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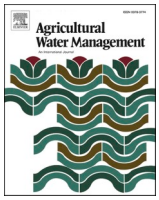

What is the past, present, and future of scientific research on the Yellow River Basin? —A bibliometric analysis

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ABSTRACT

China's Yellow River Basin (YRB) has large watershed but scarce water resources. More importantly, most parts of the YRB are located in semi-arid areas of Northwest China, where the ecology and environments are fragile. So, ecological restoration and agricultural production always are the key research topics of the YRB. However, the specific research interest of YRB changed over time and was always closely related to the implementation of government policies. Hence, we conducted a comprehensive analysis of YRB's research topics based on the methods of bibliometrics. The results showed that the number of papers about YRB's research experienced a change from slowly increasing (1998–2010, 83 papers) to rapidly increasing (2011–2015, 128 papers), and then to exponentially rising (2016–2020, 369 papers). Secondly, the main research fields of the YRB included farming, crops, water, soil, environment, and etc. The journal of *Agriculture Water Management* had the highest global total citations and H-index, even local cited references were the highest among all of the reference papers about the YRB. Through summarizing the most cited papers and references, we found the most important research hotspots about the YRB were: the impacts of climate change and human activities on the amount of sediment in the YRB, the management of soil erosion and vegetation restoration in the YRB, and the relationship between crops and environment and management in the Loess Plateau of China. In addition, "*Loess Plateau*" was the most frequent keyword in the past ten years and the popularity of "*climate change*" rose sharply in the past five years. For YRB's research in near future, how to effectively control carbon emissions, greenhouse gas (GHG) emissions, and carbon surplus is becoming an important implication for YRB's agricultural production and ecological restoration in the future. In general, this research is expected to promote a comprehensive and quantitative understanding of the past, present and future of YRB's research.

1. Introduction

The Yellow River is the second longest river in China and the Yellow River Basin (YRB) covers nine provinces, accounting for 30.3% of the country's population. However, the YRB's water resources are scarce, or only about 2.6% of the country's total water resources. Thus, water is fairly limited for industry and agriculture in the region (China, 2021). In fact, most parts of the YRB are located in semi-arid areas of Northwest China, where not only soil erosion is very serious, but also the ecosystem is very fragile, especially in the Loess Plateau (Fu et al., 2011b; Li et al., 2016). It is a big challenge for agricultural production in YRB because of the extremely scarce land and water resources need to feed such a large population. As for agriculture, the Hetao Irrigation District in Inner Mongolia and the Loess Plateau depend heavily on water resources of the Yellow River (Ren et al., 2018). In early years, backward irrigation technology, uncontrolled irrigation, and excessive fertilization have led to serious soil salinization in the Hetao Irrigation District (Gao et al., 2015). In order to prevent vegetation degradation and soil erosion, the

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'Grain for Green Project' consumed more water resources in the Loess Plateau, causing a potential conflict between vegetation restoration and agricultural production (Cao et al., 2009). Therefore, how to effectively control soil erosion and restore the ecological environments, so as to expand the agricultural production to feed more population based on the limited water resources, remains an important challenge in the YRB.

Although most scientific research on YRB's agriculture had the similar ultimate goals, the research emphasis of each period showed a variant tendency over time. In past studies, the productivity of crops in the upper YRB was severely limited because of the shortage of soil moisture (Fan et al., 2010). More importantly, a large amount of soil was brought into the Yellow River through wind and/or water erosion, resulting in vegetation degradation and destruction of ecosystems (Shi and Shao, 2000a). Thus, more attentions should be paid to protecting the fragile ecosystem in the YRB during this period. Thereafter, China implemented two national policies: the Natural Forest Conservation Program and the 'Grain to Green Project' in order to deal with the environmental crises and improve human well-being (Liu et al., 2008; Xu et al., 2006a). However, two new problems arose then, e.g. the expansion of land for vegetation restoration and the limitation water resource for agriculture (Feng et al., 2005; Xu et al., 2006b). These could obviously affect the development and yield of crops.

To handle food crisis, it was not only necessary to clarify the intrinsic relationships between crops, water, and nutrients, but also necessary to develop efficient water-saving measures to deal with the dilemma of water shortage. In fact, they were two different research directions. For internal mechanism of efficient crop water use, crops were proved to withstand water stress of environmental conditions through regulating signal transduction of abscisic acid (ABA) in different organs, tissues and guard cells (Kuromori et al., 2018). This was because the ABA synthesized by root tissue would be transmitted to shoots through the xylem duct and finally close the stomata when the soil drying began (Geiger et al., 2011). The closing of stomata could remarkably affect leaf gas exchange especially CO_2 and limit photosynthesis of crops. However, elevated atmospheric CO_2 concentration could attenuate the impacts of drought stress on crops by increasing water use efficiency (WUE), thus contribute to crop yield (Li et al., 2020). Similarly, Assmann and Jegla (2016) suggested that the response of stomata to elevated atmospheric CO_2 concentration was also related to ABA concentration in the plant. Therefore, clarifying how ABA regulates stomata has a great significance to the growth and yield of crops in the future climate with elevated atmospheric CO_2.

On the other hand, some efficient water-saving measurements and technologies were applied in YRB's agricultural production with the progress in science and technology. Plastic film mulching can effectively alleviate the negative effects of soil water stress on crop growth. It could not only reduce water loss through evaporation, but also increase the depth of water infiltration in soil (Zhang et al., 2009). Therefore, plastic film mulching has obviously improved water use efficiency and yield of many crops in the YRB (Bu et al., 2013; Li et al., 2013c). Similarly, the technology of film-mulching drip irrigation replaced traditional flood irrigation in many places and greatly saved water resources (Tian et al., 2017; Zhang et al., 2017). Some other techniques and management strategies were also used to improve water use efficiency of YRB's agriculture over the past decades, such as the ridge and furrow rainfall harvesting (RFRH) system, the gravel-sand mulched fields (GSMF), aerated irrigation (AI), and etc. (Du et al., 2018; Li, 2003; Li and Gong, 2002). In general, these technologies and measurements have indeed improved water use efficiency of crops. Nonetheless, more efficient and practical technologies should be developed under future climate changes and the international goal of energy conservation and emission reduction.

Previous studies strongly indicated that YRB's agriculture is very complicated because it not only involved the intrinsic mechanism and management measures for efficient crop water use, but also needed weighing water consumption between ecological restoration and agricultural production (Cao et al., 2021). Therefore, it was very necessary to understand the directions and key points of YRB's agricultural research in the past and present. More importantly, we need some reasonable tools to summarize and visualize YRB' research so as to provide a clear research direction for researchers in the future. The technique of bibliometrics could integrate the findings of previous research and use existing databases to promote scientific research and help researchers maintain professional judgment and expertise through quantitative analysis (Aria and Cuccurullo, 2017; Guler et al., 2016). So far, the bibliometrics has often been used to quantitatively analyze the status of research and the contributions of individuals, institutions, and countries. In the end, we could use bibliometrics to dynamically evaluate the research trend in the future. In this study, we comprehensively reviewed relevant YRB's research based on bibliometrics. The objectives were to: (1) categorize the research directions and key points, and understand the historical development of YRB's research; (2) evaluate the contributions of individuals, institutions, and countries to YRB research; and (3) explore the variation of research topics over time and then predict the future research directions of the YRB.

