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Review

Bibliometric and Visual Analysis of Crop Water Footprint: A Widely Used Agricultural Water Resources Evaluation Method

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Abstract: As a new theme in agricultural water resources evaluation, the crop water footprint (CWF) has attracted much attention, and the number of published studies has shown rapid growth. In order to explore the research prospects of the CWF, this paper conducted a visual bibliometric analysis of its development context, hot topics and knowledge base, by using CiteSpace (version 5.6. R5, Chaomei Chen, Philadelphia, PA, USA). Up to the retrieval time, there were, in total, 838 articles based on the Web of Science core collection database. In terms of contribution, China, the Netherlands and the United States were the three most representative countries, and the University of Twente and Arjen Y. Hoekstra were the most productive institution and author, respectively. In terms of the discipline background, Environmental Sciences & Ecology, Environmental Sciences and Water Resources were the three most relevant categories. Based on the co-occurrence analysis of the keywords, the hot topics of the three periods has been illustrated, and assessing the climate change impact on the water-use efficiency of crop production is the focus of the current research. The knowledge background of the CWF was elaborated by the co-citation and cluster analysis of references, which consists of four parts: concept, quantification, evaluation and reduction. Reducing the water requirement to improve crop water productivity through rainwater harvesting and formulating reasonable hydro-policies is the main responsive strategy to improve agricultural water-use efficiency. In particular, the accurate differentiation of the blue, green and gray water footprint calculation, considering multiple pollutants, the exploration of mitigation policies for the climate change impact and the combination of the CWF and traditional indicators, will be the focuses of future research in the CWF.

Keywords: agricultural water evaluation; crop water footprint; CiteSpace; bibliometric analysis

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1. Introduction

More than 90% of human demand for water resources comes from the agricultural production sector, and green and efficient water use in agriculture is a necessary way to alleviate the pressure on regional water resources and water environment [1,2]. The theory, method, index and enhancement mechanism of agricultural water-use efficiency evaluation have been an important concern for scholars. With the evolution of population growth, rural revitalization, ecological environment construction, urbanization and dietary structure, the increasing demand for primary agricultural products not only poses new challenges to the improvement of the water resources utilization efficiency during the crop growth stage, but also gives rise to the systematic demand for a scientific and comprehensive response to water quantity and water environment issues to promote the efficient and sustainable utilization of regional water resources [3–5].

The water footprint (WF) is a comprehensive indicator to quantify the consumption of water resources by human activities, used to assess the impact on water quantity and quality [6]. Specifically, for agricultural production systems, it measures the total water demand in the whole growth period of crops. Particularly, it consists of three components: the blue, green and gray water footprint, where the blue and green water footprints are the irrigation water and effective precipitation consumed in the form of evapotranspiration and no longer reused, respectively. The gray water footprint is the amount of water required to dilute the system's emissions of pollutants (e.g., nitrogen) to meet environmental standards [7]. Obviously, it not only takes the impact of green water on crop water demand into account, but also considers the environment impact of human activities on water resources in crop growth periods, which can more truly reflect the relationship between the generalized water resources and crop water consumption, providing a new perspective on agricultural water resources evaluation.

As the crop water footprint (CWF) accounts for a huge proportion of the global water footprint, the accounting, assessment and regulation of the water footprint of agricultural production has become an important element of efficient and sustainable use of regional water resources. Specifically, with the help of crop models, the calculation and analysis of the water footprint of crops on different regional and spatial scales was the main content of the early CWF research [8–10]. On this basis, scholars have carried out a large number of micro-judgements on the sustainability and management mechanism of regional agricultural water use. Pfister and Bayer [11] estimated the water stress on a monthly scale due to global crop blue–green water consumption; Zhuo et al. [12] revealed the impact of the variation in the water footprint of crops on the degree of blue water scarcity in the Yellow River basin; Cao et al. [13] found that ignoring the water footprint and generalized water endowment would underestimate the severity of the water shortage in an arid area through the comparison of indicators. These studies demonstrated the necessity of water footprint regulation and prompted its application in regional agricultural water management. Wu et al. [14] combined the grain water footprint and an assessment of the regional virtual water flows in China, suggesting agricultural water footprint control as a means to agricultural water-saving; Duan et al. [15] attempted to provide a reference for a reduction strategy by revealing the driving factors of the regional CWF variation. Studies on the impact of the changes in factors such as the climate and cropping structure on the water footprint of the regional crop production, and how to cope with them, have also been reported [16–18]. Roux et al. [19] constructed the sustainable evaluation indicators of irrigation water use under the framework of the water footprint; Wang et al. [20] evaluated the water-use efficiency of regional food production based on the crop blue–green water footprint. However, macroscopic evaluations often limit the reliability of the study results due to problems such as those oriented to the farm perspective, the quantification of the green water, assumption of the gray water parameters and neglect of the irrigation levels and irrigation processes. For this reason, Karandish et al. [21] and Chukalla et al., [22] respectively, analyzed the role of irrigation and fertilizer changes in reducing the blue–green and gray water footprint of crops. Barbosa et al. [23] evaluated the water footprint of crop production under drip-irrigation conditions. It is clear that the research on the CWF has proven to be fruitful, and these results have an important role in guiding the development of regional agricultural water management strategies and inspiring the use of water footprints for agricultural water use evaluation. Therefore, a bibliometric analysis is needed to make it more convenient for readers to understand the knowledge background of the CWF; this is a quantitative analysis method for database-indexed publications, based on statistical and computational techniques, and has been widely used in the literature review studies [24–26].

The purpose of this study is to provide a comprehensively and systematically bibliometric review of the research on the CWF by using CiteSpace. Specially, the aims of our analysis are to (1) introduce the development characteristic of the CWF research and identify the main research outputs of countries, institutions and authors; (2) illustrate the discipline categories and potential development fields; (3) summarize the popular hot topics and challenges of the three stages; and (4) demonstrate the knowledge background and sub-fields of the CWF research in the references.

