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Review

Progress in Research on the Effect of Litter on the Carbon Cycle

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Abstract

The carbon cycle is a crucial biochemical process that constitutes the mechanism of carbon turnover, circulation, and storage in the Earth's system. During this process, litter, as one of the main sources of soil organic carbon pools, has a significant impact on the dynamic processes of the global carbon cycle. Based on the Web of Science Core Collection literature, 2,600 publications on the influence of litter on the carbon cycle published from 1990 to 2023 were visualized and analyzed using VOSviewer software. The majority of publications (72.31%) appeared between 2012 and 2023. The United States is at the center of the international collaboration network, with the highest level of collaboration with China, Germany, and the United Kingdom. The Chinese Academy of Sciences is the most productive organization, and Yiqi Luo is the most published Chinese scholar. The top three core journals in the field are *Soil Biol. Biochem.*, *Glob. Chang. Biol.*, and *Ecology*. There are differences in research hotspots at different stages. Currently, the hotspots are "enzyme activity", "microbial community", "bacteria", "inter-root", "soil temperature sensitivity", "Loess Plateau", "carbon storage", and "organic carbon turnover". Meta-analysis showed that litter significantly enhanced soil total nitrogen, soil respiration, soil organic carbon, soil moisture, pH, and β-glucosidase activity. The results of the study indicate that related topics, such as the regulatory mechanisms of litter and the carbon cycle and the expression of functional genes, are becoming potential frontiers for future research, providing a perspective for future innovation research.

Keywords: litter, carbon cycle, visual analysis, bibliometrics, meta-analysis

Introduction

The carbon cycle mainly refers to the transport and transformation of carbon between the atmosphere, biosphere, soil, and lithosphere [1]. In terrestrial ecosystems, more than 90% of the net production of the above-ground portion is returned to the surface through litter [2], and the quality and quantity of litter determine the structure of soil microbial communities [3], which in turn affects the soil carbon cycling process [4]. Under the decomposition of microorganisms, litter matter returns key nutrients required for plant growth

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back to the soil for reuse by plants [5]. As exogenous organic matter, litter is not only an important link in the material cycle and energy flow in grassland ecosystems, but its production, decomposition, and related processes also directly affect the atmospheric CO_2 concentration and the terrestrial carbon cycle [6]. CO_2 release from soil carbon mineralization is a key pathway and indicator of soil carbon pool stability.

In view of the "four-thousandths soil carbon increase plan" announced by the United Nations Framework Convention on Climate Change (UNFCCC) and China's overall goal of achieving carbon neutrality by 2060 [7], research on soil carbon cycling is crucial for predicting future changes in atmospheric carbon dioxide concentrations and understanding the mechanisms of interaction between the atmosphere and the biosphere. In recent years, domestic and international scholars have conducted extensive research on the impact of leaf litter on carbon cycling, with primary research areas including leaf litter decomposition indices [8, 9], leaf litter decomposition processes [10], factors influencing leaf litter decomposition (climatic and environmental) [11, 12], ecological respiration, soil respiration, and carbon dioxide flux generated by litter decomposition [13-16]. The litter decomposition process converts organic carbon into CO_2 (released back into the atmosphere) or stabilizes it as soil humus (long-term carbon sequestration) through microbial and enzymatic reactions. The structure (e.g., Acidobacteria phylum, Ascomycota phylum) and function (e.g., lignin-degrading bacteria) of microbial communities directly determine decomposition efficiency [17]. β-glucosidase activity shows a significant positive correlation with CO_2 emissions during the early stages of decomposition. CO_2 produced from litter decomposition is returned to the atmosphere through autotrophic respiration, participating in the global carbon cycle [18]. This study provides a systematic and comprehensive account of the development of research on the impact of litter input on the carbon cycle.

So far, the mechanism of carbon turnover and storage in the carbon cycle process in response to litter has not been clarified. The carbon cycle is complex and involves reactions such as photosynthesis, respiration, carbon mineralization, and many biochemical reactions, including nitrification and ammonification within the soil. The types of ecosystems and the reactions involved in the carbon cycle have been studied in a single way, and it is not possible to systematically and comprehensively analyze the regulatory mechanism of litter on the carbon cycle in the context of global climate change and the specific impacts on the important indicators involved in the carbon cycle. Bibliometrics focuses on macro-level structural analysis (e.g., research hotspots, knowledge networks), while meta-analysis quantifies empirical evidence by integrating the results of multiple independent studies (e.g., effect size integration). Nevertheless, there are few reports on meta-analysis based on bibliometrics, combining quantitative and qualitative analyses to study the effects of litter on the carbon cycle. This study marks the first combination of bibliometric analysis and meta-analysis on literature related to the study of litter affecting the carbon cycle. Existing bibliometric studies on the impact of litter on the carbon cycle often face the dilemma of being "structured but lacking depth", while meta-analyses may be limited by the scope of their topics. By combining the two approaches, this study systematically identifies key variables (bibliometric analysis) and verifies their actual impact (meta-analysis), forming a closed-loop research framework. Therefore, conducting a meta-analysis based on the results of bibliometric analysis verifies the statistical significance of the effect values of these key indicators, reduces the influence of publication bias, and thereby enhances the precision and accuracy of the meta-analysis. This bidirectional verification mechanism enhances the reliability of the conclusions, allowing us to understand the research trends and future research hotspots regarding the impact of litter on the carbon cycle.

Therefore, this study comprehensively explores the research trends and possible future research hotspots on the effects of litter on the carbon cycle and assesses the impacts of litter on the carbon cycle through a comprehensive analysis of bibliometric and meta-analysis. This study intends to address the following problems: (1) bibliometric analysis clarifies the research progress and future research hotspots of litter in the carbon cycle; (2) the combination of quantitative and qualitative analysis and meta-analysis based on bibliometric analysis can clearly and intuitively reveal the influence of litter on the main indicators in the carbon cycle. This is of great significance and application value for exploring the carbon cycle of terrestrial ecosystems, as well as for the sustainable development of resources, and it helps us better protect the ecological environment and cope with the challenges of global climate change.

Materials and Methods

In this study, the analysis of the impacts of litter on the carbon cycle was mainly based on a systematic review method combining qualitative and quantitative approaches [19, 20]. First, bibliometric analysis was used to provide an overview of the development of litter research and to identify the hotspots related to the impacts of litter on the carbon cycle. Some scholars define bibliometric analysis as a quantitative study of bibliographic material that provides an overview of the research field [21]. Second, using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), the qualitative reading of 62 articles and further extraction of relevant indicators for secondary analyses helped to truly understand the content of the current literature on the impact of litter on the carbon cycle. This is something that conventional bibliometric or meta-analysis cannot achieve in a comprehensive assessment.

Bibliometric methods, including frequency analysis, cluster analysis, and citation burst detection, can horizontally compare journals, countries, institutions, and publications at different times, thus obtaining keyword clustering and presenting the research hotspots and the evolution path of research topics. Thus, future research directions can be found [20]. Through keyword clustering, this work focuses on the relationship between litter and the carbon cycle and the evolutionary process of keywords over time. In order to further explore the effect of litter on the carbon cycle, a meta-analysis was performed based on the results of bibliometrics.

Search Strategy and Data Collection

The data in this paper were obtained from Clarivate Analytics' Web of Science Citation Index Expanded (SCIE) database (WoS, https://apps.webofknowledge.com) [22]. WoS is an authoritative and comprehensive database of academic information resources that is widely utilized in the social sciences, engineering sciences, natural sciences, arts, and humanities [23]. Advanced search methods were used several times to retrieve and compare keywords. According to the literature [22], the topic terms were searched as follows: TS = ("litter") and ("soil carbon cycle" or "carbon cycle"). Literature type is "Review" OR "Article", language is "English", and time span is "1990-2023". In addition, titles and abstracts were manually reviewed to exclude irrelevant articles. Finally, 2,600 papers were exported from the advanced search of the Web of Science (WOS) core collection database (14 articles were excluded, leaving 2, 600 articles) (Fig. 1). The data consisted of complete records and references for authors, titles, abstracts, keywords, classifications, and source publications, exported in plain text format with the title "download_.txt". Data from all records and cited references were downloaded and imported into the VOSviewer software for further data cleaning and subsequent analysis.

Bibliometric Analysis

Combining bibliometric methods with network analysis and data visualization techniques, the formal attributes of knowledge domains have been studied [24, 25]. The implementation of bibliometric analysis allows us to understand the frequency and network of keywords, authors, institutions, and countries [26]. For the bibliometric analysis and visualization of retrieved literature, around thirty free bibliometric mapping tools have been developed [27]. One of the most frequently used software programs is VOSviewer, for graphical analysis and co-occurrence based on data [28]. VOSviewer can be downloaded for free from the website (https://www.vosviewer.com) and consists of five modules: co-authorship, co-occurrence, bibliographic coupling, citation, and co-citation (see the VOSviewer version 1.6.16 manual for details) [29]. In addition, the main framework for bibliometric analysis in the VOSviewer software is listed in detail (Fig. 2) [30].

Methods

VOSviewer software constructs and presents bibliometric maps showing distance, size, and density differences between nodes based on the principles of co-citation and high citation of literature. Clustering, overlay, and density observations are used to evaluate the research directions and hotspots of the literature [28]. VOSviewer runs in a Java environment and supports importing literature in Web of Science format. By clicking "Create" in VOSviewer, documents were imported into the software, objects were selected, and thresholds were set according to the analysis objectives [31]. The distance between nodes indicates the proximity and similarity of the subject terms, the size of the nodes indicates the frequency of occurrence, and higher density indicates a closer connection and stronger relevance [32]. In this study, the type of analysis was chosen as co-occurrence, and the units of analysis were keywords, authors, organizations, and full counts. A keyword co-occurrence frequency of more than

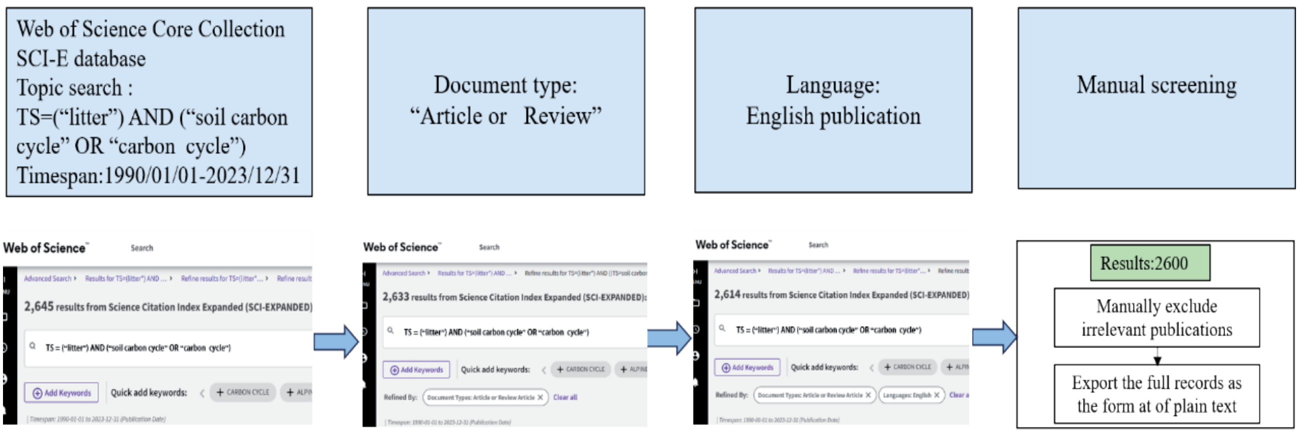

Fig. 1. Literature search strategy and flowchart for the impact of litter on the carbon cycle.

