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# A Scientometric Analysis and Visualization of Forest Soil Contamination Research from Global Perspectives

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**Abstract:** Forest soil contamination is a significant problem with risks to ecosystems and human health. It reduces soil quality, hampers plant growth, and disrupts ecosystems. To understand current research and identify future directions, this study analyzed 2659 documents on forest soil contamination published on the *Web of Science* from 1970 to 2023. Using bibliometrics, this study systematically analyzed the knowledge structure, research hotspots, and development trends in forest soil pollution. China, the United States, and Poland were the top contributors, with 11.28%, 8.42%, and 7.15% of publications, respectively. Despite fewer publications, the Netherlands and Sweden had significant research influence. The Chinese Academy of Sciences had the most publications. The primary research topics included heavy metals, ecosystems, deposition, air pollution, and organic matter. Keyword cluster and burst analysis highlighted the importance of heavy metals, microbial communities, atmospheric deposition, and organic matter. Notably, microplastics emerged as a notable gap in the existing research by highly cited papers analysis, indicating they can be a future research focus. Overall, this paper provides a comprehensive analysis of forest soil contamination, offering insights into current research themes and emerging trends.

**Keywords:** forest; soil contamination; bibliometrics; visualization

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## 1. Introduction

Forest soil is a critical component of the forest ecosystem and plays a vital role in material circulation and energy flow [1]. The quality of forest soil has a significant impact on the ecological environment, food, water resources, and ecosystem functions [2]. However, due to rapid industrial and economic development, contamination of forest soil has become a prevalent and increasingly severe environmental problem. Most contaminants that enter the forest ecosystem come from human activities such as agriculture, forestry practices, industrial activities, and tourism. These activities have led to elevated levels of potentially toxic substances like heavy metals [3–5], persistent organic pollutants [6–8], and emerging pollutants like nanoparticles, pharmaceuticals, and plastics in the soil [9–11]. These contaminants can negatively impact soil quality, biodiversity, and the overall functioning of forest ecosystems [12]. Consequently, understanding the extent, sources, and consequences of forest soil contamination has become a crucial area of research in environmental science.

The study of forest soil contamination has evolved significantly in recent decades. Early research primarily focused on identifying and characterizing contaminants in forest soils and their spatial distribution and persistence over time [13]. These studies provided valuable insights into the sources and behavior of contaminants such as heavy metals in forest soils, highlighting the long-term effects of historical industrial activities on soil contamination [14]. Furthermore, advancements in analytical techniques such as X-ray fluorescence spectroscopy [15], inductively coupled plasma mass spectrometry [16], and high-performance liquid chromatography [17] have enabled researchers to accurately measure the concentrations of various contaminants in forest soils, thereby enhancing our understanding of their distribution and mobility within the ecosystem. These technological developments have paved the way for more comprehensive assessments of soil contamination, leading to improved management strategies and remediation efforts.

In addition to characterizing the nature and extent of forest soil contamination, recent research has also focused on elucidating the ecological impacts of these contaminants on soil microorganisms [18], plant communities [19], and wildlife [20]. For example, heavy metal contamination exhibits adverse effects on soil microbial diversity and activity, potentially disrupting crucial ecosystem functions such as nutrient cycling and decomposition [21]. Furthermore, pesticides negatively affect forest plant diversity and the health of wildlife populations, causing far-reaching consequences of soil contamination on forest ecosystems [22]. The implications of forest soil contamination extend beyond ecological concerns, as there is growing recognition of the potential risks posed to human health through the consumption of contaminated forest products and exposure to polluted soil and water. Forest pollution levels are increasing in many parts of the world, with detrimental effects on ecology and human health. It is estimated that more than 9 million people worldwide died prematurely in 2015 due to exposure to environmental pollution. Although environmental pollution is a global problem, its impact is unevenly distributed [23]. On a global scale, the Lancet Commission on Pollution and Health concluded that > 90% of pollution-related deaths occur in low- and middle-income countries [24]. Contaminants can transfer from forest soils to food crops and wild edible plants, raising concerns about the safety of forest-derived products for human consumption [25]. Additionally, forest soil contamination threatens the health of local communities and indigenous populations [26], particularly in regions where traditional livelihoods are closely linked to forest resources. These advancements demonstrate that the study of forest soil contamination has evolved from a focus on mere contamination identification to a broader understanding of its ecological, human health, and societal implications [27]. However, there has been a lack of systematic and quantitative studies on the scientific trends and knowledge gaps in this field. Bibliometrics, a qualitative and quantitative analysis of a particular field using mathematical statistics, can address this gap [28]. By integrating bibliometric analysis and visual presentation, researchers can rapidly assess and identify a topic's strengths, research trends, and emerging interests [29]. Recent applications of bibliometric analysis have included reviews of forest carbon sequestration and forest genetics within the forestry research area [30].

The objective of this study is to analyze the research progress of global forest soil contamination using a data-driven bibliometric method. This work aims to achieve the following specific objectives: (1) provide a comprehensive understanding of the literature in this field, including the number of papers, citation frequency, and influential journals; (2) identify the distribution of research efforts in the field, including prominent countries, institutions, and authors; (3) clarify the existing knowledge base of the research field; (4) identify the main areas of current research interest and predict future research trends.

## 2. Methodology

All relevant datasets analyzed in this paper are derived from the *Web of Science* (*WOS*) core collection database, including all citation indexes (SCI-EXPANDED, SSCI, AHCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC). The *WOS* database is one of the most authoritative and important databases for obtaining scientific and academic information on a global scale. The retrieval condition was Topic = (contamination OR contaminated OR pollution OR polluted) and Topic = ("forest* soil*" OR forestry OR "forest ecology*" OR "Forest Ecosystem*") and Topic = soil* not Title = water*. A total of 2659 documents were collected between 1970 and 2023 for analysis using bibliometric tools. These tools enabled the exploration of various aspects, including keywords, authors, institutional affiliations, journals, and citations. This analysis aimed to gain a comprehensive understanding of the topic at hand. Bibliometrics is a valuable quantitative method for analyzing academic literature. We utilized bibliometric tools to visually represent the statistical results, including the Bibliometrix (version 4.1.2) package and CiteSpace (version 6.1.R6). The visualization of data related to institutes, authors, and keywords was presented through figures. In these figures, nodes represent institutes, authors, or keywords, with the size of the nodes corresponding to the number of publications. The connections between nodes are depicted by lines, with the lines' thickness indicating the connection frequency. Figure 1 illustrates a schematic illustration of this study.

