Geodiversity and geoheritage: detecting scientific and geographic biases and gaps through a bibliometric study

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Abstract

Many scientists have recognized that there is diversity in nature, including biodiversity, geodiversity, and pedodiversity. Studies in biodiversity date back as far as the 1700s, but geodiversity and pedodiversity studies are much more recent, dating to the late 1970s to early 1980s. Given that we are now approaching 40 years of geodiversity and geoheritage work, this study was undertaken to determine areas that have been well addressed and where current gaps are. This was accomplished by reviewing the publications in the journal "Geoheritage", the Scopus and Google Scholar databases, and established geoparks according to UNESCO records. It was found that geodiversity studies typically do not include the findings or utilize the techniques of biodiversity and pedodiversity research, despite the fact that common definitions of geodiversity include soils. Including the findings and techniques of bio- and pedodiversity would expand geodiversity work. Likewise, geoheritage preservation sites are not geographically balanced, with European countries, Brazil, Australia, and China publishing the large majority. The European and East Asian countries, especially China, have dominated in the establishment of geoparks. The most pressing need in future studies is more balanced geographic distribution, as the current strong slant towards a limited portion of the world cannot adequately capture (on the research front) and preserve (on the geoparks front) global geodiversity. Finally, there is a need investigate whether the spatial patterns of biodiversity are idiosyncratic or are also a characteristic of abiotic resources, permitting the standardization of diversity research methods. This review contends that there are intriguing similarities in biodiversity, geodiversity, and pedodiversity patterns that should be explored, something that would benefit all of these research areas.

Keywords: geodiversity; pedodiversity; biodiversity; geoheritage; geoparks; Scopus; Google Scholar

Introduction

Human perception of nature and society is a key issue for the understanding of the interaction of humans and nature (Huxley, 1954), and understanding the interactions between humans and nature is a growing field of study (Pereira et al., 2016; Teshome al., 2016). These perceptions are relevant as they will affect policies, land management, and as a consequence, the future of landscapes (Tempesta et al., 2010; Soini et al., 2012). The traditional biophysical approach to nature issues is now completed with societal, economic and perception studies to understand the Earth system from a holistic perspective. For example, this has been documented in agriculture lands were the perception of the use of catch crops and weeds to protect the soil must be designed in a system that includes the opinion of the farmers (e.g. Cerdà et al., 2018).

Humans have recognized that some landscapes are more diverse than others, regardless of observed natural resources. All environmental scientists understand that some areas are richer than others in living organisms, rocks, landforms, soils, or a combination of these. The concept of diversity is clear and intuitive regardless of the studied subject, and terms such as biodiversity, geodiversity, and pedodiversity have been assigned to the study of this concept with a focus on various aspects of the natural system. Many definitions have been proposed for the concepts of biodiversity, geodiversity and biodiversity. However, in the absence of consensus, such proliferation turns out to be more harmful than beneficial. In our opinion, the following definition of diversity by Huston (1994) is applicable to all types of natural resources, so it turns out to be enlightening. According to Huston, diversity can be conceptually defined as: "*The concept of diversity has two primary components, and two unavoidable value judgements. The primary components are statistical properties that are common to any mixture of different objects, whether the objects are balls of different colours, segments of DNA that code for different proteins, species or higher taxonomic levels, or soil types or habitat patches on a landscape. Each of these groups of items has two fundamental properties: 1. the number of different types of objects (e.g., species, soil types) in the mixture or sample; and 2. the relative number or amount of each different type of object. The value judgements are 1. whether the selected classes are different enough to be considered separate types of objects; and 2. whether the objects in a particular class are similar enough to be considered the same type. On these distinctions hangs the quantification of biological diversity*" (Huston 1994, p. 65).

From a scientific point of view the problem is to propose concepts that can be useful in order to determine the diversity of the physical landscape; to achieve sustainable management it is necessary to understand and quantify all landscape diversities, irrespective of whether they are biotic or abiotic. When the former purpose is reached we call this the operationalization of a concept. An operational concept is the first step in the birth and progress of a given discipline (i.e., Steward, 1986; Jacobs et al., 2009). In general the sciences start with qualitative conceptual development that with time gives rise to semi-quantitative and finally quantitative concepts that allow us to compare the objects of study. The operationalization of the concept of diversity has not been an easy task in any of the natural resources disciplines because there are many obstacles that complicate it (Bunnell, 1998; Valls et al., 2015). The first is that nature is complex and multifaceted. For example, biodiversity can be estimated from many points of view such as genetic diversity, taxonomic diversity (e.g. biological species), diversity of ecosystems, or functional diversity (Noss, 1990; Sites and Marshall, 2004). The same occurs within the emergent field of geodiversity.

The current difference between the studies of biodiversity and geodiversity is that the scientific community has studied the first for many decades, while the second interest has emerged more recently. Studies in biodiversity have a relatively long history in terms of trying to understand diversity in natural systems, with some dating the earliest biodiversity studies to the 1700 and 1800s (Harper and Benton, 2001; Huston, 1997; Naeem et al., 2002), while geodiversity and pedodiversity studies are more recent, dating to the late 1970s to early 1980s (Beckett and Bie, 1978; Karjalainen, 1983). In fact, published pedodiversity research preceded the more general geodiversity research (Ibáñez et al., 1990, 1994, 1995; De-Alba et al. 1993), despite the fact that geodiversity experts will often claim pedodiversity as part of their field.

Given that we are now approaching 40 years of geodiversity and pedodiversity studies, it seems appropriate to conduct an analysis of and detect current gaps in the trends in these studies to quantify their coverage, identify areas with ~~of~~ different diversities, to select areas that merit protection. Therefore, the goal of this study was to utilize a datamining of the papers published in the journal “Geoheritage” as well as the Scopus and Google Scholar databases to investigate these trends, including a focus on the place that soils have had in geodiversity studies as well as to what extent geodiversity studies have been able to detect the areas of the earth's surface that must be protected due to the uniqueness of their geological resources in the broadest sense of the term at the worldwide level.

Materials and Methods

All the contents of Geoheritage Journal were analyzed from the first issue in 2009 to November 2016, totaling 187 papers. The number of times that individual countries were mentioned, the country(ies) where the authors of the articles worked, and the number of times selected key terms (as determined by the authors of this paper, not the key words in the strict sense of the terms that appear in the papers) appeared that were considered relevant directly or indirectly in order to understand the frequency of subjects / disciplines addressed were analyzed. Similarly, the papers were carefully classified "ad hoc" in order to provide a general idea of the scientific approaches adopted in each article. UNESCO (2016) data was analyzed to see which countries have been most active in establishing geoparks, as this was seen as being a measure of broader national interest in geodiversity that was somewhat independent of the countries where authors conducting geodiversity studies are located and of the number of times that various countries were included in academic geodiversity studies. Likewise it seems of paramount importance to understand if current geoparks coverage is geographically distributed in such a way that it is able to provide a representative picture of the geodiversity of the planet. Rank abundance plots, the most common form of sorting data in biodiversity and pedodiversity studies (e.g. Magurran, 2004), were used to analyze the subjects addressed in the articles reviewed when such analysis was appropriate. Similarly, the data was tested to see if it fit a linear regression model or a power law model. In diversity analysis the data usually fits a power law better than a lineal distribution. Some key terms give direct information of the main objectives where as others inform of the main focus of the papers. This is an approach to try a type of data meta-analysis to improve understanding of the context of the main key terms to achieve the purposes of this study.

