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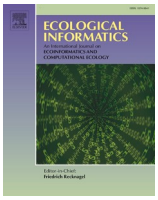

A bibliometric review of ecological research on the Qinghai–Tibet Plateau, 1990–2019

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ABSTRACT

Ecological research on the Qinghai–Tibet Plateau (QTP) has become a hotspot in recent years, and a great number of related research papers have been published. Here, a bibliometrics method was utilized to analyze 4315 papers from the Web of Science published from 1990 to 2019, and a comprehensive overview based on metrics, including the publication growth, first author' institutions and countries, research areas, international cooperation, high-impact journals and papers, and research hotspots and topics, is presented. The results revealed the following: (1) The number of published papers has grown exponentially, with China and India being the main research countries. However, China and the USA have the greatest weights in country cooperation. The Chinese Academy of Sciences has a relatively strong influence and plays the leading role in institutional cooperation. Wang Shiping, Zhang Zhenhua, Luo Caiyun, and seven other authors are highly influential. *GLOBAL CHANGE BIOLOGY* is the scientific journal that has published the greatest number of papers on the subject, and 'Environmental Sciences & Ecology' is the key research area; (2) Grazing, Precipitation, Soil moisture, Aboveground biomass, and Temperature are the top five core keywords. The research hotspots were mainly ecosystem services, biodiversity research, forest protection, and ecological adaptation under the background of climate change; and (3) Both new and old research topics appear in the periods 1990–1999, 2000–2009, 2010–2014, and 2015–2019, but all the periods focused on the impacts of rising temperature on natural elements, such as soil, forests, rivers, and lakes. Many recent also focused on the harmonious coexistence of human beings and nature. On the basis of these findings, some research suggestions and agendas are proposed for future research on the QTP. This is the first visualization and analysis of the hotspots and trends in ecological research on the QTP.

1. Introduction

The Qinghai–Tibet Plateau (QTP, or Tibetan Plateau) is well known as the "Roof of the World", "Asian Water Tower", and "Third Pole" (Cheng et al., 2019; Yao et al., 2012). It is a region sensitive to global climate change and an ecological barrier that plays critical roles as a "driver" and "amplifier" of global change (Cheng et al., 2019; Immerzeel and Bierkens, 2010; Li, 2017). It also has the highest elevation and largest area of permafrost in the middle and lower latitudes of the earth (Cheng et al., 2019). In addition, the QTP is the highest biogeographic unit in the world. Owing to its high, cold, and drought-prone environment, its alpine ecosystem is very sensitive to climate change and human activities, providing a natural laboratory for global climate change research and becoming a hot region for ecological and environmental change-related research (Li, 2017).

Since the 1980s, global warming has become more prominent in the QTP (Yao et al., 2012; Yasunari et al., 2013), and its heating rate is about twice the global average (Chen et al., 2015; Yao, 2019). The plateau ecosystem has undergone profound changes, which has had a profound impact on the surrounding areas. Coupled with the severe impacts of human activities, ecosystem in the QTP has undergone significant changes. Problems such as decreased ecosystem stability and increased pressure on resources have become more and more prominent. The ecological security of the QTP is facing unprecedented challenges (Piao et al., 2019; Zhang et al., 2015). From the 1970s to 1990s, China conducted the first large-scale and long-term scientific investigation in the

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QTP and produced fruitful scientific results (Yao, 2019). To understand the processes and mechanisms of environmental change centered on ecosystems and human activities, in 2017, the Chinese Academy of Sciences (CAS) launched the Second Tibetan Plateau Scientific Expedition and Research program, which focuses on the environmental changes that have taken place over the past 50 years and their impacts on human society, with the goal of strengthening the ecological buffer capacity of the QTP (Yao, 2019). Therefore, ecological research on the QTP has important strategic significance.

The research on the ecological environment of QTP has drawn much attention for a long time. In a previous study, the research history of the QTP was divided into four stages (Li, 2017), namely, accumulation of first-hand knowledge and agriculture phase, geographical expedition phase, integrated survey and ecological environment study phase, and long-term ecosystem monitoring and global change research phase. The research also pointed out that many countries, primarily China, have greatly enhanced people's understanding of the ecological environment of the QTP as a typical area and pushed forward the in-depth and rapid research in this area through the implementation of a series of research plans and projects, which in turn delivered QTP, a large number of scientific papers and monographs (Wang, 2017).

In recent years, an array of new achievements has been made in the research on ecological environment of the QTP across many fields. For example, a growing number of research began to focus on the restoration and sustainable development of degraded ecosystems. Li et al. (2017) studied the impact of vegetation restoration on the improvement of sandy soils in the QTP. Wang et al. (2020) discussed the impact of grassland degradation in the QTP on the ecological stoichiometry of soil ecosystems. Leng et al. (2020) reviewed the research on grassland carbon balance of the QTP in the scenario of future climate change and suggested that the future carbon balance should consider the impact of human activities and plateau pikas. The sustainable management of the QTP ecosystem and regional ecological security have also aroused the interest of experts from all over the world. For example, Wei et al. (2019) focused on Energy Ecological Footprint for the QTP and assessed the high-energy ecological footprint and high-energy carrying capacity of the target area through an improved method for assessing high-energy ecological footprint, reaching to the conclusion that the ecological surplus in Tibet will continue to decrease. Jia et al. (2020) evaluated the impact of highway construction on the ecological environment of the QTP. Fang et al. (2021) studied the ecological carrying capacity of alpine grasslands on the QTP based on structural dynamics and the research result provided an important basis for the effective adaptation of alpine ecosystems to climate change. Moreover, the sustainable management of QTP ecosystem and regional ecological security have also captured the attention of experts all over the world. As a result, a large number of publications that quantitatively evaluate the ecological assets and ecosystem services of QTP have been published in many renowned international journals (Ma et al., 2017; Rasul, 2014; Semwal et al., 2004). In a recent study, Lin et al. (2021) estimated the importance of the QTP on the ecological front based on ecosystem service flows, and proposed that extremely important areas are mainly distributed in the Yarlung Zangbo River Basin, Tanggula Mountains, Hengduan Mountains and Qilian Mountains, accounting for 31.7% of the QTP. These academic papers not only record the historical changes in international ecological research on the QTP, but also reflect the continuous recognition of international ecological scientists. In addition, they also have a profound impact on the future direction of ecological research on the QTP.

The bibliometrics method has been widely used in the construction of knowledge atlases of natural science research in recent years (Zurita et al., 2020; Jiang et al., 2020). It can systematically review the relevant research history of specific scientific fields, conduct a detailed analysis of research status, identify research hotspots, build an international cooperation network between important countries, institutions, or authors, and detect future research directions in a specific field. Therefore, it plays an important reference role and can greatly support research layouts and analyses in related fields. However, as far as we know, a comprehensive and macroscopic knowledge map of the ecological research on the QTP based on bibliometrics has not been constructed. Therefore, a bibliometric analysis on the achievements of ecological research on the QTP is necessary to describe the macroscopic situation, clarify recent research topics, and suggested future directions for ecological research on the QTP.

This study aimed to address the following topics using bibliometrics: (1) The macroscopic growth characteristics of research papers, major countries, institutions, journals, and research areas, as well as the cooperative relationship between these countries, institutions, and major authors; and (2) QTP-related research hotspots and topics in 1990–2019. This study provides references and a framework for scientists, the public, government decision-makers, and other stakeholders.

2. Materials and methods

2.1. Data collection

The data were collected from the Science Citation Index Expanded and Social Science Citation Index of the Web of Science (WOS) (Fig. 1), which is a preferred option for bibliometric studies and is considered the world's leading database for the evaluation of scientific research (Aleixandre-Tudó et al., 2019). The topic search strategy was selected to collect the data using field tags, Boolean operators, parentheses, and query sets. Additionally, owing to the complexity of the search expressions, the composite search method was applied by forming and combining two search sets as follows:(1) TS = (tibet* or himalaya* or qomolangma or mt everest or qinghai or karakorum or karakoram or kunlun* or qilian* or hengduan* or muztagata or tanggula or qiangtang* or yarlung zangbo or qaidam or pamir* or gangdise or gangdese or three river* source* or three river* headwater*). This search set focused on all the publications on the QTP in the database; and (2) TS = (ecolog* or biology or bionom* or ecology or mesology or ecosystem*). This search set retrieved all the papers on ecological research in the database. By combing search sets (1) and (2), all the papers on ecological science research on the QTP were retrieved. The search sets and their combinations were executed on September 1, 2020. The types of papers selected were articles, reviews, and proceedings.

2.2. Methodology

Bibliometrics is regarded as an important and effective method to study and obtain qualitative data and quantitative information on published information (Broadus, 1987; Fairthorne, 1969; Pritchard, 1969). It has been widely used to evaluate the characteristics of many different types of academic achievements and successfully map subject knowledge spectra in multiple fields in recent years (Yang et al., 2019; Fan et al., 2020). Therefore, this method was chosen to perform a macroresearch and development review of the ecological research on the QTP.

In addition to conventional data description and analysis methods, series visualization and deep-mining software, like Thomson Data Analyzer (TDA), VOSviewer, CiteSpace, and KNIME were also used for the data analysis (Fig. 1). TDA is a central point for the analysis of field data from a variety of rich information sources, including Thomson Scientific patent and literature databases. TDA provides a variety of tools that can be used to analyze data and text. These tools are data independent and, therefore, can be applied in the same way to any type of data. VOSviewer is a tool for creating knowledge maps based on network data and for visualizing and exploring these maps (Van Eck and Waltman, 2010, 2014). It was used to construct networks of authors, institutions, countries, and keywords by co-authorship and co-occurrence analyses in this study. CiteSpace (5.7.R1) was used for burst detection. It was proposed by Kleinberg (2003) to detect keywords that have suddenly emerged or increased significantly in a short period of time (Chen, 2004, 2006). Analyses of these keywords can provide

