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Global Trends in Conservation Agriculture and Climate Change Research: A Bibliometric Analysis

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Abstract: This study provides a bibliometric analysis of global scientific production on Conservation Agriculture (CA) and its relationship with climate change mitigation. Using data from the Scopus and Web of Science databases, the research encompassed 650 articles published between 1995 and 2022. The analysis revealed significant growth in the number of publications over the past three decades, driven by increasing global interest in sustainable agricultural practices. The findings highlight key themes, including no-tillage, soil organic carbon, and greenhouse gas emissions. Collaboration networks were mapped, identifying major contributors, such as the USA, Brazil, and China, alongside thematic clusters emphasizing carbon sequestration and soil management. Results indicate that CA research is increasingly focused on its potential to mitigate climate change, particularly through practices like no-tillage, vegetative cover, and crop rotation. While carbon sequestration has been central to CA research, recent studies have expanded to include nitrous oxide and methane emissions, indicating a broadening conceptual framework. This analysis underscores the importance of CA in addressing climate challenges and offers insights into emerging research areas, such as regional adaptations and the long-term effects of no-till systems. The findings aim to guide future research and policy development in sustainable agriculture and climate mitigation.

Keywords: no-tillage; global warming; soil organic carbon; CO_2; greenhouse gas emissions; bibliometric analysis

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1. Introduction

Climate change poses a significant contemporary challenge, with profound implications for both current and future generations. Of particular concern are greenhouse gas (GHG) emissions, including carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). A robust body of scientific evidence underscores the potential of Conservation Agriculture (CA) to mitigate the adverse effects of climate change, notably through the sequestration of carbon in vegetation and soil [1–3].

To align with national and regional targets for reducing greenhouse gas (GHG) emissions and increasing carbon sequestration, Conservation Agriculture (CA) can serve as a pivotal strategy for meeting these ambitious goals. By maintaining a permanent soil cover, minimizing soil disturbance, and promoting crop diversification, CA enhances soil health and resilience, contributing to both environmental protection and climate action [4]. This approach directly supports the European Union's climate and environmental objectives outlined in the Common Agricultural Policy (CAP) 2020–2027, particularly in the areas of biodiversity conservation and sustainable land management. Moreover, by reducing emissions of potent GHGs such as methane (CH_4) and nitrous oxide (N_2O) through improved soil management and reduced synthetic inputs, CA not only facilitates carbon sequestration but also offers a holistic framework for climate change adaptation and mitigation.

Originating in the United States following the Dust Bowl crisis of the 1930s and 1940s, which was characterized by widespread soil erosion and agricultural devastation across the American Great Plains, CA emerged as a response, prompting a paradigm shift towards farming practices that prioritize soil health, minimize soil disturbance, and enhance long-term ecological resilience. CA witnessed significant research and development between 1945 and 1960 [5]. During this period, universities and agricultural departments dedicated efforts to conduct extensive research to prevent soil erosion. The studies gained momentum with the discovery of herbicides capable of effectively controlling weeds while preserving straw over the soil. Additionally, the development of the M-21 seeder further contributed to advancements in CA [6]. According to this author, research in Europe progressed more gradually under the term 'direct seeding' only after 1960.

In the USA, soybean direct seeding gained limited acceptance until after 1970, after which it gradually expanded to other countries, notably Argentina and Brazil. These countries embraced the system extensively, ultimately becoming global leaders with the largest areas under CA cultivation., as reported by [1]. Similarly, no-tillage and mulching practices were tested in West Africa during the 1970s [7,8].

According to [3], cropping systems representing maximum biomass production and eventually returning it to the soil with reduced soil disturbance are crucial for enhancing aggregate stability and soil organic carbon (SOC) levels. Increasing SOC storage can mitigate atmospheric CO_2 concentrations while improving soil functions, and the SOC benefits of cover cropping or diverse crop rotation were higher with CA than with conventional tillage systems.

In the context of climate change, considerable research has been dedicated to carbon farming and CA, aiming to understand how these agricultural practices can specifically contribute to mitigating GHGs and reducing the impact of climate change to some extent. Some successful examples on CA implementation and its relation to GHG mitigation can be found in its extensive adoption in Brazil, where extensive adoption of no-till farming in Brazil has led to significant carbon sequestration in agricultural soils, contributing to GHG mitigation. In Europe, the LIFE Agromitiga project (www.agromitiga.eu, accessed on 11 January 2025) has demonstrated how CA can be effective not only for carbon sequestration in the soil, but also for less energy consumption, which leads to fewer CO_2 emissions.

Due to their substantial importance, the number of academic publications on these topics is rapidly increasing, making it challenging to stay abreast of the latest developments. In this context, bibliometric analysis proves to be a valuable tool, encompassing a set of methods employed to study or measure texts and information, especially within extensive datasets [9].

While various approaches, such as agroforestry, integrated crop–livestock systems, and organic farming, contribute to addressing agriculturally derived climate change, CA was selected for this detailed bibliometric analysis due to its growing global adoption [1] and the substantial body of scientific literature highlighting its potential for carbon sequestration and climate mitigation. This focused analysis provides deeper insights into the research trends, gaps, and opportunities specific to CA.

This article was developed with the objective of conducting a bibliometric study on CA and soil carbon to identify key themes, influential authors, pivotal publications, and leading countries in the field in recent years. Moreover, it seeks to illuminate emerging areas of research and to forecast future developments, thereby fostering international and interdisciplinary collaboration and bridging regional research gaps. It should be noted that further research could encompass methane (CH_4) and nitrous oxide (N_2O) emissions within a CA framework, particularly given the emerging significance of N_2O emissions from agriculture.

2. Materials and Methods

To address the research question 'Is Conservation Agriculture a viable strategy for mitigating climate change, supported by sufficient scientific evidence?', a systematic search process was initiated. The question was formulated to guide the investigation. Subsequently, a thesaurus-based approach was employed to identify comprehensive synonym sets related to the key terms associated with CA and climate change. For instance, terms aligned with FAO's Conservation Agriculture principles [4] were accepted, while other practices were not considered. As an example, some authors consider minimum or reduced tillage as part of CA practices, whereas FAO does not. Therefore, those terms were not considered in this study.

For the design of this framework, the PICO strategy outlined by the National Institute for Health and Care Excellence was followed [10]. The PICO acronym consists of the following parameters: Population (P), Intervention (I), Comparison, Control or Comparator (C), and Outcome (O). In our case, each of these parameters was defined as follows:

- P: Agricultural ecosystems with extensive herbaceous crops.
- I: No-till (direct seeding).
- C: Conventional management system.
- O: Reduction in greenhouse gas emissions and increase in soil carbon.

Based on this, a search string was formulated using the terms outlined in Table 1. The authors are aware that the language of the articles can introduce a bias by restricting the inclusion of some relevant studies, potentially over-representing research conducted in English or within specific academic disciplines. This can lead to skewed results and hinder the generalizability of the findings.

This thorough selection of terms aimed to encompass the diverse facets of CA and its impact on reducing climate change. The search encompassed two widely recognized databases, Web of Science (WoS) and Scopus. The inclusion criteria were limited to articles published in journals positioned within the Q1 and Q2 quartiles based on their impact factors, ensuring the inclusion of high-quality information. In this study, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol was applied, involving key steps, such as identification, screening, and inclusion, as depicted in Figure 1. A total of 3101 articles were initially identified in January 2023. To ensure the integrity of the dataset, a careful filtering process was applied to eliminate duplicates. In cases where articles appeared in both Scopus and WoS, precedence was given to the data from WoS, which emerged as the primary source hosting the majority of research papers. This meticulous approach ensured the reliability and coherence of the dataset, forming the basis for subsequent analyses and responses to the research question. Following the removal of duplicate papers, a total of 2113 unique articles remained.

Table 1. Terms and logical operators used in the search string employed in the Scopus and Web of Knowledge databases. The asterisk represents a wildcard symbol that expands the search to include words beginning with the same letters. Source: own compilation.

	Terms Related to No-Till/Direct Seeding	**Terms Related to Climate Change**
Operator used between terms of the same group: "OR"	No till * No-till * Zero till * Zero-till * Direct drill * Direct seed * Direct sow * Conservation agriculture Conservation till *	Climate change Cabon dioxide fixation Carbon dioxide sequestration CO_2 fixation CO_2 sequestration Carbon sequestration C sequestration Carbon fixation C fixation Carbon sink * C sink * Greenhouses emission * GHG emission * Carbon dioxide emission * CO_2 emission * Nitrous oxide emission * N_2O emission * Methane emission * CH_4 emission *
	Operator used between terms of different groups: "AND"	

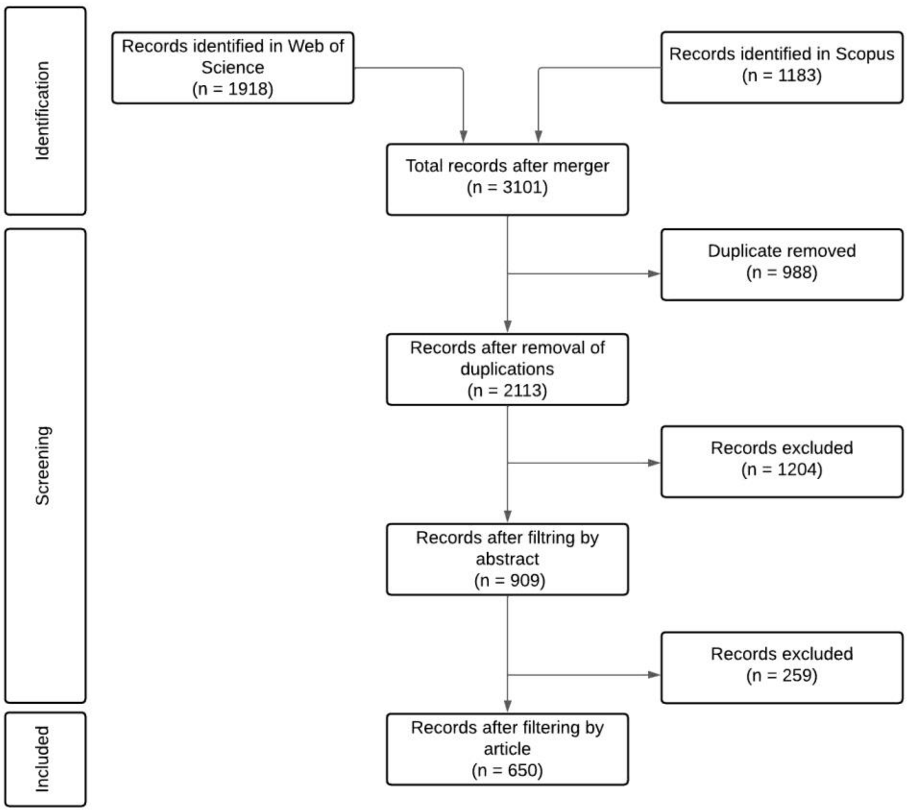


Figure 1. Data collection flow diagram. Source: own compilation.

