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# Does land use legacy matter for current soil functioning? A bibliometric study (2001–2020)

Ninon Delcourt , Anne-Marie Farnet-Da Silva, Catherine Rébufa, Claude Perissol, and Nathalie Dupuy

Aix Marseille University, Avignon Univ, CNRS, IRD, IMBE, 13397, Marseille, France

Corresponding authors: Anne-Marie Farnet-Da Silva (email: [anne-marie.farnet@imbe.fr](mailto:anne-marie.farnet@imbe.fr)); Nathalie Dupuy (email: [nathalie.dupuy@imbe.fr](mailto:nathalie.dupuy@imbe.fr))

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## Abstract

This article applies the tools of bibliometric analyses to explore the evolution and strategic orientation of research focusing on the temporal dynamics of land use, which can be considered as an important proxy to assess soil vulnerability. With 1416 papers published in 417 different journals, the investigation showed a growing interest in the subject during the period ranging from 2001 to 2020. The main countries working on that topic are the USA, China, and certain countries of the European Union with a worldwide collaboration regarding coauthors. A cluster analysis of the keywords generated 6 main themes of research, each focusing on different issues and approaches, that is, greenhouse gas emissions, soil nutrients, climate change, erosion risk, human disturbances as well as resilience of soil functioning. Finally, it appears that the effect of land use legacy is poorly considered in the context of climate change, which could represent a future line of research.

**Key words:** Bibliometrics, historical ecology, land use legacy, agricultural activities, forest soils, soil functioning

## 1. Introduction

In 2015, the United Nations (UN) member states adopted the “2030 Agenda for Sustainable Development” containing 17 Sustainable Development Goals (SDGs) (UN General Assembly 2015). These objectives include fight against global warming, conservation of terrestrial ecosystems and food safety. Human activities indeed have a significant impact on ecosystems by strongly modifying biogeochemical cycles, biodiversity and thus ecosystem functioning (Canadell et al. 2010; Lana-Renault et al. 2020). Under this context, soil science is a field of growing interest in environmental sciences since soil functioning supports many ecosystem services such as organic matter turnover, primary production and carbon (C) flux regulation (Barot et al. 2017; Dominati 2013). Human *f* significantly altered soil structure and functions: for example, some agricultural practices have led to unproductive agricultural systems, and pollutants in soils such as heavy metals have degraded soil biodiversity, plants, water as well as food quality (Valentin et al. 2005; Smith et al. 2016). While an intensification of agricultural practices has been observed since the beginning of the 19th century, hampering land degradation occurring in all parts of the world is an urgent priority to protect biodiversity and ecosystem services (Olagunju 2015; IPBES 2018; Winkler et al. 2021).

The adverse impacts of human activities have thus led to an increased interest in soil conservation as well as goods and services they provide (Agyeman et al. 2020; Pan et al. 2021). To anticipate both short- and long-term effects of current land uses, many scientists had discussed on the resilience

of ecosystem functioning (Bürgi et al. 2017; Meli et al. 2017; Requena-Mullor et al. 2018) by multidisciplinary approaches (Senanayake et al. 2020; Vázquez et al. 2020). Many publications have indeed focused on the immediate effects of land use (*i.e.*, when the system is established) on the soil biological and physicochemical properties (Foley et al. 2005; Delcourt et al. 2019). However, authors have shown that the effects of past land use continue to influence ecosystem functioning even after it has been replaced by another land use (Dupouey et al. 2002; Falkengren-Grerup et al. 2006; de la Peña et al. 2016). Land use legacy is thus a persistent effect of land use change on both soil and vegetation structure and composition, which could shape actual pattern and process across the world (Foster et al. 2003; Bürgi et al. 2017). Some publications indeed highlighted that land use, that is, agriculture, burning, and grazing have persistent effects on the physical, chemical, and biological properties of soils (Standish et al. 2006; Zornoza et al. 2009; Macdonald et al. 2012). These last decades, studies from multidisciplinary fields have thus investigated the effects of land use legacy on soil functioning (*i.e.*, carbon flux, water regulation, fertility), looking at different past land uses (*i.e.*, logging, cropping, burning, and mining) and their associated deforestation—reforestation dynamics (Latty et al. 2004; Duguay et al. 2007; Bachelot et al. 2016).

The aim of the present study is thus to provide a global overview of academic research between 2001 and 2020 on the temporal dynamics of land use and their consequences on soil functioning. We focus on forests and agricultural lands

since they are the two predominant types of land use and land cover on the planet, and both forests and croplands have the highest change rate, with a net decrease in forested lands and a net increase in cropped areas (Ritchie and Roser 2013; FAO 2016; Winkler et al. 2021). It will (i) identify the main scientific questions, (ii) how these investigations have been conducted (scientific domain, approaches, and tools) and (iii) suggest prospects for future research requiring more attention.

## 2. Methodological approach

Bibliometric analyses are used by scientists to provide a clear understanding of the scientific contribution and its evolution in time of a research topic. Bibliometrics indeed provide a qualitative and quantitative overview of the knowledges and technologies associated by mapping the science produced (*i.e.*, scientific publications) and determining the trend in a specific area of knowledge. This statistic approach highlights the main relevant disciplines or individual scientists that are the most involved in a research domain and identifies the important role of a collaboration in scientific publications by a network analysis to visualize relationships between countries, and authors.

Bibliometric reviews can use different scenarios to delineate the literature of a research field (Chen and Song 2019). The overview landscape of academic research on past land use and their consequences on soil functioning, was conducted by extracting data from the journals referenced in the Web of Science Core Collection (WOS) database covering the period 2001 and 2020. References were obtained on 18 January 2021, at this date, publications registered in 2020 will be slightly under-estimated by WOS database. Keyword searches were conducted in “TOPIC” field (equivalent to subject research) covering simultaneously different fields such as “title”, “abstract”, “authors keywords” and “keywords plus” automatically generated by WOS (extracted from the titles of the cited references by Thomson Reuters to optimize the query of the database by enriching its indexing (Zhang et al. 2016). A search for exact expressions was done using quotes and a combination of keywords using Boolean operators. A combination of all used expressions eliminated duplicates. The following terms were thus searched: soil\* AND (“land-use” OR “landuse” OR “land use”) AND (past OR histor\* OR legac\* OR abandonment) AND (forest\* OR wood\* OR afforest\*) AND (crop\* OR agricult\*).

