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A Scientometric Analysis of Worldwide Intercropping Research Based on Web of Science Database between 1992 and 2020

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Citation: Lv, W.; Zhao, X.; Wu, P.; Lv, J.; He, H. A Scientometric Analysis of Worldwide Intercropping Research Based on Web of Science Database between 1992 and 2020. *Sustainability* **2021**, *13*, 2430. https://doi.org/10.3390/su13052430

Academic Editor: José Manuel Mirás-Avalos

Received: 23 January 2021
Accepted: 19 February 2021
Published: 24 February 2021

Abstract: Intercropping has been practiced worldwide in both traditional and sustainable agriculture to feed the growing population. This study aims to analyze the research status and evolution of intercropping, to identify the influential authors, research centers, and articles, and to reveal the main research topics between 1992 and 2020 based on the Web of Science Core Collection database. The results show that the volume of publications in this field has increased rapidly over the past three decades. The analysis identifies the top three authors (i.e., Meine Van Noordwijk, Wenyu Yang, and Teja Tscharntke), top three contributing organizations (i.e., the World Agroforestry Center (ICRAF), the Chinese Academy of Science, and the INRA), and three most productive countries (i.e., the USA, India, and China). Co-occurrence analysis demonstrates that studies on intercropping can be divided into four clusters as centered by keywords of intercropping/maize, biodiversity/conservation, agroforestry, and carbon, respectively. Lal 2004 is the most influential study with the greatest number of citations and Agroforestry Systems is the most utilized journal. Perspectives on future studies were also given. This study helps researchers to clarify the current research status in the field of intercropping and put forward its future research.

Keywords: intercropping; crop mixture; agroforestry; monocropping; bibliometric analysis; research trends; research output; research hotspots

1. Introduction

Intercropping is the agronomic practice of simultaneously growing two or more crop species in the same field in close proximity for a considerable proportion of their growing season [1–3]. The main types of intercropping include agroforestry, hedgerow intercropping, relay intercropping, mixed intercropping, row intercropping, and strip intercropping [4]. Intercropping has been widely applied around the world in both tropical and temperate regions for both traditional, intensive farming systems, and sustainable agriculture systems [4–7]. The intercropping systems vary from place to place as a result of variations in local climate, soil, and socio-economic structure and status. For instance, there are multistrata agroforestry and jungle rubber-based agroforestry in tropical areas of Indonesia, India, Niger, and Mali. There are silvopastoral systems, coffee agroforests in Central America, dehesa agroforestry in Spain/Portugal, and cocoa agroforestry worldwide [4,8,9]. In both Africa and Latin America, beans and peas climb tall cornstalks, whereas pumpkins and squash cover the ground below [10]. In temperate regions, peas are grown with barley or oat, wheat is grown with canola or pea, and broccoli is grown with peas, beans, potatoes, oats, cauliflower, or cabbage in Canada. In the USA, maize (corn) and soybeans are intercropped [4]. In Europe, there are barley/pea intercropping in Denmark, the United Kingdom, France, Italy, and Germany, and wheat/pea intercropping in Denmark, popcorn/melon and potato/cabbage intercropping in the United Kingdom, berseem clover/barley, common vetch/wheat, triticale, barley, or oat intercropping in Greece, fennel/dill intercropping in Italy, maize/bush bean intercropping in Spain, leek/celery intercropping in Switzerland, and various vegetables/vegetables intercropping (e.g., cabbage, cauliflower or strawberry intercropped with bean, cos lettuce, leaf lettuce, onion, or radish) in Turkey [4,11,12]. In China, India, Iran, Nepal, Sri Lanka, and Thailand, there are many kinds of intercropping, including spring wheat/spring maize, maize/soybean/flax, winter wheat/spring maize, wheat/soybean, wheat/faba bean, maize/potato, wheat/potato, wheat/sunflower, wheat/vegetables, Peking cabbage, and onion, maize/vegetables, maize/pea intercropping [4].

Crops selected for intercropping normally have different abilities to use the resources available for growth [13]. The major benefits of intercropping include: (1) improved yields, yield stability, and farmers' profitability [14,15], with a decreased risk of reducing total crop production due to climate change; (2) enhanced competitive ability of crops for use efficiency of resources such as nutrients, water, light, and heat [3–5]; (3) improved management of weeds, pest/insects, and disease/pathogens due to enhanced competition, physical dominance, space occupation, and allelopathic influence [16–18], sometimes the main objective of planting the second crop in intercropping farming is to control weeds; (4) intercropping with cash crops for higher profitability, provide shade/shelter and support to the other crop, and act as insurance against crop failure in abnormal years due to extreme weather such as drought, hurricanes/cyclones, and torrential rain; (5) reduced erosion, enhanced soil carbon sequestration and nitrogen fixation [19], and increased microbial diversity [20]. Compared with monocropping or a monoculture system, the disadvantages of intercropping may include: (1) more input of resources (e.g., seeds, fertilizer, irrigation, gasoline, and manpower-difficult to harvest) [21,22]; (2) significant allelopathic interactions between crop species if species were inappropriately combined [23]; (3) decreased yield due to differences in their competitive abilities.