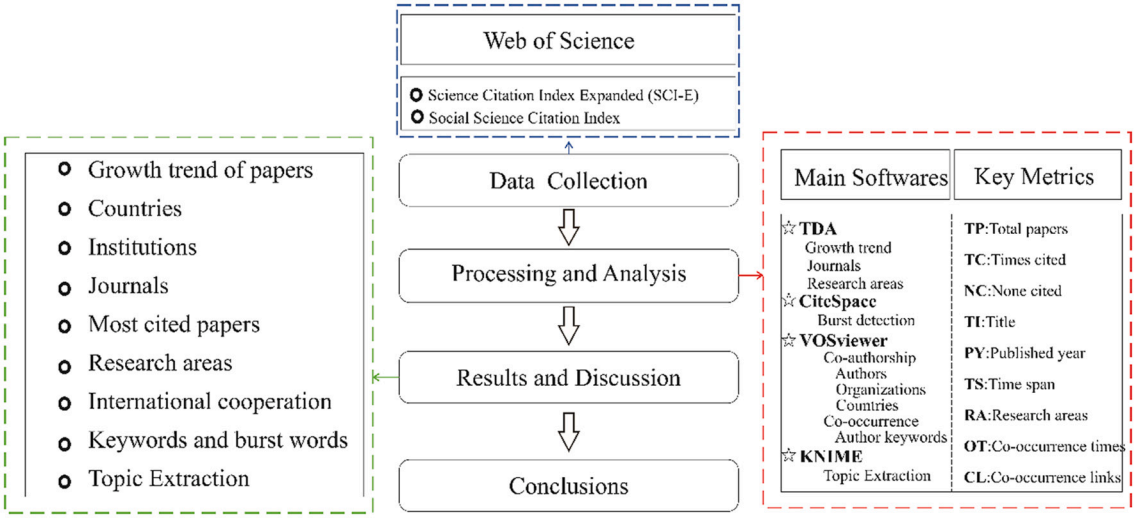

Fig. 1. This study's workflow.

insights into future research interests (Zhu and Hua, 2017). The Topic Extractor node of the KNIME Analytics Platform extracts topics from publication abstracts. KNIME is considered the leading open solution for data-driven innovation and was designed for discovering the potential hidden in data, mining for fresh insights, and predicting new future topics (Chen and Yang, 2012). It provides a topic extraction workflow that shows how to extract topics from text documents using the Topic Extractor node (Andisa and Kilian, 2017). This workflow can preprocess the textual data by tagging, filtering, or lemmatizing. It also provides the "Elbow Method" to accumulate the number of topics needed to conduct topic extraction. The topic words and their weights can be exported in an Excel table and a tag cloud can be created to visualize a topic's terms.

3. Results and discussion

Using the data collection operation described in the above section, 4920 papers were obtained. Interestingly, although the first ecological research paper on the QTP appeared in 1961 and the second appeared in 1964, the total number of papers was relatively small before 1990, with an average of 0.73 per year, which was not a sufficient quantity to effectively carry out a bibliometrics analysis. Therefore, the search time was selected as 1990 to 2019, encompassing 30 years. Thus, the following analysis only focuses on papers published since 1990. Using this filter, 4315 papers related to ecological research on the QTP were obtained.

The following sections analyzed the various bibliometric elements such as the number of papers, countries, institutions, authors, journals, keywords, research topics from a quantitative and qualitative perspective and discussed the scientific significance of each element to draw a macro-knowledge map of ecological research on QTP. In addition, only the relevant situation of the first authors' country and affiliation are discussed in the influence analysis of countries and institutions.

3.1. Growth trend of papers

From 1990 to 2019, ecological research on the QTP developed

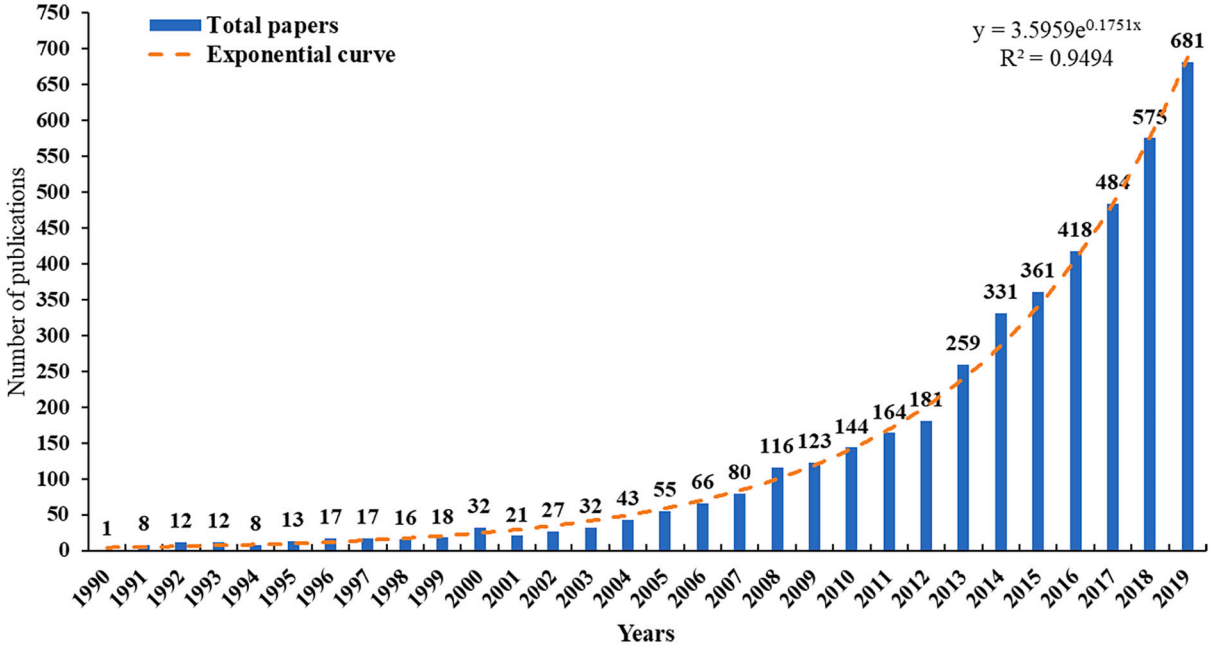

Fig. 2. Total numbers of published ecological research papers on the QTP from 1990 to 2019.

rapidly, which was fully reflected in the number of published research papers. As shown in Fig. 2, there was an exponential increase in ecological research papers on the QTP since 1990. In fact, the growth rate was relatively slow from 1990 to 2009, with a cumulative increase of 717 papers, accounting for 16.61% of all the papers. The annual number was only 35. In contrast, 3598 papers were published from 2010 to 2019, accounting for 83.4% of all the published papers in the 30-year period analyzed, with an average of 359 papers annually. Therefore, it is conceivable that the QTP will continue to be an ecological research hotspots, which makes it more important to understand its developmental trend at a macro level.

3.2. Analysis of countries

The scientific paper output and its influence are the direct manifestations of a country's research strength, which can also effectively reflect the importance each country attaches to this field. The influence of the first author's papers are a direct manifestation of the research strength of a country. Therefore, this study counted the total papers (TP) published by a first author from the top 20 of the 62 countries represented in related publications and analyzed the influence of these countries from the perspectives of TP, Times cited (TC), cited times per paper (TC/TP), None cited (NC), and their proportion of all the papers (Table 1).

The statistical results revealed that the TP values of China, India, and the USA were the highest among the top 20 countries, with China accounting for 60.07% (2592) of the TP, followed by India at 15.64% (675), and the USA at 5.96% (257). In addition, the TP values for these three countries exceeded the average number of papers in the top 20 countries (207.85). In terms of TC values, China ranked first, being cited 42,036 times, followed by the USA at 10,301 citations and India at 6525 citations.

Considering the differences in TP values, the TC/TP values and the proportions of NC (NC/TP) were considered to be more representative in the analysis of the degree of research influence. The TC/TP values revealed that the UK ranked first, with a ratio of 48.21, followed by Japan (41.53) and the USA (40.08). This indicated that papers from these three countries are the most influential. Moreover, even though the TP values of France, Norway, and Austria were less than 27, their TC/TP ratios exceeded 30, indicating that these countries are also influential. Notably, China ranks 14th in this statistic, indicating that it can increase its influence. This revealed that the most influential ecological research on the QTP is presented by countries that do not rank among the top positions based on TP values. In fact, the NC/TP ratio also supported this conclusion. The data showed that China ranks 16th, with a value of 7.75%, which is slightly lower than the average value of 8.25%. It may be that Chinese scholars have contributed many papers on the QTP, resulting in a large TP numerical base. However, the contributions of most papers according to the TC value is low, even zero, which directly affected the TC/TP and NC/TP ratios of China. In contrast, among the top three countries based on TP, the USA (4.28%) performed better, while India (13.48%) ranked 17th. Norway, Switzerland, and the Czech Republic had NC/TP values of zero.

Table 1
Top 20 countries represented by the total papers published on the ecology of the QTP in 1990–2019.

R	Country(1st)	TP	TC	TC/TP	NC	NC/TP(%)
1	China	2592	42,036	16.22	201	7.75
2	India	675	6525	9.67	91	13.48
3	USA	257	10,301	40.08	11	4.28
4	Germany	114	3148	27.61	3	2.63
5	UK	87	4194	48.21	2	2.30
6	Pakistan	76	748	9.84	14	18.42
7	Japan	43	1786	41.53	1	2.33
8	Nepal	43	745	17.33	3	6.98
9	Australia	40	990	24.75	3	7.50
10	Canada	31	375	12.10	1	3.23
11	Norway	27	953	35.30	0	0.00
12	Czech Republic	24	287	11.96	0	0.00
13	Italy	23	401	17.43	1	4.35
14	France	21	756	36.00	1	4.76
15	Switzerland	21	367	17.48	0	0.00
16	New Zealand	20	316	15.80	2	10.00
17	Russia	19	94	4.95	6	31.58
18	Poland	16	175	10.94	1	6.25
19	Austria	15	457	30.47	1	6.67
20	Spain	13	244	18.77	1	7.69
MEAN	–	207.85	3744.9	18.02	17.15	8.25

Abbreviations: R = Rank; TP = Total papers; TC = Times cited; NC = None cited.

Thus, on the basis of the comprehensive analysis of these metrics, although China and India are the main countries conducting ecological research on the QTP, the USA, UK and Japan produced papers of higher quality. It may be that because China and India have unique geographical advantages for carrying out ecological research on the QTP, it is easier for researchers from these two countries to carry out their research on the QTP, leading to more publications of a lower quality. However, these studies are vital for the two countries' self-interests. In addition, developed countries, including the USA, UK, and Japan, developed theories, methods, and technologies related to ecological research earlier than China or India; therefore, their research programs are more mature. Thus, the papers from these developed countries are more easily recognized by peers and cited more frequently, resulting in a greater academic influence. In general, there is no correlation between the volume and influence of ecological research publications on the QTP. However, the national influence is closely correlated with the research capacity.

3.3. Analysis of institutions

Metrics, including TP, TC, TC/TP, NC, and NC/TP, were used in the academic influence analysis of the top 20 institutions (Table 2). In addition, the country origin analysis of these affiliations was also taken into consideration.