2. Materials and Methods

2.1. Data Source

In order to ensure the depth and quality of our data, the core collection of the Web of Science (WOS) was selected as the data source. The WOS is an academic journal database with comprehensive contents (more than 12,000 disciplines), world authority and high influence. In particular, it records important information about publications, including the titles, authors, countries, institutions, keywords and references, which makes it convenient for bibliometric analysis [24]. In this paper, the date of the data collection was 27 June 2022, and the data was collected in two steps. Firstly, there were 3547 publications based on the topic of "water footprint" OR "virtual water" (TS = "water footprint" OR "virtual water") and then a refined search, based on the term "crop", which resulted in 838 documents.

2.2. Analysis Method

Based on the Java operating environment, CiteSpace is an information visualization analysis software developed by Professor Chaomei Chen of Drexel University [27]. It combines multi-dimensional scale analysis (e.g., network analysis and cluster analysis), mainly including cooperation analysis (author, institution, country), co-occurrence analysis (keyword, category, source), co-citation analysis (reference, cited author, cited journal) and coupling analysis. In analyzing the maps, each node represents an item, and the link between it describes the co-reference or co-occurrence relationship [24,25]. In particular, to include more or fewer nodes, the node selection is based on the g-index, with the scaling factor (k) of 25 or 8 and the link-retaining factor (LRF) of 3, the look-back year (LBY) is 5, and the annual citation threshold (e) is 1. In addition, the betweenness centrality is an important indicator to measure the influence of the nodes in the network, and it was defined by the following equation:

$$\text{Centrality}\ (\text{node}_i) = \sum\nolimits_{i \neq j \neq k} \frac{\rho_{ik}(i)}{\rho_{ik}},$$

where ρ_{ik} represents the number of the shortest paths between node j and node k, and $\rho_{ik}(i)$ represents the number of those paths that pass through node i. The larger the value, the thicker the outermost purple circle of the node, especially when the value is more than 0.1, indicating the node is the key node in the network [24,28]. The CiteSpace used in this study was version 5.6. R5 (64 bit), based on Java 8.

3. Results and Discussion

3.1. Temporal Development Analysis

According to the citation report from 2001 to 2022, there were, in total, 838 publications included in the core collection of the WOS, increasing from 1 in 2001 to 114 in 2021 (Figure 1). The number of citations is usually recognized as an important index to evaluate the influence of articles and also reflects the attention of researchers, to some extent. Based on the trend of the annual number of citations, the development process of the CWF could be roughly divided into three stages. In detail, the concept of the "water footprint" was firstly proposed in 2002 [29], and the number of publications in the CWF field showed a fluctuating trend during the period of 2001–2011. The total number of publications and the number of citations per article were only 65 and 14.72, respectively, indicating the research on the CWF was in the initial stage of concept diffusion. However, with the widespread application of the WF theory in the water resources evaluation of crop production [9], the average annual number of publications increased from 5.91 to 46.2. The number of citations per article reached 22.74, displaying a significant upward trend, from 2012 to 2017, indicating the research on the CWF had entered the steady growth stage. During the period from 2018 to 2022, the number of publications was 496, an increase of 79.1% compared to the previous stage, accounting for 59.2% of the total number of articles published from 2001 to 2022, which undoubtedly marked the arrival of a rapid growth stage in the CWF research.

In particular, the number of publications decreased in 2021, but the number of citations per article was the highest, indicating that the growing trend of CWF research continues.

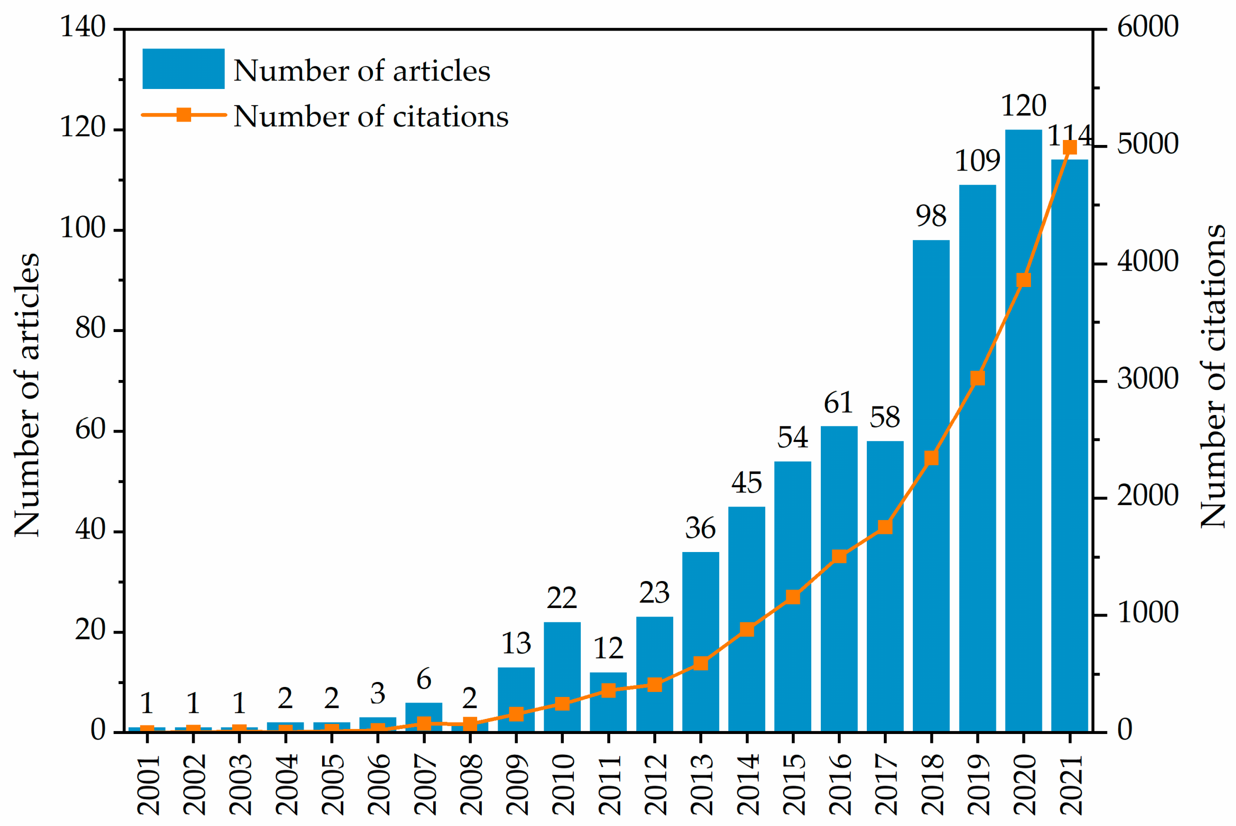

Figure 1. Annual total articles and citations from 2001 to 2021.

