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Bibliometric Analysis on the Impact of Climate Change on Crop Pest and Disease

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Abstract: Affected by global warming, the frequency of crop pests and diseases have increased, causing huge losses to agricultural production. To better grasp the development and trends of research on the effects of climate change on crop pests and diseases, the literature on the impact of climate change on crop pests and diseases published from 1990 to 2021 in the Web of Science (WOS) core collection database was used. This study explores the literature characteristics and hotspot evolution through the bibliometric visualization analysis software COOC, VOSviewer, and CiteSpace, with a view to identifying the changing characteristics and trends of research changes in this field. The results showed that the number of literature on the impact of climate change on crop pests and diseases increased rapidly. The main fields involved include environmental sciences, ecology, and agronomy. Papers in these fields mainly published in journals, such as *PLos One*, *Forest Ecology and Management*, and *Frontiers in Plant Science*. The country with the highest number of publications was the United States, followed by China and Australia. The most prolific authors in the top 20 are research scholars from China. The first author of the top 20 highly cited papers was from the United States. It was found that that current research on the impact of climate change on crop pests and diseases mainly focuses on agricultural production and food safety. Modelling and crop growth has maintained steady development. At present, research in this field mainly focuses on pest management strategies under the impact of climate change, the response of single species, and the complex ecological mechanisms behind the response. This study provides unique insights into the research field of the impact of climate change on crop pests and diseases and provides a reference direction for future research development in this field.

Keywords: agriculture; crop pests and diseases; bibliometric study; visualization

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1. Introduction

Climate is a key determinant affecting the change and distribution of ecosystems, such as water resources, agriculture, forestry, oceans, and land [1]. The United Nations Intergovernmental Panel on Climate Change (IPCC) stated that global temperatures are still on an upward trend and global warming has not stalled. The global average surface temperature in the last 10 years (2011–2020) is 1.09 (0.95–1.20) °C higher than that in 1850–1900, and 0.19 (0.16–0.22) °C higher than that in 2003–2012 °C [2]. Climate change will have strong impacts on natural ecosystems and socioeconomic development as temperature increases and the frequency of extreme events increases, especially in agricultural production and water use [3,4]. Agricultural production is extremely dependent on climatic conditions, and this vulnerability makes agriculture one of the sectors most sensitive and significant to the effects of climate change [5]. Increased temperatures, elevated atmospheric CO_2

concentrations, and the change of precipitation patterns can have significant impacts on crop pests and diseases [6].

It is projected that global crop production will need to double by 2050 to meet growing societal demands [7]. However, all countries/regions share the problem of crop pests and diseases that spread across countries and continents threatening food security [8]. Climate directly affects the physiology and phenology of crop pests, and thus indirectly affects their spread [9], which has a huge impact on the production and prevalence of crop diseases [10]. Pests and diseases are the main factors affecting crop production. Crop pests are sensitive to climate change as most of them are cold-blooded organisms, and their body temperature is influenced by the ambient temperature, water availability, and suitable temperature rank pretty highly [11]. Temperature changes can directly affect pest survival, reproduction, dispersal, and population dynamics, and indirectly affect the relationship between pests and natural enemies [12,13]. New serious pest problems are expected to emerge in the coming decades due to the effects of climate change. The *Leptinotarsa decimlineata* has continued to spread northward from Europe in recent decades, and is expected to be more widespread and damaging in the future [14]. Crop pests are important vectors for the transmission of many crop diseases, such as viruses, phytoplasmas, and bacteria [15]. It is estimated that crop pests and diseases cause more than $70 billion dollars in economic losses globally each year [16].

The impact mechanisms of climate change on crop pests and diseases are complex, involving not only pest population growth and geographic expansion, but also the interaction of multiple factors in the ecosystem. Therefore, it is important to study the hotspots and development directions in this field for researchers to clarify the development trends in the research field of the impact of climate change on crop pests and diseases.

Bibliometrics is a discipline that studies the research status and development trend of a certain field [17]. It is a knowledge system that integrates mathematics, statistics, and the literature, focusing on quantification, and is a research method that can deal with a large amount of literature in related fields and analyze their knowledge orientation [18]. Therefore, with the strengthening of basic theoretical knowledge and the development of knowledge frontiers, using bibliometric methods to analyze the current status and identify the research frontiers in the field of climate change impact on crop pests and diseases, is important for future researchers to study crop pest and disease control. This study used bibliometric and data on visualization software COOC, VOSviewer, and CiteSpace to conduct a bibliometric analysis of research on the impact of climate change on crop pests and diseases published in the Web of Science core database from 1990 to 2021, in order to clarify the development history, research status of research, and trends in this research field. Web of Science, Scopus, and CABI are widely recognized databases worldwide. Web of Science and Scopus are comprehensive academic information resource data covering multiple disciplines, covering almost all disciplines in natural science, social science, engineering technology, biomedicine, humanities, and arts [19]. CABI is one of the most authoritative agricultural and forestry abstract databases, which mainly includes related disciplines in agriculture, forestry, and life sciences [20]. Web of Science and Scopus have become internationally recognized as authoritative tools for the objective and quantitative evaluation of academic journals and scientific research results due to their wide range of subject coverage [19]. Compared with Scopus database, Web of Science has a long history of establishment, covers a long period of publication index records, and provides more detailed citation analysis than Scopus. Therefore, Web of Science data were selected for bibliometric analysis in this study. The main elements of this study are: (1) The number of research papers published each year, journal, country/region, authors, institutions, and cooperation were analyzed by bibliometric methods. (2) Identify the development trends and research hotspots in this field by analyzing the highly cited papers and high-frequency keywords. (3) The overall evolution of the development of the field was captured through the study of frontier identification.

2. Material and Methods

2.1. Data Sources

The Web of Science (WOS) core collection database contains high-quality and authoritative literature data, which has become the current mainstream literature retrieval resource library [21,22]. This study conducted a literature search based on the Web of Science core collection database on 22 August 2022, using the advanced search mode. The publication period was set from "1 January 1990" to "31 December 2021", and the language was English; the literature types were "ARTICLE" and "REVIEW", excluding conference papers and patents. The literature search formula was: (Topical Subject (TS) = (climate change or climate warming or warming or global warming) AND TS = (Crop diseases or crop pests or insect pests or pests) AND Document Type (DT) == ("ARTICLE" OR "REVIEW") AND Language (LA) = =("ENGLISH")). A total of 4558 documents were retrieved, including 3735 research articles and 823 reviews. Data sources include information on the use of publication indexes consisting of the following data: year of publication, author/authors, affiliation, or data identifying the journal from which the given text comes. Articles published since 1 January 2022 were excluded, as any collection after this period would include incomplete bibliometric data for that year.

2.2. Data Preprocessing

There were publication duplicates and synonyms in the original data, so the preprocessing of literature data was the key to make the analysis results more reliable. Based on the bibliometric software Co-occurrence 12.8 (COOC), this study conducts data preprocessing through the comprehensive extraction of items. The processes were as follows: (i) delete duplicate publications, (ii) delete nonsense items, and (iii) merging synonyms. COOC software is based on accurate character segment recognition algorithms, which can effectively guarantee the quality of data processing. In addition, COOC software can convert processed data into other common formats for importing into other visualization software for subsequent analysis.