2. Materials and methods

Before bibliometric analysis, a large number of databases about research on the Yellow River Basin (Fig. 1) should be extensively collected. As the most authoritative and comprehensive scientific database, the "Web of Science Core Collection" database of Web of Science (WOS, https://www.webofscience.com/) was used to construct a bibliographic database for the YRB's research. More specifically, according to the "Advanced Search" of WOS, we searched the fields and information (Table 1) based on Boolean operators. The specific "Advanced Search" strategies could be obtained from the "Web of Science All Databases Help". However, the search results should be manually screened to eliminate articles that were not related.

2.1. Workflow of bibliometrics based on "bibliometrix" package

Recently, Aria and Cuccurullo (2017) developed a bibliometric tool (or the "*bibliometrix*" package in R language, which not only follows the logical workflow of classic bibliometric but also combines statistical calculation and visualization together. The "*bibliometrix*" package has fully made use of the statistics and drawing capabilities of R language. And more importantly, the R language also was an object-oriented and functional programming language, meaning that the "*bibliometrix*" package can be combined with other packages to create new functions. After obtaining the database about YRB's research in WOS (saved as text file), we conducted the biliometric analysis about the scientific research on the YRB according to the following procedures:

(a) We first loaded it into R language through the "*readFiles*" function, and then the "*convert2d*" function was called to convert this database into a bibliographic data frame.

(b) The "*biblioAnalysis*" function summarized the results of bibliometrics. And the "*summary*" counted different fields of bibliometric results, such as the most published journals, country, authors and papers; the frequency of keywords, and etc.

(c) The "*citations*" function analyzed the global citations in the bibliometric results, mainly including the most cited countries, authors, papers and references. The local citations can be counted with the "*localCitations*" function.

(d) The H-index is a ranking index of journals and authors, which mainly describes H papers that have been cited at least H times (Hirsch, 2005). The "*Hindex*" function was used to calculate the H-index in "*bibliometrix*" package.

(e) The "*biblioNetwork*" function aims to show the networks about institutional collaboration and keywords co-occurrence. It constructed a binary matrix (also a bipartite network) between different papers and then extracted the required information through the

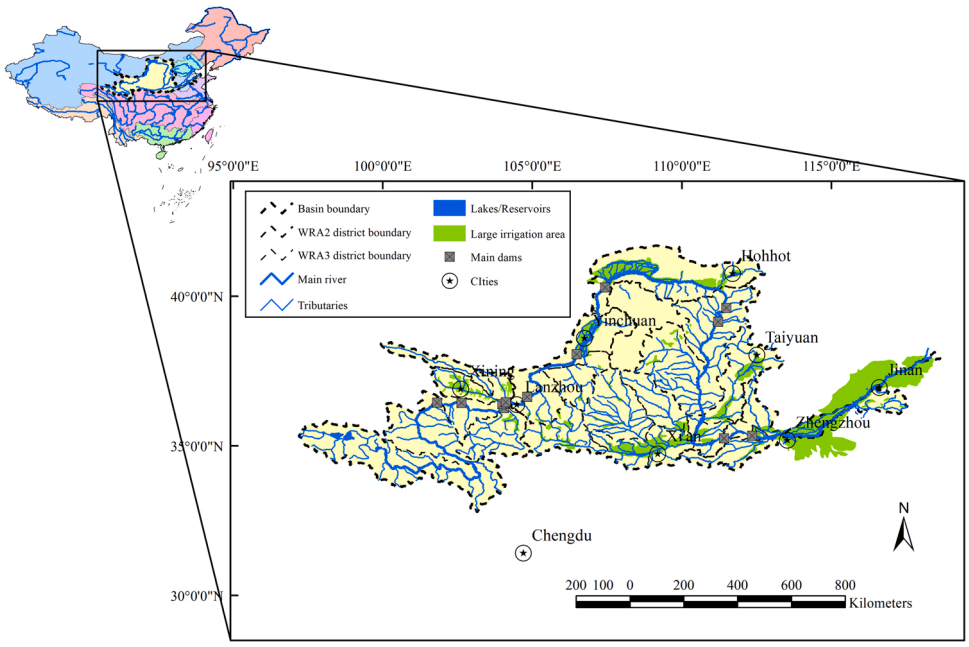

Fig. 1. Location of the Yellow River and the Yellow River Basin (YRB) in China.

Table 1
Search strategy for reference papers about relevant research on the Yellow River Basin based on the "Advanced Search" in the Web of Science[a].

Search field	NO.	Search information
TS[b]	1	Yellow River Basin OR Huanghe River Basin OR Agricultural OR water management
	2	Qinghai OR Sichuan OR Gansu OR Ningxia OR Inner Mongolia OR Shaanxi OR Shanxi OR Henan OR Shandong OR Hetao OR Loess plateau OR Yellow river delta
	3	crop AND water AND water management AND yield AND water use efficiency
	4	Farmland irrigation AND Agronomy of Drainage AND Ecological effect AND Rain-fed agriculture AND water management
	5	Water 'and' fertilizer coupling AND Nutrient loss AND Water quality AND Greenhouse Gas
	6	Soil erosion AND Soil conservation 'and' water retention
	7	Water resources protection
	8	Water management AND environment
SU	1	Agriculture OR Environmental Sciences & Ecology OR Physiology OR Plant Sciences OR Meteorology & Atmospheric Sciences OR Water Resources OR Remote Sensing OR Horticulture OR Environmental & Occupational Health

Note:
[a] The "Advanced Search" strategies could be obtained from the "Web of Science All Databases Help", or http://images.webofknowledge.com//WOKRS535R111/help/WOK/hp_advanced_search.html
[b] AND and OR are Boolean operators. TS (Topic) and SU (Research Area) are the field identifiers to be retrieved. The final search strategy was TS ((1 AND 2) AND (3 OR 4 OR 5 OR 6 OR 7 OR 8)).

"*metaTagExtraction*" function. Finally, the network was visualized through the "*networkPlot*" function, which can classify the network and display it in different colors through different clustering algorithms. Louvain algorithm was a heuristic method that based on modularity optimization. It can mine the hierarchical structure in the data network and finally achieve hierarchical clustering (Blondel et al., 2008). So, in this study, we used the Louvain algorithm to cluster the information in the network.