The analysis of papers from a single journal necessarily suffers from biases that cannot be avoided. To help avoid such logical shortcomings a similar approach was used searching terms that are most closely related to the subject of this study using the Google Scholar and Scopus databases beginning in 1980. The Google Scholar database was analyzed on 02 February 2017 and Scopus through 29 November 2016. The results obtained from these two databases were similar. In Google Scholar single terms related to geodiversity, pedodiversity, and geoheritage were searched first and after that the search was refined as first entries and related terms in a second search.

Finally, an “ad hoc” classification of the papers submitted to Geoheritage Journal, according to their main focus, was carried out. The papers were classified as being case studies of local interest, case studies of general interest, papers that sought to develop theoretical or methodological aspects of geodiversity, papers that were educational in nature (focused on the role of geoheritage preservation in the education of students, the public, etc.), thematic papers (those focused on a single feature of geodiversity, such as karst, fossils, etc.), reviews, and others (papers that didn’t fit any of the other subdivisions, which included editorials). This type of classification has some shortcomings but permits conclusions to be reached concerning to what extent the concepts and their quantification are formalized, as well as whether the global coverage of the items addressed is balanced.

The data was analyzed in several ways. The number of publications and geoparks were summed and the total numbers compared by country and region. Similarly, the number of times that a given key term appeared in the database searches was determined and the most frequently used key terms determined. Common diversity indices (richness –S-, Shannon index –H-, and equitability –E-, as well as the models of distribution of abundance) (Shannon and Weaver, 1949) were applied to the key terms to determine their distributions and equitability. The most common abundance distribution models are the geometric series, the logarithmic series, the logarithmic normal distribution, and the “broken stick” model (Ibáñez et al., 1995). Of these, the geometric series is the least equitable, meaning that a few objects in the classification are dominate while all others are very rare. This is followed by the logarithmic series and the logarithmic normal distribution, with the “broken stick” model being the most equitable. While some natural distributions fit other models, the use of these four as often as possible has been recommended as a way to standardize methods and allow comparisons between studies (Ibáñez et al., 1995; Magurran, 2004).

Results and Discussion

Publications and geoparks by country using Geoheritage papers and UNESCO geoparks

The distribution of studies were not equitable by country or continental region (Tables 1-3). The data for author nationality, countries investigated by the research projects, and the establishment of geoparks followed hollow curve distributions (Figures 1-4), which is the dominant structure found in diversity data (e.g. Ibáñez et al., 1995; Magurran, 2004). However, the results obtained were not equitable as occurs in biodiversity and pedodiversity analyses for natural data. Geodiversity research seems to be concentrated in a few countries that are interested in the analysis of the preservation of geological heritage with rapid decrease in attention from most countries (a typical hollow curve); researchers from many countries have not published a single paper. Researchers in the European countries have shown particular interest in geodiversity work, with seven of the top 10 countries in terms of numbers of authors publishing papers being from Europe (the “several countries” entry in Table 1 being ignored for the purposes of this evaluation). In terms of the number of papers in which a given country was included, the top 17 countries are European. Brazil, China, and Australia are additional countries with researchers who have shown a fairly large interest in geodiversity through their publication records (Tables 1 and 2). The USA Department of State recognizes 195 independent States (US Dept. of State, 2017) while the United Nations has 193 member states (UN, 2018). Authors based in 40 countries (only about 20% of the world’s nations) have authored papers in Geoheritage. Geoheritage is a young journal, but it is notable that geologists in some countries with healthy, vibrant geological communities such as the USA or Russia do not seem to show much interest in sharing and discussing their knowledge and initiatives in this journal/area.

Obviously we should not infer that the experts of countries that publish more papers are more interested than others based only on this data. However, the unequal distribution of studies and researchers should be a matter of concern considering that a scientific discipline's progress benefits from multiple perspectives and viewpoints (Scheffer, 1999). This is something that should be achieved when experts from many countries share information with their colleagues in the international scientific community concerning their respective strategies and methodologies. If each country designs its own strategies without interest in the work carried out by others, this will limit progress and leave us far from achieving shared universal strategies that can serve to advance geological heritage into a scientifically healthy and mature discipline. Such a situation was observed in soil science in the late 1800 and early 1900s, when the failure to effectively communicate ideas across national boundaries was one factor that slowed the advancement of soil science as a field of study (Brevik et al., 2016) and in some cases continues to be an issue today (Rodrigo Comino et al., 2018).

The number of geoparks that have been established by country and continent as of the end of 2017 are shown in Tables 4 and 5. Twenty-four of the 35 countries that have established geoparks are in Europe, providing abundant and diverse geoparks opportunities within Europe. In total, 57% of the world's geoparks were found in Europe. Eastern Asia was also fairly well represented with 38% of the world's geoparks in six countries. China established more than three times more geoparks than any other individual country (27% of all geoparks world-wide), and UNESCO (2016) recognized the European countries and China as the regions with the most interest in geoparks. Japan ranked 4th on the list of geoparks established by country, and Indonesia, Malaysia, the Republic of Korea, and Vietnam have also established geoparks. There are only four geoparks in North America (two in Canada and two in Mexico), two in South America (in Brazil and Uruguay), and one in Africa (Morocco). No geoparks have been established in Oceania. This does not mean countries that do not have UNESCO geoparks such as Australia and the USA do not value parks and the conservation of nature; each of these countries has a vibrant national parks system. However, there does not seem to be a strong drive to establish geoparks in countries such as these at this time. Table 5 presents a particularly desolate scene. The geographical distribution of geoparks is biased and cannot represent a true picture of the Earth's geoheritage. This is true even though the UNESCO criteria used to establish the UNESCO Geoparks label tries to help/encourage developing countries to improve their living conditions and progress towards sustainable development. Likewise, it is noteworthy that European countries that have large tourism industries have achieved great success in getting the UNESCO labels, which will help them to diversify and strengthen their offerings to a greater number of visitors and generate economic income in the future. Within the geoparks concept, the preservation of geomorphological heritage has aroused much greater interest than other natural objects included in the concept of geodiversity (e.g. Reynard et al. 2007; Coratza and Giusti 2005; Testa et al., 2013; Melelli et al., 2017) with some exceptions such as paleontological sites (e.g. Sá dos Santos et al., 2016).

There are interesting similitudes and differences between the publication data from Geoheritage Journal (Tables 1-3) and the UNESCO geoparks data (Tables 4 and 5). For instance, the European expert community is the most active both in the number of papers published and the number of geoparks established, with the southern European countries being more active than the northern ones. In contrast, the ratio of papers published in Geoheritage by Chinese experts is low with respect to the number of geoparks in that country. The opposite trend occurs with South America, and specially Brazil, where authors have been active publishing in Geoheritage but few geoparks have been created, and despite interest in the research community there are no geoparks in Australia. The data indicates a lack of equitability between the scientific (papers) and pragmatic (number of geoparks) progress among countries and continents.