2.3. Research Methods

Bibliometrics is a discipline that integrates structural representation, dynamic description, evaluation, prediction, and scientometrics [23]. Software, such as VOSviewer v1.6.19, CiteSpace v6.1.2, and COOC 12.8, have been widely used for bibliometric analysis. COOC software can preprocess the literature data and construct multi-dimensional relationships, such as frequency statistics, co-occurrence, coupling, and clustering relationship. VOSviewer and CiteSpace software can visualize the data processed by COOC. However, each software has its own limitations, COOC software data visualization function is weak, VOSviewer and CiteSpace software cannot preprocess data and multi-dimensional relationship construction. This study first used COOC software for literature data processing and statistics, and conducts visual analysis of published journals, authors, countries, publishing institutions, funding agencies, highly cited papers, and high-frequency keywords. Then, the VOSviewer software was used to map subject distribution, country/region, author, and keyword co-occurrence networks to study their connections and collaborative relationships [24]. Finally, the knowledge map of clustering genealogy tree of hot keyword-journal bimodal matrix system was drawn by COOC software, to study the correlation between hot keywords and major journals and the development trend of this field. CiteSpace software was used to draw the evolution of hotspots in time zones to understand the history and future direction of climate change in the field of crop pest and disease research.

3. Results

3.1. Analysis of Basic Characteristics of Literature

3.1.1. Annual Literature Distribution

The change in the number of articles published annually can reflect the development trend and knowledge accumulation in the field of research on the effects of climate

change on crop pests and diseases. The number of relevant research papers published between 1990 and 2021 showed a steady and rapid growth trend (Figure 1). The development process of the field in the past 30 years (1990–2021) can be divided into the following three stages:

1. Initial germination stage (1990–1998): A total of 41 papers were published, accounting for about 0.9% of the total number of papers. Only a few researchers were engaged in research on the effects of climate change. Among them, there are two representative research papers: Kaukoranta (1996) studied the effect of climate warming on yield loss and disease control requirements for potato late blight by constructing a late blight epidemic time model and a potato growth model limited by late blight [25]. The results showed that disease was expected to break out when the total effective temperature accumulated to above 8 °C after potato emergence reached 156 days. Cannon (1998) research found that migratory pests respond faster to climate change than plants, and may settle in new habitats and endanger crop growth in the future [26]. The expansion of pest and disease ranges and the elimination of edge effects could lead to an increase in species populations near the northern boundary of the UK. These findings have promoted a steady transition from the nascent to the primary development stage in the field of research on the effects of climate change on crop pests and diseases.
2. Primary growth stage (1998–2012): Research on the effects of climate change on crop pests and diseases has gradually increased, with the number of published articles increased from 24 in 1998 to 177 in 2012. Representative studies include: Patterson et al. (1999) studied the geographic distribution, viability, virulence, and impact on agriculture production of weeds, insects, and plant pathogens under the influence of climate change [27]. Environmental instability and increased extreme weather were found to reduce the effectiveness of pesticides against target pests, causing more harm to non-target organisms, and increasing the challenges of pests for future agriculture [28]. Roos et al. (2011) studied the effects of global warming on plant diseases and insect vectors in Sweden, and found that increased temperatures and changes in precipitation patterns could lead to changes in crop health [29]. These research results provide great help for subsequent scholars to deeply explore the impact of climate change on crop pests and diseases.
3. Rapid development stage (2012–2021): The number of published articles showed a rapid growth trend, accounting for about 83% of the total number of published articles. The research content was more comprehensive and rich, and they were closely related to "global warming". Global warming drives the movement of pests and pathogens [30]. Lehmann et al. (2020) evaluated the interactions between pest range expansion, life history, and population dynamics, and showed that this field still has great potential for future research [14].

3.1.2. Subject Distribution

The research field of the impact of climate change on crop pests and diseases involves multiple disciplines, and the distribution of research topics is complex. The distribution of disciplinary categories in this research area is shown in Figure 2, where nodes represent disciplines, node size represents disciplinary output, color represents joint creation clusters of different disciplines, connection between nodes indicates knowledge links between disciplines, and line thickness indicates the closeness of the links. The main disciplines involved in this research field include environmental sciences, ecology, agronomy, plant sciences, and biodiversity conservation. The discipline of environmental sciences was most closely related to other disciplines, and most closely related to ecology and biodiversity conservation disciplines. The disciplines of agronomy and plant sciences were closely related. In general, research on the impact of climate change on crop pests and diseases mainly focuses on three aspects: environmental sciences, ecology, and plant sciences.

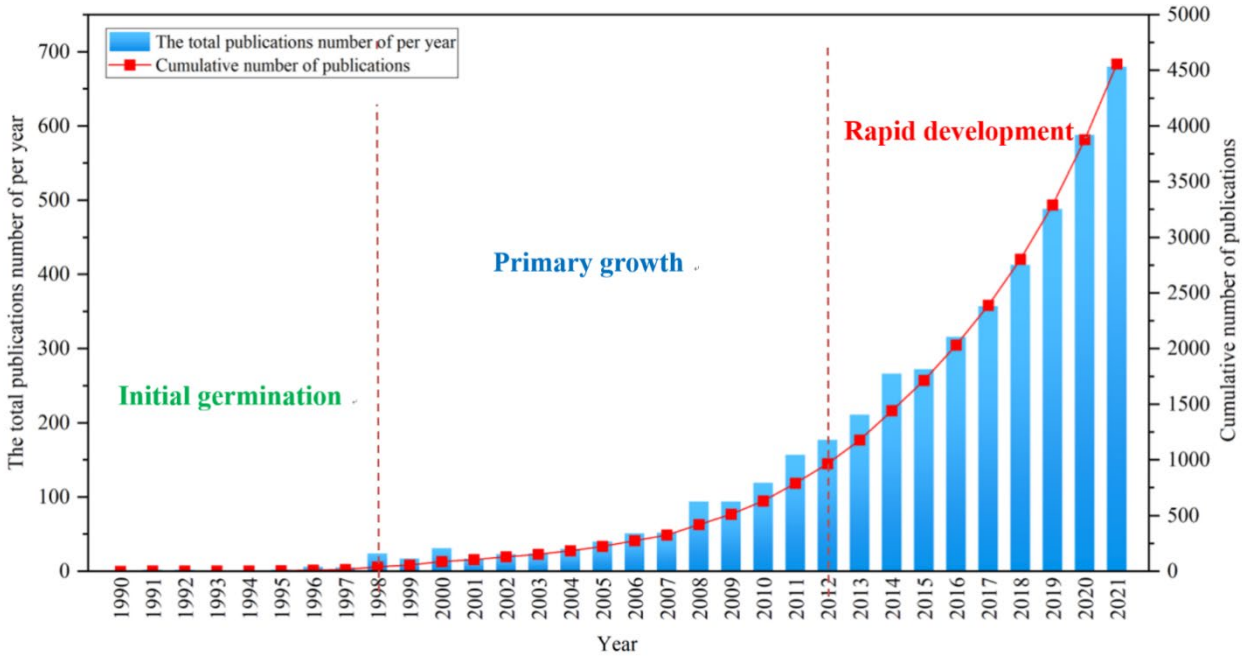

Figure 1. Distribution of the number of literature in the field of climate change impact on crop pests and diseases research from 1990–2021.