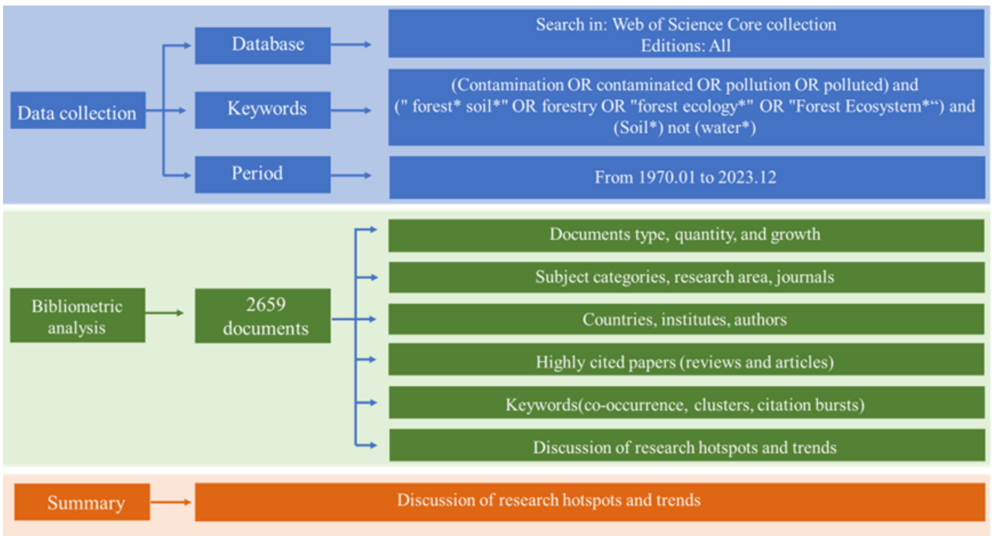


**Figure 1.** The methodological framework of this study.

## 3. Results and Discussion

### *3.1. Descriptive Statistics*

Figure 2a shows the number of publications and citations of studies on forest soil contamination from 1990 to 2023. The development of this field can be categorized into three stages. Between 1990 and 2003, only a few papers were published each year. However, from 2004 to 2014, there was a gradual development, with an annual publication of over 70 papers and a steady increase in citations. Since 2014, the field experienced a period of rapid growth, characterized by a noteworthy increase in both the number of publications and citations. The number of publications has surged from 88 in 2014 to 144 in 2021, while the number of citations has risen from 3577 to 7611. This trend can be attributed to a lengthier publication cycle, enhanced financial investment in scientific research, and a growing community of forest science experts. Moreover, there is no denying that researchers are increasingly focusing on the issue of forest soil pollution. We can anticipate further advancements and expansion in this research area in the near future. Although the number of publications in 2023 and 2024 has decreased, the number of citations remains high, which can be seen as a normal fluctuation. Overall, a total of 2640 articles were published from 1990 to 2023, with an average of 31.77 citations per document and a total of 83,868 references.

Figure 2b shows the characteristics of different document types with 2391 articles (83.78% of the 2391 documents), 4.27% review articles, 9.85% proceeding papers, and 2.10% other types. To gain insights into the research topic, articles and review papers underwent further analysis using the *Web of Science* category [31], and the top 15 subject categories are listed in Table S1. The category of Environmental Sciences ranks first, with 1317 articles (49.53% of the total 2659 articles). Soil Science follows with 413 articles (15.53%), followed by Ecology with 244 articles (9.18%), Water Resources with 218 articles (8.20%), Forestry with 216 articles (8.12%), Engineering Environmental with 162 articles (6.09%), Meteorology Atmospheric Sciences with 161 articles (6.05%), Geosciences Multidisciplinary with 126 articles (4.74%), Plant Sciences with 117 articles (4.40%), and Microbiology with

85 articles (3.20%). The cumulative percentage of these subject categories exceeds 100% because journals can be assigned to multiple categories [32]. The field of Environmental Sciences includes various studies that focus on pollutant removal. Figure 2c lists the top 10 categories and Figure 2d further displays the publication trend for the top 5 categories. These categories have gained significant attention in recent years, particularly after 2014. While research on pollutant removal has plateaued in the Environmental Sciences and Soil Science category since 2014, the Forestry category has been gaining popularity since 2019. This indicates that future studies will likely shift their focus from pollutant removal to protecting the entire forest ecosystem, taking into account environmental concerns.

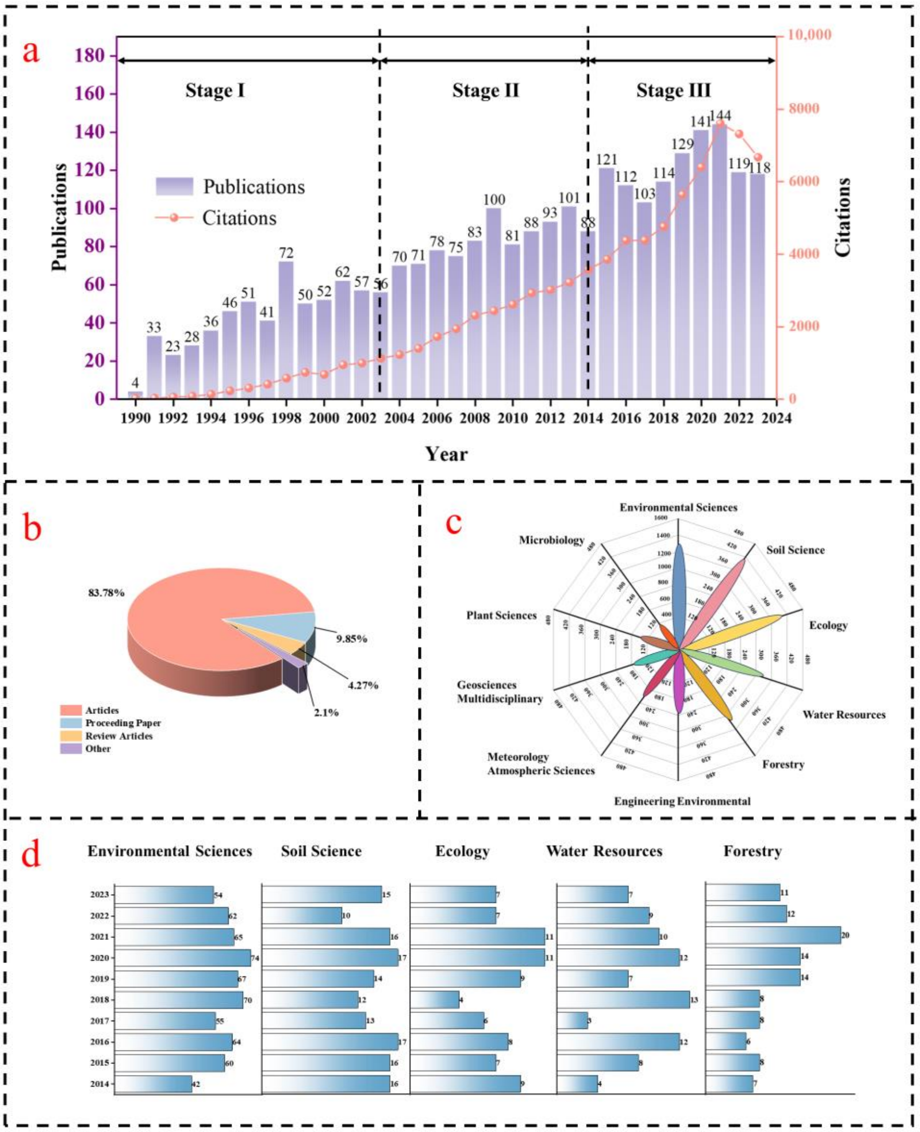


**Figure 2.** (**a**) Publications and citations from 1990 to 2023, (**b**) document types, (**c**) the top 10 *Web of Science* categories, (**d**) the publication trend of the top 5 *Web of Science* categories.

Table S2 presents the top 10 research areas, indicating their respective number of articles and the percentage they represent out of a total of 2659 articles. The leading research area is Environmental Sciences Ecology, with 1500 articles accounting for 65.41% of the total. Agriculture follows with 516 articles (19.41% of the total), then Water Resources with 218 articles (8.20% of the total), Forestry with 216 articles (8.12% of the total), and Engineering with 207 articles (7.78% of the total). These top 5 research areas align well with the subject categories of the *Web of Science* (Figure S1).

### 3.2. Most Influential Sources

The 2659 papers were published in 658 journals, which were categorized into 116 *Web of Science* categories. As shown in Table 1, the top 10 most productive journals include *Science of the Total Environment* with 167 articles (6.28% of 2659 articles), *Environmental Pollution* with 116 articles (4.36%), *Water, Air and Soil Pollution* with 105 articles (3.95%), *Environmental Science and Pollution Research* with 59 articles (2.22%), *Chemosphere* with 57 articles (2.14%), *Soil Biology and Biochemistry* with 44 articles (1.65%), *Forest Ecology and Management* with 34 articles (1.58%), *Geoderma* with 34 articles (1.28%), *Environmental Pollution* with 32 articles (1.20%), and *Applied Soil Ecology* with 30 articles (1.13%). For the top three journals, *Science of the Total Environment* and *Environmental Pollution* are favored by researchers because of their comprehensiveness (many types of reception). *Water, Air and Soil Pollution* has a research theme similar to forest soil pollution and is favored by researchers. Although *Environmental Pollution* has published fewer papers than *Science of the Total Environment*, its h-index, m-index, g-index, and citation frequency are higher. The earliest report in the top 10 journals predates 2000, and the years are relatively close. Furthermore, most of these top 10 journals fall within the environmental category, suggesting a strong research focus on the ecological perspective. This aligns with the analysis conducted on the *Web of Science*.