There are many studies reviewing various aspects of intercropping, including yield stability [24–26], water and nutrient utilization [27–31], biodiversity [32–39], allelopathy [17,40–44], agroforestry [29,45–51], or species-dependent intercropping such as cereal-legume or maize-based intercropping [7,31,52,53]. However, no study has investigated the overall research tends and features of intercropping. Previous studies [45–48,54,55] have shown that scientometrics is a powerful tool for quantitative and statistical demonstration of research trends and features of a certain topic. The objective of this study is to quantitatively analyze the growth and evolution of intercropping research based on the scientometric method based on the Web of Science database. It is hoped that this study would provide information to the novice and expert alike to guide them on the advantages, limitations, development, and the applications of intercropping.

2. Materials and Methods

The Web of Science Core Collection (WoSCC) is among the most comprehensive and widely utilized databases for scientometric analyses [54–56], it contains quality controlled full literature data (e.g., title, author, abstract, keywords, references, and citations) since 1985 up to present. The data between 1985 and 2020 were downloaded from the WoSCC on Jan 2, 2021 for analysis based on the preset query sets. The query sets used for the literature search are TS = ("intercrop*" OR "interplant*" OR "crop mixture" OR "undercrop sow*" OR "agroforest*" OR "hedgerow"), where TS is a field tag indicating topic in the Web of Science. The search results were further restricted by languages and document types and only articles, letters, notes, books, book chapters, data papers, database reviews, and reviews written in English were retrieved. This search process returned a total of

14,001 publications and they were saved as tab-limited text files (UTF-8) containing the "full record with citation data".

VOSviewer 1.6.15 (The Centre for Science and Technology Studies, Netherlands) and CiteSpace 5.7.R1 (Drexel University, USA) were used to perform scientometric analysis. VOSviewer 1.6.15, a Java-based software developed in 2009 by van Eck and Waltman [57], is a tool for building and visualizing a scientometric network, which can quickly observe knowledge and research in a specific field. The annual trend of publication volume, the main authors, countries and institutions, the most utilized journals, the highly impacted studies, and occurrence network of keywords were analyzed. CiteSpace is a Java-based software tool to present the rules and structure of scientific knowledge [58], which is used to analyze the burst time of keywords that reflect the development and revolution of research hotspots.

3. Results

3.1. Overview of Publication Trend

It is noted that query sets in Section 2 returned no data between 1985 and 1991, which was also reported in other studies as the main SCI-expanded database of WoSCC began archiving since 1992 [54,55], where SCI is short for Science Citation Index. There is an increasing trend in the number of publications, from 241 (1.72%) in 1992 to 1258 (8.99%) in 2020 (Figure 1). This indicates that research on intercropping has received increasingly more attention. For the 14,001 publications, most of them fall into the Web of Science category of agronomy (4638 or 33.13%), forestry (2555 or 18.25%), environmental science (2158 or 15.41%), agriculture multidiscipline (1907 or 13.62%), ecology (1847 or 13.19%), plant science (1461 or 10.44%), and soil science (1460 or 10.43%). The dominant document type is an article, which accounts for 13,287 or 94.90% of the total publications, followed by a review that accounts for 620 papers or 4.43% of the total publications.

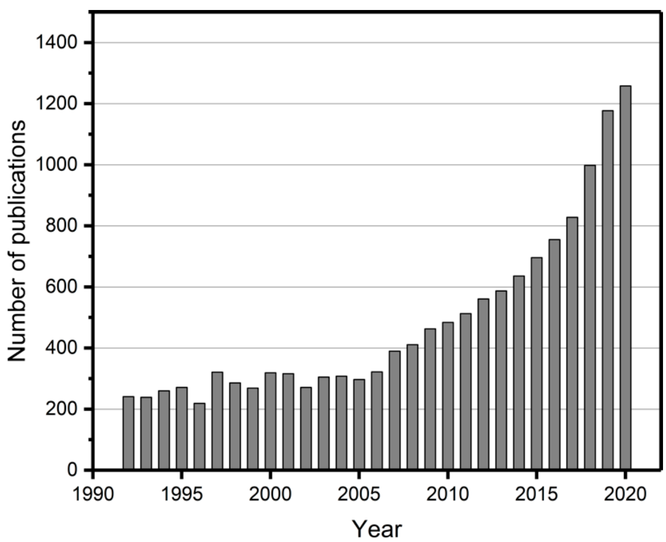
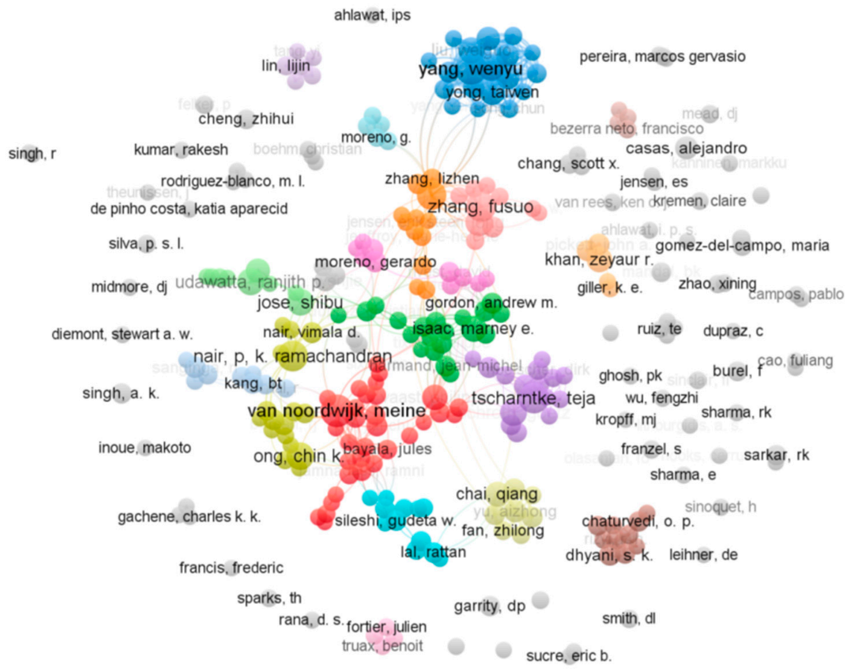


