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Knowledge Map of Soil Nutrient Migration Analysis Based on WOS (Web of Science) Database

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Abstract

It is important to understand the research trends and hotspots of global soil nutrient migration and control. Based on the core collection of WOS (Web of Science), citespace knowledge map analysis tool was used to analyze the number of publications, cooperation networks, disciplines, research hotspots and frontier trends on nutrient migration in soil. The results showed that: the number of publications on the study of soil nutrient migration showed a good growth from 1990 to 2021. 173 countries had cooperative relationships. The number of articles published in the United States and China was significantly higher than that in other countries, while Chinese Academy of Sciences was the institution with the largest number of publications. It was a comprehensive system that permeates with agriculture, environmental science, botany and other disciplines. The research of nutrient migration in soil mainly focused on the measures of microbial community in different land types to promote nutrient transformation, improve soil fertility and reduce nutrient loss. In the future, the research trends will be the management measures of soil nutrient loss, the relationship between the change of soil nutrient and plant community diversity, and the remediation of agricultural contaminated soil. Through the above analysis, there was an overall understanding of soil nutrient migration. The research on nutrient migration may continue to increase in the future. It is suggested that Chinese research institutions, teams and universities need to strengthen international cooperation, and speed up their integration with the international community.

Keywords

CiteSpace, Soil Nutrients, Visual Analysis, Research Progress, Nutrient

Migration

1. Introduction

Fertilization has become the main effect of increasing the yield of food crops. However, the migration of soil nutrients is the key factor affecting fertilizer utilization rate, and nutrients are essential nutrient elements for plant growth [1] [2]. Nutrient transfer refers to the movement of nutrients between ecosystems. The mechanism and main influencing factors of nitrogen migration are different within certain ecosystem [3]. Soil nutrient migration is influenced by the interaction of root growth, soil physical and chemical properties, topographic conditions, rainfall intensity, climate, land use patterns, management measures and fertilization methods [4] [5] [6] [7]. Among them, the main influencing factors of soil nutrient migration to root system are soil nutrient concentration and soil water content, which provide a medium for nutrient migration and directly affect nutrient migration quantity [8]. The migration and loss of soil nutrients were influenced by many factors, and the process was complicated, involving a wide range of disciplines and contents. There have been many research results on the migration [9], loss [10] [11] and factors affecting migration of nutrient elements (N, P, K) in the soil [12] [13] [14]. Song H X *et al.* [15] used summer corn as experimental crops, indicating that NO_3^--N can absorb water with plants, transfer to plant roots as solute, and uniformly distribute in rhizosphere soil, while NH_4^+-N is not affected by root growth and soil water supply. CiteSpace software is a visual analysis software developed based on scientometrics and data visualization theory. It can effectively find out the literature that has a key impact on the development of a discipline by analyzing the citation relationship of the literature, and show the development trend and trend of a discipline or knowledge field in a certain period [16]. Researchers used Citespace to study hot issues and research trends in the fields of soil ecosystem [17], soil microorganism [18], soil erosion [19], soil remediation using biochar [20], soil heavy metal [21], soil microplastics [22], soil pollution [23], soil health [24] and so on (heavy metal contaminated soil remediation, soil respiration, soil microorganism, soil pesticide pollution, soil erosion, soil heavy metals). Chen *et al.* [17] used CiteSpace to analyze and study the knowledge map of soil ecosystem, and revealed the evolution law and driving factors of research topics in this field, changes of research hotspots and future research trends. However, there is little research on the visual analysis of soil nutrient migration from a macro perspective to understand the general situation and development trend of the research field of soil nutrient system migration, and analyze the hot spots and frontier trends of international soil nutrient migration research. Based on the WOS (Web of Science) database, CiteSpace, a bibliometric software, is used to analyze the scientific knowledge of soil nutrient research, which provides reference for the research field of nutrient migration in soil.

2. Materials and Methods

2.1. Data Collection

The literature data adopted in this study came from the core collection database of Web of Science, using advanced search, searching the topic "topic = soil nutrient transfer or topic = soil nutrient movement", selecting Article and Review as the literature type and English as the language. The retrieval time span was from 1990 to 2021, and a total of 3997 articles were retrieved, excluding meetings, briefings, book abstracts, etc. which were imported into Citespace software for deduplication processing, and 3852 articles were obtained.

2.2. Research Method

With the help of CiteSpace (version 5.8. R 1), this paper made a knowledge visualization map analysis of the literature on soil nutrient migration published from 1990 to 2021, mainly analyzing the number of published articles, countries, authors, research institutions, discipline categories, key words and cited literature. The unified time slice was set to 1 year, and other operations were set by default, and graphic analysis of different node types was carried out.

3. Results and Discussion

3.1. The Quantity and Time Characteristics of Publication

From 1990 to 2021, the literature distribution of soil nutrient migration was shown in Figure 1. The number of papers in this field is generally on the rise. There were only 10 papers in 1990 and the highest number was 285 papers at the end of 2021. It could be roughly divided into three stages: preliminary rising

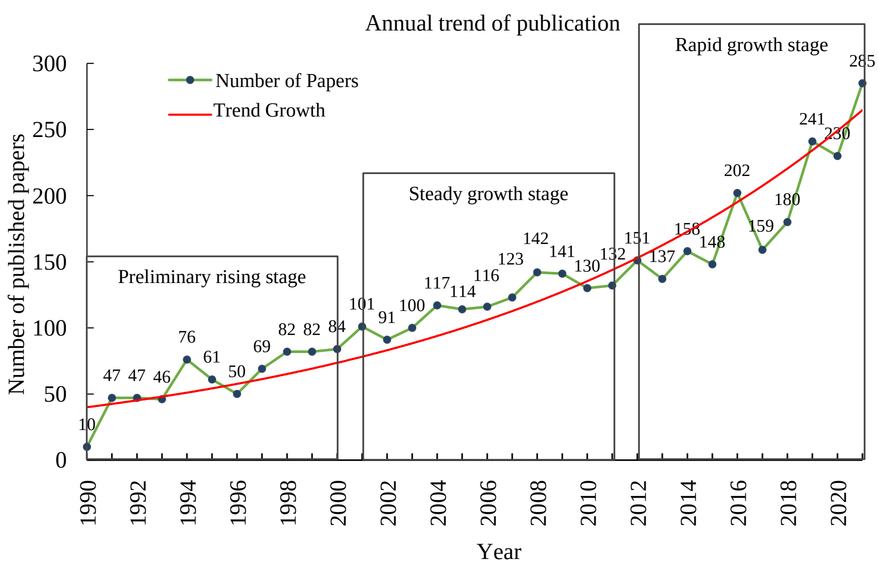

Figure 1. Chronological changes of the literatures.

stage, steady growth stage and rapid growth stage.