**Table 1.** Top 10 most productive journals during 1970–2023.

| Journal | Total Publications | | Index | | | Number of Citation | Average Citation | Initial Year |
|---|---|---|---|---|---|---|---|---|
| | Num. | % | h | m | g | | | |
| *Science of the Total Environment* | 167 | 6.28 | 45 | 1.36 | 70 | 6158 | 36.78 | 1992 |
| *Environmental Pollution* | 116 | 4.36 | 46 | 1.59 | 79 | 6373 | 58.08 | 1996 |
| *Water, Air and Soil Pollution* | 105 | 3.95 | 30 | 0.83 | 50 | 3089 | 29.42 | 1989 |
| *Environmental Science and Pollution Research* | 59 | 2.22 | 20 | 0.74 | 29 | 1020 | 17.29 | 1998 |
| *Chemosphere* | 57 | 2.14 | 28 | 0.97 | 54 | 2938 | 51.54 | 1996 |
| *Soil Biology and Biochemistry* | 44 | 1.65 | 28 | 0.57 | 44 | 3111 | 70.70 | 1976 |
| *Forest Ecology and Management* | 42 | 1.58 | 23 | 0.68 | 42 | 1894 | 45.10 | 1991 |
| *Geoderma* | 34 | 1.28 | 21 | 0.78 | 34 | 1623 | 47.74 | 1998 |
| *Environmental Pollution* | 32 | 1.20 | 25 | 0.86 | 32 | 2193 | 68.53 | 1996 |
| *Applied Soil Ecology* | 30 | 1.13 | 20 | 0.67 | 30 | 1309 | 43.63 | 1995 |

### 3.3. Countries, Institutes, and Authors Analysis

Table 2 presents the top 20 productive countries. Among these countries are 13 from Europe, three from Asia, three from the Americas, and one from Oceania. China leads the list with a total of 300 articles, which represents 11.28% of the total 2659 articles. The USA comes in second place with 224 articles, accounting for 8.42% of the total. Poland follows closely behind with 190 articles (7.15%), followed by Russia with 184 articles (6.92%), and Germany with 152 articles (5.72%). Poland secured third place thanks to the immeasurable contributions of influential authors with many publications. Magiera T (15 papers) mainly focused on the harm and influence of man-made magnetic particles contained in industrial dust and fly ash into forest soil. Niklinska M (12 papers) systematically studied the effects of different soil chemical properties on microbial community structure and diversity in different heavy metal-contaminated soils. Blonska E (11 papers) was dedicated to the impact of organic pollution (such as polycyclic aromatic hydrocarbons) on the physical and biological characteristics of forest soils. The diversity and long-term influence of their research on forest soil make Poland hold the third place. It is important to note that the total percentage may exceed 100% because some papers may be assigned to multiple countries. These numbers indicate the level of activity in the specific field for each country [33]. Forest soil contamination is a topic that is receiving significant attention worldwide, particularly in developing countries. Among the countries studied, the Netherlands ranks first with an average citation score of 76.40 per paper, and Sweden closely follows with a score of 63.10, indicating their high research influence despite fewer publications. The highest cited article is from Sweden, with a citation count of 1301. This article analyzed the phospholipid fatty acid (PLFA) patterns of forest humus soil and cultivated soil contaminated with different concentrations of Cd, Cu, Ni, Pb, and Zn. The results showed that the response of PLFAs to different metal pollution levels was different in the two soil types and the PLFAs pattern variation indicated changes in the microbial community [34], which laid an original methodology for characterizing the microbial community by PLFA analyses. The second-highest-cited article is from the Netherlands, with a total of 1119 citations. This paper reviewed the effects of increased atmospheric nitrogen input from NOy and NHx on the diversity of various semi-natural and natural ecosystems. It highlighted the critical impact of nitrogen deposition and soil acidification, which guided the research direction of the forestry ecosystem [35]. In contrast, China has a relatively low average citation score of 26.40, although it has the most publications. The leading country stands out in both categories due to its impressive publication output. To measure the extent of global collaboration, we calculate the ratio of publications with international cooperation to total publications (ICP ratio) for each country. Figure 3 portrays the cooperative relationships between countries in research, emphasizing notable collaboration, particularly among the top three countries. Figure 4a compares publication numbers for the top 10 countries, while Figure 4b illustrates the publication trend for the top 5 countries. These figures reveal different trends among the countries. China's publications have gradually increased over the past decade, while the number of publications in the USA has remained stable. Poland and Germany have experienced fluctuating publication numbers, and Russia has exhibited a volatile trend, with its highest publication output recorded in 2020.

In addition to countries, institutions provide more detailed information regarding research on the topic. This includes well-known institutions in the field and their collaborations. Table 3 displays the top 10 productive institutions from various countries. These include one institute from China, one from Russia, two from France, two from the USA, two from the Czech Republic, one from Sweden, and one from Finland. It is worth noting that there are no institutions in Poland and Germany despite them being among the top 5 most productive countries. The Chinese Academy of Sciences is the leading institution with 255 articles (9.59% of the total 2659 articles), followed by the Russian Academy of Sciences (5.27%), Centre National De La Recherche Scientifique (3.38%), United States Department of Agriculture (3.05%), Indian United States Forest Service (2.37%), Czech University of Life Sciences Prague (2.33%), Czech Academy of Sciences (2.26%), Swedish University of Agricultural Sciences (2.03%), Inrae (1.84%), and the University of Helsinki (1.58%). The total percentage exceeds 100% because some authors are affiliated with multiple institutions. Figure 5a illustrates the cooperative relationship map of the institutions. The size of each circle corresponds to the publication count of a particular institution, while the lines depict the collaborative relationships between the institutions. The color coding indicates the variation over time. Most top institutions have close collaborations, with the University of Helsinki standing out as relatively independent in its research. The larger nodes of several institutions demonstrate active research in the field. Centrality denotes the strength and significance of institutions in the research field [36]. The Centrality value for the Chinese Academy of Sciences is above 0.1, indicating its critical role in the cooperative relationship map [37].

**Table 2.** The list includes the top 20 countries with the highest productivity levels.

| Country | Total Publications | | Total Citations | Average Citations per Paper | Single Country Publications | | International Collaboration Publications | | ICP Ratio |
|---|---|---|---|---|---|---|---|---|---|
| | Num. | % | | | Num. | % | Num. | % | |
| China | 300 | 11.28 | 7918 | 26.40 | 223 | 0.74 | 77 | 0.26 | 0.257 |
| USA | 224 | 8.42 | 12,561 | 56.10 | 181 | 0.81 | 43 | 0.19 | 0.192 |
| Poland | 190 | 7.15 | 4846 | 25.50 | 171 | 0.90 | 19 | 0.10 | 0.100 |
| Russia | 184 | 6.92 | 1369 | 7.40 | 170 | 0.92 | 14 | 0.08 | 0.076 |
| Germany | 152 | 5.72 | 5473 | 36.00 | 116 | 0.76 | 36 | 0.24 | 0.237 |