The analysis tools available in the WOS database allowed for the treatment and classification of the results, according to the year of publication, the journal and country of origin of the scientific articles. The impact factors (IF-2020) and category quartile ranks (Q, indicating the rank of the journal considered compared to the other journals in its category) were retrieved from InCites Journal Citation Reports (Clarivate Analytics).

For each found paper, all items in citation information (*e.g.*, authors, document title, year, citation count and references), bibliographical information (*e.g.*, affiliations: institution and country of the institution), the field of the research (*e.g.*, abstract and author keywords) were selected and exported in

TXT format, to be treated by the Matheo Analyzer<sup>®</sup> software (Matheo Software, n.d.), a flexible and an easy-to-use software exploring efficiently important volumes of data and converting them into strategic information.

Matheo clustering was used to get a dynamic classification to reveal some thematic groups using author keywords. Thus, keywords present in at least 10 publications were subjected to a K-means analysis and allowed to create 6 definitive number of clusters. To converge the clustering approach, the following keywords, the most common, were excluded: “land use and land cover change”, “land use history”, “land use legacy”, “agricultural abandonment”, “soil”, “forest”, and “agriculture.”

The cluster analysis was done exclusively on the author keywords. These words are chosen by the authors to be the three to five most relevant words to summarize the topics of the article as well as tools that are used in the study (Pesta et al. 2018). Additionally, author keywords are separated by a specific punctuation allowing analysis software to consider the complete term contrary to the title. The analysis of title thus may not separate the compound words correctly (*e.g.*, use of spaces in a composite word such as “land use”). We therefore chose the keywords that summarize the relevant information and for which the form is more adapted to the cluster analysis with the Matheo Analyzer<sup>®</sup> software. Authors keywords are thus a good tool to highlight emerging research fields and have been used in other bibliometric analyses (Pesta et al. 2018; Maléchaux et al. 2020; Sweileh 2020).

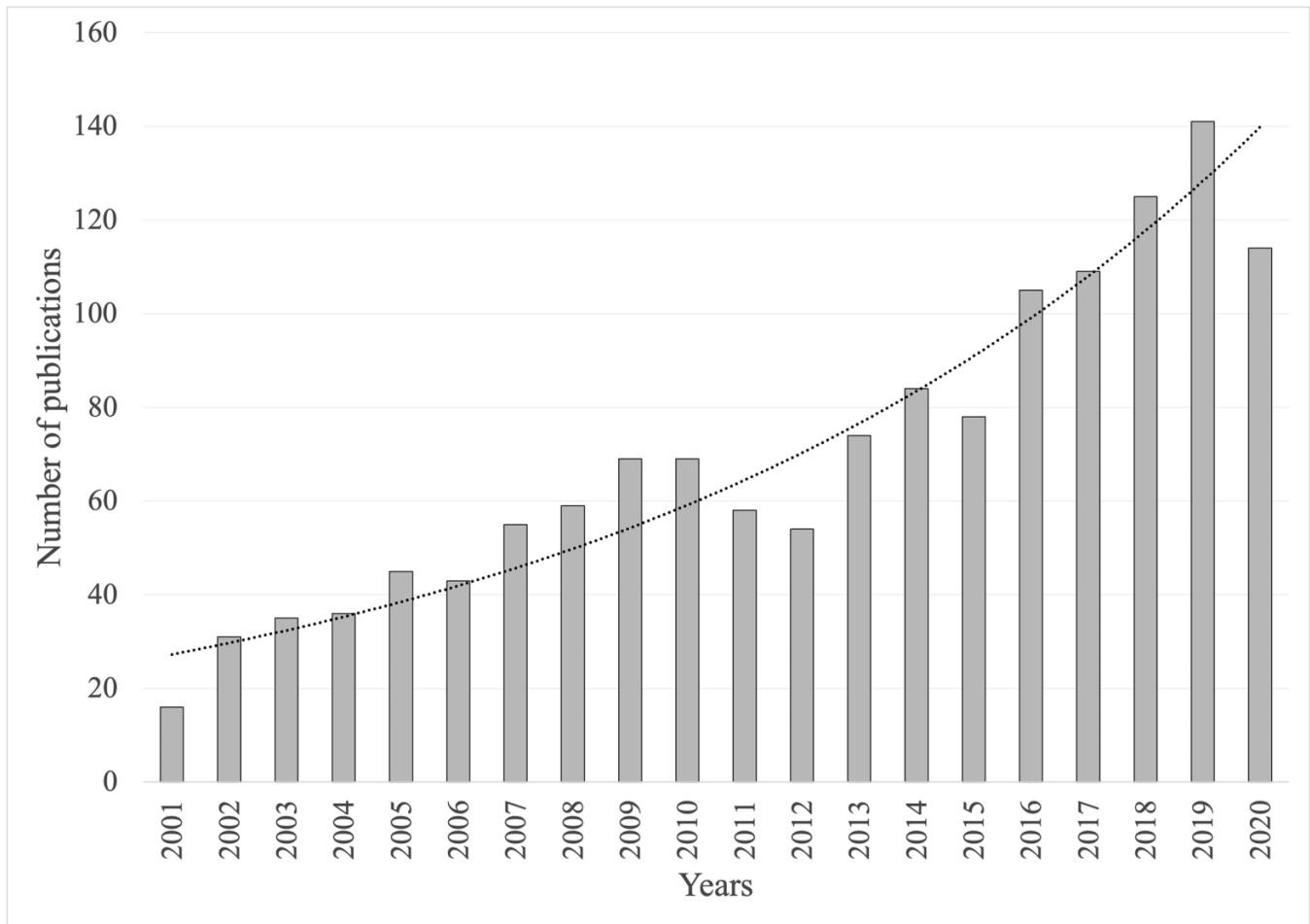
Here, only one database (WOS) was used because the export format of data from other databases was not compatible with the Matheo Analyzer<sup>®</sup> software.