From 1990 to 2000, the average number of papers on soil nutrient migration was 65.4 per year, which was in a preliminary rising stage. At the end of the 20th century, the research on soil resources, environment and ecosystem promoted the development of pedology [25], and at the same time promoted the research and development of soil nutrient migration, which increased from 10 articles published in 1990 to 84 articles published in 2000. From 2001 to 2011, the number of published articles increased steadily, and the number of published articles basically exceeded 100, with an average annual rate of 130.7 articles. The minimum number of published articles was 91 in 2002, and gradually increased to 132 in 2011. During the period of rapid growth from 2012 to 2021, there was an average of 210 articles every year. Although it declined sometimes, the number of articles published mainly exceeded 200, reaching the highest value (285) at the end of 2021. There is a good growth trend between the number and year of the research literature on soil nutrient migration published internationally.

3.2. Spatial Distribution Characteristics

The number of articles published by research institutions and countries can intuitively judge the degree to which an institution or a country attaches importance to the research field of soil nutrient migration, and provide reference for evaluating its academic influence on social relationships between scholars, countries or institutions.

3.2.1. Country Cooperation Network

The map of national cooperation could be used to reveal the distribution of cooperation areas and intensity among countries [26]. As shown in **Figure 2**, the national cooperation map has 173 nodes and 750 links, which show that from 1990 to 2021, 173 countries had cooperated in different degrees and ways in the field of soil nutrient migration. Among them, the United States, Germany, China, Australia and Britain had larger nodes, which indicated that these countries had more relevant research and were closely connected to each other. It could be seen that the mutual cooperation research among these countries was frequent.

Generally, when the intermediary center of a node was ≥0.1, the node could be regarded as a key node [27]. As can be seen from **Table 1**, the top five countries were the United States, China, Australia, Germany and Britain. During this period, the United States co-published 1083 papers, accounting for 28.09%. With an intermediary centrality of 0.57, it indicated that the research field of soil nutrient migration in the United States had the greatest influence at the international forefront. From the intermediary centrality, it showed that the United States had more cooperation with other countries.

China published 427 papers, accounting for 11.85% of the total number of published papers. With an intermediary center of 0.06, it showed that there was

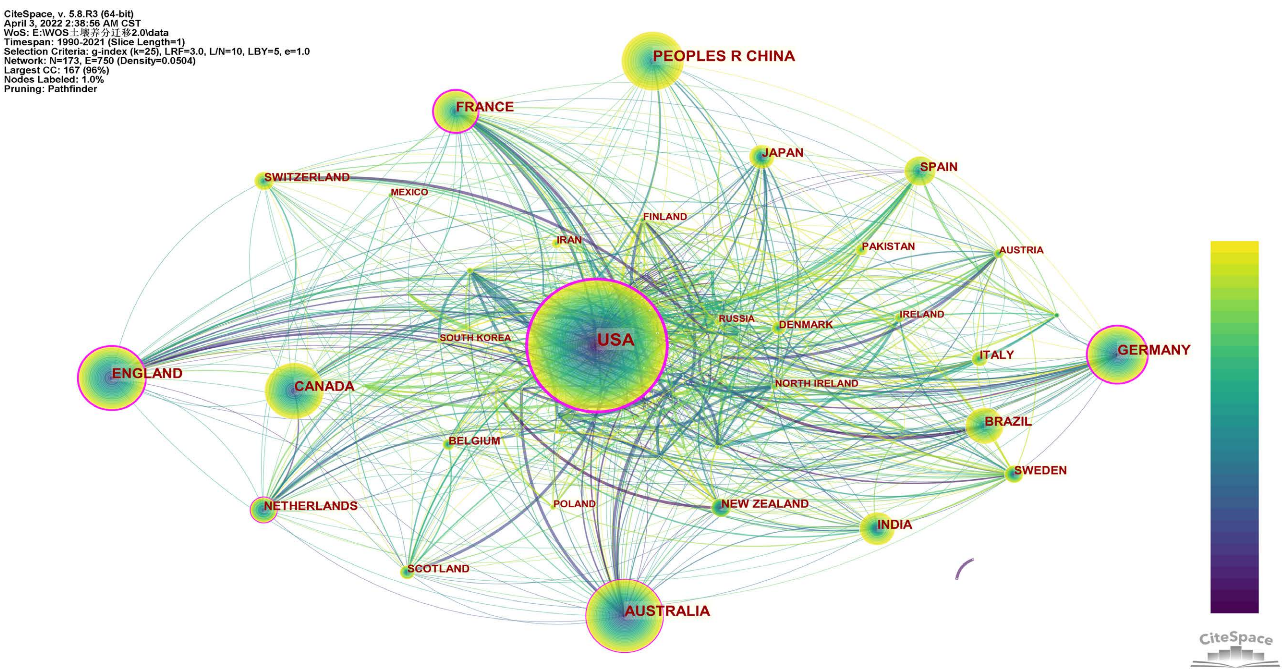

Figure 2. Network of country cooperation. The color bar in the picture represents the year, blue is the earlier year and yellow is the later year. Circular nodes represent different countries, and their size is directly proportional to the number of papers published in cooperation. The connection between nodes indicates that there is a cooperative relationship. The color of the annual ring indicates the year in which it appeared, and the thicker the year, the higher the frequency of papers published. The purple outer circle is intermediary-centered, and the thicker it is, the stronger the country's activity in the cooperative network and the greater its influence [28].

Table 1. Characteristics and frequency of country cooperation from 1990 to 2021.

Order	Number of articles	Centrality	Country	Starting year
1	1083	0.57	USA	1990
2	427	0.06	PEOPLES R CHINA	1999
3	302	0.17	AUSTRALIA	1992
4	297	0.22	GERMANY	1990
5	264	0.21	ENGLAND	1992
6	233	0.05	CANADA	1991
7	218	0.31	FRANCE	1993
8	147	0.09	BRAZIL	1991
9	144	0.03	INDIA	1993
10	131	0.08	SPAIN	1994
11	118	0.10	NETHERLANDS	1991
12	115	0.02	JAPAN	1991
13	96	0.08	SWEDEN	1991
14	95	0.04	NEW ZEALAND	1990
15	92	0.04	ITALY	1997

little cooperation with other countries in this field. The research on soil nutrient migration started late in China, but it was actively approaching the world. The centrality in Australia, France, Germany, Britain and Netherlands was more than 0.1.

3.2.2. Network of Author Cooperation

Through the author cooperation network, it could analyze the cooperation and mutual citation among the key figures and researchers. As could be seen from Figure 3, there were 1007 nodes in the author's cooperation network, which indicated that 1007 scholars cooperated with others to carry out on research of nutrient migration in soil and published 564 academic papers from 1990 to 2021. According to the connection color, C. Hamel and DL Smit, EMH Wellington and N. creswell cooperated more in 1991. By 2014, cooperation groups with P JORDAN, Quan Jiuwang and others were formed.

According to statistics, the top 10 core authors were listed in Table 2, and it was found that P JORDAN had published the most articles, for 10 articles. According to Price Law, the authentication formula of core authors was $M \approx 0.749 \times \sqrt{N_{\max}}$, and $N_{\max}$ was the number of authors who publish the most papers; M was the core author with the lowest number of documents [29].