**Table 2.** *Cont.*

| Country | Total Publications | | Total Citations | Average Citations per Paper | Single Country Publications | | International Collaboration Publications | | ICP Ratio |
|---|---|---|---|---|---|---|---|---|---|
| | Num. | % | | | Num. | % | Num. | % | |
| Czech Republic | 147 | 5.53 | 4102 | 27.90 | 113 | 0.77 | 34 | 0.23 | 0.231 |
| Japan | 120 | 4.51 | 2025 | 16.90 | 92 | 0.77 | 28 | 0.23 | 0.233 |
| Finland | 94 | 3.54 | 2926 | 31.10 | 78 | 0.83 | 16 | 0.17 | 0.17 |
| Canada | 93 | 3.50 | 3569 | 38.40 | 68 | 0.73 | 25 | 0.27 | 0.269 |
| Sweden | 85 | 3.20 | 5363 | 63.10 | 65 | 0.76 | 20 | 0.24 | 0.235 |
| France | 84 | 3.16 | 3041 | 36.20 | 63 | 0.75 | 21 | 0.25 | 0.250 |
| Spain | 82 | 3.08 | 2664 | 32.50 | 64 | 0.78 | 18 | 0.22 | 0.220 |
| United Kingdom | 80 | 3.01 | 4136 | 51.70 | 62 | 0.78 | 18 | 0.23 | 0.225 |
| Italy | 65 | 2.44 | 1380 | 21.20 | 43 | 0.66 | 22 | 0.34 | 0.338 |
| Brazil | 60 | 2.26 | 1256 | 20.90 | 38 | 0.63 | 22 | 0.37 | 0.367 |
| Netherlands | 49 | 1.84 | 3742 | 76.40 | 34 | 0.69 | 15 | 0.31 | 0.306 |
| India | 43 | 1.62 | 843 | 19.60 | 35 | 0.81 | 8 | 0.19 | 0.186 |
| Switzerland | 38 | 1.43 | 2079 | 54.70 | 25 | 0.66 | 13 | 0.34 | 0.342 |
| Australia | 33 | 1.24 | 1763 | 53.40 | 27 | 0.82 | 6 | 0.18 | 0.182 |
| Belgium | 33 | 1.24 | 1711 | 51.80 | 25 | 0.76 | 8 | 0.24 | 0.242 |

**Table 3.** A list of the top 10 institutes with the highest number of publications during 1970–2023.

| Rank | Affiliation | Total Publications | |
|---|---|---|---|
| | | Num. | % |
| 1 | Chinese Academy of Sciences | 255 | 9.59 |
| 2 | Russian Academy of Sciences | 140 | 5.27 |
| 3 | Centre National De La Recherche Scientifique | 90 | 3.38 |
| 4 | United States Department of Agriculture | 81 | 3.05 |
| 5 | United States Forest Service | 63 | 2.37 |
| 6 | Czech University of Life Sciences Prague | 62 | 2.33 |
| 7 | Czech Academy of Sciences | 60 | 2.26 |
| 8 | Swedish University of Agricultural Sciences | 54 | 2.03 |
| 9 | Inrae | 49 | 1.84 |
| 10 | University of Helsinki | 42 | 1.58 |

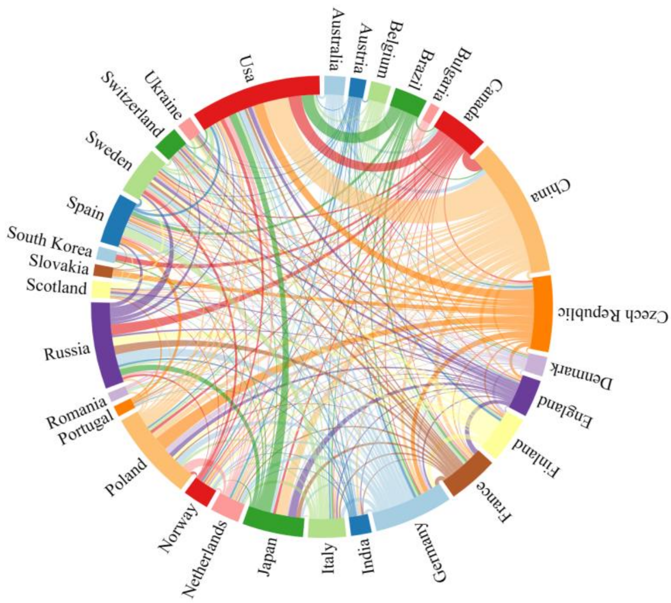


**Figure 3.** A network diagram that illustrates the cooperative relationships between countries.

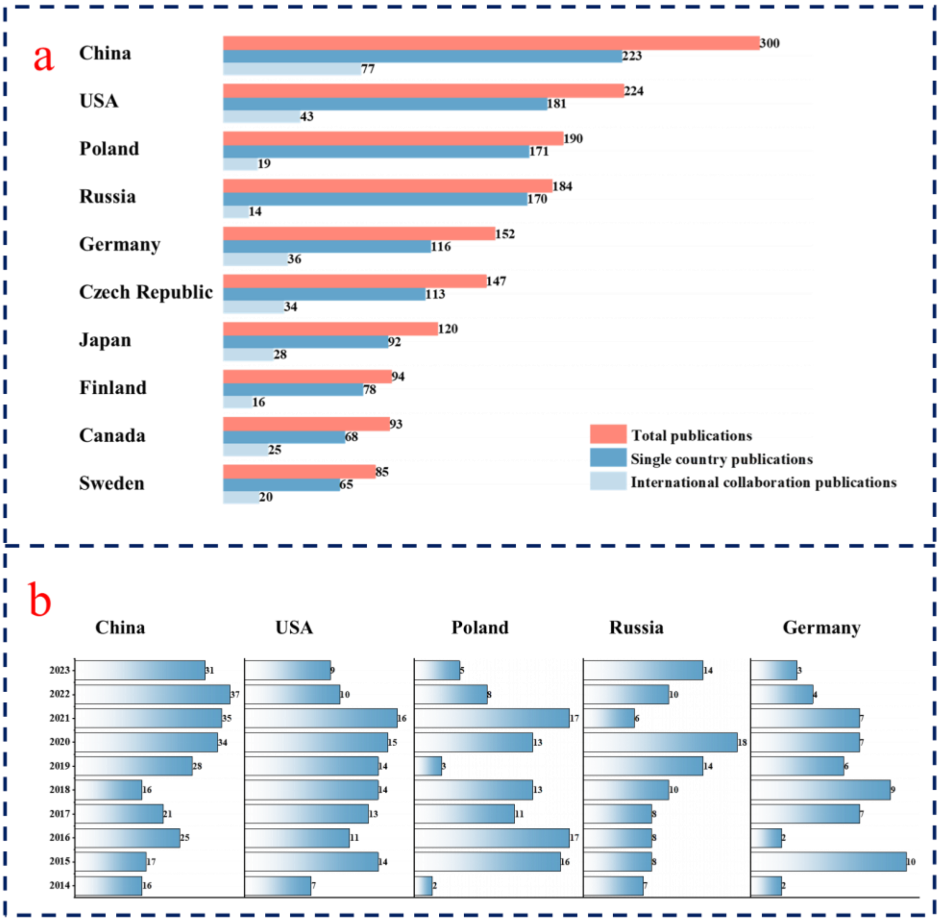


**Figure 4.** (**a**) The top 10 countries with the largest number of publications from 2000 to 2021; (**b**) the publication trends for the top 5 countries.