3.2. Analysis of Discipline Background

The discipline categories are an important way to delineate the research direction in the fields. Figure 2 shows the co-occurrence map based on extracting the top 50 categories every year, in which each node represented a type of discipline category. The CWF is a topic developed by multiple disciplines, containing a total of 86 types of categories (N = 86) and 274 links between the nodes, closely related to each other (E = 274, density = 0.075). In a comprehensive approach towards freshwater use and scarcity, it is necessary to consider the consumption of green and blue water, as well as pollution [6]. Therefore, based on the frequency of co-occurrence, Environmental Sciences & Ecology (459), Environmental Sciences (445) and Water Resources (242) were the three most popular categories, followed by Engineering (203), Science & Technology-Other topics, (176) and Agriculture (173), showing the great relevance to the ecological sustainability of crop water use in agricultural production. In addition, based on the thickness of the outmost purple circle rings of nodes, Environmental Sciences (0.28) was the category with the highest influence, connecting the various disciplines with each other in the interdisciplinary process, followed by Energy & Fuels (0.26), Chemistry (0.24) and Engineering (0.21); each of them were key areas related to the CWF. In particular, there are other categories that have low frequency but high centrality value, such as Chemistry (13/0.24), Biotechnology & Applied Microbiology (19/0.18) and Public, Environmental & Occupational Health (5/0.12), which may be areas requiring more attention in the future.

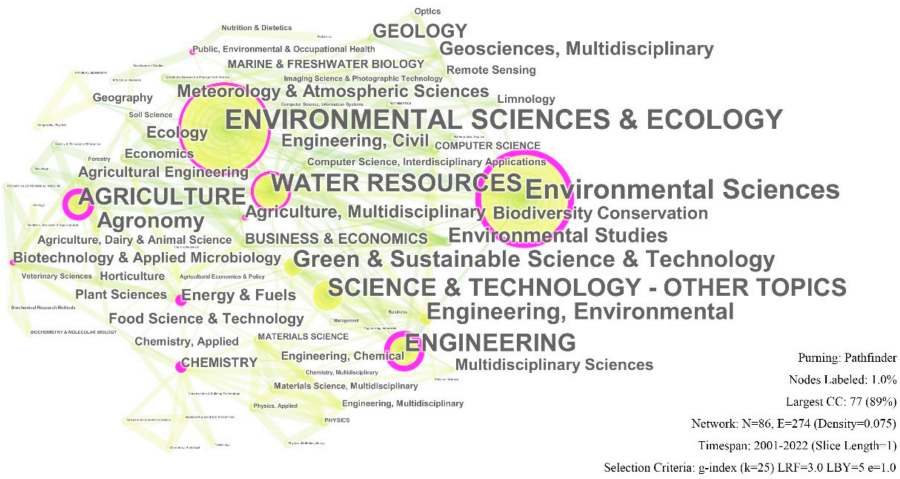

Figure 2. Co-occurrence network of categories.

3.3. Collaboration Network Analysis

The collaboration network can show the distribution of countries, institutions and authors, according to the affiliation of the articles. The size of each node represents the number of published articles and, the more the number of articles published, the larger the node size. Furthermore, the color and thickness of each node ring refers to the number and the time of the articles published. The links between the nodes represent the cooperation relationship, and the color and thickness reflect its starting time and strength, respectively.

3.3.1. Country/Regions

Based on the number of publications, Figure 3 shows the time-zone view of countries' co-occurrence network. Research on the CWF has been conducted by 84 countries or regions in the world (N = 84), and the United States (2001), Sweden (2002) and the Netherlands (2003) were the three earliest to start. Although China (2008) was a late starter, it has become a leader in this field. In particular, five of the top ten are from Europe, with China (253/30.2%), the United States (146/17.4%) and the Netherlands (110/13.1%) being the top three countries with more than 60% of the publications, contributing significantly to the development of the CWF research, followed by Italy (75/8.9%) and Germany (57/6.8%). In addition, according to the centrality value, the United States (0.31), India (0.19) and China (0.17) were the three most influential countries, playing an important role in international cooperation with the most frequent collaboration, followed by Spain (0.15), Australia and Austria (0.14).

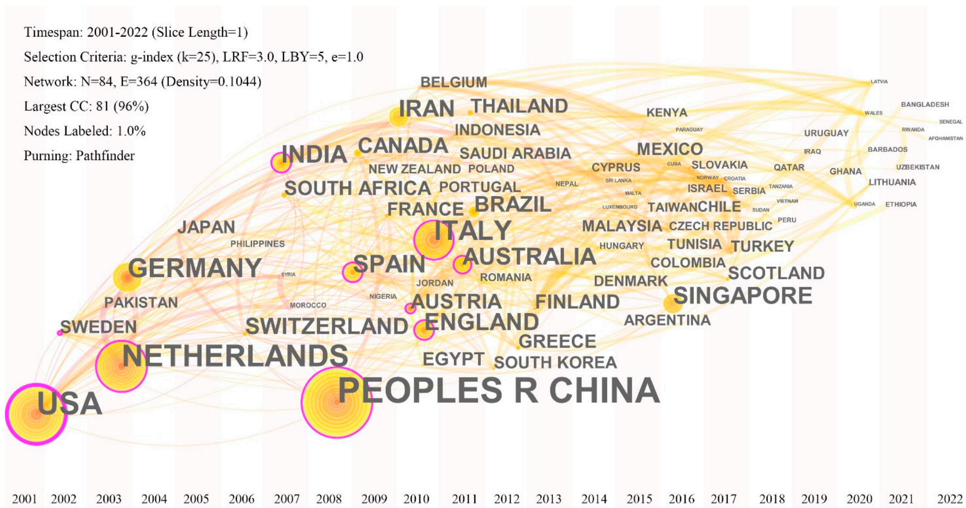

Figure 3. Time-zone view of country collaboration network.

