Review

Knowledge mapping of the extant literature on the environmental impacts of using cover crops—A scientometric study

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Abstract: This study examined the last four decades of the existing academic literature related to the environmental impacts of using cover crops in agricultural production systems. Data were collected from the Web of Science database, resulting in a sample of 3,246 peer-reviewed articles published between 1980 and 2021. We combined two advanced scientometrics analysis software (i.e., CiteSpace 6.0.R1 and Gephi 0.9.2) to identify the trajectory of the literature, hotspots, and frontiers. We developed authorship-, institution- and country-levels networks to examine academic cooperation over the last forty years. Our findings revealed that the number of peer-reviewed outputs documenting the environmental effects of cover crops has consistently increased, with a notable rise in publications between 2015 and 2021. Eighteen salient research topics were identified in the literature, including winter cover crops' effects on soil health, cover crops' effects on nitrous oxide emissions, and the relationship between cover crops and nitrate leaching. Based on the citation-clustering analysis, the trajectory of the literature may be divided into three stages. Studies in Stage 1_A (1980-2000) mainly assessed the role of cover crops in nitrogen management. In Stage 1_B (2001-2010), the research evaluated the impact of using different cover crop mixtures on farming systems. In Stage 2 (2011-2021), studies primarily addressed the environmental impacts of cover crops, particularly their effects on physical and chemical soil properties. Finally, the countries with the most outputs were the United States, Brazil, and Spain. The U.S. Department of Agriculture-Agricultural Research Service was the main contributor to the literature on the environmental impacts of cover crops.

Keywords: cover crops; environment; scientometrics; network analysis

1. Introduction

Cover crops (CC) have played a role in land management for centuries and remained a key practice in maintaining and replenishing soil fertility until the development of synthetic fertilizers (Jiang, Li, Chen, Cai, & Liu, 2017; King, 2011). The research about CC use and effects on soil properties is long, with written records extending back centuries in Asia and Europe. Even in the New World, the written research record goes back to the 1700s. Soils in the U.S. were already nutrient-poor by the time of the American Revolution, and both Thomas Jefferson and George Washington conducted research with CC and disseminated their findings (Groff, 2015).

Research about CC's role as a source of nutrients waned when synthetic fertilizers, especially nitrogen fertilizers, became widely available and affordable in the mid-20th century. However, interest in preventing soil erosion and other potential benefits of CC increased during this same period. Protecting the soil, building soil organic matter, and improving soil moisture retention were critical research concerns in the mid-1900s due in large part to the enormous damage to soil resources that occurred in the Dust Bowls in the United States and Australia (Qi Hu, Torres-Alavez, & Van den Broeke, 2018; Sauter, 2015).

A third wave of CC research emerged as concerns over the sustainability of input-intensive agriculture grew in the late 20th Century. Three different terms used in this period reveal the increased scope of CC research as a more ecological approach to soil management emerged. The terms primarily reflect differences in the primary goal for planting CC: maintaining organic matter and increasing nitrogen availability (green manures); preventing soil erosion (cover crop); or preventing nutrient leaching (catch crop) (Magdoff & van Es, 2010). Various forms of "ecological agriculture" emerged as alternatives to input-intensive agriculture in the last two decades of the 20th Century. The call for more ecologically based and sustainable farming systems started primarily in the industrial and post-industrial nations (Hamilton, 2019; Laforge & Levkoe, 2018) but quickly became influential in developing countries as well (Acevedo-Osorio & Chohan, 2020; Kansanga, Luginaah, Bezner Kerr, Lupafya, & Dakishoni, 2020; Mdee, Wostry, Coulson & Maro, 2019; Nemes, 2019).

The growing interest in sustainable and ecological agriculture stimulated a new round of research about CC. Programs like the U.S. Department of Agriculture (USDA)'s Sustainable Agriculture Research & Education Program (SARE) and the USDA Agricultural Research Services (ARS) in the U.S. have supported a large body of research covering many potential benefits to CC and resulting in a much-expanded body of knowledge (SARE, 2015; SARE, 2020; USDA-ARS, 2022; USDA ERS, 2022). Unlike research in the earlier two waves, the topical areas tackled in this new, third round of research are broad and address the needs of many cropping systems. The growth of organic agriculture globally also played an important role. The EU led the way with organic certification in 1991, and the passage of the Organic Foods Production Act of 1990 laid the way for the development of the U.S. National Organic Standards in 2003. Both sets of regulations require CC in any organic farming system, which has become a norm in most nations (OFPA, 1990; NOP, 2000; EC, 1991; 1992; 1999).

1.1. Purpose of the study and contribution to the literature

The purpose of this study is to explore the research activity of the literature on the environmental impacts of CC. Over the last forty years, the body of knowledge resulting from CC research has grown in geographic scope, topical coverage, and research approach. The potential for a scientometric analysis to reveal consistent patterns and salient themes of results over numerous studies can help steer future research into the avenues with the most significant potential (Chen, 2006; Lee, 2008; Zhang et al., 2018).

Previous studies have conducted reviews of the literature related to the benefits of CC on soil properties (Blanco-Canqui & Ruis, 2020; Haruna et al., 2020; Adetunji et al., 2020; Bolinder et al., 2020; Bergtold et al., 2019; Thapa, Mirsky & Tully, 2018; Osipitan et al., 2018; Bowles et al., 2017; Alvarez et al., 2017; Kaye & Quemada, 2017; Poeplau & Don, 2015; Basche et al., 2014; Kartika et al., 2007; Snapp et al., 2005; Creamer & Dabney, 2002; Dabney et al., 2001). However, the main foci of previous studies have been to provide technical and descriptive summaries of the documented benefits and, in some cases, the quantifiable impact of CC on soil health and quality (e.g., meta-analysis). To our knowledge, no previous study has examined and summarized the existing CC literature using scientometric analysis. The present research complements prior efforts and contributes to the literature by mapping the evolution of the literature (Mulchenko, 1969; Börner, Chen & Boyack, 2003). Scientometric methods find links between concepts and themes in the literature that may be easily overlooked in manual review studies, reducing the subjectivity and impressionistic description inherent in traditional review articles (Su & Lee, 2010; Markoulli, Lee, Byington & Felps, 2017).

2. Methods

2.1. Data collection

We initiated the search of records by selecting a set of keywords representative of the area of study, including *"cover crop," "cover crops," "cover cropping," "environment," "soil quality," "air quality," and "water quality."* This study selected Thomson ISI Web of Science (WoS) as the database for extracting relevant publications related to the environmental impacts of CC. WoS is deemed the most comprehensive database for scientific publications (Olawumi & Chen, 2018) and covers journals and records from the most important academic publishing houses (e.g., Elsevier, Wiley, Taylor and Francis, Springer, Emerald, Palgrave, MDPI, among others). In WoS, we retrieved records from the Science Citation Expanded (SCIE) and Social Science Citation Index (SSCI) databases. The search was delimited to peer-reviewed journal articles published in English between 1980 and 2021. The search was last conducted on March 30th, 2022. We performed an artificial data-cleaning procedure to improve the search's reliability and reduce the potential noise or missing values. The search yielded a total of 3,246 article records. Table 1 summarizes this study's specific parameters for searching academic papers.

Table 1. Detailed search setting parameters.