After calculation, $M \approx 0.749 \times \sqrt{10} = 2.369$, then the authors publishing at least three articles were the core authors. According to statistics, there were 53 core authors, and 213 papers had been published. The total number of papers

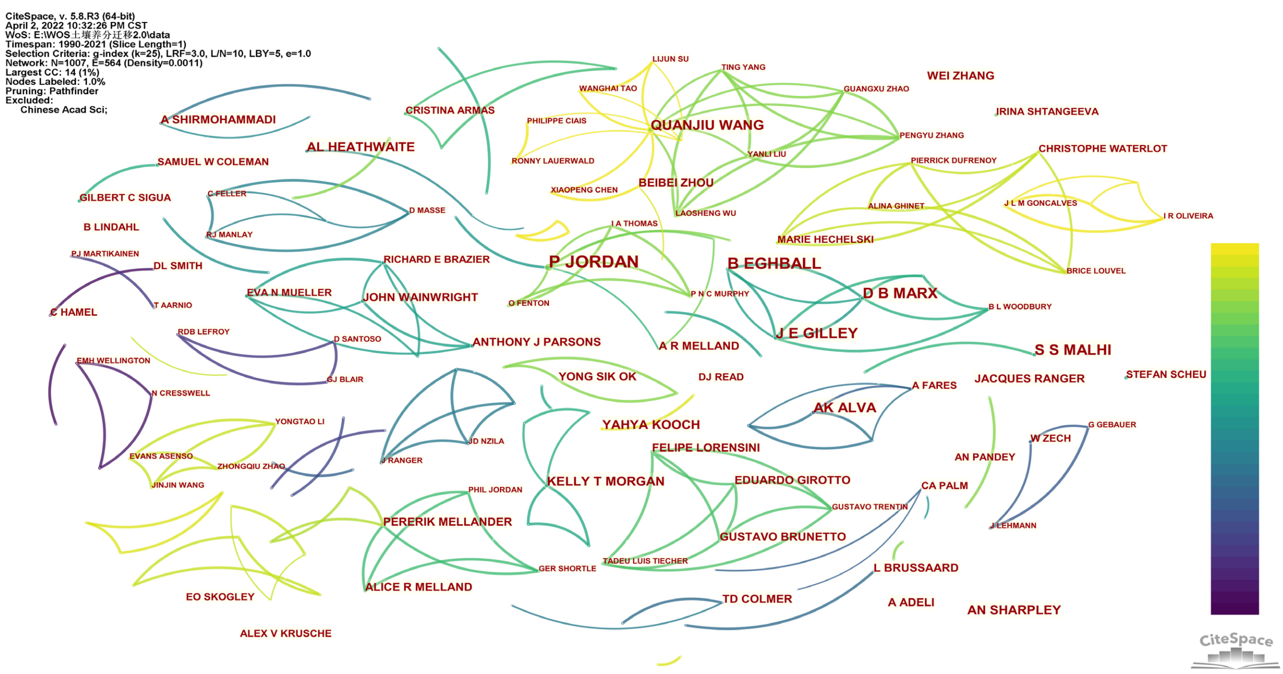

Figure 3. Network of author cooperation. The size of the circular nodes in the figure reflects the number of articles published by the current authors. The connection between the nodes indicates that the two authors appear in a document together and have a cooperative relationship. The thickness of the connecting line indicates the cooperation intensity, the color corresponds to the year, the blue line corresponds to the early co-authors, and the green line corresponds to the recent co-authors.

Table 2. Characteristics and frequency of author cooperation from 1990 to 2021.

Order	Number of articles	Strength	Starting year	Authors
1	10	3.49	2007	P JORDAN
2	8	3.15	1999	B EGHBALL
3	7	4.17	2009	S S MALHI
4	7	3.88	2007	J E GILLEY
5	7	3.88	2007	D B MARX
6	6	3.32	1998	AK ALVA
7	6	2.54	2016	QUANJIU WANG
8	5	0.00	1998	AL HEATHWAITE
9	5	0.00	2020	YAHYA KOOCH
10	5	3.12	2009	KELLY T MORGAN

was small, accounting for only 5.52%, which indicated that there was no stable core author group in the world at present [30].

3.2.3. Network of Institutional Cooperation

Through the institutional cooperation network, it could know the cooperation between the core research institutions in a certain field. CiteSpace was used to draw the cooperation diagram of international research institutions (**Figure 4**). There were 780 research institutes with 893 links. The density of the co-occurrence map was only 0.0029, which showed that the cooperation between international research institutions was not close. It can be clearly seen from the figure that the Agricultural Research Center of the United States Department of Agriculture-Agricultural Research Service (USDA-ARS) and China Academy of Sciences were the main research institutions with the highest eccentricity of 0.1.

As could be seen from **Table 3**, the Chinese Academy of Sciences (Acad SCI) and China Agricultural University (China Agr Univ) had also published many papers, and research institutions in China has made great contributions in soil nutrient migration research. In addition, foreign institutions such as USDA-ARS, University of Florida (UF) and Institut Nationaldela Recherche Agronomique (INRA) had also published many papers in this field. The national co-occurrence chart showed that China, the United States and France were the main contributors to this field, which verified the conclusion of the co-occurrence chart of research institutions.

The suddenness of the testing institutions can reflect the key research institutions, rising time and activity degree of soil nutrient migration. As can be seen from **Table 4**, the emergent value of soil nutrient migration studied by the Chinese Academy of Sciences was 12.40 in terms of emergent intensity, which was the most active research and development organization in the world. The emergency value of USDA ARS was as high as 9.84, while that of Lancaster University

Table 3. Characteristics and frequency of institutional cooperation from 1990 to 2021.

Order	Institutions	Number of articles	Centrality	Starting year
1	Chinese Acad Sci	147	0.16	2003
2	USDA ARS	122	0.11	1991
3	Univ Florida	59	0.02	1998
4	INRA	50	0.03	1994
5	Univ Western Australia	45	0.06	2000
6	Agr & Agri Food Canada	44	0.04	1999
7	ARS	42	0.04	1997
8	Univ Nebraska	30	0.00	1999
9	Univ Lancaster	29	0.03	2005
10	China Agr Univ	28	0.02	1999
11	Cornell Univ	28	0.03	1998
12	CSIC	26	0.03	1997
13	Univ Calif Davis	25	0.02	1998
14	Swedish Univ Agr Sci	24	0.03	2005
15	Univ Wisconsin	24	0.01	1998

Table 4. Research institutions with strongest citation bursts in soil nutrient transfer study.

Top 15 Institutions with the Strongest Citation Bursts					
Institutions	**Year**	**Strength**	**Begin**	**End**	**1990-2021**
CSIRO	1990	8.22	**1992**	2007	
USDA ARS	1990	9.84	**1997**	2009	
Univ Nebraska	1990	5.00	**1999**	2008	
Univ Wageningen & Res Ctr	1990	5.55	**2001**	2008	
USDA	1990	4.70	**2002**	2005	
Univ Calif Davis	1990	5.09	**2004**	2008	
Univ Lancaster	1990	8.68	**2005**	2012	
Agr & Agri Food Canada	1990	5.35	**2009**	2013	
Landcare Res	1990	4.40	**2009**	2015	
TEAGASC	1990	6.70	**2011**	2018	
Univ Ulster	1990	6.26	**2011**	2016	
Univ Agr Faisalabad	1990	5.55	**2016**	2021	
Northwest A&F Univ	1990	4.57	**2016**	2021	
Chinese Acad Sci	1990	12.40	**2017**	2021	
Univ Lorraine	1990	4.71	**2017**	2021	

The red line in the table indicates the time span of this institution.