3.3.2. Institutions

Figure 4 exhibits the co-occurrence network of 189 research institutions, to which 838 publications belonged (2001–2022). In detail, four of the top five were from China and eight of the top ten. The University of Twente (77), Northwest A & F University (50), Hohai University (47), the Chinese Academy of Science (37) and the China Agricultural University (27) are the top five institutions with the highest number of articles. The University of Twente (0.14) had the highest central influence, and its research findings were representative, followed by Hohai University (0.12) and the Beijing Forestry University (0.08). In particular, Aalto University (14, 0.08) published less, but its articles had a high influence. In addition, from the color of the innermost ring, we can see that there are some institutions that have become the backbone of this research although they started late, such as the National University of Singapore (26, 2017), the Chinese Academy of Science & Ministry of Water Resources (19, 2015) and the University of the Chinese Academy of Sciences (15, 2015), all of which deserve special attention.

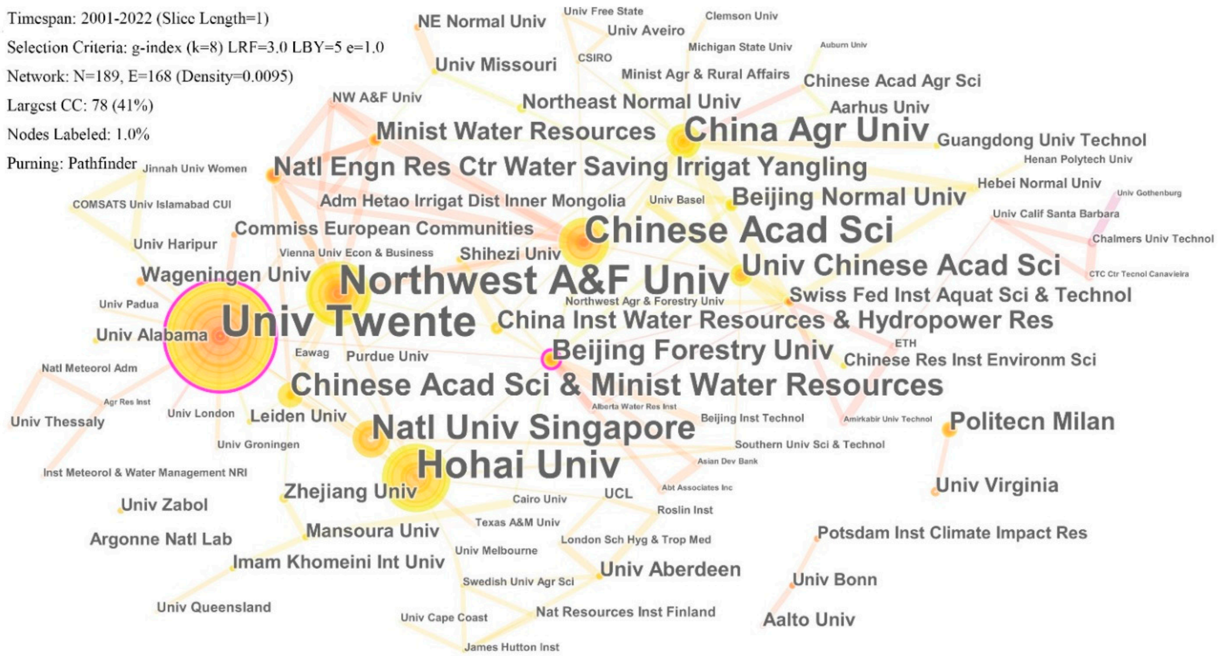

Figure 4. Cooperation network of institutions.

3.3.3. Authors

Authors are the backup force for the future development of a research field. Figure 5 demonstrates the main productive scholars from 2001 to 2022. In detail, there were three of the top five from China, and the most productive author was Arjen Y. Hoekstra (64), who first proposed the concept of the "water footprint" in 2002 [29], followed by Pute Wu (26), La Zhuo (23), Xinchun Cao (20) and Mesfin M. Mekonnen (17). Moreover, from the perspective of links, the scholars play the role of communication bridges in collaboration networks, mainly Arjen Y. Hoekstra, Pute Wu, La Zhuo and Xi Yang, thus their betweenness centrality is high. In particular, the closest linkage is between the Chinese researchers, led by Pute Wu, La Zhuo, Xinchun Cao, Yubao Wang Mengyang Wu and Hong Yang, indicating that China attaches great importance to the sustainability of its agricultural water use, which may be related to the social context of a large population, insufficient water resources per capita and a high demand for the food supply. However, a total of 477 scholars have participated in this field (N = 477), but they are relatively scattered and less collaborative (E = 531, density = 0.0047). Therefore, there is an urgent need to strengthen the academic exchange between the authors, especially between countries.

Figure 5. Cooperation network of authors.

3.4. Research Hotspots Analysis on Keywords

The keywords are the concentration and summary of the main content of an article. Thus, analyzing the high-frequency keywords can reveal the research hotspots, frontier topics and provide clues to predict potential trends [26]. Due to the different expression forms, the keywords with a similar meaning were combined when using CiteSpace, such as water footprint and waterfootprint, green water and green, life cycle assessment and LCA, etc. According to the trend of the publication, the time was divided into three stages, which were 2001–2011, 2012–2017 and 2018–2022; then, three co-occurrence networks of the keywords were obtained: Figures 6–8. In these maps, each node represents a keyword, and the size of the nodes reflects the total frequency in which it appears. The larger the number, the higher the degree of attention, and the color and thickness of the link reflects the co-occurrence condition. Correspondingly, Appendix A Table A1 lists the top 15 keywords in the three periods.