Statistical evaluation of key terms

The choice of some generic terms (such as geology, mineral, soils, etc.) that appear in Tables 6-8 necessarily suffer from certain arbitrariness. They were selected as reference words to show the current relevance of those most directly related to the objectives this paper (geodiversity, geoheritage, pedodiversity, etc.). However, if we analyze the number of times each word appears in the tables and apply certain basic indexes commonly used in diversity analysis we observe some interesting regularities. In all of them the distributions conform to the hollow curve, as is usual in pedodiversity and biodiversity studies (see Ibáñez and Bockheim, 2013 and several chapters there in). Furthermore, in most of the cases the best fits occur with log normal and logarithmic distributions, instead of geometric distributions and the so termed “broken stick” model, as is also the rule in biodiversity and pedodiversity analyses. The equitability is in general a little higher, but is also in the expected range of the above mentioned diversities. Likewise in all cases the data shown in these tables fits a power law better than a linear distribution (Table 9) as is ubiquitous in biodiversity and pedodiversity analysis but also in other many structures and processes of nature (e.g. Schroeder, 1992) and in natural languages as described by Zipf's law (word frequency distributions for a large enough piece of text) (Moreno Sánchez et al., 2016). Although the data provided by the tables are inconclusive, whether or not Zipf's law could be extended to key term searches in the Internet, or any type of data mining, would be an interesting line of study.

Importance to understanding the history of geodiversity studies

This type of basic datamining can offer great insights regarding the history of a field. For example, Sharples (1993) has been credited with being the first to coin the term geodiversity in 1993 (Gray, 2004, 2008). However, the search in Scopus showed that the term geodiversity first appeared in the scientific literature more than ten years before Sharples' work (see Karjalainen (1983) and references there in). Also, while Sharples (1993) focused attention on geoconservation, that same year De-Alba et al. (1993) conducted the first study that simultaneously quantified geodiversity as a function of lithodiversity, landform diversity and pedodiversity, the three topics that are most often included in the definition of geodiversity. In a similar fashion, the word pedodiversity was coined by McBratney (1992) in parallel with biodiversity some months after the Rio Summit that launched the popularity of the word biodiversity. However, earlier studies on the quantification of soil diversity were conducted by the Russian scientist Fridland as well as Ibáñez and coworkers (see Ibáñez, 2014 and references therein). Therefore, reviews such as the one conducted in this study have the ability to clarify the history and development of geodiversity and pedodiversity studies.

Classification of papers using Geoheritage Journal

Results of the classification of papers are shown in Table 10. A large portion of the papers published in Geoheitage Journal were case studies (83%), while there were relatively few papers that proposed and debated theoretical and methodological aspects of geodiversity (7%). Zwoliński et al. (2018) also determined that few authors have addressed methodological issues. Educational, thematic, review papers, and other types of papers were published in very low amounts (1-3% of total papers).

Key terms in Geoheritage Journal, Scopus, and Google Scholar databases

The frequency of key terms use related to geodiversity studies in Geoheritage Journal, Scopus, and Google Scholar are shown Tables 6-8, respectively. These key terms have been further subdivided into papers focused on diversity studies into geology, geomorphology, paleontology, and pedology. However, it is important to note the term geodiversity can be applied to rocks, landforms, or fossils, etc. The terms geodiversity and geosites are used in a broad sense in many instances. Certain key terms commonly occurred in all of the databases for a given focus. The key terms “geoheritage”, “geodiversity” or “geological diversity”, and “geosites” were the five most common key terms for diversity studies in geology. “Landforms”, “geomorphosites”, “relief”, and “geomorphology” were common key terms across all three databases for diversity studies in geomorphology. “Fossils”, “paleontological heritage”, “diversity of fossils” and “fossil diversity”, and “dinosaurs” were all common key terms in paleontological diversity studies across all three databases. And studies focused on soil diversity frequently used the key terms “soil erosion”, “soil diversity”, and “paleosols”. However the relative abundance of papers focused on soil diversity (pedodiversity) were surprisingly rare.

An analysis of the scientific studies published in the Scopus database does not give the exact same perspective with respect to the results obtained by analyzing Geoheritage Journal and Google Scholar, although there are similarities. The relative difference between the abundances of the papers that contemplate geodiversity and pedodiversity is reduced when investigating papers included in Scopus as compared to those indexed in Google Scholar. Pedodiversity studies were surprisingly rare in Google Scholar, although not practically nonexistent as was the case in Geoheritage Journal. This fact is surprising because geodiversity should incorporate multiple earth science disciplines and thus incorporate a number of researchers, whereas pedodiversity interest is focused in a single discipline that is, in fact, part of geodiversity. However, this result indicates that there is much more gray literature on geodiversity in general than there is on pedodiversity, which affects a subset of the experts in geodiversity studies in the broadest sense of the term. We reach this conclusion because Google Scholar contains much more gray literature (graduate theses, books and book chapters, conference proceedings, etc.) than Scopus, which is more focused on peer-reviewed journal articles. It seems that pedologists are focused mainly on scientific studies that are published in indexed journals, whereas a considerable part of the geodiversity literature is found in other more applied outlets such as those produced by government agencies during the creation and promotion of geoparks and the exploitation of their economic value (geotourism).

It was found that most or all of the papers in Scopus used the terms geodiversity, geoheritage, geotourism, and to a lesser extent geosites more or less at the same time. This suggests that practical purposes of economic interest are enhancing the publication of such studies, in contrast to the pedologists who are more interested in “soil diversity” analysis. Furthermore, plotted curves of increases in the numbers of papers through time demonstrate this trend, but sequentially, from the most basic terms to the more applied ones. For example, geodiversity curves began to grow slowly between the years 1998-2001, then increased, and showed exponential growth from 2009 (Figure 5); pedodiversity followed a similar trend (Figure 6). The geoheritage curve shows the same pattern but the slow part of the growth curve persisted until 2005 before beginning exponential growth, also around 2009 (Figure 7). Geoparks showed a very sudden move into exponential growth in the late 1990s (Figure 8), suggesting a unique and sudden driving force that triggered an interest in the subject within the scientific community. It is notable that this coincides with the deliberations and approval of the Geoparks Programme by the UNESCO in 1999.

Considerations in the key terms analysis

Tables showing simple words or a combination of words provide interesting information, but these key terms should also be carefully evaluated. Many words can appear in research without being the focus of that research or with a variety of meanings. Some words, such as "diversity", are too generic and widely used, being utilized by writers to designate technical aspects or simply as synonyms of concepts different from those analyzed here. The reader should take such limitations into account. Logically, the more generic the database is the more carefully information gathered from it should be scrutinized. For this reason the most reliable conclusions in this study can be drawn from the data mining of the Geoheritage Journal's papers, followed by Scopus, with the information provided by Google Scholar being the most ambiguous. This is because the information in Geoheritage and Scopus is specifically focused on geoheritage, geodiversity and pedodiversity whereas the Google Scholar database-provides more ambiguous information about the topics treated, with many of the references identified being gray literature.