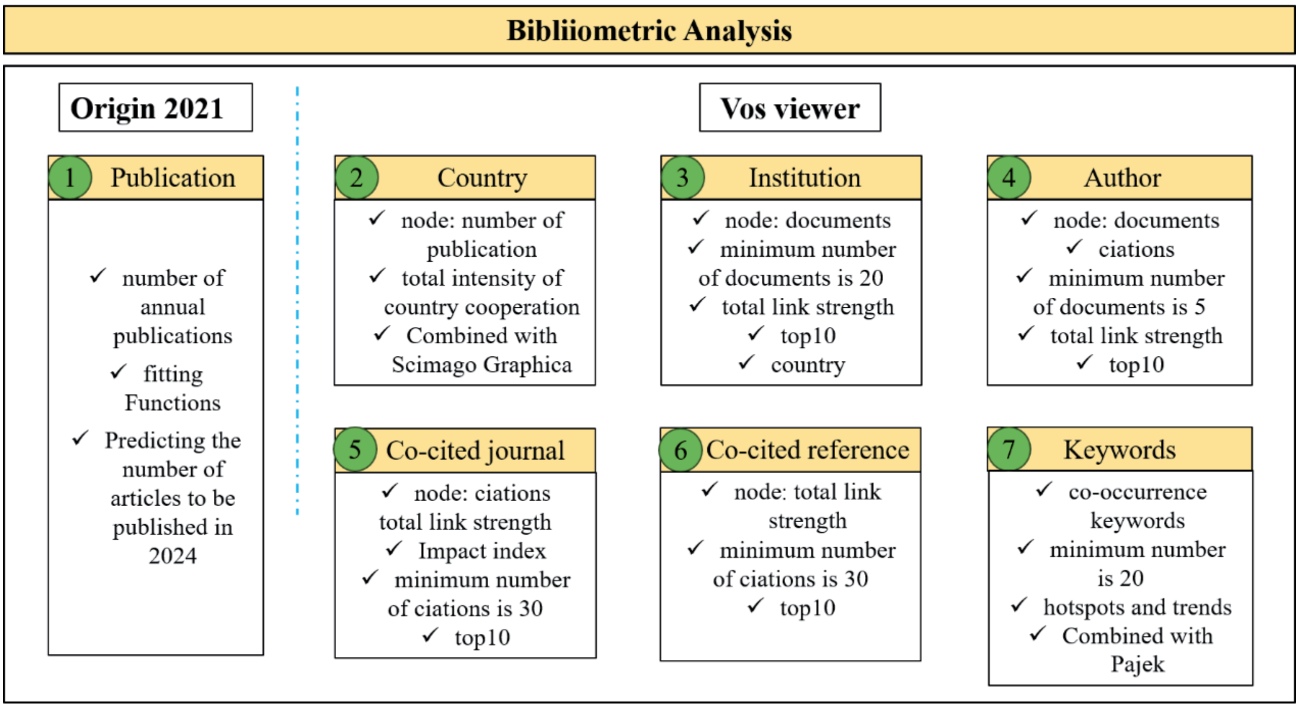

Fig. 2. Research framework for bibliometric analysis.

25 times represents a high-frequency word and indicates a research hotspot.

In order to make the clustering effect of the network mapping generated by VOSviewer more obvious, the results of VOSviewer were saved in Pajek format, and the files were named .net, .clu, and .vec, respectively. Then, the saved files were imported sequentially into Pajek software (Pajek software, a large complex network analysis tool, is a powerful tool for the study of various complex nonlinear networks that exist today). Pajek runs in the Windows environment and is used for analyzing and visualizing large networks with thousands or even millions of nodes, performing reordering and clustering, and then importing the results into the VOSviewer software [33].

The number of national publications and the total intensity of collaboration between countries were produced by the VOSviewer software together with the Scimago Graphica software [34]. All data exported from Web of Science (WOS) were imported into VOSviewer in ".txt" format, and in the "VOSviewer thesaurus files (option)", you must import the "synonym replacement" files. For example, in the analysis of country cooperation, the authors used "China" to replace "Taiwan", "Hong Kong", and other Chinese regions; in the analysis of keywords, the authors merged "plants" with "plant", and removed "effect", "influence", "model", and other meaningless words. In "Choose thresholds", the value of "Minimum number of documents of a country" was set to 20, then the file was run and saved in the format "country.gml". Subsequently, the "country.gml" file was imported into Scimago Graphica software for further visualization.

Meta-Analysis

A meta-analysis is a statistical analysis of the results of independent studies. It examines the sources of differences in study results and, if the results are assessed to be sufficiently similar, quantitatively summarizes the findings. It is widely used in the field of ecology because of the increased validity of statistical tests, the discovery of deficiencies, and the effectiveness of quantitative studies [35, 36]. Nevertheless, the data provided in the literature are not always fully translatable to the desired data. Strict screening of articles is required before meta-analysis [37], and the following screening criteria were set: (1) experimental data were based on field trials of the effects of litter on the carbon cycle, excluding indoor trials; (2) trials included both experimental and control groups with more than three replications; (3) each trial had to be independent of the others; (4) if an article included a variety of vegetation types, site treatments, or ecosystems, each data point was considered an independent observation; (5) the trial data consisted of specific values or graphs and had to include the mean, standard deviation, or standard error. After rigorous screening, supplementation, and secondary screening of the articles, a total of 62 articles from different regions and time zones were finally included in the meta-analysis (Fig. 3).

Analyzing Methods

When collecting data from the literature, if the data in the literature were listed in the form of text or tables, they were read directly; if the data were presented

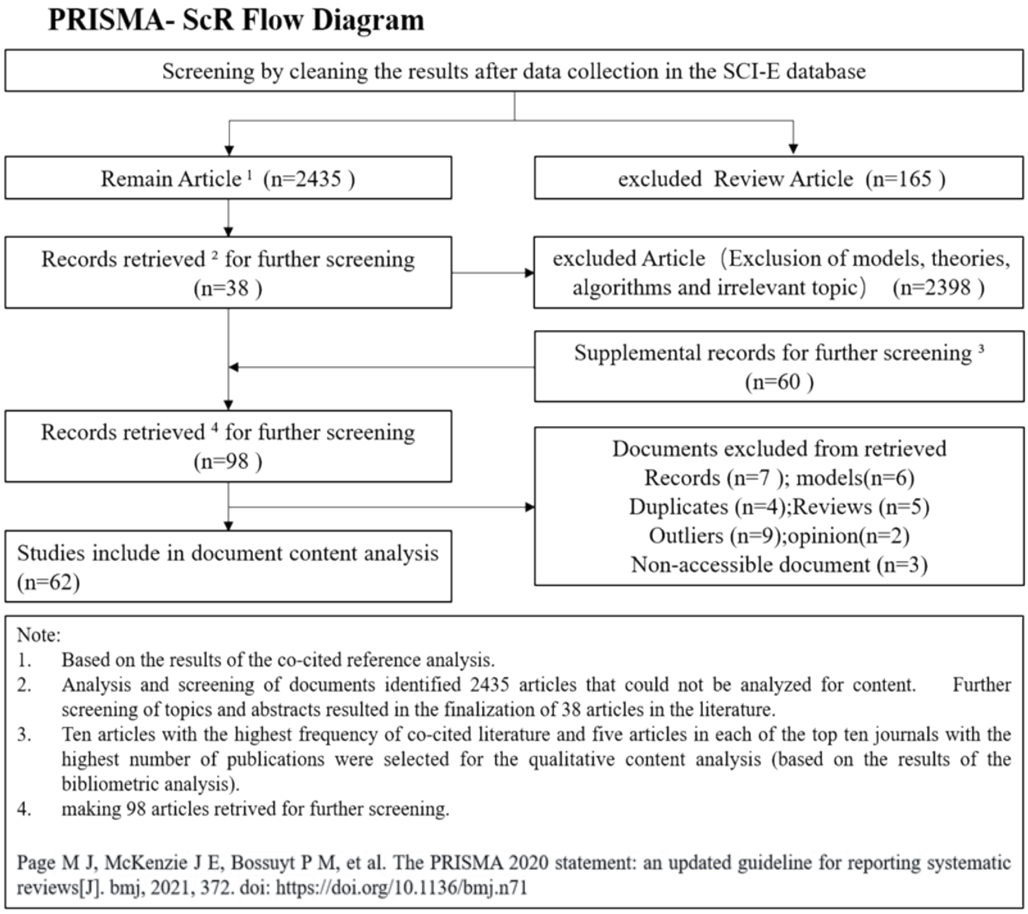

Fig. 3. Flowchart of meta-analysis.

in the form of graphs, they were extracted using Web Plot Digitizer [38]. The natural log-transformed response ratio (*lnRR*) developed by Hedges [39] is frequently employed to assess the impacts of litter on the carbon cycle [40]. It is formulated as follows:

$$lnRR_{ij} = \ln\left(\frac{T}{C}\right) = \ln(T) - \ln(C)$$

in the formula: T represents the treatment group value, and C indicates the control group value.

Variance (v_{ij}) was calculated using the following formula:

$$v_{ij} = \frac{(Vt)^2}{nt(T)^2} + \frac{(Vc)^2}{nc(C)^2}$$

in the formula: *Vt* represents the treatment group standard deviation, *Vc* represents the control group standard deviation, *nt* indicates the treatment group sample size, and *nc* indicates the control group sample size.

