term in conjunction with geomorphodiversity to describe the abiotic features of a territory relative to scale. The spatial aggregation of abiotic and biotic components, namely relationships between plant functional community types and soil and geological variance, has also been termed ‘biogeodiversity’ [56]. The diversity of abiotic elements across a temporal scale was also included in some definitions of geodiversity [57]. Other alternative perspectives that recognize geodiversity as a more numerical, quantitative measurement used the term to refer only to topographic variation in the abiotic environment [58] or only to the qualitative

variations in the pre-recognized geoheritage sites within an area [4,59–61]. Similarly, the variation in the qualitative values of ‘geosingularities’ (elements of geodiversity that stand out most to tourists) in geoparks [62] was termed ‘geodiversity’.

It should be noted, however, that apparent non-usage of the definition found in [1] did not always imply that researchers and authors disagreed with it in the works we analyzed. Some of the literature that we explored was focused on the broader implications of usage of geodiversity as a component of abiotic conservation [4], and other works recognized the potential for geodiversity to incorporate qualitative and quantitative elements, measures and representations [5,39]. Thus, while not all researchers used the concept found in [1] as part of their academic discourse and research, it was evident that even geodiversity values that were derived from interpretations of the concept found in [1] varied with expertise, preference, and topic area. This has profound implications for the application of geodiversity to the seemingly (on the surface) analogous concept of biodiversity. Every varied application of the broad definition provided a tangible example of what the term geodiversity represented to these authors in practice, which in turn informs new versions of the concept, contributing to an increasingly expansive and varied perspective of geodiversity (Figure 1).

4.3. Qualitative Elements of Geodiversity and Biodiversity Ensure Mutual Enjoyment of Non-Equivalent Values

In this study, we observed that many of the values and motivations for discussing geodiversity aligned with geoscientific interests, appreciation of the abiotic environment in recreation, culture, and natural history, and economic purposes such as geotourism. Even where authors made it clear that they were not interested in the geoscientific aspects of geodiversity, their value-set was geocentric and not encompassing of the ecosystem as a whole, e.g.:

“We do not engage in empirical geoscientific evaluation of the geoheritage of the Izu Peninsula Geopark in this paper: we mainly analyze(d) the qualitative aspects of heritage conservation, especially issues like social perception of natural processes, stakeholder dynamics of conservation, aspects of resource use, and tourism impact” [63].

Hence, we posit that the term ‘geodiversity’ has been claimed almost exclusively by researchers who are interested in the conservation of, and recreation within, spaces containing geoscientifically ‘valuable’ or ‘notable’ places. That is, the term ‘geodiversity’ belongs to geoconservation and geotourism and is not a causative indicator of biodiversity within the broader remit of nature conservation. This ‘separation’ between geodiversity and biodiversity only makes sense when each are distinctly viewed as qualitative elements from which associated value(s) of aesthetic beauty, culture, and educational knowledge can be derived. In this context, geodiversity and biodiversity function as two separate indicators of environments worthy of enjoyment and (perhaps) conservation or restoration, and therefore it is reasonable for them to be described and interpreted by experts in their respective fields. Indeed, this is largely the approach taken when geodiversity has been qualified as part of natural capital and ecosystem services policies, such as within The Australian National Heritage Charter and the UNESCO world heritage list [17].

In recognizing geodiversity and biodiversity as two separate elements or qualitative components in nature conservation, however, important inter-relationships between measurable, quantitative geodiversity and biodiversity elements are ignored. Divisions, which are necessary due to the specific expertise required to detect and quantify the respective potential geo- and biodiversity elements, impede a shared understanding of the potential inter-relationships between the concepts. Thus, while a fifth of the literature reviewed in our sample did specifically recognize geodiversity as a supporting stage for the spatial differentiation of biodiversity values and as a primary contributor to ecosystem services (e.g., [64,65]), this was mostly done by geoscience professionals, who viewed geodiversity as integral to delivering economic, environmental, and social benefits to society. For example, ref. [66] emphasised the need for fluvial forms and processes to be part of a geodiversity definition because of the value they contribute to human health; “Fluvial geomorphological forms and processes exert a fundamental influence on riverine processes and functions. They thereby contribute significantly to

beneficial services for humanity, yet remain largely undervalued. Major ecosystem service studies to date tend to overlook the contribution of geodiversity and geomorphological processes, particularly of fluvial geomorphology, to human well-being.”.