The use of single word searches in the Geoheritage Journal database must also be approached with caution. For example, three terms widely used in papers published in this journal are erosion, diversity and soils. The word erosion appear in many papers, but in most of the cases it was not related to any interest in soils on the part of the author(s). For example, in several papers the authors call the readers' attention to the damage that current erosion processes could cause to the preservation of certain structures of geological interest (Panizza et al., 2009; Hjort et al., 2015). The use of the term erosion in a manuscript may also imply positive connotations with respect to the preservation of landform geodiversity; some papers call attention to the need to preserve badlands landscapes in view of the high biodiversity harbored in gullies of different ages and sizes. For this reason erosion appeared in the search even more than the word soil. In both examples above the papers that discussed erosion were not related to soils and pedodiversity preservation. Regrettably the word soil also appears in a large number of articles because the authors discuss definitions of geodiversity at the beginning of their papers, and that definition almost always includes soils (Huston 1994; Sharples, 1993; Gray 2004). However, most of these manuscripts do not actually address the importance of soils as part of geoheritage in the research they report. Only one paper in Geoheritage published during the time covered by this study (Conway, 2010) had a strong focus on soil preservation, and even this paper failed to mention pedodiversity analysis and the efforts of pedologists to preserve “pedoheritage” or “soil heritage”. There is also ambiguity with respect to the use of important terms in physical geography, probably due to the different uses of these terms by different national schools. While geomorphology is the study of the morphology and genesis of landforms, many geomorphology papers in Geoheritage Journal made use of physiographic information only. GIS and related technologies permit easy use of certain landform metrics. For example, a more or less flat relief could be formed by different process and as a result the soil coverage over this area could be significantly different from place to place across the landscape, such as occurs with peneplains, pediplains, etchplain, etc. (King, 1983; Gerrad, 1992) or in the flat bottoms of ancient lakes (Brevik and Fenton, 1999). The same situation can occur with their intrinsic geoheritage values. A physiographic approach estimated by landscape metrics via GIS software cannot replace sound scientific classification. Beyond such limitations, the results obtained are interesting to analyze their use in the three datasets in a comparative way.

Some gaps in available studies – future needs

Probably the most immediate gap that was identified by this review was the uneven geographic distribution of geodiversity studies (Tables 1-3) and geoparks (Tables 4 and 5) at the beginning of 2017. If we are going to truly understand global geodiversity it is important that a broader and more representative distribution of such studies is completed (Scheffer, 1999).

There are a plethora of papers and books concerning the relationships between soils and landforms (e.g. Ollier and Pain, 1996; Birkeland, 1999; Brevik and Fenton, 1999), soils and lithology (e.g. Zinck et al., 2016), lithology and landforms (e.g. Bridges, 1990; Zink, 2013), geology and plants (e.g. Kruckeberg, 2002), geology and soils (e.g. Kolay, 2010; Brevik and Miller, 2015; Zinck, 2016), landforms and vegetation (e.g. Howard and Mitchell, 1985; Stallins, 2006), and soils and vegetation (eg. Jobbagy and Jackson, 2000; Eyre, 2013; Ibáñez et al., 2016). However, the literature reporting the relationships among the respective diversities of these natural bodies is scarce and recent. Most of these papers show exciting relationships between pedodiversity and aboveground and soil biodiversity, landforms, lithodiversity and so on (see bibliography in Ibáñez and Bockheim, 2013, Ibáñez, 2014). There is great interest in the scientific literature on biotic and abiotic surrogate indicators of biodiversity. In fact many researchers contend that the exhaustive corroborated diversity-area relationship (that conforms to a power law) hides another more predictive power: biodiversity-habitat heterogeneity relationships (e.g. Harner and Harper, 1976; Johnson and Simberloff, 1974; Williamson, 1981; Hupp, 1990; Triantis, 2003; Ibáñez and Feoli, 2013; Ibáñez et al., 2014, among many others). All these diversity-area relationships datasets also fit to a power law (see bibliography in Ibáñez and Bockheim, 2013, Ibáñez, 2014). Consequently, there is sufficient evidence to justify researching whether the spatial patterns of biodiversity are idiosyncratic or are also a characteristic of abiotic resources. If geodiversity patterns could be the driving forces behind the biodiversity patterns, this would open a fascinating and unexplored research field to expand the horizons of geodiversity studies, which are currently restricted to the protection of geological heritage (with a few exceptions such as mineral diversity). That would make new opportunities and funds available to experts in geology, landforms and soils. At this date the bibliography on this topic is in its infancy (e.g. Pemberton, 2007; Parks and Mulligan, 2010; Matthews, 2014; Bétard et al., 2017). For example, in some environments and lithological materials rainfall produces soil erosion and eroded sedimentary sequences inducing the development of badlands landscapes, increasing the biodiversity of such sites (Gallart et al. 2013). Some human practices can interfere with badlands formation when these should be preserved as part of biodiversity and geodiversity heritages (Phillips, 1998).

This review of the literature showed that there is currently a lack of universal criteria utilized to conduct geodiversity studies, a conclusion that has also been reached by others working in this field (Zwoliński et al., 2018, p. 27). The criteria used by geologists in the main stream geodiversity studies differs from those used by the biodiversity and pedodiversity communities; the biodiversity and pedodiversity communities are utilizing similar criteria. The adoption of universal criteria is a prerequisite for the progress of any scientific discipline, and it seems that the adoption of universal criteria by the various communities studying natural resource diversity would be a major step forward in allowing the results of these different groups to be compared, contrasted, and utilized in the policy-making process.
As mentioned above, a fascinating exception in the geodiversity bibliography concerns mineral diversity. R.M. Hazen as well as G. Ausubel and cowokwers used the universal classifications of mineral types and the Mindat database (which specifies its spatial distribution at the worldwide level) to carryout very interesting research with findings that are very similar to those detected in pedodiversity analysis (Hazen et al., 2015; Hazen and Ausubel, 2016; Hystad et al. 2015a,b). These authors were able to predict the number of mineral species not yet described, their relative abundance, patterns of spatial distribution, the percentage of minerals that appeared due to the influence of life and proposed models of mineral evolution throughout the history of the earth. However, it is surprising that such studies have not aroused the interest of geodiversity experts from other disciplines involved.

Conclusions

As both a science as well as a scientific paradigm, studies of the diversity of a given natural resource began in the disciplines of ecology and conservation biology. After the Rio Summit, when the neologism biodiversity was popularized, the neologisms geodiversity and pedodiversity were proposed. However, studies of geodiversity and pedodiversity have been conducted by different communities of practitioners who followed different paths and there has been little communication between them. While pedologists followed the tradition of biodiversity experts with a view to understanding the structure and spatial distribution of soil landscapes, geologists focused primarily on geoconservation without addressing the literature already available in the fields of biodiversity and conservation of biological resources. The only exception detected is the recent research into mineral diversity that is similar in many ways to the approaches followed in biodiversity and pedodiversity studies.

Currently, the scientific community is focused on transdisciplinary studies that break boundaries with the goal of obtaining a more holistic view of natural resources. If this doctrine had been followed, surely studies in both geodiversity and pedodiversity would have progressed in more fruitful ways. It should not be forgotten that pedodiversity is one of the many elements that make up geodiversity. However, the first quantitative studies on pedodiversity were carried out and published before the Rio Summit.

The literature review showed that there is considerable geographic imbalance in the geodiversity studies that were conducted through the beginning of 2017. This imbalance threatens to hinder the development of geodiversity as an area of academic study, as it is important to consider diverse perspectives and viewpoints to achieve complete development of a field. There is also a strong geographic imbalance in the establishment of geoparks, which means global geodiversity is not adequately cataloged or protected. Future work should seek to correct this geographic imbalance, investigate whether the spatial patterns of biodiversity are idiosyncratic or are a characteristic of abiotic resources (lithology, landforms, soils, etc.), and standardize natural diversity research methods.

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Figure 1. An idealized hollow curve.
Figure 2. The number of authors who have published papers in Geoheritage Journal by country.
Figure 3. The number of times a given country was included as part of a research project reported on in Geoheritage Journal.
Figure 4. The number of geoparks by country.
Figure 5. The use of the term “geodiversity” over time.
Figure 6. Use of the term “pedodiversity” over time.
Figure 7. The use of the term “geoheritage” over time.
Figure 8. Use of the term “geoparks” over time.