The weighting coefficient (ω_{ij}) was calculated using the formula:

$$\omega_{ij} = \frac{1}{v_{ij}}$$

in the formula: the weighted response ratio ($lnRR_{++}$) was calculated using the formula:

$$lnRR_{++} = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} lnRR_{ij}\omega_{ij}}{\sum_{i=1}^{m} * \sum_{j=1}^{n} \omega_{ij}}$$

in the formula: n is the observation count within each compared group, and m is the count of groups being assessed.

The effect size is used to assess the impact of litter on important indicators related to the carbon cycle, and is calculated using the formula:

$$Effect\ size(\%) = (e^{lnRR_{++}} - 1) * 100\%$$

Data Processing

Upon completion of data extraction, missing values for some studies were filled in with the median of the extracted data. If less than 50% of the data were extracted for a metric, that metric was removed to avoid errors (e.g., CO_2 flux, urease, and other indicators related to the carbon cycle are excluded). This was done using the "mice" package, the "zoo" package, and the "vim" package in R4.4.1. The heterogeneity test and I^2 test (Table 1) were performed on the effect values of the studies, and the results showed that there was significant heterogeneity in the overall effect values ($P<0.05$; $I^2>75\%$), which indicated that there was a large difference between the mean values of the collected experimental data. The variation between the results of the different studies was caused by the random error; therefore, the random effect model was used for the meta-analysis [41]. Random Forest analysis was performed on the data using the "Random Forest" package to determine the response of each indicator in the collected data to litter. All data analysis was done in R4.4.1.

Results

Bibliometric Analysis

Annual Number of Publications

Trends in paper publication are quantitative indicators of scholarly activity and the level of interest in a particular field [27]. From the publication years of the 2,600 papers counted, the overall number of papers in the field of litter impacts on the carbon cycle showed an increasing trend, especially in the last 10 years, with the highest number of papers published in 2021, which amounted to 237 papers (Fig. 4). Linear fitting using origin Pro 2021 yielded an overall linear trend in the number of publications with the equation

Table 1. Heterogeneity test and I^2 test for different indicators of meta-analysis.

Character	I^2	Model	Heterogeneity	
			Q	P
TN	91.94%	Random Model	992.837	0.000
SR	99.28%	Random Model	6674.681	0.000
SOC	99.81%	Random Model	24567.611	0.000
SM	97.41%	Random Model	2320.581	0.000
PH	98.00%	Random Model	1593.885	0.000
MBC	99.53%	Random Model	9884.014	0.000
βG	90.20%	Random Model	586.863	0.000

Note: In the above table, βG is β-glucosidase, MBC means soil microbial biomass carbon, pH is soil pH, SOC means soil organic carbon, SM means soil moisture, SR means soil respiration, and TN means total nitrogen. Same as below.

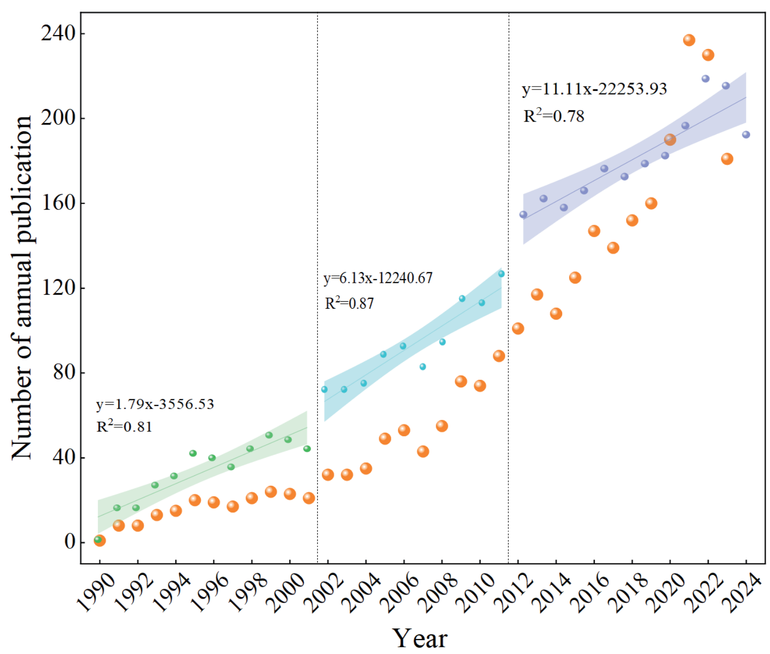

Fig. 4. Annual number of publications on research on the impact of litter on the carbon cycle.

y = 11.11x - 22253.93, R^2 = 0.8783. This curve exhibits a highly significant linear relationship and predicts 233 publications in 2024.

The development history of the research on litter affecting the carbon cycle can be roughly divided into three stages. In the first stage (1990-2001), this research field was in its embryonic stage, with fewer than 30 articles published annually. In the second stage (2002-2011), the field entered an ascending phase, with 30-90 articles published per year. In the third stage (2012-2023), this research entered an exponential growth phase, with more than 100 articles published per year, showing a steady year-by-year increase. Litter affects the carbon cycle with a mature theoretical basis and has entered the stage of theoretical application. The number of articles published during this period accounts for 72.31% of the total number of articles published.

Country Analysis

As can be seen from Fig. 5, we found that the countries with high publication volume are the United States, China, Germany, the United Kingdom, and France. These countries not only have strong scientific capabilities, but also have extensive cooperation networks, and primarily contribute to the research results of the carbon cycle influenced by litter. The United States is the leading country in the field of litter-affected carbon cycle research, followed by China, and the two countries are far ahead of others. The results show that China has established international cooperative relationships with many countries, with the United States being the closest partner, followed by Germany and the United Kingdom. This indicates that the countries with the most papers in this research field are China and the United States. At the same time, the number of papers co-authored by China and the United States is comparatively high. Therefore, cooperative relationships with other neighboring countries should be strengthened, and academic exchanges should be encouraged.

Institution Analysis

The study found that 2,507 academic institutions worldwide have published papers related to the impact of litter on the carbon cycle, among which 1,590 institutions have published only one paper (Fig. 6). The top 10 academic institutions with the highest number of publications are listed in Table 2. The institution with the highest number of publications is the Chinese Academy of Sciences (284), followed by the University of Chinese Academy of Sciences (98), Univ Oklahoma (43), and Univ Colorado (42). In addition, CAS and Univ Oklahoma are the most cited institutions with 10,827 and 5,809 citations, respectively. They are closely followed by Colorado State Univ (573 times), and Univ Colorado Science (5,553). It is noteworthy that the structure with the most publications and the institution with the most citations are both from China and ranked first. This further indicates that China is paying more and more attention to the protection of the ecological environment.

Author Analysis

As can be seen from Fig. 7, a total of 10,492 researchers worldwide published papers related to the influence of litter on the carbon cycle; of them, only 1,758 authors (16.76%) have published more than 2

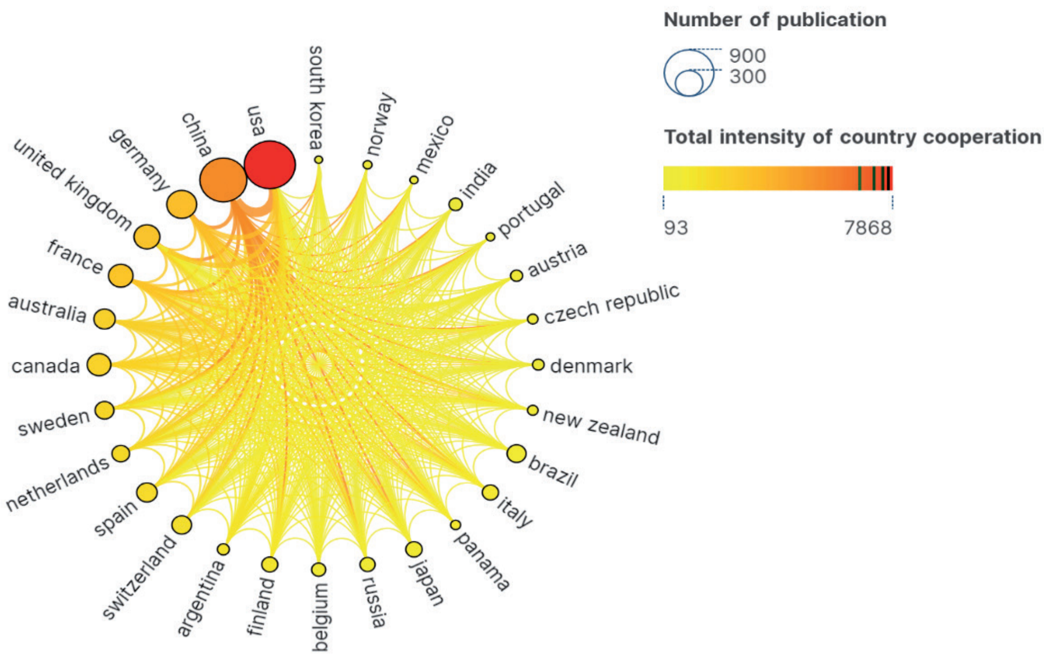

Fig. 5. Mapping of countries/regions analyzing research on the impact of litter on the carbon cycle (threshold of 20 documents).

papers. We identified the top 10 authors in terms of the number of publications (Table 3). These authors were mainly from China (50%) and published 130 papers, accounting for 5% of the total number of publications. The most active authors in this field are Yiqi Luo from China, with 40 publications and up to 4,036 citations, followed by Yakov Kuzyakov from Germany, with 27 publications and up to 1,982 citations. Bo Tan from China, with 24 publications and a Total Link Strength of 118, ranked first, indicating that this author has a close working relationship with other authors and is also recognized by them.