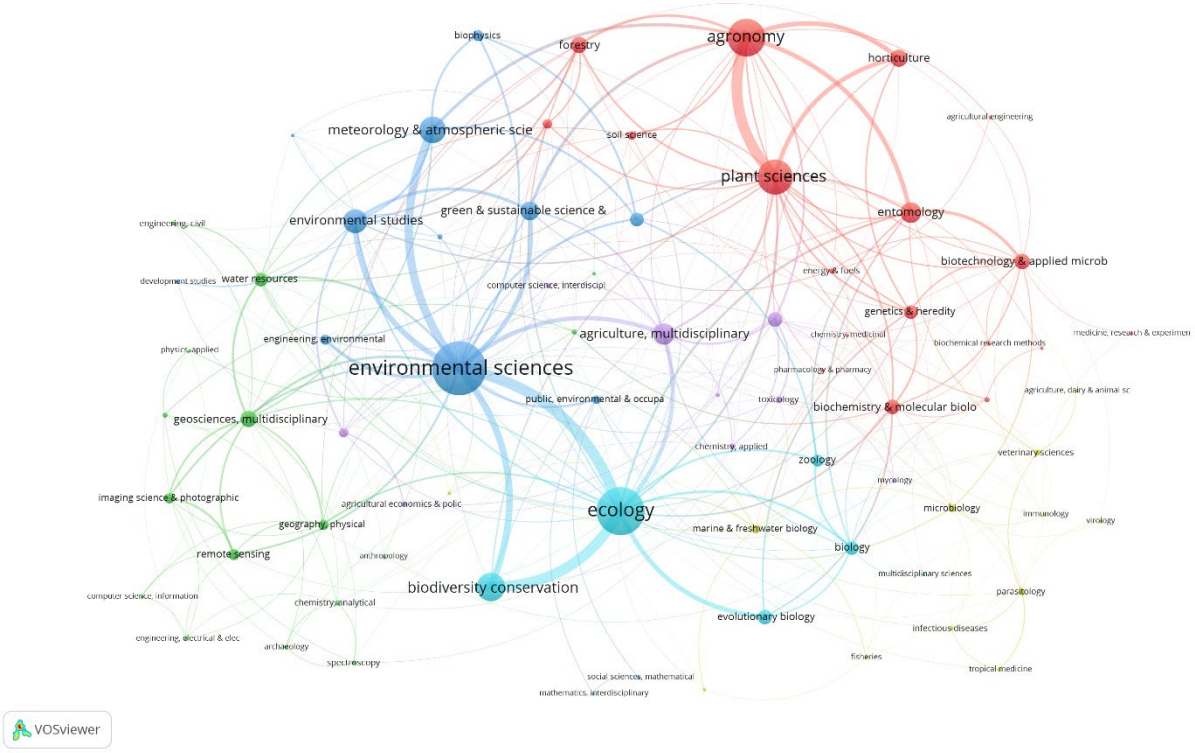

Figure 2. Distribution map of discipline categories.

3.1.3. Journal Distribution

Journals are the most important source and indicator of scientific reports and academic research, which can determine the research directions and core values of related research fields. A total of 1021 journals published studies on the effects of climate change on crop pests and diseases from 1990 to 2021. The top 15 journals in terms of number of published articles are shown in Table 1, with 5 from the UK, 4 from the

United States, and 3 each from the Netherlands and Switzerland. The *PLoS ONE* journal published in the United States had the highest number of publications with a total of 119 papers published. It is worth noting that *Global Change Biology* is the top journal in the field of global change and ecology. Although the number of published papers is far less than that of *PLoS ONE*, its *h*-Index (217) is at the forefront, indicating that the journal has a greater influence in the research field [31].

Table 1. Top 15 Journals in terms of number of articles published.

Rank	Journal Title	Country	Number of Publications	IF	*h*-Index
1	*PLoS ONE*	USA	119	3.752	268
2	*Forest Ecol. Manag.*	The Netherlands	92	4.384	152
3	*Front. Plant. Sci.*	Switzerland	74	6.627	83
4	*Forests*	Switzerland	67	3.282	33
5	*Climatic Change*	The Netherlands	66	5.174	162
6	*Insects*	Switzerland	62	3.139	23
7	*Global Change Biol.*	UK	59	13.211	217
8	*Agr. Ecosyst. Environ.*	The Netherlands	58	6.576	151
9	*J. Econ. Entomol.*	USA	52	2.447	90
10	*Sci. Rep.-UK*	UK	51	4.996	149
11	*Pest Manag. Sci.*	USA	48	4.462	107
12	*Agronomy-Basel*	UK	48	3.949	14
13	*Crop Prot.*	UK	46	3.036	87
14	*Agr. Forest Entomol.*	UK	46	2.126	49
15	*Environ. Entomol.*	USA	42	2.387	77

IF-Impact factor (selected JCR year: 2021).

3.2. Contribution and Collaboration Analysis

3.2.1. Influential Countries/Regions

A total of 146 countries/regions have participated in research on the impact of climate change on crop pests and diseases. The top five countries in terms of number of articles published were the United States, China, Australia, the UK, and France, with 1246, 469, 454, 434, and 345 articles published, respectively (Table 2). The United States was the country with the most research in this field, and has published far more articles than any other country. In addition, the United States cooperates closely with other countries and was the country with the strongest degree of international cooperation. This was followed by the United Kingdom, France, Germany, Australia, and China, with France and Germany cooperating most frequently, followed by Australia and China (Figure 3). Of course, it is worth recognizing that other countries have also made great efforts and contributions to the development of research on the effects of climate change on crop pests and diseases. The development trend of this research field is jointly participated and promoted by many countries/regions.

3.2.2. Author Contribution and Collaboration

It was found that a total of 17,660 researchers conducted studies related to the effects of climate change on crop pests and diseases from 1990 to 2021 through the summary and analysis of the literature information. Among the top 20 authors, in terms of number of articles published, the most authors were from China, followed by authors from Australia (Table 3). The three authors with the most publications were Johnson, S.N., Kriticos, D.J., and Hoffmann, A.A. from Australia, with 21, 21, and 18 articles, respectively. Johnson mainly focuses on crop, pest, and pathogen research in this field. He comprehensively analyzed the effects of climate on crop growth, yield, crop pests, and pathogens, and described the possible interactions between crops, pests, and pathogens under the influence of climate change. He believed that understanding the role of pests and pathogens in crop production systems would help enhance food production security [32]. Kriticos had predicted the potential geographic distribution of specific pests and the serious threat of

pests to crops mainly through modeling. His main contribution was the development of a set of global terrestrial climate datasets at 10′ and 30′ resolution, which could be applied to research in agricultural conservation and pest management [33]. Hoffmann mainly studied the effects of future climate change on crop pests and their natural enemies [34]. Additionally, analyzed the extensive impacts of climate change from genes to biomes to humans, suggesting that climate action and policy must focus on biodiversity and ecosystem conservation [35]. Hoffmann is the highest in terms of influence and contribution, with the total citation frequency of 45,998 and *h*-Index of 102. The *h*-Index of Kriticos and Johnson were 38 and 33, respectively. They have also made great contributions to the research field of climate change on crop pests and diseases, although their influence was weaker than Hoffmann.

Table 2. Top 15 countries in terms of number of articles published.

Rank	Country	Number of Publications
1	USA	1246
2	China	469
3	Australia	454
4	UK	434
5	France	345
6	Germany	313
7	Canada	310
8	India	310
9	Italy	262
10	Spain	214
11	Brazil	168
12	Sweden	160
13	South Africa	144
14	Switzerland	132
15	Scotland	127

The co-authorship knowledge domain map can provide valuable information for analyzing the contributions and collaborations of authors in this field and help to explore future collaborative teams and co-investigators in this research field. The nodes in Figure 4 represents the authors, and node size represents the number of articles published by authors. The connection between nodes indicates the collaboration relationship, the wider the connection line means the closer the collaboration between authors, and different colors indicate different clusters of collaboration between authors [36]. Several clusters of authors working closely together are presented in Figure 4, such as the clusters represented by Willocquet, L., Ma, Chun-Sen, and Chidawanyika, F. However, the different clusters were relatively independent and less connected, implying relatively little collaboration among authors globally. Therefore, more attention and importance should be paid to interdisciplinary, inter-institutional, and inter-country authorship cooperation in the future development process to enhance teamwork to promote the rapid and diversified development of this research field.

3.2.3. Major Publishing Institutions and Fund Projects

This study found that a total of 4849 institutions have published relevant articles in this field. Among the top 15 institutions in this research field, 6 were from the United States, 3 were from Australia, 2 were from China, and 1 each was from France, Sweden, Canada, and the UK (Table 4). The highest number of publications was published by institutions from the United States, with a total of 439 articles. The National Institute for Agricultural Research from France ranked first with 102 articles, followed by the Chinese Academy of Sciences from China and the United States Forest Service from the United States, with published 88 relevant articles, respectively. The collaborative knowledge mapping of the major publishers showed that the clusters of institutions represented by

the larger nodes National Institute for Agricultural Research, University of Queensland, University of Florida, and United States Forest Service were closely linked, indicating frequent collaboration among institutions (Figure 5).