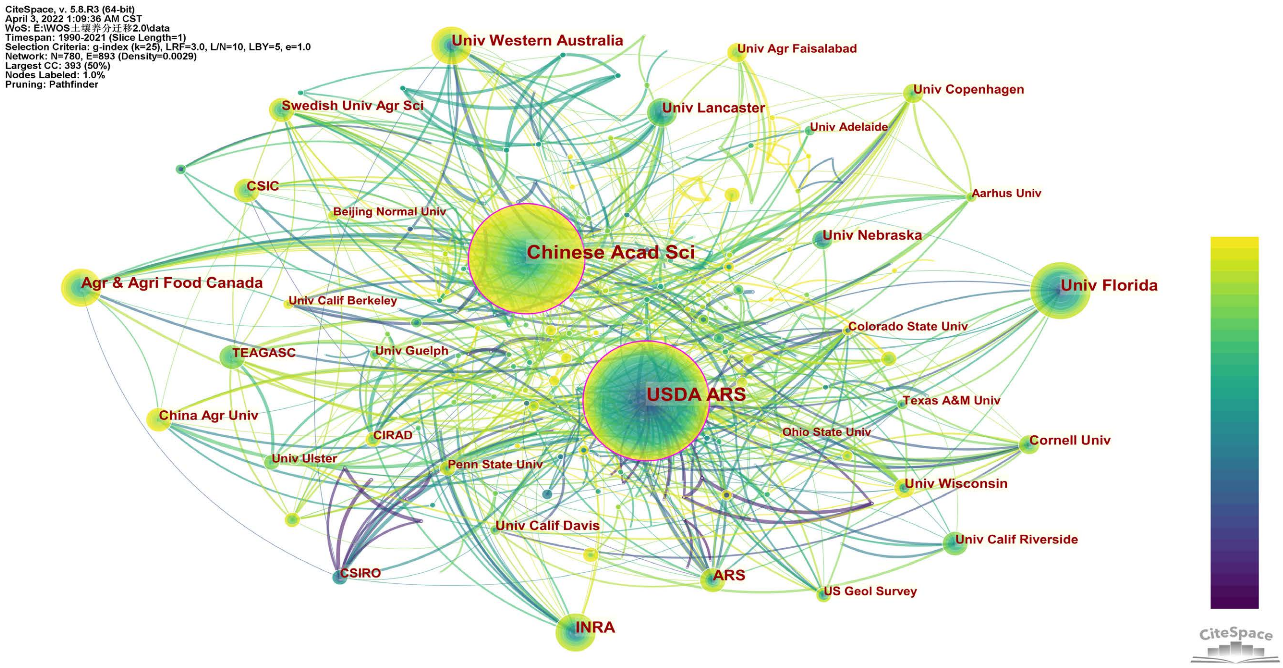

Figure 4. Network of institutional cooperation. The size of circular nodes in the map reflects the number of posts published by the organization, and the thickness of annual rings indicates the frequency of posting. The connection between nodes means that different institutions appear in a paper at the same time, indicating that there is a cooperative relationship among these institutions.

was 8.68. From the perspective of emergence, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) first appeared and had lasted for 16 years. The emergence time span of institutions such as the Agriculture and Food Development Authority (TEAGASC), Wageningen University & Research, the University of Nebraska and other institutions also exceeded 8 years.

3.3. Network of Discipline Co-Occurrence

Co-occurrence analysis of disciplines could construct the association network among disciplines and reveal the internal relationship between disciplines. According to the co-occurrence diagram of disciplines in Figure 5, there were 129 nodes and 512 connections. Among them, 129 nodes showed that 129 disciplines are inter-related around the research of soil nutrient migration, concentrating in environmental sciences & ecology, agriculture, environmental sciences, plant sciences and other fields. According to the number of connecting lines indicating cooperation frequency and thickness of cooperation intensity, it could be seen that environmental sciences & ecology, environmental sciences, ecology and agronomy had the closest cooperation, while soil science, plant sciences and agronomy had less cooperation. As Table 5 showed the first one was environmental sciences & ecology with a co-occurrence frequency of 1429. The betweenness centrality of ecology, environmental science and botany was all greater than 0.1, which indicated that they crossed most widely with other disciplines, and the frequency of cross-cutting between soil science and agronomy was high but the betweenness centrality was not high.

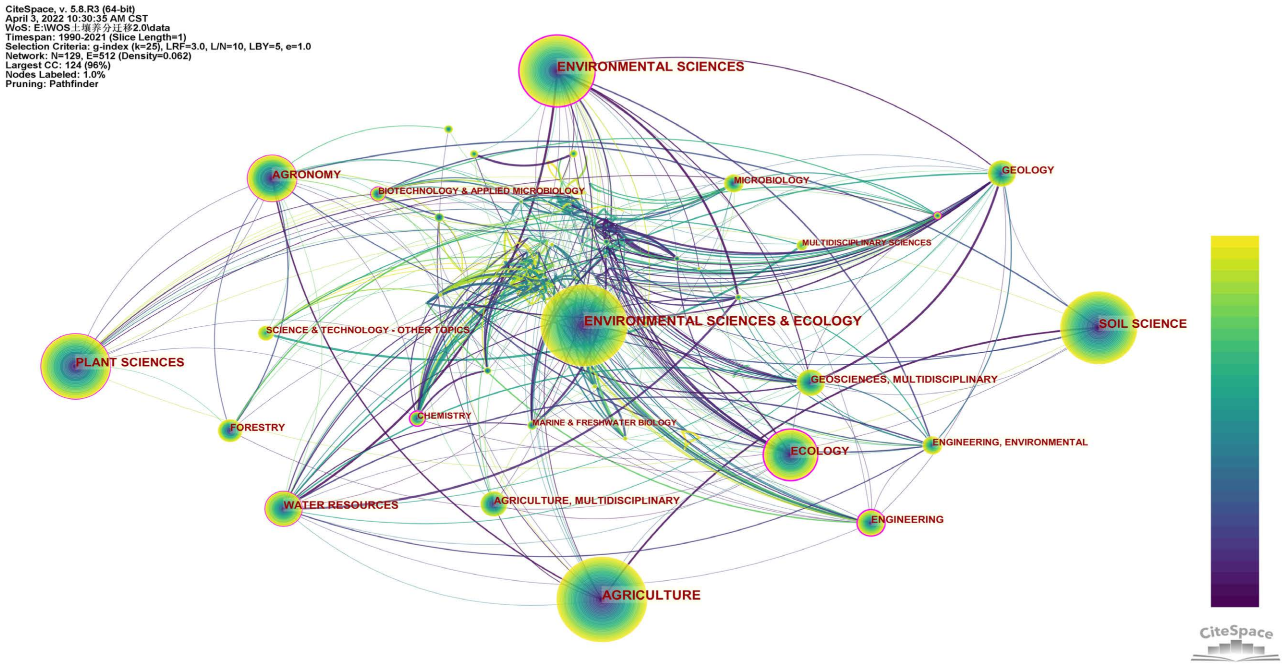

Figure 5. Network of discipline co-occurrence. The size of circular nodes in the atlas reflects the frequency of disciplines, and the thickness of annual rings indicates the frequency of the corresponding years. The link between nodes means the co-occurrence of disciplines.