Where tentative indications of a potential progression towards unification of concepts became evident in our research, it was through life-land feedbacks. At least some researchers recognised that all biological ecosystems originate in some way from geological or geomorphological basis [65]. Others included soils and topography as valuable contributors to ecosystem services more generally [67]. Additional terms emerged in the literature sample as researchers aimed to describe increasingly specific aspects of geodiversity [42] and/or attempted to produce concepts equivalent to those found in biodiversity theory. Yet wholly coherent and unified explorations of geo- and biodiversity were infrequent in our research, and the lack of inclusion of geodiversity within broader concepts of bioconservation and protected areas governance is also increasingly being recognised.

4.4. Are Quantitative Applications and Interpretations of Geodiversity the Way to Foster Cross-Disciplinary Research and Linkages with Biodiversity?

Geodiversity has been described as the abiotic ‘equivalent’ of biodiversity in which high geodiversity equates to a high spatial concentration of a diverse range of selected abiotic elements, and, (more qualitatively) where abiotic features or processes considered rare or of a high natural quality are representative of valuable geodiversity [68,69]. Opportunities for exploring relationships between spatial or quantitative elements of geodiversity and biodiversity require advancement in the quantitative detection of geodiversity, for without this, it will be difficult for geodiversity to be included in or alongside biological assessments in a manner that is universally understood [56].

Findings from quantitative studies examining the relationships between geo- and biodiversity generally indicated that high geodiversity correlated positively with high rates of biodiversity [11], albeit that to date, the scope of such assessments has primarily been limited to more ‘obvious’ parameters such as soil type [56,70] and climate interactions [71]. Promising developments in GIS and remote sensing methodologies to map the spatial variation of ecosystem services using environmental variables (such as geodiversity) have also occurred recently [2] for which parameters such as lithology, morphometry, soil physical characteristics [72], and relief [34] have been used. Obviously, limitations in the availability of quantitative datasets at present constrain opportunities for richer or more comprehensive quantitative studies.

However, even expressly quantitative abiotic applications of geodiversity are potentially so expansive as to become one meta-definition [7], which might require further terminological refinements before use in quantitative abiotic–biotic relationship analyses. In our study, some authors expanded on the initial concept given in [1] to recognise and quantify land-climate feedbacks and surface waters as components of geodiversity and even benthic habitat biodiversity [32,34]. Without unifying terminologies or consistent usage of the concept, such expansive additions may in fact limit conceptual inclusion of geodiversity in biodiversity studies because they beg the question: to what extent are *all* abiotic systems part of geodiversity? Nonetheless, attempts to quantify elements of geodiversity may in fact be the fastest way to bring geoscientific and geoconservation researchers into collaborative or mutually-reinforcing research relationships with biological scientists. As new statistical or predictive associations between biotic and abiotic components of the ecosystem are explored globally, researchers might develop shared understandings and solve conceptual challenges instead of remaining constrained by (seemingly) mutually exclusive qualitative value-sets. Indeed, as the definition and conceptual understanding of the term ‘biogeodiversity’ improves, so too might there be a corresponding increase in the recognition of abiotic system support values in general biological and ecological discourse.

4.5. Notwithstanding Logistical Constraints, Why Hasn't There Been Much Crossover between Geodiversity and Biodiversity Research and Discourse in Academic Literature?

The applied study of what is now considered biodiversity long exceeds geodiversity [3]. In gaining more general acceptance, biodiversity has been increasingly used in a simplistic sense; for example, it is often used as a substitute for more precise terms (e.g., “species diversity” is the proxy for biodiversity value, especially with red-listed species numbers). The initial cohesive concept as to what constitutes biodiversity being subject to even the slight misuse or more casual use of the term, especially in the semi-political sense, may have been part of the reason why ‘biodiversity’ achieved rapid dissemination and acceptance, especially as humans tend to gravitate toward simple solutions [42].

We suggest two additional reasons for the lack of recognition of geodiversity, the first of which relates to the temporal aspects of geodiversity and a lack of easy-to-apply and comparable analogues to biodiversity and the second of which is the lack of its inclusion, until recently, in broader discussion about conservation, due to lack of recognition of the value of geodiversity in nature conservation.

That abiotic geodiversity elements such as rocks and soils can be considered as a function of time makes it more difficult to provide a ‘transferable context’ and index for geodiversity outside of geoscientific applications of geopark research and reserve planning. Within geoparks it is easy to see how a quantitative index or ‘count’ of various landforms and elements in a given area would be worthy of comparisons with other areas in order to inform park design and ranking criteria for new parks. Additional educational values can also be derived from the understanding of how temporal processes have shaped in situ geodiversity (e.g., through an explanation of why a specific combination of five rocks, landforms, or soils occur in one area, but not others).