3. Results

3.1. Main Information about paper collection

From 1998–2020, there were a total of 580 papers on the Yellow River Basin (YRB) that were published in 172 sources, including 561 articles, 3 editorial materials, 2 meeting abstracts, and 14 reviews. The number of papers can reflect the popularity of research to a certain extent. From 1998–2010, only 83 papers about the YRB were published, accounting for 14.31% of the total papers. The number of papers grew remarkably between 2011 and 2015 (128 papers, or 22.07% of total papers), where annual average paper number increased from 6.3 (1998–2010) to 25.6. From 2016–2020, the paper number increased exponentially to 369, accounting for about 63.62% of the total papers (Fig. 2a). This showed that research about the YRB increased rapidly in recent years and related scientific problems also were paid more attentions. For the citation of papers, the highest mean value of global total citations was 131.6 times in 2000, and it was the lowest in 2020, or only 2.49 times (Fig. 2b). In addition, interannual variation would also affect the number of citations of the papers about research of the YRB. The mean total citations per papers per year were also calculated. The highest mean total citations were 8.46 in 2007 and 8.30 times in 2009, while the lowest mean total citations were only 1.10 times in 2003 (Fig. 2c). In general, about 25.22 papers about research on the YRB were published in each year. The total global citations reached 13,102 times and each paper was cited about 22.59 times on average. Additionally, a total of 2030 authors participated in the research on the YRB and contributed 1632 keywords at the same time (Fig. 2d). Therefore, the research about the YRB has been receiving more and more attentions and affirmation from publishers, regions, institutions, and researchers.

3.2. Publisher's citations and sources

For the research of the YRB, most of the papers were published in journals of the fields of agriculture, water resources, and environmental science. The top five journals with global total citations were Agricultural Water Management (1772), Field Crops Research (1228), Catena (693), Global and Planetary Change (685), and Environmental Earth Sciences (559) (Table 2). The top five journals with most published papers were Environmental Earth Sciences (35 papers), Agricultural

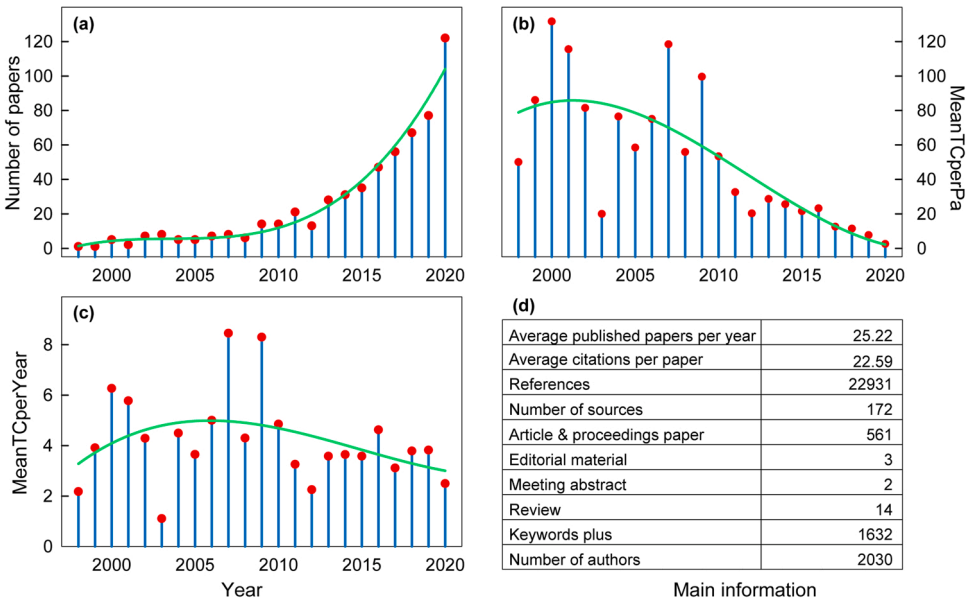

Fig. 2. Based information about the research of Yellow River Basin from 1998 to 2020, including (a) the number of papers from 1998 to 2020; (b) mean total cited per paper (MeanTCperPa) from 1998 to 2020; (c) mean total cited per year (MeanTCperYear); and (d) additional information about this research on the Yellow River Basin. The green lines indicated the trend of change.

Table 2
Information of most relevant sources of research papers about the Yellow River Basin from 1998 to 2020.

Rank	Sources	TC	TP	H-index	IF
1	Agricultural Water Management	1772	28	18	4.0
2	Field Crops Research	1228	23	17	4.3
3	Catena	693	23	13	4.3
4	Global and Planetary Change	685	5	5	4.4
5	Environmental Earth Sciences	559	35	15	2.2
6	Soil & Tillage Research	456	10	9	4.6
7	Science of The Total Environment	419	24	11	6.5
8	Ecological Engineering	411	18	11	3.5
9	Agricultural and Forest Meteorology	407	4	4	4.7
10	European Journal of Agronomy	367	7	5	3.7
11	Land Degradation & Development	283	18	10	3.8
12	Agriculture Ecosystems & Environment	278	11	8	4.2
13	Journal of Applied Ecology	266	2	2	5.8
14	Journal of Arid Environments	239	7	5	1.8
15	Continental Shelf Research	227	2	2	2.4
16	Ecological Indicators	193	13	6	4.2
17	Geoderma	189	7	4	4.8
18	Australian Journal of Agricultural Research	185	2	2	NA
19	Hydrological Processes	180	7	5	3.3
20	Journal of The American Water Resources Association	175	2	2	2.5

Note: TC is global total citations; TP is total papers; and IF is impact factor.

Water Management (28 papers), Water (27 papers), Science of The Total Environment (24 papers), and Catena (23 papers) (Table 2). The H-index, which indicates H papers have been cited at least H times, was usually used to evaluate the academic influence of journals or individuals. Thus, H-index could represent the academic achievements of journals or individuals. The journal of Agricultural Water Management (18) had the highest H-index among all of the journals related to YRB's research (Table 2). For local cited references in all papers, the top five journals were Agricultural Water Management (1236), Journal of Hydrology (921), Field Crops Research (700), Catena (698), and Soil & Tillage Research (691) (Fig. 3). Generally, the main directions of the YRB's research were agriculture, crops, water, soil, environment, and etc. The journal of Agricultural Water Management ranked high in the number of papers, references citation, and H-index (Table 2 and Fig. 3).