Subsequently, these papers underwent a meticulous screening process based on their abstracts, aligning with predefined eligibility criteria as follows:

- CA practices considered: Simultaneous application of the three principles of CA (no-tillage, vegetative cover, and crop rotation). Articles that mention no-till but do not include the practice of any of these three principles were excluded.
- Study types: Only those studies focusing on climate change mitigation in agroecosystems involving CA practices and compared with those that do not apply them, regardless of other mitigation strategies used (nitrification inhibitors, precision agriculture, etc.), were included. There were no language restrictions, and studies were not excluded based on the publication date.
- Studies focusing on CA but lacking an evaluation of soil carbon or effectiveness in reducing emissions of CO_2, N_2O, and CH_4 were also excluded.
- The scientific literature was included up to the year 2022. The year 2023 was excluded as this research was conducted before its completion.

After abstract-based filtering, 1204 records were excluded from the dataset. A detailed analysis was then conducted at the article level, involving a thorough reading of each article to select the final set for inclusion in the study according to the eligibility criteria cited. Ultimately, 650 papers met the criteria and were included for further analysis. This rigorous process ensured the inclusion of relevant and high-quality research, aligning closely with the study's objectives and criteria.

After collecting and selecting the 650 articles, they were subjected to bibliometric analysis using the Bibliometrix R-tool [11]. This analytical approach was applied to two merged databases to facilitate a comprehensive examination of the selected literature.

To enhance our understanding of the development of themes over time, we segmented the analysis into three distinct periods. The initial period spans from the publication of the first article until 2002. Subsequently, we divided the succeeding years into two 10-year intervals: the second period covering 2003–2012, and the third period spanning 2013–2022. It is important to emphasize that these sub-periods were used solely to examine the thematic evolution. These analyses incorporated both keywords and author's keywords to provide comprehensive insights into the temporal evolution of themes. The period pre-2002 laid the groundwork for subsequent policy discussions and initiatives on climate change and agriculture. The 2003–2012 period reflects the influence of early climate policies on research and the development of CA practices, whereas 2013–2022 reflects a more scaled-up implementation of climate-smart agricultural practices and research interest in agriculture related to global warming. The entire period (1995–2022) was employed for the other analyses, including co-citation networks at the author, source, and reference levels. Additionally, it was used for examining collaboration networks at the author and country levels, annual scientific production, sources' production over time, the most collaborative countries, authors' production over time, the top 10 authors' production over time, scientific production by source, the most relevant documents, Keywords Plus over time, and the most relevant keywords. The details of these analyses are provided in Table 2.

In order to represent the co-citation and collaboration networks associated with each level of analysis, the graphs were characterized according to Table 3.

Table 2. Specifications of the analysis. Author keywords (DE) = keywords defined by the authors; Keywords Plus (ID) = keywords designated by the WoS or Scopus databases. Source: own compilation based on [11].

Level of Analysis	Metrics	Unit of Analysis	Bibliometric Technique	Statistical Technique	Structure
Author	Most productive authors and Annual production per author Most collaborative countries	Authors	Co-citation and collaboration Collaboration		Intellectual and social Social
Document	Most-cited documents Most frequent author keywords (DE) Most frequent Keywords Plus (ID)	References Author keywords (DE) and Keywords Plus (ID)	Co-citation Co-words	Network Network thematic mapping and Thematic evolution	Intellectual Conceptual
Source	Source dynamics Most productive source	Journal	Co-citation	Network	Conceptual

Table 3. Specification of co-citation and collaboration networks. Source: own compilation.

Network	Co-Citation			Collaboration	
	Source	Authors	References	Authors	Country
Clustering	Walktrap	Walktrap	Walktrap	Walktrap	Waltrap
Nodes	50	60	50	50	60
Min. edge	2	2	2	2	1
N. labels	500	500	1000	1000	1000
Cluster layout	Automatic	Automatic	Automatic	Automatic	Automatic

Min. edge: this indicates the min frequency of edges between two vertices. N. labels: this indicates how many labels associate with each cluster.

3. Results and Discussion

3.1. Main Information

Although Conservation Agriculture has been a significant topic for soil conservation since the first half of the 20th century, with considerable efforts toward its development during that period, it was not until the late 20th century that CA and climate change gained widespread popularity and research on the subject intensified. As a result, the earliest article identified in this search was published in 1995. Accordingly, our research covers articles published between 1995 and 2022. To enhance comprehension, the results were divided into three periods: the first period from 1995 to 2002, followed by ten-year intervals, resulting in a second period from 2003 to 2012 and a third period from 2013 to 2022.

The analysis of the entire period revealed 650 papers published across 69 different sources. During the initial period, research activity was limited, with only eight papers published. However, research efforts expanded significantly after 2002, with the number of documents increasing fivefold during the second period (Figure 2).

To provide context that may explain some of the turning points, the major international agreements on climate change were signed in the following years:

- United Nations Framework Convention on Climate Change, UNFCC (1992). Signed at the Earth Summit in Rio de Janeiro, it established a framework for global efforts to combat climate change.
- Kyoto Protocol (1997). Adopted in Kyoto, Japan, it was the first international treaty to set binding emission reduction targets for industrialized countries.

- Paris Agreement (2015). Adopted during the 21st Conference of the Parties (COP21) in Paris, it aims to limit global warming to well below 2 °C above pre-industrial levels, with efforts to limit the increase to 1.5 °C.

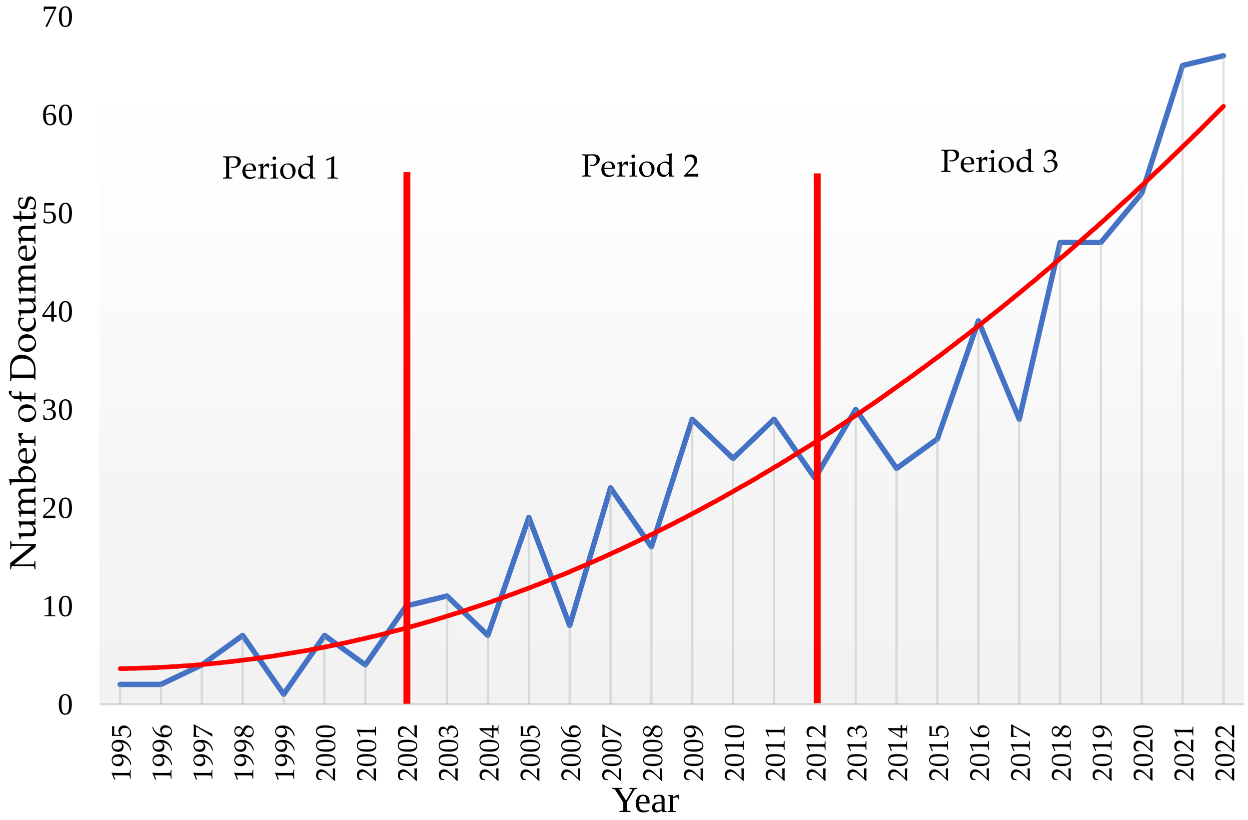


Figure 2. Annual scientific production total period. Source: own compilation.

As mentioned, the Kyoto Protocol played a pivotal role in shaping this trend. The protocol committed industrialized countries and economies in transition to limit and reduce GHG emissions in accordance with agreed individual targets. This heightened global focus on sustainability prompted many countries to explore carbon sequestration, particularly through soil organic carbon. Consequently, the scientific research in this area experienced a notable uptick after 2002, driven in part by the impetus provided by the Kyoto Protocol. It is crucial to acknowledge that scientific research within this domain necessitates substantial temporal and financial resources owing to the inherent complexity of the experimental methodologies. For instance, long-term field trials investigating no-tillage agricultural practices have been conducted continuously since the 1980s [12–14].

The exponential growth in the number of papers published, particularly evident from 2002 onwards and further amplified in the third period, can be attributed to the increasing importance of this topic considering the accelerating reality of climate change. As awareness of environmental challenges has grown, so too has the urgency to address them, leading to a surge in research output on CA and related topics. Alongside the exponential growth in papers, there has also been a corresponding increase in the number of sources publishing research in this area. The number of authors involved in research on CA has also significantly increased, almost tripling from the second to the third period (Table 4).