Table 1. Country of institutional affiliation for authors of papers in Geoheritage Journal.

Country	Number of papers	Country	Number of papers	Country	Number of papers
Italy	36	Germany	2	Cuba	1
Several countries*	28	Greece	2	Egypt	1
Brazil	15	Malaysia	2	Iran	1
Spain	15	Mexico	2	Nigeria	1
Australia	13	Russia	2	Netherlands	1
United Kingdom	12	Serbia	2	Romania	1
Portugal	9	Turkey	2	Slovenia	1
France	6	Saudi Arabia	1	Switzerland	1
China	4	Arab Emirates	1	Tunisia	1
Poland	4	Argentina	1	Ukraine	1
Bulgaria	2	Bangladesh	1	USA	1
Cameroon	2	Belgium	1	Vietnam	1
Canada	2	Chile	1		
Czech Republic	2	Colombia	1		

* - papers written by authors of multiple countries
Diversity Statistics: Richness = 40; H (Shannon Diversity Index) = 2.90; E or Equitability = 0.78

Table 2. The number of papers in which the name of a given country was included as part of the research as reported in Geoheritage Journal.

Country	Number of studies	Country	Number of studies	Country	Number of studies
Spain	73	United Kingdom	12	Laos	5
Italy	67	Australia	12	Fiji	4
France	59	Brazil	11	Mauritius	4
Germany	55	China	11	Oman	3
Netherlands	50	Cuba	11	Serbia	3
Belgium	39	Ukraine	10	Morocco	3
Greece	39	Russia	10	Colombia	3
Turkey	33	Argentina	9	Vietnam	3
Portugal	31	Chile	8	Cambodia	3
Poland	31	Saudi Arabia	8	Republic of Korea	2
Bulgaria	22	Egypt	7	New Zealand	2
Iceland	18	Israel	7	Iran	2
Austria	17	Bangladesh	6	Malaysia	1
Czech Republic	14	India	5	USA	1
Ireland	14	Cameroon	5		
Malta	13	Nigeria	5		

Table 3. The number of studies as grouped by major geographic regions as reported in Geoheritage Journal.	
Continent	Number of studies
Europe	82
European Union*	41
North and South America	36
Asia	23
Africa	23
Oceania	1
* - The European Union (EU) was also looked at separately from the rest of Europe to determine if there were any research trends by membership or lack thereof in the EU. The Europe number also includes studies by EU countries.	

Table 4. The number of geoparks by country (UNESCO, 2017)

Country	Number of geoparks	Country	Number of geoparks	Country	Number of geoparks
China	35	Hungary*	2	Finland	1
Spain	11	Iceland	2	Malaysia	1
Italy	10	Indonesia	2	Morocco	1
Japan	8	Mexico	2	Netherlands	1
United Kingdom*	7	Norway	2	Northern Ireland*	1
Germany*	6	Republic of Korea	2	Poland*	1
France	6	Slovenia*	2	Romania	1
Greece	5	Brazil	1	Slovakia*	1
Austria*	4	Croatia	1	Turkey	1
Portugal	4	Cyprus	1	Vietnam	1
Ireland*	3	Czech Republic	1	Uruguay	1
Canada	2	Denmark	1	TOTAL	130

Diversity Statistic S or Richness = 35; H or Shannon Diversity Index = 2,8103; E or Equitability = 0.807

* - transnational UNESCO Global Geoparks have been assigned to each of the involved countries

Table 5. The number of Geoparks by continent (UNESCO, 2017).	
Continent	Number of studies
Europe	74
Asia	49
North America	4
South America	2
Africa	1
Oceania	0
Diversity Statistics; Richness =6; H (Shannon Diversity Index) = 0.85623; E or Equitability = 0.47787	

Table 6. The number of times that key terms related to geodiversity studies were used in Geoheritage Journal, divided by geoscience subfield.

Geology		Geomorphology		Paleontology		Soil Science	
Geology	183	Landforms	100	Fossils	108	Soils	93
Geoheritage	183	Geomorphology	94	Paleontological heritage	46	Soil Features	14
Geosites	124	Relief	51	Dinosaur	34	Soil Erosion	8
Geodiversity	110	Geomorphosites	44	Paleontological sites	14	Pedology	7
Minerals	95	Geomorphosyte	35	Diversity of fossils	2	Soil Types	7
Mineral diversity	68	Geomorphological diversity	5	Fossil diversity	1	Paleosols	5
Mineral preservation	64	Diversity of Landforms	3	Paleontological diversity	0	Soil Diversity	3
Lithology	34	Diversity of relief	3	Paleontological Conservation	0	Soil Science	3
Lithologies	26	Geoforms	2			Conservation of Soils	2
Lithological diversity	23	Diversity of Geoforms	2			Soil conservation	2
Geological diversity	1	Relief diversity	0			Soil Sites	2
						Diversity of soils	1
						Erosion of Soils	1
						Soil Directive	1
						Soil Heritage	1
						Pedodiversity	0
						Pedosites	0
						Preservation of soils	0
						Soil preservation	0
						Soil Units	0

Table 7. The number of times that key terms related to geodiversity, geoheritage and pedodiversity studies were used in Scopus, divided by geoscience subfield.

Geology		Geomorphology		Paleontology		Soil Science	
geodiversity	1150	geodiversity & Landforms	329	fossil diversity	344	soil & diversity	229357
geotourism	964	geoheritage & geomorphosites	195	diversity of fossils	248	soil & biodiversity	12525
geoheritage	887	geodiversity & geomorphosites	162	paleontological heritage	67	diversity & soil types	11898
geosites	755	geomorphic (geomorphological) diversity	147	paleontological diversity	1	diversity of soils	6919
geodiversity & Biodiversity	400	geomorphosites & geotourism	146			soil diversity	1623
mineral diversity	400	diversity of Landform(s)	27			pedodiversity	426
geomorphosites	377	landforms diversity	17			soil reserves	176
geodiversity & Geoheritage	361	diversity of relief	11			geodiversity & pedodiversity	35
rock diversity & diversity of rocks	285	relief diversity	3			geodiversity & Paleosol(s)	12
geodiversity & geosites	280	geomorphological preservation	1			pedotourism	0
geological diversity & geologic diversity	193	diversity of geoforms	0			pedodiversity inventory	0
geodiversity & reserves	165						
sediment diversity	115						
diversity of minerals	114						
geoheritage and reserves	101						
mineral(s) preservation	98						
lithological diversity	79						
geoheritage conservation	48						
geosites inventory	39						
lithodiversity	29						
geoheritage reserves	6						
Richness = 46; H (Shannon Diversity Index) =2.18; Equitability = 0.57							

Table 8. The number of times that key terms related to geodiversity, geoheritage and pedodiversity studies were used in Google Scholar, divided by geoscience subfield.