Utilizing collaborative author networks to reveal the collaborative relationships between authors of litter influenced carbon cycle studies. Fig. 7 shows the collaborative author network consisting of ten clusters. The first cluster (red area) consists mainly of authors Yiqi Luo, Xuhui Zhou, and Yuanhe Yang. The second cluster (orange area) represents an author collaboration network mainly composed of Yakov Kuzyakov. The third cluster (yellow area) includes authors such as Wanqin Yang, Bo Tan, and Fuzhong Wu. Cluster four (green area) consists of authors Amy T. Austin and Jennifer S. Powers. Cluster five (blue area) centers

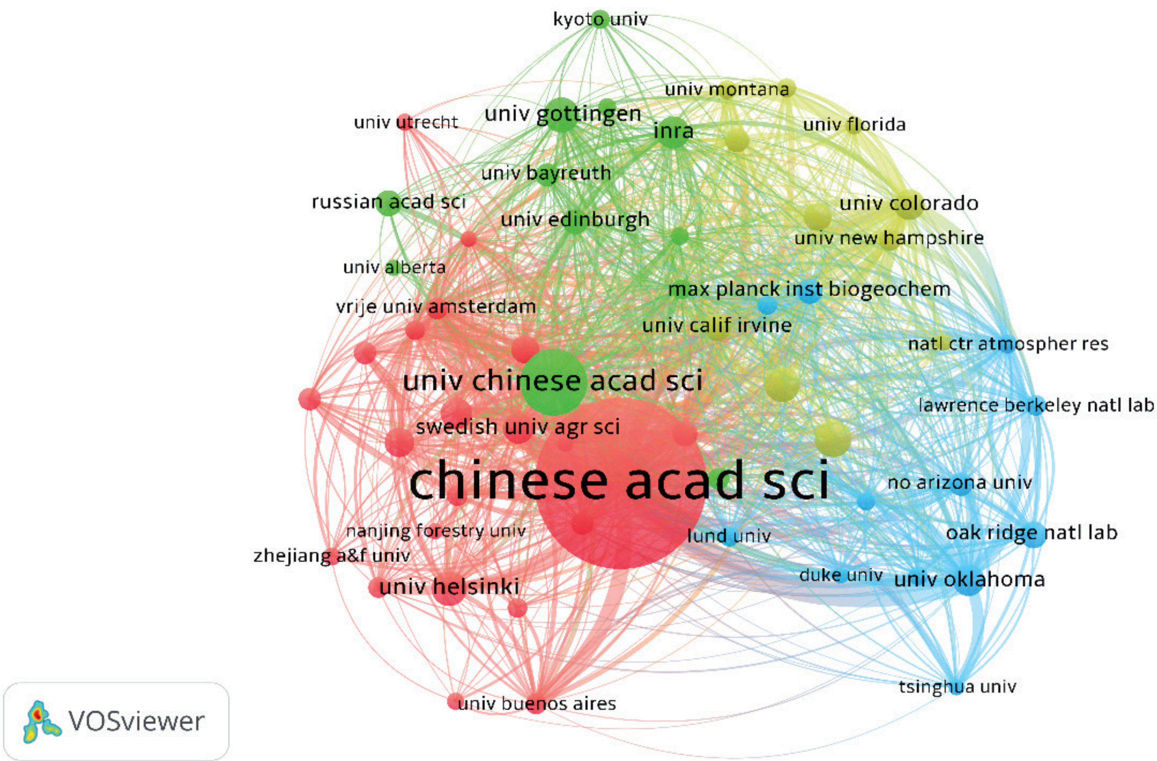

Fig. 6. Institutional network mapping of litter affecting the carbon cycle (threshold of 20 documents).

Table 2. Top 10 institutions in terms of publications in the research field of litter affecting the carbon cycle.

	Institution	Country	Documents	Citations	Total Link Strength
1	Chinese Acad Sci	China	284	10827	219
2	Univ Chinese Acad Sci	China	98	2384	116
3	Univ Colorado	Usa	42	5553	58
4	Oak Ridge Natl Lab	Usa	36	3262	54
5	Univ Oklahoma	Usa	43	5809	54
6	Natl ctr Atmospher Res	Usa	25	2801	53
7	No Arizona Univ	Usa	31	2240	51
8	Lawrence Berkely Natl Lab	Usa	27	1079	50
9	Colorado State Univ	Usa	34	5773	49
10	Univ Minnesota	Usa	38	5338	45

around Johannes H.C. Cornelissen. The clusters show that researchers in this field are mainly organized within their own teams, with close cooperation inside the teams but limited collaboration between them, indicating that communication among researchers and international partnerships is not yet conducive to the development of this field. Strengthening academic exchanges and cooperative relationships among researchers will be beneficial to progress in this research area.

Co-Cited Journal Analysis

It has been found that the number of co-citations indicates the impact, visibility, and quality of a publication [42]. Nonetheless, some studies have found that

Table 3. Top 10 authors in the research field of litter affecting the carbon cycle.

	Name	Country	Documents	Citations	Total Link Strength
1	Yiqi Luo	China	40	4036	96
2	Kuzyakov Yakov	Germany	27	1982	17
3	Wanqin Yang	China	26	544	98
4	Bo Tan	China	24	420	118
5	Fuzhong Wu	China	21	478	83
6	Austin Amy T.	Argentina	20	2037	5
7	Xuhui Zhou	China	19	2166	57
8	Josep Penuelas	Spain	19	928	44
9	William R. Wieder	Usa	17	2318	35
10	Philippe Ciais	France	17	648	27

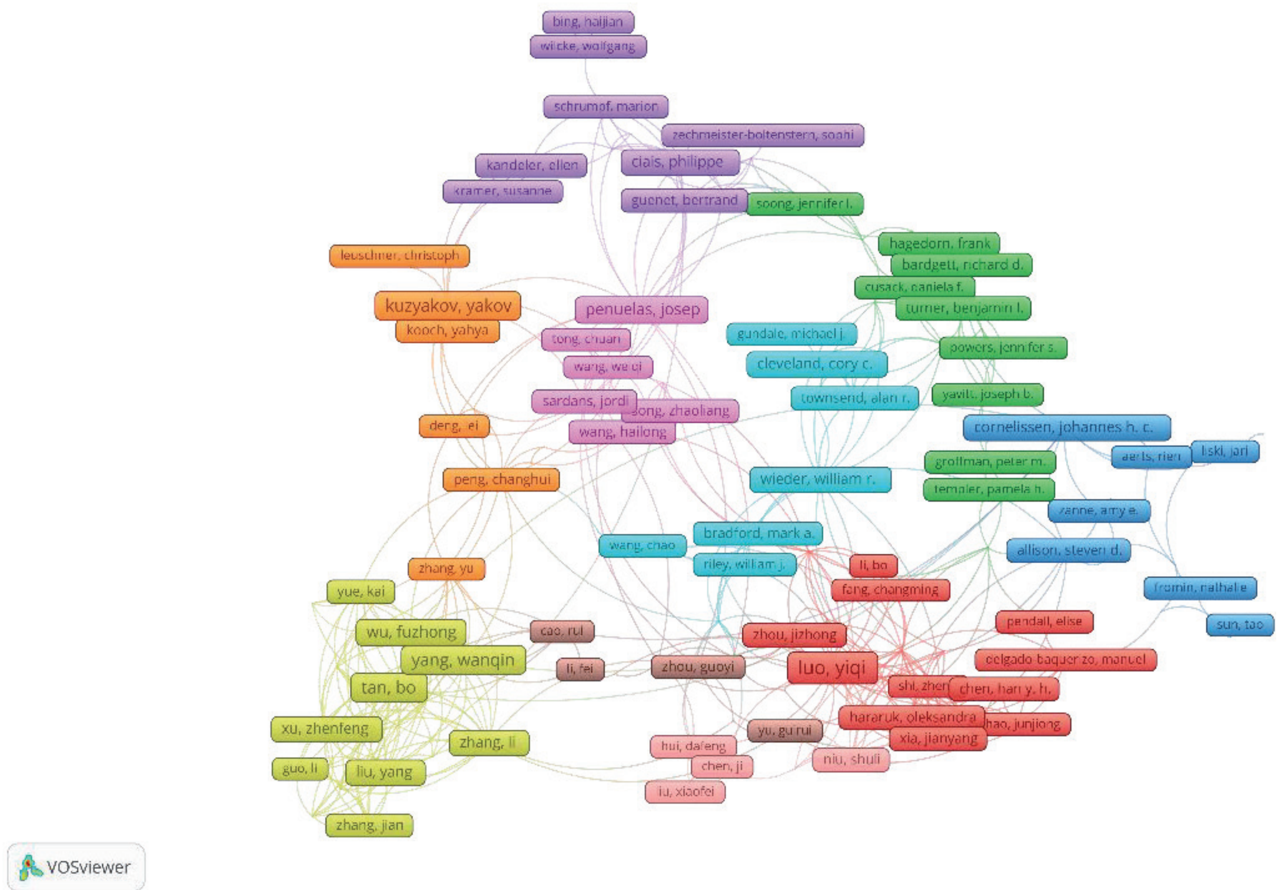

Fig. 7. Author network mapping in the research field of litter affecting the carbon cycle (threshold of 5 documents).

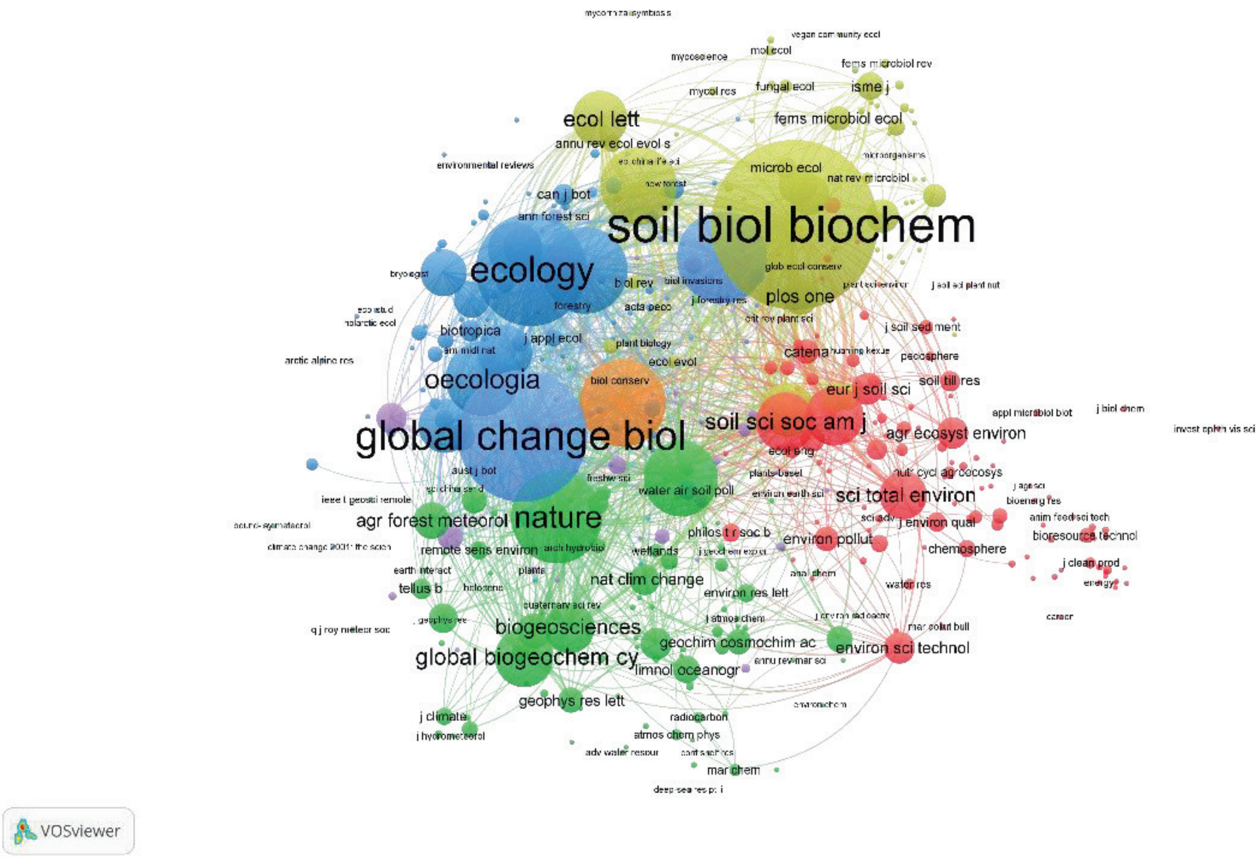

Fig. 8. Network map of co-cited journals of litter affecting the carbon cycle (threshold of 30 citations).