The top 20 institutions are led by CAS, with 1269 TP, followed by Lanzhou University (Univ) with 186 TP and Beijing Normal Univ with 103 TP. These institutions are well-known research units in China. In fact, among the top 20 institutions, 16 institutions are from China and 4 institutions are from India. As the professional institution of Tibetan Plateau studies in India, GB Pant Institute of Himalayan Environment and Development (Environm & Dev) (36) was ranked eighth in TP. Thus, Chinese institutions have the main strongest QTP-related ecological research units.

Because of the obvious gap in TP values, this study did not simply analyze the TC and NC, but mainly used TC/TP and NC/TP. Sichuan Univ ranked first, with a TC/TP value of 74.63, followed by Beijing Forestry Univ at 40.85. In addition, TC/TP values of 7 institutions, including Kumaun Univ and Gansu Agriculture (Agr) Univ both exceeded the average TC/TP value (17.44) of the top 20 institutions. In contrast, China Agr Univ (7.13), Tsinghua Univ (7.02), and Lanzhou Univ (5.87) ranked in the last three positions, having TC/TP values of no more than 10. However, NC/TP values are relatively inconsistent compared with TC/TP values. For example, the Sichuan Univ NC/TP value (23.33) was last in the ranking, because 7 of 30 TP were NC. In contrast, Peking Univ and China Univ of Geosciences (Geosci) performed better, with an NC/TP value of zero. Notably, Indian agencies GB Pant Institute of Himalayan Environm & Dev and Kumaun Univ ranked 3rd and 4th, respectively. In fact, among the top 20 institutions, only 9 institutions had NC/TP values lower than the 6.03 average.

Thus, it was concluded that Chinese institutions have a relatively great influence in ecological research performed on the QTP; however, the comprehensive strengths of the different institutions are not consistent. In the future, these institutions need to continue to devote more attention to increasing the impact of their papers.

Table 2
The top 20 institutions represented by the total papers published on the ecology of the QTP in 1990–2019.

R	Institutions (1st)	Country	TP	TC	TC/TP	NC	NC/TP (%)
1	Chinese Acad Sci	China	1269	23,964	15.61	61	4.81
2	Lanzhou Univ	China	186	2573	5.87	16	8.60
3	Beijing Normal Univ	China	103	2014	33.1	7	6.80
4	Peking Univ	China	76	2627	34.46	0	0.00
5	Sichuan Agr Univ	China	53	418	29.99	6	11.32
6	Nanjing Univ	China	40	652	12.74	2	5.00
7	Wuhan Univ	China	37	439	13.17	2	5.41
8	GB Pant Inst Himalayan Environm & Dev	India	36	407	27.05	1	2.78
9	Kumaun Univ	India	34	511	34.16	1	2.94
10	Sichuan Univ	China	30	231	74.63	7	23.33
11	Univ Kashmir	India	30	396	16.41	6	20.00
12	China Univ Geosci	China	29	454	22.42	0	0.00
13	Northwest A&F Univ	China	29	264	13.96	1	3.45
14	Univ Delhi	India	29	333	13.96	3	10.34
15	China Agr Univ	China	28	444	7.13	1	3.57
16	Gansu Agr Univ	China	28	178	33.89	4	14.29
17	Beijing Forestry Univ	China	27	190	40.85	2	7.41
18	Chinese Acad Agr Sci	China	26	437	13.24	3	11.54
19	Tsinghua Univ	China	26	539	7.02	3	11.54
20	Chinese Acad Forestry	China	23	242	33.66	3	13.04
MEAN			106.95	1865.65	17.44	6.45	6.03

Abbreviations: R = Rank; TP = Total papers; TC = Times cited; NC = None cited.

3.4. Analysis of journals

As direct providers of academic research, journals play important roles in bibliometrics research. The top 10 journals with the largest TP values were obtained for analysis (Table 3). Core metrics, including TP, TC, and TC/TP, were used to evaluate the impacts of these journals. Furthermore, many new metrics, like total cumulative number of authors (TA), country with the most papers (CM), total papers of the country with the largest number of papers (TCM), TCM/TP, and the impact factor of the journal in 2019 (IF_{2019}), were developed for evaluating these journals.

The statistical results showed that excellent journals, including *PLOS ONE*, *SCIENCE OF THE TOTAL ENVIRONMENT*, and *SCIENTIFIC REPORTS*, ranked in the top 10 journals publishing manuscripts on the ecology of the QTP. *PLOS ONE* ranked first with a TP of 106 and a TC of 2380, followed by *SCIENCE OF THE TOTAL ENVIRONMENT* with a TP of 82 and a TC of 1293 and *SCIENTIFIC REPORTS* with a TP of 77 and a TC of 823. For TC/TP values, *GLOBAL CHANGE BIOLOGY* performed better, with a TC/TP value of 71.65. *AGRICULTURAL AND FOREST METEOROLOGY* and *PLOS ONE* ranked 2nd and 3rd, with values of 31.09 and 22.45, respectively. The TA value can reflect the attention to a particular journal. Using this metric, *PLOS ONE* (652), *SCIENCE OF THE TOTAL ENVIRONMENT* (591), and *SCIENTIFIC REPORTS* (500) ranked in the top three positions. A comprehensive analysis of CM, TCM, and TCM/TP metrics revealed that the countries with the most papers published in the top 10 journals were China and India. In contrast, China had nine seats while India had only one seat, which showed that China is a major force in ecological research on the QTP. In total, 92.19% of the papers in *AGRICULTURAL AND FOREST METEOROLOGY* were from China, and 90.74% of the papers in *CURRENT SCIENCE* were from India. For the other journals, the number of papers published by Chinese authors exceeded 62% of the TP published in these journals. As an internationally accepted index for evaluating the influence of journals, IF represents the comprehensive strengths of journals. Among the top 10 journals, the highest IF_{2019} was *GLOBAL CHANGE BIOLOGY* at 8.55, followed by *SCIENCE OF THE TOTAL ENVIRONMENT* at 6.551 and *AGRICULTURAL AND FOREST METEOROLOGY* at 4.651. Among these three journals, the proportions of papers published by Chinese authors were 65.31%, 81.71%, and 92.19%, respectively. Therefore, Chinese authors' ecological research papers on the QTP have been published in high-quality journals in recent years.

In summary, the results and importance of ecological research on the QTP have been recognized by internationally renowned journals. A few high-quality journals, including *GLOBAL CHANGE BIOLOGY*, *SCIENCE OF THE TOTAL ENVIRONMENT*, and *AGRICULTURAL AND FOREST METEOROLOGY* have published large numbers of papers on this research topic. As a major country in this field of study, China has published many papers in high-quality journals and made the greatest contribution to ecological research on the QTP.

3.5. Analysis of most cited papers

The subjects of papers that are highly cited often indicate research hotspots in a field. The number of times a paper is cited is often used to evaluate its academic quality (Usman and Ho, 2020). However, papers published earlier are more likely to accumulate higher TC values, which may lead to an unfair evaluation. Therefore, this study developed two new metrics, "Time Span (TS)" and TC/TS, to avoid cumulative effect-related bias (Table 4).

Only two of the 10 most highly cited papers were published in 1990–2000, while five were published in 2001–2010, and three were published in 2011–2019. Judging from the number of citations in the WOS database, the highest TC (Manel et al., 2001) was 1082. In

Table 3
Top 10 journals publishing the most papers on the ecology of the QTP in 1990–2019.

R	Journal	TP	TC	TC/TP	TA	CM	TCM	TCM/TP	IF_{2019}
1	*PLOS ONE*	106	2380	22.45	652	China	72	67.92	2.740
2	*SCIENCE OF THE TOTAL ENVIRONMENT*	82	1293	15.77	591	China	67	81.71	6.551
3	*SCIENTIFIC REPORTS*	77	823	10.69	500	China	68	88.31	3.998
4	*JOURNAL OF MOUNTAIN SCIENCE*	75	435	5.80	346	China	47	62.67	1.550
5	*AGRICULTURAL AND FOREST METEOROLOGY*	64	1990	31.09	459	China	59	92.19	4.651
6	*ECOLOGICAL INDICATORS*	57	998	17.51	342	China	40	70.18	4.229
7	*ECOLOGY AND EVOLUTION*	55	373	6.78	334	China	45	81.82	2.392
8	*CURRENT SCIENCE*	54	683	12.65	191	India	49	90.74	0.725
9	*GLOBAL CHANGE BIOLOGY*	49	3511	71.65	440	China	32	65.31	8.555
10	*REMOTE SENSING*	49	548	11.18	307	China	43	87.76	4.509

Abbreviations: R = Rank; TP = Total papers; TC = Times cited; TA = Total cumulative number of authors; CM = Country with the most papers; TCM = Total papers of the country with the largest number of papers; IF_{2019} = Impact factor of the journal in 2019.

Table 4
Top 10 most frequently cited academic papers published on the ecology of the QTP in 1990–2019.

R	TI	TC	PY	TS	TC/TS	RA	Reference
1	Evaluating presence-absence models in ecology: the need to account for prevalence	1082	2001	19	56.95	Biodiversity & Conservation; Environmental Sciences & Ecology	Manel et al., 2001
2	Bioprospecting for microbial endophytes and their natural products	933	2003	17	54.88	Microbiology	Strobel and Daisy, 2003
3	Origin, dispersal, cultivation and variation of rice	683	1997	23	29.70	Biochemistry & Molecular Biology; Plant Sciences	Khush, 1997
4	Elevation-dependent warming in mountain regions of the world	669	2015	5	133.80	Environmental Sciences & Ecology; Meteorology & Atmospheric Sciences	Pepin et al., 2015
5	Proteins Under Pressure - The Influence of High Hydrostatic-Pressure on Structure, Function And Assembly of Proteins And Protein Complexes	537	1994	26	20.65	Biochemistry & Molecular Biology	Gross and Jaenicke, 1994
6	Greening of the Earth and its drivers	502	2016	4	125.50	Environmental Sciences & Ecology; Meteorology & Atmospheric Sciences	Zhu et al., 2016
7	The Melting Himalayas: Cascading Effects of Climate Change on Water, Biodiversity, and Livelihoods	401	2009	11	36.45	Biodiversity & Conservation; Environmental Sciences & Ecology	Xu et al., 2009
8	Experimental warming causes large and rapid species loss, dampened by simulated grazing, on the Tibetan Plateau	291	2004	16	18.19	Environmental Sciences & Ecology	Klein et al., 2004
9	Grazing intensity alters soil respiration in an alpine meadow on the Tibetan plateau	266	2004	16	16.63	Agriculture	Cao et al., 2004
10	The impacts of climate change and human activities on biogeochemical cycles on the Qinghai-Tibetan Plateau	250	2013	7	35.71	Biodiversity & Conservation; Environmental Sciences & Ecology	Chen et al., 2013