## 3. Findings and discussion

### 3.1. Publication overview

This query yielded 1416 references, classified by WOS into one or several document types such as 1301 scientific articles + 63 reviews + 94 proceedings papers + 30 book chapters + 6 editorial materials + 1 letter + 1 data paper, all of which will be referred to as “publications” for this study. According to Fig. 1, in almost 20 years, the number of publications has increased from 16 publications in 2001 to 141 publications in 2019. A total of 114 publications are registered in 2020 but this number may be slightly underestimated if some papers published at the end of the year have not been recorded yet by WOS at the date the research was performed (*i.e.*, January 2021). This increase corresponds to a global trend for all scientific topics for the last 20 years. Previous bibliometric analyses related to soil health and conservation (*e.g.*, soil nutrient or soil contamination) also showed the same tendency, highlighting that the scientific world has seized these issues (Yanan et al. 2020; Pan et al. 2021; Shi et al. 2021). This interest in soil health and conservation seems not to concern only the scientific world since The United Nations declared the year 2015 as the “International Year of Soils”, recognizing soils as an essential part of the environment, defining it as a non-renewable resource supporting food production, planet’s biodiversity, water conservation and play-

Fig. 1. Number of documents over the period 2001–2020 (barplot) and associated exponential trendline (dotted line).



ing a key role in the carbon cycle in a context of climate change. The Paris agreement entered into force in November 2016 with the adhesion of 191 acceding countries also demonstrate a will of countries to rethink land use managements and slow down forest degradation rates, which could encourage the scientific production about this topic. A major research effort to understand the effect of past land use and to differentiate between good and bad practices has thus been conducted internationally.

The 1416 publications of the corpus are published in 417 different journals between 2001 and 2020, with 56% of the journals having only one publication dealing with our research. Table 1 presents the top 15 journals which published at least 20 publications. Journals that appear on the top of the ranking were Agriculture Ecosystems Environment on one hand and Forest Ecology and Management on the other hand, with 59 and 57 publications, respectively, followed by Catena with 51 publications (Table 1). Global Change Biology is the journal with the best IF-2020 (IF of 10.863), followed by Science of the Total Environment and Soil Biology & Biochemistry (IF of 7.963 and 7.609, respectively). Journals from several disciplines (*i.e.*, geosciences multidisciplinary, water resources and biodiversity conservation) have published about the effect of past land use and land cover on soil func-

tioning indicating that this issue has brought together different approaches and methodology. The presence of more generalist journals in ecology (environmental sciences and ecology) also indicates that this subject needs a global approach, which considers the relations and interactions among the various components of the ecosystems (Gellrich et al. 2007; Jangid et al. 2011; Bruun et al. 2015).

The most cited publication with 559 citations is founded in Catena (Valentin et al. 2005) (Table 1). Authors discuss the historical causes of soil erosion in Europe, underlining environmental factors that influence this process such as agricultural practices, rainfall and vegetation cover. These authors also discussed about the links between land use legacy and soil vulnerability as other publications of this rank. The notion of “soil vulnerability” is linked to the risk of loss and deterioration of soil such as a decrease in soil fertility, exposure to erosion and compaction as well as soil contamination (*e.g.*, sulphur and nitrogen deposition and heavy metal pollution) (Smith et al. 2016). Several authors thus investigate causes and consequences of past land use on soil functioning with different approaches by assessing various proxies, that is, carbon stock, organic matter content or microbial communities (Lemma et al. 2006; Jangid et al. 2011; Bruun et al. 2015). In other publications, variables identified as influenc-

**Table 1.** Journals with at least 20 publications on the subject between 2001 and 2020, sorted by their publication number, with their associated IF, subject category(ies), ranking in each category notified by their Q, most cited publication with number of citations associated and type of document.

Journal	Articles	IF-2020	Category: Q 2020	Most cited article	Citation count	Type of document
Agriculture Ecosystems Environment	59	5.567	Agriculture, multidisciplinary: Q1; Environmental sciences: Q1; Ecology: Q1	Gellrich et al. (2007)	320	Article
Forest Ecology and Management	57	3.558	Forestry: Q1	Zimmermann et al. (2006)	209	Article
Catena	51	5.198	Soil science: Q1; Geosciences multidisciplinary; Water resources: Q1	Valentin et al. (2005)	559	Article; proceedings paper
Science of the total environment	43	7.963	Environmental sciences: Q1	Pacheco et al. (2014)	112	Article
Land degradation development	28	4.977	Soil science: Q1; Environmental sciences: Q2	Bruun et al. (2015)	116	Article
Geoderma	26	6.114	Soil science: Q1	Lemma et al. (2006)	91	Article
Land Use Policy	24	5.398	Environmental studies: Q1	Valle Junior et al. (2014)	88	Article
Global Change Biology	20	10.863	Biodiversity conservation: Q1; Environmental sciences: Q1; Ecology: Q1	Smith et al. (2016)	260	Review
Soil Biology & Biochemistry	20	7.609	Soil science: Q1	Jangid et al. (2011)	221	Article

IF, impact factor; Q, quartile.

**Table 2.** List of the 10 countries with the largest number of publications over the period 2001–2020.

Countries	Number of publications	% of 1416 publications
USA	427	30.2
China	190	13.4
Germany	162	11.4
Spain	113	8.0
France	96	6.8
Brazil	89	6.3
UK	85	6.0
Belgium	78	5.5
Australia	75	5.3
Italy	64	4.5

ing soil vulnerability, are used to predict the effects of land use changes that may occur in the future on soil functioning. Some authors are exploring environmental factors such as rainfall, slope and soil class (Pacheco et al. 2014; Valle Junior et al. 2014), while other authors focus on socio-economic factors (causes of land abandonment, cultivation costs and benefits) (Gellrich et al. 2007).

### 3.2. Countries

Since 2001, there are 106 different countries working on past land use and its effect on soil functioning, representing 54% of the 195 countries recognized by the UN. Land use legacy issues are thus largely discussed by the scientific community around the world. The 10 most productive countries are presented in function of the number of publications in Table 2. The top 5 countries represent almost 70% of total publications and are composed of the USA, China, Germany, Spain, and France, respectively (Table 2). Off these countries

are those that contribute the most to scientific publications in all subject categories (China, the USA, UK, and Germany), but we cannot the absences of India and Canada despite their great interest in soil health (Yanan et al. 2020).