Table 4. Main information per period and total. Author keywords (the frequency distribution of authors' keywords, DE) and Keywords Plus (the frequency distribution of keywords associated with the manuscript by SCOPUS and Thomson Reuters' ISI Web of Knowledge databases, ID). Source: own compilation.

Description	Period 1 (1995–2002)	Period 2 (2003–2012)	Period 3 (2013–2022)	Total (1995–2022)
Main information about data				
Sources (Journals, Books, etc.)	8	35	58	69
Documents	37	188	425	650
Annual Growth Rate (%)	25.85	8.54	9.16	13.83
Document Average Age	24.6	15.6	5.59	9.56
Average Citations Per Doc	157.9	84.74	32.89	55.01
References	1064	5993	16,513	21,598
Publications/Year	4.62	18.8	42.5	23.2
Document contents				
Keywords Plus (ID)	198	765	1348	1754
Author Keywords (DE)	125	503	1118	1468
Authors				
Authors	126	666	1876	2493
Authors of Single-Authored Docs	0	3	0	3
Author Collaboration				
Single-Authored Docs	0	3	0	3
Co-Authors Per Doc	3.84	4.71	6.44	5.79
International Co-Authorships (%)	8.11	28.19	37.65	33.23

To summarize the main results of the bibliometric analysis, a generic function summary was used in [11]. This function provides key information about the bibliographic data frame and generates several tables, including annual scientific production, top manuscripts by number of citations, most productive authors, most productive countries, total citations per country, most relevant sources (journals), and most relevant keywords.

The main information table (Table 4) outlines the size of the collection in terms of the number of documents, authors, sources, keywords, the time span covered, and the average number of citations. The number of sources has increased over time, as well as the number of documents published. The annual growth rate of the scientific production in percentages is also shown and calculated as a compound annual growth rate, which represents the smoothed average annual growth rate over the entire period. Additionally, various co-authorship indices are presented. Specifically, the authors per article index is calculated as the ratio of the total number of authors to the total number of articles. Full information on the methodology can be found in [11].

3.2. Sources

Analysis reveals that *Soil and Tillage Research*, a journal dedicated to investigating the physical, chemical, and biological alterations in soil induced by tillage and field traffic, constitutes 29.54% of the publications across the entire study period. Notably, it emerged as the most prolific source since the inception of the research, establishing itself as the primary publication outlet within this scientific domain. *Agriculture, Ecosystems & Environment* follows, contributing 12.77% of the publications and maintaining a presence since the initial period. *Science of the Total Environment* demonstrated a significant increase in both publication output and total citations over the past decade (Figure 3).

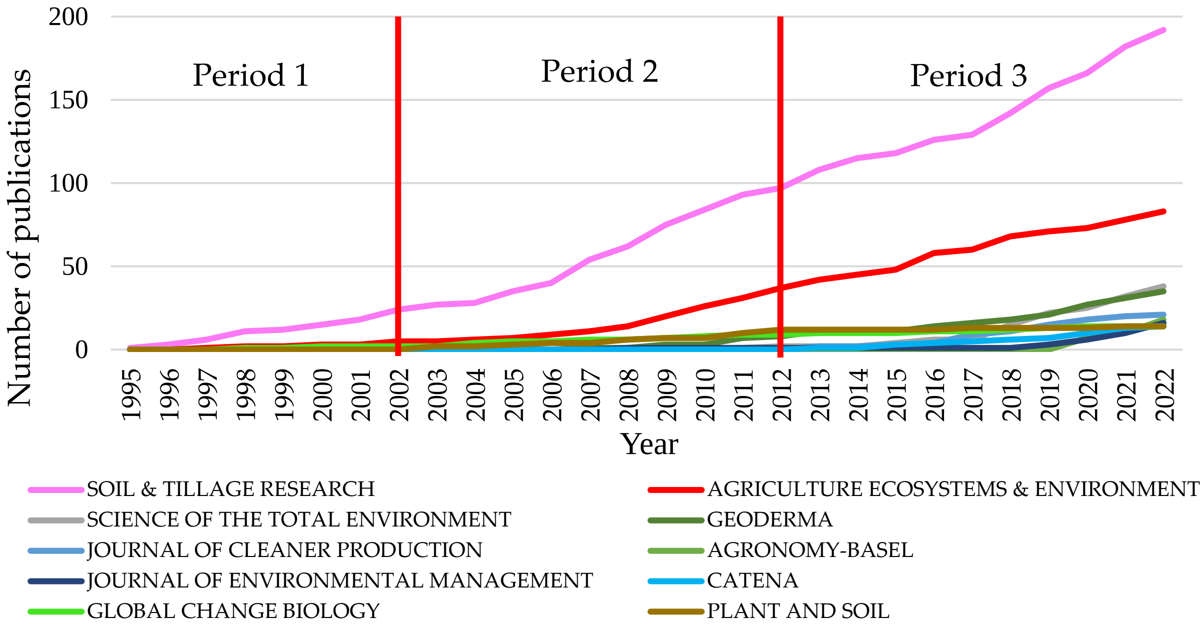


Figure 3. Sources' production over the time. Source: own compilation.

With regard to the total number of citations (TC) *Soil and Tillage Research* is the most-cited source, followed by *Agriculture Ecosystems & Environment*, *Global Change Biology*, and *Science of the Total Environment* (Table 5).

Table 5. Scientific production by source. Source: own compilation.

Ranking	Source	Publication	h_Index	Total Citations	Co-Citation Cluster
1	*Soil and Tillage Research*	192	70	13,335	2
2	*Agriculture Ecosystems & Environment*	83	44	6322	2
3	*Science of The Total Environment*	38	20	1083	1
4	*Geoderma*	35	20	991	2
5	*Journal of Cleaner Production*	21	18	875	1
6	*Global Change Biology*	14	14	2355	2
7	*Plant And Soil*	14	13	695	2
8	*Soil Biology and Biochemistry*	13	12	759	2
9	*Catena*	14	10	535	2
10	*Land Degradation & Development*	13	10	581	2

Analysis of the source co-citation network reveals two distinct clusters: Cluster 1, visually represented by red, and Cluster 2, represented by blue (Figure 4). Cluster 1 incorporates two of the top ten sources, namely the *Journal of Cleaner Production* and *Science of the Total Environment*. The latter journal also stands out among the most frequently cited sources and has demonstrated a notable increase in significance within the most recent research period. Cluster 2 encompasses a substantial portion of the published literature and includes the eight most influential sources. Notably, sources situated at the periphery of each cluster exhibit diminished co-citation relationships with sources within the opposing cluster. The size of the node label corresponds to the degree of interaction. Intra-cluster relationships are visually depicted by lines matching the respective cluster color, while inter-cluster relationships are represented in gray.

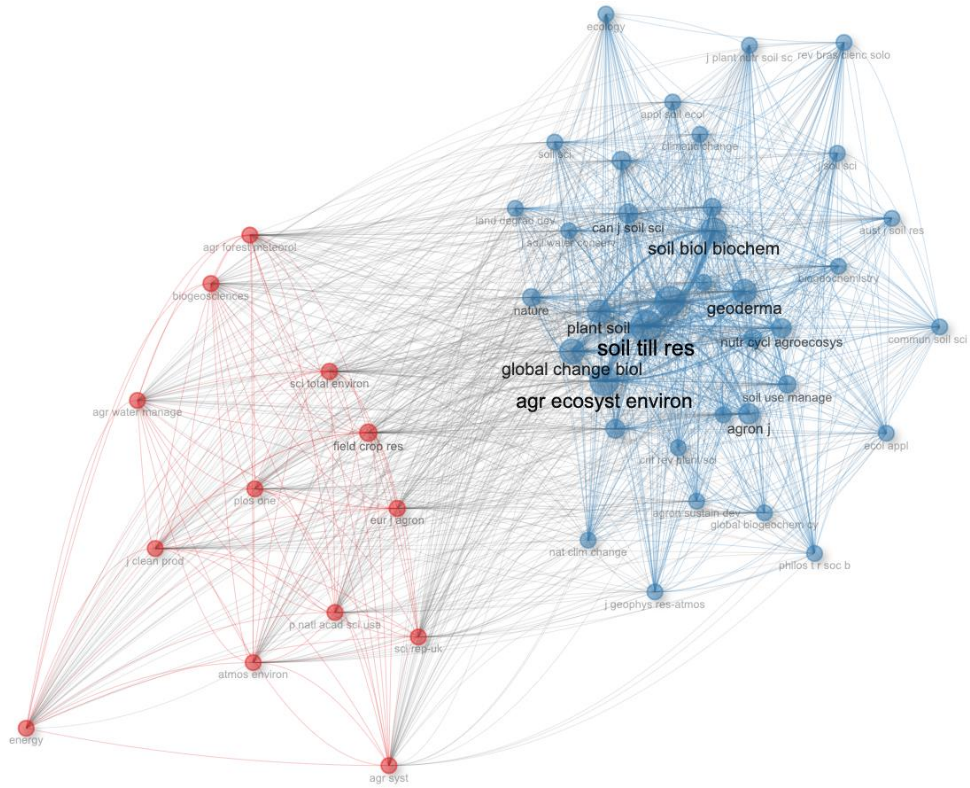


Figure 4. Co-citation of sources. Source: own compilation.

3.3. Authors

An analysis of authorship within the studied scientific field provides valuable insights into its social and intellectual structure. Concerning the social structure, bibliometric analysis enables the identification of collaborative networks among authors and the mapping of relationships between the countries where their affiliated institutions are located. Conversely, data pertaining to author productivity and co-citation relationships within individual documents offer valuable information regarding the intellectual structure of the field.

In addition to the observed increase in the number of sources, the number of authors also exhibited a significant upward trend, rising from 126 in the initial period to 1876 in the third period, resulting in a total of 2480 authors across all periods. A concurrent increase in collaborative research activities was evident, with the average number of co-authors per document rising from 3.84 in the first period to 6.44 in the third period. Furthermore, international collaboration within these author networks is evident, with international co-authorship rates observed at 8.11%, 28.19%, and 37.65% in the respective periods.

Regarding international collaboration, the country collaboration network depicted in Figure 5 reveals several distinct clusters. Three major clusters (red, blue, and green) and one smaller cluster (purple) were identified, along with individual countries exhibiting collaborative relationships with one or more other nations.