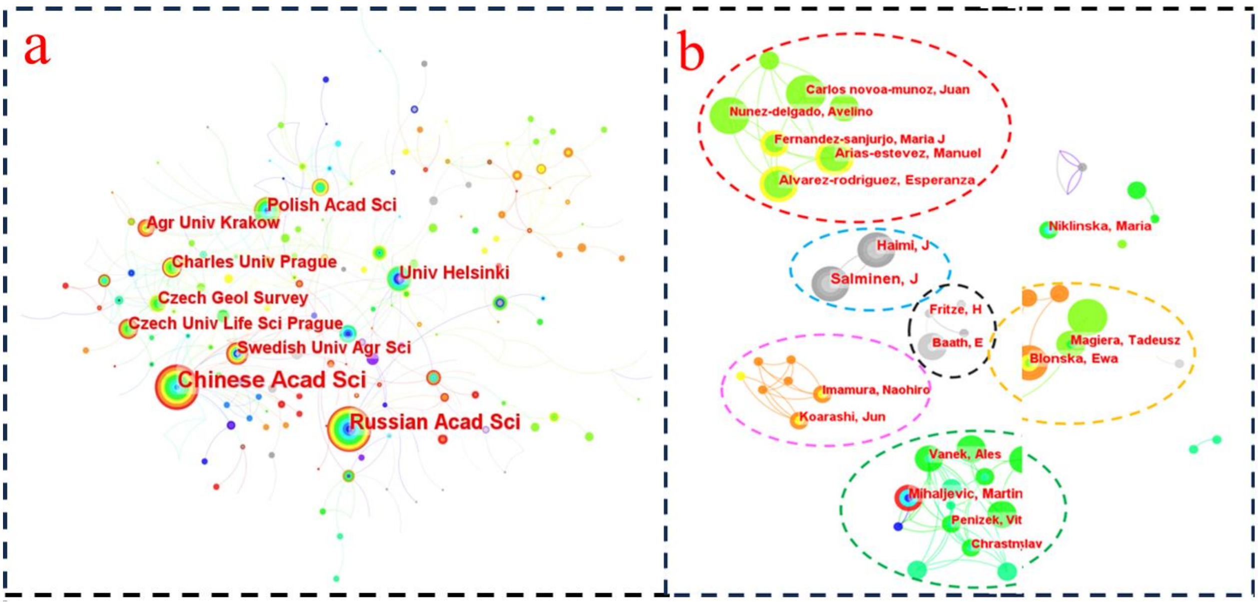


**Figure 5.** (**a**) The cooperative relationship among the institutes, and (**b**) the co-authorship groups.

The authors and their teams are vital in advancing a research field. By analyzing the co-occurrence and collaboration of authors, we can pinpoint teams that closely collaborate and communicate effectively within a particular field. Reading their literature allows us to keep up with the latest academic advancements. Co-citation analysis and author cooperation also help us identify the most influential and authoritative academic groups, who are the leaders in the research field. In the case of research on forest soil contamination, a total of 8442 authors have made contributions. Information on the top 10 authors is presented in Table 4. We analyzed 2659 articles, including 238 single-author articles (51.14 citations per article) and 2421 multi-author articles (35.11 citations per article). The total percentage exceeds 100% because multiple authors have contributed to many papers. The results showed that Bindler R ranked first in the number of published papers with 16 papers, followed by Magiera T (15), De Vries, W (14), Probst, A (14), Mihaljevic, M (14), Novak, M (13), Haimi, J (13), Nóvoa-muñoz, JC (13), Álvarez-rodríguez, E (13), Arias-estevez, M (13). The total number of papers published by the top ten authors was close. As to the total citations, the rankings were followed by De Vries, W (894), Probst, A (778), Bindler R (714), and Magiera, T (662). Based on the average number of citations per paper, the top three authors were De Vries, W (63.86), Probst Anne (55.57), and Bindler R (44.63).

**Table 4.** Top 10 authors with published articles.

| Author | Total Publications | | Index | | | Number of Citation | Average Citation per Paper | Initial Year |
|---|---|---|---|---|---|---|---|---|
| | No. | % | h | m | g | | | |
| Bindler R | 16 | 0.60 | 11 | 16 | 0.423 | 714 | 44.63 | 1999 |
| Magiera, T | 15 | 0.56 | 13 | 15 | 0.481 | 662 | 44.13 | 1998 |
| De Vries, W | 14 | 0.53 | 11 | 14 | 0.407 | 894 | 63.86 | 1998 |
| Probst, A | 14 | 0.53 | 11 | 14 | 0.500 | 778 | 55.57 | 2003 |
| Mihaljevic, M | 14 | 0.53 | 11 | 14 | 0.550 | 626 | 44.71 | 2005 |
| Novak, M | 13 | 0.49 | 9 | 14 | 0.300 | 239 | 18.38 | 1995 |
| Haimi, J | 13 | 0.49 | 11 | 13 | 0.379 | 311 | 23.92 | 1996 |
| Nóvoa-muñoz, JC | 13 | 0.49 | 7 | 13 | 0.412 | 176 | 13.54 | 2008 |
| Álvarez-rodríguez, E | 13 | 0.49 | 7 | 11 | 0.636 | 143 | 11.00 | 2014 |
| Arias-estevez, M | 13 | 0.49 | 7 | 11 | 0.636 | 141 | 10.85 | 2014 |

A co-authorship map, created using Citespace software, is displayed in Figure 5b. Each node on the map represents an author, with its size indicating the number of publications by that author. The lines connecting the nodes represent collaborations between authors. Six research groups specializing in forest soil contamination have been identified, and they have significantly contributed to this field through extensive research and collaborations. (1) The group of authors led by Alvarez-Rodriguez Esperanza, Arias-Estevez Manuel, and Fernandez-Sanjurjo Maria J (highlighted by the red circle) primarily focused on studying the pollution and removal mechanisms of Cr(VI) and As(V) in heavy metals in forest soil [38–40]. (2) The group of authors led by Haimi J and Salminen J (highlighted by the blue circle) primarily investigated the effects of heavy metals on soil microbial communities, with a specific emphasis on nematode analysis [41]. (3) The group of authors led by Fritze H and Baath E (highlighted by the black circle) mainly explored the impact of heavy metals on soil microbial tolerance [42]. (4) The group of authors led by Imamura Naohiro and Koarashi Jun (highlighted by the purple circle) primarily focused on studying the mechanisms of radioactive cesium's impact on forest soil [43,44]. (5) The group of authors led by Magiera Tadeusz and Blonska Ewa (highlighted by the yellow circle) primarily examined the mechanisms of organic matter's impact on forest soil, with a specific focus on polycyclic aromatic hydrocarbons [6]. (6) The group of authors led by Mihaljevic Martin, Vanek Ales, Penizek Vit, and Chrastny Vladislav (highlighted by the green circle) mainly investigated soil pollution caused by human mining activities [45,46].

### 3.4. Most Influential Articles

The publications that usually attract the most attention and interest are typically those with high citation counts [47]. The highly cited articles can help to track the development of important ideas and technologies, which in turn drives progress in the field. Table S3 lists the top 11 highly cited review papers. These reviews mainly focus on four research directions: methods for treating contaminated forest soils, including microbial treatment (two articles), plant enrichment (one article), and biochar application (three articles); contamination of forest soils due to human activities, including metal smelters (one article) and mining activities (one article); the relationship between global change and forest soil (two articles); and evaluation of soil pollution levels (one article). The most cited review, as reported by Smith et al., is published in *Global Change Biology* and has received 571 citations. This publication offers the latest understanding of the soil pressures caused by global changes, identifies knowledge gaps and research challenges, and highlights actions and policies to minimize the adverse environmental impacts of these global change drivers [48]. Another highly cited review by Levy-Booth et al. was published in *Soil Biology and Biochemistry* and received 550 citations. This work analyzes the abundance and community structure of functional genes involved in the nitrogen biogeochemical cycle in forest soils, providing a method to directly link microbial communities to soil characteristics and ecosystem processes [49]. Kowalska et al. reported a review in *Environmental Geochemistry and Health*, which has received 469 citations, focusing on using different indicators to evaluate heavy metal soil pollution [50]. Suman et al. 's paper, published in *Frontiers in Plant Science* with 245 citations, introduced three basic strategies for extracting heavy metals from plants [51]. Ettler reviews more than 160 studies on soil pollution near non-ferrous metal smelters in *Applied Geochemistry*, with 242 citations [52]. Tang et al., in the *Journal of Environmental Management* with 235 citations, summarize the changes in different microbial indicators and the response mechanism of microorganisms to soil heavy metal stress [53]. Yang et al., in *Applied Sciences-Basel* with 156 citations, summarized the application of biochar in soil remediation, including the removal of heavy metals and persistent organic pollutants (POPs) and the improvement of soil quality [54]. Dai et al., in the *Journal of Cleaner Production*, with 152 citations, summarized the research status of biochar on N and P adsorption, including the influencing factors and adsorption mechanism of nitrogen and phosphorus [55]. Worlanyo et al., in the *Journal of Environmental Management*, with 113 citations, reported on the impacts of mining, post-mining reclamation, and post-mining land use from a global perspective [56]. Ji et al., in *Environmental Pollution*, with 103 citations, reviewed the selection guidelines for biochar, specifically for different types of soil pollution [57]. Penuelas et al., in *Forests* with 51 citations, focused on the main trends in forest change in the current literature on global change, emphasizing the main threats to maintaining these forests and proposing management solutions [58].