Six of the 10 most productive countries are part of the European Union (EU) (Table 2). The EU indeed represented 64% of total publications and it is not surprising since the early 2000 s the EU has shown a particular interest in soil protection with the creation of the European Soil Forum (ESF) (Bachmann et al. 1999). The ESF was intended to facilitate the development of protection policies and new technical soil protection directives, which might have encouraged scientific production (Bertrand 2018). In this ranking, Mediterranean countries (e.g., Spain, Italia and France for its South part) are also very concerned by soil degradation with soil leaching and erosion processes, more especially in semi-arid area (García-Ruiz et al. 2013; Requena-Mullor et al. 2018). The stakes are high for this area, which is considered as a hotspot of biodiversity (Quézel and Médail 2003) but also as a climate change hotspot (Giorgi and Lionello 2008). Moreover, since 1860, a progressive abandonment of traditional crops (i.e., agricultural terraces) is observed, resulting in forest recovery, with a slight acceleration of the process after 1958 (Serra et al. 2008; Abadie et al. 2017). Scientific production of Belgium represented almost 5% of total publications (Table 2). It mainly focused on plant communities, dealing with colonization capacity, seed bank, functional traits as well as forest herbs (de Frenne et al. 2011). Belgium seemed particularly interested in past land use. This strong interest can be explained by the major ecological challenges facing Belgium which has the 5th highest ecological footprint in the world (i.e., 7.45 global hectares in 2014) (WWF 2014). Belgium must, therefore, improve its natural resource management by involving its soil and water conservation policies. Belgium is also among the first countries to have built a detailed soil



map of the whole country, giving access to the description and analyses of soil profiles (Legrain et al. 2011). Such a map is a valuable research tool that could facilitate the assessment of soil degradation and vulnerability.

The USA alone represented 30% of total publications (Table 2) with publications in its territory, which were mostly focused on the northeast of the USA (*i.e.*, New England area and Ohio and New York States) (Flinn et al. 2005; Holmes and Matlack 2017; Fulton and Yansa 2020). This area has known successive land use and land cover changes over the past 200 years (Gerhardt and Foster 2002).

About 13% of total publications were published by China (Table 2). China is the country with the highest population in the world, inducing greatest need for food production. It is, therefore, essential for China to preserve soil quality with more sustainable policies and practices (Huang et al. 2006; Chen 2007). More than a quarter of these publications focused on the Loess Plateau in North China considered as one of the regions in the world with the most severe soil erosion (Zheng and Wang 2014). Also Chinese government was conducting ecological restoration operations (“Grain-for-Green” project) to reduce soil and water loss on the Loess Plateau (An et al. 2014; Deng et al. 2014). In this way, afforestation has been implemented to control soil erosion notably by constructing check dams and terraces (Jiao 2014; Xu et al. 2021).

It is no surprise that Brazil appeared in this classification since this country has 12% of the world forest area making it the second country after Russia with the highest forest area in the world. However, Brazil represented only 6% of total publications. Issues related to Brazil were different from those of other countries cited above. This was the only country of the rank for which a decrease in forest cover was observed. The Amazon Forest is the subject of many studies, publications generally dealing with mechanisms of resilience after deforestation, that is, shifting tropical rain forest—an extremely rich and diversified ecosystem also considered as a carbon pool—in cultivated areas (Lennox et al. 2018; Tosi et al. 2020). Forest recovery in this area was difficult to predict since the strong diversity in plant and fauna has only been partially explored (Hubbell et al. 2008; ter Steege et al. 2013). Moreover, the Brazilian savanna (Cerrado) was also investigated in many studies. Authors studied the effect of land conversion on soil functioning with specific attention focused on palm and eucalyptus plantations (López-Poma et al. 2020; Sales et al. 2020). Brazilian authors collaborated with other scientists from various countries, highlighting the global interest in Tropical Forest conservation. Amazonian forest was indeed at the center of many environmental issues like carbon sequestration, global warming and biodiversity conservation. In this research, many Central and South American countries were impacted by deforestation, for example, Mexico, Argentina and Peru (Gasparri et al. 2008). South America had the second-highest average annual rate of forest loss in 2010–2020, but this loss has dropped by half compared to 2000–2010, that could explain an increase in publications dealing with reforestation in these countries (Feldpausch et al. 2005). Other countries have published about deforestation in South-Eastern Asia, that is, Indonesia, Vietnam and North Korea (Lawrence 2005; Ziegler et al. 2012; Lim et al. 2017) and few

publications in Africa (mainly publications from Madagascar) (Raharimalala et al. 2010; Randrianarison et al. 2016) despite Africa had the highest net loss of forest area in the decade to 2020 (FAO 2020a). However, these countries may not appear in this study due to language barriers. In Africa, Asia, Latin America and Europe, many scientists indeed still publish their work in national journals, mostly written in their local language, limiting the international visibility of their work (Meneghini and Packer 2007; Amano et al. 2016). Nevertheless, a high level of international collaborations involving African countries (*i.e.*, Ethiopia, Morocco and Madagascar particularly) was observed (Morin-Rivat et al. 2016; Toledo et al. 2018).

Regarding forest area, China, Australia, the USA, France, and Italia were among the ten countries that have the higher annual increase in forest areas over the period 2010–2020, while Brazil was among the ten countries that have the greatest annual losses of forest surfaces over the same period (FAO 2020a). Two types of opposing dynamics were thus studied in this corpus of articles. Tropical and subtropical forests were submitted to deforestation and shifting cultivation issues, whereas temperate forests were rather expanding and were studied regarding agricultural abandonment consequences and ongoing secondary succession. Interestingly, Boreal forests (Russia and Canada with 3.2% and 3.7% of the total publications, respectively) received less attention despite Russia have the largest forest areas in the world with 20% of world forest area (FAO 2020a).