Abbreviations: TI = Title; R = Rank; TC = Times cited; PY = Published year; TS = Time span; TC/TS = Citations per year; RA = Research area.
Note: Time span refers to the period from the year of publication to 2019. The TC values used in this table were gathered from the Web of Science on September 2, 2020.

addition, five papers (Strobel and Daisy, 2003; Khush, 1997; Pepin et al., 2015; Gross and Jaenicke, 1994; Zhu et al., 2016) have been cited more than 500 times, making them high-impact papers in this research field. However, when considering the TC/TS metric, an article published in 2015 (Pepin et al., 2015) ranks first, with a value of 133.8, followed by an article published in 2016 (Zhu et al., 2016), with a value of 125.5. Papers published in 2001–2009 (Manel et al., 2001; Strobel and Daisy, 2003; Xu et al., 2009) ranked 3rd to 5th, with values of 56.95, 54.88 and 36.45, respectively. Therefore, on the one hand, papers (Pepin et al., 2015; Zhu et al., 2016) have been recognized by their peers, while, on the other hand, the numbers of citations of high-quality, high-impact papers have no absolute correlations with the length of time since publication. In fact, the most critical factor affecting this indicators are still the quality and content of the paper. For example, the 6th paper (Zhu et al., 2016) is a letter published on April 25, 2016, which uses three long-term satellite leaf area index records and 10 global ecosystem models to investigate four key drivers of leaf area index trends during 1982–2009. It determined that climate change leads to the greening of high-latitude regions and the QTP. The 4th paper (Pepin et al., 2015) is a review article published on April 23, 2015. It focuses on the impact of elevation-dependent warming on mountain ecosystems and biodiversity, and suggests that improvements in observations, satellite remote sensing, and model simulation will increase the understanding of mountain temperature trends and their control mechanisms. Thus, the number of times a paper is cited depends on the value of the paper itself.

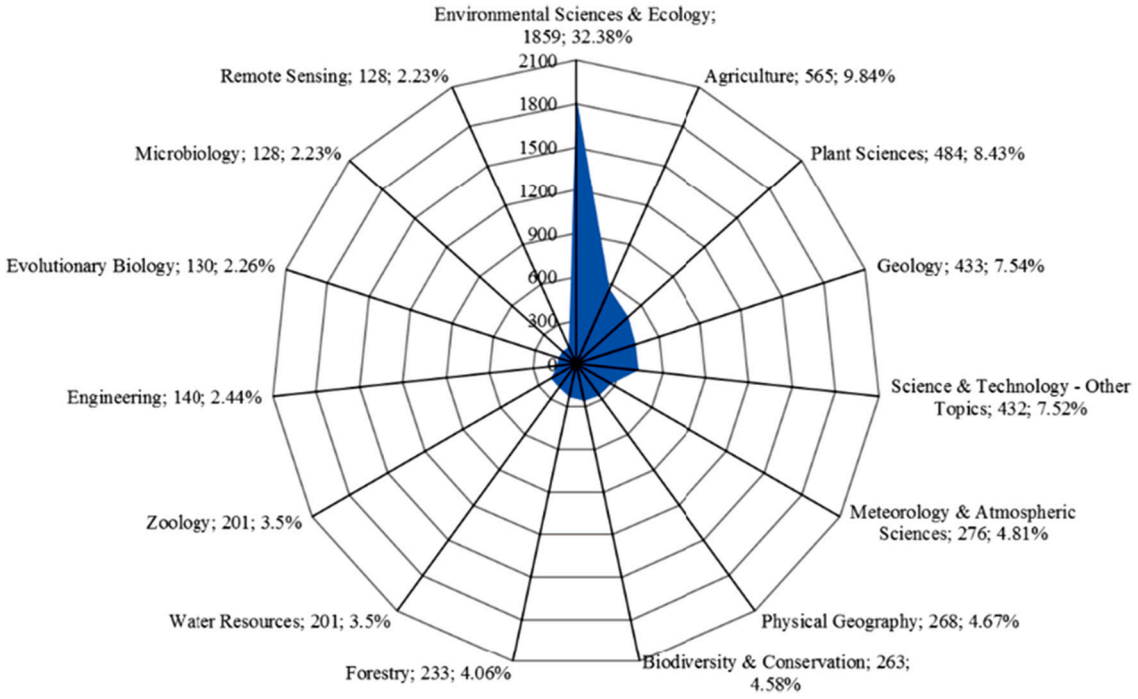

Fig. 3. Top 15 ecological research areas of the QTP in 1990–2019.

3.6. Analysis of research areas

Journals and books covered by the WOS are assigned to at least one category. Each category is mapped to at least one research area. This study filtered the top 15 research areas in terms of TP to determine which areas were the foci (Fig. 3).

The same article in the WOS database will be placed in different research areas. Therefore, the number of papers in the top 15 research areas reached 5741, exceeding the TP (4315). Statistics showed that the field of 'Environmental Sciences & Ecology' ranked first with 1859 papers. It accounted for 32.38% of the 5741 papers in the top 15 research areas. Other research areas that accounted for a relatively high proportions were 'Agriculture' (565; 9.84%), 'Plant Sciences' (484; 8.43%), 'Geology (433; 7.54%), and 'Science & Technology-Other Topics' (432; 7.52%). Papers on these research' areas all exceeded 430, accounting for more than 7.4% of the 5741 total. Research areas with more than 200 papers included 'Meteorology & Atmospheric Sciences' (276), 'Physical Geography' (268), 'Forestry' (233), 'Water Resources' (201), and 'Zoology' (201).

An analysis of these areas revealed that ecological research on the QTP is interdisciplinary and comprehensive. For this research, not only is the systematic ecological theory needed to support related questions, but also the advantages and strengths of other disciplines need to be integrated to support more systematic, specific, and in-depth research and analyses. By analyzing the top 15 research areas, we found that the proportions of 'Agricultural' and 'Plant Sciences' were 9.84% and 8.43%, respectively, indicating that the fields of 'Environmental Sciences & Ecology', 'Agriculture', and 'Plant Sciences' have high degrees of integration characteristics in this field. Agricultural and Plant sciences have played full supporting and complementary roles. In fact, for extremely ecologically sensitive areas like the QTP, all the agricultural production activities have huge impacts on the regional ecology. Therefore, these areas have received the attention of researchers. In addition, plant scientific research is an important part of ecological environmental research. For example, various vegetation change indicators, such as NDVI (normalized difference vegetation index), are used in the assessment of the ecological environment in the QTP. As the "Roof of the World" and "Third Pole" (Cheng et al., 2019; Yao et al., 2012), the ever-changing characteristics of the geological environment also affect the ecological environment. An adequate research laboratory studying the geological background guarantees the investigation of one of the important areas of ecological research. Furthermore, with researchers' interests in emerging technologies, methods, software, and tools in recent years, 'Science & technology-other Topics' has gradually become a hot topic in this field. Additionally, the technological progress has promoted the rapid development of ecological research on the QTP. In fact, as we described in the introductory section, the QTP is known as the "Asian Water Tower" and "Climate Amplifier", which explains why the Top 15 research areas include 'Meteorology & Atmospheric Sciences', 'Physical Geography', 'Forestry', and 'Water Resources'. In short, ecological research on the QTP will use multi-disciplinary approaches in the future.

3.7. Analysis of international cooperation

This study analyzed international cooperation from three dimensions, authors, institutions, and countries (Figs. 4–6). In the network visualization of VOSviewer software, items can be selected by cooperation or co-occurrence thresholds and represented by a combination of labels and circles. The sizes of the label and circle are determined by the weight of the item. The larger the label and circle, the greater the weight of the item. In addition, to avoid overlapping labels, some items' labels may not be displayed. The color of the items is determined by the cluster to which they belong. The line between each item indicates the strength of the link. A value called "Total link strength" represents the importance and connectivity of items in the network. In the VOSviewer software, the "Total link strength" attribute is one of the standard weight attributes that indicates the total strength of the links of an item with

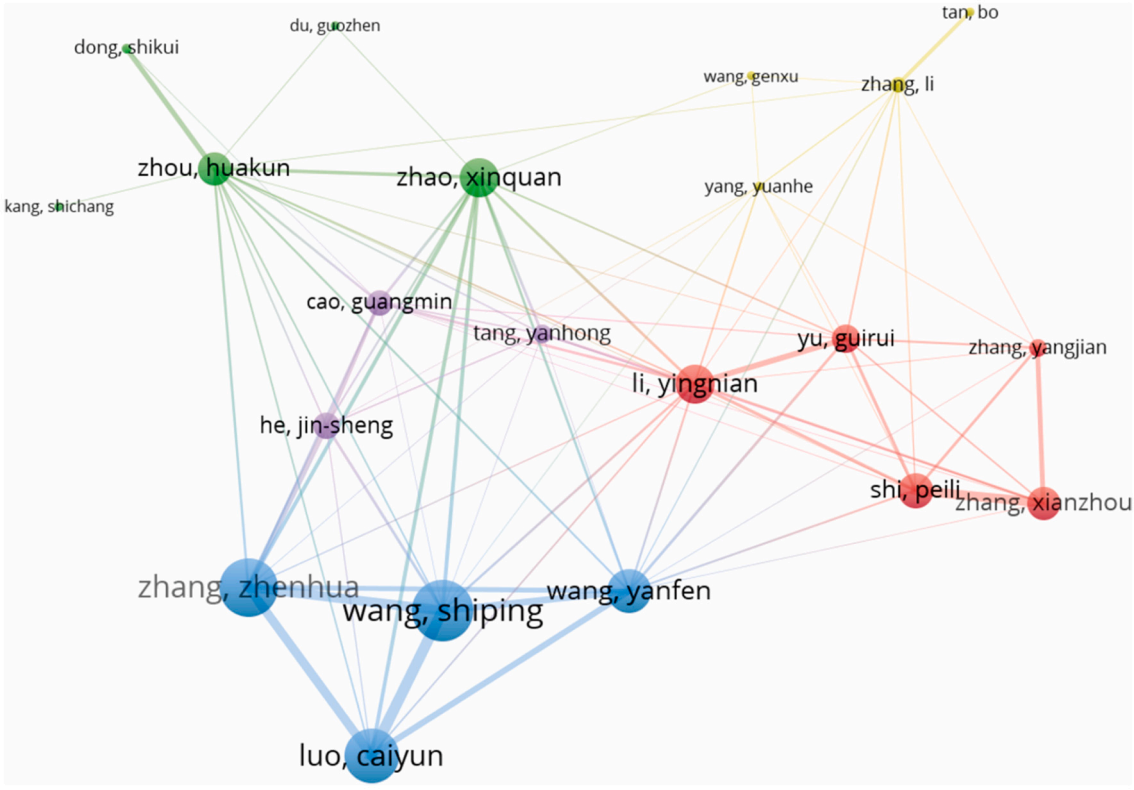

Fig. 4. Co-authorship network map of authors who published on the ecology of the QTP in 1990–2019.