3.3. Top ten countries for published and cited papers in different periods

The number of published papers and global citations about a research by a country can reflect the country's scientific research level and emphasis. There were a total of 24 countries that have conducted research on the YRB from 1998 to 2020. The results showed that the number of papers published and cited were the highest in China (68 papers and 5445 citations), but Australia (179 citations per paper) had the highest citations per paper during 1998–2010 (Table 3). During 2011–2015, China (118 papers and 2980 citations) maintained the highest number of papers and citations, while Germany (132 citations per paper) had the highest citations per paper. During 2016–2020, the number of published papers in China (347 papers) greatly increased compared to the 2011–2015 period and the number of total citations (3184 citations) was also the highest among all of the countries involved. However, Germany (31 citations per paper) was still the country that had the highest number of citations per paper in 2016–2020 (Table 3). In general, China maintained a high level for total papers published and total citations of research on the YRB in the three periods. Moreover, China has been gradually narrowing the gap with other developed countries in terms of research influence and quality.

3.4. Most influential authors and cooperation of institutions

As the development of scientific research, more and more studies were accomplished through the mutual cooperation of different countries and institutions, because it can produce higher influence and scientific research value. Through the Louvain algorithm to cluster all production institutions, and then selected top 20 institutions that published articles to explore the cooperative relationships between institutions (Fig. 4). The cooperation network was mainly clustered into three categories, which were represented by Northwest A&F University (NWAFU) of China, the Chinese Academy of Sciences (CAS), and the Xi'an Jiaotong University (XJTU) of China. The NWAFU had published the most papers (222 papers). These papers mainly focused on (a) the impacts of climate variability and human activities on the flow of the Yellow River (Zhao et al., 2014a), (b) the protection of soil erosion in the

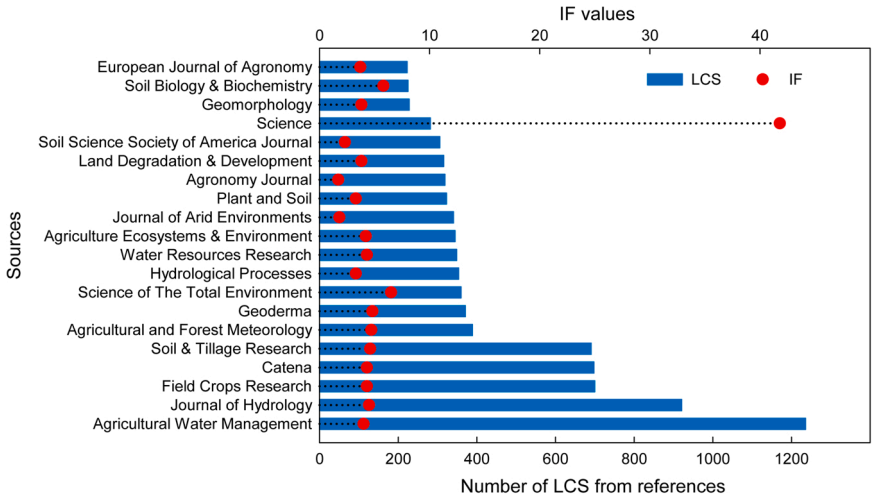

Fig. 3. Most local cited sources (LCS) about the research of Yellow River Basin from 1998 to 2020. The blue histogram represented the number of LCS (bottom X axis) and the red dot was the impact factor of journals (upper X axis).

Table 3
Dynamic changes of total papers (TP) and total citation (TC) of top 10 countries about research on the Yellow River Basin from periods 1998–2010, 2011–2015, and 2016–2020.

Rank	Periods								
	1998–2010			2011–2015			2016–2020		
	Nation	TP	TC	Nation	TP	TC	Nation	TP	TC
1	China	68	5445	China	118	2980	China	347	3184
2	Canada	3	44	USA	2	15	USA	5	46
3	UK	3	107	Australia	1	68	Canada	4	65
4	Philippines	2	204	Austria	1	10	Germany	2	62
5	USA	2	236	Germany	1	132	Netherlands	2	12
6	Australia	1	179	Italy	1	37	Turkey	2	9
7	Belgium	1	23	Japan	1	1	Argentina	1	7
8	France	1	79	New Zealand	1	3	Costa Rica	1	1
9	Netherlands	1	38	Singapore	1	36	Hungary	1	3
10	Sweden	1	21	Spain	1	8	Iran	1	22

Note: TP is total papers and TC is global total citations.

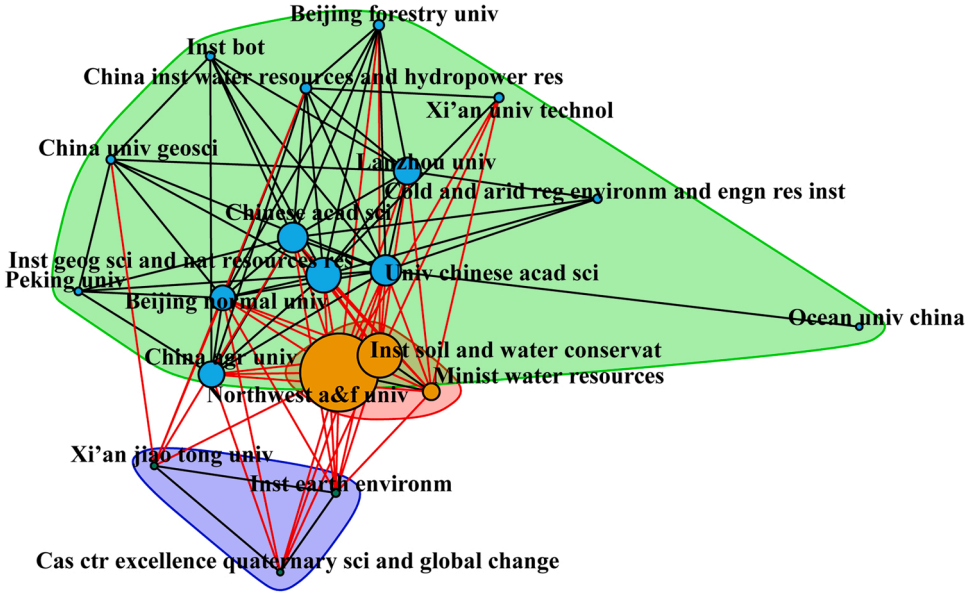

Fig. 4. Collaboration network analysis of top 20 productive institutions or universities based on the Louvain clustering algorithm. The nodes represented different institutions or universities. Different color regions represented different clustering results. The red and black connecting lines indicated the cooperative relationship between institutions or universities. The size of each node represented the number of papers that an institution or university published.

Loess Plateau of China (Zhao et al., 2013b), and (c) the impacts of tillage systems on crop yields and water or fertilizer use efficiency (Li et al., 2013b), and etc. The CAS and its cooperative institutions had many research directions on the YRB, but the main directions were (a) the impacts of climate variability and human activities on the discharge and sediment discharge of the Yellow River (Gao et al., 2011; Miao et al., 2011; Wang et al., 2016), (b) the hydrological and climatic trends of the YRB (Fu et al., 2004; Zhao et al., 2014a), (c) the vegetation cover dynamics in YRB (Miao et al., 2012; Xin et al., 2008), and (d) soil erosion and crop tillage in the Loess Plateau (Huang et al., 2005b; Shi and Shao, 2000b), and etc. The cooperative institutions represented by the XJTU explored (a) the impacts of anthropogenic curtailing on the Yellow River's runoff and sediment load (Liu et al., 2020), (b) the precipitation variation in the Loess Plateau over years (Tan et al., 2014), and (c) water cycle and vegetation restoration in the Loess Plateau (Qiu et al., 2017), and etc.