Source	Web of Science Core Collection
Citation	Science Citation Expanded (SCIE) and Social Science Citation Index (SSCI)
Search Steps	TS= ((“cover crop*”) and ((environment) or (“soil quality”) or (“air quality”) or (“water quality”)) AND LANGUAGE (ENGLISH) AND DOCUMENT TYPES:(Article)
Time span	1980 - 2021
Qualified records	3,246

* is attached to the stem of a word and searches for any words and variants of that word that includes that stem. For example, crop* includes crops and cropping.

2.2. Research Design and Analysis

This study employed network analysis methods to assess the extant body of knowledge on the environmental effects of using CC in agricultural systems. We combined network analysis methods with graph theory to visualize networks, including co-citation networks, co-occurrence networks of subject terms, and collaboration networks among authors, institutions, and countries. Mainly, we aimed to identify salient research domains and frontiers, high-frequency terms, and the links among various authors, institutions, and countries. Figure 1 provides a schematic of the research design used in the present study.

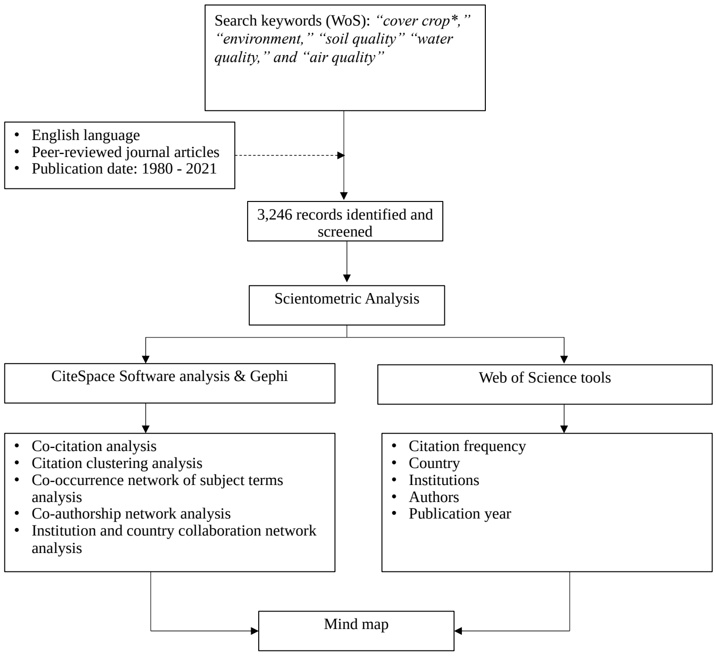

Figure 1. A schematic of the research design.

We used co-citation network analysis to determine pairs of articles that other publications have cited. The more times a particular pair was cited, the more strength of co-citation and more similarity between these two articles (Boyack & Klavans, 2010; Hsiao & Yang, 2011). Co-citation network analysis is one of the core methods in social network analysis (SNA). This method has been widely used to find a domain's knowledge structure and highly-cited articles (Shiau et al., 2017). Based on the co-citation networks, we conducted citation-clustering to visualize salient research topics related to the literature on CC and soil properties. We also used co-occurrence network analysis to search for research frontiers. Lastly, we assessed authorship, academic institution, and country collaboration networks. The visualization of these networks allowed for examining cooperation and knowledge sharing among authors, institutions, and countries. This study evaluated networks using the following statistical indices: network density, betweenness centrality, and closeness centrality. See appendix A for a description of these indicators and equations.

We adopted two commonly used scientometric software to analyze the literature records. First, we used CiteSpace 6.0.R.1 to visualize our networks and identify research hotspots–the software, developed by Chen et al. (2010), is available via http://cluster.cis.drexel.edu/~cchen/citespace/. This software includes useful tools for visualizing progressive knowledge domains and finding critical points in the evolution of a research field (Chen, 2004). The second software employed in this study was Gephi 0.9.2 (Bastian et al., 2009), available at https://gephi.org/. Gephi is a powerful and leading software for network analysis (Bastian et al., 2009); it allows for computing statistical indicators (e.g., network density, closeness centrality, betweenness centrality) for networks to assess the importance of nodes within the network (Golbeck, 2013; Zhang & Luo, 2017).

3. Results and Discussion

3.1. Distribution of publications over the years and cited journals

In the last four decades, 3,246 manuscripts concerning CC's environmental impacts were published in referred journals. The histogram in Figure 2 displays the number of outputs and citations per year. As shown, the number of peer-reviewed journals related to the topic of interest was limited before 1990, whereas the number of publications grew

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consistently from 1991 to 2010, reaching 92 publications in 2010. Notably, in the two decades (2010-2021), the number of records increased exponentially, from 112 publications in 2011 to 402 in 2021. Similarly, the number of citations followed the same trend as the number of publications. These tendencies reflect a growing and sustained interest from scholars and policymakers in CC as a conservation practice, the increased rate of funding provided to CC research, and the development and implementation of programs and guides promoting CC adoption in agricultural systems (SARE, 2015; SARE, 2020; USDA-ARS 2022; USDA ERS,2022; NRCS, 2021).

Tables 2 and 3 provide the list of top 10 peer-reviewed journals and top 10 subject categories for the literature related to CC and soil properties. As shown in Table 2, the leading journal with the most publications is *Agronomy Journal*, totaling 233 peer-reviewed articles since 1980. Other important journals are *Soil Tillage Research*, *Agriculture, Ecosystems & Environment*, *Soil Science Society of American Journal*, and *Journal of Soil and Water Conservation*. Each of the aforementioned journals published more than 100 articles within the last forty years. Most manuscripts addressed biological and environmental issues, and the subject categories included agronomy, soil science, environmental sciences, plant sciences, agriculture multidisciplinary, ecology, water resources, and horticulture.

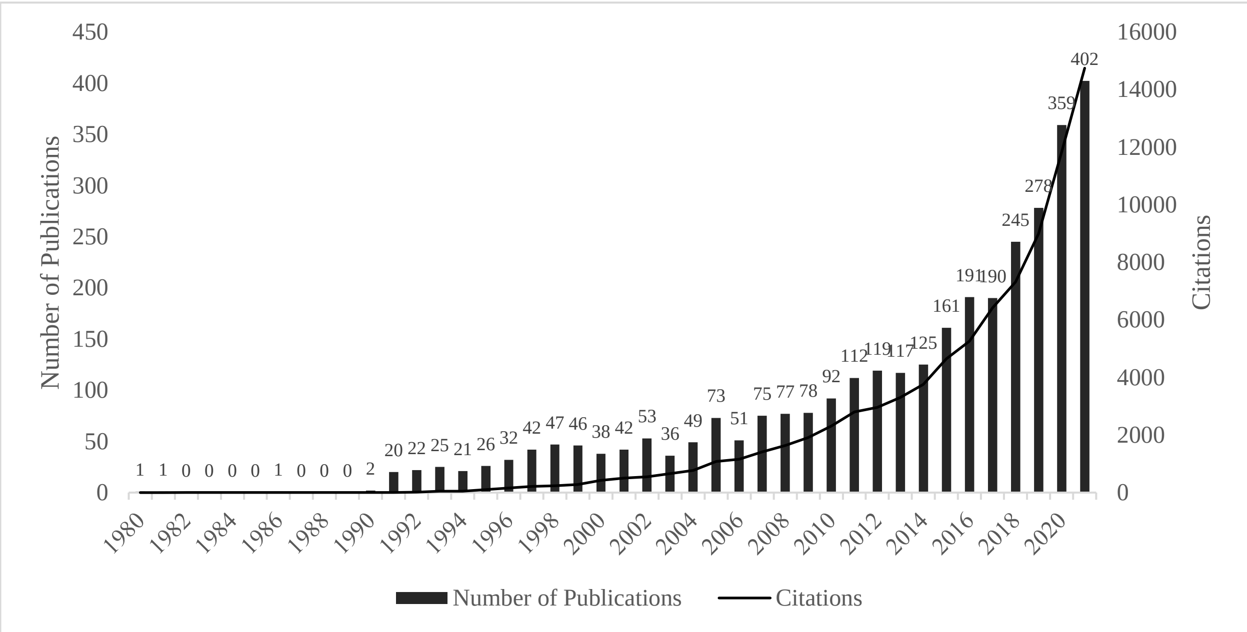

Figure 2. The basic descriptive of publications from 1980 to 2021.