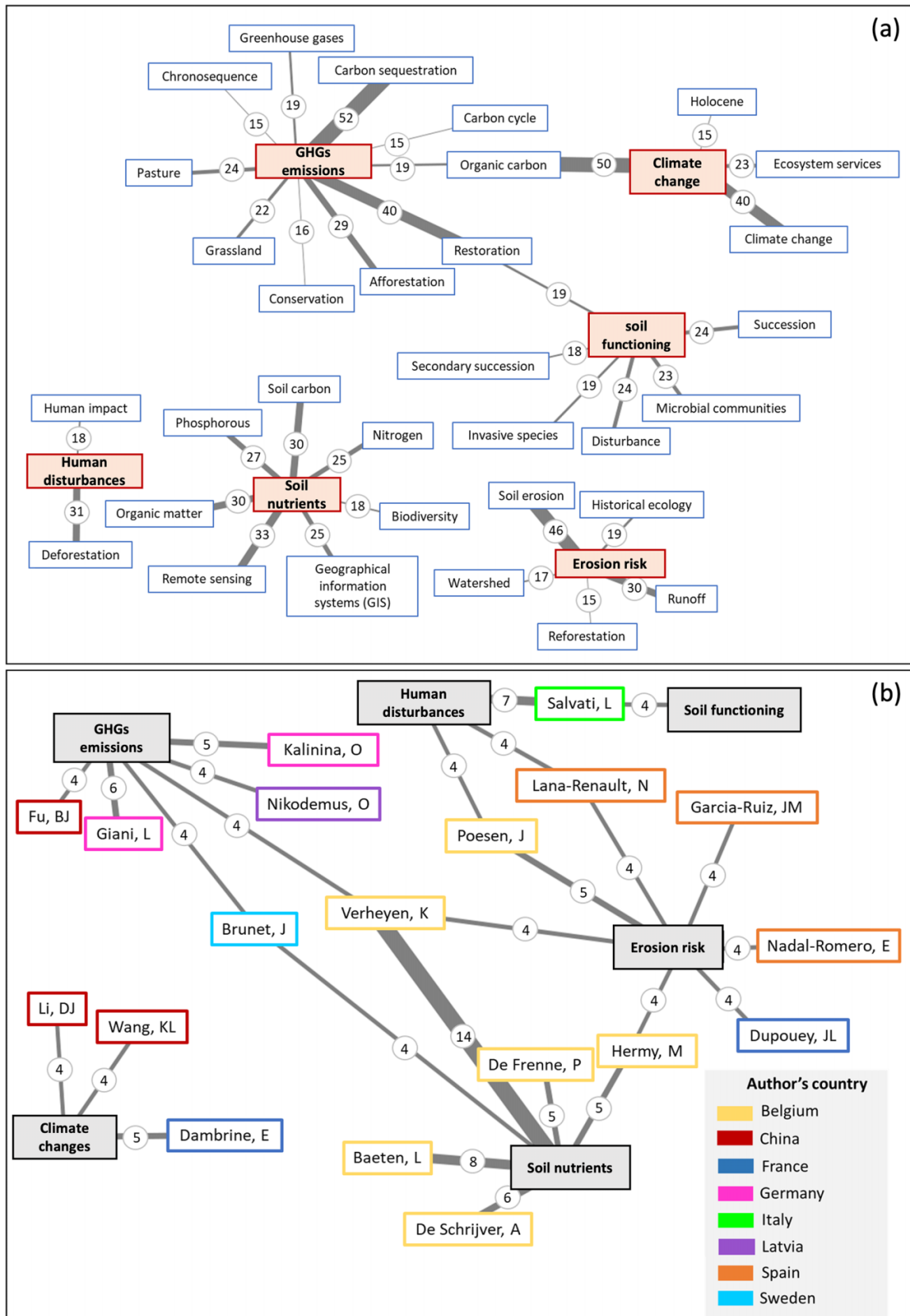
### 3.3. Publications by specific issues

Figure 2a shows the resulting network of keywords and their distribution through 6 thematic clusters with pair frequencies greater than 15. Fig. 2b shows the network of the main authors (with the indication of their nationality), having published at least 6 publications, and associated at least 4 times with one or more of the thematic clusters. Fig. 3 presents the evolution of the number of publications in these clusters between 2001 and 2020. We choose to show the temporal evolution of the 6 clusters using ranges of years since the emergence of the different topics did not occur at the same time (*e.g.*, soil functioning emerged more from 2011 to 2015), while soil erosion had a greater increase than the other topics in the last five years.