Figure 1. Annual trend in publications on research pertaining to intercropping based on data between 1992 and 2020 from the Web of Science Core Collection (WoSCC).

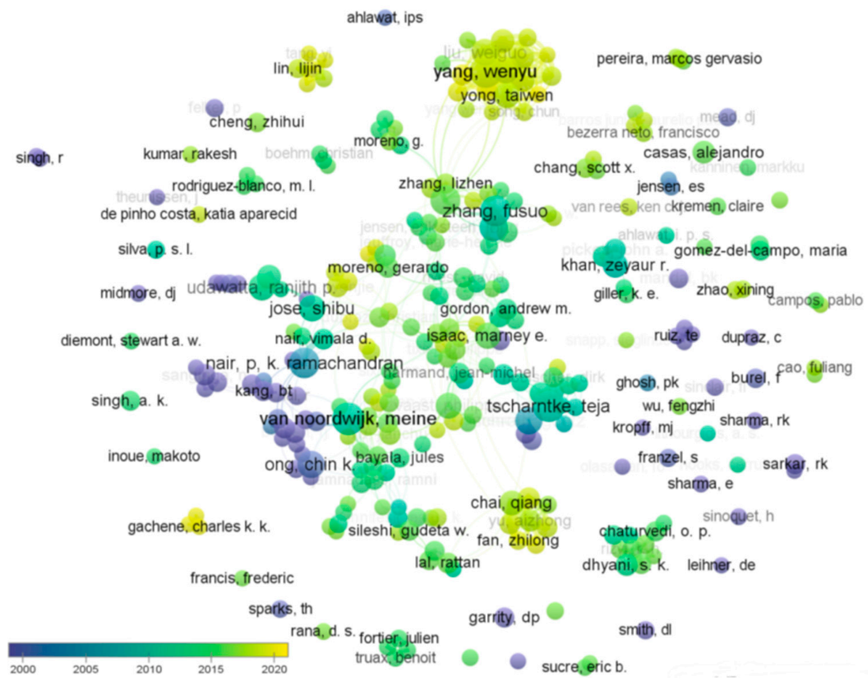
3.2. The Co-Authorship of Authors

There are 291 out of 38,704 authors meeting the threshold of a minimum of 10 publications (Figure 2). They are grouped in 77 clusters, where a cluster indicates a group of closely collaborating authors. The largest set of connected authors consists of 184 researchers centered in Figure 2a. The colors in Figure 2b indicate the active periods of authors, with the "yellow" indicating that researchers published intercropping studies in recent years, "green" indicates that most papers of the authors were published around 2010, while "blue" around 2000. For instance, Drs. Wenyu Yang and Taiwen Yong from Sichuan Agriculture

University (China) have been publishing on intercropping [59–61], they are also the top productive authors on these topics (Table 1). This is similar to Drs. Qiang Chai and Zhilong Fan from Gansu Agriculture University (China, Table 1) and Dr. Lijin Lin from Sichuan Agriculture University (China) [27]. Other productive researchers such as Dr. Fusuo Zhang (China Agriculture University, China, Table 1) and Meine van noordwijk (Wageningen University and Research, Netherlands, Table 1) were active around 2010, while Dr. Chin K. Ong (World Agroforestry Center, Kenya, Table 1) was active around 2000 [49].



(**a**)



(**b**)

Figure 2. Network visualization (**a**) and overlay visualization (**b**) of co-authorship for authors with a minimum of 10 publications on research pertaining to intercropping based on Web of Science Core Collection (WoSCC) data between 1992 and 2020.

Table 1. Top 25 authors with publications on intercropping. VOSviewer is used to count document number (N), citations (C), and total link strength (TLS). Values of N and C are recorded by Web of Science Core Collection (WoSCC) from data between 1992 and 2020, while C/N indicates the calculated average citations per publication. The total link strength (TLS) indicates the total strength of the links of an item with other items.