Table S4 presents the top nine highly cited articles. Six articles address the pollution of heavy metals in forest soils, two discuss the effects of nitrogen, and only one delves into the impact of microplastics on forest soils. These findings indicate that the pollution of heavy metals in forest soils has received significant research attention. The most cited article by Li et al. (published in *Soil Biology and Biochemistry* with 333 citations) discusses the significance of nitrification in the nitrogen cycle and plant nutrition. Nitrification, a process mediated by organisms, contributes to the loss of nitrogen fertilizer and can cause environmental pollution. The two most critical environmental factors that impact the soil nitrification rate are soil pH and substrate concentration, typically ammonia ($NH_3$) [59]. Chodak et al.'s highly cited article (published in *Applied Soil Ecology* with 299 citations) explores the detrimental effects of heavy metal accumulation in the organic layer of forest soil on microbial communities. The researchers evaluated how various soil chemical properties influenced the structure and diversity of microbial communities in heavy metal-contaminated soils [60]. Mazurek et al. assessed soil quality when exposed to heavy metal pollution in the Roltoche National Park. They calculated pollution indexes such as the enrichment factor (EF), accumulation index (I-geo), Nemerow pollution index (PINemerow), and potential ecological risk (RI) based on the levels of heavy metals (Pb, Zn, Cu, Mn, Ni, and Cr) in the soil, gathering 261 citations [61]. Examining microbial adaptation mechanisms to contaminated sediments under natural conditions, Chen et al. utilized metagenome sequencing, 16S rRNA sequencing, and quantitative polymerase chain reaction (qPCR). This study, published in *Science of the Total Environment* with 250 citations, focused on understanding how microbial communities adapt to polluted sediments [62]. Jiang et al.'s study revealed that the main environmental variables affecting bacteria classification and composition were soil texture (31%) and organic carbon (14%). Soil pH (32%) and soil texture (14%) influenced microbial diversity [63]. Cools et al.'s investigation in *Forest Ecology and Management*, with 199 citations, challenged the notion of using the C:N ratio as a general indicator of forest nitrogen status in Europe without considering tree species explicitly. The authors cautioned against drawing misleading conclusions and emphasized the importance of accounting for tree species [64]. In *Geoderma*, Zhao et al.'s work (154 citations) analyzed the distribution of heavy metal pollution sources in 188 soil samples collected from Lin'an City, a prominent pecan-producing area in China. The study revealed that mining activities primarily contributed to Cu, Ni, and Cr contamination, while Pb was closely associated with fertilization. Cd and Zn contamination had multiple sources [14]. Ng et al.'s research, published in the *Journal of Hazardous Materials* (102 citations), investigated the impact of aged low-density polyethylene (LDPE) and polyester fiber (polyethylene terephthalate, PET) on forest microbiomes. The results indicated that aging microplastics in the environment can influence forest soil microbiomes, potentially affecting soil respiration and climate change [65]. Anaman et al.'s study emphasized the necessity of determining the source and transport route of heavy metals in soil for effective pollution control. By employing principal component analysis (PCA), positive matrix factorization (PMF), and geographic information system (GIS) mapping, the researchers identified smelter emissions and soil parent materials as the primary sources of heavy metals. The study also revealed the transportation routes of different heavy metals [66].

### *3.5. Keywords Analysis*

The essence and core of an article are often captured by its keywords, which provide a centralized description of the topic. By analyzing the co-occurrence of these keywords, valuable insights can be gained, such as research topics, frontiers, and hotspots within a specific field of study. We used the CiteSpace software to conduct a co-occurrence analysis of collected keywords in the literature from 1990 to 2023. To ensure more accessible and accurate results, we pre-processed the original data by merging similar keywords. For instance, keywords like "pollution" and "contamination", "ecosystem" and "forest ecosystem", and "deposition" and "atmospheric deposition" were merged. The co-occurrence analysis generated a network map in CiteSpace, visualizing the relationships between keywords and highlighting the scientific hotspots in forest soil contamination research. In Figure 6, each node represents a keyword, with larger nodes indicating higher frequency. The thickness of the links between nodes represents the co-occurrence frequency, with thicker links indicating more frequent occurrences.

After undergoing pre-treatment and visual analysis, it was determined that the keyword "soil" played a prominent role in this study, acting as a central element and facilitating connections. Following closely behind was the keyword "heavy metal", which appeared a total of 506 times. Other significant keywords included "pollution" (397 times), "ecosystem" (254 times), "deposition" (250 times), "air pollution" (156 times), "organic matter" (146 times), "accumulation" (140 times), "growth" (117 times), "cadmium" (113 times), "copper" (104 times), and "sediment" (98 times). These keywords have all emerged as crucial components in the network due to their high frequency of occurrence.

In addition, we utilized the CiteSpace software to analyze the keyword clusters and investigate their relationships [67]. Keyword cluster analysis focuses on the frequency of co-occurrence between keywords and employs statistical methods to simplify the co-occurrence network [68]. Cluster analysis is a widely used and effective research method for identifying research hotspots in a specific field [69]. In this study, we used CiteSpace's clustering function to identify clusters. We then applied the log-likelihood ratio (LLR) weighting algorithm to analyze the keyword clustering. To evaluate the quality of the clusters, we utilized the Silhouette Index, which ranges from 0 to 1. A value above 0.5 indicates a highly reliable and coherent clustering result [70]. Figure 7 displays the main clusters that were generated, and it is evident that many of them overlap with each other despite having different labels. The top ten clusters, ranked by their Silhouette Indexes, are listed below.