The most prominent collaborations involve the USA, which exhibits significant ties with both China and Brazil, as evident from the density of the connecting lines. The USA is situated within the red cluster, where it shares space with many European countries such as Germany, Spain, and Italy. These European nations not only collaborate extensively among themselves but also engage in partnerships with countries from other clusters.

China, also part of the red cluster, maintains substantial collaboration with the USA, as previously noted. Additionally, it connects to the blue cluster, which comprises other Asian countries including India, Pakistan, and Nepal, as well as Oceanian countries like Australia and New Zealand.

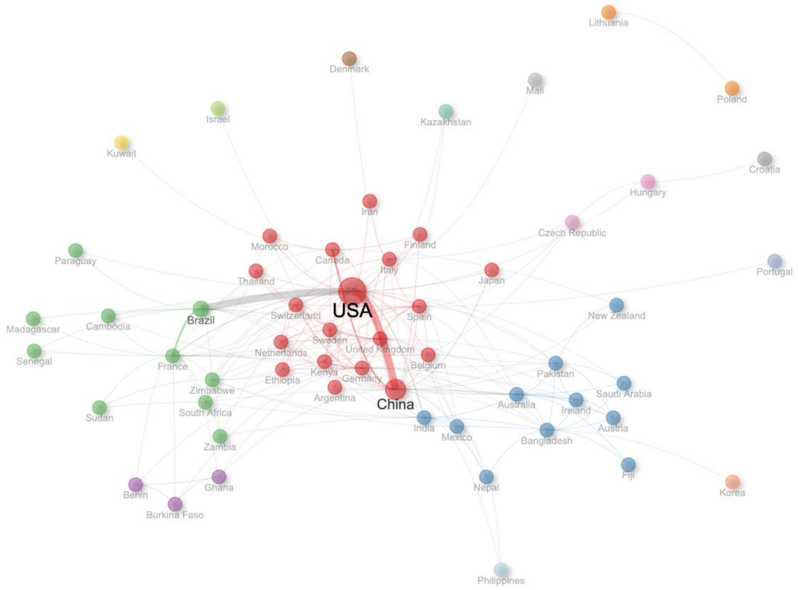


Figure 5. Country collaboration network. Source: own compilation.

In contrast, the green cluster displays lower levels of collaboration compared to the red cluster. Included in the green cluster are Brazil and Paraguay from South America, but most of the countries in this cluster are African, such as South Africa, Zimbabwe, and Senegal. This cluster shares similarities with the smaller purple cluster, which encompasses African nations like Ghana, Burkina Faso, and Benin. Bordering countries in the network exhibit limited collaboration with others. For instance, Lithuania and Poland collaborate solely with each other, without engaging with any other countries in the network.

Corroborating the findings from the country collaboration network, Figure 6 illustrates the geographical distribution of publications. While the USA emerges as the most prolific country in terms of publication output, China stands out for its significant number of multi-country publications, followed by Brazil and India. These countries, all of which are classified as developing nations, hold significant importance within the agricultural sector and are experiencing notable growth in scientific research within this field.

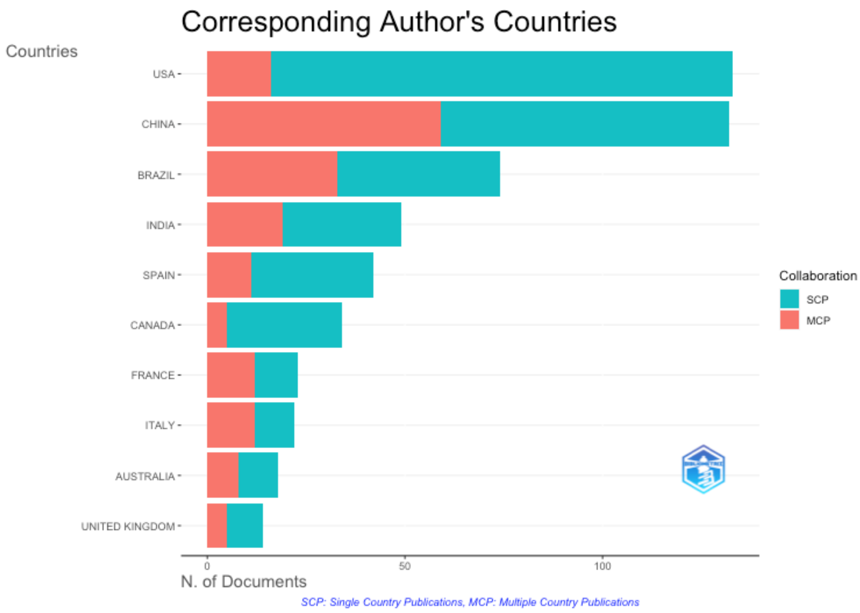


Figure 6. Most collaborative countries. MCP—multi-country publication. SCP—singular country publication. Source: own compilation.

Social structure shows how authors or institutions relate to others in the field of scientific research, indicating groups of regular authors and influent authors [15]. As depicted in Figure 7, our analysis of the author collaboration network revealed 14 primary clusters, with 4 key interconnected clusters identified and enumerated as 1, 2, 3, and 4. Cluster 1 emerges as the largest, with connections to five smaller clusters.

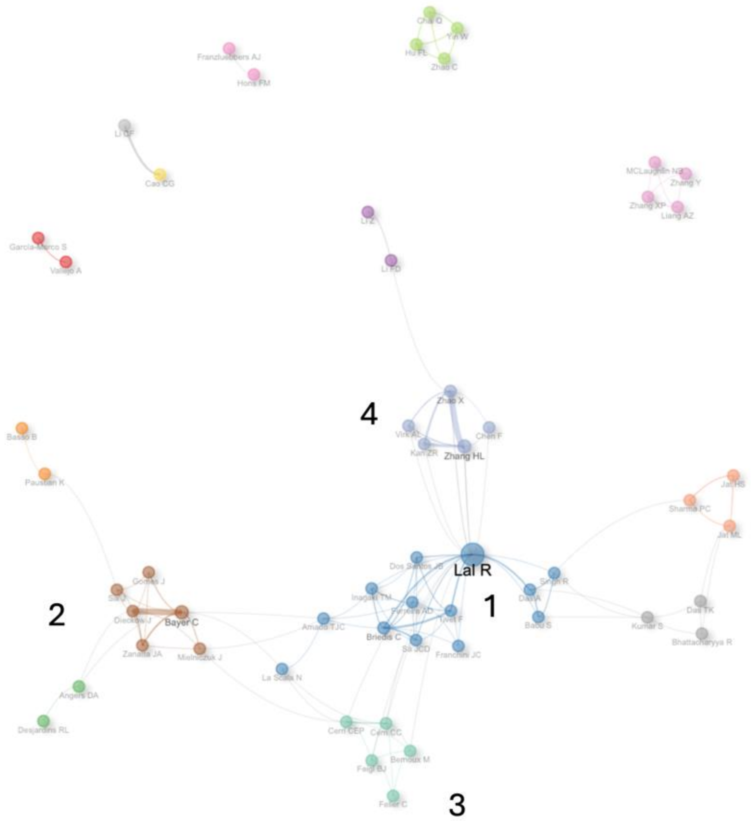


Figure 7. Author collaboration network. Source: own compilation.

Regarding the content of each of the clusters in the collaboration network, Cluster 1, the most relevant of all and to which the most productive author belongs, focuses on the effect of the transformation of natural ecosystems on soil carbon dynamics in tropical and subtropical climates. Among the identified transformations is the transition to agricultural ecosystems managed under CA. Some of the conclusions reached in the works of this collaboration network indicate that one way to recover the lost natural capital in agricultural systems, mainly due to the loss of soil organic carbon, is through no-tillage systems [16]. The adoption of no-tillage practices varies across regions due to differences in climatic and soil conditions, with a significant impact on soil organic carbon (SOC) dynamics. In tropical regions like South America, no-tillage combined with cover crops enhances SOC by reducing erosion and maintaining continuous soil cover, despite high residue decomposition rates due to elevated temperatures. In temperate regions, such as North America and parts of Europe, no-tillage effectively increases SOC by minimizing soil disturbance, which slows organic matter breakdown and enhances carbon sequestration. However, in arid and semi-arid regions like Australia and parts of Africa, SOC gains are limited by low biomass production, which reduces the amount of residue available for carbon inputs. Despite regional differences, no-tillage contributes to long-term SOC accumulation by improving soil structure, enhancing microbial activity, and increasing residue retention, especially when integrated with diverse cropping systems and cover crops. Cluster 2 authors primarily focus on tropical and subtropical climates, with a particular emphasis on carbon sequestration and GHG mitigation. Specifically, the focus is on carbon sequestration [17–20] and GHG emission mitigation, such as CO_2 [21], N_2O [22], and CH_4 [23].

Authors within Cluster 3 conducted studies primarily in Brazil, one of the countries with the largest number of areas under CA and a significant contributor to agricultural productivity. Cluster 4 represents a group of collaborating authors primarily based in China. This cluster encompasses a broader understanding of the relationship between CA and its capacity to mitigate climate change. Research within this cluster not only focuses on increased carbon sequestration resulting from CA practices [24] but also addresses its impacts on reducing emissions of CO_2, N_2O, and CH_4 [25]. Authors situated within peripheral clusters exhibit lower connectivity with other clusters and consequently possess less extensive collaborative networks.

Figure 8 depicts author timelines, where line length represents research duration, bubble size corresponds to the number of published documents, and color intensity reflects the annual average of total citations [11]. The authors with the longest timelines are *Lal R.*, *Paustian K.*, and *Bayer C.*, spanning from the late 1900s to the 2020s. *Lal R.* stands out as one of the most prominent authors in the field due to his extensive timeline, coupled with a continuous increase in production even during the third period, both in terms of the number of articles and total citations. Additionally, it is noteworthy that *Zhang H.L.* and *Zhao X.*, whose timelines began after 2010, are experiencing rapid growth in their number of articles and total citations per year.