the number of times a publication is cited by others does not necessarily indicate its quality but rather measures its visibility [43]. Thus, the co-citation of papers can help identify scholars and institutions that have made significant contributions or have been active in the field for a long time. As shown in Fig. 8, there are 462 journals (with a co-citation threshold of 30). The top 10 journals are listed in Table 4, with *Soil Biology and Biochemistry* in first place (10,688 co-citations), followed by *Global Change Biology* (7,286), *Ecology* (5,792), *Nature* (4,356), and *Plant and Soil* (4,249).

Co-Cited Reference Analysis

As shown in Fig. 9, there are 96,399 papers co-cited globally in the field of litter-carbon cycle research. With a threshold of 30 co-citations, 245 papers are co-cited

Table 4**.** Top 10 co-cited journals in the field of litter affecting carbon cycle research.

	Journal	Country	Citation	Total Link Strength	2023 Impact Index
1	Soil Biol. Biochem.	England	10688	638191	9.7
2	Glob. Chang. Biol.	England	7286	488975	11.6
3	Ecology	United States	5792	375608	4.8
4	Nature	England	4356	309593	64.8
5	Plant Soil	Nether Lands	4249	293463	4.9
6	New Phytol.	England	3308	275291	9.4
7	Niogeochemistry	Nether Lands	3947	272617	4
8	Forest Ecol. Manag.	Nether Lands	3928	251104	3.7
9	Science	United States	3149	232757	56.9
10	Oecologia	Germany	3128	206714	2.7

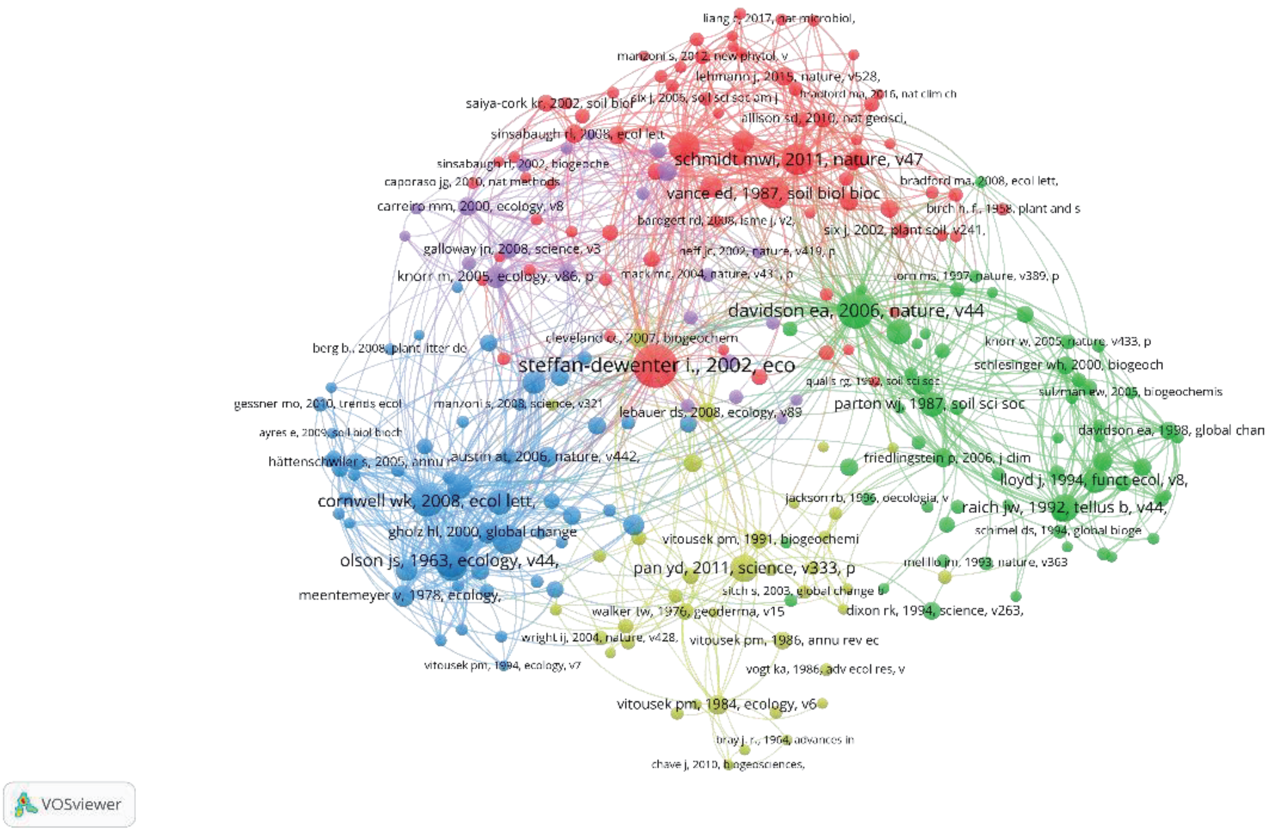

Fig. 9. Network mapping of co-cited papers on litter affecting the carbon cycle (threshold of 30 co-cited).

in five clusters. The first cluster (red area) is centered on Cotrufo M.F. (2013), *Global Change Biology*. The second cluster (green area) is centered on Davidson E.A. (2006), *Nature*, 444. The third cluster (blue area) is centered on Cornwell W.K. (2008), *Ecology Letters*. The fourth cluster (purple area) is centered on Knorr M. (2005), *Ecology*, 85. The fifth cluster (yellow area) is centered on LeBauer D.S. (2008), *Ecology*, 89. The top ten co-citations are shown in Table 5, with the highest ranking being Steffen Dewenter et al. (2002), published in *Ecology* with a total of 247 citations, followed by Davidson and Janssens (2006), published in *Nature* with a total of 189 citations.

Research Hotspots and Trends

A total of 10,327 keywords were obtained from 2,600 documents. The accuracy and frequency of keywords are two important factors in ensuring that co-occurrence analysis accurately identifies research hotspots in the field [44]. To make the analysis results more accurate, the keywords in the literature were first cleaned and organized, mainly including the unification of singular and plural forms, full names and abbreviations, and near-synonyms. The cleaned keywords were counted using VOSviewer software, and keywords with a frequency greater than 30 were defined as high-frequency keywords [31]. Keywords with high frequency but no analytical significance, such as "response", "influence", "model", "mechanism", and other insubstantial words, were excluded.

According to keyword co-occurrence network analysis, the current research direction on litter affecting the carbon cycle can be roughly divided into five major categories. They are: Green area – soil carbon mineralization, soil microbial biomass carbon (nitrogen), soil temperature sensitivity, soil respiration and ecological respiration, and other research directions. Blue area – litter decomposition, enzyme activity, microbial community characteristics and diversity, and other research directions. Red area – nitrogen, phosphorus, nutrient limitation and dynamics, ecological stoichiometric characteristics. Yellow area - climate change, CO_2 flux and emission, and carbon cycle. Purple area – litter quality and lignin (Fig. 10). Superimposing the publication time on the keyword co-occurrence network yields a keyword time overlay graph (Fig. 11), the different colors correspond to the average number of years that the keywords have appeared in the literature, which allows for the identification of trends in the evolution of research in the field.

Meta-Analysis

The above study systematically develops the visualization and analysis of the influence of litter on the carbon cycle and the prediction of development

Table 5. Top 10 Highly cited literature in the field of litter affecting carbon cycle research.

	DOI	Citation	Total link strength
1	Davidson E A, Janssens I A. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change[J]. Nature, 2006, 440(7081): 165-173. doi:10.1038/nature04514	189	1848
2	Schmidt M W I, Torn M S, Abiven S, et al. Persistence of soil organic matter as an ecosystem property[J]. Nature, 2011, 478(7367): 49-56. doi:10.1038/nature10386	153	1549
3	Cornwell, William K., et al. "Plant species traits are the predominant control on litter decomposition rates within biomes worldwide"[J]. Ecology letters, 2008, 11(10): 1065-1071. doi:1111/j.1461-0248.2008.01219.x	158	1511
4	Steffan Dewenter, Ingolf, et al. "Scale-dependent effects of landscape context on three pollinator guilds" [J]. Ecology, 2002, 83(5): 1421-1432. doi:1890/0012-9658(2002)083[1421-1432]	247	1468
5	Cotrufo M F, Wallenstein M D, Boot C M, et al. The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: do labile plant inputs form stable soil organic matter? [J]. Global change biology, 2013, 19(4): 988-995. doi:10.1111/gcb.12113	147	1426
6	Jerry S. Olson. Energy Storage and the Balance of Producers and Decomposers in Ecological Systems[J]. Ecology,1963, 44(2),322-331. doi:2307.1932179	164	1202
7	Melillo, Jerry M., John D. Aber, and John F. Muratore. "Nitrogen and lignin control of hardwood leaf litter decomposition dynamics" [J]. Ecology 63.3 (1982): 621-626. doi:10.2307.1936780	139	1160
8	Knorr M, Frey S D, Curtis P S. Nitrogen additions and litter decomposition: A meta-analysis[J]. Ecology, 2005, 86(12): 3252-3257. doi:10.1890/05-0150	88	1107
9	Parton, William, et al. "Global-scale similarities in nitrogen release patterns during long-term decomposition" [J]. science, 2007, 315(5810):361-364. doi:1126/scienxe.1134853	106	1097
10	Jobbágy E G, Jackson R B. The vertical distribution of soil organic carbon and its Relation to climate and vegetation[J]. Ecological applications, 2000, 10(2): 423-436. doi:10.2307/2641104	104	1052

trends and research hotspots in this field. According to the first cluster of the keyword co-occurrence network analysis, soil microbial biomass carbon, soil temperature sensitivity, and soil respiration and ecological respiration are the current research hotspots (Fig. 10). After rigorous and scientific literature screening and meta-analysis following data extraction (Fig. 3), litter had a significant positive effect on soil respiration, soil organic carbon, soil moisture, soil pH, and βG (Fig. 12) ($P<0.01$).