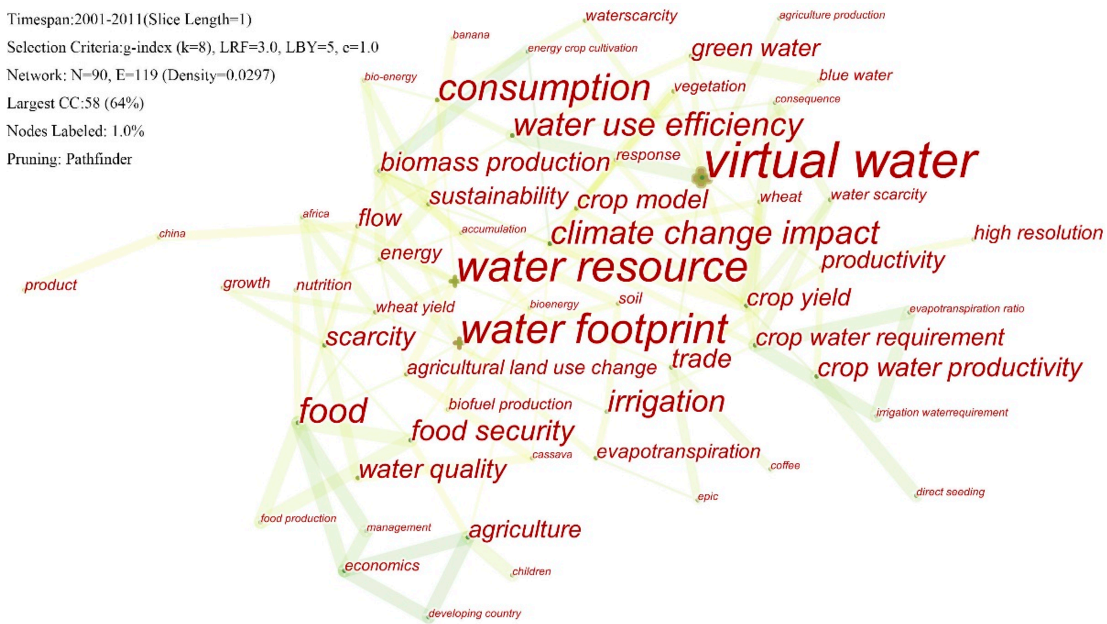

Figure 6. Co-occurrence network of keywords from 2001–2011.

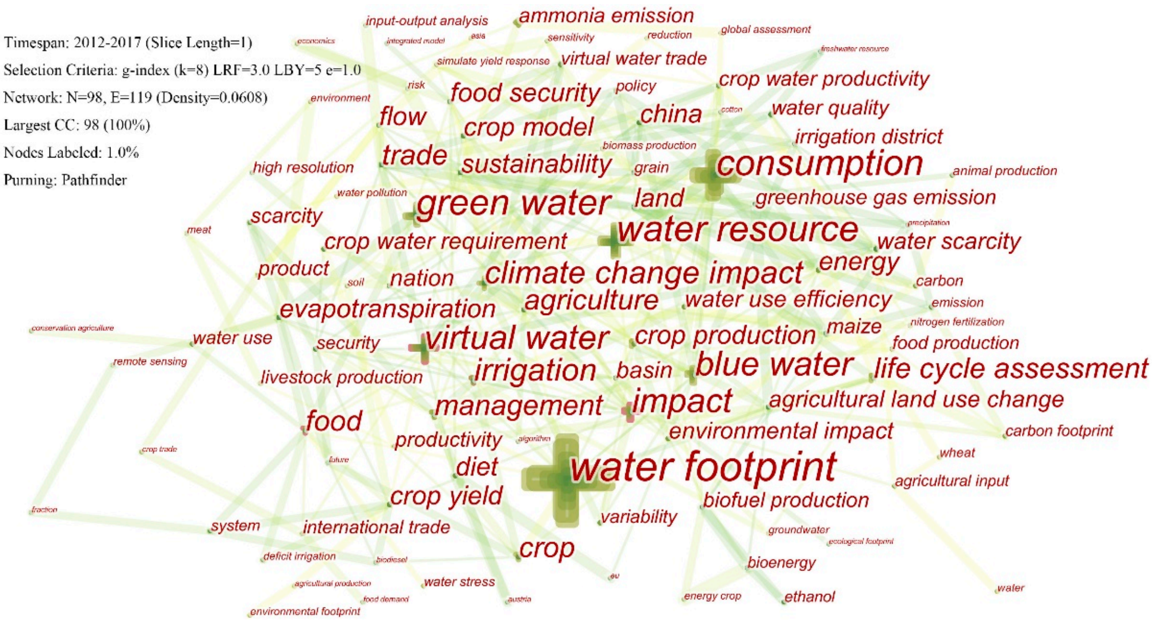

Figure 7. Co-occurrence network of keywords 2012–2017.

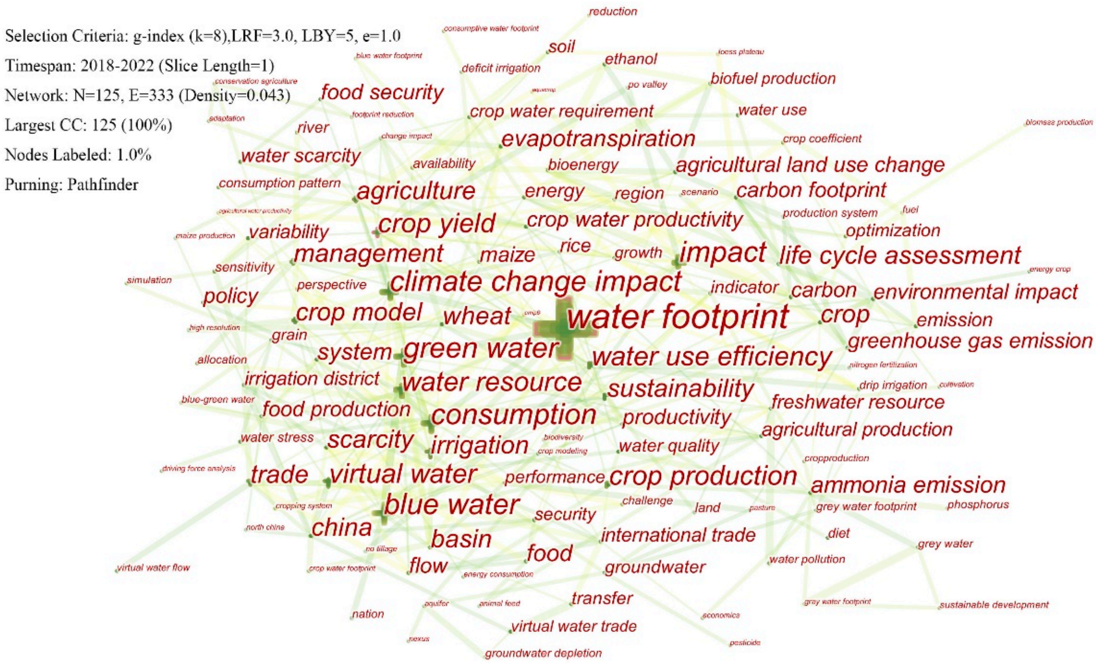

Figure 8. Co-occurrence network of keywords from 2018–2022.