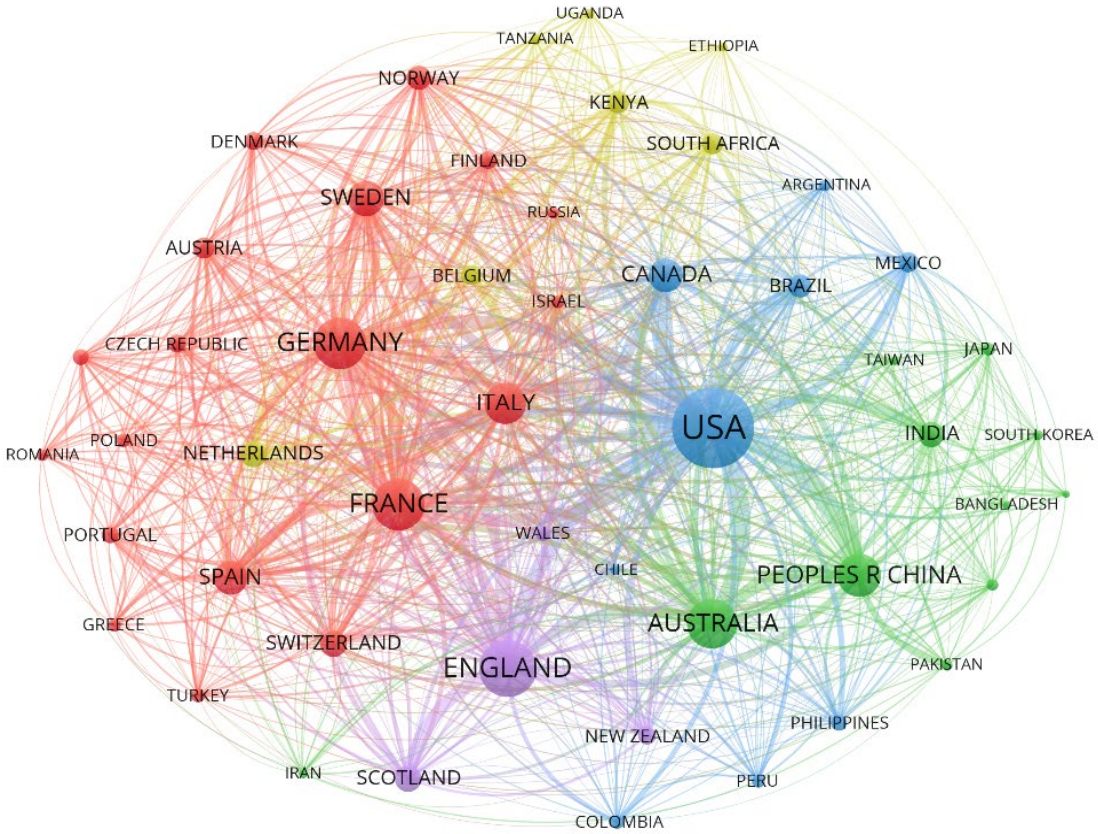

Figure 3. Knowledge mapping of cooperation between countries/regions the impact of climate change on crop pests and diseases.

Table 3. Information on the top 20 authors in terms of number of articles published.

Rank	Author	Country	*h*-Index	Number of Publications
1	Johnson, Scott N	Australia	33	21
2	Kriticos, Darren J	Australia	38	21
3	Hoffmann, Ary	Australia	102	18
4	Fitt, Bruce D. L.	England	40	15
5	Ge, Feng	China	34	15
6	Garrett, K. A.	USA	33	15
7	West, Jonathan S	England	29	15
8	Ma, Chun-Sen	China	20	15
9	Battisti, Andrea	Italy	36	14
10	Savary, Serge	Philippines	30	14
11	Olfert, O.	Canada	24	14
12	Nyamukondiwa, Casper	Botswana	16	14
13	Jactel, Herve	France	39	13
14	Zong, Shi Xiang	China	12	13
15	Rao, M. Srinivasa	India	8	13
16	Frank, Steven	USA	28	12
17	Willocquet, Laetitia	France	27	12
18	Weiss, R. M.	Canada	19	12
19	Tonnang, Henri	Peru	19	12
20	Ge, Xuezhen	China	6	12

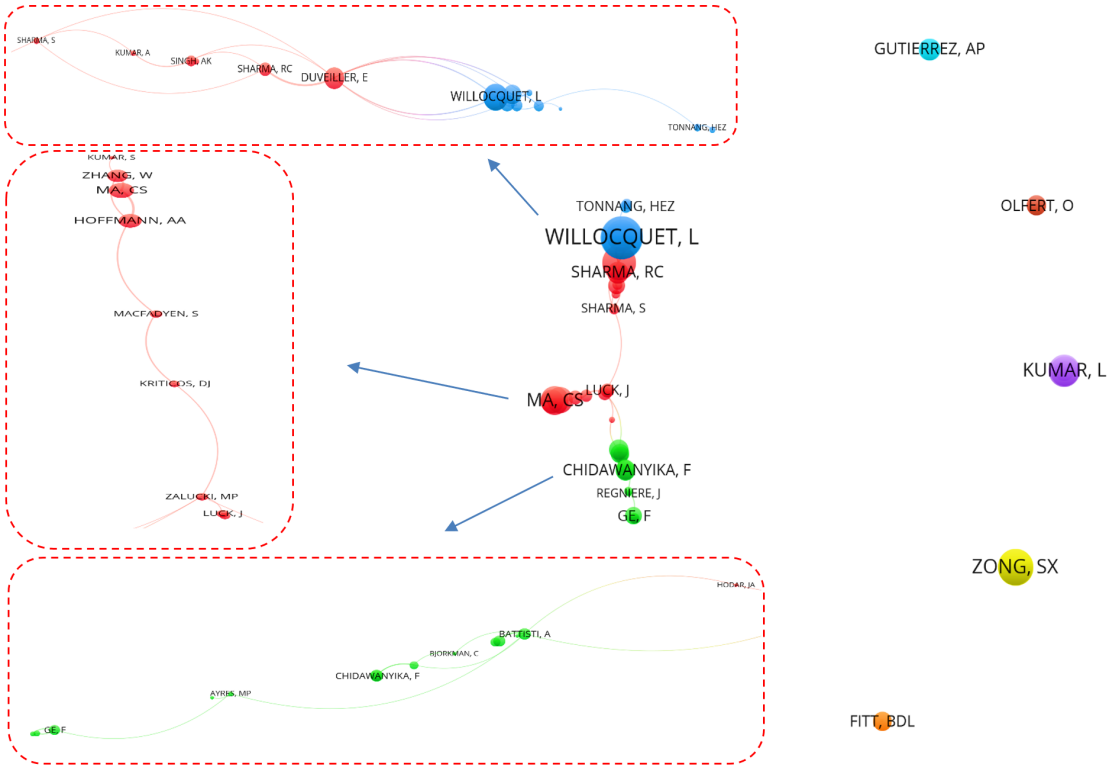

Figure 4. Co-author knowledge domain graph.

Table 4. Top 15 institutions in terms of number of published articles.