Table 5. Characteristics and frequency of discipline co-occurrence.

Order	Subject area	Frequency	Centrality	Starting year
1	ENVIRONMENTAL SCIENCES & ECOLOGY	1429	0.06	1990
2	AGRICULTURE	1369	0.06	1990
3	ENVIRONMENTAL SCIENCES	1068	0.23	1990
4	SOIL SCIENCE	792	0.03	1990
5	PLANT SCIENCES	689	0.19	1990
6	ECOLOGY	519	0.26	1991
7	AGRONOMY	441	0.10	1990
8	WATER RESOURCES	334	0.11	1990
9	GEOLOGY	226	0.09	1991
10	GEOSCIENCES, MULTIDISCIPLINARY	221	0.09	1991
11	ENGINEERING	216	0.30	1992
12	AGRICULTURE, MULTIDISCIPLINARY	203	0.07	1990
13	FORESTRY	166	0.03	1991
14	ENGINEERING, ENVIRONMENTAL	146	0.03	1993
15	MICROBIOLOGY	141	0.07	1991

3.4. Research Hotspots and Frontiers

3.4.1. Research Hotspots

It can be seen from **Figure 6** that there were 756 nodes and 3990 links in the

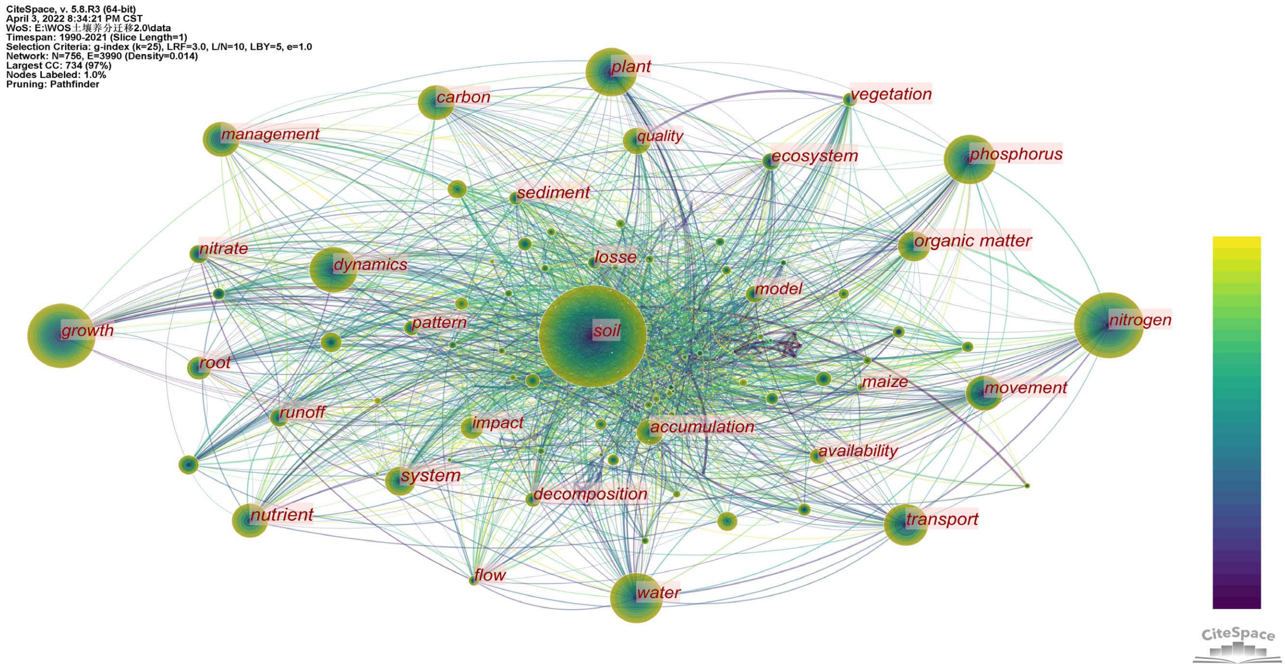

Figure 6. Network of keywords co-occurrence. The circle node in the figure is the keyword frequency, which is proportional to the size. The color of annual rings corresponds to the year, and the thickness is the frequency of occurrence. Node refer to two keywords that appear in the same document, and the degree of thickness reflects the co-occurrence strength of keywords.

co-occurrence graph. In the research field of soil nutrient migration, except for the three key words "soil", "nutrient" and "movement". There have been research hotspots (Nitrogen, phosphorus, growth, plant, carbon, dynamics, organic matter, water, transport, management, etc.) in this field in the past 30 years.

Keywords Co-occurrence diagram shows the hot spots of soil nutrient migration, the time of heat occurrence and its evolution law. As can be seen from Table 6, since 1990s, hot keywords with high emerging values have appeared, such as ecosystem, fungi, bacteria, movement, seeding, etc. These words had been the hot spots in the research of soil nutrient migration in the last 30 years. Since the new century, many key words had appeared in the first decade, among which corn, pasture, loss and fertilizer were the most prominent, which indicated that the important research focused at the beginning of the 21st century was the migration and loss of different types of land and its soil nutrient. After 2010, the key words with high emerging values were crop, surface water, environment, etc. In the last five years, the key words were microbial community, surface runoff, wastewater, arbuscular mycorrhizal fungi, etc. The research field focused on the impact of soil nutrient migration on the surrounding environment, and explored the interaction between microbial community and nutrient migration.

3.4.2. Research Frontier

Co-citation analysis can explore the key topics in the research field, their development process, research direction or the closeness between topics, and automatically cluster them based on the graph clustering algorithm, so as to extract

Table 6. Keywords with strongest citation bursts.