There were totally 2030 authors participated in relevant research on the YRB from 1998 to 2020. The highest individual total citations (1274) and local total citations (127) were from LI F. M. (Li Fengmin) in the Lanzhou University of China (Table 4). His main research included the agricultural ecology and vegetation variation on the Loess Plateau located in the YRB (Zhao et al., 2014b; Zheng et al., 2019). The most individually published papers about YRB were from LIU Y. (Liu Yu) in the Chinese Academy of Sciences, whose main research direction was dendroclimatology and the management of YRB's sediment load under climate change (Liu et al. (2020). FU B. J. (Fu Bojie) from the Chinese Academy of Sciences had the highest H-index (15) and the second highest number of papers (17). The research of FU mainly included the impacts of human activities on sediment transport in the YRB (Wang et al., 2016), soil erosion control service in the Loess Plateau (Fu et al., 2011b), and impacts of water resources on revegetation in the Loess Plateau (Feng et al., 2016b), and etc.

3.5. Most cited papers and references

Conventionally the amount of paper's citations would directly reflect the quality and influence of this paper globally or locally. In this study, we compiled the top 20 cited papers about research on the YRB (Table 5). The most totally cited paper was published in the journal of Global and Planetary Change by Wang et al. (2007). And the paper published by Zhou et al. (2009) in the journal of Field Crops Research was the most locally totally cited paper during 1981–2020. It was necessary to classify papers according to the contents of the research. Wang et al. (2007) mainly explored the impacts of climate change and human activities on the amount of sediment in the Yellow River. Cao et al. (2009) mainly discussed some successful or unsuccessful examples to restore the fragile environments of the YRB by the 'Grain for Green Project' of China. Their ultimate goal was to take reasonable measures to protect the local ecological diversity. Cai et al. (2008) compared the weathering intensity and HCO_3 flux in the world's major rivers including the YRB. Zhang (2009) introduced China's South-to-North Water Transfer Project and discussed its impacts on the riverine environments of upper Yellow River. Su and Fu (2013) and Wang et al. (2011) studied the evolution of land use and vegetation characteristics on dried soil layers and ecosystem of the Loess Plateau of China. Dotterweich (2013) and Fu et al. (2000) also conducted research on soil conditions and soil erosion on the Loess Plateau. The interaction relationship among crops, environment and management on the Loess Plateau was one of the momentous studies on the YRB in 1988–2020. These studies mainly included: (a) the effects of mulching on crops and soil moisture or fertility (Li et al., 2004a, 2004b; Zhang et al., 2009), (b) the effects of irrigation measures on crop yield and growth (Kang et al., 2000, 2002; Liu et al., 2010; Sadras and Angus, 2006; Wang et al., 2009), (c) the effects of tillage measures on crops and resource utilization (Su et al., 2007), and (d) the effects of multi-factor coupling on crops and soil (Li et al., 2001; Liu et al., 2009; Zhou et al., 2009).

About references, the paper with the highest TC and LTC was from Shi and Shao (2000b), which mainly investigated the problem of soil and water loss in the Loess Plateau and putted forward the existing problems and measures of comprehensive control (Table 6). In fact, 19 of the top 20 citations were related to studies of the Loess Plateau. The concerns of these references were also consistent with the research directions of the Loess Plateau located in the YRB in 1988–2020 (Table 6). One exception is that Berner et al. (2012) studied the biomass distribution, fire regime, and post-fire recovery of Cajander larch (*Larix cajanderi* L.) in

Table 4
Most cited authors for research on the Yellow River Basin based on two statistical indicators (TC and LTC) and number of published papers (TP) from 1998 to 2020.

Rank	Author/ Institution	TC	LTC	TP	H-index
1	LI FM/ Lanzhou Univ	1274	127	15	10
2	FU BJ/ Chinese Acad Sci	957	40	17	15
3	KANG SZ/ China Agr Univ	703	32	6	6
4	WANG Y/ Ocean Univ China	601	14	11	5
5	ZHOU LM/ Nanjing Univ	565	51	3	3
6	WANG J/ Yangzhou Univ	551	35	10	6
7	JIN SL/ Yangzhou Univ	547	49	2	2
8	SAITO Y/ Shimane Univ	539	10	2	2
9	WANG HJ/ Ocean Univ China	539	10	2	2
10	YANG ZS/ Ocean Univ China	539	10	2	2
11	LI XY/ Zhejiang A&F Univ	502	51	8	8
12	SHAO MA/ Northwest A&F Univ	482	31	14	9
13	LIU JP/ North Carolina State Univ	460	9	1	1
14	SUN XX/ Ocean Univ China	460	9	1	1
15	WANG YQ/ Chinese Acad Sci	431	30	10	6
16	ZHANG L/ Northwest A&F Univ	431	28	7	5
17	LIU Y/ Chinese Acad Sci	418	25	20	8
18	CHEN LD/ Chinese Acad Sci	406	19	7	6
19	GONG JD/ China Meteorol Adm	403	45	3	3
20	LI XG/ Lanzhou Univ	375	31	6	5

Note: TC is global total citations; LTC is local total citations; and TP is total papers.

Table 5
Most cited published papers about research on the Yellow River Basin based on two statistical indicators (TC and LTC) from 1998 to 2020.

Rank	Author	DOI	TC	LTC
1	Wang et al. (2007)	10.1016/j.gloplacha.2007.01.003	460	9
2	Zhou et al. (2009)	10.1016/j.fcr.2009.04.005	317	29
3	Fu et al. (2000)	10.1016/s0341–8162(99)00084–3	274	11
4	Kang et al. (2002)	10.1016/s0378–3774(01)00180–9	271	23
5	Cao et al. (2009)	10.1111/j.1365–2664.2008.01605.x	260	12
6	Wang et al. (2011)	10.1016/j.agrformet.2010.11.016	243	15
7	Liu et al. (2009)	10.1016/j.eja.2009.08.004	230	20
8	Wang et al. (2009)	10.1016/j.agwat.2008.09.012	187	20
9	Kang et al. (2000)	10.1016/s0378–4290(00)00095–2	184	5
10	Sadras and Angus (2006)	10.1071/ar05359	179	5
11	Li et al. (2001)	10.1016/s0378–3774(01)00105–6	179	18
12	Li et al. (2004a)	10.1016/j.soilbio.2004.04.040	161	9
13	Cai et al. (2008)	10.1016/j.csr.2007.10.014	146	0
14	Su et al. (2007)	10.1016/j.agwat.2006.08.005	141	17
15	Zhang et al. (2009)	10.1016/j.still.2008.07.019	140	14
16	Liu et al. (2010)	10.1016/j.agrformet.2010.02.003	139	11
17	Dotterweich (2013)	10.1016/j.geomorph.2013.07.021	132	0
18	Li et al. (2004b)	10.1016/j.still.2003.12.009	131	14
19	Zhang (2009)	10.1111/j.1752–1688.2009.00357.x	129	0
20	Su and Fu (2013)	10.1016/j.gloplacha.2012.12.014	117	6

Note: DOI is digital object unique identifier; TC is global total citations; and LTC is local total citations.