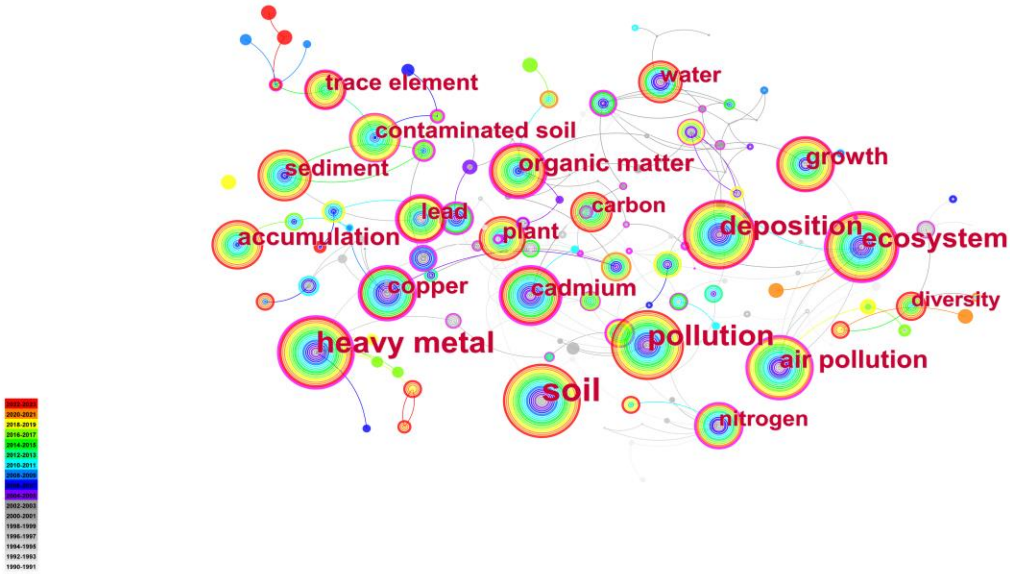


**Figure 6.** The keyword co-occurring network on forest soil contamination.

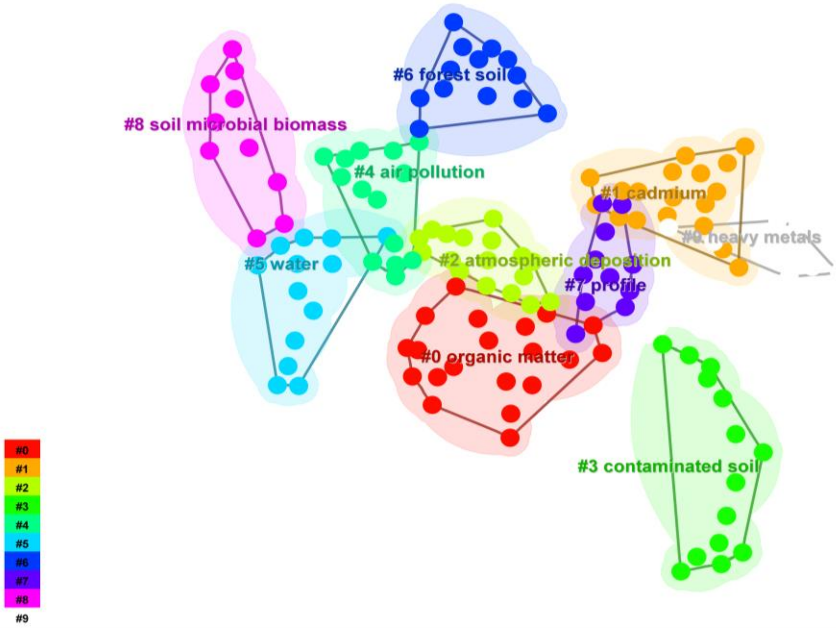


**Figure 7.** Cluster analysis of the keywords on forest soil contamination.

In cluster #0, which focuses on "organic matter", the top five keywords are "organic matter", "decomposition", "migration", "nuclear magnetic resonance", and "C-13 NMR". This cluster reveals that the quality of the soil's organic material, as determined by different vegetation types, plays a significant role in the leaching of components from the soil [71]. C-13 NMR is a crucial tool for analyzing the chemical structure of organic compounds. Numerous researchers have investigated the impact of organic matter on the interaction between soil and radioactive cesium and its influence on the transfer of cesium from soil to plants after the Chernobyl incident [72].

For cluster#1 of "cadmium", the top five keywords included "accumulation" (20.06%), "cadmium" (16.19%), "copper" (14.90%), "plant" (13.75%), and "zinc" (7.02%). Metal contamination in soil ecosystems is a permanent and often intense selection pressure [73]. Therefore, numerous studies have been conducted on the migration, transformation, and remediation of cadmium, copper, and zinc in forest soil. Many researchers have studied using plants, animals, and microorganisms to enrich heavy metals and remove forest soil pollution. For instance, Ciupa et al. evaluated the capacity of bilberry leaves to accumulate heavy metals. The main goal was to identify the leaf traits and ecophysiological responses of this species to heavy metal stress. The findings and methods employed in this research have the potential to enhance biomonitoring efforts and can be applied in various forest ecosystems, particularly in areas affected by heavy metal pollution [74]. Ernst et al. investigated the bioaccumulation of Hg, Cd, and Pb by eight earthworm species in various forest soils. The findings revealed that Cd had the highest bioconcentration factors (soil-earthworm), followed by Hg and Pb [75]. In addition, Zheleznova et al. analyzed the factors that influence the sustainability of forest ecosystems, specifically focusing on heavy metals such as Cu, Zn, and Cd, in the sub-taiga ecosystems of the southern Meshchera region in Ryazan Oblast. Their studies showed that the phytomass of sub-taiga ecosystems can immobilize up to 46% of atmospheric depositions of Cu and Zn, but less than 10% of the atmospheric input of Cd, which is considered toxic [76].

Cluster #2 of "atmospheric deposition" consists of the following top five keywords: "deposition" (61.27%), "acidification" (9.56%), "nitrogen deposition" (8.33%), "sulfur" (5.15%), and "mineralization" (2.45%). These deposition changes have a significant impact on forests [77]. The global concern of atmospheric deposition contributes to soil acidification and biodiversity changes in forest ecosystems [78]. The main focus of Cluster 2 is to discuss the effects of sulfur deposition, acid deposition, and N deposition on forest soil and their mechanisms. Over the past century, human activities have resulted in a significant rise in nitrogen (N) emissions and deposition in the atmosphere. This excessive deposition of nitrogen has now reached a critical point where it has already caused, or is expected to cause, changes in the structure and functioning of various ecosystems across the United States [79]. Climate change and excessive airborne nitrogen (N) deposition are among the primary stressors affecting floristic biodiversity. According to Thomas et al., the expected climate change will increase the occurrence of thermophilic plant species while reducing the presence of cold-tolerant species. Furthermore, climate change scenarios have also increased the probability of oligotrophic species due to higher N immobilization in woody biomass, leading to soil N depletion [80].

For cluster#3 of "contaminated soil", the top five keywords included "sediment" (18.49%), "contaminated soil" (18.30%), "trace element" (17.74%), "lead" (17.17%), and "sewage sludge" (6.60%). Cluster 3 mainly discusses the pollution sources in the sediments of mine wasteland and the pollution of metal smelter emissions to forest soil. Mutale et al. studied the differences in physical and chemical properties between the sediments of mining wastelands and the nearby forest soils and whether there are potential pollution sources of heavy metals in the sediments of mining wastelands. The findings show that metal mine tailings and overburden materials pose serious harm to human health and agricultural productivity through surface water or groundwater pollution, off-site pollution caused by wind-sand diffusion and water erosion, and soil absorption [81].

For cluster#4 of "air pollution", the top five keywords included "ecosystem" (49.42%), "air pollution" (30.35%), "climate change" (5.45%), "Norway spruce" (3.50%), and "response" (2.14%). Cluster 4 mainly discusses the impact of air pollution on forest ecosystems, especially the impact of ozone and nitrogen on forest ecosystems. Excessive inputs of reactive nitrogen (Nr) from the atmosphere can disrupt forest ecosystems in various ways. These disturbances include acidification of soil and stream water, imbalances in plant nutrients, changes in species compositions leading to biodiversity losses, and leaching of nitrogen (N) into stream water [82]. To understand how climate change will change the structure and function of forest ecosystems, Karnosky et al. studied how $O_3$ affects the flow of carbon through ecosystems from the leaf level to the root and soil microorganisms under current and future atmospheric $CO_2$ conditions [83]. Aathokleous et al. studied the effects of ozone on ecosystems, including plant assemblages, faunal organisms, soil food webs, or interactions with other biotic or abiotic stresses [84].

For cluster#5 of "water", the top five keywords included "water" (40.50%), "Pb" (22.50%), "Zn" (9.50%), "transport" (6.00%), and "lake sediment" (5.00%). Cluster 5 mainly discussed the effect of water on forest soil contamination. Kikuchi et al. investigated how forest litter affects the chemical composition of water solution. The results of the experiment described in this paper confirm that deacidification, resulting from the leaching of organic matter, is caused by cation exchange not only in the upper mineral soil but also in the litter layer. Furthermore, the presence of litter restricts the leaching of labile Al ions [85]. Wang et al. studied the effect of sewage sludge on the degradation of hexazinone and the formation of its primary metabolites in four forest soils collected in Zhejiang Province, China [86].

For cluster#6 of "forest soil", the top five keywords included "soil" (84.01%), "nitrogen" (7.23%), "land use" (3.28%), "forest" (2.99%), and "pine forest" (0.39%). Cluster 6 mainly discussed the physical and chemical properties of forest soil. The specific species composition of edaphon in forests is determined by various factors, including forest soil, the mulch covering it, its chemical composition, oxygen conditions, pH, moisture, and food resources. Forest ecosystems have a unique physiology and layered structure, which lead to dynamic transport and transfer processes that differ significantly from those in agricultural ecosystems. In their study, Steiner et al. provide a qualitative survey of these dynamic transport processes in forests and their relevance for radiation exposure to humans [87].

For cluster#7 of "profile", the top five keywords included "pollution" (85.01%), "decomposition" (4.71%), "microbial biomass" (3.00%), "microorganism" (2.57%), and "fraction" (1.07%). Cluster 7 mainly discussed the effect of microbial decomposition on forest soil contamination. The decomposition of litter plays an essential role in the return of forest soil nutrients, as well as the growth and productivity of plants [88]. Salminen et al. studied the effects of zinc pollution on forest soil nutrients and its indirect effects on microbial biomass and activity by microscopic experiments using experimental contaminated humus soil. The results showed that the impact of pollution on key organisms may fundamentally change the function of the soil ecosystem.