Figure 6 depicts the co-occurrence network of keywords in 2001–2011. "Virtual water (35)" was the most frequent keyword, followed by "water resources", "water footprint", "water-use efficiency" and "consumption", at 18, 15, 12 and 11 times, respectively. Generally speaking, the consumption of water resources is ultimately related to the consumption of consumers. With the growth of the global population, so does the demand for consumption, especially for the crop products that consume a lot of water, such as food, bio-energy and natural fiber materials [30,31]. The water footprint, as an indicator to describe the amount of freshwater resources required to produce or consume products and services, provides a way to measure the impact of human activities on water consumption [6]. In the water footprint network (WFN), the water footprint of a region is composed of two parts, internal and external, and the import and export trade of products generates virtual water flows embedded in the process of product production [32]. In particular, the virtual water trade through the import of water-intensive agricultural products and the export of low water-consuming products could maximize the value of limited water resources for use as a tool to improve global water-use efficiency and achieve food and water security in water-scarce regions [33,34].

During 2012–2017, the keywords network (Figure 7) became more complex, and the number of nodes and links increased significantly (N = 98, E = 289), which symbolized the arrival of the diversification research. In detail, "green water", "blue water" and "impact" were the three most obvious keywords of frequency change. As we all know, precipitation (green water) and irrigation (blue) water are the direct sources of crop water consumption in agricultural production. Since the pressure on water resources will only get worse with the increase in population and, thereby, consumption, there is more potential to reduce water consumption from the perspective of agricultural production, which contributes 92% of global consumptive water use, compared with the methods related to the population consumption [1,35]. In particular, the degree of green water utilization by crops is different in the different growth seasons. Blue water can be used directly by other socio-economic sectors, but green water cannot [6,36]. Therefore, distinguishing the different roles of blue–green water would be helpful to water resources classified management. It is generally believed that the volume of consumption, consumption pattern, climate and agricultural practices are the four direct factors determining the water footprint of a region [1,35]. To effectively manage the water resources in agricultural production, Cao et al. [37] and de Figueiredo et al. [38] analyzed the contradiction between irrigation, crop yield and water availability. The impact of other factors on the WF of crop production has also been reported, for example: agricultural land use change [39,40], climate change [16,41] and combined with agricultural management technology [42,43], etc.

As shown in Figure 8, the frequency of keywords achieved a further leap in 2018–2022 (N = 125, E = 333). Similarly, "climate change impact" ranked from 8th to 3rd, with a frequency of 106, representing the main contents of this period. The climate was a key factor determining the production source and productivity of agricultural activities [44]. Due to global warming, the changes in climate conditions, such as temperature and rainfall, shorten the crop phenology, which affects the evapotranspiration, water-use efficiency and crop yield [45,46]. However, to meet the rapid growth of food demand, it is urgent to seek adaptation measures and mitigation policies [47–49]. The frequency of "water-use efficiency" was 72, which also deserves attention. Limited to the global water availability, improving the water-use efficiency is an important way to alleviate water scarcity, especially in the agricultural sector, which consumes the most water [1]. Particularly, the CWF that considers both water quantity and water environment together makes it more comprehensive to reflect the relationship between agricultural production and water resources. Combining the water footprint with traditional paradigms, mainly the irrigation efficiency (IE) and water productivity (WP), has become the major focus of the CWF research [50,51]. In addition, the term "crop model" ranked 14, with a frequency of 62. Based on the definition of the CWF, it refers to the water consumption during crop growth, which is mainly driven by the evapotranspiration of the crop field [52]. Due to the lack of a database and field experimental data, using the crop model is the main approach to simulate the WF of a crop field, which can provide information on the soil moisture, water requirement, leaf area index (LAI), evapotranspiration and crop yield, etc. [53,54]. Examples include the hydrological models: CROPWAT [55,56], crop water productivity model: AquaCrop [12,22], Environmental Policy Integrated Climate (EPIC) model [57,58] and the GIS-based EPIC model (GEPIC) [59], etc.

3.5. Reference Analysis

3.5.1. Highly Co-Cited Articles

In bibliometric terms, the intellectual base is constituted of co-cited articles [24]. Table 1 lists the top 10 articles with the most co-cited frequency. In detail, the most cited book "the Water Footprint Assessment Manual: Setting the Global Standard" set global standards for the WFA system in terms of the background, concept, evaluation objectives, accounting methods and limitations of the water footprint indicator, which laid a theoretical foundation for the CWF research [29]. The accurate quantification of water resource consumption is the basis for regional water resources management. Hoekstra et al. [1] quantified the water footprint of humanity, finding out that agricultural production is the largest contributor to global water consumption, accounting for 92%. Mekonnen et al. [56] estimated the global water footprint of 146 crops and derived crop products. Chapagain et al. [60] calculated the global water footprint of rice from the perspective of production and consumption, which provided rich databases while providing a reference for CWF optimization calculations. In particular, Lovarelli et al. [9] summarized the application of the water footprint in crop production, including the definition, methodology, research progress, limitations and recommendations. However, because of the spatial and temporal variations of water demand and availability, freshwater scarcity is becoming a threat to the sustainable development of human society. Zhuo et al. [12] revealed the impact of changes in the water footprint of crops in the Yellow River basin on the degree of water scarcity, pointing out the necessity to improve crop water productivity. Zhuo et al. [61] evaluated the effect of the variability of the consumption, production, trade and climate on crop-related water footprints, expressing their sensitivity and uncertainty. Mekonnen et al. [62] assessed the situation of global water scarcity based on the water footprint theory, demonstrating the urgent need for improving water-use efficiency and productivity in crop production. Purposefully, Mekonnen et al. [63] and Chukalla et al. [22] analyzed the water-saving potential of crop production by establishing a set of global WF benchmark values for crops and exploring the effect of three management practices on the soil–water balance and plant growth, respectively, providing valuable information for formulating agricultural water-saving strategies. On the whole, according to the contents of publications, the knowledge base of the CWF research mainly consists of four parts: concept (1st), quantification (2nd, 3rd, 4th, 9th), evaluation (5th, 6th, 10th) and reduction (7th, 8th).