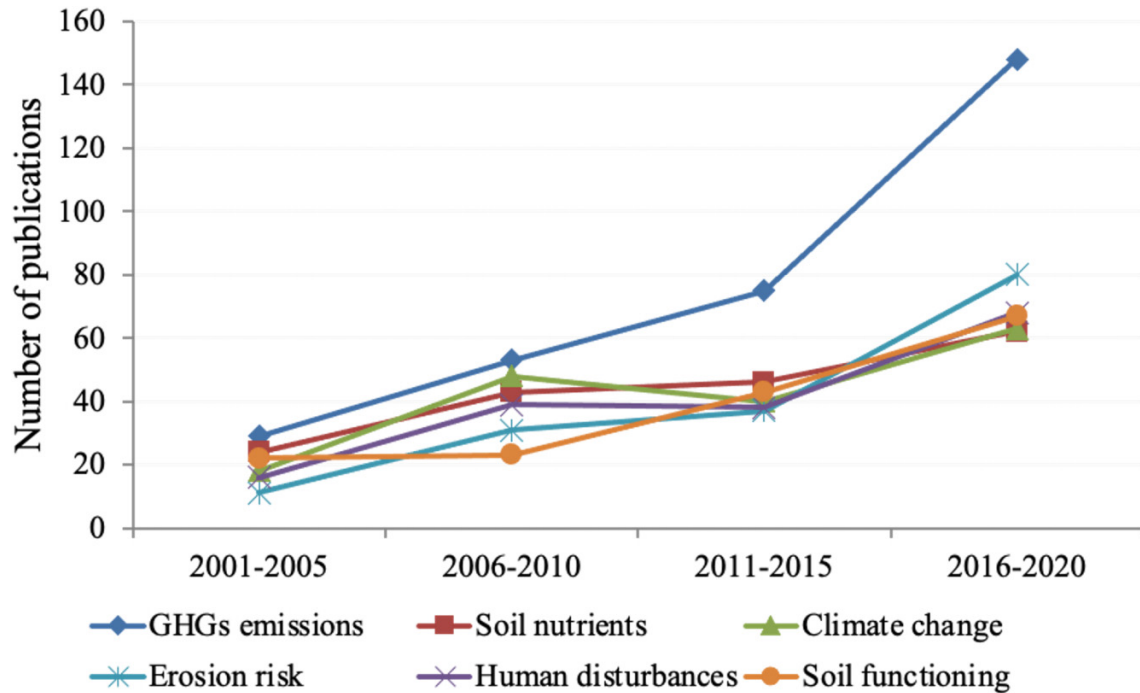
#### 3.3.1. Cluster 1—GHG emissions

Cluster 1 was the cluster containing the largest number of publications with 212 publications and is the most productive cluster over the period 2001–2020 (Fig. 3). The major contributing keywords of this cluster were “greenhouse gases” (GHGs), “carbon sequestration”, “carbon cycle”, “organic carbon”, “restoration”, “afforestation”, “conservation”, “grassland”, “pasture” and “chronosequence” (Fig. 2a). In this cluster, studies aimed to assess and predict the consequences of land-use change on GHG emissions mainly through the gain or loss of carbon in soils. For example, grassland conversion to new croplands has been identified as a major source of GHGs (Spawn et al. 2019), while afforestation has a positive

**Fig. 2.** (a) Network of the main keywords and the thematic clusters with pair frequencies of at least 15 publications and (b) network of the main authors (and their associated country) and the thematic clusters with pair frequencies of at least 3. The number of articles associating one author or keyword to a cluster is specified in the circle. GHGs, greenhouse gases.



**Fig. 3.** Evolution of the number of publications for each thematic cluster (i.e., GHG emissions, soil nutrients, climate change, erosion risk, human disturbances and soil functioning) over the period 2001–2020 (5 year intervals). GHGs, greenhouse gases.



impact on soil carbon storage that can mitigate GHGs emissions. Additionally, change in forest structure and composition have an impact on most soil functions, including GHG emission or carbon stock (Foster et al. 2003; Berenguer et al. 2014; Lewis et al. 2015). Authors studied soil’s carbon storage capacity under different contexts such as natural reforestation after agricultural abandonment or human-induced reforestation (i.e., habitat restoration). China is recorded as the largest emitters of GHGs and the agricultural sector in China is responsible for 17%–20% of annual emissions (Wang et al. 2020). Among actions taken to reduce GHG emissions, China promoted afforestation and forest conservation actions to increase carbon sinks. Yang et al. (2020) claimed that forestry carbon sink capacity in China was enhanced especially by afforestation in recent years. Concerning Germany, this country is the world’s sixth largest emitter of GHGs and the first largest emitter in the EU. Agricultural production contributed 11% to the total German GHG emissions that may also explain the strong contribution of Germany to this cluster (Röder et al. 2015). Sweden also worked to modify agricultural practices and have successfully reduced emissions from the agricultural sector since 1990. Swedish government currently counts on the declining use of mineral fertilisers and the reduced leaching of nitrogen in soils to reduce nitrous oxide emissions (Ministry of the Environment Sweden 2014). The strong increase in publications in this cluster for the period 2016 to 2020 could be explained by a growing political awareness in the world as mentioned above (Fig. 3). It is therefore not surprising that a major research effort was observed in these countries since they are committed to substantially reduce and mitigate GHG emissions to achieve the objective set out during the COP-21.

### 3.3.2. Cluster 2—soil nutrients

Cluster 2 containing 195 publications predominantly focused on organic matter and soil nutrients, which explained why this cluster was linked to keywords “organic matter,” “soil carbon,” “nitrogen” and “phosphorous” (Fig. 2a). Interestingly, the most productive authors in this cluster were all associated with Belgium focusing on plant-soil feedbacks in post agricultural forests (Fig. 2b). Authors explored mechanisms driving plant communities in post-agricultural forests and their indirect effects on soil organic matter with a particular attention to forest herbs (Baeten and Verheyen 2017; Blondeel et al. 2019). Results have shown higher pH, higher nitrate and phosphorous concentrations but lower organic matter in soils from post-agricultural forest compared to soils from ancient forests (Blondeel et al. 2019). Publications highlighted that land use legacies modified trajectory of forest succession by shifting herbs and tree recruitment. Seed dispersion was notably influenced by physicochemical properties of soil (phosphorous, nitrogen and soil acidity) as well as by light diffusion through canopy (Valtinat et al. 2008; Baeten and Verheyen 2017; De Lombaerde et al. 2020). Physico-chemical properties of soil were thus directly modified by agricultural input but also indirectly through the modification of plant diversity affecting litterfall composition. Despite the strong interest in plant-soil feedback in this cluster, few publications have been studying organisms involved in organic matter transformation playing a key role in soil functioning (i.e., microbial communities, mesofauna and macrofauna). Among publications studying plant-soil feedbacks, Faggioli et al. (2019) observed a distinctive community composition of arbuscular mycorrhizal fungi



in roots from post-agricultural soils and [de la Peña et al. \(2016\)](#) observed differences in composition and abundance of microbial functional groups depending on past land use as well as a higher abundance of root-feeding nematodes in post-agricultural soils than in soils from ancient forests. Additionally, keywords “remote sensing” and “Geographical Information System” also contributed to this cluster ([Fig. 2a](#)) since authors used these tools to identify vegetation cover and plantation activities. These tools gave detailed geo-referenced information showing the temporal trends in land use and land cover change and allowed to identify the areas at risk of soil degradation ([Santos et al. 2018](#); [Senanayake et al. 2020](#)). Cluster 2 was thus linked to changes in vegetation cover but no keyword in this cluster was directly relevant to vegetation or plant species underlining the limits of using keywords proposed by authors sometimes too specific or often voluntarily different from words mentioned in the title.