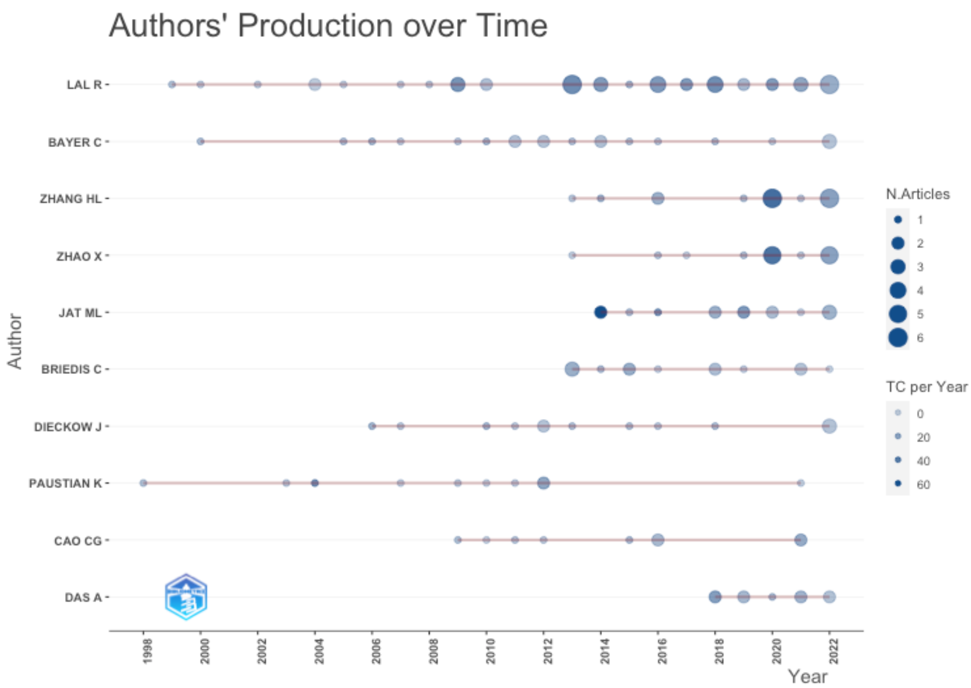


Figure 8. Top 10 authors' production over time. Source: own compilation.

It is important to highlight that these main authors belong to different clusters. *Zhang H.L.* and *Zhao X.* are part of the same cluster, Cluster 4, known for conducting studies in China. *Lal R.*, *Briedis C.*, and *Das A.* are associated with Cluster 1, while *Bayer C.* and *Dieckow J.* are clustered in Cluster 2. *Jat M.L.* and *Cao C.G.* belong to distinct border clusters.

It is unsurprising that the top 10 most prolific authors are affiliated with research institutions in the four countries with the highest research output in this field, as depicted in Figure 6. Two prominent figures in the field, *Lal R.* and *Paustian K.*, are affiliated with research institutions in the USA, the country where Conservation Agriculture originated and early research in this area was conducted. These authors have been publishing since the first period. Three authors, *Briedis C.*, *Bayer C.*, and *Dieckow J.*, are affiliated with research institutions in Brazil, where Conservation Agriculture and related research initiatives were first established in the 1970s. Additionally, the list includes authors from China (*Zhang H.L.* and *Zhao X.*) and India (*Das A.* and *Cao C.G.*). With the exception of *Cao C.G.*, who began publishing in the later years of the second period, these authors commenced their research careers in the third period and are currently demonstrating rapid growth in their publication output.

Analysis of the authors' co-citation network (Figure 9) reveals four distinct clusters. Two of these clusters, denoted by green and red, encompass a larger number of authors and exhibit greater prominence within the network. The co-citation network refers to the co-citation of two documents when both are cited in a third document [26]. Here, we observe that the most important authors are in the red cluster, as indicated by the size of the nodes and the strong connections between *Lal R.*, *Six J.*, and *West T.O.* These authors also have connections with the other clusters, as represented by the gray lines connecting them.

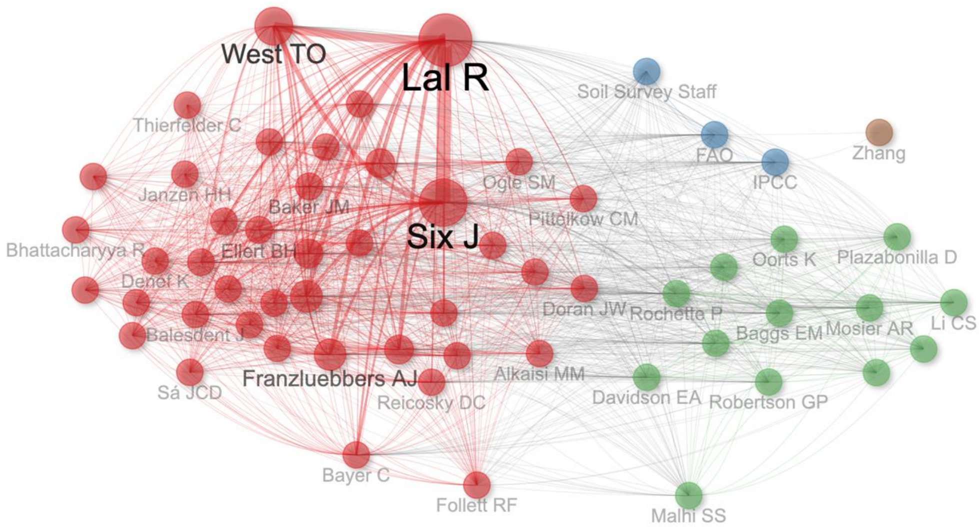


Figure 9. Authors' co-citation network. Source: own compilation.

3.4. Documents

Analysis of the selected documents provides valuable insights into the conceptual structure of the studied scientific field. This structure elucidates the primary research areas within the field [27] and their evolution over time. This understanding can be achieved not only through a comprehensive analysis of the documents and their inter-relationships, as revealed through co-citation analysis, but also by examining the keywords used within the literature and investigating the co-occurrence networks formed by these keywords.

Following the analysis of 650 filtered documents, the top 10 globally cited publications were identified (Table 6). Global Citations refers to the total number of citations received by a document across all publications indexed within a given source (Scopus, WOS), while Local Citations refers to the number of citations a document receives from other documents within the specific search performed or sample [28].

Analysis of the references' co-citation network (Figure 10) reveals two distinct clusters. The core documents within each cluster align with the most-cited papers identified in this study.

Table 6. Most relevant documents. Source: own compilation.

Document	Total Citations	Total Citations/Year	Local Citations	Source	Year
Greenhouse gases in intensive agriculture: contributions of individual gases to the radiative forcing of the atmosphere [29].	971	40.45	42	*Science*	2000
A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States [30].	893	40.59	43	*Agriculture ecosystems & Environment*	2002
The potential to mitigate global warming with no-tillage management is only realised when practised in the long term [31].	611	30.55	82	*Global change biology*	2004
Limited potential of no-till agriculture for climate change mitigation [32].	501	50.10	50	*Nature climate change*	2014
Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments [33].	494	35.28	60	*Agriculture ecosystems & Environment*	2010
Soil carbon sequestrations by nitrogen fertilizer application, straw return and no-tillage in China's cropland [34].	327	21.80	14	*Global change biology*	2009
Land-use intensity effects on soil organic carbon accumulation rates and mechanisms [35].	294	17.29	3	*Ecosystems*	2007
Managing soil carbon for climate change mitigation and adaptation in mediterranean cropping systems: a meta-analysis [36].	293	26.64	17	*Agriculture ecosystems & Environment*	2013
Nitrous oxide emissions following application of residues and fertiliser under zero and conventional tillage [37].	263	12.52	41	*Plant and soil*	2003
Tillage, nitrogen and crop residue effects on crop yield, nutrient uptake, soil quality, and greenhouse gas emissions [38].	258	14.33	16	*Soil and Tillage Research*	2006

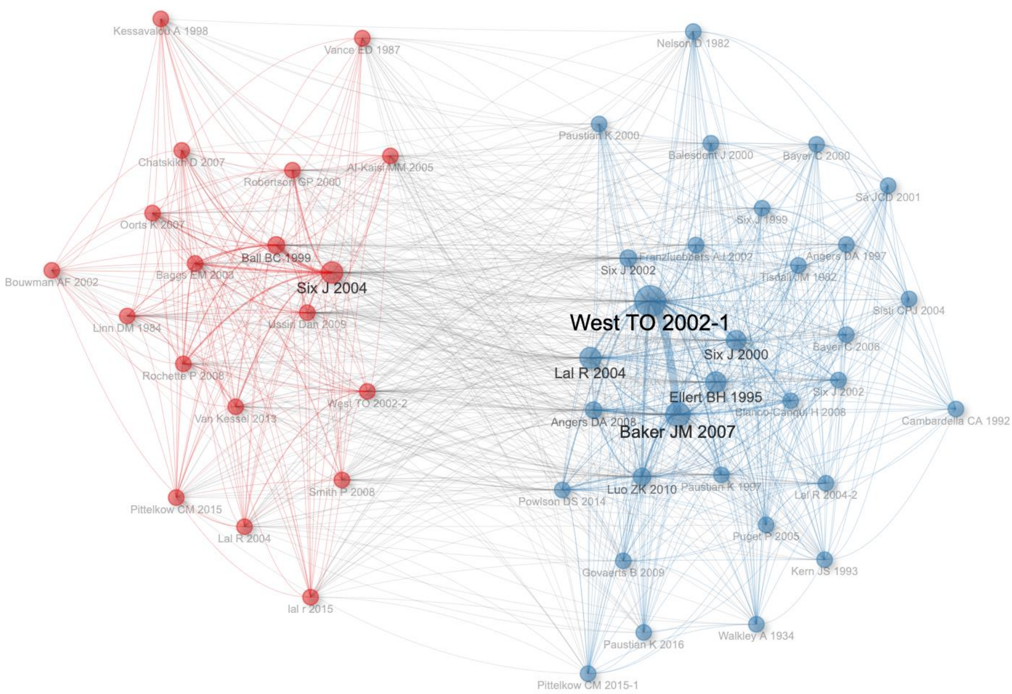


Figure 10. References' co-citation network. Source: own compilation.

In the blue cluster, the most significant document, indicated by the node size, is "A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States" [30]. In this study, the authors found that the carbon sequestration potential for reduced tillage is insignificant, but no-tillage has the potential to reduce carbon emissions and improve carbon sequestration through increased biomass and soil organic matter. Reference [29], comparing cropped and nearby unmanaged ecosystems, found that no-till is the soil management system with the closest soil carbon accumulation to mitigating all other sources of greenhouse gases, including CH_4. Reference [34], studying China's production regions, suggested that no-till and straw return have the potential to sequester carbon in these zones and mitigate carbon emissions in their country.