Table 1. The top-10 cited articles with co-citation frequency.

Citation	Title	Author	Year	Source (Abbreviation)
109	The Water Footprint Assessment Manual: Setting the Global Standard	Hoekstra AY	2011	-
94	The green, blue and grey water footprint of crops and derived crop products	Mekonnen MM	2011	HYDROL. EARTH SYST. SC.
64	Water footprint of crop productions: A review	Lovarelli D	2016	SCI. TOTAL ENVIRON.
63	The water footprint of humanity	Hoekstra AY	2012	PROC. NATL. ACAD. SCI. USA
62	Four billion people facing severe water scarcity	Mekonnen MM	2016	SCI. ADV.
54	Inter-and intra-annual variation of water footprint of crops and blue water scarcity in the Yellow River basin (1961–2009)	Zhuo L	2016	ADV. WATER RESOUR.
52	Water footprint benchmarks for crop production: A first global assessment	Mekonnen MM	2014	ECOL. INDIC.
45	Green and blue water footprint reduction in irrigated agriculture: effect of irrigation techniques, irrigation strategies and mulching	Chukalla AD	2015	HYDROL. EARTH SYST. SC.
44	The blue, green and grey water footprint of rice from production and consumption perspectives	Chapagain AM	2011	ECOL. ECON.
43	The effect of inter-annual variability of consumption, production, trade and climate on crop-related green and blue water footprints and inter-regional virtual water trade: A study for China (1978–2008)	Zhuo L	2016	WATER RES.

Note: The first quoted publications was a book, so there was no journal source.

3.5.2. Cluster Analysis

In order to get a more comprehensive understanding of the CWF research, based on a co-citation analysis of the references, Figure 9 demonstrates the map of the main clustering blocks, using the log-likelihood ratio (LLR) algorithm on the keywords, and its detailed information is listed in Appendix A Table A2. In viewing the map, the value of the modularity in the cluster network is Q = 0.7633 > 0.3, and the value of the silhouette (S), which is normally used to measure the internal homogeneity of the cluster, were in the range of 0.705–0.992. In particular, when S > 0.5, it indicates the clustering process is reasonable and, when S > 0.7, it indicates the clustering process is convincing. In a word, the result of the clustering process was good and could be used for this analysis [26,64]. Specifically, the largest cluster (#0) contains 137 articles and has a silhouette value of 0.796; it mainly includes "blue water footprint", "rice production" and "green water footprint", and it is labeled "blue–green water". The second largest cluster (#1) has 97 members and a silhouette value of 0.745, and it is labeled the "Beijing-Tianjin-Hebei region". Cluster (#2) consists of 90 publications and the average date was 2009; it was labeled "crop water productivity".

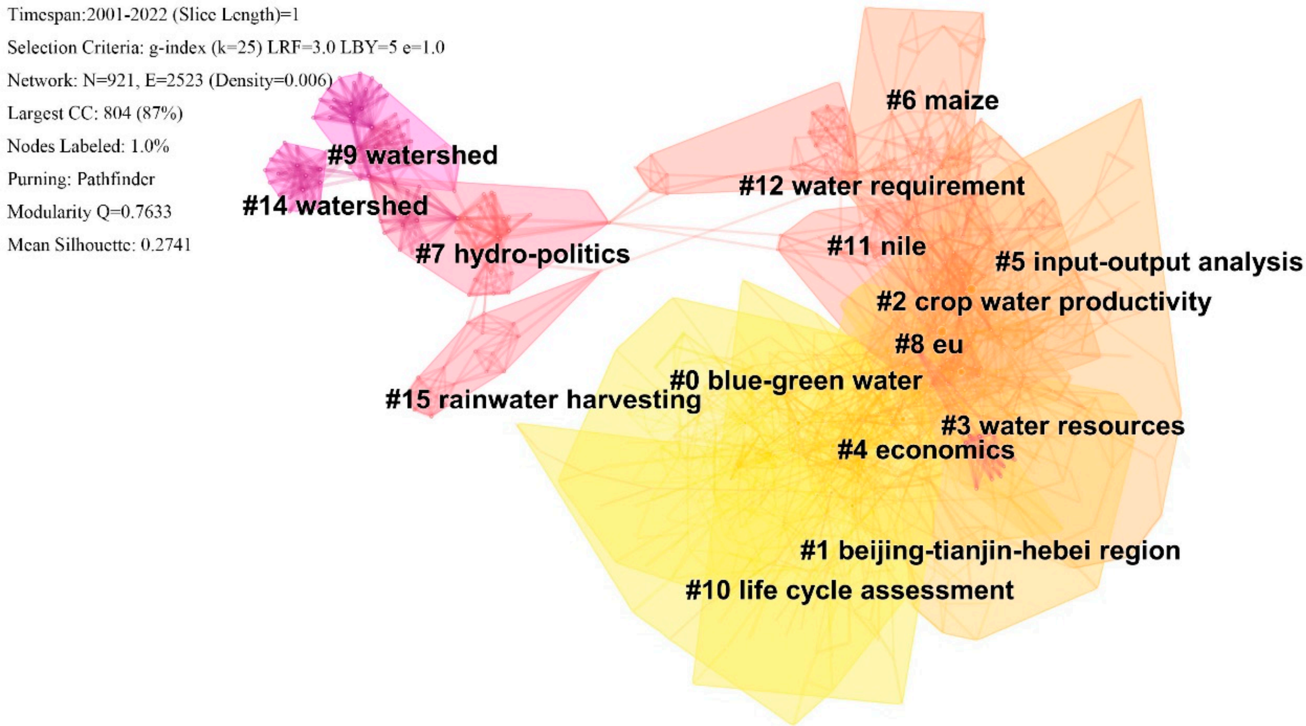

Figure 9. Reference clusters in the field of crop water footprint.