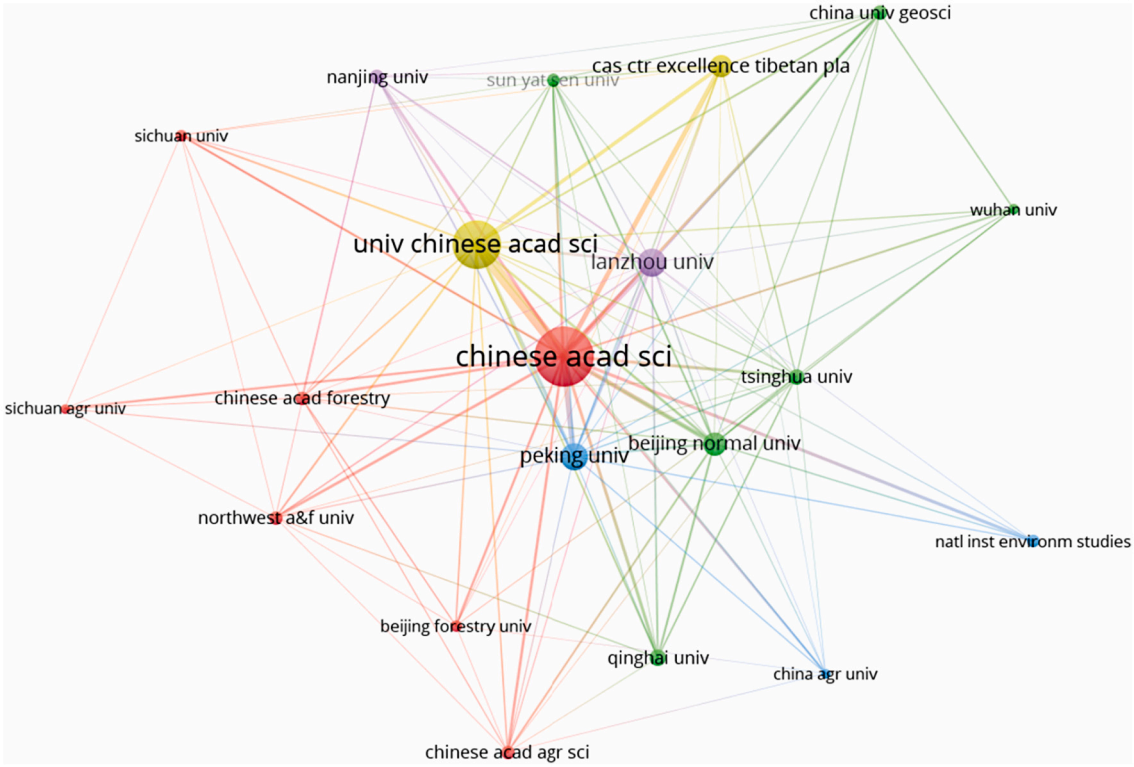

Fig. 5. Co-authorship network map among institutions that published on the ecology of the QTP in 1990–2019.

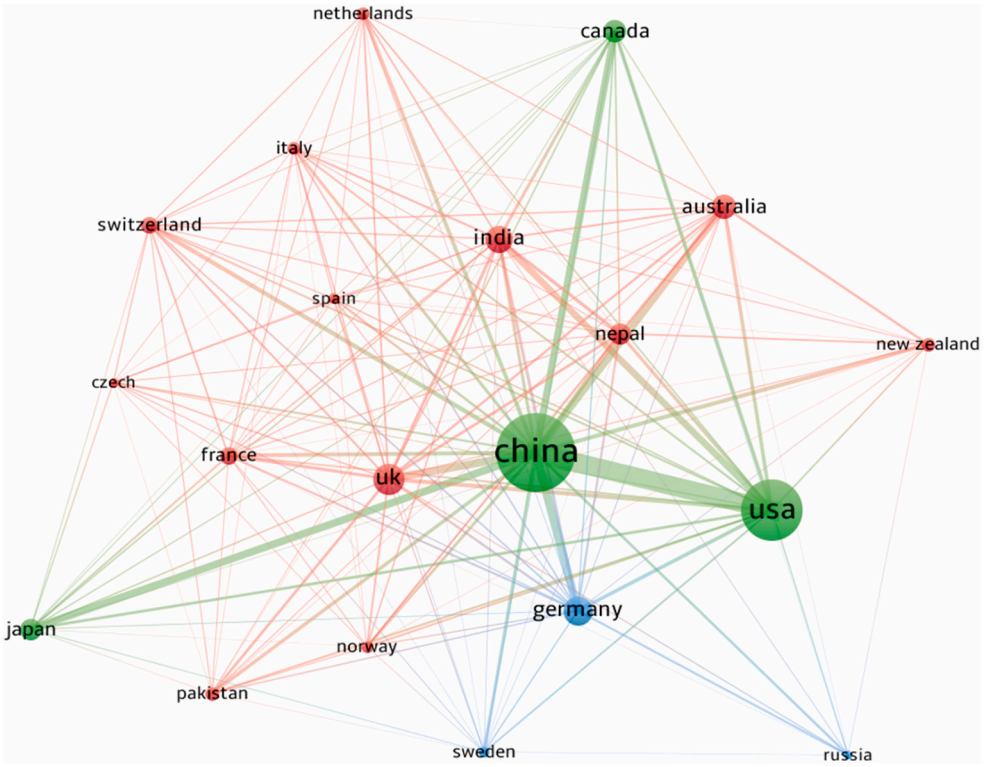

Fig. 6. Co-authorship network map among countries that published on the ecology of the QTP in 1990–2019.

other items. For example, in the case of co-authorship links between researchers, the "Total link strength" attribute indicates the total strength of the co-authorship links of a given researcher with other researchers. It should be noted that not all the papers in this section were analyzed using first authors.

3.7.1. *Authors cooperation analysis*

In total, 21 scholars with outstanding research were selected by

setting the minimum number threshold of papers for an author as 30. They were automatically divided into five clusters using the co-authorship module of the VOSviewer software (Fig. 4).

The first cluster (red circle) formed a cooperative network represented by five people, Li Yingnian, Shi Peili, Yu Guirui, Zhang Xianzhou, and Zhang Yangjian. The second cluster (green circle) also had five high-yield authors, Dong Shikui, Du Guozhen, Kang Shichang, Zhao Xinquan, and Zhou Huakun. The four representative authors of the third cluster (blue circle) were Luo Caiyun, Wang Shiping, Wang Yanfen, and Zhang Zhenhua. The fourth cluster (yellow circle) had four main authors, Tan Bo, Wang Genxu, Yang Yuanhe, and Zhang Li. In the fifth cluster (purple circle), the representative population was relatively small, with only three authors, Cao Guangmin, He Jin-Sheng, and Tang Yanhong. In addition, the sizes of all the circles in this study represent their total link strength values, which indicate their importance and influence (Fig. 4). Therefore, seven authors, Wang Shiping, Zhang Zhenhua, Luo Caiyun, Wang Yanfen, Li Yingnian, Zhao Xinquan, and Shi Peili, were important members of the author network of ecological research on the QTP.

3.7.2. Institutional cooperation analysis

The minimum threshold of papers for an institutions was set at 48, resulting in 20 major institutions (Fig. 5).

The top 20 institutions were divided into five distinct clusters, which were closely related (full names of the institutions mentioned below are omitted). The first cluster (red circle) had the largest cooperation network, including seven institutions, Beijing Forestry Univ, Chinese Acad Agr Sci; Chinese Acad Forestry, CAS; Northwest A&F Univ, Sichuan Agr Univ, and Sichuan Univ. The number of institutions in the second cluster (green) was six, Beijing Normal Univ, China Univ Geosci, Qinghai Univ, Sun Yat Sen Univ, Tsinghua Univ, and Wuhan Univ. The third cluster (blue circle) contained the three main institutions, China Agr Univ, Natl Inst Environm Studies, and Peking Univ. The fourth cluster (yellow circle) had only two institutions, CAS Ctr Excellence Tibetan Pla and Univ Chinese Acad Sci. Lanzhou Univ and Nanjing Univ were classified into the fifth cluster (purple circle). For the entire co-authorship network map, six institutions, CAS, Univ Chinese Acad Sci, Lanzhou Univ, Peking Univ, Beijing Normal Univ, and CAS Ctr Excellence Tibetan Plateau Earth Sci, had the largest total link strength values in the network, which means that these institutions represent the most important connection nodes.

The analysis of the cooperation network between these authors and institutions revealed that high-output authors' and core institutions were more consistent. For example, most of the researchers in the most influential author cluster (blue) are from CAS. In addition, it was easier to form a closer cooperation network by unifying the author contents of the institutions. In the cooperation networks of different institutions, there were individual authors who played important linking roles; consequently, it was necessary to pay attention these personnel in the cooperation network.

3.7.3. Country cooperation analysis

In the analysis of country cooperation, 20 countries were selected. In the VOSviewer software, the threshold number of papers per country was 43. These countries were divided into four clusters (Fig. 6).

The first cluster (red circle) was the largest, containing 13 countries, Australia, Czech Republic, France, India, Italy, Nepal, Netherlands, New Zealand, Norway, Pakistan, Spain, Switzerland, and the UK. The second cluster (green circle) contained four countries, Canada, Japan, China, and the USA. The third cluster (blue circle) included Germany, Russia, and Sweden. Among total link strength values, China, the USA, Germany, the UK, and India had the greatest weights in the network, and their roles and influence were the most obvious.

In summary, for author collaboration, Wang Shiping, Zhang Zhenhua, Luo Caiyun, Wang Yanfen, Li Yingnian, Zhao Xinquan, and Shi Peili are important authors of ecological research on the QTP. For institutional cooperation, CAS, Univ Chinese Acad Sci, Lanzhou Univ, Peking Univ, Beijing Normal Univ, and CAS Ctr Excellence Tibetan Plateau Earth Sci formed the strongest influence and cooperation network. At the country cooperation level, China, the USA, and Germany had the greatest weights in the international cooperation network. The findings of important authors will help institutions attract future talent. Cooperation among countries is necessary for ecological research on the QTP and for better future research development.