Rank	Institution	Country	Number of Publications
1	National Institute for Agricultural Research	France	102
2	Chinese Academy of Sciences	China	88
3	United States Forest Service	USA	88
4	United States Department of Agriculture—Agricultural Research Service	USA	87
5	Swedish University of Agricultural Sciences	Sweden	85
6	University of Florida	USA	77
7	Agricultural Research Service	USA	71
8	University of California Davis	USA	68
9	University of Queensland	Australia	66
10	Chinese Academy of Agricultural Sciences	China	59
11	Agriculture and Agri-Food Canada	Canada	52
12	University of Melbourne	Australia	51
13	Rothamsted Research	UK	51
14	Michigan State University	USA	48
15	University of Western Australia	Australia	47

As an important subject of government funding for basic research, the science foundation performed a crucial role in supporting the development of basic research. Among the top 15 funding agencies in the field of impacts of climate change on crop pests and diseases, top 5 fund the most research, namely Natural Sciences and Engineering Research Council of Canada, Swiss Agency for Development and Cooperation (Sdc), Swedish International Development Cooperation Agency (Sida), Kenyan Government, and European Union (Table 5).

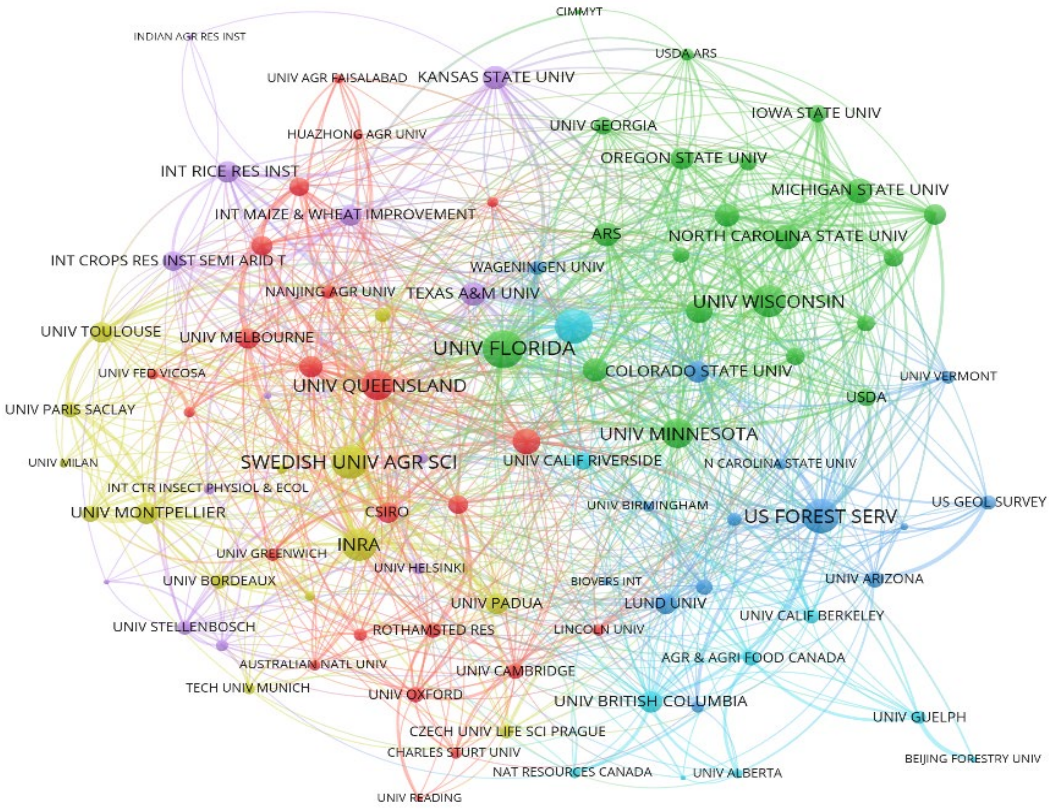

Figure 5. Knowledge map of relevant institutions in the field of climate change's impact on crop pest and disease research.

Table 5. Top 15 funding institutions.

Rank	Fund Supporting Organizations	Times
1	Natural Sciences and Engineering Research Council of Canada	14
2	Swiss Agency for Development and Cooperation (Sdc)	13
3	Swedish International Development Cooperation Agency (Sida)	12
4	Kenyan Government	12
5	European Union	11
6	BBSRC	9
7	National Science Foundation	9
8	Genome British Columbia	9
9	Agriculture and Agri-Food Canada	8
10	Fundamental Research Funds for The Central Universities [2016zcq07]	8
11	Cgiar Trust Fund	7
12	Cgiar Research Program on Climate Change, Agriculture and Food Security (Ccafs)	7
13	Usaid	7
14	Grains Research and Development Corporation	7
15	Usda Forest Service	7

3.3. Highly Cited Papers

Highly cited papers are the key information for laying the foundation of related research fields, and the analysis of their research contents can reflect the development and hot directions of related fields to a certain extent. The top 20 most cited articles in the field of research on the impacts of climate change on crop pests and diseases are shown in Table 6. They have performed a great role in the establishment and development of research theories, research ideas and methods, and core ideas in this field. The top four papers cited were published in "Nature" and "Science" journals, indicating that research papers

published in high-quality journals are more forward-looking and easier to be noticed and valued by researchers.

Table 6. Top 20 highly cited papers.

Rank	First Author	Title	Journal	Country	CF
1	Piao, Shilong	The impacts of climate change on water resources and agriculture in China	*Nature*	China	2026
2	Ripple, William J.	Status and ecological effects of the world's largest carnivores	*Science*	USA	1775
3	Harvell, Cd	Ecology—climate warming and disease risks for terrestrial and marine biota	*Science*	USA	1721
4	Patz, Ja	Impact of regional climate change on human health	*Nature*	Switzerland	1695
5	Philippot, Laurent	Going back to the roots: the microbial ecology of the rhizosphere	*Nat. Rev. Microbiol.*	Netherlands	1506
6	Hulme, Philip E.	Trade, transport and trouble: managing invasive species pathways in an era of globalization	*J. Appl. Ecol.*	New Zealand	1430
7	Allen, Craig D.	On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the anthropocene	*Ecosphere*	USA	1254
8	Power, Alison G.	Ecosystem services and agriculture: tradeoffs and synergies	*Philos. T. R. Soc. B*	USA	1147
9	Challinor, A. J.	A meta-analysis of crop yield under climate change and adaptation	*Nat. Clim. Change*	USA	973
10	Simberloff, Daniel	The role of propagule pressure in biological invasions	*Annu. Rev. Ecol. Evol. S.*	USA	946
11	Anderson, Pk	Emerging infectious diseases of plants: pathogen pollution, climate change and agrotechnology drivers	*Trends Ecol. Evol.*	USA	939
12	Jump, As	Running to stand still: adaptation and the response of plants to rapid climate change	*Ecology Letters*	Spain	927
13	Lin, Brenda B.	Resilience in agriculture through crop diversification: adaptive management for environmental change	*Bioscience*	USA	706
14	Hatfield, J. L.	Climate impacts on agriculture: implications for crop production	*Agronomy Journal*	USA	695
15	Vanbergen, Adam J.	Threats to an ecosystem service: pressures on pollinators	*Front. Ecol. Environ.*	Scotland	690
16	Sih, Andrew	Evolution and behavioural responses to human-induced rapid environmental change	*Evolutionary Applications*	USA	688
17	Patz, Ja	Effects of environmental change on emerging parasitic diseases	*Int. J. Parasitol.*	USA	641
18	Kozlowski, Tt	Acclimation and adaptive responses of woody plants to environmental stresses	*Botanical Review*	USA	595
19	Witzgall, Peter	Sex pheromones and their impact on pest management	*J. Chem. Ecol.*	USA	594
20	Logan, Ja	Assessing the impacts of global warming on forest pest dynamics	*Front. Ecol. Environ.*	Canada	576

CF-Citation frequency.