Table 2. Top 10 journals with peer-reviewed articles related to CC.

Journal name	Impact Factor	Number of outputs	%
Agronomy Journal	2.240	233	7.178
Soil Tillage Research	5.374	146	4.498
Agriculture, Ecosystems & Environment	5.567	130	4.005
Soil science society of America Journal	2.307	112	3.450
Journal of Soil and Water Conservation	2.330	107	3.296
Journal of Environmental Quality	2.751	76	2.341
Agronomy	3.417	76	2.341
Plant and Soil	4.192	68	2.095
Agricultural Water Management	4.516	62	1.910
Field Crops Research	5.224	59	1.818

Table 3. Top 10 subject categories with peer-reviewed articles related to CC.

Subject	Publications	%
Agronomy	999	30.776
Soil Science	953	29.359
Environmental Sciences	606	18.669
Plant Sciences	392	12.076
Agriculture Multidisciplinary	371	11.429
Ecology	323	9.951
Water Resources	311	9.581
Horticulture	179	5.514
Agricultural Engineering	91	2.803
Geosciences Multidisciplinary	79	2.434

3.2. Co-citation analysis

The co-citation network analysis provided a picture of the evolution and trajectory of the literature. We used CiteSpace software to build and visualize the co-citation network. In particular, we set the time span from 1980 to 2021 and the slice length to one year. The "top N per slice" parameter in CiteSpace was set at "50" to obtain the top 50 most cited documents by each year (i.e., cited frequency per year). The structure of the co-citation network for the past four decades is displayed in Figure 3 (1583 nodes, 5362 edges; the average degree [1]of this network was 6.773, and the network density was 0.004). Consistent with our observations from Figure 1, the number of outputs and frequency of co-cited documents consistently increased throughout the last forty years. Notably, the frequencies of nodes (i.e., references in this network) and bursts mainly were concentrated between 2015 and 2021.

Table 4 provides the top ten most cited articles based on co-citation frequency. As shown, Blanco-canqui et al. (2015) and Poeplau & Don (2015) are the most co-cited articles, each with a co-citation frequency of 86 times. While co-citation frequency (i.e., the frequency with which two documents are cited together by another document) is valuable for discovering the similarity between publications (Torres-Pruñonosa et al., 2021), this indicator may not necessarily reflect the importance of the references in the whole co-citation network. In order to identify the articles with a rapid rise in citations in the last

[1] In network theory, degree also can be used as a measurement of degree centrality, which denotes the total amount of direct links with other nodes (Zhang & Luo, 2017).

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decade academic and characterize the dynamics of the research field in question (Amjad et al., 2022), we assessed citation bursts during the previous four decades. Figure 4 provides the top twenty articles with the strongest citation bursts between 1980 and 2021. The most influential research articles that ranked at the top were Blanco-canqui et al. (2015) (strength: 25.86), Poeplau & Don (2015) (strength: 21.21), and Schipanski et al. (2014) (19.5). The period (i.e., 2015-2021) in which the articles were published and the citation bursts occurred is a commonality among these influential articles. This trend reflects the growing interest of scholars in CC research and a significant increase in the contribution to the body of knowledge in the last five years.

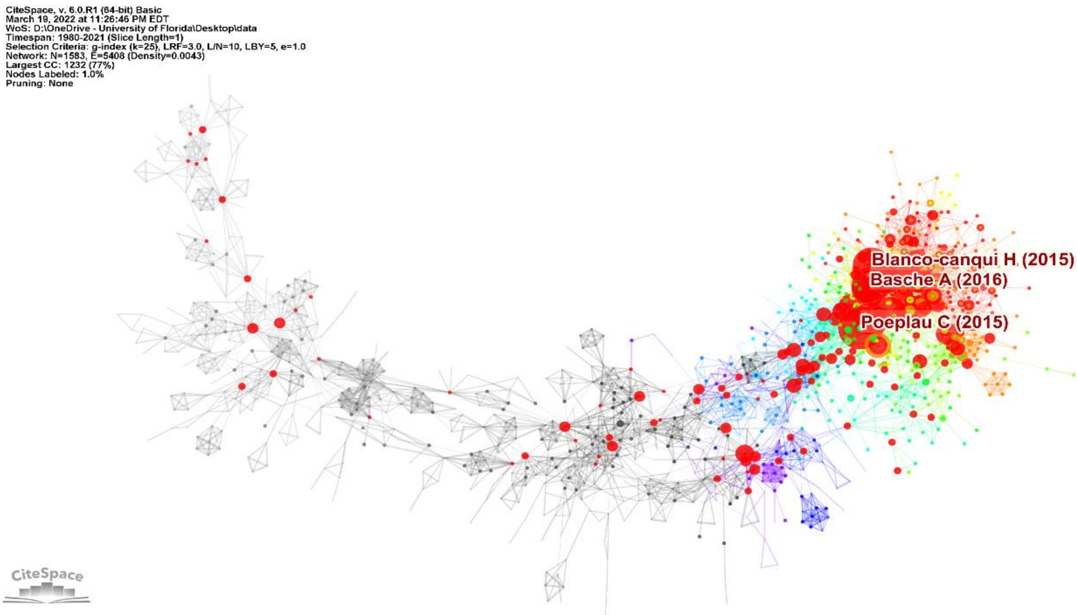

Figure 3. The overview of the co-citation network.