Geology		Geomorphology		Paleontology		Soil Science	
geology (geological)	5310	erosion	3330	fossils	1660	soil erosion	543
geoheritage	4790	geomorphology	2730	dinosaur	340	soil conservation	194
minerals	2840	relief	2220	paleontological heritage	53	pedodiversity	129
geological diversity	1990	landforms	2010	diversity of fossils	10	soils	93
geosites	1400	geomorphosites	573	fossils diversity	1	soil diversity	87
lithologies	940	geoforms	155	paleontological diversity	1	paleosols	79
lithology	934	geomorphological diversity	98			diversity of soils	24
“lithological diversity”	38	diversity of landforms	50			soil features	14
“diversity of minerals”	24	relief diversity	25			soil sites	13
“mineral diversity”	7	diversity of relief	8			erosion of soils	10
“mineral preservation”	0					soil preservation	10
						conservation of soils	7
						pedology	7
						soil types	7
						soil directive	7
						soil science	3
						pedosites	0

Richness = 42; H (Shannon Diversity Index) =2.64; Equitability = 0.71

Table 9. The number of times that each term was used in the Google Scholar and Scopus tables.		
Distribution model	Linear fit	Power Law fit
Geodiversity single term	0.64	0.66
Geodiversity and other terms	0.62	0.84
Geoheritage and other terms	0.36	0.93
Scopus data (*)	0.25	0.81
(*) deleting the highest term: soil & diversity		

Table 10. Classification of papers by general topic in Geoheritage Journal.	
Topic	Number of papers
Case studies of local interest	122
Cast studies of general (broad) interest	30
Theoretical/Methodological	14
Educational	6
Thematic	3
Review paper	2
Others	6

Highlights for second submission

- Geodiversity and pedodiversity should receive as much attention as biodiversity
- Pedodiversity is part of geodiversity but rarely considered in geodiversity studies
- Pedodiversity studies followed biodiversity methodologies, geodiversity did not
- Geodiversity has focused on the proposal of geoparks, geotourism, and education
- Researching relationships between bio-, pedo- and geodiversity would be fruitful

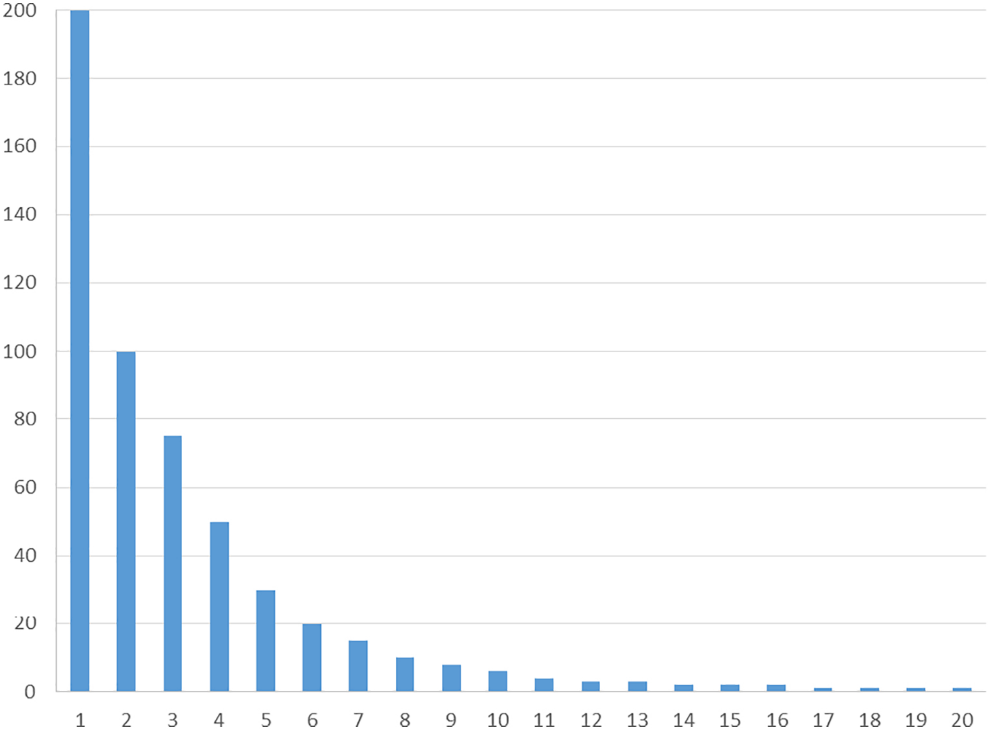
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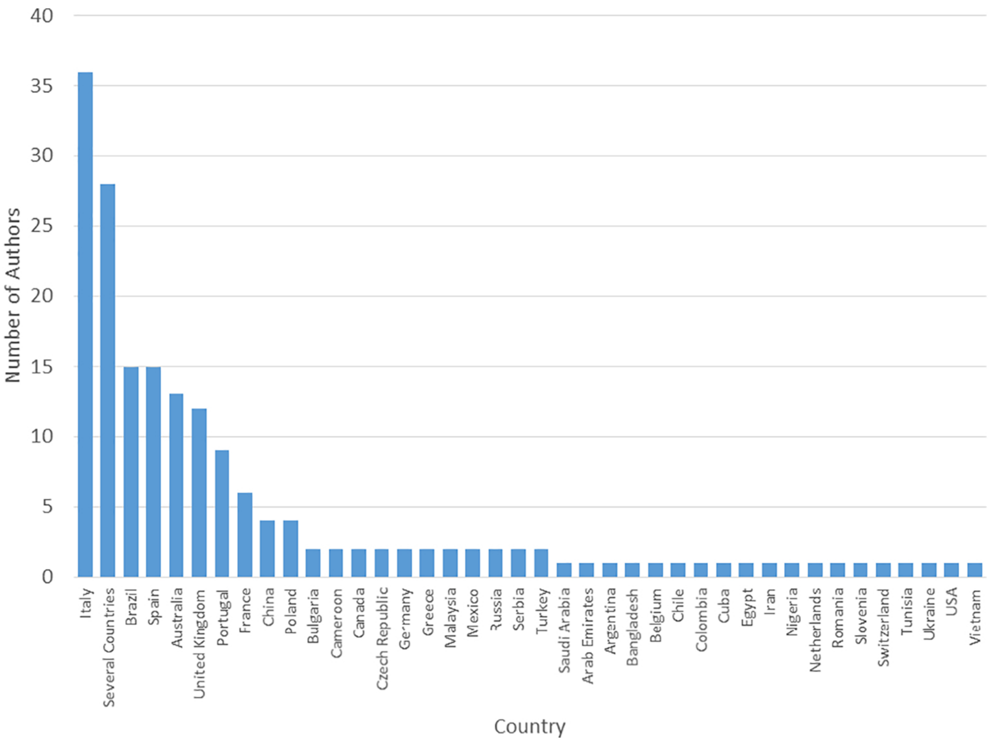
Figure 1