### 3.3.3. Cluster 3—climate change

Cluster 3 contained 184 publications dealing with “organic carbon” and “climate change”. Publications focused on long-term successional dynamics on soil organic carbon stocks and authors studied the complex interactions between land use and climate change. Some publications analysed paleo-climate reconstructions using paleo-data to assess the present and predicting the future state of soils explaining why “Holocene” ([Fig. 2a](#)) has strongly contributed to the cluster ([Pérez-Lambán et al. 2018](#); [Novenko et al. 2019](#)). Two of the three major contributing authors were linked to China which is the largest emitters of GHGs as mentioned above. This strong contribution is therefore not surprising since the estimation of the size and changes in soil organic carbon (SOC) stocks is essential to adopt measures in soil protection and to develop strategies for mitigation of GHGs. Authors indeed highlighted that both land use change and climate change must have been considered in models assessing soil vulnerability and predicting changes in carbon stocks ([Chuenchum et al. 2020](#)). Regarding this cluster, the evaluation of soil vulnerability was often based on the services it provides (*i.e.*, water purification, soil erosion control, food and water provision) ([Sun et al. 2018](#); [Yi et al. 2018](#)). Storage of soil organic carbon is indeed an essential function of ecosystems providing numerous environmental services and some authors highlighted that past land use influence these ecosystems services ([Nijmeijer et al. 2019](#)). Climate regulation is part of the ecosystem services supported by carbon sequestration ([Smith et al. 2013](#); [Daba and Dejene 2018](#)). The conversion of forests to agricultural land is known to increase carbon emissions from deforested land and decrease sequestered carbon in soil ([FAO 2020b](#)). Conversely, reforestation activities thus may accelerate carbon sequestration but may be at the expense of cultivated area, which has led some authors to discuss about the trade-off between food provision and regulating and supporting services. For example, [Sun et al. \(2018\)](#) highlighted that vegetation restoration could improve regulating and supporting services at the expense of food provision services and suggested the development of

new ways of farming (*e.g.*, vertical agriculture). The dynamics of land use changes over time must therefore be taken into consideration when assessing climate change prediction ([Dale 1997](#)).

### 3.3.4. Cluster 4—erosion risk

This isolated group containing 176 publications dealing with erosion ([Fig. 2a](#)) had the second highest number of publications over the period 2016–2020 ([Fig. 3](#)). Erosion has indeed become a global challenge in ecology and soil erosion has been recognized as the main cause of land degradation ([Bakker et al. 2007](#)). Soil erosion has a damaging effect on soil resources by impacting organic matter and water retention capacity. Among the principal keywords associated to this cluster was “historical ecology” probably referring to past land use (*i.e.*, agricultural activities) ([Fig. 2a](#)). Agricultural practices (*e.g.*, tillage, slash and burn) were often cited as one of the main causes of erosion process ([Harden 2001](#); [García-Ruiz et al. 2013](#)). Interestingly, agricultural abandonment was cited both as a cause and a consequence of soil erosion. Soil erosion may indeed lead to unproductive scrubland resulting from a drastic reduction of soil fertility that often led to agricultural abandonment ([Valentin et al. 2005](#)). Nevertheless, it was also observed that soil erosion can be significant during the first stage of plant colonisation after the abandonment of cropland ([Lana-Renault et al. 2020](#)). Nevertheless, other environmental factors like fire and extreme rainfalls have been documented in the literature as a cause of erosion ([Valentin et al. 2005](#)). Therefore keywords “runoff” and “watershed” were also associated with this cluster referring to these causes of erosion ([Fig. 2a](#)). Moreover, “reforestation” was also included in cluster 4 since reforestation was mentioned as the best solution against erosion regardless of its origin (*i.e.*, natural forests or planted forests) ([Fig. 2a](#)). Many countries, for example, the USA, China, Sri Lanka, Sweden or Spain, have thus looked for identifying and preventing the causes of erosion ([Teng et al. 2019](#); [Olson and Gennadiev 2020](#); [Senanayake et al. 2020](#); [Yang et al. 2020](#)). Among them, Mediterranean countries are particularly affected ([García-Ruiz et al. 2013](#)). Mediterranean pedoclimatic conditions are characterised by humid winter and intense summer drought. Low rainfall and quick mineralization of carbon slow down soil formation rates resulting in sparsely developed soils with little organic matter. Soil erodibility is thus promoted by a combination of environmental factors (*i.e.*, limited vegetation, wildfires, extreme rainfalls and wind) ([Quézel and Médail 2003](#); [Torrent 2005](#)). Mediterranean climate reduces the capacity of vegetation to recolonize abandoned fields, and without a perennial vegetation, soils are quickly removed by wind and water erosion. Changing agriculture occurred in Mediterranean area since 1860, has thus aggravated soil erodibility: some areas were subjected to extreme land-use intensification, while other areas were particularly affected by the abandonment of traditional agricultural activities (*e.g.*, terraces) with an acceleration of the process since 1950 ([Serra et al. 2008](#); [Abadie et al. 2017](#)). Farmland abandonment has notably occurred in Spain, because

of the extremely low productivity of rainfed fields that explains the strong contribution to cluster 4 by Spanish authors (*i.e.*, García Ruiz JM, Nadal-Romero E and Lana-Renault N) (Fig. 2b).

### 3.3.5. Cluster 5—human disturbances

This isolated cluster containing 173 publications dealt with the impact of human activities on past and current landscapes. The major contributing keywords of this cluster were “Human impact” and “deforestation” (Fig. 2a). Authors notably used past land cover reconstructions to understand current landscape using palynological and geochemical data (Coombes *et al.* 2009; Brown *et al.* 2019). Numerous publications discussed about evidence of human land use such as deforestation, mining, infrastructure building, and farming (*i.e.*, cultivation and animal husbandry) found during Holocene, Anthropocene or medieval period in Northern European countries (Coombes *et al.* 2009; Wieckowska-Lüth *et al.* 2017; Brown *et al.* 2019). Moreover, European mountains (*i.e.*, subalpine belt) were affected by severe deforestation processes from Neolithic times resulting in intense soil erosion (Sanjuan *et al.* 2018). This may explain why the most productive authors of cluster 5 come from EU countries and why these authors are also linked to cluster 4 and 6 dealing with erosion and long-term successional process (Fig. 2b). In publications regarding the most recent period, deforestation was the most studied disturbance. Deforestation is indeed caused by human activities such as forest exploitation and shifting cultivation, but the effect of climate change may also exacerbate deforestation by increasing the risk of wildfires (Flannigan *et al.* 2000, 2009; Olagunju 2015). Surprisingly, there was no author from South America or South-Eastern Asia despite these areas are strongly impacted by deforestation, as mentioned above.