Top 25 Keywords with the Strongest Citation Bursts					
Keywords	**Year**	**Strength**	**Begin**	**End**	**1990-2021**
ecosystem	1990	12.22	**1990**	2001	
fungi	1990	5.55	**1990**	1993	
bacteria	1990	6.14	**1992**	2000	
model	1990	6.76	**1993**	1999	
movement	1990	8.4	**1994**	2000	
seedling	1990	6.76	**1994**	2001	
corn	1990	8.52	**1996**	2008	
losse	1990	5.51	**1996**	2007	
pasture	1990	5.61	**1997**	2009	
fertilizer	1990	5.87	**1999**	2005	
potassium	1990	5.77	**2004**	2013	
microorganism	1990	7.32	**2006**	2011	
population	1990	5.49	**2008**	2011	
crop	1990	7.34	**2009**	2015	
surface water	1990	5.84	**2011**	2018	
environment	1990	6.79	**2012**	2018	
speciation	1990	5.51	**2012**	2021	
arabidopsis	1990	6.16	**2014**	2021	
contaminated soil	1990	5.54	**2014**	2019	
microbial community	1990	7.78	**2016**	2021	
arbuscular mycorrhizal fungi	1990	5.74	**2016**	2019	
surface runoff	1990	6.77	**2017**	2021	
waste water	1990	6.76	**2017**	2021	
abundance	1990	6.56	**2017**	2021	

The red line segment in the table reflects the time span of keyword appearance.

clustering keywords. Figure 7 showed that there were 1537 nodes and 2957 lines forming 30 large groups. The modularity value of the map was 0.9415, and the silhouette value was 0.9739, which indicated that the cluster structure formed was remarkable and the similarity of cluster themes was high. CiteSpace calculated the modularity value Q and average silhouette value S according to the network structure and cluster definition of the atlas, which could be used to judge the rendering effect. The modularity value of 0.4 - 0.8 was regarded as a graph meeting the requirements. The index of internal similarity was measured by silhouette, which was a decimal from 0 to 1. The greater the value, the higher the similarity [31]. According to the clustering color block from blue to yellow,

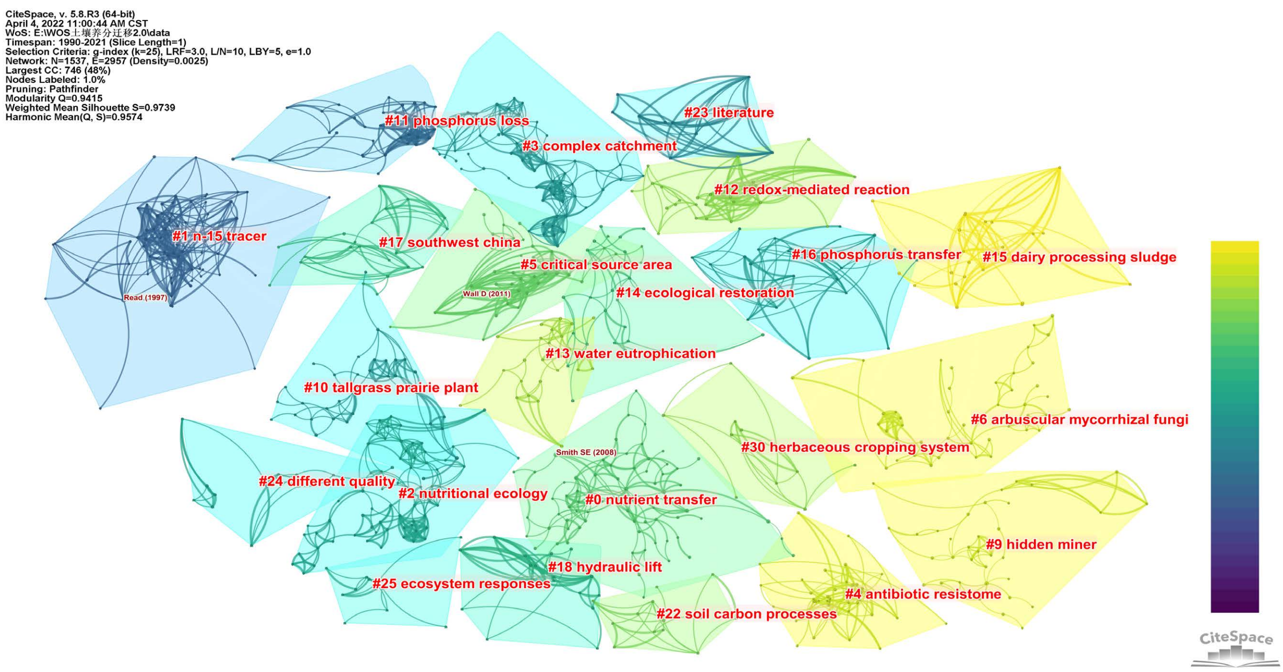

Figure 7. Network of document co-citation of organic fertilizers. The size of circular nodes in the atlas reflects the citation frequency of literatures, and the connection between nodes indicates the co-citation relationship between literatures. The color blocks of clustering reflect the special topics in the research field. The color corresponds to the color bar on the right, which represents the year. Blue is the earlier year, and yellow is the latest.

the research topics in different periods were illustrated. Among them, there were 74 reference points for nutrient transfer in group 0, and 11 reference pointed for herbaceous cropping system in group 30, the smallest.

According to the results of cluster analysis, Table 7 showed that the cluster #0 nutrient transfer ranks first, with a cluster size of 74. This cluster mainly studied the relationship between mycorrhiza and soil nutrient absorption. The second place was #1 n-15 tracer (n-15 tracer) with a cluster size of 71, and #2 Nutrition Ecology was the third place with a cluster size of 68.

According to the document co-citation time Figure 8, the research on soil nutrient migration had been focused on #0 nutrient transfer and #5 critical source area since the 21th century. After the first decade, #4 antibiotic resistome, #6 arbuscular mycorrhizal fungi, #9 hidden miner, #15 dairy processing sludge, which could be regarded as the frontier of soil nutrient migration in recent years.

3.5. Discussion

In the face of massive literature data, it was obviously difficult how to be rapid and accurate qualitative analysis and visual expression. CiteSpace software was used to analyze the citation relationship among literatures, which could quickly find the literatures with key influence on the development of soil nutrient migration research, and showed the development status and trend of related disciplines or knowledge fields.

Table 7. Topic and main research content of each group.

Cluster ID	Size	Cluster name	Mean year	Silhouette	Main research contents
0	74	nutrient transfer	2010	0.980	The effects of fungal hyphae in soil on nutrient absorption and transport to host plants, the regulation of fungal-plant interface, the nitrogen cycle in ecosystem and the mechanism of mycelium network (CMN) controlling nutrient transport to a single host plant were studied [32] [33] [34].
1	71	n-15 tracer	1998	0.974	The nitrogen cycle in forest soil was deeply studied. Isotope data of nitrogen transfer to plants, soil and mycorrhizal fungi were labeled with N-15 tracer to understand the effects of nitrogen on nutrient cycle, plants and soil [35] [36] [37] [38].
2	68	nutritional ecology	2005	0.974	The effects of crop soil roots on rhizosphere, physical, chemical and biological environment of plant growth, the relationship and interaction among roots, rhizosphere, mycorrhiza and soil, and their effects on the dynamics of carbon flow and nutrient cycle at ecosystem scale were studied [39] [40] [41].
3	64	complex catchment	2003	0.940	The sources and impacts of phosphorus migration in complex river basins were monitored, and the mitigation strategies of nitrogen and phosphorus migration and diffusion were discussed. Model monitoring and erosion mapping were used to estimate the long-term dynamics and trends of particulate bound phosphorus and nitrate in agricultural rivers [42] [43].
4	49	antibiotic resistome	2016	0.990	The diffusion mechanism of antibiotic resistance genes in fecal soil and its effects on soil microorganisms, as well as the effects of fecal microbial community and soil microbial community on nitrogen and phosphorus dynamics were studied [44] [45].
5	45	critical source area	2011	0.956	For the key source areas in agricultural activities, the diffusion and transfer of nutrients in the soil to water sources leads to the enrichment and eutrophication of phosphorus in water bodies, which have caused great pressure on river systems. The mitigation measures to control phosphorus concentration and watershed management should be studied to protect water areas from nitrogen and phosphorus pollution [46] [47].
6	43	arbuscular mycorrhizal fungi	2015	0.976	AM obtained low-mobility nutrients from soil, and found the physiological, molecular and regulatory mechanisms of nitrogen absorption and plant phosphorus transportation, as well as the main role of AM in plant growth, zinc nutrition and phytoremediation [48] [49].
9	36	hidden miner	2016	0.962	The influence of soil microbial community activities on soil carbon and nitrogen dynamics, changing the distribution of unstable carbon and nitrogen in soil, affecting the spatial pattern of soil nutrient dynamics, and the interaction between crops and soil microorganisms in the phosphorus cycle of agro-ecosystem [50] [51].
10	34	tallgrass prairie plant	2002	0.990	Grain-bean intercropping increased the formation of mycorrhiza, and then improved the regulation of leguminous plants, the acquisition of nitrogen and phosphorus and the transfer of nitrogen [52].