Table 6
Most cited references of published papers about research on the Yellow River Basin from 1998 to 2020.

Rank	Author	DOI	TC	LTC
1	Shi and Shao (2000a)	10.1006/JARE.1999.0618	569	44
2	Deng et al. (2006)	10.1016/J.AGWAT.2005.07.021	514	25
3	Zhao et al. (2013a)	10.1002/LDR.2246	447	24
4	Feng et al. (2016a)	10.1038/NCLIMATE3092	444	22
5	Fu et al. (2011a)	10.1016/J.ECOCOM.2011.07.003	426	20
6	Zhou et al. (2009)	10.1016/J.FCR.2009.04.005	413	29
7	Kang et al. (2002)	10.1016/S0378–3774(01)00180–9	361	23
8	Li et al. (1999)	10.1016/S0378–4290(99)00027–1	335	20
9	Chen et al. (2015)	10.1038/NGEO2544	307	17
10	Gan et al. (2013)	10.1016/B978–0–12–405942–9.00007–4	301	25
11	Liu et al. (2009)	10.1016/J.EJA.2009.08.004	293	20
12	Chen et al. (2008)	10.1016/J.GEODERMA.2007.10.013	283	23
13	Li et al. (2001)	10.1016/S0378–3774(01)00105–6	259	18
14	Wang et al. (2009)	10.1016/J.AGWAT.2008.09.012	252	20
15	Huang et al. (2005a)	10.1016/J.AGWAT.2004.09.012	230	31
16	Li et al. (2013a)	10.1016/J.AGWAT.2012.10.001	217	20
17	Wang et al. (2010)	10.1016/J.JHYDROL.2009.09.042	208	18
18	Bu et al. (2013)	10.1016/J.AGWAT.2013.03.015	197	24
19	Li et al. (2013c)	10.1016/J.AGWAT.2012.10.004	197	19
20	Berner et al. (2012)	10.5194/BG-9–3943–2012	75	35

Note: DOI is digital object unique identifier, TC is global total citations and LTC is local total citations.

northeastern Siberia to improve predictions of net climatic feedbacks associated with landscape-scale forest disturbances in northern Eurasia that includes the Loess Plateau. These references provided important enlightenment for the relationship between climate and forests of the YRB and the impacts of future climate change on terrestrial ecosystems. Through summarizing the research contents of these highly cited papers and references, the main key findings included the following parts. First, climate change and human activities have jointly affected the sediment load of the YRB, and human activities (including agricultural water consumption, soil conservation practices, and etc.) were the main reasons for the reduction of sediment load. Next, the 'Grain for Green Project' has made researchers to focus on the relationship between vegetation restoration and efficient use of water and soil. The relevant studies found that reducing the intensity of farming and grazing should be considered together as the primary tool in this project to reduce afforestation. Finally, for agricultural production in the YRB, researchers mainly focused on the technology and methods about high crop yields based on efficient resource utilization. Therefore, the research focuses were not only related to the government's policies, but also to the actual problems faced by the YRB at different times.

3.6. Keywords' evolution and co-occurrence

A paper's keywords not only indicate the research direction of this paper, but also the variation of hot topics of relevant research. In this study, we screened out the top-20 frequent keywords for the research on the YRB from 1998 to 2020 (Fig. 5). All keywords relatively had a lower frequency during 1998–2010, suggesting that the YRB's research were still in infancy (Fig. 5). The keywords and their frequencies changed in different periods. The keywords of "loess plateau", "management", "water-use efficiency (WUE)", "yield", and "land-use" were the top-5

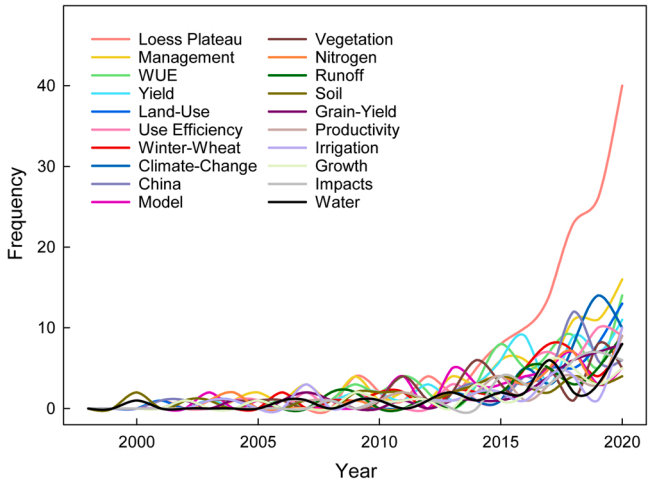

Fig. 5. Changes of the occurrence frequency the top 20 keywords of all articles investigated about the research of the Yellow River Basin from 1998 to 2020. Different colored lines represented different keywords.

high-frequency keywords during this period (Fig. 5). In more detail, the keywords of "management", "soil", "loess plateau", "Yield", and "irrigation" was the five most frequent keywords from 1998 to 2010, implying that efficient use of soil was the hot topic in this period. Efficient crop water use was so necessary in the Loess Plateau that some scientific and reasonable management measures should be adopted (Table 7). Between 2011 and 2015, the frequency of all keywords increased indistinctively, indicating that the YRB's research experienced a slow but steady growth during this period (Fig. 5). The top-5 keywords in this period were "loess plateau", "water-use efficiency (WUE)", "management", "vegetation", and "model". Some models such as crop models, statistical models, and machine learning models were gradually applied in YRB's research. In addition, vegetation restoration and soil erosion in the YRB attracted more and more attentions in 2011–2015. Among these keywords, the frequency of "loess plateau" increased exponentially since 2015 (Fig. 5). The keyword of "climate-change" also suddenly increased and ranked third in 2016–2020 (Table 7). In general, the YRB's research developed rapidly during this period and paid more and more attentions to future climate change as well.