Discussion

Basic Information on the Impact of Litter on the Carbon Cycle

Our analysis of litter-influenced carbon cycle research shows an average of more than 160 publications per year since 2019 (Fig. 4). The number of annual publications in 2020 equals the cumulative number of publications from 1990 to 2001 (190), and most of the publications (72.31%) appeared in the third phase of the field's development (2012-2023). There has been a significant increase in the number of publications in research on the impact of litter on the carbon cycle (Fig. 4). This can be explained by the fact that international and national governments, as well as researchers, are increasingly recognizing the important role of litter-impact research on the carbon cycle, which has attracted the attention of the international academic community [45]. Meanwhile, the relevant theories, research methods, and application technology systems are becoming increasingly mature [46, 47]. As a result, the number of publications has increased significantly and exponentially since 2019 (Fig. 4). Our findings suggest that the United States and China are the largest contributors to this field. The United States leads the way, with China showing strong collaboration with the United States, Germany, and the United Kingdom (Fig. 5). This may be due to historical factors (the country has tied technological cooperation to geopolitics, forming a technology-political alliance) [48], institutional factors (consolidating economic and technological hegemony through rule-making) [49], and financial factors (DARPA's massive investments) [50], which have collectively formed the underlying logic of the United States' international cooperation center. China and the United States both have a high number of publications from their respective countries, as well as a high number of papers co-authored by the two countries. However, there is much closer collaboration between research institutions within each country, such as the Chinese Academy

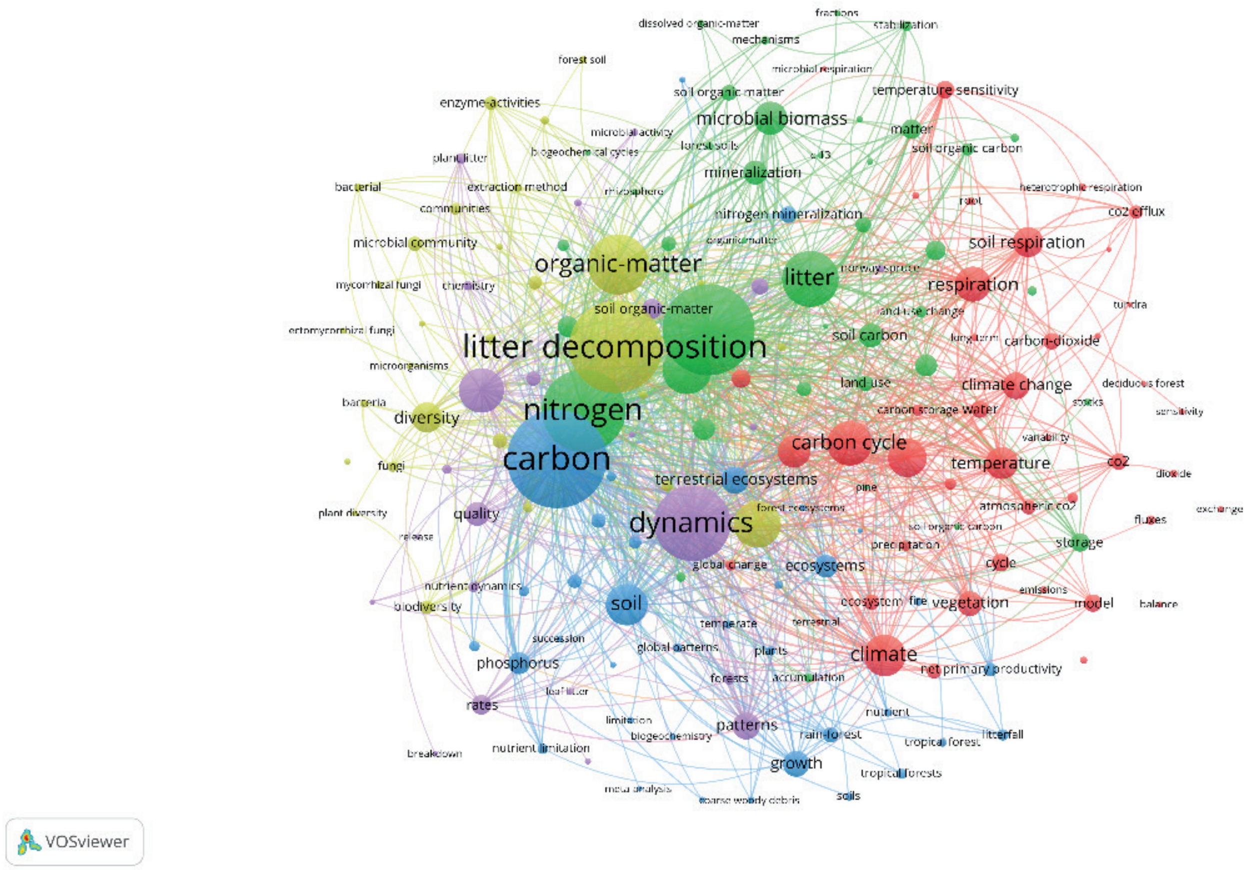

Fig. 10. Keyword co-occurrence network mapping of litter affecting the carbon cycle (threshold of 30 co-occurrences).

of Sciences (CAS) and the University of Chinese Academy of Sciences (UCAS) in China (Fig. 6, blue clusters), and between institutions in the United States (Fig. 6, green clusters). Notably, the Chinese Academy of Sciences is the most productive institution with the greatest centrality (i.e., the greatest number of publications (237) (Table 2; Fig. 5). Meanwhile, 50% of the top ten active authors are Chinese scholars (Table 3; Fig. 7).

Chinese scholars have carried out many studies on the impact of litter on the carbon cycle [51, 52]. As mentioned above, increased attention of Chinese government institutions and scholars to the impacts of litter on the carbon cycle, the increased importance of the field, and increased financial support have all contributed to the development of the field in China [53]. The top ten journals are from the United Kingdom, the United States, Switzerland, and Germany. The major journals in the study of litter affecting the carbon cycle are *Soil Biol. Biochem.*, *Glob. Chang. Biol.*, *Ecology*, *Nature*, *Plant Soil*, *New Phytol.*, *Biogeochemistry*, *For. Ecol. Manag.*, *Science*, and *Oecologia* (Fig. 8; Table 4). This may be because these international, multidisciplinary, and authoritative journals publish original and review articles on the impact of litter on the carbon cycle, exploring in depth the responses and driving factors at the plant-soil-microbe-atmosphere interface and contributing to the understanding of the mechanism [54]. China should strengthen cooperation and exchange with countries such as the United States and Germany, while promoting the establishment of an open data platform, the Global Carbon Cycle Observation Database, to enhance research transparency and reproducibility.

Knowledge Base on the Impact of Litter on the Carbon Cycle

Co-cited reference analysis is used to analyze the intellectual structure and indicate the influence of a document in scientific research [55]. We have scrutinized the top 10 most highly cited references to facilitate a quick and comprehensive overview of research on the effects of litter on the carbon cycle for researchers not in the field. The top highly cited article is Davidson and Janssens (2006), published in Nature, which examines the factors of soil carbon decomposition and the feedback mechanisms to climate change. The authors suggest that combining substrate effectiveness (e.g., Michaelis-Menten kinetics) with temperature sensitivity (Arrhenius kinetics) could improve soil carbon kinetic measurements and modeling, and address the difficulty of estimating soil carbon substrate diversity and concentration.

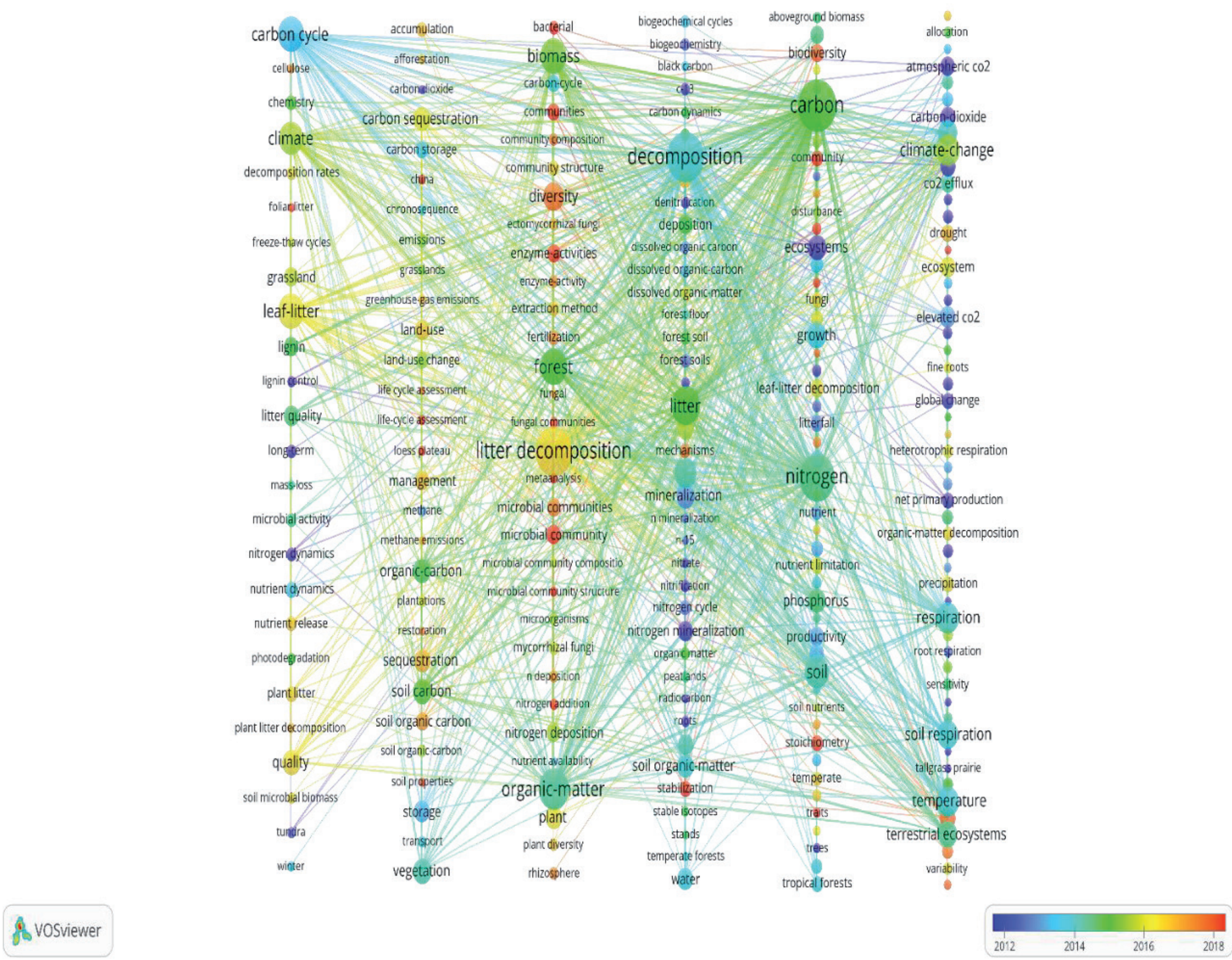

Fig. 11. Time-overlapping co-occurrence clustering mapping of keywords of litter affecting the carbon cycle.