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Poland
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Canada
Czech Republic
Germany
Greece
Malaysia
Mexico
Russia
Serbia
Turkey
Saudi Arabia
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Bangladesh
Belgium
Chile
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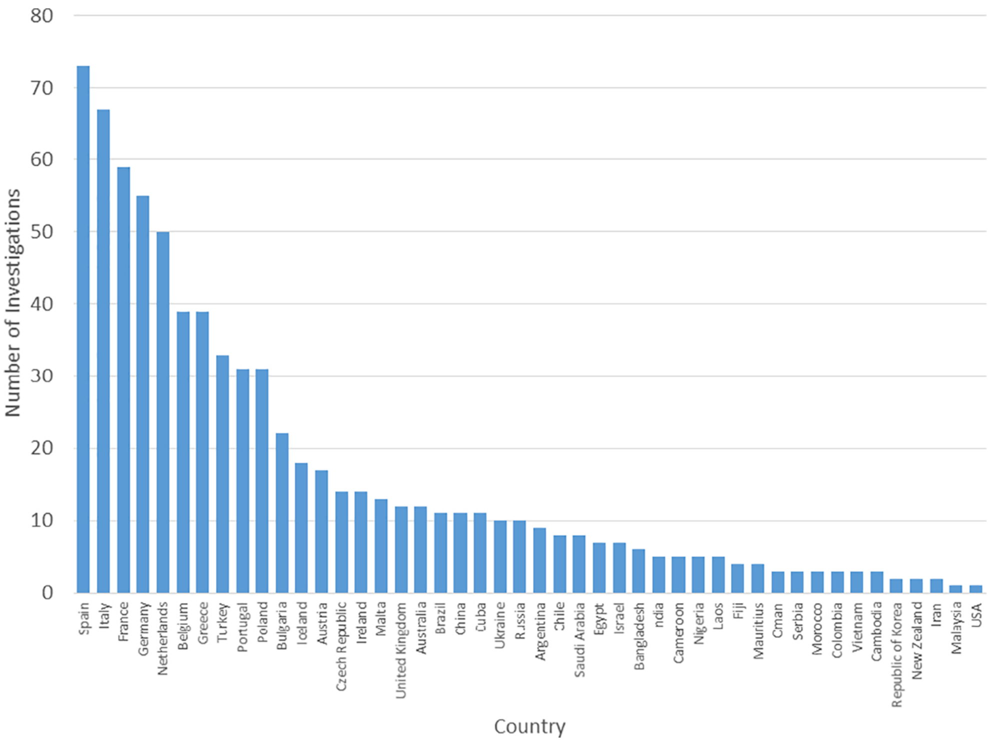
Vietnam
Country

Figure 2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Turkey
Portugal
Poland
Bulgaria
Iceland
Austria
Czech Republic
Ireland
Malta
United Kingdom
Australia
Brazil
China
Cuba
Ukraine
Russia
Argentina
Chile
Saudi Arabia
Egypt
Israel
Bangladesh
ndia
Cameroon
Nigeria
Laos
Fiji
Mauritius
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Morocco
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Vietnam
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Republic of Korea
New Zealand
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Malaysia
USA
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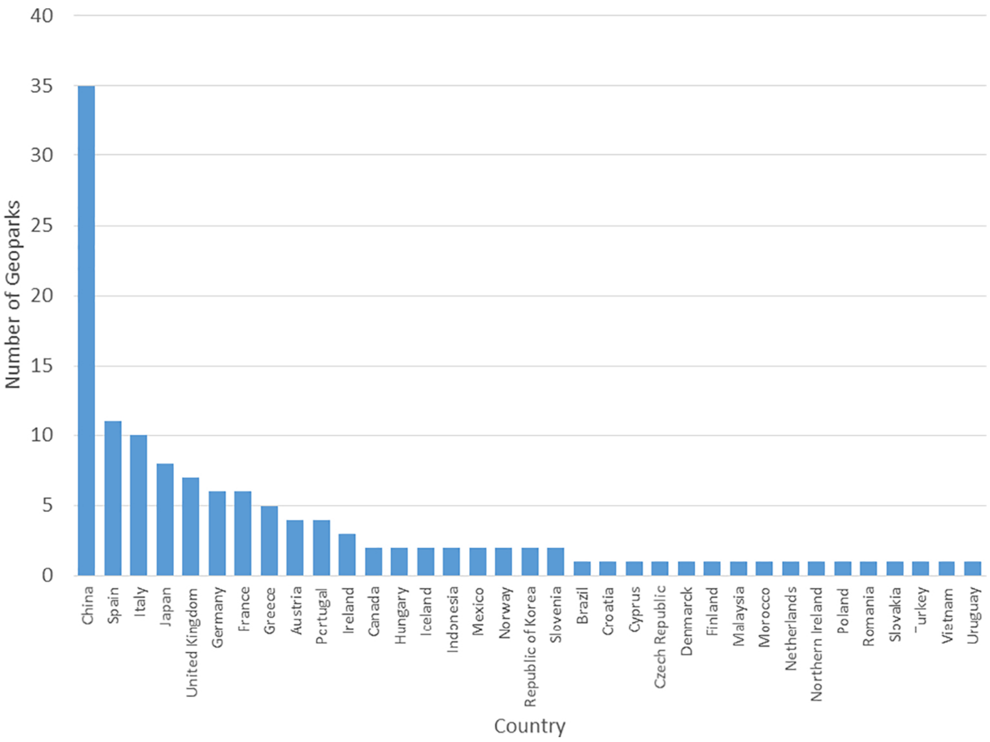
Figure 3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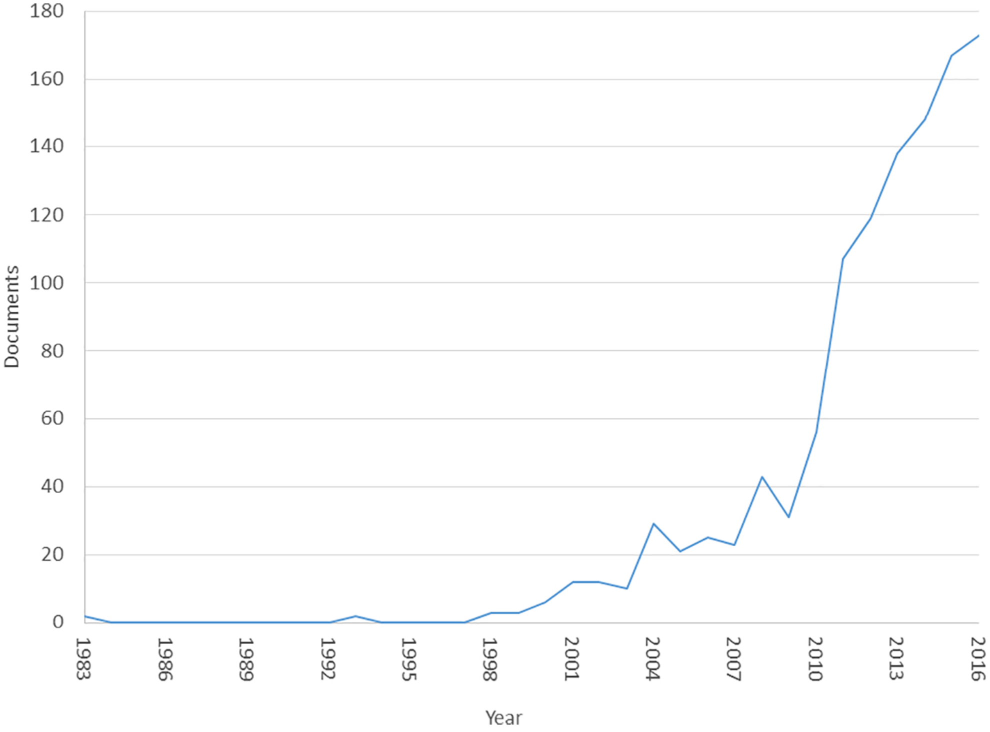
Iceland
Indonesia
Mexico
Norway
Republic of Korea
Slovenia
Brazil
Croatia
Cyprus
Czech Republic
Denmarck
Finland
Malaysia
Morocco
Netherlands
Northern Ireland
Poland
Romania
Slovakia
Turkey
Vietnam
Uruguay
Country