Top 20 References with the Strongest Citation Bursts

References	Year	Strength	Begin	End	1980 - 2021
Blanco-canqui H, 2015, AGRON J, V107, P2449, DOI 10.2134/agronj15.0086, DOI	2015	26.86	2017	2021	
Poeplau C, 2015, AGR ECOSYST ENVIRON, V200, P33, DOI 10.1016/j.agee.2014.10.024, DOI	2015	21.21	2017	2021	
Schipanski M, 2014, AGR SYST, V125, P12, DOI 10.1016/j.agsy.2013.11.004, DOI	2014	19.5	2015	2019	
Celette F, 2009, EUR J AGRON, V30, P41, DOI 10.1016/j.eja.2008.07.003, DOI	2009	13.48	2010	2014	
Mbuthia L, 2015, SOIL BIOL BIOCHEM, V89, P24, DOI 10.1016/j.soilbio.2015.06.016, DOI	2015	12.06	2017	2021	
Kladivko E, 2014, J SOIL WATER CONSERV, V69, P279, DOI 10.2489/jswc.69.4.279, DOI	2014	11.26	2015	2019	
Kaspar T, 2007, J ENVIRON QUAL, V36, P1503, DOI 10.2134/jeq2006.0468, DOI	2007	10.47	2008	2012	
Strock J, 2004, J ENVIRON QUAL, V33, P1010, DOI 10.2134/jeq2004.1010, DOI	2004	10.37	2005	2009	
Basche A, 2016, AGR WATER MANAGE, V172, P40, DOI 10.1016/j.agwat.2016.04.006, DOI	2016	9.75	2017	2021	
Mirsky S, 2012, RENEW AGR FOOD SYST, V27, P31, DOI 10.1017/S1742170511000457, DOI	2012	9.1	2013	2017	
Malone R, 2014, J SOIL WATER CONSERV, V69, P292, DOI 10.2489/jswc.69.4.292, DOI	2014	8.92	2015	2019	
Kaye J, 2017, AGRON SUSTAIN DEV, V37, P0, DOI 10.1007/s13593-016-0410-x, DOI	2017	12.94	2018	2021	
Kaspar T, 2012, AGR WATER MANAGE, V110, P25, DOI 10.1016/j.agwat.2012.03.010, DOI	2012	12.28	2014	2017	
Snapp S, 2005, AGRON J, V97, P322	2005	11.14	2007	2010	
Finney D, 2016, AGRON J, V108, P39, DOI 10.2134/agronj15.0182, DOI	2016	10.13	2018	2021	
Celette F, 2008, EUR J AGRON, V29, P153, DOI 10.1016/j.eja.2008.04.007, DOI	2008	10.03	2010	2013	
Pittelkow C, 2015, NATURE, V517, P365, DOI 10.1038/nature13809, DOI	2015	9.18	2016	2019	
Basche A, 2014, J SOIL WATER CONSERV, V69, P471, DOI 10.2489/jswc.69.6.471, DOI	2014	11.23	2017	2019	
Steenwerth K, 2008, APPL SOIL ECOL, V40, P359, DOI 10.1016/j.apsoil.2008.06.006, DOI	2008	9.14	2011	2013	
Decker A, 1994, AGRON J, V86, P126, DOI 10.2134/agronj1994.00021962008600010024x, DOI	1994	8.69	1997	1998	

Figure 4. Top 20 References with the Strongest Citation Bursts.

Table 4. Top ten articles based on co-citation frequency.

Authors	Title	Journal	DOI	Frequency
Blanco-canqui et al. (2015)	Cover Crops and Ecosystem Services: Insights from Studies in Temperate Soils	Agronomy Journal	10.2134/agronj 15.0086	86
Poeplau & Don (2015)	Carbon sequestration in agricultural soils via cultivation of cover crops – A meta-analysis	Agriculture, Ecosystems & Environment	10.1016/j.agee. 2014.10.024	86
Basche et al.(2016)	Soil water improvements with the long-term use of a winter rye cover crop	Agricultural Water Management	10.1016/j.agwat.2016.04.006	70
Finney et al. (2016)	Biomass Production and Carbon/Nitrogen Ratio Influence Ecosystem Services from Cover Crop Mixtures	Agronomy Journal	10.2134/agronj 15.0182	67
Kaye & Quemada (2017)	Using cover crops to mitigate and adapt to climate change. A review	Agronomy for Sustainable Development	10.1007/s13593-016-0410-x	67
Schipanski et al. (2014)	A framework for evaluating ecosystem services provided by cover crops in agroecosystems	Agricultural Systems	10.1016/j.agsy. 2013.11.004	50
Basche et al. (2016)	Simulating long-term impacts of cover crops and climate change on crop production and environmental outcomes in the Midwestern United States	Agriculture, Ecosystems & Environment	10.1016/j.agee. 2015.11.011	47
Mbuthia et al. (2015)	Long-term tillage, cover crop, and fertilization effects on microbial community structure, activity: Implications for soil quality	Soil Biology and Biochemistry	10.1016/j.soilbio.2015.06.016	39
Wittwer et al. (2017)	Cover crops support ecological intensification of arable cropping systems	Scientific Reports	10.1038/srep41 911	38
Pittelkow et al. (2015)	Productivity limits and potentials of the principles of conservation agriculture	Nature	10.1038/nature13809	35

3.3. Citation-clustering analysis

Figure 5 and Table 5 present the results of citation-clustering analysis for the co-citation network; the clustering is generated via cluster optimization with the graphical method in CiteSpace software. Citation-clustering analysis can be beneficial for assessing the research domains and identifying changes in development trends in different periods. Our findings revealed that research clusters (i.e., a group of studies addressing similar and connected topics) increased primarily in the last decade, totaling 18 salient domains. Overall, research clusters of the literature may be categorized into three groups, namely Stage 1_A (1980-2000), Stage 1_B (2001-2010), and Stage 2 (2010-2021). In the early stage, studies primarily concentrated on the role of CC for nitrogen management and weed sup-

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pression purposes. In the second stage, research significantly focused on examining differences among types of CC in farming systems. Finally, in the last stage, research domains and hotspots in the literature generally revolved around the impact of CC on soil health.

In Stage 1_A, there were three salient subclusters with the following core terms: live and desiccated hairy vetch (a winter annual CC), Nitrate Leaching, and Economic Analysis Package (NLEAP), and nitrogen fertilization. The research studies in Stage 1_A predominantly assessed the role of a set of CC types for nitrogen management in cropping systems. Studies examining the use of hairy vetch CC and nitrogen management, such as Utomo et al. (1990), Hoffman et al. (1993), Teasdale (1993), Teasdale and Shirley (1998), Delgado (1998), and Rosecrance et al. (2000), represented examples of the research scope in this first stage. The next cluster, Stage 1_b (2001-2010), contained five salient research areas (i.e., subclusters), including winter CC use, tillage CC, mulch-based cropping system, olive grove, and nitrous oxide emission. Examples of studies published in this stage included Strock et al. (2004), Snapp et al. (2005), Hobbs et al. (2008), Celette et al. (2008; 2009), and Kaspar et al. (2007). We should note that research examining whether CC reduces N_2O emissions from the soil surface bridged the scopes of research in Stages 1_B and 2. The last stage, Stage 2 (2011-2021), encompassed the majority of knowledge domains and bursts for the topic of interest in this scientometric review. Particularly, the following subclusters were salient: extractable carbon, subtropical oxisol, nitrate leaching, reduced tillage, olive orchard, soil health, and winter CC effects. A small cluster but one with recent publications and with the potential for further expansion is soil health indicators (i.e., cluster #59). As noted earlier, the majority of influential articles with the strongest citation bursts and co-cited articles were published in this Stage (See Table 4 and Figure 4). A common theme across studies in this late stage—and a research frontier— was assessing the environmental effects of incorporating CC into crop rotations, particularly the potential benefits on physical and chemical soil properties. The most prominent hotspot in this stage and across Stages is the research focus on the winter CC effect (Refer to Figure 5, Stage 2, Cluster #0).