No.	Author	N	C	C/N	TLS
1	Van Noordwijk, Meine (Wageningen Univ. and Res., Netherlands)	84	2482	30	353
2	Yang, Wenyu (Sichuan Agr. Univ., China)	80	1091	14	836
3	Tscharntke, Teja (Univ. Gottingen, Germany)	73	4928	68	379
4	Nair, Ramachandran P.K. (Univ. Florida, USA)	70	3272	47	153
5	Zhang, Fusuo (China Agr. Univ., China)	68	4717	69	366
6	Van Der Werf, Wopke	64	1584	25	451
7	Li, Long (China Agr. Univ., China)	51	3666	72	286
8	Ong, Chin K. (World Agroforestry Ctr, Kenya)	50	2011	40	157
9	Schroth, Goetz (Mars Inc, Brazil)	48	2054	43	166
10	Jose, Shibu (Univ. Florida, USA)	46	1720	37	144
11	Udawatta, Ranjith p. (Univ. Missouri, USA)	46	1132	25	138
12	Yang, Feng (Sichuan Agr. Univ., China)	46	797	17	520
13	Liu, Weiguo (Sichuan Agr. Univ., China)	44	662	15	503
14	Isaac, Marney E. (Univ. Toronto, Canada)	42	804	19	127
15	Vaast, Philippe (Univ. Montpellier, France)	41	913	22	228
16	Khan, Zeyaur R. (Int. Ctr. Insect Physiol. and Ecol. ICIPE, Kenya)	40	1842	46	192
17	Yong, Taiwen (Sichuan Agr. Univ., China)	40	702	18	425
18	Chai, Qiang (Gansu Agr. Univ., China)	37	501	14	229
19	Anderson, Stephen H. (Univ. Missouri, USA)	33	830	25	103
20	Liu, Jiang (Sichuan Agr. Univ., China)	31	392	13	367
21	Du, Junbo (Sichuan Agr. Univ., China)	30	455	15	369
22	Wang, Xiaochun (Sichuan Agr. Univ., China)	29	467	16	351
23	Casas, Alejandro (Univ. Nacl Autonoma Mexico, Mexico)	28	382	14	134
24	Yu, Aizhong (Gansu Agr. Univ., China)	27	347	13	185
25	Clough, Yann (Lund Univ., Sweden)	26	1384	53	153

3.3. The Top Contributed Organizations and Countries

There are 8037 organizations that published research on intercropping, the World Agroforestry Center (ICRAF) ranked first on the publication volume (n = 326), followed by Chinese Academy of Science (n = 307), INRA (n = 260), China Agriculture University (n = 217), and University of Gottingen (n = 213). The top 25 organizations are tabulated in Table 2. In terms of average per publication citation times, the University of Gottingen ranked first (C/N = 42), followed by the University of California (C/N = 35), and the University of Florida (C/N = 34). The average per-publication citations of the University of Missouri, the China Agriculture University, and INRA are equal to or greater than 30, which indicates the high influence of these institutions. In addition, the World Agroforestry Center (ICRAF), the China Agriculture University, and INRA collaborated more with other organizations as indicated by their greater TLS (over >10,000), CSIC and the University of California Davis had the least inter-organization collaborations among the top 25 organizations.

In addition, there are 169 countries that published research on intercropping, with the USA (n = 2468), India (n = 1470), China (n = 1437), and Brazil (n = 1164) are the top four countries (Table 2, Table 3 and Figure 3). They consist of the research centers for study on intercropping. It is interesting to notice that the average citations of Indonesia ranked first (C/N = 29), followed by the USA, Australia, Denmark, and Costa Rica that had C/N = 28. The USA collaborated most with other countries with the greatest TLS = 35,512, followed by France and Germany with TLS = 21,916 and 21,538, respectively.

Table 2. The top 25 organizations with publications on intercropping. VOSviewer was used to count document number (N), citations (C), and total link strength (TLS). Values of N and C are recorded by Web of Science Core Collection (WoSCC) data between 1992 and 2020, while C/N indicates the calculated average citations per publication. The total link strength (TLS) indicates the total strength of the links of an item with other items.

No.	Organizations	N	C	C/N	TLS
1	World Agroforestry Center (ICRAF)	326	6638	20	11,988
2	Chinese Academy of Science, China	307	5694	19	4736
3	INRA	260	7756	30	10,390
4	China Agriculture University, China	217	6753	31	11,651
5	University of Gottingen, Germany	213	8946	42	8794
6	University of Florida, USA	203	6973	34	6953
7	CIRAD, France	200	4060	20	9898
8	Wageningen University, Netherlands	170	3913	23	7167
9	University of Missouri, USA	155	4966	32	3466
10	INT INST TROP AGRICULTURE	146	3132	21	2548
11	Swedish University of Agricultural Sciences, Sweden	137	4013	29	3705
12	Sichuan Agriculture University, China	132	1597	12	4667
13	University Fed Vicosa, Brazil	130	1632	13	2013
14	USDA ARS, USA	129	2529	20	1715
15	University of Montpellier, France	121	597	5	5495
16	University of Copenhagen, Denmark	118	2114	18	3363
17	University of Sao Paulo, Brazil	113	969	9	2198
18	Cornell University, USA	111	3011	27	1906
19	University of Hohenheim, Germany	110	1538	14	2439
20	CATIE, Costa Rica	105	2726	26	6384
21	University of Chinese Academy of Science, China	102	697	7	1891
22	University of California Davis, USA	95	3332	35	1745
23	CSIC, Spain	93	1954	21	1086
24	University of Guelph, Canada	93	1843	20	2683
25	Michigan State University, USA	91	2461	27	1835