Among the top 20 highly cited articles, eight articles had more than 1000 citations. The rapid accumulation of paper citations indicates that the field of climate change's impact on

crop pests and diseases is receiving increasing attention from research scholars. The first highly cited article was published in the journal *Nature* titled "The impacts of climate change on water resources and agriculture in China" [37], with a citation frequency of 2026 times. The article studies the impact of climate change on China's economy, water resources, and agriculture, and the study provides a solid foundation for the development of the research on the impact of climate change on crop pests and diseases. The second most highly cited article was published in the journal *Science*, entitled "Status and ecological effects of the world's largest carnivores" in the journal Science, with 1775 citations [38]. The article proposes that future large carnivores will influence the extent to which individual species, biomes, and ecosystems respond to climate change. Growing human resource needs and a changing climate will affect crop pest diversity and ecosystem resilience. The third most highly cited article was published in the journal *Science*, entitled "Ecology-Climate warming and disease risks for terrestrial and marine biota", with 1721 citations [39]. The article proposed that many pathogens of plant groups were sensitive to temperature, rainfall, and humidity, producing synergistic effects that would affect biodiversity. Climate warming increases pathogen development, survival, disease transmission, and host susceptibility. In order to improve the ability to predict epidemics in plant populations, it is necessary to distinguish between the independent and interactive effects of multiple climate drivers on plant diseases. The fourth most highly cited article was published in the journal *Nature*, entitled "Impact of regional climate change on human health" [40]. The article focuses on the impact of climate change on food security and human health. The study shows that future climate change will pose increasing health risks, and that the warming trend of recent decades has already led to increased crop morbidity and mortality in many parts of the world. The fifth most highly cited article was published in the journal *Nature Reviews Microbiology*, entitled "Going back to the roots: the microbial ecology of the rhizosphere", with a citation frequency of 1506 times [41]. The article proposed that interactions between microbes and invertebrates influenced the Earth's biochemical cycles, plant growth, and tolerance to biotic and abiotic stresses. These studies involve assessing the development of micro-flora and macro-flora for sustainable agriculture, nature conservation, and bioenergy crops. In addition, researchers from the United States have made more contributions to this field. The first author of 13 articles from the United States in the cited frequency of top 20 articles, indicating that United States researchers have made great contributions to the development of the field.

3.4. Research Hotspots and Development Trends

3.4.1. High Frequency Keywords

Keywords as the core of paper research and the label of disciplinary information, can highly summarize the main content of research. It can reveal the research hotspots and research directions in related fields through the analysis of high-frequency keywords. The keywords "Climate Change", "Agriculture", "Food Security", "Temperature", and "Invasive Species" had higher frequencies, with 1030, 119, 116, 109, and 98 times, respectively, indicating that under the influence of climate change agriculture, food security, and invasive species were the hot spots in this field (Table 7). The research found that the research hotspots in this field focused on the distribution and spread of crop pests and diseases, and on this basis, research on the impact on agricultural production and food safety.

Among the hot keywords (Figure 6), the blue cluster centered on Climate Change was the largest cluster, and it was closely linked to Invasive Species (red cluster), Global Warming (yellow cluster), Pests (green cluster), and Agriculture (purple cluster). The red cluster has a wide distribution and focuses on the expansion and management of pests under climate change, including keywords, such as invasive species, climate, phenology, pests management, and range expansion. The yellow cluster mainly includes forest pests, drought, carbon dioxide, forest management, livestock, etc. The cluster focuses on the impact of global warming on forest ecosystem management and forest pests. The green

cluster mainly includes keywords, such as insects, maize, rice, wheat, yield, potato, abiotic stress, and disease. The cluster focuses on studying the impact of climate change on the yield of specific crops and crop diseases. The purple cluster mainly includes agriculture, ecosystem services, biodiversity, sustainability, and conservation. The cluster focuses on the study of biodiversity and the development of sustainable agriculture.

Table 7. Top 15 high frequency keywords.

Rank	Keyword	Times
1	Climate Change	1030
2	Agriculture	119
3	Food Security	116
4	Temperature	109
5	Invasive Species	98
6	Global Warming	97
7	Pests	97
8	Drought	67
9	Pests Management	67
10	Ecosystem Services	62
11	Integrated Pests Management	59
12	Phenology	58
13	Adaptation	55
14	Biological Control	48
15	Population Dynamics	47

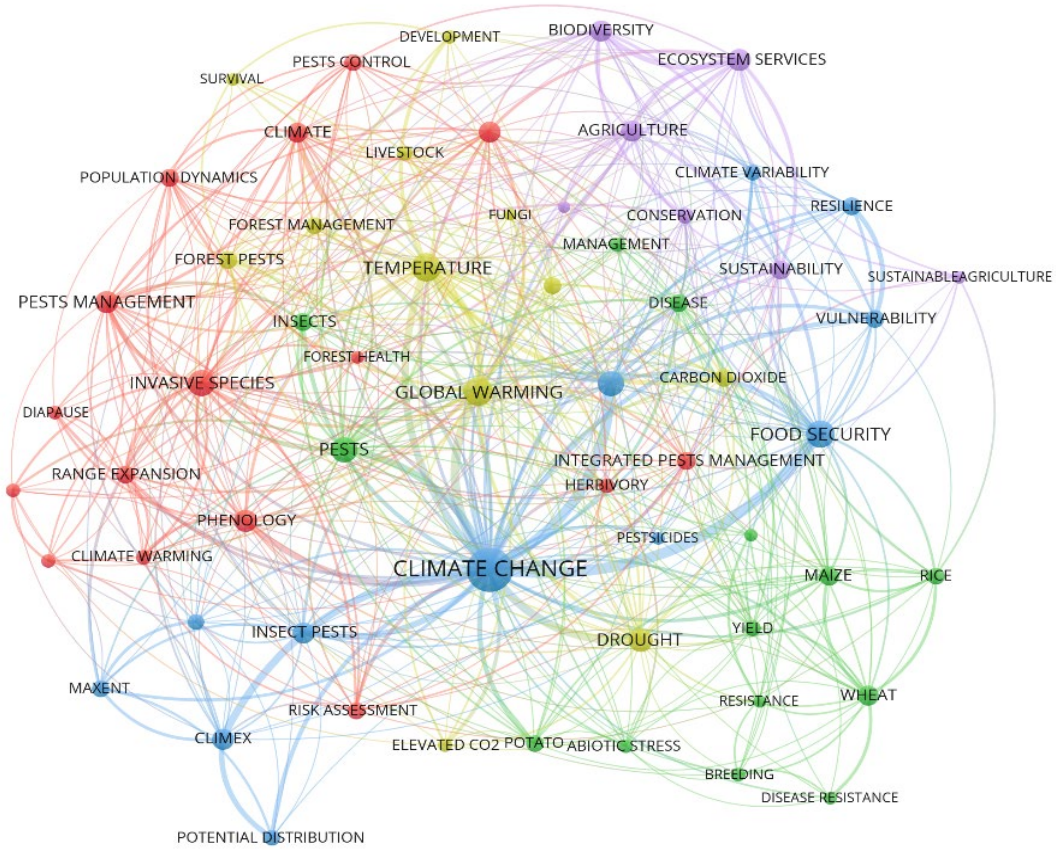

Figure 6. Knowledge graph of keyword co-occurrence networks.

3.4.2. Clustering Analysis Based on Bimodal Matrix

Cluster analysis can directly display the relationship between research objects and judge their degree of association [42]. In this study, a two-mode matrix system clustering

genealogy tree knowledge map of hot keywords and popular journals was constructed by using Co-occurrence 12.8 (COOC) software. The clustering analysis based on bimodal matrix is improved on the basis of traditional unidimensional system clustering algorithm, which can realize the dual clustering of keywords and journals. Euclidean distance algorithm is used to calculate the distance between samples, Ward minimum variance method is used for sample clustering, Z-Score normalization method is used for matrix normalization [36]. The two-way clustering results of high-frequency keywords and journals in the field of climate change impact on crop pests and diseases research are shown in Figure 7. The box lines in the figure represent the high-frequency keywords and journals corresponding to each column and row. Different color depths indicate the co-occurrence frequency in published articles. The vertical and horizontal clustering trees indicate the clustering results of high-frequency keywords and high-frequency journals, respectively. The hot research directions and popular journal groups in the field can be derived by analyzing the clustering results of hot keywords and popular journals.