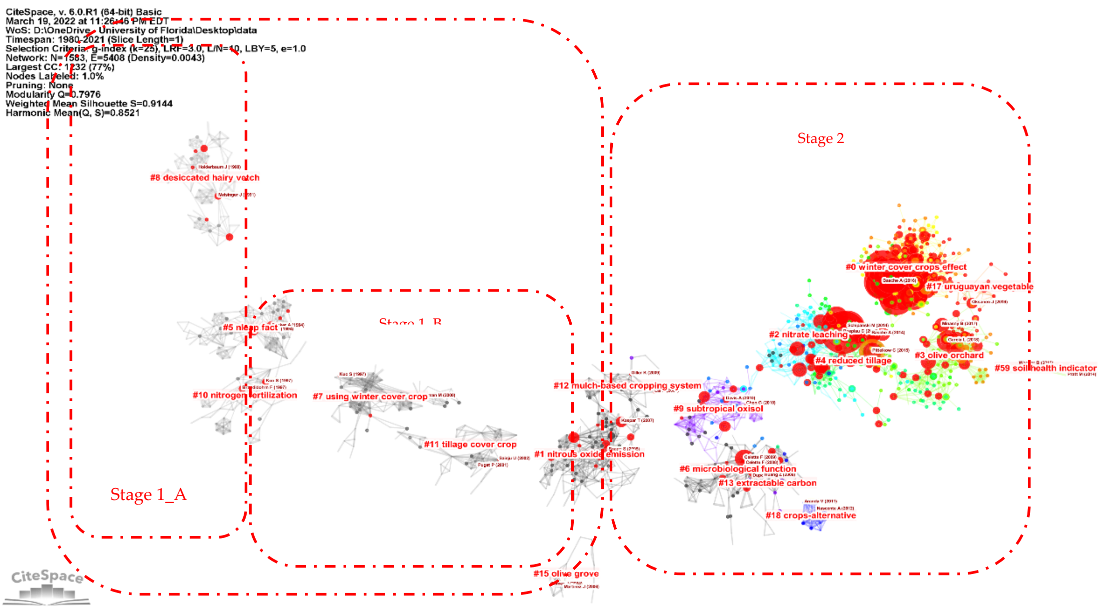

Figure 5. Cluster view of the co-citation network.

Table 5 provides the list of the 18 research hotspots in detail by the year's slice. The second column provides the size of the cluster—that is, the number of cited articles in a given cluster. The Silhouette value (third column in Table 5) denotes the efficiency and validity of clustering; a value greater than 0.6 indicates acceptable homogeneity (Jia et al., 2020). In our study, the Silhouette values for clusters were well over 0.6. The year column denotes the average publication year for articles within a cluster; for example, cluster #8 contained 68 articles, most of which were published around 1990. Finally, the column of top 5 terms presents the top five research terms in a specific cluster, ranked by latent semantic indexing (LSI). Results in this section were consistent with the hotspots and frontiers discussed in Figure 5. CC effects on nitrogen dynamics and soil quality were the two dominant research topics across all three stages. Moreover, the top 5 terms highlighted research foci by stage. For example, the terms "hairy vetch" and "Nitrogen" consistently appeared in clusters (i.e., 5, 8, 9, and 10) with articles published in the first stage (1980-2000). In the second stage (2001-2011), "nitrogen fertilization" and "mulch-based cropping system" were recurring terms. Finally, key terms used by studies published in the last stage include "cover crop effect" and "soil properties," denoting the current research frontiers of CC research.

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Table 5. Top 5 terms in citation-clustering results.

Cluster-ID	Cluster Label	Size	Silhouette	Year	Top 5 Terms (LSI)
#8	Desiccated hairy vetch	68	0.994	1990	weed suppression; desiccated hairy vetch; hairy vetch residue; cover crop; herbicide replacement
#5	NLEAP	86	0.967	1994	winter cover crop; nitrate loss; nitrogen management; NLEAP fact; nitrogen dynamics
#10	Nitrogen fertilization	52	0.963	1997	nitrogen fertilization; fresh market tomato yield; soil nitrogen; physical properties; tillage intensity
#7	Using winter cover crop	70	0.973	1999	carbon sequestration; nutrient cycle; west Asia; dryland ecosystem; north Africa
#11	Tillage cover crop	39	0.965	2001	nitrogen fertilization; underlying soil; carbon accumulation; nitrogen fertilization effect; coastal plain field
#1	Nitrous oxide emission	119	0.880	2004	nitrous oxide emission; rye cover crop; tile drainage; winter cover crop; cover crop effect
#15	Olive grove	13	0.993	2005	olive grove; soil erosion; soil properties; soil management effect; southern Spain
#12	Mulch-based cropping system	30	0.970	2006	cropping system; mulch-based cropping system; north Cameroon; mulching practice; multi-locational on-farm assessment
#6	Microbiological function	74	0.880	2007	cover crop; microbiological function; water conservation dilemma; steep vineyard; green cover
#9	Subtropical oxisol	53	0.927	2009	subtropical oxisol; Brazilian oxisol; organic agriculture; contrasting tillage system; crop-establishment period
#13	Extractable carbon	22	0.978	2008	different cover crop residue; extractable carbon; microbial metabolic diversity; nitrogen pool; winter crop
#18	Crops-alternative	11	0.999	2010	upland rice yield; no-tillage system; crops-alternative; upland rice development; cover crop
#2	Nitrate leaching	112	0.924	2011	cover crop; cropping system; nitrate leaching; soil crop model; catch crop
#4	Reduced tillage	89	0.891	2013	cover crop; crop yield; N_2O emission; reduced tillage; greenhouse gas emission
#59	Soil health indicator	3	0.993	2014	upland rice yield; no-tillage system; crops-alternative; upland rice development; cover crop
#3	Oliver orchard	104	0.934	2015	cover crop; olive orchard; European vineyard; Mediterranean vineyard; rainfed vineyard;
#0	Winter cover crops effect	265	0.840	2016	cover crop; soil properties; soil health; cover crop effect; soybean yield
#17	Uruguayan vegetable	12	0.978	2018	soil microbiota; organic amendment; Uruguayan vegetable; farming system; soil health

3.4. Co-occurrence network of subject terms analysis

This section presents the results co-occurrence network of subject terms analysis. Yu et al. (2017) argued that the keywords and co-occurrence networks could identify research hotspots in the literature on a particular topic. Figure 6 displays the co-occurrence network of subject categories (398 nodes, 1590 edges; average degree of 7.99 and network

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density of 0.02). Similar to our findings in Figure 5 or Table 5, the most important keywords used in the literature were yield, Nitrogen, soil organic matter, water quality, and conservation tillage. Further, we calculated a set of indicators (i.e., frequency, degree centrality, betweenness centrality, and closeness centrality) for the co-occurrence network. We should note that we excluded keywords, such as CC and word extensions (e.g., cover crops, cover cropping) from the top five subject terms listed in Table 6. Overall, the salient hotspots in the literature were topics such as Nitrogen and weed management and conservation tillage. Importantly, CC research emphasizing corn cropping systems and wheat (used as a CC and in the crop rotation of other cash crops) appears to be hotspots in the literature. These results are consistent with our findings in the citation-clustering analysis (see Table 5).

Table 6. Top five subject terms in co-occurrence network by four indexes.