We used the Louvain algorithm to cluster the top-50 keywords related to the YRB's research from 1998 to 2020. All keywords were clustered into three types in the co-occurrence network (Fig. 6). The red cluster had a total of 21 keywords, which mainly were loess plateau, management, water-use efficiency (WUE), yield, use efficiency, and etc. Thus, this clustering focused on the management of crops in the Loess Plateau of China. Efficient use of water and nutrients were also hot topics so that the growth and yield of crops could be improved with limited water resources. Based on the cluster analysis, it was found that the main crops were maize and wheat on the Loess Plateau located in the YRB, especially winter wheat (Fig. 6). Thus, the red cluster mainly focused on agricultural production. The blue clusters with a total of 26 keywords, mainly including land use, climate change, China, model, vegetation, and etc. (Fig. 6). The YRB still faced serious soil erosion in this period, which were bound to cause changes in land use and population characteristics of vegetation under future climate change. Thus, the main research directions of blue clustering were environment, ecology, meteorology, and hydrology. The green cluster had only three keywords of carbon, conservation, and organic matter (Fig. 6). More importantly, these three keywords appeared only in recent years. Since the Chinese government wants to achieve the goals of reducing carbon emissions and achieving carbon neutrality by 2060, the research on carbon emissions/greenhouse gas (GHG) emissions and carbon surplus is coming under global spotlight now, especially under future climate change. Generally, the management of crops, utilization of water and

Table 7
Dynamic changes of the top 20 keywords about research on the Yellow River Basin in periods from 1998 to 2010, 2011–2015, and 2016–2020.

Rank	Years					
	1998–2010		2011–2015		2016–2020	
	Keyword	Times	Keyword	Times	Keyword	Times
1	management	14	loess plateau	20	loess plateau	113
2	soil	10	water-use efficiency	17	management	49
3	loess plateau	8	management	16	climate-change	40
4	yield	8	vegetation	16	water-use efficiency	40
5	irrigation	7	model	15	yield	39
6	water-use efficiency	7	yield	14	use efficiency	37
7	wheat	7	soil	12	land-use	34
8	environment	6	restoration	11	china	32
9	grain-yield	6	land-use	10	winter-wheat	32
10	runoff	6	nitrogen	10	nitrogen	28
11	use efficiency	6	productivity	10	grain-yield	27
12	vegetation	6	carbon	9	runoff	27
13	winter-wheat	6	forest	9	impacts	25
14	erosion	5	inner-mongolia	8	dynamics	24
15	growth	5	organic-carbon	8	model	24
16	land-use	5	temperature	8	erosion	23
17	productivity	5	winter-wheat	8	impact	22
18	region	5	china	7	evapotranspiration	21
19	responses	5	impact	7	growth	21
20	systems	5	responses	7	vegetation	21

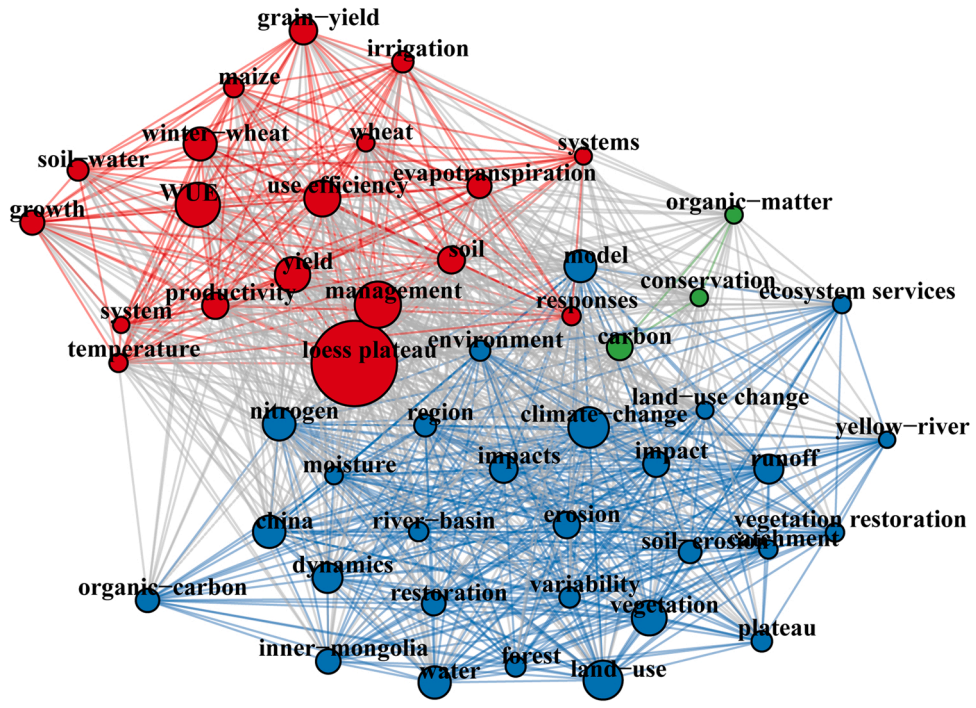

Fig. 6. Co-occurrence Network analysis of top 50 keywords based on louvain clustering algorithm. Different color regions represented different clustering results. The red, blue, green and gray connecting lines indicate the co-occurrence of kewords. And, the size of each node represented the frequency of kewords that has occured in article.

fertilizer in the Loess Plateau, and the ecological restoration were still the main research directions of the YRB. However, more and more YRB's research will integrate carbon emissions and carbon neutrality under future climate change.

4. Discussion

Although the ecosystem was relatively fragile, the Yellow River basin (YRB) still urgently needed to increase its agricultural productivity to feed more population in the future. It was well-known that there was a greater conflict between vegetation expansion for ecological restoration and agricultural farmland in respect of land and water use (Chen et al., 2015; Feng et al., 2016b). The way to resolve this conflict depends on the formulation of government policies. However, advanced water-saving technologies and management, as well as water consumption mechanisms of crops were also needed to understand (Cao et al., 2020). It was exciting that the YRB's research has attracted more and more attentions from researchers in different countries about either ecological restoration or agricultural production, especially in the past five years (Fig. 2a). Based on journal paper analysis, the fields of YRB's research mainly included agriculture, water resources, soil, and environment. In addition, the journal of Agricultural Water Management gained great

influence in the YRB's research because of the highest number of citations and the second largest number of papers among all journals (Table 2 and Fig. 3). This means that an increasing number of researchers focused on the relationship between crops and water, and efficient use of water and fertilizer in agriculture (Deng et al., 2006; Ren et al., 2018). This was also proven by the cooperation between institutions and the highly cited authors, which were more related to research about agriculture in the YRB (Fig. 4 and Table 4).