Table 3. The top 25 countries with publications on intercropping. VOSviewer was used to count document number (N), citations (C), and total link strength (TLS). Values of N and C are recorded by Web of Science Core Collection (WoSCC) data between 1992 and 2020, while C/N indicates the calculated average citations per publication. The total link strength (TLS) indicates the total strength of the links of an item with other items.

No.	Country	N	C	C/N	TLS
1	USA	2468	69,554	28	35,512
2	India	1470	12,969	9	7980
3	China	1437	22,546	16	19,372
4	Brazil	1164	13,375	11	11,395
5	Germany	974	25,029	26	21,538
6	France	868	20,675	24	21,936
7	UK	790	26,838	34	18,296
8	Canada	654	15,851	24	10,147
9	Kenya	648	16,183	25	16,973
10	Australia	586	16,203	28	11,515
11	Spain	527	8921	17	7458
12	Netherlands	414	10,429	25	11,495
13	Italy	347	7366	21	6614
14	Mexico	323	6955	22	5087
15	Indonesia	316	9116	29	9201
16	Nigeria	310	5196	17	2495
17	Switzerland	250	6754	27	8366
18	Denmark	240	6674	28	6322
19	Sweden	234	6354	27	5491
20	South Africa	233	6098	26	4042
21	Belgium	218	4175	19	4311
22	Japan	213	3182	15	2373
23	Ethiopia	212	2266	11	3851
24	Pakistan	195	1795	9	2915
25	Costa Rica	194	5461	28	7875

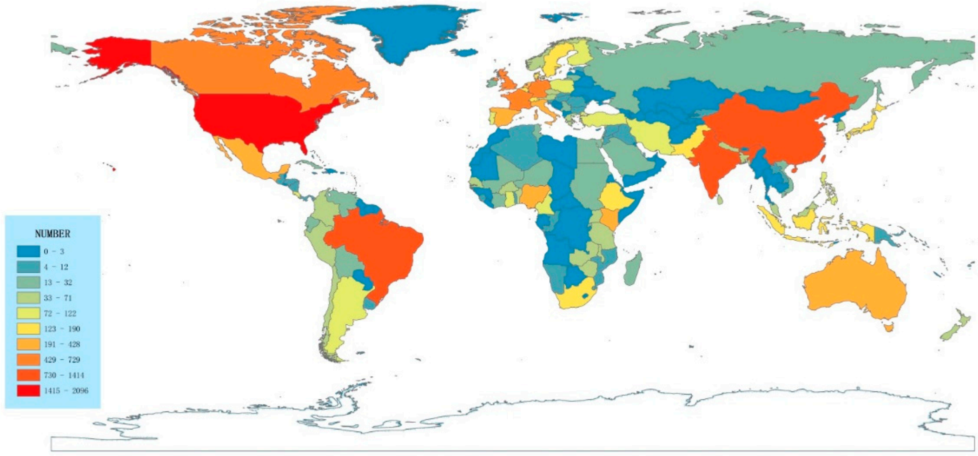


Figure 3. World map of countries contributing to research on intercropping based on Web of Science Core Collection (WoSCC) data between 1992 and 2020.

3.4. The Co-Occurrence and Burst Time of Keywords

There are 37,398 keywords in the title, abstract, and author-provided keyword list, and 338 keywords meeting the threshold of 60 occurrences. These keywords are grouped into four clusters: red, green, blue, and yellow (Figure 4), and the top 25 keywords were tabulated in Table 4. The red-colored cluster in Figure 4 is pertaining to crop intercropping as represented with high-frequency keywords of "maize", "yield", "wheat", and "soybean" etc. [59,62,63]. Among them, the "maize" (corn) based intercropping system is the dominant type around the world [31,53,62,63]. The green-colored cluster is mainly related to "biodiversity" or "conservation" and management of intercropping systems [34,36,64]. One of the popular topics is to increase "biodiversity" without compromising yield in the intercropping system [65]. The blue-colored cluster is themed with "agroforestry" or "sustainability" [66–69], while the yellow-colored cluster is featured with "nitrogen", "carbon sequestration", and "microbe biomass" etc. [70–73].