Beyond this, however, one cannot simply ‘count’ geodiversity at a given latitude or climate region and provide a meaningful comparison to other areas due to landscape evolution processes and plate tectonics. Put simply, there is not necessarily anything meaningful to be gained from stating that five rock types occur in one area, when three rock types, of vastly distinct geological eras, occur elsewhere. Additionally, because landscape evolution and plate tectonics are site-specific, ‘counts’ of geodiversity indicators (e.g., rock type) do not have the same convergent evolutionary processes and climate controls that biological entities do. The oldest trees on earth are but a speck in the geological history of time, and therefore the controls that determine biodiversity are far more contemporary and relevant to spatial ‘counts’ as comparisons.

Therefore, ‘accounting’ for geodiversity may seem less relevant outside of geoscientific and geotouristic literature simply because its etiology is much more complex and less relevant to nature quantitative conservation approaches and assessments as a whole outside of intrinsic and aesthetic value sets. Even where it is proposed that site-scale geodiversity can be measured to achieve biodiversity conservation targets in an area [65], challenges and contradictions to the relationship between concepts arise. For instance, high quantitative geodiversity ‘scores’ do not always translate into high biodiversity values. As a case in point, south-western Australian flora exhibits high endemism and diversity in areas of low abiotic complexity, rarity, or diversity [73]. Indeed, recent attempts to relate soil, geological, and vegetation distributions concluded that other geodiversity elements (pedogenic factors and hydrographic features, not always delineated as soil features) were responsible for the spatial aggregation of plant functional and community types [56]. Thus, the lack of ‘equivalency’ between terms, and the subtle complexities associated with the long temporal evolution of quantitative geodiversity indicators and elements, creates extra challenges for cross-disciplinary recognition, understanding, and appreciation.

Finally, being ‘claimed’ by earth scientists [1] has not prevented some authors from feeling that the lack of recognition of geodiversity has affected the holistic or ecosystem model of conservation [74]. Many geoscientists view geodiversity as integral to ecosystem services [18]. The previous confusion surrounding the definition of geodiversity has been reflected in the underrepresentation of geodiversity in broad scale conservation policies and frameworks, which in 2004 was suggested to have prevented the discipline of geoconservation from achieving the widespread social diffusion afforded to biological

conservation [1]. These observations subsequently proved correct, as in 2005, the Millennium Ecosystem Assessment neglected to include an adequate representation of the contribution of geodiversity, and the more contemporary United Kingdom National Ecosystem Assessment (UKNEA) includes a limited account of geodiversity values that are generally implicitly referred to rather than explicitly stated.

It is therefore apparent that geoconservation is advancing and that so too is the conceptual understanding of geodiversity. However, the separation of biotic and abiotic components of natural systems into separate value-sets has led to uneven recognition, preservation, and understanding of geodiversity in nature conservation and protected areas research.

5. Conclusions

The importance of recognizing geodiversity as a unified concept was proposed by [14] but has existed since the Millennium Ecosystem Assessment. It could be argued that a broad or even flexible definition of geodiversity ensures relevance and facilitates application across different domains such as the geosciences, tourism fields, ecological terrains, and jurisdictions [42]. However, it has recently been suggested that inconsistency between interpretations and usage is preventing geodiversity from becoming a fully operationalized concept [3].

Our research has demonstrated, contrary to previous research, that most published literature does follow a prescribed, albeit broad, interpretation of geodiversity as a concept. Challenges for future research and practice, however, exist because geodiversity is a relatively new term being used almost exclusively by geoscientists and geoconservation professionals and will need time to permeate into other areas of intellectual discourse and conservation practice. The way in which geodiversity might contribute more broadly to protected areas research and its significance as part of biodiversity conservation require further exploration. Remote sensing and GIS approaches have greatly improved in recent years, and thus spatial detection of abiotic parameters that could reasonably be expected to be included under the banner of geodiversity is now much easier to incorporate into assessments, leading to some researchers loosely describing abiotic-biotic associations as ‘biogeodiversity’. However, the extent to which many authors have expanded upon the ‘accepted’ definition to include climatic and aquatic parameters as part of geodiversity actually risks dilution of the concept such that it remains potentially as broad and vague to biological scientists as to not be useful. In order for the ‘true’ value of geodiversity in biodiversity conservation and ecological modelling to be realized, dialogue between various stakeholders and increased cross-disciplinary collaboration is now essential.

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