In the context of global change, studying the multiple processes that control the environmental constraints on substrate availability to enzymes contributes to ecological conservation and coping with climate extremes. Secondly, Schmidt et al. (2011) published their study in Nature, where they incorporated their findings into a new generation of experimental and soil carbon modeling approaches to improve the prediction of soil organic matter responses to global warming. The authors emphasize that future research should identify drivers of the carbon cycle based on six factors: climate, biology, topography, parent material, time, and human activity, in order to understand and model thresholds for soil organic matter storage and loss. Meanwhile, Ranjard et al. (2010) combined new technologies with carbon cycle research. The authors modified the current soil model and provided suggestions on how to incorporate the latest advances into it [56]. The third most highly cited paper was published by Cornwell et al. (2008) in Ecol. Lett. The authors investigated a new link between plant carbon strategies and biogeochemical cycling by collecting data from 818 independent measurements in 66 litter decomposition experiments across 6 continents, contributing to an understanding of vegetation-soil feedbacks and improving predictions of the global carbon cycle. Long-term ecological observation networks already exist in scientific institutions in some countries, but most of them are designed with vegetation as a target. Experimental methods for carbon cycle research need to be improved. Follow-up research should apply new analytical techniques and instrumentation to isotope labeling and molecular techniques. Isotope tracing may track marker elements in the environment (e.g., ^{14}C) and "track" specific plant compounds and microbial products in the soil, reveal decomposition pathways and partitioning strategies, and deeply understand the molecular turnover and cycling of litter matter between plant-soil-microbial-atmosphere.

The above discusses the possibility of increased publications and research progress in the field of litter's impact on the carbon cycle. Breakthroughs in research methods and national support are conducive to the rapid development of this field, which also reflects social development and scientific and technological progress. The development of this field contributes to ecological restoration, grassland management, and policy development and is critical to global ecological conservation. Nevertheless, there are also some

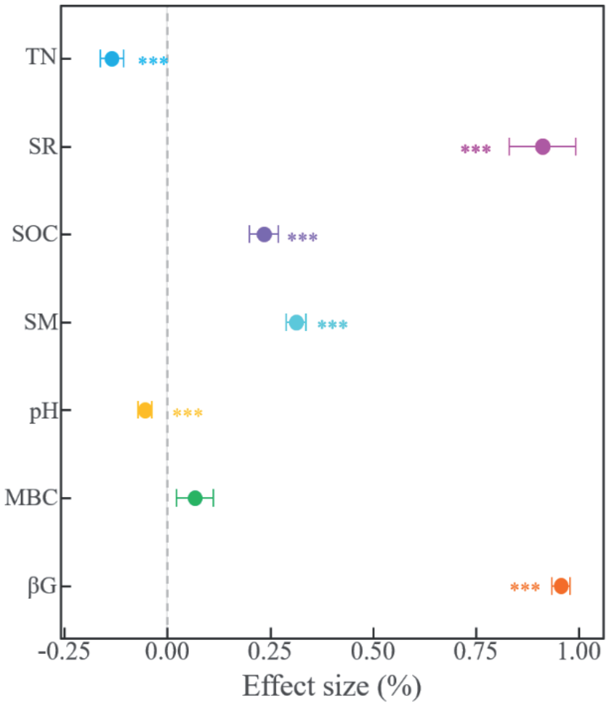

Fig. 12. Meta-analysis of litter on important indicators related to the carbon cycle.
Error bars represent a 95% confidence interval. ***: $P<0.001$. (Table 1 shows the heterogeneity test and I^2 test for the effect values of the meta-analysis, and the results showed that there was significant heterogeneity in the overall effect values ($P<0.05$; $I^2 > 75\%$), and the variation between the results of different studies was caused by random errors, so the random effects model was used for the meta-analysis).

potential negative effects of litter's impact on the carbon cycle: CO_2 released during the decomposition of litter leads to a decrease in the stability of soil carbon [57], a decrease in the diversity of soil microbial communities and microbial activity [58], an increase in CO_2 emissions that exacerbates the greenhouse effect [59], a reduction in ecosystem stability and resistance [60], and disruption of nutrient cycling [61]. Therefore, litter has a dual effect on the carbon cycle. Future research should avoid issues such as research homogenization and excessive resource concentration, fully consider its potential positive and negative impacts, and take corresponding measures to optimize its ecological functions. Future work can be carried out by formulating policies (such as (1) prioritizing the "rotational grazing+reseeding with suitable species" pattern in degraded grassland restoration, accompanied by incentive mechanisms. (2) Establishing a "ecological relocation+wetland restoration" linkage mechanism and exploring coupled models between carbon sink projects and ecological compensation. (3) Addressing the issue of low temperatures limiting microbial activity in alpine meadows on the Qinghai-Tibet Plateau by proposing a "winter grazing ban" policy and promoting subsidies for the cultivation of cold-tolerant nitrogen-fixing plants (such as alpine grasses) and other easily implementable policies. These measures can assist in ecological restoration, grassland management, and carbon cycle management.

Research Hotspots and Development Trends of Litter Affecting the Carbon Cycle

High-frequency keywords refer to keywords with high co-occurrence frequency, and a keyword that appears with high frequency in a certain period of time may be a research hotspot or a research focus in a certain field at that time [62]. Through the co-occurrence analysis of visualization software, the topical structure and hot issues in the field can be revealed, which is conducive to the comprehensive analysis of the research hotspots in a certain field [32]. In addition, temporally overlapping co-occurrence maps of emergent keywords can be used to present an overall picture of cutting-edge research issues and the evolutionary trajectory of emerging trends in recent years [63]. We categorized the research period (1990-2023) into 3 periods. During the exploration period (1990-2001), there were fewer articles related to the study of litter affecting the carbon cycle, with an annual publication volume of less than 30 (Fig. 4). The keywords of the papers were focused on "litter quality", "lignin", "litter decomposition process", "factors affecting litter decomposition", "plant communities", "soil nutrient dynamics" [8, 64] (Figs 10 and 11), indicating that litter influences on the carbon cycle have been noticed by researchers in the field and initial explorations have begun. The bibliometric analysis of countries (Fig. 5), authors (Fig. 6; Table 3), and keywords (Figs 10 and 11) corroborate this view, indicating that many countries and researchers around the globe have begun to study the carbon cycle and fields related to the carbon cycle.

Subsequent studies have allowed the continuation of the main research hotspots of the previous phase, and a large number of new high-frequency terms were found during the developmental period (2002-2011). The results showed that "diversity", "microbial biomass", "nitrogen mineralization", "CO_2 flux", "climate", and "microbial community characteristics" gradually became the most frequently mentioned keywords. This shows that in terrestrial ecosystems, forests were researched before grassland and agricultural types, and more and more researchers have begun studying the effect of litter on the carbon cycle (Fig. 7; Table 3). Meanwhile, awareness of ecological protection has been gradually strengthened in various countries (Fig. 5). In the theoretical application phase (2012-2023), carbon cycle-related papers show a significant growth trend. The phenomenon of accelerated growth in publication volume in 2012 can be explained by the dual factors of policy-driven and technological progress. The preparatory work for the IPCC Fifth Assessment Report (AR5) directly encouraged domestic scholars to participate in global climate modeling and impact assessment research, creating a policy-academic synergy effect. During the preparatory phase of China's dual-carbon policy (2012-2015), financial investments and policy support from China contributed to increased academic output. Keyword analysis and keyword time co-occurrence analysis show that the research hotspots – including "enzyme activity", "microbial community", "bacteria", "inter-root", "soil temperature sensitivity", "Loess Plateau", "carbon storage", "carbon stability", and "organic carbon turnover" – were the most frequently mentioned keywords (Figs 10 and 11). Meanwhile, the journal analysis and co-citation analysis of the bibliometric data confirmed that litter's effect on the carbon cycle is a research hotspot in today's scientific community, further emphasizing the importance and necessity of this field (Figs 8 and 9). Against the background of global warming and increasing nitrogen deposition, exploring the mechanisms and key factors driving the regulation of carbon cycling from litter is crucial for maintaining ecosystem stability. In most terrestrial ecosystems, soil carbon stocks are three times higher than plant carbon stocks, especially in alpine meadows that exhibit perennial low temperatures [65]. Meanwhile, litter decomposition affects soil microbial biomass and community characteristics, and both its quality and quantity affect soil nutrients, enzyme activities, and consequently soil respiration and CO_2 emissions [66, 67].