Rank	Frequency	Degree centrality	Betweenness centrality	Closeness centrality
1	Management (756)	Residue (39)	water quality (4575)	Nitrogen (0.426)
2	Nitrogen (475)	Nitrogen (38)	Weed Management (4567)	Management (0.423)
3	Yield (470)	wheat (38)	Quality (4199)	Wheat (0.418)
4	Tillage (439)	conservation tillage (36)	Germination (3976)	Carbon (0.417)
5	Soil (432)	Management (36)	Residue (3780)	Corn (0.416)

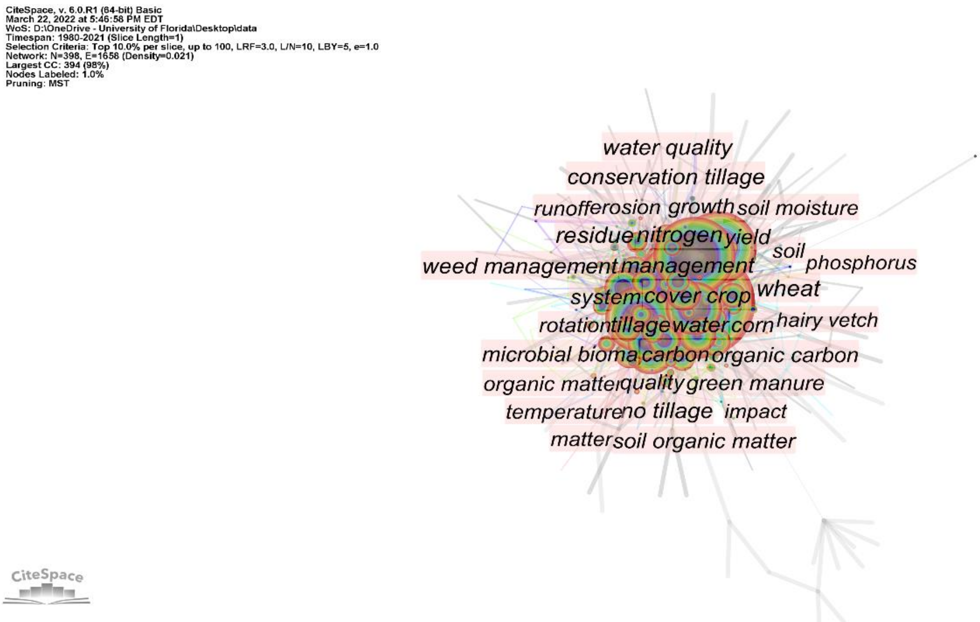

Figure 6. Co-occurrence network of subject terms.

3.5. Academic cooperation among authors, institutions, and countries

Academic collaboration among scholars, institutions, and countries is vital for advancing knowledge and promoting the development of new technologies (Koseoglu, 2016; Choe & Lee, 2017). Collaboration analyses help understand scholarly communication and knowledge diffusion (Chen, 2006; Fang et al., 2018). In this paper, we constructed three collaboration networks—author-level, institutional, and country-level—to analyze links and patterns of academic collaboration as reflected in the literature on the environmental effects of CC.

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3.5.1. Co-authorship network analysis

Figure 7 depicts the author's collaboration network for literature on the environmental effects of CC research. We used Gephi software to analyze the network structure and characteristics. The nodes and edges of the co-authorship network were 1,227 and 2,412, respectively. In this network, nodes represented individual authors, and links illustrated patterns of cooperation among authors. The size of each node represented the number of publications, and the thickness of the links represented the strength or level of collaboration among a set of authors (Olawumi & Chan, 2018; Zandi et al., 2019). The average degree of this network was 3.92, and the network density was 0.003, indicative of a dispersive network. In other words, scholars, particularly those with significant contributions to the literature, may seldom co-author publications. Table 7 provides a set of indicators—i.e., citation frequency degree centrality, betweenness centrality, and closeness centrality—to represent the impacts of authors (Zandi et al., 2019). Based on the indicators above, the following were the most prominent scholars in the literature regarding the environmental effects of CC: Dr. José Alfonso Gómez Calero (Research Scientist in the Institute for Sustainable Agriculture, Spanish National Research Council [Consejo Superior de Investigaciones Cientificas]), Dr. Tom Kaspar (Retired Plant physiologist at USDA-ARS), Dr. Rattan Lal (Distinguished University Professor of Soil Science at The Ohio State University), Dr. Steven Mirsky (Research Ecologist at USDA-ARS), Dr. Eric Justes[2] (Senior scientist in agronomy and Agroecology at the French Agricultural Research Centre for International Development [Centre de Coopération Internationale en Recherche Agronomique pour le Développement, CIRAD]).

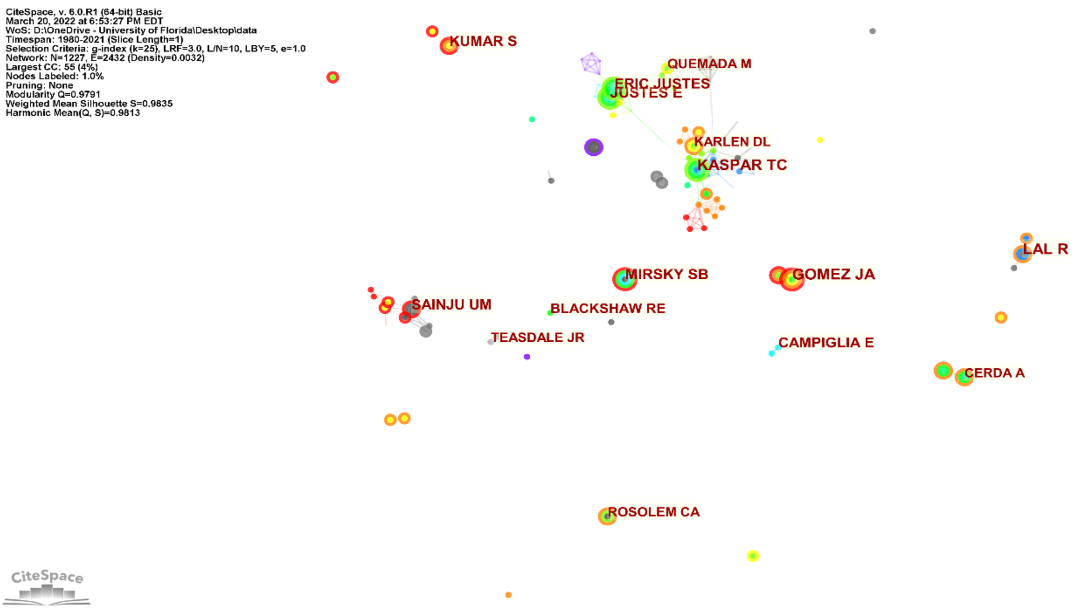

Figure 7. The results of co-authorship network analysis.

[2] In the co-authorship network, the name of author Eric Justes, Ph.D. was listed as Eric Justes and Justes E. The CiteSpace software cannot identify these two names variants as the same author automatically, nor does it combine the outputs attributed to this author. Importantly, we should note that the combined citation frequency for Dr. Eric Justes makes him the most productive author in the network.

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Table 7. The centrality of the top 5 productive authors in the co-authorship network.