3.8. Analysis of keywords and detection of burst words

Author keywords can provide research information about the author's or institution's preference for a certain topic, and they are considered to have high research values (Wang et al., 2012). The minimum number of occurrences' threshold of a keyword was set as 29 in the co-occurrence module of VOSviewer. After cleaning and merging some similar keywords, a co-occurrence network of 50 author keywords was mapped. All these keywords were divided into five clusters having complex relationships (Fig. 7). In addition, the co-occurrence times (OT) and co-occurrence links (CL) of all the author keywords are shown in Table 5.

The first cluster (red circle) contained the largest number of keywords, with 16 items. The main keywords were Adaptation, Biodiversity, Biogeography, China, Climate change, Conservation, Distribution, Ecology, Ecosystem, Ecosystem services, Forest, Himalaya, India, Land-use change, Nepal, and Taxonomy. They represent the topics of ecosystem services, biodiversity research, forest protection, climate change adaptation, and other related topics in the context of climate change. In comparison, the second cluster (green circle) had 10 keywords, Alpine ecosystem, Carbon cycle, Carbon sequestration, Degradation, Global warming, Grassland, Grassland degradation, Soil organic Carbon, Soil properties, and Wetland. The topics indicated by this group of keywords were alpine ecosystem changes, grassland and wetland degradation, and carbon cycle processes, as they relate to global warming. The third (blue circle) and the fourth (yellow circle) clusters each had nine keywords. Among them, the core terms of the third cluster were Aboveground changes, Alpine levels, Changes, Elevation gradient, Net primary productivity, Productivity, Species diversity, and Species richness. These keywords focused more on assessing species abundance and biodiversity, as well as biomass and productivity at high altitudes. The fourth cluster consisted of nine keywords, Alpine meadow, Ecosystem respiration, Eddy covariance, Evapotranspiration, Grazing, Qinghai–Tibetan Plateau, Remote sensing, Soil respiration, and Warming, indicating that the research topics were alpine meadow, ecosystem respiration, evapotranspiration, soil respiration, and grazing effects on the QTP under global warming conditions. The fifth cluster (purple circle) had the fewest keywords, Altitude, NDVI, Permafrost, Precipitation, Temperature, and Vegetation. The subject of these keywords was the influence of precipitation, temperature, and vegetation changes on permafrost in high altitude areas.

The OT and CL rankings of the author's keywords indicated that some high frequency keywords, such as Qinghai–Tibetan Plateau, Himalaya, and China, have limited scientific meaning in the research trend analysis (Table 5). Therefore, this study developed a new metric (CL/OT) to reflect the value of CL when the keywords OT value was only 1.

The analysis, as shown in Table 5, revealed that the top 15 keywords with the highest CL/OT values were Grazing (3.85), Precipitation (3.46), Soil moisture (3.25), Aboveground biomass (3.13), Temperature (3.06), Ecosystem respiration (3.05), Net primary productivity (3.02), Forest (3.00), Permafrost (2.96), Warming (2.93), Carbon cycle (2.90), Ecosystem (2.88), Soil organic carbon (2.81), Global warming (2.78), and Wetland (2.67). These keywords and the research directions they represent were consistent with the current overall research hotspots on the QTP.

The strongest citation bursts are shown in Fig. 8.

The top 20 keywords, except those representing the research countries, China and India, had important research direction significance.

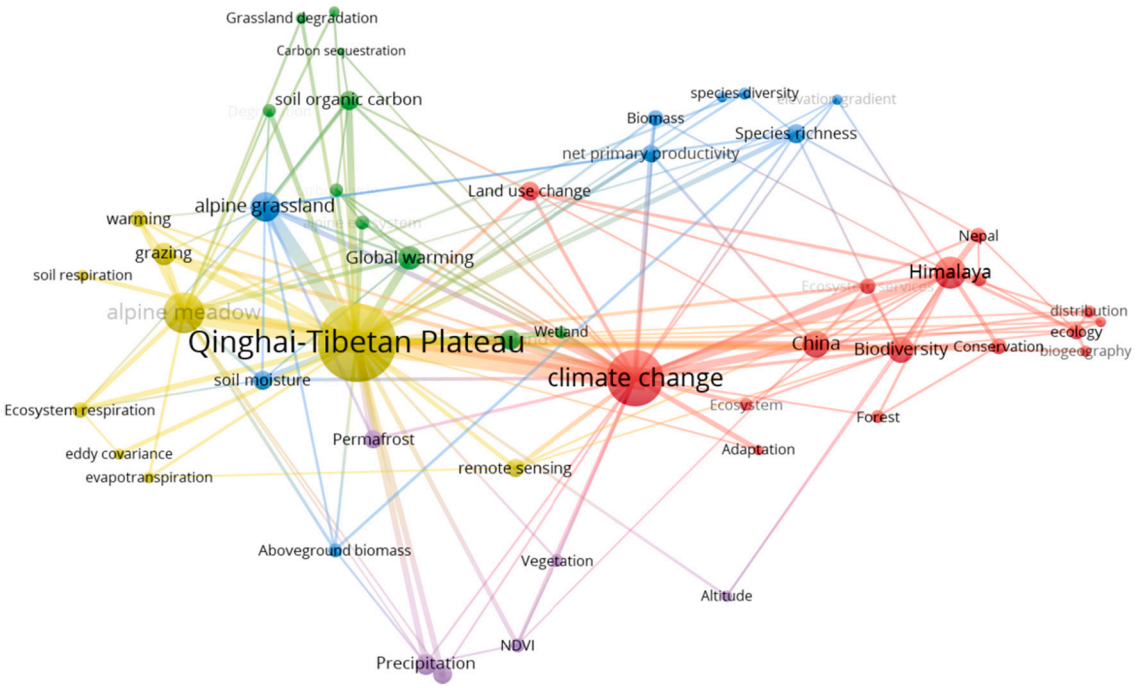

Fig. 7. Author keyword co-occurrence network in papers published on the ecology of the QTP in 1990–2019.

Table 5
Author keywords with the most occurrences and their co-occurrence link strengths in papers published on the ecology of the QTP in 1990–2019.

Keywords	OT	CL	CL/OT	keywords	OT	CL	CL/OT
Qinghai-Tibetan Plateau	674	1368	2.03	alpine ecosystem	45	104	2.31
climate change	367	836	2.28	warming	43	126	2.93
alpine meadow	214	508	2.37	NDVI	41	104	2.54
Himalaya	200	356	1.78	Ecosystem respiration	40	122	3.05
China	136	266	1.96	Vegetation	35	88	2.51
alpine grassland	121	314	2.60	eddy covariance	35	74	2.11
Biodiversity	115	254	2.21	Degradation	34	88	2.59
Global warming	77	214	2.78	Adaptation	34	64	1.88
remote sensing	73	148	2.03	Taxonomy	33	64	1.94
Land use change	71	162	2.28	species diversity	32	82	2.56
Conservation	70	116	1.66	soil respiration	32	72	2.25
grassland	67	174	2.60	Grassland degradation	32	70	2.19
Species richness	62	158	2.55	Ecosystem	32	92	2.88
India	62	98	1.58	distribution	32	78	2.44
Ecosystem services	61	122	2.00	Aboveground biomass	32	100	3.13
soil organic carbon	59	166	2.81	carbon cycle	31	90	2.90
ecology	59	120	2.03	Wetland	30	80	2.67
temperature	53	162	3.06	Soil properties	30	62	2.07
grazing	53	204	3.85	Forest	30	90	3.00
Precipitation	52	180	3.46	elevation gradient	30	66	2.20
Nepal	51	114	2.24	biogeography	30	72	2.40
Permafrost	50	148	2.96	Altitude	30	72	2.40
soil moisture	48	156	3.25	Productivity	29	68	2.34
net primary productivity	47	142	3.02	evapotranspiration	29	76	2.62
Biomass	46	122	2.65	Carbon sequestration	29	44	1.52

Abbreviations: OT = co-occurrence times; CL = co-occurrence links.

Among these keywords, Soil organic carbon had the greatest burst strength value (6.9205), followed by Grazing (5.7705) and Ecology (5.77). The keywords with burst strength values greater than 5 included Himalaya (5.2248), Nitrogen addition (5.222), Soil temperature (5.0202), and Western Himalaya (5.0034). For the start and end times, there were 11 words after 2010 and 5 words after 2015. The three words maintained in 2019 were Nitrogen addition, Western Himalaya, and Grazing intensity. These words are also considered to represent current hotspots of ecological research on the QTP.

Based on the synthesis of the above three sections, this study summarizes the current hotspots and research keywords in ecological research on the QTP, as follows: (1) Ecosystem services, biodiversity research, forest protection, and climate change adaptation under the background of climate change; (2) Alpine ecosystem changes, Grassland and wetland degradation, carbon cycling, and other changes related to global warming; (3) Evaluation of species abundance, biodiversity, biomass, and productivity in high altitude areas; (4) Effects of global warming on alpine meadows, ecosystem respiration, evapotranspiration, soil respiration, and grazing; and (5) Effects of precipitation, temperature, and vegetation changes on permafrost in high altitude areas. In these areas, the most important keywords were Grazing, Precipitation, Soil moisture, Aboveground biomass, Temperature,