According to the top 20 most cited papers, the YRB's research mainly focused on the relationship between crops, soil and water (Table 5). Because serious soil erosion of the YRB restricted agricultural production, some scientific management measures were developed. Rainfed agriculture based on mulching was always valued by researchers (Li et al., 2001; Liu et al., 2009). And different tillage measures were also an important research content (Wang et al., 2009). In fact, irrigation conditions were usually lacking in the Loess Plateau located in the YRB. Mulching the soil with plastic film was believed to inhibit the evaporation from soil during planting. The moisture of deeper soil layers transferred to the topsoil, making the topsoil water content relatively stable. In addition, solar radiation formed a diffuse reflection between the plastic film and topsoil, leading to an accumulation of heat in the root zone. Thus, the accumulated temperature during crop growing season was increased compared to no-mulching field, which contributed to the increase of yield in the semi-arid areas of the YRB (Zhang et al., 2009). As for tillage measures, the practice of double ridges and furrows mulched with plastic film to collect rainwater could improve water use efficiency of crops, resulting in an increase of crop yield. This management practice was widely used in semi-arid areas of the YRB and almost completely replaced conventional tillage practice (Zhou et al., 2009). Thus, a great emphasis was placed on water-saving technology and management for crops in the past, since it could directly and efficiently provide benefits for actual agricultural production. Moreover, most of the top20 most cited reference papers were related to crop water management and technology (Table 6). However, the water balance between ecological restoration and agricultural production in the YRB was still a hot research topic.

The topic of research generally focused on the problems that demanded prompt solution or the implementation of national policies. The evolution of keywords in different periods could be the bellwether of research topics. From 1998–2010, the keywords uniformly had low frequency due to the smaller number of papers. The keywords of "management", "soil", "loess plateau", "yield" and "irrigation" were the top-5 frequent ones (Table 7). This means that crop management based on soil and irrigation was the main research direction in the early stage of YRB's research. Because of the intuitive impact of water shortage on agriculture in the semi-arid area of the YRB, researchers were forced to quantitatively control irrigation in order to save water while minimizing the impacts on yield (Kang et al., 2002; Li et al., 2001; Wang et al., 2009). From 2011 to 2015, the frequency of all keywords increased compared to the past ten years. Except for "loess plateau" and "management", the top-5 frequent keywords also included "water use efficiency", "vegetation", and "model". The accelerated implementation of 'Grain for Green Project' of China ensured the effective restoration of ecology in the YRB. However, the expansion of vegetation also raised several misgivings. First, in respect of water resources, the reduction in YRB's runoff caused by vegetation restoration affected the amount of water available for human activities, which might cause negative socio-economic consequences (Feng et al., 2016b; Miao et al., 2012). Second, utilizations of land and water must be balanced between vegetation and crops to avoid exacerbated food shortages (Chen et al., 2015). Therefore, the research during this period mainly relied on the Grain for Green Project of China to weigh and simulate the vegetation restoration and agricultural production in the YRB. The frequency of keyword "Loess Plateau" increased exponentially since 2015. Additionally, the frequency of keyword "climate change" also remarkably increased. Temperature was one of the main factors that regulate the growing seasons of vegetation. Many studies showed that the growing seasons of vegetation in the middle and high latitudes of the northern hemisphere were prolonged due to global warming (Jeong et al., 2011; Liu et al., 2016; Piao et al., 2020). Thus, it is very meaningful for policy making and technological innovation to study the vegetation restoration and crop growth in the YRB under future climate changes.

After understanding the past and current goals of research on the YRB, it was necessary to explore the trend of future research. In the cluster analysis of top-50 keywords, the red clusters mainly concentrated on agricultural production, while the blue clusters mainly focused on the ecological restoration of the YRB. Both two clusters were the main research directions in the period of 1998–2020. However, the green cluster only included three keywords of "carbon", "conservation", and "organic matter", whose frequencies just increased in the past five years. Terrestrial plants fix carbon dioxide (CO_2) into organic matter. This process was also called gross primary production at the ecological level. As the world's largest carbon flux, GPP drives the carbon cycle in the ecosystem and helps offset anthropogenic carbon emissions (Beer et al., 2010; Chapin et al., 2009; Lu et al., 2017). The CO_2 in the atmosphere is expected to rise to 800 ppm at the end of this century and intensifies the process of global warming (van Vuuren et al., 2011). In fact, agricultural production has contributed about 19–29% of global anthropogenic GHG emissions. The dependence of growing population on food production and the impact of climate change on crops both raise serious concerns about GHG emissions in the future (Vermeulen et al., 2012). Thus, how to effectively control greenhouse gas (GHG) emissions and carbon surplus was of great importance to agricultural production and ecological restoration in the YRB in the future. More importantly, the consequences of rising CO_2 should be additionally taken into consideration to bring new directions in policy making and technological innovation.

5. Conclusions

In this study, we comprehensively and quantitatively evaluated the focuses and evolution of global research on the Yellow River Basin (YRB) in China using the method of bibliometrics. The "Advanced Search" of "Web of Science" (WOS) based on the "Web of Science Core Collection" database was used to screen out a total of 580 papers, including 561 articles, 3 editorial material, 2 meeting abstract, and 14 reviews. Then, the "*bibliometrix*" package in R language was used to analyze all papers about research on the YRB. Some main conclusions were drawn as follows.

(1) The number of published papers about YRB's research slowly increased in 1998–2010 (83 papers), then rapidly increased in 2011–2015 (128 papers), and exponentially rose in 2016–2020 (369 papers), indicating a perspective about YRB's research in the future.

(2) The main research areas of the YRB were summarized, including agriculture, crops, water, soil, environment, and etc. Most of the research papers involved were published in the journal of Environmental Earth Sciences. However, the journal of Agriculture Water Management had the highest global total citations and H-index, as well as the highest local citations among all of the reference sources about the YRB.

(3) For the contributions of different countries, institutions and individuals to the YRB's research, the number of papers and total citations of China always maintained a high level in the periods of 1998–2010, 2011–2015 and 2016–2020. The cooperation between institutions was mainly represented by the Northwest A&F University (NWAFU), the Chinese Academy of Sciences (CAS), and the Xi'an Jiaotong University (XJTU) of China for different research characteristics and directions. As for individuals, LI F. M. (Li Fengmin), LIU Y. (Liu Yu), and FU B. J. (Fu Bojie) were the most influential and competitive authors for the YRB's research.

(4) Based on summary of the most cited papers and references, the most important research hotspots were the impacts of climate change and human activities on the amount of sediment in the YRB, the

management of soil erosion and vegetation restoration in the YRB, and the relationship between crops and environment and management on the Loess Plateau located in the YRB.

(5) The keywords of "loess plateau", "management", "climate change", "water use efficiency", and "yield" were the focuses of YRB's research over the past five years. This can also be proved by the clustering results the top-50 keywords about the research in the YRB. In addition, carbon emissions/greenhouse gas emissions under future climate change may become hotspot in near future. In general, this study systematically revealed the development, evolution, and prospects of the scientific research on the YRB and could enhance our understanding about the YRB's research.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2021.107404.

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