Despite many authors reporting higher soil carbon content in no-tillage compared to conventional tillage worldwide [29,30,35,36], and the soil's potential to sequester carbon being demonstrated [39,40], some authors present divergent views. For instance, [33] found that converting from conventional tillage to no-tillage increases carbon content in the top 5 cm of soil, while below 40 cm, there are no differences between conventional tillage and no-tillage. Additionally, [32] suggested that no-tillage has the potential to mitigate climate change, but its effectiveness varies depending on location and specific circumstances.

The red cluster appears to be of lower importance compared to the blue cluster, as indicated by the smaller labels. The paper "The potential to mitigate global warming with no-tillage management is only realised when practiced in the long term" [31] stands out as the most significant in this cluster. It emphasizes that no-tillage must be practiced over the long term to effectively reduce greenhouse gas emissions. This paper also underscores the importance of studying N_2O emissions in agriculture. Indeed, nitrous oxide has emerged as a critical theme in climate change discussions due to its potent greenhouse gas (GHG) properties and long atmospheric lifespan. With a global warming potential approximately 300 times greater than CO_2 over a 100-year period, N_2O plays a significant role in agricultural emissions, primarily from soil management and synthetic fertilizer application. Its inclusion in climate change policy is gaining prominence, as reducing N_2O emissions is essential to achieving ambitious climate targets. This emerging focus could significantly influence agricultural policies by incentivizing practices that minimize nitrogen losses, such as optimized fertilizer use, increased adoption of cover crops, and improved soil health management. Furthermore, integrating CA practices—including no-tillage and crop rotations—could reduce N_2O emissions by enhancing nitrogen use efficiency and soil organic matter, strengthening the argument for widespread adoption. Thus, addressing N_2O emissions aligns closely with both mitigation and adaptation goals, making it a vital consideration in future agricultural and environmental policies.

Reference [37] reported higher emissions of N_2O from fertilized no-tillage treatments compared to fertilized, conventional tillage treatments. However, [29] concluded that it is not solely fertilizer or tillage that accelerates N_2O fluxes from cropping systems, but rather the high availability of soil nitrogen. Additionally, [36] found that conventional tillage with nitrogen fertilizer promotes greater N_2O emissions than no-tillage with fertilizer.

3.5. Keywords

Author keywords represents a curated list of terms selected by the authors themselves to most accurately encapsulate the core content of their research. Conversely, Keywords Plus, generated through an automated computational process, consists of words or phrases frequently encountered in the titles of the article's cited references. These algorithmically derived keywords may not necessarily appear within the article's title or among the Author Keywords [11,41]. In this paper, we have analyzed both author keywords (the frequency distribution of authors' keywords, DE) and Keywords Plus (the frequency distribution of keywords associated with the manuscript by the SCOPUS and Thomson Reuters' ISI Web of Knowledge databases, ID), and we present the most relevant keywords found in Table 7. It is evident that the keywords are very similar in terms of occurrences, and the differences between the two types of keywords are minimal. For instance, in the ID category, we find "system," which encompasses all agricultural management systems, while in the

DE category, we encounter terms such as conservation tillage, Conservation Agriculture, and conventional tillage, indicating different types of systems. Based on this observation, we conclude that ID and DE are closely related, and both can be utilized to enhance our understanding of the themes and topics covered. It is important to note that Keywords Plus are generated by the WoS database, while Scopus does not generate this type of keyword. Given this limitation, this study exclusively utilizes author keywords for its analysis.

Table 7. Most relevant keywords. Source: own compilation.

Author Keywords	Occurrences	Keywords Plus	Occurrences
no-tillage	99	management	158
soil organic carbon	96	sequestration	128
carbon sequestration	93	no-tillage	125
tillage	83	nitrogen	115
no-till	50	carbon sequestration	113
conservation tillage	49	tillage	91
conservation agriculture	47	nitrous-oxide emissions	90
nitrous oxide	46	systems	89
soil organic matter	35	agriculture	86
conventional tillage	34	no-till	85

Among the most relevant keywords, "soil organic matter" stands out as the most frequently utilized. Naturally, the occurrence of all keywords has increased over time, mirroring the growth in the number of papers. However, the rate at which each keyword grows varies. For instance, since the second period, the term "soil organic carbon" has been growing faster than "soil organic matter", indicating a heightened focus on soil organic carbon, which is a component of soil organic matter. Soil organic carbon (SOC) content has long been recognized as one indicator of soil quality [14]. While soil organic matter continues to be an important keyword, it is noteworthy to observe this shift in thematic emphasis.

This analysis reveals a notable preference for the term "no-tillage" over "no-till" within the literature, despite both terms being employed since the initial period. This preference is evident from the higher occurrence count of "no-tillage" (99 occurrences) compared to "no-till" (50 occurrences). A similar trend is observed with "tillage" and "conventional tillage", where "tillage" is preferred over "conventional tillage".

Within this same thematic area, the keyword "Conservation Agriculture" has shown growth since the second period. It is important to note that Conservation Agriculture is a concept based on three principles, with no-tillage being one of them [42]. The significance of greenhouse gas (GHG) emissions is underscored by keywords such as "carbon sequestration" and "nitrous oxide". While the importance of carbon is evident (93 occurrences), there has also been notable growth in the occurrence of "nitrous oxide", especially in the third period (Figure 11).

The keywords were grouped into three different clusters (Figure 12), primarily divided by management system and carbon sequestration ("no-tillage", "soil organic carbon", "tillage"), representing the largest cluster with the majority of keywords. Additionally, "nitrous oxide" ("greenhouse gas", "carbon dioxide", "methane") forms another cluster, with a smaller cluster linking aggregate stability and tillage systems. These clusters are interconnected, reflecting the inter-related nature of the keywords and their respective themes.

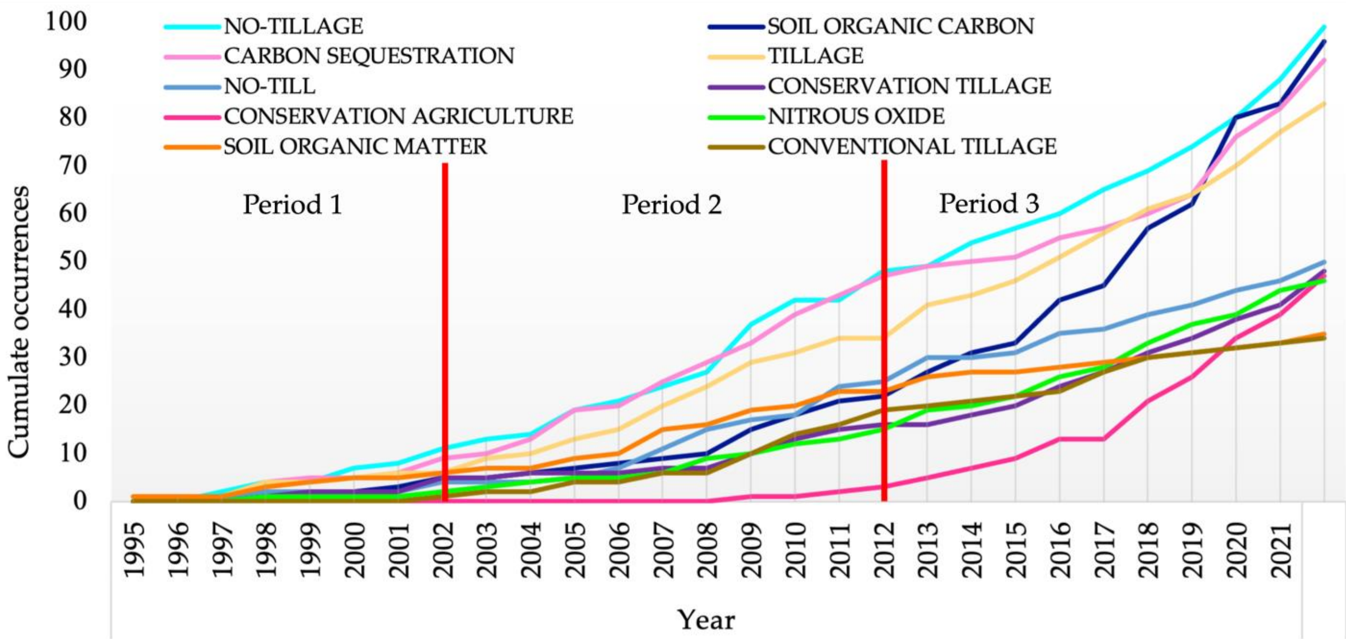


Figure 11. Authors' keywords over time. Source: own compilation.

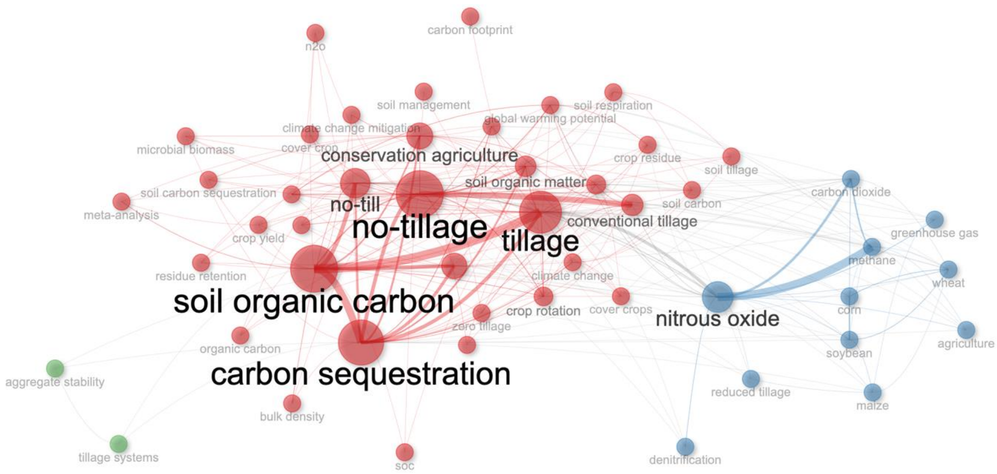


Figure 12. Co-occurrence network by authors' keywords. Source: own compilation.

3.6. Themes and Thematic Areas

The thematic evolution, divided into three distinct periods as previously described, reveals discernible trends in the convergence and divergence of research topics (Figure 13). Specifically, the analysis highlights instances where previously distinct themes have merged into broader conceptual frameworks, while other themes have undergone a process of differentiation, splintering into more specialized sub-topics. It is possible to observe that the themes were split into several themes from the first to the second period. Subsequently, they merged from the second to the third period.