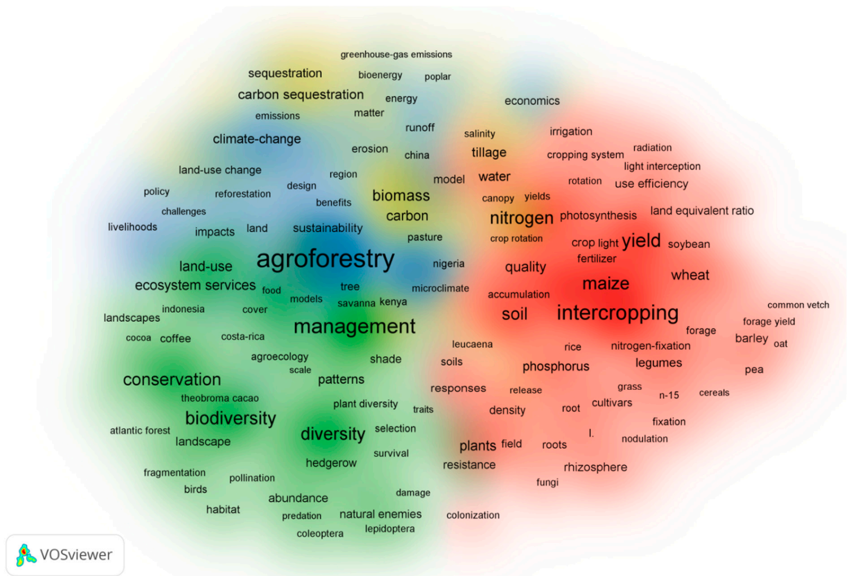


Figure 4. Cluster density visualization map of 338 keywords each occurring 60 times or more in the title, abstract, and keyword list (produced by VOSviewer 1.6.15). Note: the number of co-occurrences of *n* keywords indicates the number of publications in which all *n* keywords occur together. Font size and density (background color) of keywords are used to represent the total link strength (TLS). A greater font size indicates greater TLS. The distances between each of the keywords indicate the relatedness of these research topics. The top keywords, their times of occurrence, and their TLS are shown in Table 4.

Table 4. High-frequency keywords for research on intercropping and word frequency analysis from 1992 to 2020 with VOSviewer 1.6.15. The total link strength (TLS) indicates the total strength of the links of an item with other items.

No.	Keyword	Occurrences	TLS
1	agroforestry	2634	11,594
2	intercropping	1547	6685
3	management	1515	8201
4	growth	1386	6921
5	yield	1237	6292
6	systems	1040	5623
7	biodiversity	1031	5798
8	maize	985	5202
9	nitrogen	983	5732
10	diversity	953	4963
11	conservation	886	4567
12	soil	859	4336
13	productivity	721	4144
14	forest	686	3623
15	dynamics	654	3677
16	agroforestry systems	633	3128
17	competition	616	3446
18	biomass	587	3237
19	wheat	500	2889
20	quality	492	2522
21	trees	474	2326
22	agriculture	453	2563
23	land-use	449	2512
24	carbon	440	2482
25	ecosystem services	435	2460

The burst time of keywords was used to illustrate the development and evolution of research directions. Figure 5 shows that the 1990s featured different intercropping species as indicated by keywords such as "wheat", "cassava", "barley", and "groundnut". Agroforestry is also the hot research topic as indicated by "alley cropping", "multipurpose tree", and "tropic forest". Crop species including "cowpea", "maize", and "sorghum" became the research focus, while land-use type and management also gained attention as indicated by "hedgerow" and "fallow". In the 2010s, research topics on intercropping shifted to "ecosystem service" and "carbon sequestration" under "climate change".

3.5. The Highly Impacted Publications

There are 361 out of 14,001 publications meeting the threshold of 100 citations, they are divided into 98 clusters with the largest set of connected documents consisting of 270 papers (Figure 6). Lal [74], Smith et al. [75], and Reich et al. [76] are the top three studies that were cited over 1000 times based on the record of WoSCC, with the first two being mainly about carbon sequestration or greenhouse gas emission mitigation in agriculture.

3.6. The Widely Utilized Journals

There are 1291 journals that published research on intercropping, among which 15 journals each published over 100 papers (Figure 7). Agroforestry Systems is the most utilized journal that published over 1500 papers, followed by Agriculture Ecosystems and Environment that published around 500 papers between 1992 and 2020 based on the Web of Science Core Collection (WoSCC).