### 3.3.6. Cluster 6—soil functioning

Cluster 6 was the smaller cluster with 152 publications from 2006. The major contributing keywords of this cluster were “succession”, “microbial communities”, “disturbance”, “invasive species”, “secondary succession” and “restoration” (Fig. 2a). In this cluster, the number of publications increased only from 2006 that was much later than the other clusters (Fig. 3). In this cluster, agricultural activity legacies were often considered as a disturbance and publications focused on secondary succession after several types of human activities (agricultural activities but also mining) (Adesipo *et al.* 2020; Peña-Angulo *et al.* 2019). Authors thus studied distinct stages of successional vegetation, that is, grassland, shrubland and forests (Sokołowska *et al.* 2020). Issues dealt in cluster 6 are like those of cluster 2, which focuses on forest succession trajectory. Nevertheless, cluster 2 deals with plant diversity and land cover dynamics, whereas cluster 6 with functional ecology. Authors assessed the resilience capacity of soil functioning through the study of various proxies (*i.e.*, microbial communities and soil physicochemical properties) (Nadal-Romero *et al.* 2018; Vázquez *et al.* 2020). As observed previously, two case studies could be dis-

tinguished: replanted forests that have been sourced from a forest restoration project or natural secondary succession after agricultural abandonment or deforestation (Buisson *et al.* 2019; Martínez-Ramos *et al.* 2016; Peña-Angulo *et al.* 2019). Among the different disturbances described in this cluster, plant invasive species were mentioned as an important legacy of past agricultural activities and Holmes and Matlack (2019) highlighted that non-native richness in post agricultural forest were significantly greater than in undisturbed forest, even 80 years after abandonment. Some authors assessed the effect of past land use on soil functioning using microbial markers. Soil microbial responses to agricultural legacies and restoration is indeed important since microbial communities (*i.e.*, bacteria and fungi) have a key role in soil formation and fertility. Microbial functioning was explored using different approaches such as microbial carbon and nitrogen, microbial respiration, phospholipid fatty acid analysis, enzymatic activities as well as DNA extraction (Fanin *et al.* 2016; Maslov and Maslova 2020; Tripathi *et al.* 2016). Most of the studies have shown a persistent legacies of past agricultural land use on microbial biodiversity, even more than 60 years after agricultural abandonment even after intensive restoration activities. Natural or human-induced reforestation were thus not enough to restore pristine conditions (Maslov and Maslova 2020; Turley *et al.* 2020). Nevertheless, authors also highlighted that agricultural intensity and duration modulated the effect of land use legacy and that past land use effect differed according to other environmental factors such as vegetation cover and climate (Kurganova *et al.* 2019). For example, Vázquez *et al.* (2020) observed lower microbial biomass and enzymatic activities with increasing human disturbances (*i.e.*, tillage). They also observed a more positive impact of natural revegetation on microbial indicators than pine plantations because of the acidic nature of needle litters. Lastly, these results may also vary depending on the microbial marker considered. In their study, Delelegn *et al.* (2018) notably highlighted that land use legacy effects on vegetation cover had a greater effect on fungal communities while bacterial communities were affected by changes in soils physicochemical properties. Only one author was linked to this cluster (*i.e.*, Salvati L) and his research interests focused on cartography and GIS, notably in the field of rural geography. This result highlights the importance of these types of tools in historical ecology, which are essential to define the past and current land use of the study area. Interestingly land use legacy effects on other decomposers (*i.e.*, macrofauna and mesofauna) were also little explored in this cluster despite their role in organic matter turn-over.

### 3.3.7. Potential research directions

Despite the significant effects of climate change and its influence on many processes essential to ecosystem functioning, cluster 3 (*i.e.*, land use legacy and climate change) was an isolated cluster (no link between clusters when keyword-pair frequencies are lower than 15). Although global warming was often cited in the introduction of publications, it was not integrated in the studies as a potential factor influencing the effects of past land use. However, this cluster could have been

expected to have a central position on past land use issues. For example, in the Mediterranean region, considered as a climate change hotspot, land use legacy effects could be modified by climate changes (*i.e.*, changes in precipitation regimes, intensification of summer drought) (Diffenbaugh et al. 2007). By affecting the physico-chemical and biological properties of soils as well as revegetation, land use legacy may modify post-agricultural soil responses to global warming (Foster et al. 2003; Ackermann et al. 2019). Thus, it would be interesting to consider historical land use when assessing the vulnerability of ecosystems to climate change, which could contribute to select more sustainable practices across the world. Finally, the effect of land use legacy on soil fauna has been little explored. Land use legacy effects on soil biodiversity as well as on soil food web involved in organic matter decomposition could thus represent future insights of research.

## 4. Conclusion

This bibliometric investigation from 2001 to 2020 focusing research on the temporal dynamics of land use and their consequences on soil functioning showed a great increase in publications overtime. The 1416 publications recorded were mainly distributed over the USA, China, and Germany, countries with the higher annual increase in forest areas over the last ten years. The analysis of the journal sources highlighted the multidisciplinary aspect in this research work involving various scientific domains (*e.g.* geosciences, water resources, biodiversity conservation, microbiology, and remote sensing). Regarding the most cited publications, authors questioned the effects of past land use on soil vulnerability (decrease in soil fertility, exposure to erosion and soil contamination) as well as the potential consequences of future land use and land cover changes on soil functioning. Moreover, these references can be distributed into six clusters by a K-means analysis performed on their keywords, allowing to identify six main themes of research: GHG emissions, soil nutrients, climate change, erosion risk, human disturbances as well as soil functioning. Each of these six thematic clusters had its own network of authors which were often associated with the same country. Nevertheless, regarding co-authors, this bibliometric study also highlighted a worldwide collaboration between authors from different countries. Through these publications, several types of proxies were investigated to understand how historical land use still modified current soil properties (*e.g.*, carbon and nitrogen, vegetation cover, microbial communities, seed bank and fossil pollen grains) and it is worth noting that mapping and remote sensing have proven to be crucial tools. Finally, the effect of land use legacy was poorly considered in the context of climate change, which could represent a future line of research.

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## Author information

### Author ORCIDs

Ninon Delcourt <https://orcid.org/0000-0002-9804-8509>

### Author contribution

Conceptualization: ND

Data curation: CP

Formal analysis: ND

Investigation: ND, CP

Methodology: CR, ND

Project administration: AMFS, ND

Supervision: AMFS, CR

Validation: AMFS, CR, ND

Visualization: AMFS, ND

Writing – original draft: ND

Writing – review & editing: ND

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