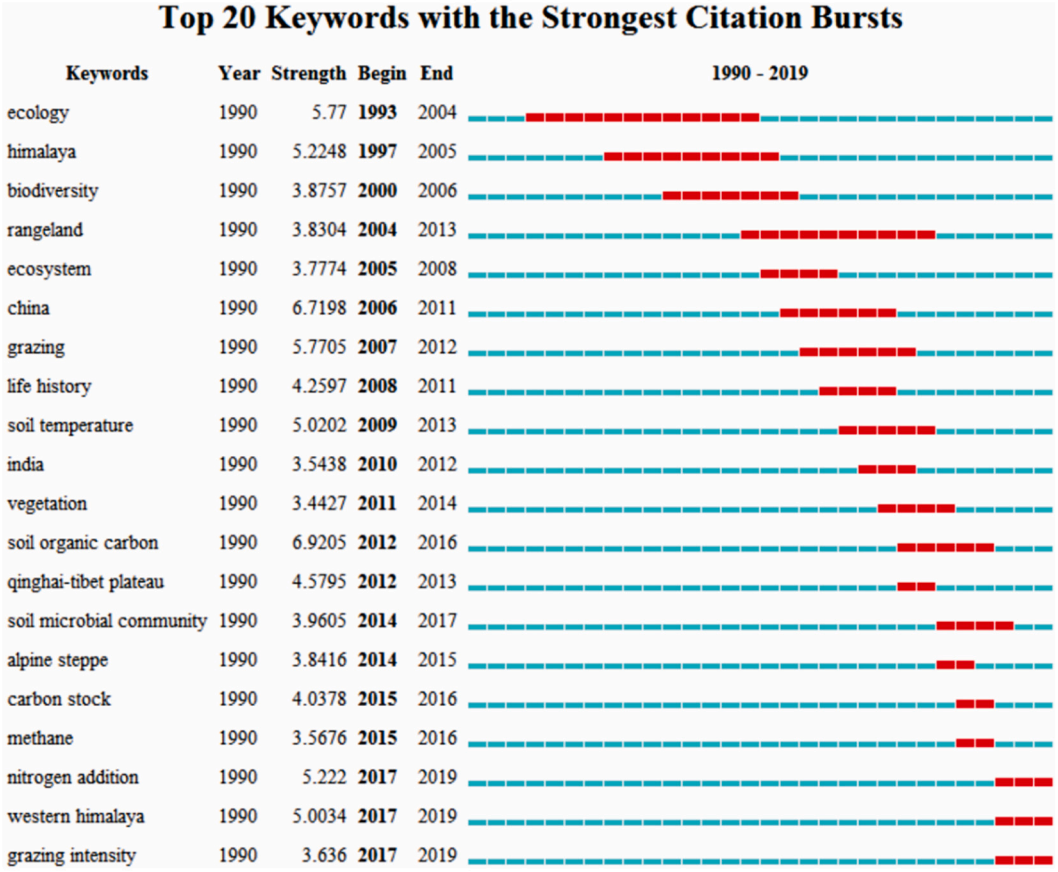

Fig. 8. Top 20 keywords with the strongest citation bursts for publications on the ecology of the QTP in 1990–2019.

Ecosystem response, Net primary productivity, Forest, Permafrost, Warming, Carbon cycle, Ecosystem, Soil organic carbon, Global warming, and Wetland. In addition, the three keywords Nitrogen Addition, Western Himalaya, and Grazing intensity received special attention from 2017 to 2019.

3.9. Topic extraction based on abstract text deep learning

To clarify the topic characteristics of ecological research on the QTP, this study extracted abstracts from 4315 papers, obtained the top six topics and their topic keywords, and weighted them using the text mining function of KNIME. The 10-year periods were the basic divisions for the research papers in this study. However, the numbers of TP (1990–1999: 122; 2000–2009: 595; 2010–2019: 3598) revealed a serious imbalance when the analysis was performed using the 10-year time scale. In addition, because ecology-related theories, methods, and techniques significantly progressed from 2010 to 2019, it was necessary to further refine the research topic analysis in this decade using a 5-year time scale (2010–2014: 1079; 2015–2019: 2968). Therefore, to balance the number of papers in different time periods and refine the ecological topics analysis in the last decade (2010–2019), this study divided the past 30 years into four time periods. For ease of analysis, these four time periods were designated A (1990–1999), B (2000–2009), C (2010–2014), and D (2015–2019) (Fig. 9), by referring to the TP growth trend shown in Fig. 2. The abstracts were also divided into four classes according to the timeframes. Then, this study conducted a characteristics analysis of the research topics in the four periods to reveal the changes and dynamics of the ecological research on the QTP and provide relevant references (Fig. 9; Table 6).

As shown in Fig. 9, there are differences and similarities among the topic keywords present in the different time periods. The top five topic keywords were forest, nutrient, habitat, plantation, and energy in 1990–1999. However, all the top five keywords changed, being soil, CO_2, temperature, plant, and China, in 2000–2009. In contrast, two topic keywords, soil and plant, were retained in 2010–2014, and the new hot topic keywords were change, climate, and vegetation. In the last five years (2015–2019), the keywords plant, change, and vegetation were still prominent, while temperature and forest were once again top-five keywords. Therefore, under the background of climate warming and temperature increase, changes in forests, vegetation, soil, and other elements, as well as carbon dioxide emissions, were the core issues of ecological research on the QTP in recent years.

According to the topic keywords listed in Table 6 and their weights, this study summarized the research topics of the four different periods, as follows:

Topics in 1990–1999: (1) Relationship between community population and water resources on the QTP; (2) Forest ecosystem nutrients and soil research; (3) Habitat and forest cover in high altitude areas; (4) Modeling of river and environmental changes in mountainous areas of the QTP; (5) Forest system biome, evergreen, and coral studies; and (6) Relationship between human grazing and wildlife habitat.

Topics in 2000–2009: (1) Forest resource protection and community land management; (2) Habitat distribution and species diversity in China; (3) High altitude plant seed resources and flower pollination in plateau regions; (4) Soil biomass and carbon concentrations in forests and grasslands; (5) Model construction of vegetation, water resources, and lakes in the context of climate change in the plateau region of China; and (6) Soil carbon flux under the background of temperature change.

Topics in 2010–2014: (1) Forest conservation, land resource management, and biodiversity; (2) Changes in grassland carbon, nitrogen, and water content in the context of warming temperatures; (3) Effects of community grazing behavior on vegetation and grassland species

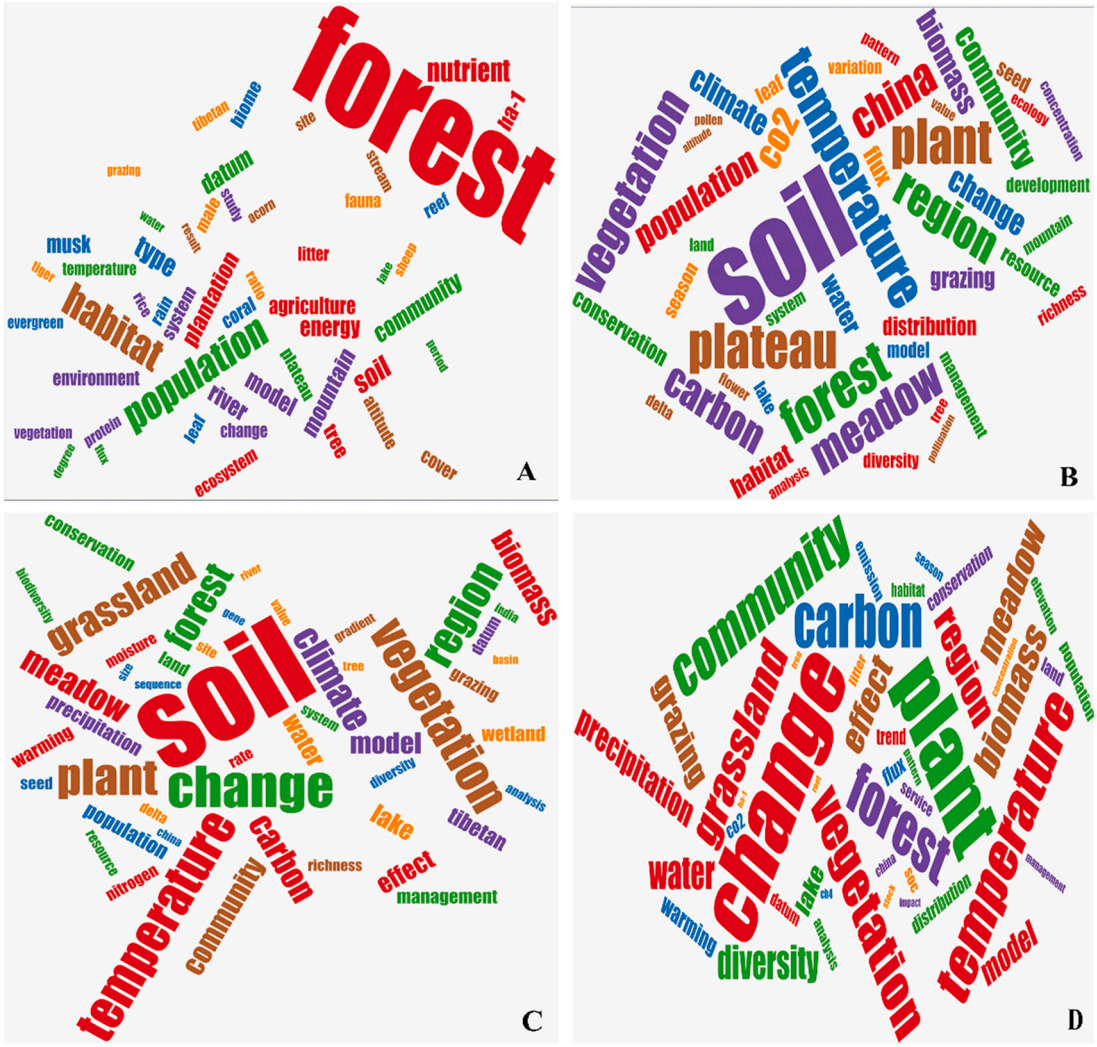

Fig. 9. Topic word clouds of ecological research on the QTP in 1990–2019. A: 1990–1999; B: 2000–2009; C: 2010–2014; D: 2015–2019.

abundance; (4) Modeling of the influence of precipitation and temperature on the vegetation and grassland of the QTP under the background of climate change; (5) Germplasm resources and diversity in Tibet; and (6) Water resource storage in rivers, lakes, wetlands, and forest areas of the QTP.

Topics in 2015–2019: (1) Analysis of the relationship between lake, community distribution, and habitat in high altitude areas; (2) Variation trend and scenario analysis of vegetation and grassland under different precipitation and temperature backgrounds; (3) Effects of community grazing behavior on vegetation and biodiversity; (4) Significance of forest protection, land resources, water resources management, and ecological service values in China; (5) Changes in grassland carbon flux and carbon emissions caused by climate warming; and (6) Forest biomass and the role of soil organic carbon in carbon management.

Topics A-1 and C-6 focused on water resources of the QTP; A-3, B-5, and C-1 focused on forest resources, community land management, and regional habitats; A5, B-2, C-1, and D-1 focused on biodiversity and biological communities; A-6, C-3, and D-3 focused on grazing behavior and its impacts on vegetation, grassland, biodiversity, and wildlife habitats; B-3 and C-5 focused on the diversity of planting resources on the QTP; B-4 and D-6 focused forest and grassland biomass and soil carbon concentration; B-5, C-4, and D-2 focused on the influence of precipitation and temperature on forest and grassland under the background of climate change; and B-6, C-2, and D-5 focused on the carbon and nitrogen emissions of grassland under the background of climate change. D-4 discussed the relationship between forest protection, land resources, water resources management, and the values of ecosystem services, indicating that the significance of ecosystem services is now being evaluated. This comprehensive analysis showed that the topics of ecological research on the QTP have both changed and been maintained over this 30-year period. Research on the characteristics of natural elements, such as forests, soils, and rivers, has long been a hot topic in this area. However, with increased climate warming, research has focused on the severe challenges brought about by rising temperatures, including soil carbon flux, water resource reserves, precipitation changes, lake evolution, carbon emissions, and governance. In addition, with the increase in human activities on the QTP, the relationships between human communities and the natural elements have also attracted attention. The relationship between human activities (such as uncontrolled grazing behavior) and factors such as forests, soil, water, and organisms has become a research hotspot. Furthermore, recent studies have discussed the relationship between the ecological service values and natural resource management, which is of great significance to the harmonious coexistence of man and nature in the future. These conclusions helped reveal the ecological research hotspots on the QTP.