Continued

11	33	phosphorus loss	1998	0.997	Excessive phosphorus input in animal husbandry increased the loss of phosphorus from land to water. In order to reduce the loss of phosphorus in water, the overall goal should include optimizing the proportion of animal feed and applying phosphorus as mineral fertilizer and manure on land to balance the input and output of phosphorus at farm and watershed levels [53] [54].
12	30	redox-mediated reaction	2013	0.994	Biochar-mediated microbial transformation of soil pollutants, the mechanism of biochar promoting electron transfer between microbial cells, pollutants and soil organic matter, and the influence of biochar-microbial community interaction for soil remediation and improvement were studied [55].
13	26	water eutrophication	2015	0.984	Aiming at the eutrophication caused by agricultural activities, the migration dynamics of total phosphorus, dissolved phosphorus, granular phosphorus and suspended sediment concentrations were evaluated, reasonable and accurate phosphorus loss simulation was provided by using monitoring technology and models, and a comprehensive evaluation of nutrient migration was established to reduce phosphorus migration to water sources [56] [57] [58].

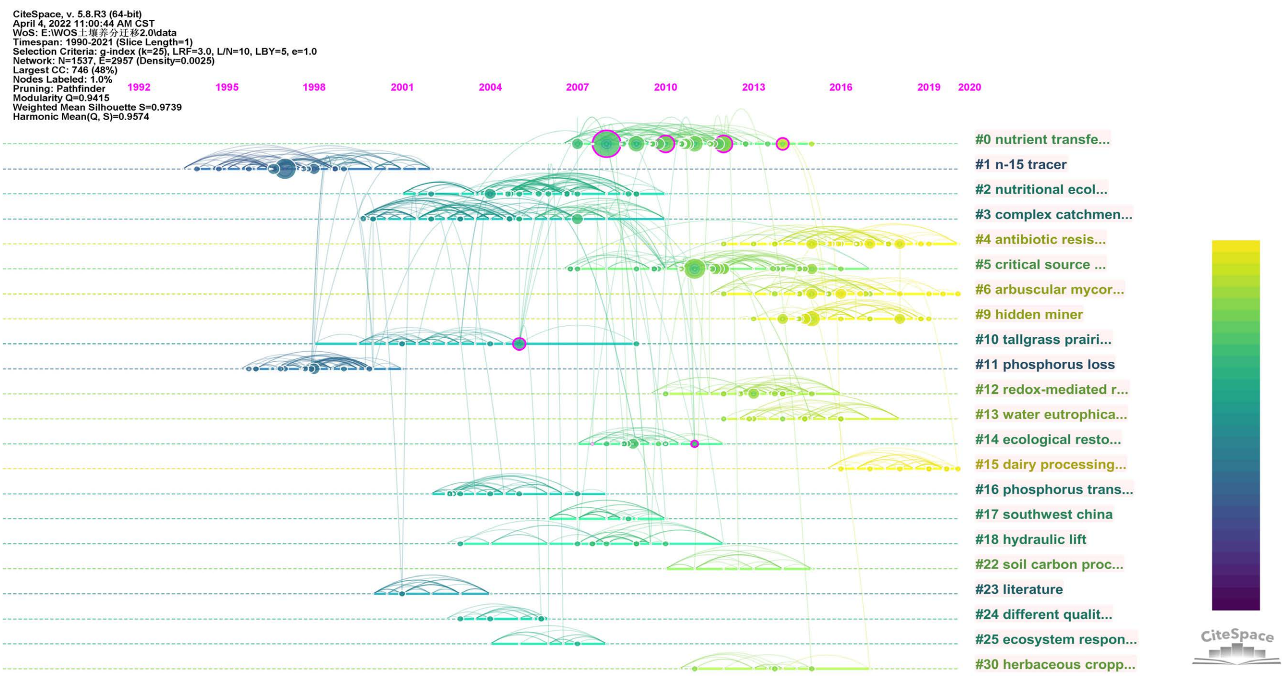

Figure 8. Document co citation timeline. The circular nodes in the graph reflect the citation frequency of the literature, and the connection between nodes indicate the co-citation relationship between the literatures.

From 1990 to 2021, the number of international publications on soil nutrient migration showed a good growth trend. The number of articles published every year was gradually increasing, from 10 in 1990 to 285 in 2021, and the overall growth rate was relatively fast. There was more and more research in this field, which was one of the research focuses of relevant researchers. The study of soil nutrient migration was still the focus of international research. During this period, the international soil science had been further developed, and the current research focused on theoretical innovation, advanced technology and methods. The scope of research was becoming more and more global and international. At the same time, it fully reflected the important soil science issues concerned by the world [17]. It could be predicted that, it will remain a hot spot in the international research field, and the number of papers published in international journals will go on increasing. At present, the number of articles published by the United States and China ranks at the forefront. The United States, Australia, France, Germany, Britain and other countries cooperated closely in the field of soil nutrient migration. Among them, the Chinese Academy of Sciences was the research institution with the most published literature. It could be seen that China had a certain academic influence in the field of soil nutrient migration. However, the research system of soil nutrient migration in China developed late, and its cooperation with other countries was less. Compared with international research institutions, universities, scientific research institutions and teams in China needed to strengthen cooperation with the international community and speeded up their integration with the international community. At present, a stable core group of authors had not been formed in the world, and the cooperation and exchanges among relevant scholars needed to be strengthened.