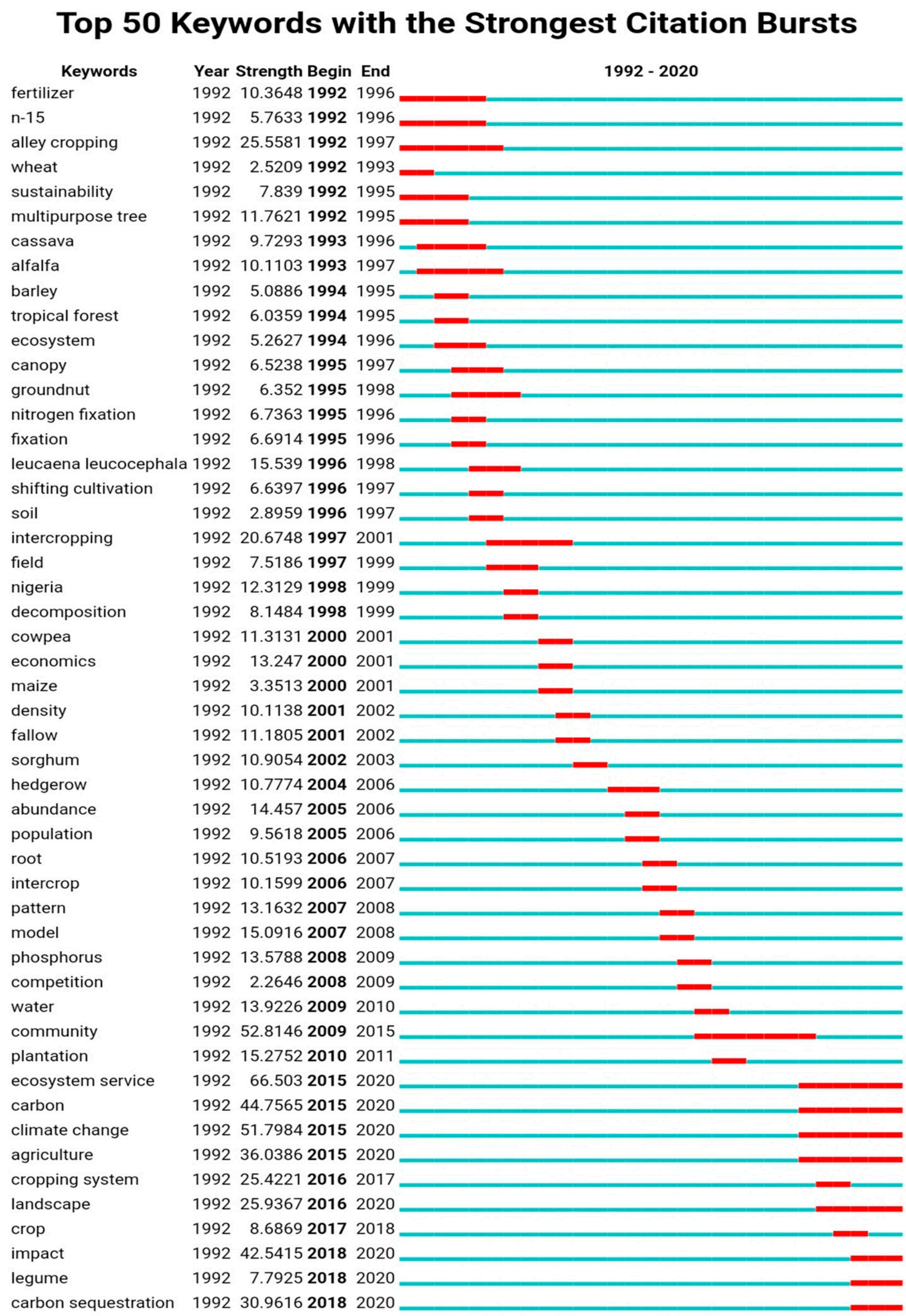


Figure 5. The top 50 keywords with the strongest citation burst between 1992 and 2020 using VosViewer based on data retrieved from the Web of Science Core Collection (WoSCC) with CiteSpace.

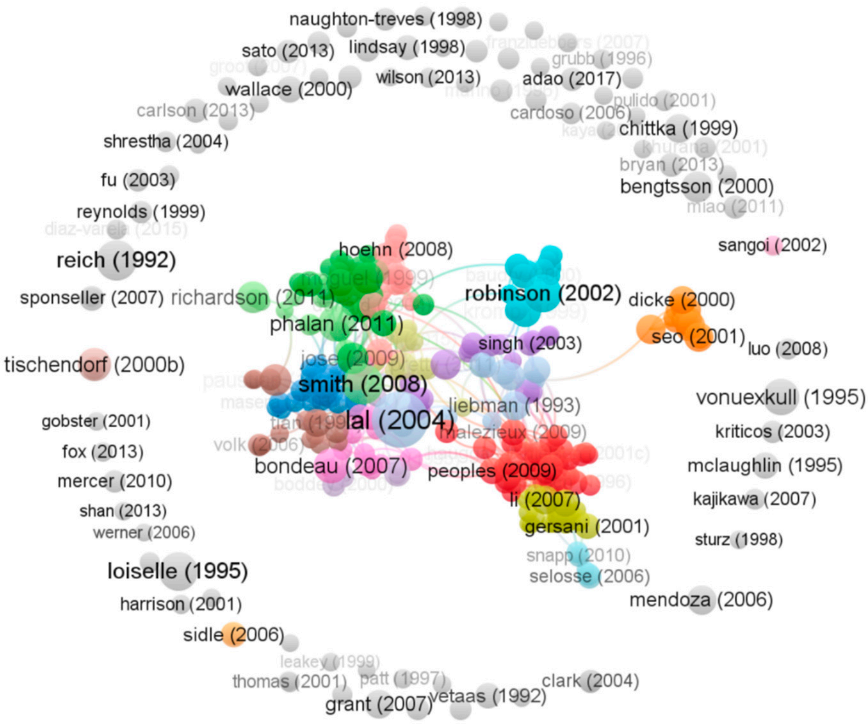


Figure 6. The network visualization map of citations for 361 publications with a minimum of 100 citations on intercropping using VosViewer based on data retrieved from the Web of Science Core Collection (WoSCC). Each node represents a publication, the size of the node represents the number of citations, the lines represent the co-citation relationship between documents, and the thicker the lines the stronger the links.