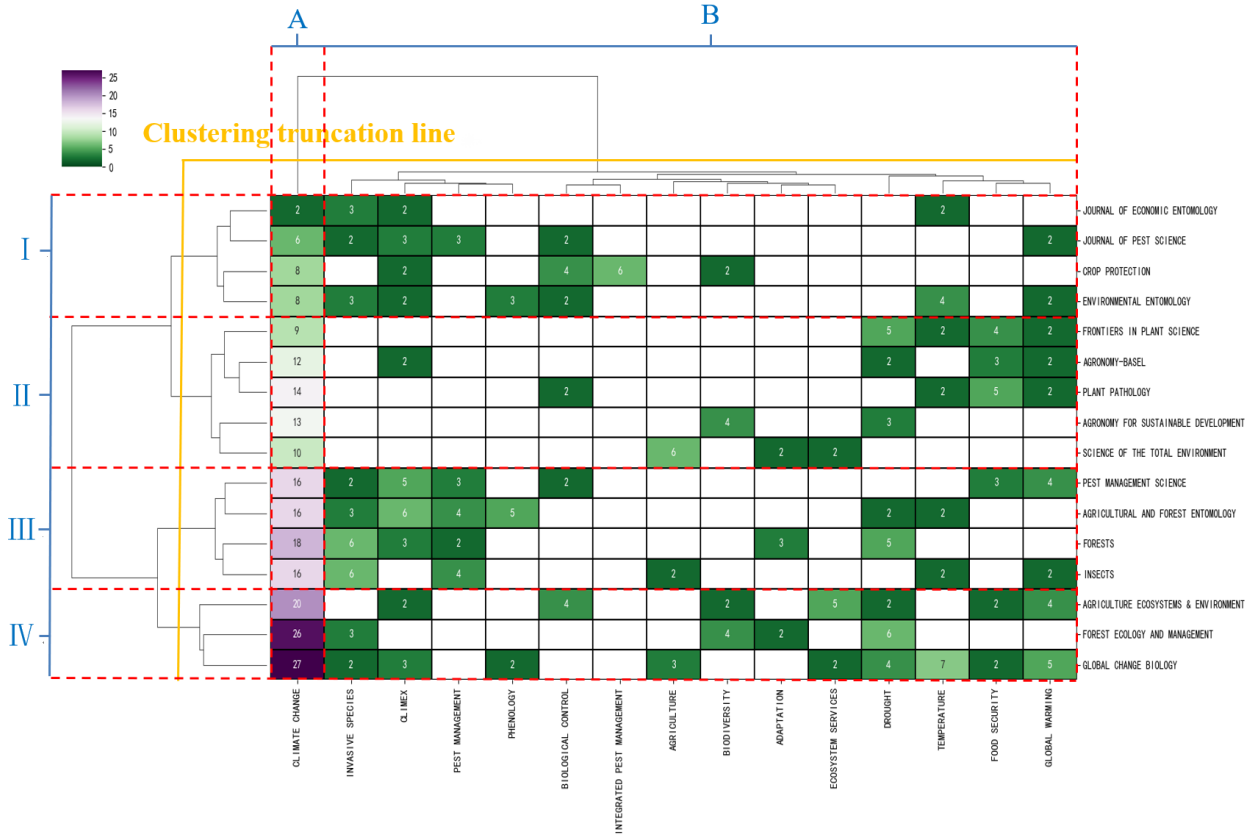

Figure 7. Knowledge mapping of systematic clustering genealogy trees based on keyword and journal two-mode matrices.

The hot spots in the research field of climate change impact on crop pests and diseases were mainly divided into two categories: (A) Focus on climate change research; and (B) focus on a series of impacts studies caused by climate change, mainly including pest management, agriculture, ecosystems, and food security. These two groups could be divided into four areas based on popular journals: (I) "Pest Research and Crop Protection" group; (II) "Plant Science Research and Global Agricultural Development" group; (III) "Pest Management Science and Agroforestry Entomology" group; and (IV) "Agroecosystems and Global Biological Change" group. (I), (III), and (IV) are popular published journals at present. "Global Change Biology" was the one with the most significant correlation with hot keywords, especially with climate change and temperature two-dimensionally. The links between research on the impact of climate change on crop pests, agroecosystems, and

food security, and other journal groups are deepening, indicating a gradual diversification of research in this field.

3.4.3. Research Frontier

This study used keywords from highly cited articles to develop a bibliometric model to analyze the research frontiers in the field of climate change's impact on crop pest and disease research. Figure 8 shows a keyword time zone graph of the top 500 highly cited articles in this field. The *Y*-axis is the hot keyword clustering, and the *X*-axis is the publication year. The larger the cross node in the graph, the higher the frequent keyword. Node connectivity indicates the existence of synergistic associations between keywords, and the higher the centrality of a node, the better the co-occurrence of connectivity with other keywords. It could be found from Figure 8 that the earliest research focus in this field was crop productivity.

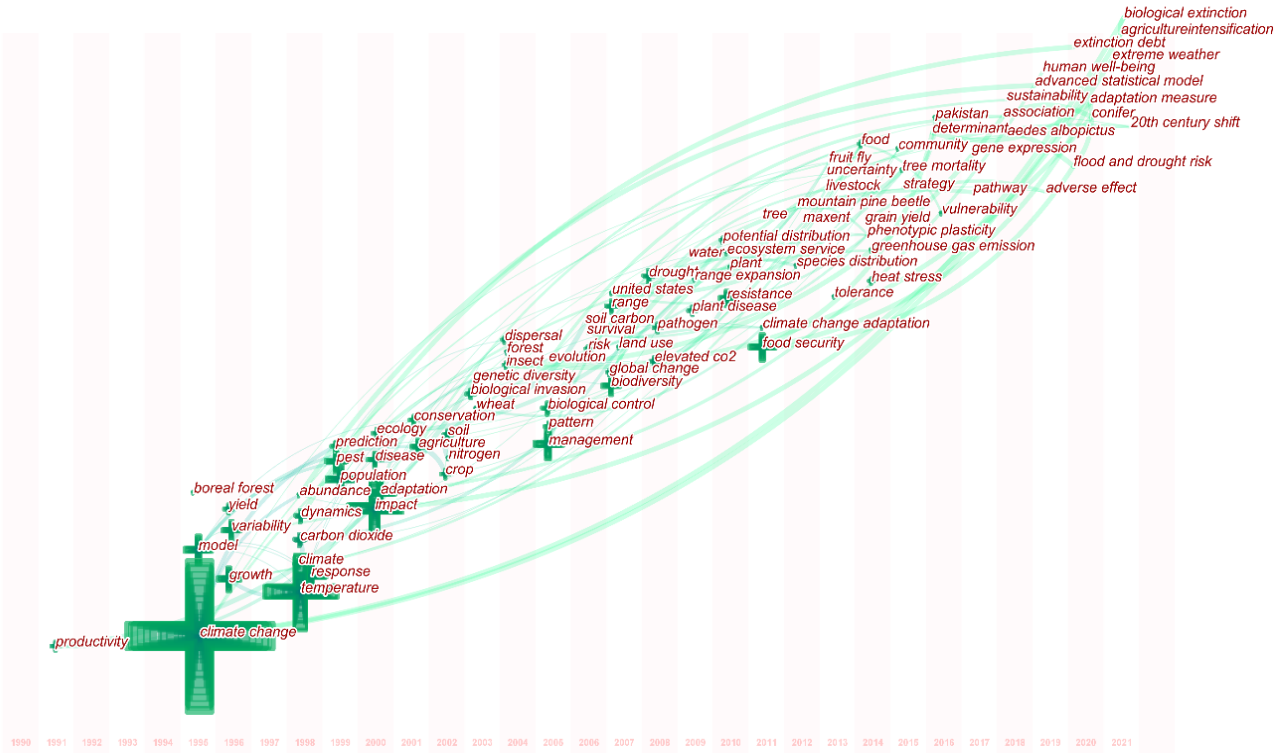

Figure 8. Keyword time zone map of highly cited papers from 1990–2021.