There was little research on the combination of chemistry and soil nutrient migration. The research focused on the migration of nutrients from soil to plants, mainly involving the migration mechanism and influencing factors of different land use types, the influence and function of soil microbial communities, the carbon and nitrogen cycle of soil and the influence of farming methods on crops. These mainly focused on nitrogen isotope labeling, arbuscular mycorrhizal symbionts, nitrogen input of forest soil, and dynamic redistribution. Nitrogen transfer pathway, ecological relevance and arbuscular mycorrhizal-mediated nutrition in the ecosystem. Focusing on nitrogen isotope labeling, arbuscular mycorrhizal symbiosis, nitrogen input and dynamic redistribution of nitrogen in forest soil, the transfer mode of nitrogen in ecosystem, ecological correlation, arbuscular mycorrhizal-mediated nutrition were studied. William S *et al.* [36] studied chronic nitrogen addition in Korean pine forest, and found that the nitrogen content of some species increased, but the biomass and nutrient cation concentration decreased. The forest had not reached nitrogen saturation, but the understory plants might be saturated. However, in the long-term and experimental increase of nitrogen input, the nitrogen absorption flux of plants in fertilization plots was in the same order of magnitude as the net assimilation flux in forest humus, and a large amount of inorganic nitrogen in soil was directly transferred to humus and related microorganisms, while the combination rate of nitrogen transfer from litter to humus was very small [37]. Be hie S W *et al.* [32] identified the genes involved in the movement of nitrogen, phosphorus and unrestricted soil nutrients between plant and fungi symbiosis and their encoded transporters.

These advances may be applied in agricultural and horticultural environments, and model fungi systems would be developed to further clarify the role of fungi in these symbiotic relationships. By changing tillage methods to improve fertilizer utilization rate, covering crops could enhance soil microbial community by increasing microbial phosphorus, enzyme activity and mycorrhizal richness, thus improving nutrient cycle, crop yield and phosphorus nutrition of agricultural system under different conditions [49]. Grain-bean intercropping increased the formation of mycorrhiza, which improved the regulation of leguminous plants, the acquisition of nitrogen and phosphorus and the transfer of nitrogen [52]. There studied on using biochar, sludge, slag and so on to improve soil to improve the absorption and utilization of soil nutrients [59] [60] [61]. Bio-carbon was an environment-friendly soil modifier, which could increase the effectiveness of soil carbon and phosphorus fixation, change the biological characteristics of soil, and improve nutrient utilization and absorption rate by reducing leaching and gaseous nitrogen loss [59]. Biochar has good adsorption capacity to keep soil moisture, improve the soil's ability to keep nitrogen, increase the availability of phosphorus and the soil's ability to keep nutrients, increase the activity of soil microorganisms and loosen soil structure [62] [63]. Sludge contains nutrients and organic substances needed by plants, which could reduce agricultural costs [60]. Iron-free slag produced in modern iron and steel industry could be used as lime material for acid soil improvement, which could reduce carbon dioxide emissions, save natural resources and raise awareness of the sustainability of some industrial activities [61]. At present, soil nutrient migration had developed into a comprehensive system which was dominated by environmental ecology and interpenetrated with agronomy, environmental science, botany and other disciplines. The degree of intersection with environmental ecology was the highest, but there were few fields that intersected with other disciplines, which were more limited to their respective disciplines. The research focused on soil nutrient transfer was highly concentrated and had formed several branches.

In addition, there were many studies on nutrient migration from soil to water, aiming at nutrient loss caused by runoff, reducing farmland fertility and polluting the environment. Pluer EGM *et al.* [64] used the matching method of soil sampling and unmanned aerial vehicle data, the spatial distribution of farmland soil characteristics and nutrient concentration was drawn, the digital terrain model was generated, and the field terrain change and erosion flow path were drawn to promote the understanding of soil erosion in various farmland and improve agricultural productivity. Poon D *et al.* [65] developed SWAT-MAC model for soil moisture management, and reasonably predicted the flow path of phosphorus groundwater when it passed through the area of macro pore soil, so as to better predict phosphorus loss in agricultural watershed and reduce surface runoff. In order to control the eutrophication of water bodies, Bender M A. *et al.* [57] investigated the dynamics of phosphorus in the rainstorm process in rural catchments areas, and the degree and time of nutrient loss. According to the forms of phosphorus loss at different times, different methods were adopted to reduce erosion, so as to reduce the migration of phosphorus to water sources and control the eutrophication process. Mccenden *et al.* [58] suggested that in key agricultural source areas, local conditions and predicted soil moisture conditions should be used to increase farmers' understanding of soil drainage characteristics, which would help strengthen the existing regulatory framework to avoid accidental nutrient transfer. Sharpley A N *et al.* [54] proposed that reducing the loss of phosphorus in water should also include balancing the input and output of phosphorus at the farmland and watershed level by optimizing the proportion of animal feed and land application of phosphorus as mineral fertilizer and manure. Protection measures should include areas with relatively little phosphorus loss but located in key watersheds. In view of the eutrophication caused by agricultural activities, the monitoring technology and model were used to comprehensively evaluate nutrient migration dynamics and improve relevant watershed management measures. Accurate prediction could provide information for preventing nutrient loss and control measures, thus reducing agricultural non-point source pollution and promoting sustainable agricultural development. On the basis of paying attention to the basic ways and influencing factors of soil nutrient migration in the early stage, researchers paid more attention to the ways to control soil nutrient migration, and studied and explored the methods of soil remediation and control from various angles. Using the interaction between biochar and microorganisms to transform soil pollutants, the interaction between crops and soil microorganisms in the phosphorus cycle of agricultural ecosystem, and rationally using agriculture, forestry, animal husbandry and water conservancy industries to comprehensively prevent and control soil erosion according to local conditions, would carry out various explorations, control and maintain better soil and water functions, effectively reduce soil nutrient loss, improve and repair soil, and realize sustainable development. Soil nutrient migration has been playing an important role in evaluating and utilizing soil resources, increasing crop yield and nutrient utilization rate, and reducing environmental pollution. In the future, it is necessary to strengthen the response to the transformation process, products and influencing factors of soil nutrients, carry out basic research and pay attention to the impact of soil nutrient migration on the surrounding environment.

4. Conclusions

CiteSpace software was used to analyze the visual atlas of research papers on soil nutrient migration in the last 32 years. The results showed that:

1) From 1990 to 2021, the number of internationally published articles on soil nutrient migration showed a good growth trend. China Academy of Sciences, USDA-ARS, University of Florida, etc. were the main publishing institutions, among which China Academy of Sciences had the largest number of publications. However, universities, research institutions and teams in China need to

strengthen cooperation with international institutions. Seventy-three countries had cooperated in soil nutrient migration research, and the United States and China were far ahead in the number of published articles.

2) Soil nutrient migration had developed into a comprehensive system which was dominated by environmental sciences & ecology and intertwined with many disciplines such as agriculture, environmental sciences and plant sciences.

3) In 1990-1996, the hotspots were fungi and bacteria promoting soil nutrient transformation. In 1997-2004, the hotspots were pasture and fertilizer. In 2005-2016, the hotspots were crop and microbial communities to improve soil fertility. In 2017-2021, the hotspots were arbuscular mycorrhizal fungi, surface runoff and waste water to control and reduce soil nutrient migration pathways.

4) The management measures for soil nutrient loss, the relationship between the change of soil nutrient content and the diversity of plant community, and remediation of polluted soil processed.

Based on the above analysis of soil nutrient migration, cooperation network, related disciplines, research hotspots and frontier trends, this study provides some reference and research directions for future research in this field.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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