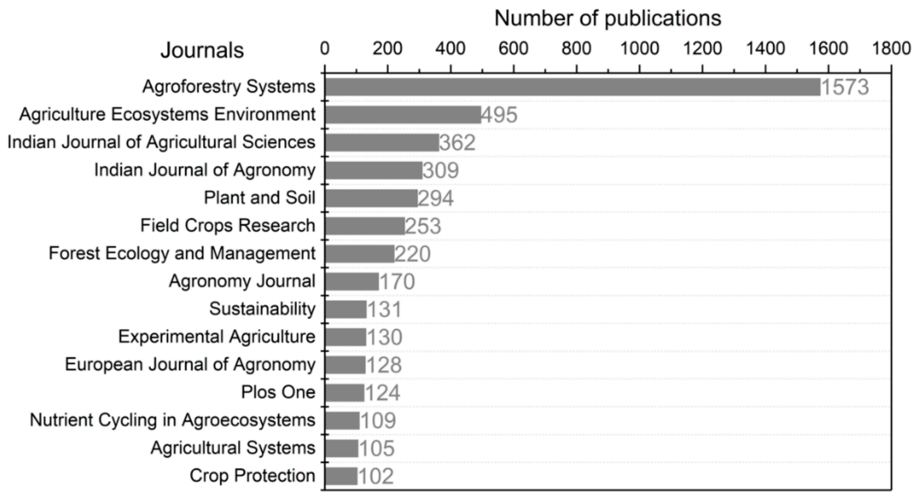


Figure 7. Top 15 journals and their publication volume on intercropping between 1992 and 2020 based on the Web of Science Core Collection (WoSCC).

4. Conclusions and Perspectives

The results show that the volume of publications in this field has increased rapidly over a period of 29 years with 241 papers (1.72%) in 1992 to 1258 (8.99%) in 2020. The analysis shows that Meine Van Noordwijk, Wenyu Yang, and Teja Tscharntke are the top three authors that published over 70 papers on this topic. The Chinese Academy of Science, INRA, and the China Agriculture University are the top three contributing organizations, while the USA, India, and China are the most productive countries for research centers on intercropping. The most influential studies are Lal [74] and Smith et al. [75] that investigated the carbon sequestration or mitigation of greenhouse gas emission. *Agroforestry Systems* is the most utilized journal that published over 1500 papers on intercropping in total.

The co-occurrence analysis demonstrates that intercropping studies generally focus on four aspects as indicated by keywords of intercropping/maize, biodiversity/conservation, agroforestry, and carbon, respectively. Given that applications of synthetic fertilizers significantly increased grain yield over the past decades, but overuse of chemical fertilizer leads to soil and environmental pollution and threatens agricultural sustainability [77], more studies are required to develop efficient approaches so as to improve the crop quality while maintaining or increasing yield to meet food security and higher demands of food quality [78–80]. As intercropping has been well studied in well-developed countries including the USA and the mostly populated countries including India and China, more intercropping studies in undeveloped countries in Africa should be conducted to fight starvation and malnutrition and to adapt to climate change [63,81]. In addition, the paradox between intercropping and automation should be properly addressed with the design and development of new compatible intercropping machineries [63,82]. Moreover, future studies are recommended to investigate the below-ground competition for water and nutrients between intercropped species, root-shoot equilibrium of intercropping, inter-zone water migration in water-saving irrigation agriculture systems, and regions with a low input level [27,83,84]. Increased attention should also be paid to innovative perennial systems with intercropping to facilitate root interactions and microbial abundance and diversity [85]. Furthermore, previous studies are generally based on experimental studies, it is desired to develop functional structural plant modeling to better understand and optimize species mixture [86]. This study helps researchers to clarify the current research status in the field of intercropping and put forward its future research.

Author Contributions: Conceptualization, P.W. and H.H.; methodology, J.L. and X.Z.; software, W.L.; validation, J.L., X.Z., and P.W.; formal analysis, W.L.; investigation, W.L.; resources, W.L. and X.Z.; data curation, W.L.; writing—original draft preparation, W.L. and H.H.; writing—review and editing, P.W., X.Z., and J.L.; visualization, W.L.; supervision, P.W. and H.H.; project administration, X.Z.; funding acquisition, P.W. and H.H. All authors have read and agreed to the published version of the manuscript.

Funding: Funding for this research was provided in part by the Northwest A & F University (Youth Talent Training Program), the 111 project (Grant No. B12007), and First-Class Discipline Construction (Ecology) for Ningxia Higher Education Project (NXYLXK2017B06).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors greatly appreciate the valuable and insightful comments by anonymous reviewers.

Conflicts of Interest: The authors declare no conflict of interest.

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