Author	Frequency	Degree centrality	Betweenness centrality	Closeness centrality
José A. Gómez	18	10	38.7	1.0
Tom Kaspar	16	15	916.4	1.0
Rattan Lal	16	2	1.0	1.0
Steven Mirsky	14	18	363.0	1.0
Eric Justes	14	6	166.0	1.0

3.5.2. Institution and country collaboration network analyses

The institution and country collaboration networks are displayed in Figures 8 and 9. The institution collaboration network contained 744 nodes and 1319 edges, while the country collaboration network had 127 nodes and 555 edges. The average degree of institution collaboration network was 3.546, and the network density was 0.005. The average degree for the country collaboration network was 8.74, with a network density of 0.069. The thicker edge in Figures 8 and 9 denotes more collaborations between two nodes, i.e., countries and institutions. Overall, we found that the country collaboration network was denser than the institution collaboration network; in other words, there is more country collaboration than inter-institutional cooperation in the extant literature.

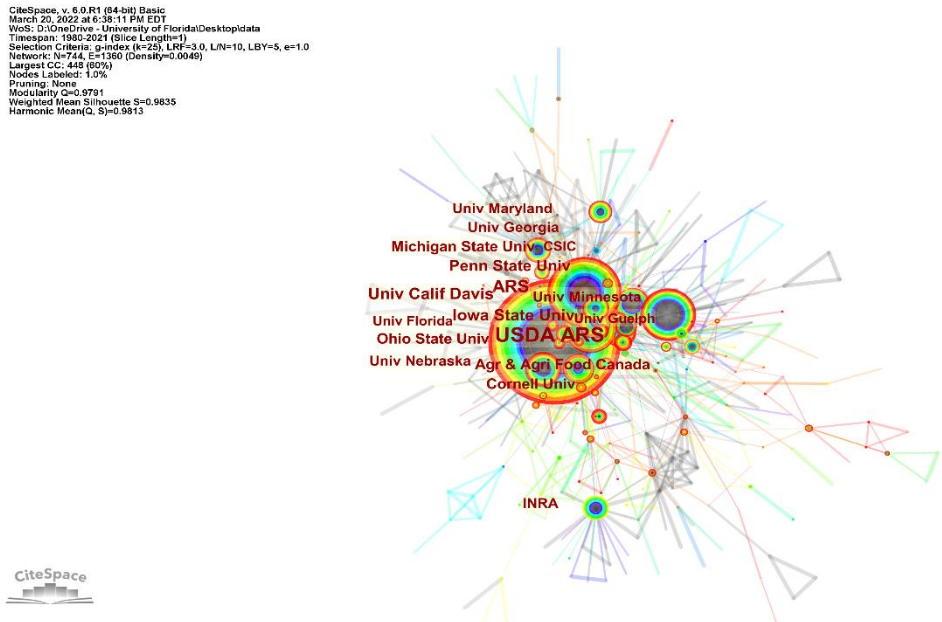

Figure 8. the results of institution cooperation network analysis.

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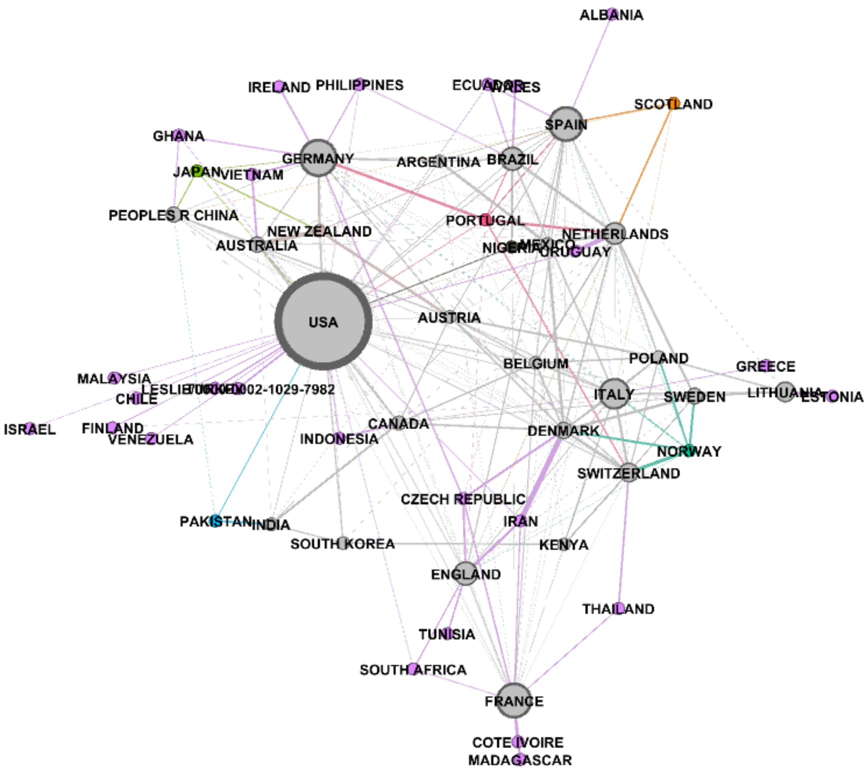

Figure 9. the results of country cooperation network analysis.

Table 8 shows the centrality indicators of the top ten institutions based on their frequency in the networks. USDA-ARS ranks at the top of the list with 397 publications or 12.23% of total records. Similarly, based on the examined indicators, USDA-ARS was the most productive contributor to the literature on CC. Other contributing institutions to the field of study are Iowa State University (107 manuscripts), University of California-Davis (96 manuscripts), The Pennsylvania State University (74 manuscripts), Agriculture and Agri-Food Canada (71 manuscripts), and Michigan State University (65 manuscripts). A salient finding is that most top contributing institutions to the CC field are in the United States.

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Table 8. Top 10 institutions based on the frequency.

Institution	Frequency	Degree centrality	Betweenness centrality	Closeness centrality
USDA ARS	397	120	35856.347	0.471
Iowa State University	107	51	5063.947	0.416
University of California Davis	96	41	9797.681	0.376
The Pennsylvania State University	74	27	7125.650	0.398
Agriculture and Agri-Food Canada	71	31	5403.697	0.379
Michigan State University	65	36	4899.075	0.395
Cornell University	64	33	9221.985	0.390
Ohio State University	61	25	3229.640	0.370
University of Minnesota	48	34	3709.021	0.39
French National Institute for Agricultural Research	53	28	8676.522	0.323

Note: USDA ARS appears in literature metadata as USDA ARS and ARS. For the purpose of this study and this table, USDA ARS and ARS are combined. The frequency for ARS was 153.

Table 8 provides the list of the ten countries with the highest rank of contribution to the literature of interest. The United States ranked first with 1,608 publications, contributing about 49.53% of the total records published in peer-reviewed journals. Likewise, the degree centrality, betweenness centrality, and closeness centrality indicators placed the United States as the highest producer of academic outputs on the relationship between CC and environmental effects. Other countries with at least 100 publications included Brazil (236 articles), Spain (203 articles), Italy (179 articles), Canada (177 articles), France (149 articles), China (145 articles), and Germany (112 articles).

Table 9. Top 10 countries based on the frequency.

Country	Frequency	Degree centrality	Betweenness centrality	Closeness centrality
USA	1608	87	3755.560	0.758
Brazil	236	25	144.465	0.541
Spain	203	35	461.344	0.565
Italy	179	32	165.041	0.543
Canada	177	21	85.837	0.518
France	149	41	565.124	0.584
China	145	29	246.070	0.548
Germany	112	49	691.823	0.610
England	83	36	304.888	0.568
Australia	74	32	654.972	0.556

4. Conclusions

Using network analysis methods and indicators (e.g., average degree, density, component, average paths length, and centrality), this study explored research frontiers, hotspots, and cooperation (i.e., at the scholar-, institution-and country-levels) in the existing literature related to the environmental impacts of CC. We retrieved and analyzed 3,246 peer-reviewed articles published in the last forty years from the Web of Science database.