Although the themes were subsequently split and merged, carbon has remained an important topic since the first period [43–45] to the present day [46–48]. These authors have studied how carbon sequestration (C sequestration) and emissions behave in different management systems, especially in no-tillage, conventional tillage, and reduced tillage. No-tillage was a highly important theme in the first period and was studied extensively worldwide, including in North America [49,50], South America [44,51], Africa [52], and Oceania [53]. The primary objective driving this field of research, both historically and presently, is to establish agricultural systems that effectively enhance carbon sequestration while simultaneously minimizing soil erosion.

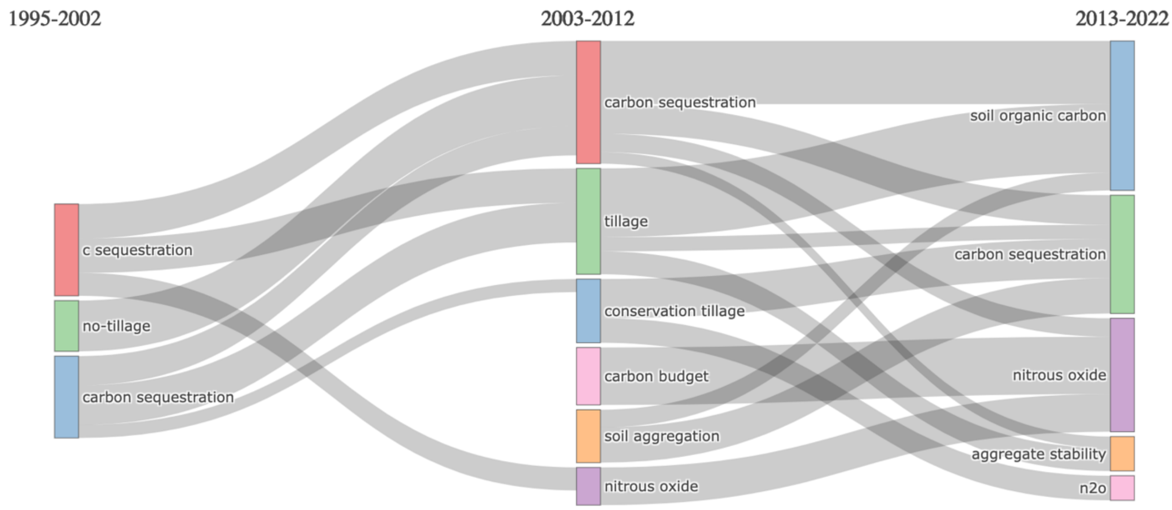


Figure 13. Thematic evolution of author keywords. Source: own compilation.

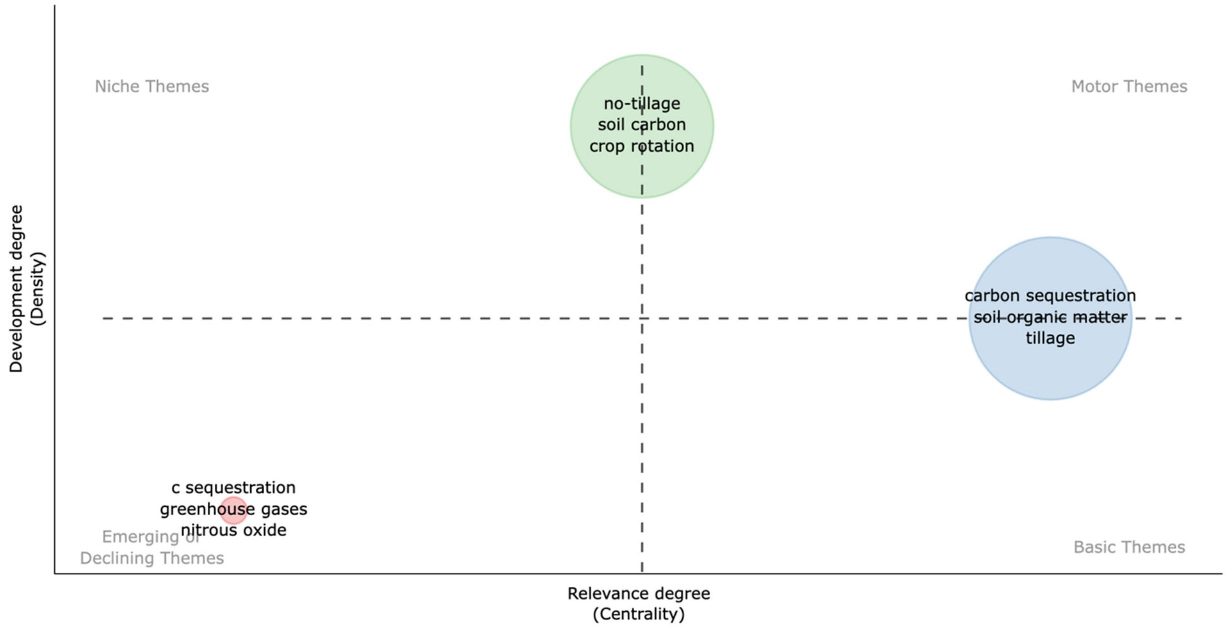
In the second period, there is a larger number of themes, some of which are merged in the third period as they appear synonymously with other themes. For example, "carbon budget" [54] was an important theme during this period but was later merged in the third period. One explanation for the significant importance of the carbon budget between 2003 and 2012 is the Kyoto Protocol and the environmental policies that began to gain traction during this period to meet the commitments outlined in the protocol. One can see the theme aggregation in evidence in the second period as soil aggregation [55,56] and as aggregate stability in the third period [57,58], both of which pertain to soil's physical characteristics.

Additionally, nitrous oxide gains prominence in both the second and third periods (Figure 14). As one of the most-released GHGs, nitrous oxide is influenced by nitrogen inputs in agricultural systems, such as fertilizers, which can increase these emissions. Therefore, there is significant importance in studying this area to mitigate its effects. Numerous authors conducted research on this topic [59–64] in the second period, and its importance continued to grow in the third period. In the thematic evolution, nitrous oxide also appears as N_2O, its chemical formula [65–67].

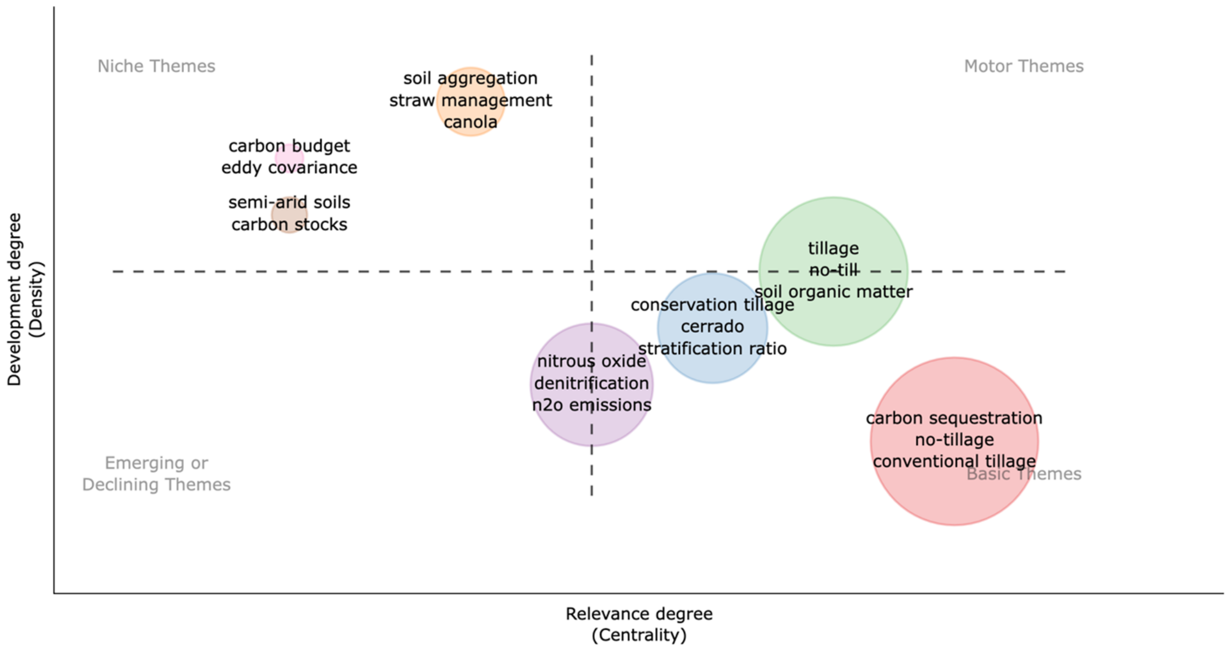
Focusing on the strategic diagram, during the first period, nitrous oxide is an emerging theme (Figure 14a). This quadrant encompasses themes that may either emerge or decline, as it includes both undeveloped and marginal topics. Analysis of the second and third periods, in conjunction with the observed thematic evolution, reveals that nitrous oxide emerged as a significant research focus during the initial period. In subsequent periods, while maintaining its importance as a key research area, nitrous oxide transitioned to a "basic theme" (Figure 14b,c), signifying a foundational topic requiring further in-depth exploration. This trajectory underscores the enduring significance of nitrous oxide research within the field.

The theme of carbon sequestration presents high centrality and a low density, which means it is an important and undeveloped theme [9]. It consistently falls within the basic and transversal quadrant across all periods (Figure 14). While numerous studies have been conducted on carbon sequestration, particularly in countries that have pioneered CA since its inception, research on this topic is relatively new in many other nations [68,69]. Consequently, carbon sequestration remains an important trend both presently and in the future.

No-tillage is situated in the middle of niche themes and motor themes in the first period, often associated with soil carbon and crop rotation. In the quadrant niche themes are the developed and important, but without external importance, very specialized themes [10]. Over time, the association of no-tillage with carbon sequestration has transformed it into a basic theme (Figure 14b,c), continuing its status as an important trend alongside carbon sequestration. Upon analyzing the strategic diagram, it is notable to include the theme of CH_4 as an emerging theme in the third period [1,70,71]. Positioned in this quadrant are emerging or disappearing themes; however, due to the significant importance of greenhouse gases and the limited research on methane, it is likely to emerge as a trend in the coming years.