Through bibliometric keyword analysis and keyword time co-occurrence analysis, it was found that the current research hotspots were mainly concentrated in the fields of "enzyme activity" and "organic carbon storage", and so on (Figs 10 and 11). Enzyme activity is a key regulatory factor in litter decomposition and the carbon cycle. β-glucosidase directly determines the degradation efficiency of cellulose and lignin in litter. Studies have shown that tree litter significantly accelerates carbon decomposition (with CO_2 emissions increasing by 130-210%) by enhancing β-glucosidase activity (310% higher than the control group). This mechanism is directly linked to the theoretical principle that "enzyme reaction rates determine carbon release fluxes" in the carbon cycle [68]. Additionally, the quantitative relationship between enzyme activity and the carbon cycle confirms that enzyme activity is a key variable linking the chemical properties of litter to the carbon cycle [69]. The composition and activity of microbial communities are key factors determining the potential for soil carbon storage [70]. Studies have shown that soil microbial communities play a role in the global carbon cycle, including decomposition, mineralization, and carbon sequestration [71]. To explore these research hotspots more deeply, 62 independent studies were identified for meta-analysis by further screening the literature based on bibliometric analysis. Specific values were used to quantify the specific effects of litter on key indicators related to the carbon cycle, such as BG, SOC, and MBC. The results showed that litter matter had significant effects on soil total nitrogen, soil respiration, soil organic carbon, soil moisture, soil pH, and βG had significant effects ($P<0.01$), and no significant effect on MBC in Fig. 12 ($P<0.05$). This is inconsistent with the results of existing studies [72]. It may be due to the differences in research design, sample selection, and environmental conditions of the researchers, which led to the inconsistency of their results. Research has shown that adding litter increases cellulase activity (25%), indicating that easily decomposable carbon sources, such as monosaccharides, promote microbial decomposition of recalcitrant organic matter (e.g., lignin) through a "synergistic metabolism" mechanism, resulting in a positive feedback effect [73]. Litter input triggers a negative feedback effect, as soil microorganisms prioritize the utilization of fresh carbon sources, reducing the decomposition of existing SOC [74]. Simultaneously, litter input alleviates phosphorus limitation. Litter decomposition releases phosphorus, promoting plant growth and indirectly increasing SOC input [75]. Differences between ecosystems may be attributed to (1) climatic factors (temperature and humidity: grasslands receive less precipitation, have weaker leaching, and better organic matter preservation; forests receive more precipitation, and leaching leads to SOC loss) [76], (2) vegetation type (in grassland ecosystems, herbaceous plants have shallow roots and are prone to death, with organic matter concentrated in the surface layer, resulting in high SOC accumulation. In forest ecosystems, woody plants have deep root systems and long survival periods, with organic matter primarily stored within the plants, resulting in lower SOC in the soil [77]), and (3) soil texture also plays a role [78]. Thus, follow-up studies should include indoor experiments related to litter to ensure sufficient sample size and to develop accurate and scientific screening criteria, which will help further develop subgroup analyses to discuss in detail the mechanisms of litter's impact on the carbon cycle within a single ecosystem. Meanwhile, we should also take into account the fact that the regulation mechanism of the carbon cycle by withered matter is disturbed by climate change, and the indirect effect of statistical methods on withered matter in meta-analysis can help to improve the reliability of meta-analysis. The decomposition of litter releases nutrients such as nitrogen, phosphorus, and potassium, which are essential for plant growth. An adequate supply of nutrients promotes photosynthesis and growth and increases plant biomass and carbon storage. Meanwhile, litter matter is one of the important sources of carbon input. When the input of litter matter increases, more organic carbon enters the soil and increases soil carbon storage. For example, in the process of vegetation restoration after deforestation, with the growth of vegetation and the accumulation of litter matter, the soil organic carbon content will gradually increase [79]. In the degradation of grassland, the productivity of vegetation decreases, the litter matter of vegetation decreases, and the source of carbon entering the soil decreases, resulting in a decrease in the soil carbon pool. Nonetheless, different estimation methods lead to different results for plant carbon pool estimates [80]. Therefore, follow-up studies should combine field sampling with indoor analysis and modeling predictions for calculating the effects of litter inputs on plant or soil carbon pools.

In ecology, a trade-off is the phenomenon of individual plants or plants and soil making trade-offs between different functions or nutrients in the allocation of limited resources [62]. The trade-offs between plant-soil and above- and belowground carbon pools contribute to understanding the transfer of carbon between plants and soils in specific grassland ecosystems under climate change. The storage of carbon in above- and below-ground plant fractions can explain plant nutrient competition and nutrient partitioning strategies regulated by environmental factors. Nevertheless, terrestrial grassland ecosystems include many types, and the carbon cycle is extremely complex. Understanding the flow, turnover, and storage of carbon among plants, soils, and microorganisms can help reveal the mechanisms of the carbon cycle in grassland ecosystems.

Shortcomings of the Study

Since this study is the first combination of bibliometric analysis and meta-analysis on the literature related to the study of litter affecting the carbon cycle, there are some limitations to this study. First of all, a single WOS database search may lead to the omission of articles related to the study of litter affecting the carbon cycle. Existing research results indicate that the number of documents retrieved, and disciplinary differences can influence research outcomes. Scopus retrieves 32% more documents than WOS and includes a greater number of non-English journals and conference papers [81]. WOS provides more comprehensive coverage in the natural sciences. The proportion of literature by European and Asian scholars in Scopus is 15% higher than in WOS, while the proportion of literature by American scholars is higher in WOS [82]. This study belongs to the field of natural sciences, so WOS is the preferred database. Secondly, low-frequency words were not analyzed in this study. According to Zipf's law, some low-frequency words cannot be excluded as potential future research hotspots [83]. Third, the search strategy relies on relevant topic terms appearing (not keywords, abstracts, etc.), so some well-known classic articles may have been excluded. Finally, the data of meta-analysis were based on the results of bibliometric analysis, and the differences in sample size and statistical methods of meta-analysis led to an incomplete assessment of the impact of litter on the carbon cycle in this study.

Follow-up studies should pay attention to (1) discussing the effect of different databases and search strategies on the bibliometric results (e.g., China Knowledge, PubMed, Scopus, and other databases) to reduce possible incomplete database coverage or search bias. Meanwhile, the papers related to the DIRT project can be analyzed as an important dataset [84, 85]. (2) Meta-analysis was treated as a key focus based on bibliometric analysis. Meta-analysis should set stricter inclusion and exclusion criteria to ensure the accuracy and reliability of the study. (3) To avoid excluding critical indicators (such as urease, CO_2 flux, and other related indicators) due to the insufficient sample size in this study, future studies should incorporate indoor experiments related to litter into the criteria to ensure the representativeness and diversity of the samples. Subgroup analyses should also be carried out to systematically explore the effect of litter on the carbon cycle and clarify the response mechanisms of the carbon cycle to litter in different ecosystems. (4) Reasonable selection of analysis software and statistical methods. This study used the software R4.4.1 for meta-analysis, which is different from Review Manager 5.3 and STATA 12.0 [20]. The effect values of meta-analysis and weighted response ratios also differed in the assessment of the study. (5) Environmental factors (latitude, longitude, altitude) and climatic factors (temperature, moisture, atmospheric CO_2) should be taken as explanatory variables [54], and a linear mixed-effects model should be constructed to comprehensively reveal the influence of withered crops on the carbon cycle. (6) The trade-off of carbon pools between plant-soil and plant-above and below-ground helps to understand the dynamics of carbon pools in specific grassland ecosystems in the context of climate change, as well as the transfer and storage of carbon pools in the process of carbon cycling. (7) Follow-up studies should further explore the carbon cycle characteristics, microbial community changes, and ecological service function responses of different types of grassland ecosystems under litter inputs, and combine indoor simulation experiments and model simulations to comprehensively reveal the regulatory mechanisms of different types of grassland ecosystems in response to litter inputs.

Conclusions

The carbon cycle is a hot research topic in ecological studies, and the effect of litter on the carbon cycle helps us understand the flow, turnover, and cycling of carbon among plants, soil, microbes, and the atmosphere. In this study, the VOSviewer bibliometric tool, supplemented with Scimago Graphica and Pajek software, was used to conduct a systematic network mapping analysis of literature related to studies on litter effects on the carbon cycle published from 1990 to 2023. These analyses were conducted from different perspectives. Publication trends, literature exchange, development trends, and influential countries, institutions, authors, journals, and highly cited references were identified and discussed. Research advances, hotspots, and frontiers in litter affecting carbon cycling were sorted and categorized. The results of the study indicate that the annual number of publications on litter affecting the soil carbon cycle has grown exponentially. The United States contributes the most publications in this field, followed by China, Germany, and the United Kingdom. The Chinese Academy of Sciences is the most productive institution, and Yiqi Luo is the most active scholar. *Soil Biol. Biochem.*, *Glob. Chang. Biol.*, and *Ecology* are the top three core journals in the field. With the development and maturity of the research, the popular keywords have shifted from “litter mass”, “lignin”, “litter decomposition process”, and “factors affecting litter decomposition”, to “plant community”, “soil nutrient dynamics”, and gradually to “enzyme activity”, “microbial community”, “bacteria”, “rhizosphere”, “soil temperature sensitivity”, “carbon storage”, “Loess Plateau”, “carbon stability”, and “organic carbon turnover”. These changes in keywords reflect the evolution of the research focus on the impact of litter on the carbon cycle. With global climate change and serious deterioration of the ecological environment leading to frequent ecological problems, domestic and foreign governments, researchers, and environmentalists have begun to consider human interventions to improve carbon cycling in the context of environmental change. Therefore, “microbial biomass”, “nitrogen mineralization”, “CO_2 flux”, “forest soil”, “global climate”, and “microbial community characteristics” have become new emerging keywords. Understanding the progress of research on litter affecting the carbon cycle and its mechanisms can help predict and respond to the current challenges of global environmental protection faced by the world today.

This study has sorted and categorized research on litter affecting the carbon cycle over the past 33 years, and such studies have gradually received more attention. Nevertheless, the following points need to be strengthened for a better understanding of research on litter and the carbon cycle. Finally, at both international and domestic levels, connections between leading authors, research institutions, countries, and disciplines should be strengthened. It is recommended that Chinese scholars collaborate with high-output countries such as the United States and Germany to conduct long-term observations of the carbon cycle mechanisms in alpine meadows, in order to strengthen academic cooperation and exchange. Secondly, advanced technological tools can compensate for the shortcomings of current research and promote the innovation of theories and methods. Recommendations for future work include utilizing molecular tools and isotope labeling techniques to explore research priorities and challenges in this field, with a view to elucidating the mechanisms by which litter influences the carbon cycle and revealing novel links between plant carbon strategies and biogeochemical cycles. Exploring the key mechanisms of multi-process coupling, multi-factor regulation, and multi-scale effects of soil microbial-vegetation relationships can help gain insights into the impact of litter on the carbon cycle [86]. Meta-analysis showed that litter had a significant positive effect on soil total nitrogen, soil respiration, soil organic carbon, soil moisture, soil pH, and βG. Considering different climate zones and grassland types, the following measures can be taken: in the restoration of degraded grasslands, prioritize the “rotational grazing + reseeding with suitable species” model, accompanied by incentive mechanisms and the establishment of an “ecological migration + wetland restoration” linkage mechanism. Explore the coupling of carbon sink projects with ecological compensation, address the issue of low temperatures limiting microbial activity in the alpine meadows of the Qinghai-Tibet Plateau, and propose a “winter grazing ban + engineering soil stabilization” policy. In conclusion, to provide a more objective and comprehensive scientific analysis of the literature, innovation in research methodology should be a key focus in the future.

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Conflict of Interest

The authors declare no conflict of interest.

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