For cluster#8 of "soil microbial biomass", the top five keywords included "growth" (36.34%), "diversity" (21.12%), "impact" (17.39%), "population" (7.14%), and "management" (6.21%). Cluster 8 mainly discussed the effects of soil microorganisms on plant growth and forest ecosystem diversity. Forest floor microbial communities are critical in decomposition and nutrient cycling [89]. Decreased root biomass in forest trees in response to anthropogenic pollutants is considered one of the first steps in forest health degradation [90].

For cluster#9 of "heavy metals", the top five keywords included "heavy metal" (78.21%), "spatial distribution" (6.65%), "agricultural soil" (6.03%), "acid deposition" (2.47%), and "chemistry" (1.85%). Cluster 9 mainly discussed the effects of heavy metals and their spatial distribution on forest soil and ecosystems. Heavy metal pollution in forest ecosystems is becoming more and more serious. There is an urgent need to understand better the ecotoxicological effects of heavy metals on the entire forest ecosystem [91]. Yan et al. explored the spatial distribution pattern of heavy metals in soil in southeastern China, the spatial correlation of heavy metal pollution in soil and bamboo shoots, and the risk assessment of heavy metals in soil [92].

The term "with bursts" refers to a keyword with a high frequency of citations, indicating that it is receiving significant attention from researchers during a specific period. Therefore, the analysis of keyword bursts can effectively identify the research frontier and future trends [93]. Using CiteSpace analysis, we selected the top 25 keywords with the most robust citation bursts from 1990 to 2023 after excluding similar and unrelated keywords (Figure 8). The results show that the research topics have varied over time. In the early 1990s, "microbial biomass" and "decomposition" were the most studied and enduring topics. They had a prolonged period of burst intensity, with values of 5.86 and

6.95, respectively. These keywords suggest that most studies focused on the microbial decomposition of pollutants in forest soils. Subsequently, the pollution of forest soil caused by atmospheric deposition became a widespread concern, particularly "acid deposition" and "nitrogen deposition". From 2012 to 2018, "Pb", "Cs 137", "removal", and "impact" emerged as common keywords, indicating that researchers were focusing on the pollution and removal of heavy metals in soil and the impact of the Chernobyl events on forest soils. Since 2018, "risk assessment", "response", "emission", and "management" have become prominent keywords, with intensities of 6.05, 6.39, 6.39, and 6.08, respectively. This suggests that researchers have started to pay more attention to investigating and assessing the risks associated with forest ecosystems.

| Keywords | Year | Strength | Begin | End |
|---|---|---|---|---|
| microbial biomass | 1991 | 5.86 | **1991** | 2005 |
| decomposition | 1992 | 6.95 | **1992** | 2001 |
| sewage sludge | 1994 | 11.26 | **1994** | 2009 |
| acid deposition | 1994 | 8.95 | **1994** | 2001 |
| biomass | 1996 | 8.29 | **1996** | 2011 |
| toxicity | 1996 | 6.56 | **2004** | 2007 |
| speciation | 2002 | 7.72 | **2006** | 2013 |
| mobility | 2008 | 6.79 | **2008** | 2011 |
| forest | 1994 | 7.66 | **2010** | 2013 |
| land use | 2010 | 5.86 | **2010** | 2013 |
| nitrogen deposition | 1992 | 10.04 | **2012** | 2017 |
| Pb | 2000 | 8.44 | **2012** | 2015 |
| climate change | 2016 | 14.67 | **2016** | 2019 |
| Cs 137 | 1998 | 10.52 | **2016** | 2019 |
| norway spruce | 1998 | 6.84 | **2016** | 2017 |
| removal | 2016 | 6.11 | **2016** | 2017 |
| impact | 2014 | 17.25 | **2018** | 2023 |
| spatial distribution | 2014 | 11.2 | **2018** | 2023 |
| accumulation | 1998 | 9.05 | **2018** | 2023 |
| biodegradation | 2018 | 6.05 | **2018** | 2019 |
| risk assessment | 2018 | 6.05 | **2018** | 2019 |
| response | 2020 | 6.39 | **2020** | 2021 |
| emission | 2020 | 6.39 | **2020** | 2021 |
| management | 2000 | 6.08 | **2020** | 2021 |

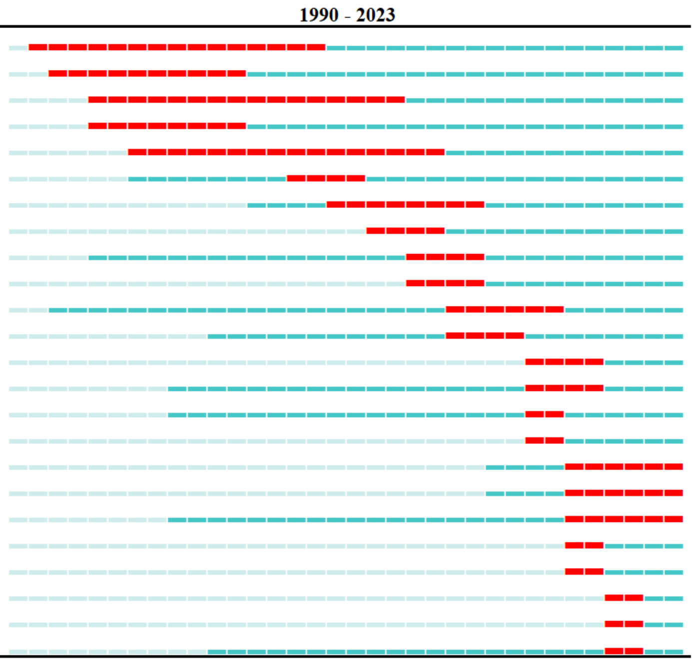


**Figure 8.** Top 25 keywords with the most robust citation bursts during 1990–2023.

## 4. Conclusions and Perspectives

(1) A total of 2659 documents from *WOS* published between 1990 and 2023 were collected for bibliometric analysis on forest soil contamination research. This research can be divided into three stages, with a noticeable rapid development stage observed after 2014. It is worth noting that there is variation in the publication patterns across different *Web of Science* categories. The top five research areas in this field are Environmental Sciences, Ecology, Agriculture, Water Resources, and Forestry and Engineering. However, the analyzed data in this study were retrieved from the *WOS* database, and data outside of this database may yield different results. Additionally, the search results were derived from keywords rather than the empirical observations presented in peer-reviewed publications, which may not comprehensively encompass all the available documents.

(2) Studies on forest soil contamination are published in a total of 658 journals, with the most productive journal being *Science of the Total Environment*. Among the 2659 publications that come from 101 different countries, China emerges as the leading country in this field, followed by the USA, Poland, Russia, and Germany, while the Netherlands and Sweden have high research influence despite fewer publications. The Chinese Academy of Sciences is the leading institute conducting research on forest soil contamination. A number of 8442 authors are actively contributing to the body of knowledge in this area.

(3) Based on keyword co-occurrence, cluster, and burst analysis, the initial research on forest soil contamination primarily focused on the treatment of heavy metal-contaminated forest soil using microorganisms, plants, and other physical and chemical processes. How-

ever, with global and atmospheric changes, researchers have shifted their focus to the impact of atmospheric deposition on forest soils, such as acid and nitrogen deposition. In recent years, there has been a growing interest in forest ecosystem risk assessment. This suggests that future research will focus not only on pollutant removal but also on protecting the entire forest ecosystem from an environmental perspective. It is worth noting that the keyword "microplastics" emerged as a significant topic in high citation analysis, indicating that research on forest soil contamination caused by microplastics may become a potential research hotspot and direction.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f15061068/s1, Figure S1: The trend of publication of the top 5 Web of Science categories; Table S1: Top 15 most productive Subject Categories during 1970–2023; Table S2: Top 10 most productive research areas during 1970–2023; Table S3: Top 11 highly cited review papers; Table S4: Top 9 highly cited article.

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