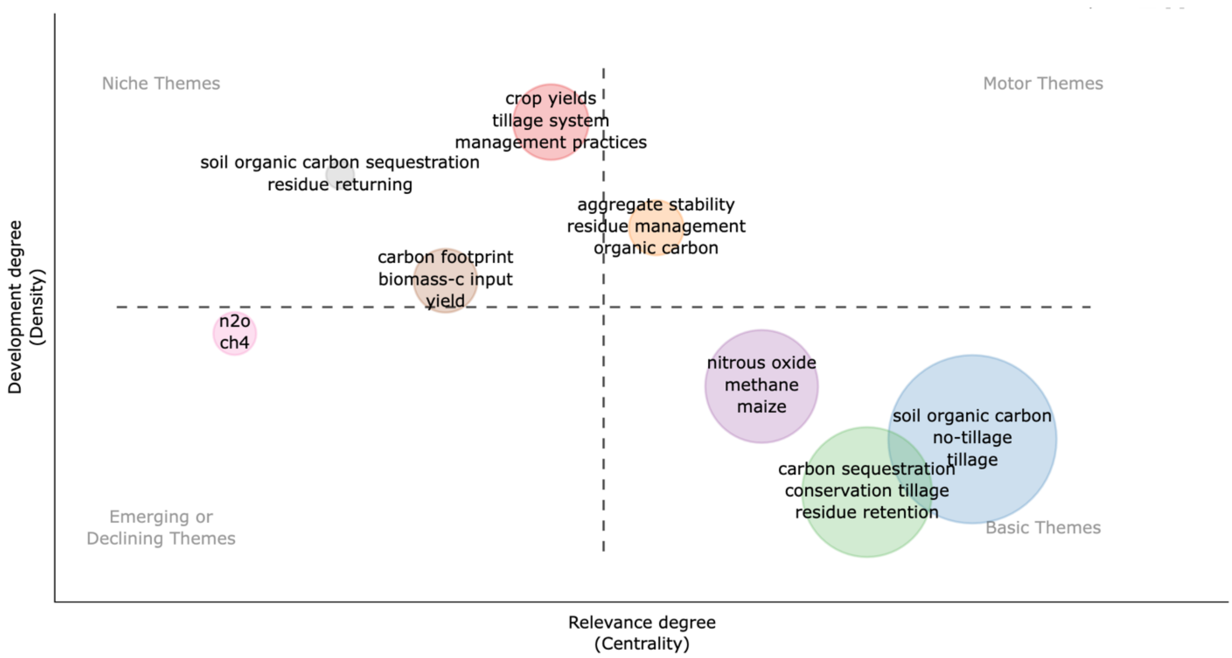


(**a**)



(**b**)

Figure 14. *Cont.*



(**c**)

Figure 14. Strategic diagram with authors' keywords. (**a**)—Period 1: 1995 to 2002. (**b**)—Period 2: 2003 to 2012. (**c**)—Period 3: 2013 to 2022. Source: own compilation.

4. Conclusions

This study aimed to characterize the scientific field pertaining to the contribution of Conservation Agriculture to climate change mitigation and to identify global trends in scientific production within this domain over time. To achieve this objective, a bibliometric analysis was conducted utilizing the Bibliometrix-R tool and employing two merged databases encompassing the period from 1995 to 2022. This comprehensive analysis enabled the delineation of the field's social, intellectual, and conceptual structures.

Bibliometric analysis reveals a significant surge in research interest concerning the potential of Conservation Agriculture to mitigate climate change in recent years. Although initial scientific publications appeared as early as 1995, the annual output of articles investigating no-tillage as a climate change mitigation strategy within high-impact journals (Q1 and Q2 quartiles) did not consistently exceed ten until 2007. Since then, scientific production has exhibited substantial growth. This trajectory likely reflects the escalating global concern surrounding climate change and its increasingly evident impacts on ecosystems and human societies.

International agreements, such as the 1997 Kyoto Protocol and, more recently, the 4 per 1000 Initiative established under the 2015 Paris Agreement, have significantly contributed to this heightened research interest. These initiatives emphasize the importance of enhancing the carbon sink capacity of agricultural soils through the implementation of practices that promote carbon sequestration, thereby stimulating scientific inquiry into these practices and their associated mitigation mechanisms.

Soil and Tillage Research has consistently emerged as the most prolific source of published articles since the inception of this research area. This prominent position can be attributed to several factors. Firstly, the journal boasts a high impact factor (2022 JCI Quartile: Q1; 2022 JCI Percentile: 94.57). Secondly, its core objectives and research focus align closely with this field of study, specifically examining the physical, chemical, and biological alterations in soil resulting from tillage and field traffic. Notably, the journal frequently features research on the impacts of soil modification on carbon and nutrient cycles, as well as greenhouse gas emissions—central themes within the scope of this bibliometric analysis. This strong alignment between the journal's scope and the research field under investigation likely influences author decisions regarding publication venue.

The bibliometric analysis has enabled the delineation of the social, intellectual, and conceptual structures within the scientific field pertaining to the contribution of Conservation Agriculture to climate change mitigation. The social structure is defined by collaborative networks among authors and the inter-country relationships between their affiliated institutions. Intellectual structure is elucidated through data such as author productivity and co-citation relationships within individual documents. Finally, analysis of the selected documents provides insights into the conceptual structure of the field, with keyword analysis and co-occurrence networks revealing the most prominent research topics and their evolution over time.

4.1. Social Structure

Regarding scientific production by country, two of the three most productive countries, the USA and Brazil, are characterized as being world leaders in Conservation Agriculture [72], which may partly explain their significant role in the scientific field studied. While these countries have always held a leading position in scientific production, China, like India, has experienced a strong increase in the last decade. This surge may be attributed to the growth of Conservation Agriculture in these countries in recent years [73,74], which likely sparked the scientific community's interest in the mitigation potential of these practices once technical limitations that restricted small-scale adoption were overcome and research efforts shifted toward improving machinery and system adaptability to local conditions. Spain also stands out, as a smaller country in terms of both territory and population than the aforementioned countries, with significant scientific production in this field. This is related to the degree of adoption of Conservation Agriculture practices, positioning Spain as a leader in Europe [72], and has been the subject of many studies by the country's scientific community.

The social analysis allowed us to visualize the degree of collaboration between countries, with China and Brazil standing out, as well as the interconnection networks between them, identifying three main clusters led by the most productive countries globally, the USA and China. The diversity of countries included in this cluster suggests that it encompasses studies with greater climatic diversity.

The analysis of author inter-relationships identified fourteen distinct clusters, with four exhibiting significant interconnectivity. While no discernible specialization within specific research branches could be definitively attributed to individual clusters, the most productive cluster, prominently featuring *R. Lal*, focuses on investigating Conservation Agriculture practices within tropical and subtropical climates. This cluster emphasizes the restoration of lost natural capital within agricultural systems, particularly addressing the decline in soil organic carbon content resulting from conventional tillage practices.

4.2. Intellectual Structure

The analysis of the authors suggested a relationship between their productivity and the evolution of this parameter in the most significant countries. Thus, apart from the fact that the top 10 authors conduct their research in the four most significant countries in this field, we can observe how some of them gained relevance simultaneously as the number of publications from their countries increased. This is the case, for example, with authors like *Zhang, H.L.* and *Zhao, X.* in China and *Das, A.* and *Cao, C.G.* in India. The reasons for this may be those discussed in the previous section on the social structure analysis.

Moreover, the co-citation analysis of authors provided insight into the leading researchers in this field, whose work serves as a foundation for other studies conducted on the topic at hand. In this case, a predominant cluster was identified, grouping the most productive authors, a second, less dense cluster focused on greenhouse gas emissions, with a greater emphasis on N_2O emissions, and a third cluster that includes co-citations from international entities and organizations.

Finally, another parameter that helped to characterize the intellectual structure of the research field is the co-citation network of documents. In this case, the analysis suggested that authors have focused on two main research branches, resulting in two clusters. The most significant and dense cluster is related to the study of Conservation Agriculture and soil organic carbon, while the second, of lesser apparent importance, is related to greenhouse gas emissions, with N_2O being one of the most studied gases in this case. At this point, it is worth noting, based on the study of the most relevant documents in each identified cluster, that these two research branches are not isolated from each other, as there are documents co-cited in both topics and appearing simultaneously in both clusters, such as those by *Lal, R.; Six, J.;* and *West, T.O.*; among others.

4.3. Conceptual Structure

The bibliometric analysis of Conservation Agriculture research revealed an evolving conceptual landscape, with a growing emphasis on key concepts related to climate change mitigation. The most frequent keywords, such as "no-tillage", "carbon sequestration", and "soil organic carbon", underscore the central research themes, reflecting the critical importance of carbon sequestration and agricultural practices that contribute to the reduction of greenhouse gas (GHG) emissions.

- Carbon and climate change mitigation: Carbon sequestration has been central throughout all phases of study. From soil organic carbon analysis to the implementation of practices like no-tillage, carbon sequestration has become a cornerstone in understanding how Conservation Agriculture can help mitigate climate change.
- Greenhouse gas evolution: In recent years, the study of other GHGs, such as nitrous oxide (N_2O), has gained relevance. While initial research primarily focused on carbon dioxide (CO_2), N_2O has emerged as a crucial topic due to its higher global warming potential. This suggests a broadening of the conceptual focus to encompass a wider range of GHGs.
- Consolidation of themes and keywords: The results show how previously separate topics, such as the carbon cycle or soil aggregate stability, have converged over time. This reflects a conceptual integration where different approaches to soil sustainability, carbon sequestration, and emission reduction merge.
- Emerging trends: Over time, emerging topics, such as methane (CH_4), which has historically received less attention, have begun to gain prominence, suggesting future research directions that could further expand the conceptual field of Conservation Agriculture.

In summary, the conceptual framework of Conservation Agriculture has evolved into a multidimensional approach, with carbon sequestration, GHG emission reduction, and soil sustainability serving as the foundational pillars driving the increasing scientific interest in its role in climate change mitigation. Future research is anticipated to further consolidate these core concepts while exploring emerging areas, such as methane emissions and the efficacy of agricultural practices, across diverse geographical contexts.

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ration, J.R.-V. and L.M.M.d.S.P.; writing—review and editing, F.M.-G. and E.J.G.-S.; visualization, Ó.V.-G.; supervision, E.J.G.-S.; project administration, Ó.V.-G.; funding acquisition, E.J.G.-S. and Ó.V.-G. All authors have read and agreed to the published version of the manuscript.

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