Keywords, such as climate change, temperature, model, and growth, that appeared from 1990 to 1998 still remain hot in 2021, indicating that these research hotspots had laid a solid research foundation during the development of this field. With the deepening of global warming research, subsequent studies on the effects of pests and diseases on crops gradually began to emerge. For example, the yield losses and the need for pest control caused by potato late blight under the background of climate warming were studied by constructing a potato growth model that comprehensively evaluated the late blight damage [25].

The research directions between 1998 and 2012 have become more and more extensive, with hot keywords, such as pest, impact, adaptation, disease, agriculture, management, biodiversity, resistance, and food security. Researchers began to focus on food security, species diversity, and pest and disease prevention measures. Dietary diversity based on different farming systems provides better nutrition and health, with additional benefits for human productivity and livelihoods [43]. Climate change affects the occurrence, prevalence, and severity of plant diseases, which in turn affects disease management, including the

timing, preference, and efficacy of chemical, physical, and biological control measures, and integrated pest management strategies. The establishment of integrated control strategies and effective quarantine systems through preventive plant protection measures (e.g., compound multi-crop variety planting, use of crop varieties with superior disease resistance and tolerance, and adjustment of sowing dates) and disease prevalence prediction were of great importance in agricultural production [44].

The research In this field was more diversified and in a period of rapid development from 2012 to 2021. Most research scholars have begun to focus on the complex responses triggered by global warming. The severity of specific pest occurrences under the influence of climate warming may increase or decrease. The multifaceted and complex nature of insect responses to the ongoing effects of global warming has led to a more comprehensive assessment of the impact of climate change on crop pests and diseases (e.g., range expansion, life history, population dynamics, and nutrient interactions) during that period [14]. Pest management strategies are needed in the future as climate change exacerbates pest problems. These management strategies include monitoring climate and pest populations, improving integrated pest management, and using modeling prediction tools [45]. At present, it is still a great challenge to predict the impact of climate warming on crop pests and diseases. In addition, exploring the effects of climate warming on pests and diseases requires the study of individual species responses and the complex ecological mechanisms underlying the responses.

4. Discussion

At present, the research field mainly focuses on the effects of elevated temperature, increased atmospheric CO_2, precipitation patterns, and relative humidity on crop pests and diseases. In addition, the top five countries in terms of the number of published articles were the United States, China, Australia, the United Kingdom, and France (Table 2). Fand et al. (2012) found that elevated atmospheric CO_2, increased temperature and decreased soil moisture may significantly affect the population dynamics of crop pests, thus affecting crop production [46]. Shrestha (2019) indicated that temperature performs an important role in crop pest metabolism, dispersal, and parasitism, and that temperature changes determine pest population dynamics [47]. The FAO report indicates that climate change has created new ecological niches that provide opportunities for crop pests to reproduce and spread in new geographic environments [8]. Skendzic et al. (2021) indicated that climate change includes not only changes in temperature, precipitation, and rising atmospheric CO_2, but also the possibility of extreme climate scenarios, such as glacial melt, permafrost melting, and sea level rise, in the future [45]. Therefore, the effects of climate change on crop pests and diseases are complex and multifaceted. Most of the current studies are on the effects of single factors caused by climate change on specific crop pests and diseases, and there is a lack of studies on the effects of multifactor interaction and future extreme climate occurrences on crop pests and diseases.

Most of the studies mainly used model simulation methods to predict the effects of climate change on crop pests and diseases, and there was a lack of field experiment observation research. The prediction model can be used to study the spread and control methods of crop pests and diseases in agricultural fields. Harvell et al. (2002) distinguished the independent and interactive effects of multiple climatic factors on crop pests and diseases through model simulation [39]. This research field should combine model predictions with field observation experiments in the future, and strengthen the research on the impacts of multi-factor interactions and extreme weather on crop pests and diseases under the background of climate change.

"Productivity", "Model", "Growth", and "Carbon dioxide" were hot keywords in the research field of the impact of climate change on crop pests and diseases from 1990 to 1998. It means that building models to predict crop growth and productivity was the main research direction in the early stage of this field. With global warming caused by massive emissions of greenhouse gases (CO_2), researchers were beginning to assess the

effects of future warming on crop yields and crop pests by constructing models [48,49]. The frequency of the earlier hot keywords increased between 1998 and 2012, and new hot keywords, such as "Agriculture", "Management", "Biodiversity", "Resistance", and "Food Security", began to appear. Global warming and increased trade between countries/regions exacerbate the rate and extent of crop pest transmission [50]. A large number of countries have begun to pay attention to pest management and food security, leading the key research direction in this field to develop into the impact of climate change on pest management and food security. Since 2012, the hot keywords have gradually diversified, with the main research direction has evolved into a series of complex ecological responses caused by global warming on crop pests, agricultural yields, and economics [51,52]. Therefore, how to effectively control greenhouse gas (CO_2) emissions is crucial for future agricultural production and crop pest management. It is important to consider the impact of continuous temperature rise, which is of great significance for future crop pest and disease control strategy and technological innovation. At present, the research on the impact of climate change on crop pests and diseases tends to be diversified. Researchers pay more attention to the complex responses of crop pests and diseases caused by climate change, such as activity range, life history, population dynamics, and nutrient interactions. In addition, it has also begun to pay attention to the pest management strategy and develop comprehensive management strategies to improve the impact of pests by monitoring the characteristics of pest populations.

This study used visualization software to extract and analysis the research hotspots and development trends in the field of climate change's impact on crop pests and diseases based on the literature data. However, the limited literature data due to the search formula setting and time span limitations make the analysis results of this study somewhat limited. In addition, the accuracy of data pre-processing using visual analysis software is low, and it is necessary to combine manual screening. The shortcomings, such as cluster overlap and low flexibility in parameter settings, that occur in data visualization are issues that need to be addressed in future research.

5. Conclusions

In this study, COOC, VOSviewer, and CiteSpace visualization software were used to analyze the literature on the impact of climate change on crop pests and diseases published between 1990 and 2021. The main conclusions were as follows:

(1) The literature published in this research field from 1990 to 2021 showed a rapid growth trend. The research is mainly related to environmental sciences, ecology, and agronomy. The three journals with the highest number of publications were *PLoS ONE*, *Forest Ecology Management*, and *Frontiers Plant Science*.

(2) The United States, China, Australia, the United Kingdom, and France have more publications in this field. The authors from China were the most among the top 20 authors in terms of number of publications. The number of publishing institutions from the United States was the largest, and the relevant publishing institutions were closely connected and cooperate frequently. There are 5 funding institutions with more than 10 articles, namely Natural Sciences and Engineering Research Council of Canada, Swiss Agency for Development and Cooperation (Sdc), Swedish International Development Cooperation Agency (Sida), Kenyan Government, and European Union. The first authors of 13 of the top 20 highly cited papers were from the United States.

(3) High frequency keywords "Agriculture", "Food Security", and "Invasive Species" indicated that the research hotspots in this field were the impacts of climate change, and crop pests and diseases on agricultural production and food security, and the management of invasive species in ecosystems.

(4) Based on the research results of this paper, the research trends in the coming years will continue to shift from the impact of climate change on individual crop pests and diseases to a series of complex responses of climate change on crop pests and diseases, and the research direction tends to be diversified. Additionally, based on

the basis, modeling, and prediction tools were used to propose pest management strategies, including monitoring climate and pest populations, to improve integrated pest management. This study can provide guidance for scholars to understand the development trend, research direction, and research hotspots in this field through the above analysis.

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