Figure 4



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120
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Documents
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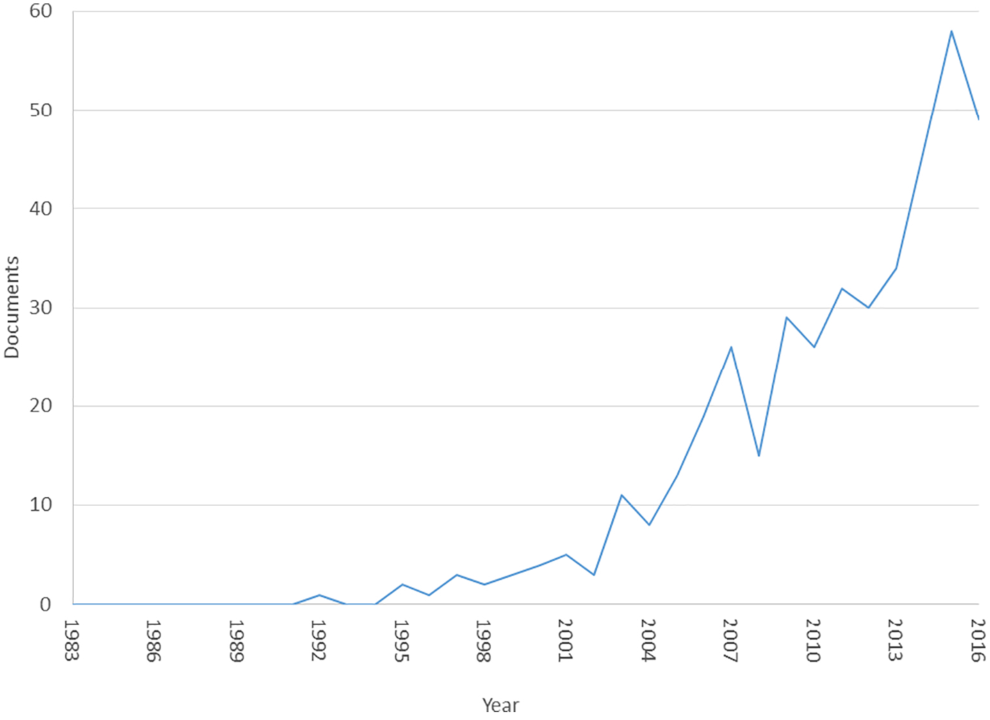
2001
2004
2007
2010
2013
2016
Year

Figure 5



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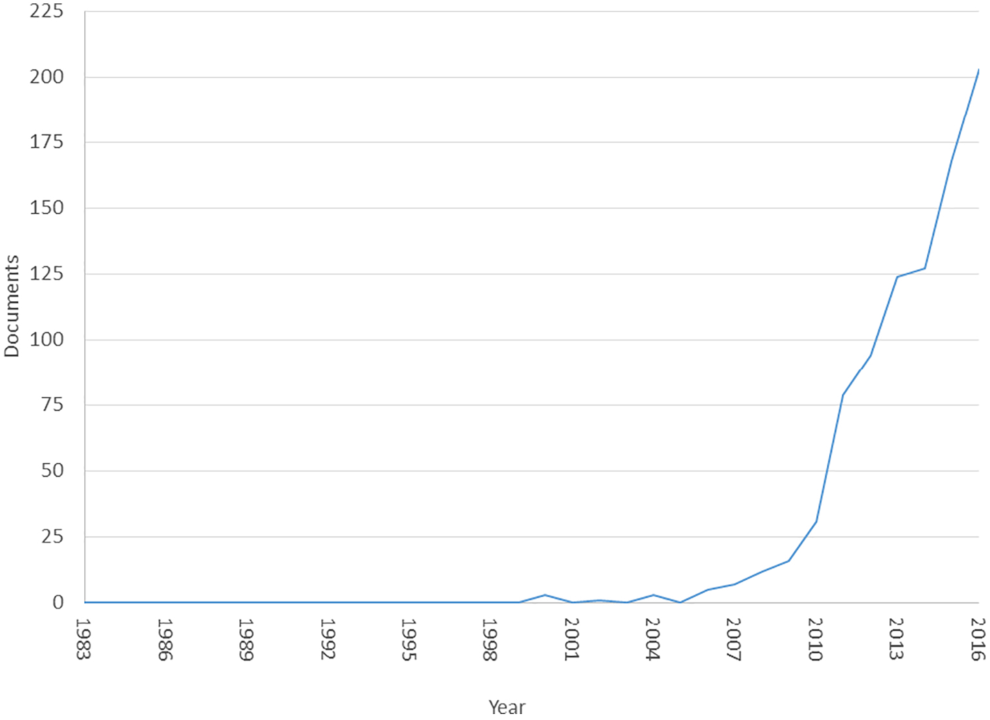
2016
Year

Figure 6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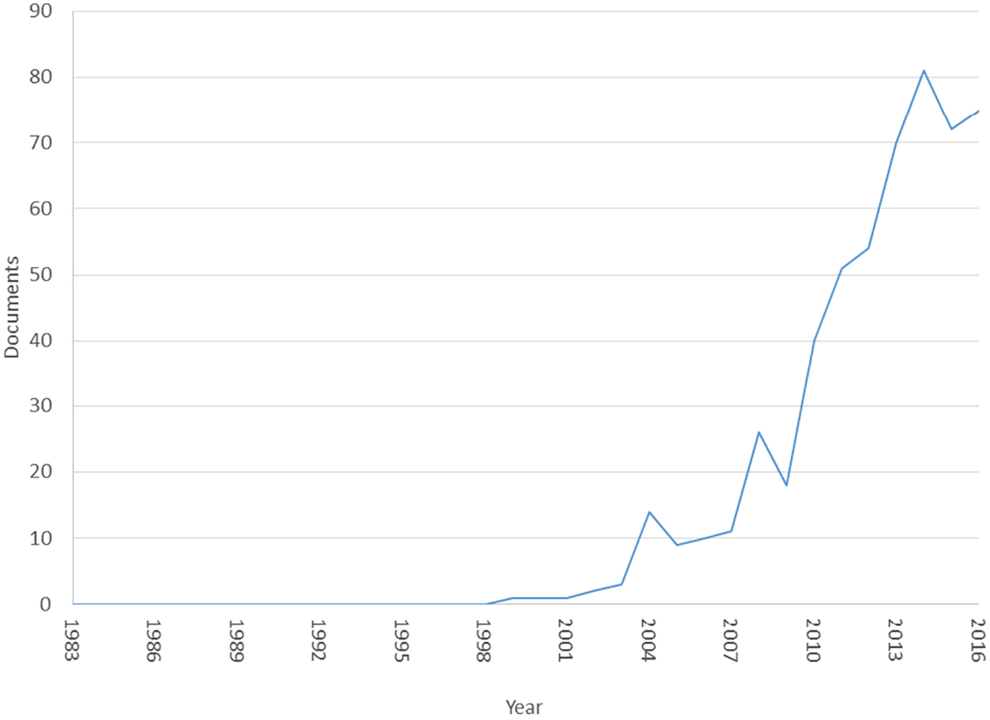
2013
2016
Year

Figure 7



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Documents
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1986
1989
1992
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1998
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2004
2007
2010
2013
2016
Year

Figure 8