Thus, climate change and increasing human activities have become the two most important driving factors of ecosystem changes in the QTP. Under their influence, many other factors, such as forest, grassland, water, species, and land, are facing severe challenges. Combining the characteristics of papers published in the past 30 years with their topic

Table 6
Topic keywords of ecological research on the QTP in 1990–2019.

Temporal interval	Topics	Topic Keywords |weight
1990–1999	1	population|47;plateau|36;temperature|33;community|27;datum|23;water|21;flux|20;lake|20;period|20;degree|20
	2	forest|99;nutrient|66;plantation|54;energy|53;ha-1|48;agriculture|45;tree|42;litter|36;ecosystem|36;soil|35
	3	habitat|45;cover|38;forest|36;altitude|34;site|30;datum|29;stream|28;acorn|26;community|24;result|22
	4	mountain|52;river|52;model|52;system|39;environment|38;change|35;protein|30;rice|30;vegetation|28;study|28
	5	forest|192;musk|48;biome|40;coral|38;leaf|36;type|36;reef|34;rain|34;evergreen|29;soil|27
	6	habitat|56;population|51;fauna|36;male|34;ratio|30;tibetan|27;sheep|26;type|25;tiger|24;grazing|20
2000–2009	1	forest|330;conservation|257;resource|224;development|199;region|186;system|181;management|180;mountain|177;land|174;community|167
	2	habitat|293;distribution|263;diversity|196;richness|187;pattern|170;population|167;ecology|163;china|161;analysis|157;tree|151
	3	plant|403;population|242;seed|228;delta|167;flower|158;plateau|158;value|145;pollen|126;altitude|110;pollination|106
	4	soil|1166;biomass|355;forest|322;grazing|292;meadow|285;plant|275;vegetation|231;community|225;carbon|175;concentration|152
	5	china|388;region|384;climate|373;change|371;vegetation|360;plateau|312;water|293;model|214;temperature|205;lake|203
	6	co2|450;temperature|440;carbon|334;meadow|285;flux|280;soil|228;leaf|223;season|207;plateau|196;variation|178
2010–2014	1	region|524;forest|506;conservation|460;management|447;land|430;system|326;change|318;resource|308;india|283;biodiversity|271
	2	soil|3474;carbon|938;temperature|652;meadow|595;biomass|497;warming|451;effect|373;nitrogen|363;rate|354;moisture|338
	3	plant|1364;community|764;grassland|635;vegetation|441;grazing|433;biomass|335;meadow|335;richness|331;effect|312;gradient|271
	4	change|1258;climate|1014;vegetation|979;temperature|828;model|727;precipitation|501;region|483;grassland|472;datum|391;tibetan|372
	5	population|523;seed|388;diversity|311;analysis|264;china|249;gene|245;size|243;sequence|218;region|212;tibetan|197
	6	lake|664;water|649;forest|577;wetland|502;site|304;delta|296;tree|269;value|266;basin|246;river|224
2015–2019	1	lake|1434;community|1229;diversity|1097;distribution|1038;population|982;habitat|881;elevation|860;analysis|857;pattern|715;plant|664
	2	change|2504;vegetation|2302;temperature|2301;precipitation|1769;model|1686;water|1198;trend|1033;region|975;datum|939;grassland|921
	3	plant|3803;grazing|1902;community|1813;grassland|1648;meadow|1436;effect|1401;biomass|1216;diversity|969;change|774;vegetation|632
	4	change|1450;region|1285;forest|1205;conservation|1025;land|991;service|884;water|858;china|764;management|676;impact|635
	5	carbon|1418;warming|1255;flux|1128;co2|982;emission|892;season|807;temperature|805;effect|666;meadow|664;ch4|658
	6	forest|1931;carbon|1777;biomass|1044;soc.|879;litter|860;tree|643;stock|614;concentration|614;root|580;ha-1|552

analysis results, the following main ecological research areas on the QTP are proposed for the future:

(1) Focus on frontier hotspots and promoting the faster development of ecological research on the QTP.

The main research areas on the QTP have focused on climate change adaptation, carbon cycling and emissions, biodiversity change and prediction, ecosystem services, the impact of global change on ecological elements, and the impact of human activities on ecology. Popular topics in the 5 years from 2015 to 2019 included scenario-based analyses of ecological effects of climate change on high-altitude lakes, grazing behavior and impact, forest protection, ecological service assessment, soil carbon fluxes, and carbon management. It is recommended that researchers continue to focus on these research topics on the QTP to promote the faster development of research in these areas.

(2) Continue to promote quantitative research on the effects of climate change and human activities on key ecosystem factors, improve the predictive ability and levels of relevant factors at different time scales, and improve research on ecological risk responses in the QTP.

With continuous improvements in technology and forecasting models, more ecological elements of the QTP have been studied quantitatively, and the research accuracy also improved. However, predictions and analyses of relevant factors on different time scales, such as short-, medium-, and long-term, are still lacking. Therefore, this study suggests increasing the quantitative assessments of future ecological risks, improving the predictive accuracy levels of short-term ecological changes, and enhancing the ability to predict ecological changes on a long-term scale, which would aid in ecological risk management on the QTP.

(3) Improve the level of ecological protection in the QTP region, balancing the developmental interests of communities and ecological protection, and ensuring the sustainable development of the QTP.

Ecological protective measures on the QTP should not only benefit the ecological health of the region, but also take into consideration the well-being of its human communities, because human beings are one of the most important controlling factors in the system. Therefore, this study suggests that the sensitivity analyses of the QTP ecosystem to human activities should be enhanced in future studies, to protect community well-being and achieve harmony between humans and nature, while carrying out measures related to ecological protection.

(4) Evaluate ecosystem assets and ecosystem services, and explore the ecological dividends of the QTP.

In recent years, the ecosystem assets and services assessments of the QTP have received attention, becoming hot topics of ecological research in China in 2015–2019. Under the double influence of global climate change and human activities, ecosystem assets and services have undergone significant changes, resulting in a series of impacts on the QTP and its surrounding regions. Quantitative assessments of the spatio-temporal variation characteristics of ecosystem assets and services in the QTP are of great significance for sustainable ecosystem management and regional ecological security. Therefore, this study suggests that quantitative research on ecosystem assets of the QTP should be continued, a systematic framework for ecosystem service value assessments should be established, and the value and role of ecological research in supporting the sustainable development of the QTP should be recognized.

4. Conclusions

Here, a bibliometric analysis of 4315 ecological research papers on the QTP from the WOS database published in 1990–2019 was performed using nine dimensions. Based on the relevant results and further analyses, the following conclusions and suggestions were drawn:

First, the QTP is becoming a popular area of global ecological research, and the number of ecological research papers has undergone an exponential growth trend. In addition to the two QTP neighboring countries, China and India, developed countries, including the USA, UK, and Japan, have also carried out ecological research on the QTP. Because of their established research traditions, they have had great influence. At the institutional level, CAS has the greatest research influence.

Second, the ecological research on the QTP is trending toward multidisciplinary and integrative studies. Based on the analysis of research areas, in addition to 'Environmental Sciences & Ecology', academic disciplines including 'Agriculture' and 'Plant Sciences' also play huge roles in the ecological research on the QTP. This multidisciplinary integration will continue, and will contribute to the increased quality of ecological research on the QTP.

Third, the level of international cooperation in ecological research on the QTP requires improvement. Analyses of the cooperation of core authors, author institutions, and countries revealed that the top 21 core authors are all from China. In addition, their institutions showed a strong national cooperation trend but the lack of international cooperation. In terms of national cooperation, more focus should be on cooperation between China and the USA. The previous loose level of international cooperation is not conducive to the long-term development of ecological research on the QTP and deserves the attention of researchers in this field.

Fourth, hotspots of ecological research on QTP are gradually focusing on the changes, responses, and feedback of different ecological elements under the combined effects of climate change and human activities, as well as research on future development scenarios for the QTP. The comprehensive analysis results of keywords, burst words detection, and topic extraction showed that ecological research on the QTP focused on the relationships between climate change, human activities, and natural factors, including forests, grasslands, wetlands, rivers, lakes, biological communities, permafrost, and soil, in recent years. Changes in indexes, including carbon and nitrogen emissions, precipitation changes, lake evolution, biomass, ecosystem services, ecosystem response, and species abundance, have also been investigated. In addition, recent studies have paid attention to the relationship between ecological service functions and natural resource management, emphasizing the harmonious coexistence of man and nature.

On the basis of the above results, this research puts forward four suggestions for future research on the QTP: (1) focusing on frontier hotspots; (2) attaching importance to quantitative research on key ecosystem factors and predicting capabilities at different time scales to improve ecological risk prevention, control, and responses in the QTP area; (3) balancing ecological protection and community welfare, promoting the sustainable development of the QTP; and (4) quantitatively assessing ecosystem assets and the ecological benefits of the QTP.

These findings and suggestions will not only help the ecological scientific research community to clarify the past research situation and plan future research directions on the QTP, but will help various research institutions and organizations in talent selection and international cooperation. In addition, it will help some countries to clarify their positions on ecological research and improve research and development on the QTP. It may even help researchers choose their research directions.

This study analyzed the characteristics of various aspects of ecological research on the QTP in detail and obtained its macro-knowledge map using bibliometrics methods. However, it still has the following limitations that should be improved in the future: (1) The database. Although the WOS is a popular and comprehensive database of papers, the papers are mainly in English, which limits the consideration of the research and achievements of non-English papers; (2) Data retrieval. Although this study tried to carry out a comprehensive data retrieval, it is still inevitable that some data was not included in the analysis; and (3) Software limitations. The bibliometrics of this research was based on a variety of measurement software programs. However, the functions and analyses of many software programs still need improvement. With the advancement of technology, software packages will provide better analysis solutions and results. In addition, the research only conducted a preliminary bibliometrics analysis from the perspective of publications, and further research needs to incorporate an analysis of the detailed texts of related cutting-edge scientific papers.

Declaration of Competing Interest

None.

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