In summary, the research on the CWF is becoming mature and mainly focuses on the following sub-fields: objective setting (#3 water resources, #6 maize); evaluation scope (#0 blue-green water, #1 Beijing-Tianjin-Hebei region, #8 EU, #9 watershed, #11 Nile, #14 watershed); sustainability assessment (#4 economic, #5 input-output analysis, #10 life cycle assessment); and responsive strategies (#2 crop water productivity, #7 hydro-polices, #12 water requirement, #15 rainwater-harvesting).

4. Challenges for the Future

Describing comprehensively the relationship between agricultural production and water resources is the basis for regional water resources management. As an indicator that distinguishes the different roles of blue–green water and unifies the amount of pollution water in crop water consumption, the CWF provides a new way to reduce the environmental load while improving water-use efficiency. However, due to the undifferentiated forms of crop water consumption and the dynamic mobility of soil water, it is difficult to account for the blue–green water consumption in precise, unambiguous ways [65]. Moreover, in order to meet the rapid growth of food demand, chemical fertilizers have been used widely in agricultural production over the past few decades. With the development of agricultural expansion and intensification, excessive fertilizer use has caused serious pollution to the water environment through water leaching and runoff [66,67]. Although the grey water footprint has measured the water pollution levels of crop production, the nitrogen and phosphorus pollution have been the focus of previous studies, while ignoring the impact of other pollutants, such as pesticides, antibiotics and heavy metals. Therefore, how to calculate the grey water footprint that considers multiple pollutants should be taken seriously [58,68].

In particular, based on the blue, green and gray water footprint, the CWF reflects the effective water consumption and polluted water of a crop field, but evaporation and seepage losses during the water distribution are also important parts of the water consumption in regional agricultural production. Therefore, the adaptive calculation of the CWF on different spatial scales is also a challenge in future, which requires the combination of the CWF and traditional indicators to provide better practical guidance for water resource management [4,43].

5. Conclusions

Based on the visual bibliometric analysis software, CiteSpace, this study comprehensively summarizes the current status of the crop water footprint (CWF) research in terms of the characteristics of the publication outputs, co-collaboration of countries/institutions/authors, co-occurrence analysis of the disciplinary categories and keywords and the co-citation and cluster analysis of the references. During the period from 2001 to 2022, there were a total of 838 articles published, and the number of publications increased rapidly. Based on the analysis of the keywords, introducing the hot topics of the CWF research in the three periods, and assessing the climate change impact on the water-use efficiency of crop production have attracted more attention in the latest five years. Based on the co-citation and cluster analysis of the references, understanding that the sub-fields and research contents of the CWF is closely associated with the concept, qualification, evaluation and reduction, and the reducing water requirement to improve crop water productivity through rainwater harvesting and formulating reasonable hydro-policies, is the main responsive strategy to improving agricultural water-use efficiency. In particular, the accurate differentiation of the blue–green water and grey water footprint calculation, considering multiple pollutants, the exploration of mitigation policies for climate change impact and the combination of the CWF and tradition indicators, will be the focuses of future research in the CWF.

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Appendix A

Table A1. Top-15 high-frequency keywords 2001–2022.

Rank	2001–2011		2012–2017		2018–2022	
	Keyword	Frequency	Keyword	Frequency	Keyword	Frequency
1	virtual water	35	water footprint	162	water footprint	296
2	water resource	18	consumption	89	consumption	112
3	water footprint	15	water resource	68	climate change impact	106
4	water use efficiency	12	green water	65	blue water	105
5	consumption	11	virtual water	63	green water	104
6	food	9	blue water	60	impact	94
7	food security	8	impact	53	water resource	84
8	irrigation	8	climate change impact	42	crop yield	80
9	climate change impact	8	irrigation	39	virtual water	74
10	crop model	6	crop	29	water use efficiency	72
11	scarcity	6	management	28	crop production	66
12	crop water productivity	6	food	28	management	63
13	green water	5	trade	28	agriculture	63
14	trade	5	life cycle assessment	27	crop model	62
15	crop water requirement	5	agriculture	26	life cycle assessment	62

Table A2. The information of main clusters on co-citation analysis.

ID	Name	Size	Silhouette	Year	Top Terms
0	blue–green water	137	0.796	2017	blue water footprint; rice production; green water footprint; field observation
1	Beijing-Tianjin-Hebei region	97	0.745	2016	production; virtual water flow; life cycle assessment; irrigation
2	crop water productivity	90	0.72	2009	grain; green water; blue water; irrigation district
3	water resources	65	0.861	2013	food security; planetary boundaries; water dependence; self-surfficiency
4	economics	62	0.705	2014	crude palm oil; winter wheat; risk; livelihood
5	input-output analysis	52	0.799	2010	pumpkin produce carbon footprint; environment water management
6	maize	48	0.887	2008	sweeteners; conflicting land-uses; food systems; bio-ethanol
7	hydro-policies	43	0.923	2003	agricultural policy; food production; food security; food trade
8	EU	42	0.835	2011	irrigation efficiency; crop pattern; virtual water trade balance
9	watershed	40	0.946	1999	canal irrigation crop; irrigation and drainage mode;water import dependence
10	life cycle assessment	39	0.919	2016	virtual water; carbon footprint; agricultural production; water depletion
11	Nile	28	0.964	2006	green-blue water; water security; virtual water; international trade
12	water requirement	25	0.96	2006	virtual water; water quality; water management; green water
14	watershed	18	0.992	1999	sensitivity analysis; economics benefits; nitrogen fertilizer; economic gap
15	rainwater-harvesting	18	0.976	2003	water scarcity; seawater desalination; marginal-quality water

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