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The main output of this article was a knowledge map of the literature (see Figure 10) that provides insight into the research activity, trajectory, and frontier of knowledge.

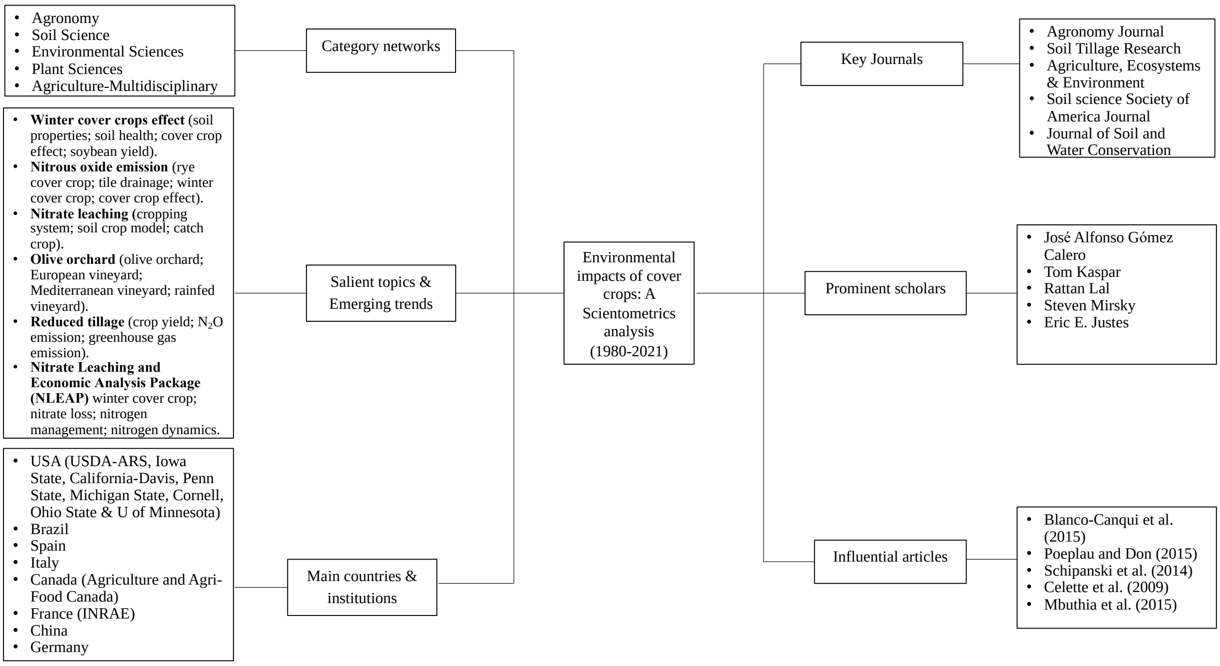

Figure 10. Mind map of this paper.

Overall, the number of peer-reviewed outputs documenting the effects of CC on the environment—particularly the relationship between the use of CC and soil properties—has consistently increased in the past 40 years, with a notable rise in publications within the last decade. Research studies have primarily addressed 18 core research topics, where the most salient domains included the impact of using winter CC in cropping systems, the relationship between CC usage and nitrous oxide emissions, reduction of nitrate leaching in agroecosystems, and the implications of incorporating CC and reduce tillage/no-tillage for soil health and field quality. The existing literature may be categorized into three stages: Stage 1_A (1980-2000), Stage 1_B (2001-2010), and Stage 2 (2010-2021). In the early stage, research mainly examined the association between CC, nitrogen management, and weed suppression. In the middle stage, CC studies assessed the impact of using different CC mixtures in farming systems. Lastly, in the last stage and current research frontier, the literature primarily addressed the environmental benefits of CC, particularly the implications for physical and chemical soil properties and soil health indicators to assess the impact of CC. The following were influential articles in the literature: Blanco-Canqui et al. (2015), Poeplau and Don (2015), Schipanski et al. (2014), Celette et al. (2009), and Mbuthia et al. (2015). Interestingly, most of these studies were published in Stage 2 between 2011-2021. The leading journals with a higher rate of publication on the environmental effects of CC included *Agronomy Journal*, *Soil Tillage Research*, *Agriculture, Ecosystems & Environment*, and the *Soil science Society of America Journal*. In terms of author-institution-and country-level networks, our findings indicated that Drs. Justes (CIRAD, France), Gómez Calero (the Spanish National Research Council), Kaspar (USDA-ARS), Lal (the Ohio State University), and Mirsky (USDA-ARS) are influential contributors to the literature on the environmental effects of CC. Further, based on network structures, country collaboration patterns were more frequent than co-authorship or institutional collaboration patterns. The countries with the most research outputs were the United States, Brazil, and Spain. Finally, the majority of top contributing institutions to the field of CC were based in the United States. USDA-ARS was the most productive contributor to the literature on CC research in the last forty years.

4.1. Limitations and future scientometric research

Several limitations must be considered when interpreting the findings from this scientometric analysis. First, the data for this study was delimited to peer-reviewed articles published in scientific journals indexed in the Web of Science—which is the most comprehensive database for scientific outputs (Olawumi & Chen, 2018). In other words, gray literature (e.g., working papers, technical bulletins, theses and dissertations, conference proceedings, government reports) and books were excluded from the analysis due to time and financial constraints. To reduce publication bias (Paez, 2017), future research studies may consider grey literature document types for the analysis and include other large science databases (e.g., Scopus and Google Scholar). A second limitation worth noting is that the literature review in this paper was limited to articles published in the English language. This particular limitation has ramifications for the findings concerning institution- and country-level networks. Finally, the scope of this scientometric analysis focused exclusively on the existing literature on the environmental impacts of CC. Future review and scientometric studies may consider a broader approach and include investigations concerning economic and social externalities of CC for analysis purposes.

Appendix A

Network analysis indicators

Network density can be represented as follow (Frey, 2018):

$$\rho = \frac{c}{n-1} \tag{1}$$

Where ρ denotes the network density, c is the mean degree of nodes in an undirected network, and n is the number of nodes. The possible value of network density ranges from 0 to 1. When the density value approaches 1, the network is denser. Otherwise, the network is more dispersive. A higher network density value means a greater connection between nodes, such as references, keywords, and authors.

Betweenness centrality is one of the centrality measurements and can be represented as follows:

$$c_B(k) = \sum_i \sum_j \frac{\rho(i,j,k)}{\rho(i,j)}, i < j, k \neq i \neq j \tag{2}$$

Where $c_B(k)$ is the betweenness centrality of node k, $\rho(i,j)$ is the number of geodesic or shortest paths between node i and node j; and $\rho(i,j,k)$ refers to the number of paths that pass-through node k. In our study, we used the betweenness centrality as an indicator to determine the importance of each node in networks.

Closeness centrality refers to the sum of distances from one node to the other nodes (Zhang & Luo, 2017). It can be given as:

$$\ell_i = \frac{1}{n} \sum_j d_{ij} \tag{3}$$

Where d_{ij} is the length of a geodesic path from i to j.

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